Achilles tendon injury rehabilitation and lower limb biomechanics

Colin Griffin

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Rééducation des lésions du tendon d'Achille et biomécanique des membres inférieurs

Colin GRIFFIN

Laboratoire Motricité Humaine, Education, Sport, Santé (LAMHESS) – UPR 6312

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Dirigée par : Jean-Benoît MORIN

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Devant le jury, composé de :
Antoine NORDEZ, PR, Université Nantes, Rapporteur (Président)
Taija FINNI, PR, Université Jyväskylä, Rapportrice
Pauline GERUS, MCF HDR, Université Côte d'Azur, Examinatrice
Alexandre RAMBAUD, PhD, Université Jean Monnet Saint-Etienne, Examinateur
Jean-Benoît MORIN, PR, Université Jean Monnet Saint-Etienne, Université Côte d'Azur, Directeur
Neil WELCH, PhD, Sports Surgery Clinic, Dublin, Membre invité

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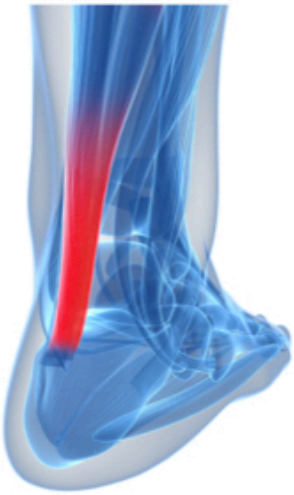
Achilles Tendon Injury Rehabilitation and Lower Limb Biomechanics

Colin Griffin MSc



Supervised by:

Jean-Benoît Morin

Jury

Reporters:

Taija Finni, Professor, University of Jyväskylä, Finland

Antoine Nordez, Professor, University of Nantes

Examiners:

Pauline Gerus, PhD, University of Côte d'Azur

Alexandre Rambaud, PhD, University Jean Monnet Saint-Etienne

Invited member:

Neil Welch, PhD, Sports Surgery Clinic, Dublin Ireland

ABSTRACT (ENGLISH)

Achilles tendon injuries are common in elite and recreational sports athletes, with functional impairments that can persist for a long time. There is a need for standardised performance tests for calf strength and lower limb biomechanics during hopping, to provide objective markers to help guide rehabilitation progression and return to sport decision-making. Traditional Achilles tendinopathy rehabilitation programs focus on one exercise mode or use pain as the sole guide to progress exercises. Therefore, a criteria-based rehabilitation program is warranted to determine a suitable entry point for the patients and to direct their progression, and ultimate return to sport. This thesis centred around two themes. In the first theme, we tested the reliability and evaluated key performance and biomechanical features in a single-leg horizontal plyometric (SLHH) exercise (Study 1), and measured the reliability of IKD PF torque at 30°/sec with the knee extended, and F_{peak} in a seated calf isometric test (study 2). In Study 1, we found moderate-to-excellent reliability for most key performance and biomechanical features in a single-leg horizontal plyometric exercise. The study also revealed that horizontal ground reaction force and peak hip joint moment correlated with rebound distance and horizontal reactive strength index. Joint power and work were highest at the ankle, while joint stiffness was higher at the knee compared to the ankle. A stable correlation with the mean for the majority of variables was reached by the third trial. In study 2, we found good reliability for plantar flexor T_{peak} (ICC = 0.87; 95% CI 0.70, 0.95) and torque at 10° dorsiflexion (ICC = 0.83; 95% CI: 0.62, 0.93), but moderate reliability for torque at 20° plantarflexion (ICC = 0.58; 95% CI: 0.19, 0.81) for an isokinetic test at 30°/sec. We showed good reliability for F_{peak} (ICC = 0.78; 95% CI: 0.51, 0.91) in the seated calf isometric test. In Theme 2, we evaluated a biomechanical and strength approach to the rehabilitation of Achilles tendon injuries. Study 3 is a protocol for a randomised-controlled trial which is currently ongoing. We evaluated the effectiveness of a rehabilitation program based on achieving strength targets to progress (SSC6) with Silbernagel's rehabilitation program (SG). In study 4, we reported on the preliminary results of the trial based on 28 participants who have thus far completed the program (SSC6: n = 16; SG: n = 12). This study was significantly impacted by Covid 19 for prolonged periods. We found that both groups significantly improved their VISA-A scores over the 12-week intervention (SSC6 + 25.6 points; $p < 0.001$; ES: 1.80 (0.92, 2.58), SG + 17.47 points; $p = 0.01$; ES: 1.20 (0.30, 2.03)), with the greatest improvements occurring in the first 6 weeks. SSC6 group had a 9.13 point greater improvement in their VISA-A scores over 12 weeks compared to SG but the difference was not significant with the current sample size (p =

0.08; ES: 0.67 (-0.10, 1.44)). Larger improvements in bent-knee PF isokinetic peak torque were observed for the SSC6 group for both injured (p = 0.05; ES: 0.91 (-0.01, 1.83)) and uninjured limbs (p = 0.04; ES: 0.93 (0.01, 1.85)) but no significant between-group differenced were detected. We found no significant biomechanical or performance asymmetries or changes over the 12-week p[program in the hop tests and running assessments. Study 5 is a case report for an athlete who underwent an Achilles tendon repair following a rupture. We documented his rehabilitation pathway over 36 weeks and collected subjective as well as performance and biomechanical data at weeks 12, 19, 26 and 36. Our testing revealed persistence injured limb deficits in plantar flexor T_{peak}, torque at 20 plantarflexion on IKD testing and F_{peak} on a seated calf isometric test. We also demonstrated impairments in Ankle peak joint power on a single drop jump and SLHH on his injured side which regained reasonable symmetry at week 36. This thesis contributed to the rehabilitation of AT injuries where a pain-guided approach and daily program of exercises may not be necessary – particularly for competitive athletes. The use of performance testing to measure PF strength and hop performance, which in our study showed good reliability, can help guide decision-making during rehabilitation and return to sport. The findings of our thesis must be considered in light of our small sample sizes and the impact of covid-19 during critical stages of data collection.

Keywords: Achilles tendon, injury, running, biomechanics, strength, plyometric training

ABSTRACT (FRENCH)

Les blessures au tendon d'Achille sont courantes chez les athlètes de sports d'élite et de loisir avec des déficiences fonctionnelles qui peuvent persister longtemps. Il est nécessaire de disposer de tests de performance standardisés pour la force du mollet et la biomécanique des membres inférieurs pendant le saut afin de guider la progression de la rééducation et la prise de décision pour le retour au sport. Les programmes traditionnels de rééducation de la tendinopathie d'Achille se concentrent sur un mode d'exercice ou utilisent la douleur comme seul guide pour faire progresser les exercices. Par conséquent, un programme de réadaptation basé sur des critères est justifié pour déterminer un point d'entrée approprié pour les patients et pour orienter leur progression et leur retour ultime au sport. Cette thèse s'est articulée autour de deux thèmes. Dans le premier thème, nous avons testé la fiabilité et évalué les performances clés et les caractéristiques biomécaniques dans un exercice de pliométrie horizontale à une jambe (SLHH) (étude 1) et mesuré la fiabilité du couple IKD PF à 30°/sec avec le genou étendu, et F_{peak} dans un test isométrique du mollet assis (étude 2). Dans l'étude 1, nous avons trouvé une fiabilité modérée à excellente pour la plupart des performances clés et des caractéristiques biomécaniques dans un exercice de pliométrie horizontale à une jambe. L'étude a également révélé que la force de réaction horizontale au sol et le moment maximal de l'articulation de la hanche étaient corrélés à la distance de rebond et à l'indice de force réactive horizontale. La puissance et le travail articulaires étaient les plus élevés à la cheville, tandis que la raideur articulaire était plus élevée au genou qu'à la cheville. Une corrélation stable avec la moyenne pour la majorité des variables a été atteinte par le troisième essai. Dans l'étude 2, nous avons trouvé une bonne fiabilité pour le T_{peak} du fléchisseur plantaire (ICC = 0.87; 95% CI: 0.70, 0.95) et le couple à 10° de dorsiflexion (ICC = 0.83; 95% CI: 0.62, 0.93), mais une fiabilité modérée pour le couple à Flexion plantaire à 20° (ICC = 0.58; 95% CI: 0.19, 0.81) pour un test isocinétique à 30°/sec. Nous avons montré une bonne fiabilité pour F_{peak} (ICC = 0.78; 95% CI: 0.51, 0.91) dans le test isométrique du mollet assis. Dans le thème 2, nous avons évalué une approche biomécanique et de force pour la réhabilitation des lésions du tendon d'Achille. L'étude 3 est un protocole pour un essai contrôlé randomisé qui est actuellement en cours. Nous avons évalué l'efficacité d'un programme de rééducation basé sur l'atteinte d'objectifs de force pour progresser (SSC6) avec le programme de rééducation de Silbernagel (SG). Dans l'étude 4, nous avons rendu compte des résultats préliminaires de l'essai sur la base de 28 participants ayant terminé le programme (SSC6: n = 16; SG: n = 12). Cette étude a été significativement impactée par le Covid 19 pendant des périodes prolongées. Nous avons constaté que les deux

terrains ont significativement amélioré leurs scores VISA-A au cours de l'intervention de 12 semaines (SSC6 + 25.6 points ; $p < 0.001$; ES: 1.80 (0.92, 2.58), SG + 17.47 points ; $p = 0.01$; ES: 1.20 (0.30, 2.03)), les plus grandes améliorations se produisant au cours des 6 premières semaines. Le groupe SSC6 a eu une amélioration supérieure de 9.13 points de ses scores VISA-A sur 12 semaines par rapport au groupe SG, mais la différence n'était pas significative avec la taille actuelle de l'échantillon ($p = 0.08$; ES: 0.67 (-0.10, 1.44)). Des améliorations plus importantes du couple maximal isocinétique PF du genou plié ont été observées pour le groupe SSC6 pour les membres blessés ($p = 0.05$; ES: 0.91 (-0.01, 1.83)) et non blessés ($p = 0.04$; ES: 0.93 (0.01, 1.85)), mais aucune différence significative entre les groupes n'a été détectée. Nous n'avons trouvé aucune asymétrie ou modification biomécanique ou de performance significative au cours des 12 semaines du programme dans les tests de saut et les évaluations de course. L'étude 5 est un rapport de cas pour un athlète qui a subi une Réparation du tendon d'Achille suite à une rupture Nous avons documenté son parcours de rééducation sur 36 semaines et collecté des données subjectives ainsi que de performance et biomécaniques aux semaines 12, 19, 26 et 36. Nos tests ont révélé la persistance de déficits du membre lésé en fléchisseur plantaire T_{peak}, couple à 20 plantarflexion sur le test IKD et F_{peak} sur un test isométrique du mollet assis Nous avons également démontré des altérations de la puissance articulaire maximale de la cheville sur un seul saut en chute et SLHH sur son côté blessé qui a retrouvé une symétrie raisonnable à la semaine 36. Cette thèse contribuée à la rééducation des blessures AT où une approche guidée par la douleur et un programme quotidien d'exercices peuvent ne pas être nécessaires - en particulier pour les athlètes de compétition. L'utilisation de tests de performance pour mesurer la force du PF et la performance du saut, qui dans notre étude a montré une bonne fiabilité, peut aider à guider la prise de décision lors de la rééducation et du retour au sport. Les résultats de notre thèse doivent être considérés à la lumière de la petite taille de nos échantillons et de l'impact du covid-19 lors des étapes critiques de la collecte de données.

Mots clés: Tendon d'Achille, course, biomechanique, force, entraînement pliométrique

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TABLE OF CONTENTS:

1. OVERVIEW

1.1. THESIS PUBLICATIONS

Publications in peer-reviewed journals:

1. Griffin, C., Daniels, K., Hill, C., Franklyn-Miller, A. Morin J.B (2021). A criteria-based rehabilitation program for chronic mid-portion Achilles tendinopathy: study protocol for a randomised controlled trial. BMC musculoskeletal disorders 22 (1), 1-14
2. Griffin, C., Daniels, K., Richter, C., Franklyn-Miller, A. Morin J.B (2022). A novel single-leg horizontal plyometric exercise task: reliability, stiffness and joint mechanical outputs**.** Sports Biomechanics (in review)

Publications due for submission:

1. Griffin, C., Ryan, L., King, E., Morin, J.B (2022). Rehabilitation and biomechanical evaluation in a football player following an Achilles tendon repair, JOSPT Cases
2. Griffin, C., Morin, J.B (2022). Test-retest reliability for a seated calf isometric strength test
3. Griffin, C., Daniels, K., Hill, C., Franklyn-Miller, A. Morin J.B. A criteria-based rehabilitation program for chronic mid-portion Achilles tendinopathy: a randomised controlled trial
   Expected publication in 2024 when the trial has concluded, and long-term follow-ups are complete

Conference presentations:

1. Griffin, C., Richter, C., Franklyn-Miller, A. Morin J.B (2018). The Number of Trials Required to Obtain a True Representation of Biomechanical Features Extracted During a Single Leg Hurdle Hop Exercise. European College of Sports Science
2. Griffin C, Richter C, Franklyn-Miller A, Morin JB (2018). A novel single-leg hurdle hop exercise: test-retest reliability of vertical stiffness, contact time, ground reaction force, total hop distance and rebound distance. World Congress of Biomechanics

1.2. List of tables

Page

1.3. List of figures

Page

1.4. Abbreviations

AT: Achilles tendon
BW: Bodyweight
CoV: Coefficient of variation
MTU: Muscle-tendon unit
MTJ: Myotendinous junction
BTJ: Bone-tendon junction
ECM: Extra-cellular matrix
PF: Plantar flexor
ISO: Isometric
IKD: Isokinetic
T_{peak}: Peak torque
F_{peak}: Peak Force
VISA-A: Victorian Institute of Sport assessment – Achilles tendon
GROC: Global rating of change
kN: Kilonewtons
N: Newtons
Nm: Newton-meters
SSC: Stretch-shortening cycle
CSA: Cross-sectional area
PCSA: Physiological cross-sectional area
HSR: Heavy slow resistance
NPRS: Numerical pain-rating scale
DLDJ: Double leg drop jump
SLDJ: Single-leg drop jump
SLHH: Single-leg horizontal rebound
JH: Jump height
CT: Contact time
RSI: Reactive strength index
hRSI: Horizontal reactive strength index
PT: Plyometric training
K: Stiffness
K_{vert}: Vertical stiffness
K_{leg}: Leg stiffness
$K_{knee:}$ knee joint stiffness
K_{ankle}: Ankle joint stiffness
K_{AT}: Achilles tendon stiffness
SWE: Shear wave elastography
GRF: Ground reaction force
vGRF: Vertical ground reaction force
hGRF: Horizontal ground reaction force
F_{leg}: Leg force
SO: Soleus
MG: Medial gastrocnemius
TS: Triceps surae
SEM: Standard error of measurement
ICC: Intra-class correlation
LG: Lateral gastrocnemius
MRI: Magnetic resonance image
US: Ultrasound
LSI: Limb-symmetry index
ES: Effect size
RA: Rheumatoid arthritis
SpA: Spondyloarthropathy
RTS: Return to sport
CoM: Centre of mass
MCV: Maximal voluntary contraction
MMP: Matrix metalloproteinase
TIMP: Tissue inhibiter metalloproteinase

1.5. Thesis structure

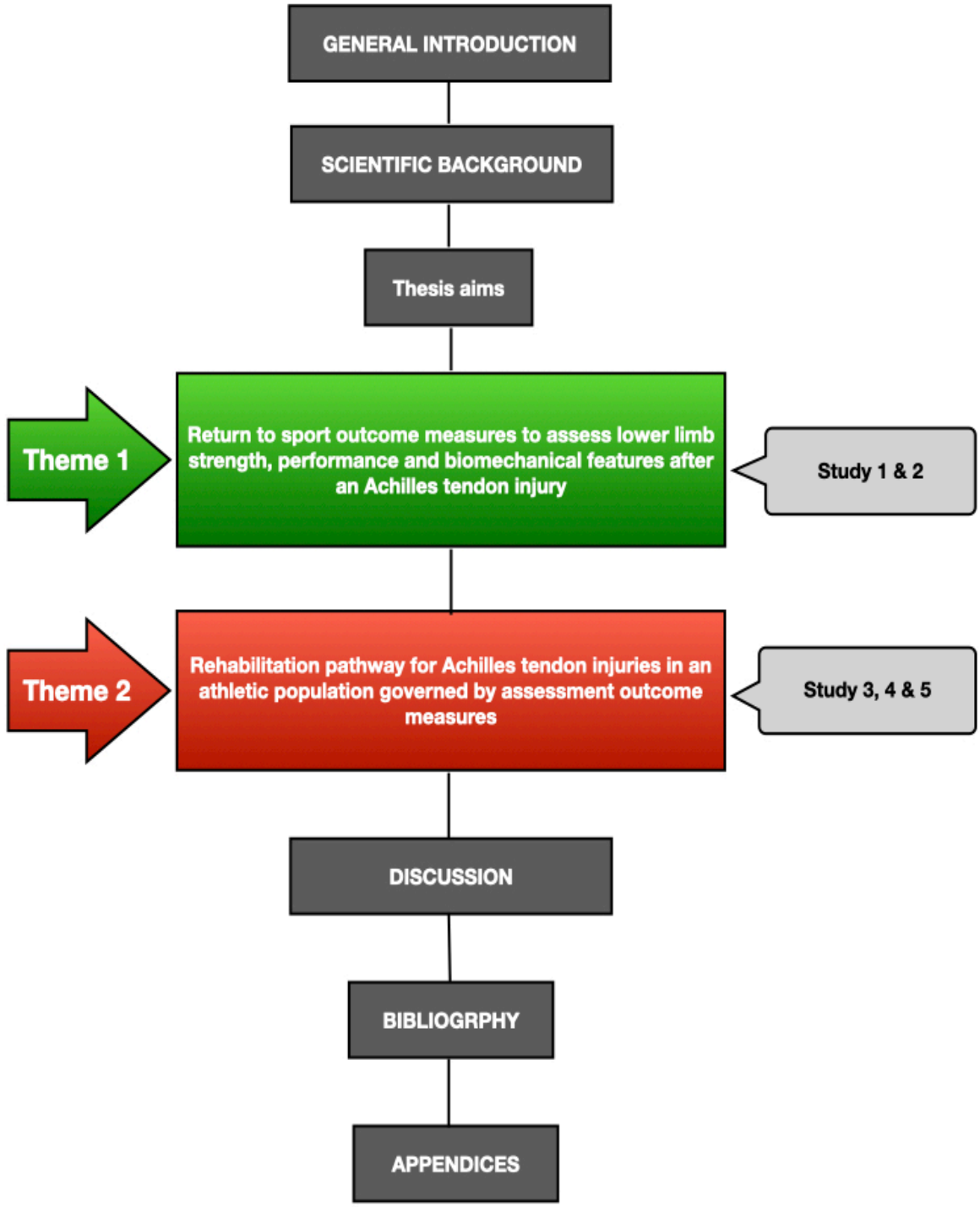


Fig. 1. Thesis thematic structure

1.6. GENERAL INTRODUCTION

Achilles tendon (AT) injuries regularly occur in elite and recreational sports, and in the general population. Among distance runners, it is the 2nd most common injury site (Francis *et al.*, 2019), with around half experiencing an Achilles tendon injury in their lifetime (Kujala *et al.,* 2005). Like most energy storage tendons, the AT can withstand high tensile forces of more than 12 times body weight and loading rates of over 150 body weights per second during high-speed running and hopping (Komi, 1990; Gheidi *et al.*, 2018; Baxter *et al.*, 2021). The AT is a highly mechanically-sensitive and metabolically active organ regulated by fibroblastic cells that reside between the collagen fibers and fascicles. When the cells sense too much or too little load, they respond accordingly, altering the extracellular matrix (ECM) composition and producing new collagen proteins (Magnusson e*t al.,* 2010; Lavagnino *et al.*, 2015). Overuse injuries to the AT, such as Achilles tendinopathy, occur when the tendon cannot adapt on demand to the repetitive loading imposed on it. Achilles tendinopathy occurs in the mid-portion of the AT and at the heel insertion. In the latter case, symptoms may also be driven by an inflamed bursa or a Haglund's deformity, which increases compressive loading around the bone. Acute AT injuries, like a rupture, occur when the tendon is stretched rapidly to a region close to tissue failure. AT ruptures are more prevalent during explosive movements such as jumping, landing, accelerating, or changing direction, and feature more commonly in jump athletes and field sports players (De la Fuente *et al.*, 2019; Tarantino *et al.*, 2020). There is evidence of pathological changes that occur in the AT before a rupture making the tissue more vulnerable (Maffulli *et al.,* 2015).

Risk factors for developing Achilles tendinopathy include reduced PF strength, biomechanical gait features, prior experience of tendinopathy, training in cold weather, consumption of ofloxacin antibiotics, metabolic factors, and alcohol consumption (van der Vlist *et al.*, 2019). Reduced PF strength may reduce the tendon's capacity to tolerate high loads. Other factors such as antibiotics, metabolic profile, or alcohol consumption may alter the tendon's metabolism to delay recovery with an incomplete remodelling in response to load-induced tissue damage. There is evidence for higher than normal levels of collagen turnover preceding the development of Achilles tendinopathy (Heinemeier *et al.*, 2018). Identifying injury mechanisms is complex, and various models have been proposed. The complex systems approach (Bittencourt *et al.*, 2016) acknowledges the multifactorial nature of sports injuries. Its model is constructed on a complex interaction between plausible risk factors with resulting pattern recognition. The

mechanical fatigue model describes the damage accumulation and failure of load-bearing biological tissue, such as tendons or bone, over repetitive cycles (Edwards, 2018). Patients with AT injuries can have long-term impairments that may affect their sports participation and quality of life. Some patients with Achilles tendinopathy can have symptoms for longer than ten years (Silbernagel *et al.*, 2007). In a cohort of NFL players, only 60% who suffered an AT rupture returned to their sport at the same pre-injury performance level (Yang *et al.*, 2019).

AT injuries can result in reduced calf muscle strength and load-bearing capacity of the AT. It can also result in altered gait features and reduced hop performance. Despite being highlighted as a risk factor, only one prospective study demonstrated reduced PF strength in military recruits who subsequently developed Achilles tendinopathy (Mahieu, 2006). However, patients with Achilles tendinopathy display reduced PF strength on their injured limb (Hasani *et al.*, 2021) or in both limbs compared to an uninjured matched cohort (McAuliffe *et al.*, 2019; O'Neill *et al.,* 2019). Achilles tendinopathy may affect muscle recruitment and coordination in the PFs with evidence of intracortical inhibition (Fernandes *et al.*, 2022) and reduced neural drive to the lateral gastrocnemius muscle observed (Crouzier *et al.*, 2019). Similarly, PF deficits, reduced heel raise height, and reduced power from the ankle are observed in athletes recovering from an AT rupture (Zellers *et al.,* 2016; Willy *et al.*, 2017; Stäudle *et al.*, 2022). These deficits are attributed to increased tendon slack length resulting in reduced muscle fascicle length and increased pennation angle to maintain optimal tension within the muscle-tendon unit (Hullfish *et al.,* 2019; Khair *et al.*, 2022). Despite these findings, there are no recommended thresholds published for PF strength as a rehabilitation target or to clear an athlete to return to performance safely. There is no consistency with IKD or isometric test protocols used by clinicians and researchers, making it difficult to compare and interpret PF force or torque values (McAuliffe *et al.*, 2019). Athletes with Achilles injuries often display impaired hop performance (Silbernagel *et al.*, 2006; Debenham *et al.*, 2016; Sancho *et al.*, 2022). Tendon stiffness is related to reactive strength and the early-phase rate of force development (Maffiuletti *et al.*, 2016). Tendinopathy alters the mechanical and material properties of the AT (Arya and Kulig, 2010). Many athletes with Achilles tendinopathy display reduced tendon stiffness on the injured limb coupled with reduced single-leg hop distance, rate of force development, and delayed recruitment of the PF muscles (Wang *et al.*, 2012). Horizontal hopping has slightly greater AT loading rates than vertical hopping (Gheidi *et al.*, 2018; Baxter *et al.*, 2021). When taking into consideration the hop test impairments observed in athletes with AT injuries, the role of tendon mechanical and material properties in hop

performance, and the loading demands on the AT during vertical and horizontal hopping; a challenging maximal effort hop test may be a robust measure of an athletes recovery from an AT injury and readiness to return to their sport at a pre-injury level. Few studies have investigated running gait features in Achilles tendinopathy despite its acknowledgement as a risk factor. During running and acceleration, the ankle contributes the highest amount of joint work when compared to the knee and hip, while the PFs contribute the largest muscle force contributions during the stance phase (Dorn *et al.,* 2012; Sanno *et al.*, 2018; Pandy *et al.*, 2021). AT forces at slow-to-moderate running speeds can be between 4-7 times bodyweight (Gheidi *et al.*, 2018; Starbuck *et al.*, 2021) and around 12 times bodyweight during maximal speed running (Komi, 1990). A recent systematic review and meta-analysis found limited evidence for neuromuscular alterations in the lower limb during running in Achilles tendinopathy patients compared to uninjured controls (Sancho *et al.*, 2019). New advances in wearable technology have made it possible to measure AT loading in real-time during running (Harper *et al.*, 2020). There is a strong need for a battery of tests that measure PF strength and hop performance, including key biomechanical features, and assess running biomechanics to observe and re-train any gait features associated with the injury.

Rehabilitation practices for Achilles tendinopathy in the 1980s and 90s focussed on eccentric calf exercise (Stanish *et al.,* 1986; Alfredson *et al.*, 1998). In recent years it has been established that contraction type alone has little or no impact on tendon adaptations and that high-intensity loading that induces sufficient strain over a long enough duration is most impactful (Beyer *et al.*, 2015; Bohm *et al.,* 2015; Lazarczuk *et al.*, 2022). However, to adequately prepare an athlete for the demands of competitive sport, a comprehensive rehabilitation involving strength and plyometric exercises has been proposed (Silbernagel *et al.*, 2007a; Cook and Docking, 2015; Silbernagel and Crossley, 2015; Mascaró *et al.*, 2018; Baxter *et al.*, 2021). The only recommended guidelines for progressing exercise loading are based on pain response to exercise with no specific relative strength, biomechanical changes, or hop symmetry targets (Silbernagel and Crossley, 2015). In the case of hamstring muscle strain injuries, Mendiguchia *et al.* (2017), proposed a criteria-based rehabilitation program. In the same injury, Hickey *et al.* (2020) demonstrated that athletes who were allowed to exercise to a maximal allowable level of pain had a similar return to play timeframe but achieved earlier improvements in knee flexor IKD strength. This same group also maintained muscle morphological properties compared to pain-free athletes who completed their rehabilitation. Similar concepts have yet to be explored for AT injuries.

In this thesis, we would like to test the reliability of a PF strength test, and a novel hop test - both clinically applicable and also explore the biomechanical features of the latter. We would also like to investigate a criteria-based rehabilitation program for AT injuries and evaluate PF strength, hop test performance, biomechanical characteristics, and running biomechanics throughout a rehabilitation pathway.

2. SCIENTIFIC BACKGROUND

2.1 OVERVIEW

The AT is the most robust tendon in the human body, capable of tolerating high levels of stress and strain before failure (Komi *et al.,* 1992; Wren *et al.*, 2001, 2003; Nagelli *et al.*, 2022). The AT has three main functions: to transfer force between muscle and bone to generate movement, to store and return elastic energy produced by the muscles, and to protect the muscle fibers as the muscle-tendon unit (MTU) experiences fast eccentric actions (Roberts and Azizi, 2011). It experiences tensile forces of up to six times body weight during distance running (Starbuck *et al.*, 2021) to 12 kN and loading rates of 150 body weights per second during high-speed running (Komi, 1990; Komi *et al.,* 1992; Baxter *et al.*, 2021). As part of an MTU with force generated by the triceps surae (TS) muscles, it plays an essential role in energy storage during stretch-shortening cycle (SSC) activities such as running and hopping, power amplification such as accelerating and jumping, and power attenuation such as landing and decelerating (Lichtwark, 2005; Lai *et al.*, 2014; Farris *et al.*, 2016). Tendon mechanical properties such as stiffness, which is a measure of the amount of elongation based on the force applied to the tendon, have been associated with running economy, sprint, change of direction, and reactive strength performance (Lichtwark and Wilson, 2008; Fletcher *et al.,* 2010; Fouré *et al.,* 2010; Albracht and Arampatzis, 2013). The "Achilles heel" is an analogy used to describe an area of vulnerability, and in athletes, the AT, despite its high load-bearing capacity, is highly vulnerable to injury. Injuries such as Achilles tendinopathies and ruptures can result in long-lasting impairments that impact an athlete's ability to return to the same level of competitiveness in their sport or their quality of life.

2.2 ACHILLES TENDON ANATOMY

The AT comprises sub-tendon fascicles from the *gastrocnemii* and soleus muscles, which fuse and connect distally to the calcaneus *(Fig. 2.1).* In a small number of people, the plantaris tendon conjoins with the AT before its insertion (Roche and Calder, 2018) [see section 2.4.4]. The AT has a length of up to 15 cm and a diameter of 2.5 cm (O'Brien, 2005). The AT is broad at its proximal origin and narrows as it runs distally before broadening and flattening over the calcaneus (Dalmau-Pastor *et al.,* 2014). The sub-tendon fascicles from the individual TS muscles rotate clockwise on the left leg and counter-clockwise on the right (Edama *et al.*, 2015). Soleus fibers which fuse anteriorly, terminate on the medial side of the AT, while fibers

from the MG fuse on the posterolateral side and anterolaterally from the LG (Szaro *et al.*, 2009; Edama *et al.*, 2015). Under tensile loading, the sub-tendon fascicles of the AT externally rotate (van Gils *et al.,* 1996; Obst *et al.*, 2014). The AT fascicles undergo non-uniform displacement during loading, with more displacements observed in the deeper anterior portion of the tendon consistent with where SOL sub-tendon fascicles run (Arndt *et al.*, 2012; Obst *et al.*, 2014). The site of the greatest torsion of fascicles is the poorest vascularised part of the AT (Theobald *et al.*, 2005; Chen *et al.*, 2009) and the area of highest stress concentration due to the lower CSA (Reeves and Cooper, 2017). It is the familiar site of tendinopathy and ruptures.

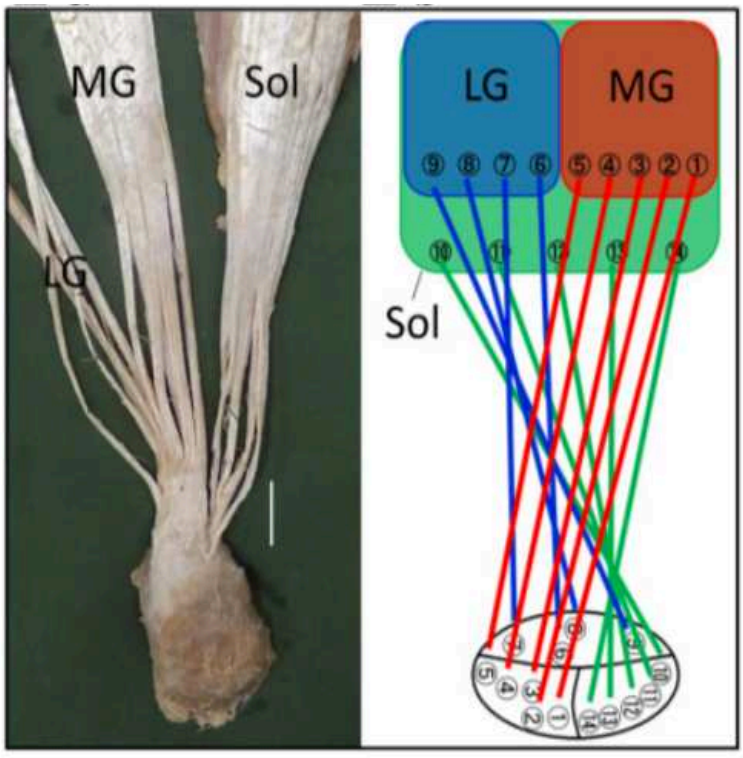


Fig. 2.1. Cadaver dissection and illustration of the twisted structure of the AT sub-tendon fascicles (Edema et al. 2015)

2.2.1 TENDON HIERARCHICAL STRUCTURE

Collagen molecules (or tropocollagen) assemble into fibrils. Both fibrils and molecules have lysyl-oxidase cross-links, which provide elastic support under tensile loading and ensure that any microdamage is contained at fibril level (O'Brien, 1997; Wang, 2006). The fibrils assemble into fibers, and in between the fibrils and fibers are the fibroblastic cells called tenocytes. The fibers and their bundles form a fascicle regarded as the tendon core or tendon proper and are the basic functional unit of the tendon (Snedeker and Foolen, 2017). A synovial sheath called an endotenon encapsulates the fascicle and an epitenon, a thin layer of loose connective tissue

with nervous, vascular, and lymphatic structures; surrounds the tendon (O'Brien, 1997; Kannus, 2000). The endotenon connects to the epitenon via separating septa and enters into the tendon tissue. The paratenon is a loose areolar connective tissue surrounding the epitenon and consists of type I and III collagen fibrils, elastic fibrils, and synovial calls (Kannus, 2000; Wang, 2006). The space between the paratenon and epitenon is also known as peritendinous tissue. These outer layers of synovial sheath tissue enable frictionless sliding to occur. Figure 2.2 illustrates the hierarchical collagen arrangement of the tendon. Nerves, blood vessels, and immune cells reside in the paratenon and terminate in the endotenon (O'Brien, 1997). Therefore, there is no vascular or nerve supply directly into the tendon core.

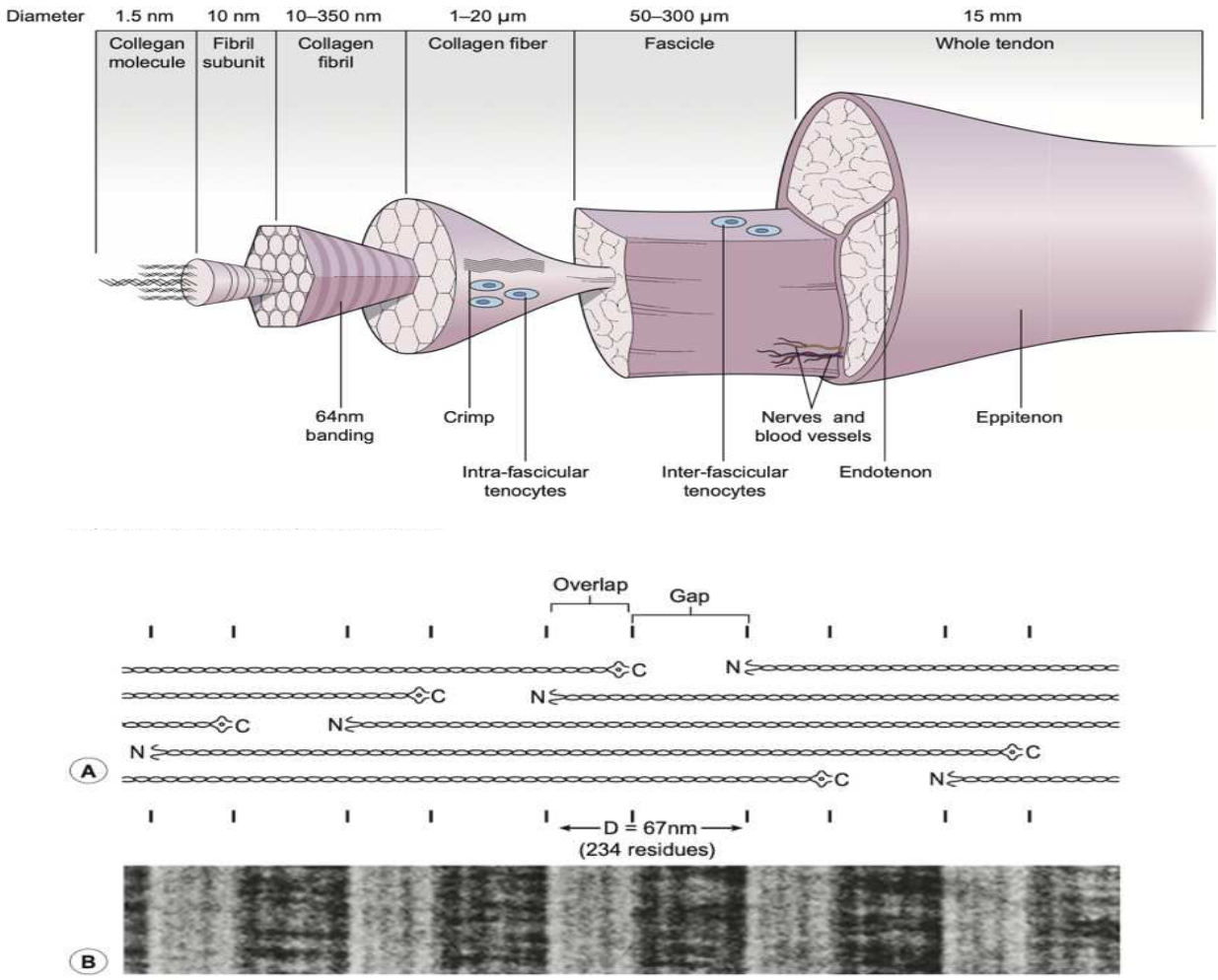


Fig. 2.2. Illustration of a tendon's hierarchical structure (Thorpe et al., 2010)

2.2.2 TENDON COMPOSITION

Tendons comprise an extracellular matrix (ECM), cells, and non-matrix proteins. The ECM comprises predominantly type I collagen molecules with smaller amounts of type III and IV, glycoprotein and proteoglycan ground substances, and anorganic proteins (O'Brien, 1997; Wang, 2006). Table 2.1 lists the various components of the ECM and their respective functions, Collagen makes up 30% of the tendon composition, with elastin 2% and the remaining 68% water. Type I collagen represents up to 95% of total collagen content in the tendon, with type III accounting for around 3% and even lesser amounts of other collagen types. At the BTJ, there are higher amounts of type II collagen – a cartilage structure designed to resist compression (Waggett *et al.*, 1998). Collagen molecules form from the assembly of three polypeptide chains – glycine, proline, and hydroxyproline (GLY-X-Y), which include a left-hand triple helix of varying lengths (O'Brien, 1997; Riley, 2005). The chains are held together by hydrogen bonds and are wound around each other to form a right-hand helix, giving collagen its rod-like shape *(Fig 2.3).* The structure of the helix centre accommodates only the amino acid glycine (O'Brien, 1997). These assembled polymers give rise to collagen fibrils.

2.2.2.1. Ground substances

The ground substance of an ECM consists of a gelatin-like material that fills the spaces between the collagen fibers and the cells and provides viscoelastic properties to the tendon, as well as lubrication and spacing for fibers to glide and interact (O'Brien, 1997). The fibroblasts produce ground substances and consist of proteoglycans (PGs) and glycoproteins (GPs), a mixture of which bind fibroblasts to fibers. They account for less than 1% of the dry weight of a tendon.

PGs subdivide into two components – small leucine-rich proteoglycans (SLRPs) and large modular PGs, of which hyalectans are the most relevant (Riley, 2005). SLRPS are composed of a small protein core in which one or more GAGs are attached and found in most connective tissues with a pivotal role in modulating cell activity. They consist of decorin, biglycan, fibromodulin, and lumican, with decorin being the most abundant in tendons. Hyalectans consist of aggrecan, versican, brevican, and neurocan. Aggrecan is found throughout the tendon but is most abundant in fibrocartilaginous regions at the BTJ and helps to hold water in the tissue and resist compression (Waggett *et al.*, 1998). Versican is found in large amounts at the mid-portion and has a role in resisting tensile forces (Waggett *et al.*, 1998). PGs regulate fibril formation, as when tropocollagen reaches its eventual size, PG content decreases. Figure 2.4 illustrates the tendon composition at the mid-portion and BTJ.

GPs consist of a protein to which carbohydrate is attached and include elastin, fibronectin, decorin, biglycan, undulin, tenascin, and vitronectin. Elastin contributes to the elastic qualities of a tendon and can elongate up to 70% of its resting length without rupturing when collagen fibers slide. They may also help collagen fibers recover their wavy formation after tensile loading.

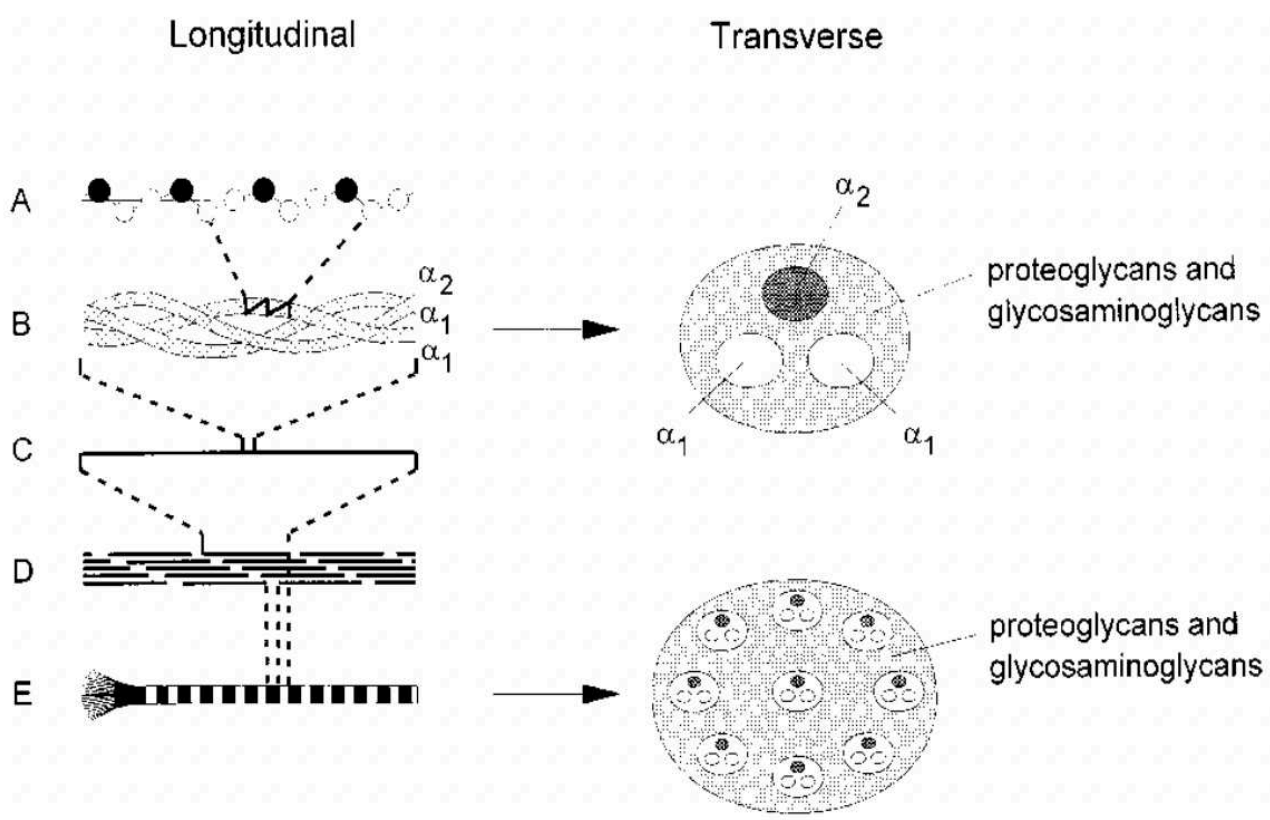


Fig. 2.3. Formation of a type I collagen fibril surrounded by ground substances (Kannus, 2000)

Anorganic proteins from less than 2% of the tendon dry mass consist of minerals such as calcium, magnesium, manganese, cobalt, copper, and zinc (O'Brien, 1997). Their primary function is to support growth, development, and regular metabolism. Copper plays a crucial role in collagen cross-linking, manganese is involved in several enzymatic reactions during collagen synthesis, and calcium supports the development of the bone-tendon junction (BTJ) (O'Brien, 1997).

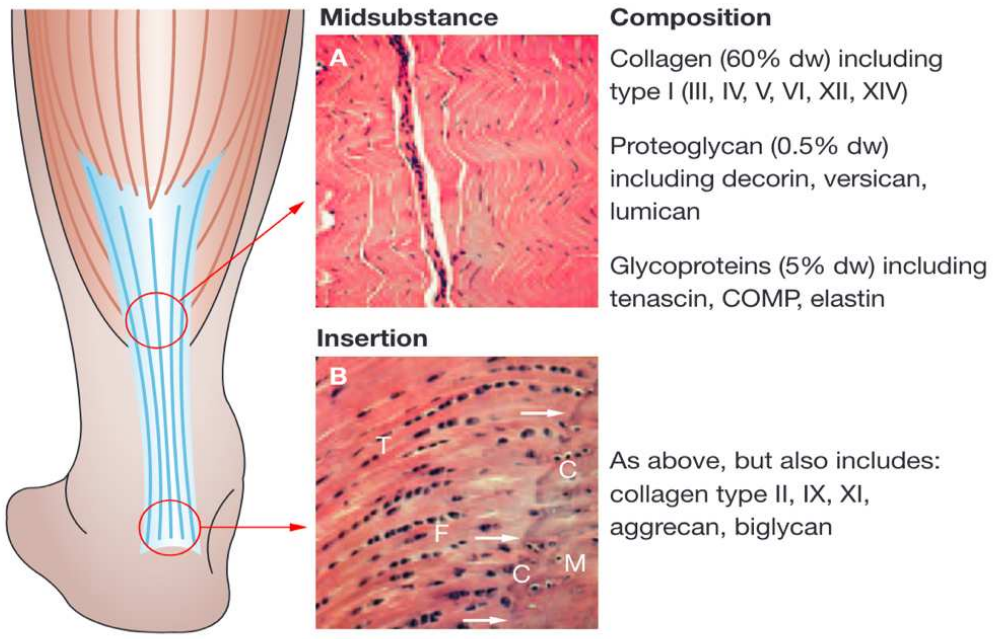


Fig. 2.4. Schematic illustration of tendon structure and composition at the mid-portion (A) and insertion (B) (Riley, 2008)

Table 2.1. Molecular composition of ECM (Riley, 2005)

Molecule	Structure/type	Location and function
Collagen		
Type I	Fibril-forming	Main constituent of tendon (~95% of total collagen)
Type II	Fibril-forming	Restricted to fibrocartilage; forms less-organised meshwork
Type III	Fibril-forming	Normally restricted to endotenon; forms smaller, less-organised fibrils
Type IV	Forms meshwork	Basement membrane of blood vessels
Type V	Fibril-forming	Core of type I collagen fibril; forms template for fibrillogenesis
Type VI	Beaded filaments	Cell-associated; found in 'seams' between fibrils
Type IX	FACIT	Mediates cell–matrix interactions with type II collagen fibril surface
Type X	Forms meshwork	Restricted to insertion fibrocartilage; associated with mineralisation?
Type XI	Fibril-forming	Core of type II collagen fibril; forms template for fibrillogenesis
Type XII	FACIT	Mediates cell–matrix interactions with type I collagen fibril surface
Type XIV	FACIT	Mediates cell–matrix interactions with type I collagen fibril surface
Proteoglycan		
Decorin	SLRP	Binds collagen, affects collagen-fibril formation, binds growth factors
Biglycan	SLRP	Binds collagen, affects collagen-fibril formation, binds growth factors
Fibromodulin	SLRP	Binds collagen, affects collagen-fibril formation, binds growth factors
Lumican	SLRP	Binds collagen, affects collagen-fibril formation
Aggrecan	Hyalectan	Resists compression; most prominent in fibrocartilage
Versican	Hyalectan	Lubricates boundary between adjacent fibrils?
Glycoprotein		
Elastin	Branched network	Forms elastic fibres; provides elastic properties of tissue
Fibrillin	Linear arrays	Forms elastic fibres; provides elastic properties of tissue
Tenascin-C	Branched molecule	Mediates cell–matrix interactions; forms 'seams' with versican
COMP	Branched molecule	Mediates cell–matrix interactions; role in fibril formation?
Fibronectin	Modular protein	Mediates cell–matrix interactions; role in tendon healing
Laminin	Modular protein	Component of basement membranes
Link protein	Globular protein	Stabilises proteoglycan–hyaluronan interactions
Thrombospondin	Modular protein	Mediates cell–matrix interactions

Abbreviations: COMP, cartilage oligomeric matrix protein; FACIT, fibril-associated collagen with interrupted triple helix; SLRP, small leucine-rich repeat proteoglycan.

2.2.2.2. Cells

During tendon injury, inflammatory cells, macrophages, and myofibroblasts are present (Jozsa and Kannus, 1997). Fibroblastic cells (tenocytes) account for up to 95% of the cellular components within a tendon, with the remainder including chondrocytes which reside at the BTJ, synovial cells, and vascular cells (Kannus, 2000). One of the main functions of fibroblast cells is to synthesize type I collagen (O'Brien, 1997).

During early childhood, the fibroblastic cells are tenoblasts which are more rounded and metabolically active with a high cell-to-matrix ratio which reduces with age. From late adolescence, the tenoblasts become more spindle-shaped and transform into tenocytes. Tenocytes have thin, flat nuclei and are highly proliferative. They have a 3-dimensional network of extensions that link with neighbouring cells and collagen fibrils via gap junctions, which may facilitate load sensing and the cell's response to load (McNeilly *et al.*, 1996). They also have a well-developed endoplasmic reticulum to synthesize polypeptides of collagen, elastin, proteoglycans, and glycoproteins. The fibroblasts produce ground substances and tropocollagen during remodelling in response to load or following injury. During the initial stages, type III collagen is deposited irregularly without cross-linking, making the structure unstable. Type I collagen, which is cross-linked and aligned with the tensile loading axis of the tendon, subsequently replaces type III (O'Brien, 1997; Riley, 2005).

2.2.3. BLOOD SUPPLY

The AT receives its blood supply from the myotendinous junction (MTJ), the bone-tendon junction (BTJ), and the paratenon (O'Brien, 2005). It is served by two arteries – primarily the posterior tibial artery, which supplies the proximal and distal regions of the AT and enters from the posterior portion, and the fibular artery at the mid-portion, where blood vessels enter from the anterior portion which is illustrated in Figure 2.5 (O'Brien, 1997; Chen *et al.*, 2009). The BTJ is the most vascularised region of the AT, while the mid-portion is the poorest. Blood supply is richest in the paratenon and, from there, runs transversely through multiple branches that enter the tendon via the endotenon and run longitudinally in parallel with the fascicles. Blood flow in the paratenon increases 2.5-fold at 2 cm and 4-fold at 5 cm, respectively, above the BTJ, during exercises compared to when at rest (Langberg *et al.,* 1998). Considering that the mid-portion is the most common site of ruptures, the previous conception that a lack of adequate vascular supply was the cause had been disputed, given that there is evidence of

degenerative changes before a rupture (Maffulli *et al.,* 2015). The mid-portion also has the lowest CSA (Reeves and Cooper, 2017). Still, when considering the number of blood vessels per unit of CSA, Ahmed *et al.* (1998) showed that the vascular supply is proportionally similar to the proximal and distal regions of the tendon. It may be plausible that the lack of adequate blood supply at the mid-portion may account for the slow healing response, coupled with the highest degree of torsion of the tendon sub fascicles and possible constriction of blood vessels under tensile loading.

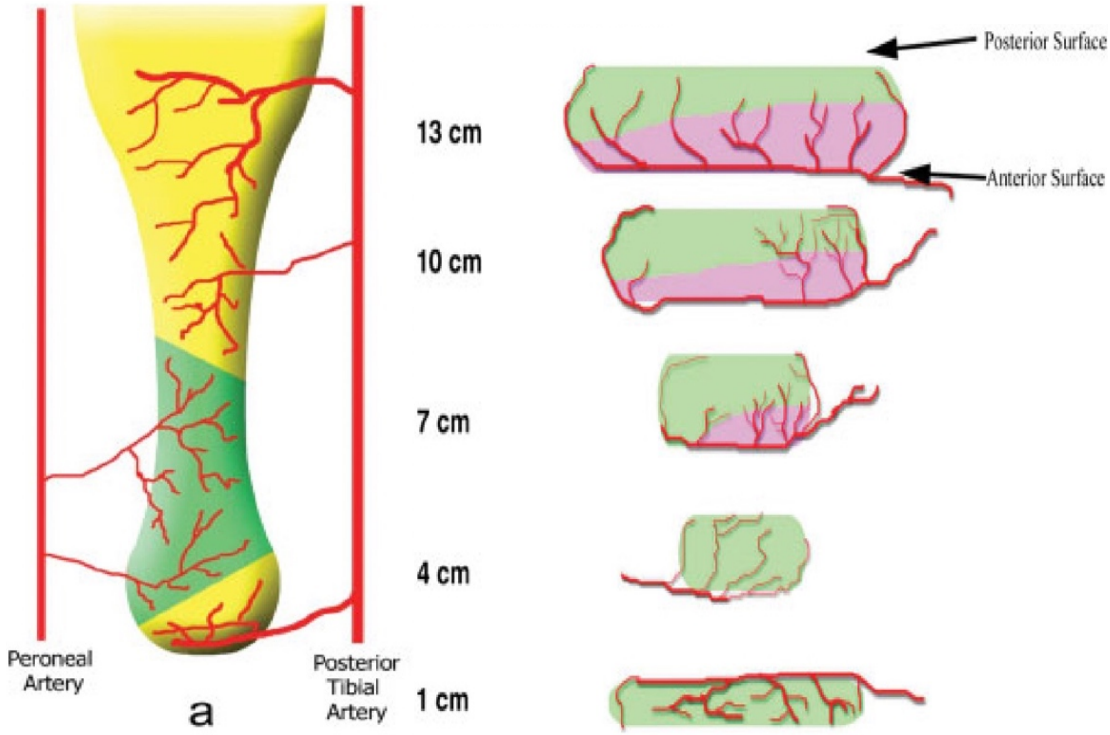


Fig. 2.5. Longitudinal view of AT blood supply (A) and coronal view of AT blood supply (B) (Chen et al., 2009)

2.2.4. NERVE SUPPLY

The AT has a low level of innervation, which may partly explain its slow healing response and the chronic nature of tendinopathies (O'Brien, 2005). It receives its nerve supply from the medial sural cutaneous nerve, a terminal branch of the tibial nerve that originates from the sciatic nerve at the popliteal fossa (Webb *et al.,* 2000; Dalmau-Pastor *et al.,* 2014). The AT also receives nerves from the triceps surae muscles (Stilwell, 1957). The medial sural cutaneous nerve, accompanied by the saphenous vein, perforates through the superficial fascia distal to

the medial and lateral gastrocnemius heads and runs posterior to the AT before crossing its lateral border close to half the length of the tendon, with some anatomical variability (Webb *et al.,* 2000; Apaydin *et al.*, 2009). Just below the mid-portion of the AT, it conjoins with the lateral sural cutaneous nerve (a branch of the common peroneal nerve) to form the sural nerve *(Fig. 2.6).* This sensory nerve continues distally with numerous branches at the lateral aspect of the foot and ankle (Apaydin *et al.*, 2009).

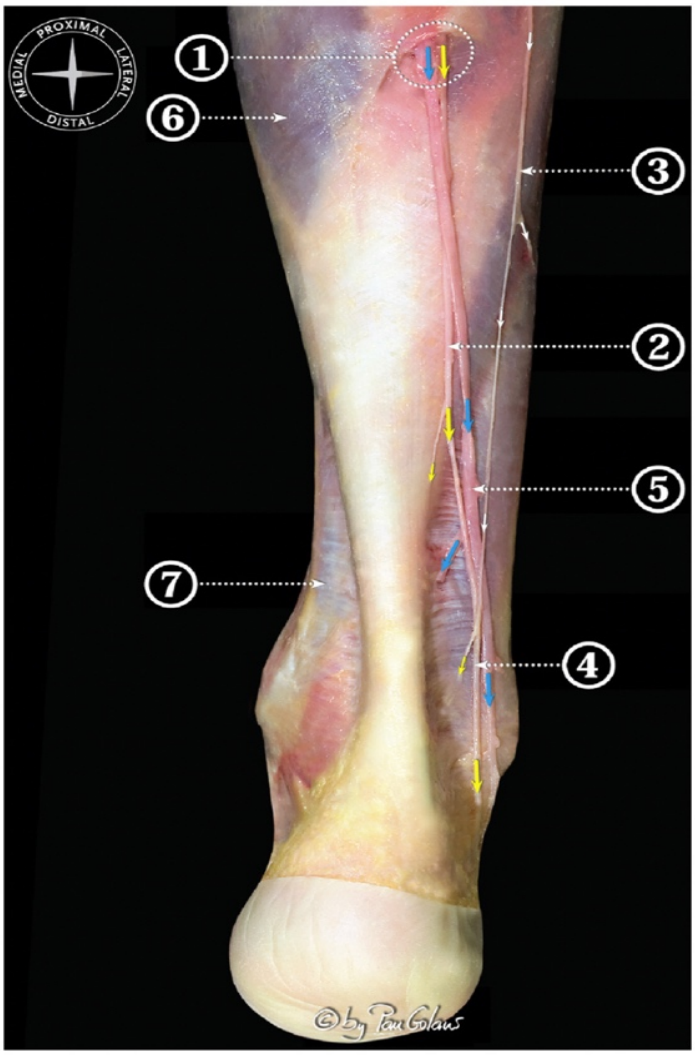


Fig. 2.6. Nerve supply to the AT. The medial branch of the sural nerve (2) runs distally in parallel with the lesser saphenous vein (5) as it perforates through the superficial fascia of the gastrocnemius (1), where it conjoins with the lateral branch of the sural nerve (3) to form the sural nerve (4) (Dalmau-Pastor et al., 2014; copyright Pau Gaulanò)

Nerve fibers do not enter the tendon core but reside in the synovial space (endotenon, epitenon, and paratenon) and terminate as unmyelinated or poorly-myelinated nerve endings (Kvist *et*

al., 1987; O'Brien, 2005). The nerve supply is predominantly afferent, and its primary functions within a tendon are mechanoception, nociception and vasomotor modulation (Ackermann *et al.,* 2013).

There are four types of receptors at the nerve endings – each with its function (O'Brien, 2005; Ackermann, 2013):

Type I: Ruffini corpuscles which are pressure and stretching sensors,
Type II: Vater-Pacini corpuscles, which are pressure sensors reacting to acceleration or deceleration of movement,
Type III: Golgi organs, which are tension receptors, found mainly at MTJ and BTJ,
Type IV: Nociceptors that mediate deep tissue pain and hyperalgesia.

Both immunoreactive and sensory markers are detected in nerve fibers of the paratenon close to blood vessels and, to a lesser degree, between the fascicles (Bjur *et al.,* 2005). They contribute to a tendon's healing response following an injury by regulating the blood supply *(Fig. 2.7).*

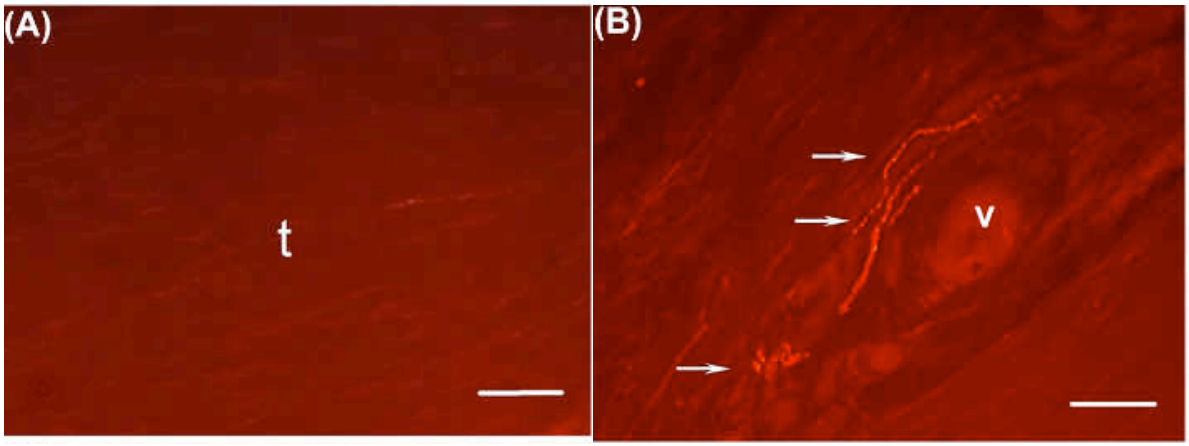


Fig. 2.7. An immunofluorescence micrograph of a healthy tendon (A) and a symptomatic tendon (B) with an ingrowth of sensory nerves as indicated by the white arrows (Ackermann et al. 2012)

2.4. NEIGHBOURING STRUCTURES

2.4.1. BONE-TENDON JUNCTION (BTJ)

The AT broadens and flattens into a deltoid shape as it wraps around the calcaneus insertion. This area is the bone-tendon junction (BTJ), also called the enthesis. Here, the tissue becomes more fibrocartilaginous as it transitions over four zones which are illustrated in Figure 2.8: (I) tendon, (II) fibrocartilage, (III) mineralised fibrocartilage, and (IV) bone (Benjamin *et al.*, 2006). The tendinous tissue at the BTJ has a higher type II and X collagen composition to facilitate mechanical load distribution between the tendon and bone (Benjamin *et al.*, 2006). The broadening of the tissue around the calcaneus's superoposterior aspect helps dissipate the high forces by reducing stress. The subcutaneous bursa resides between the AT and the skin, and the retrocalcaneal bursa lies between the tendon and the calcaneus (Dalmau-Pastor *et al.,* 2014). These synovial fluid sacs facilitate the sliding and compression of the tendon. The Kager's fat pad enables fluid movement between the tendon and bone. It is triangular shaped, lies above the calcaneus, and separates the AT from the tibia and deep PFs (O'Brien, 2005). It is richly vascularised, regulates synovial fluid in the retrocalcaneal bursa, and is the primary source of cytokine contribution to the AT delivered through its blood supply (Ward *et al.*, 2016). The potential role of the fat pad in tendinopathy is poorly understood (Ward *et al.*, 2016). The retrocalcaneal bursa connects with the AT via the paratenon. This was demonstrated when a staining dye was injected into the bursa and found to seep into the tendon (Pękala *et al.*, 2017). A Haglund's deformity is a bony prominence on the posterolateral aspect of the calcaneus where the AT inserts and features in a small percentage of the population (Vaishya *et al.*, 2016). This bone spur can cause complications with insertional Achilles pain due to increased compressional loads. The structures of the BTJ are illustrated in Figure 2.9.

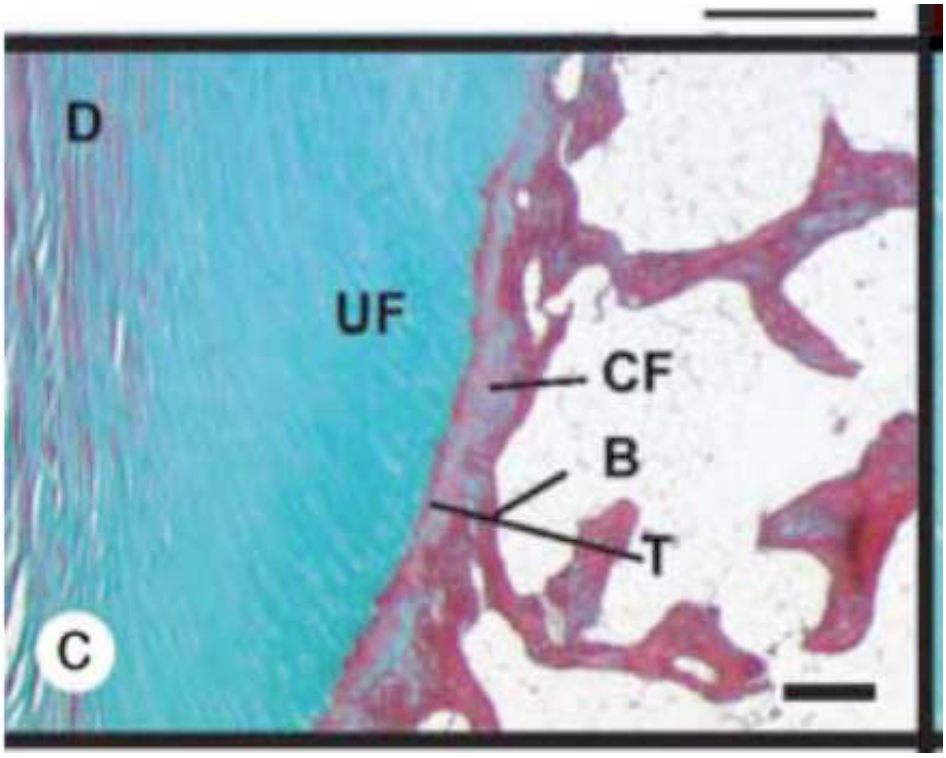


Fig. 2.8. The four zones of tissue from tendon to cartilage at the BJT (Benjamin et al. 2006)

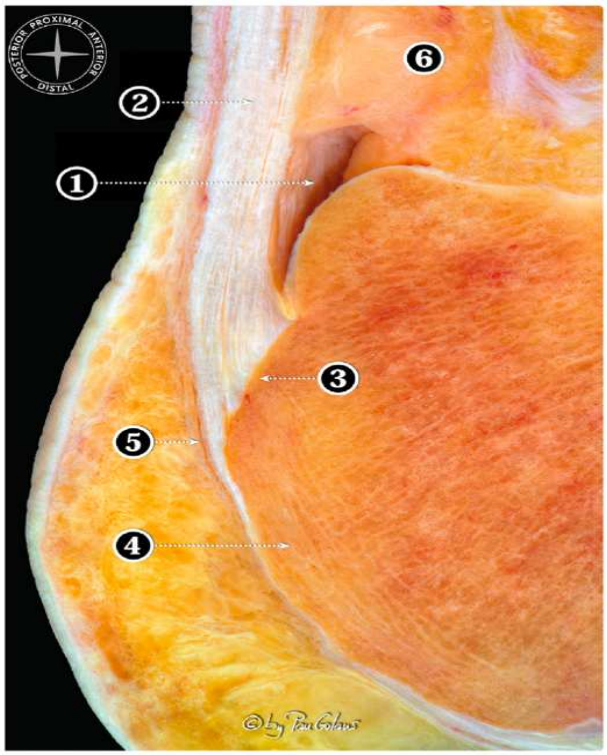


Fig. 2.9. The bone-tendon junction (BTJ) showing the retrocalcaneal bursa (1), the AT (2), the AT insertion (3), the calcaneal tuberosity (4), sub-cutaneous bursa (5), and the Kager's fat pad (6) (Dalmau-Pastor et al., 2014; copyright Pau Golanò)

2.4.2. MUSCLE-TENDON JUNCTION (MTJ)

The myotendinous junction is a complex region between the muscle and the tendon *(Fig. 2.10).* Previous 2D imaging describes a finger-like process with several extensions and inter-digitations, but 3D ultrasound imaging describes a more ridge-like fusion structure (Knudsen *et al.*, 2015). Actin filaments extending from the last sarcomere Z-line connect to subsarcolemmal proteins, interacting via trans-membrane proteins with extracellular matrix (ECM) components. These components include elements of the external lamina and proteins that link with the adjoining tendon's collagen-fibril matrix (Trotter *et al.,* 1983).

The MTJ is the primary site of force transmission. When muscle fibers shorten, the interface becomes broader, increasing the contact area and allowing collagen to increase stiffness and connect with the contracting muscle tissue to increase tension (Knudsen *et al.*, 2015). Jakobsen *et al.* (2022) revealed that type I fiber-dominant muscles have a broader MTJ contact area than type II. Muscle fibers have an abrupt ending within their fascicles before reaching the MTJ, causing lateral force transmission through the endomysium during contractions (Knudsen *et al.*, 2015). The MTJ is a robust structure that can tolerate contractile forces of between 1.8 to 3.5 x 10^4 N/m (Charvet *et al.,* 2012). Injuries at the MTJ are usually associated with failure at the muscle belly and not separation of the MTJ itself (Brukner and Connell, 2016).

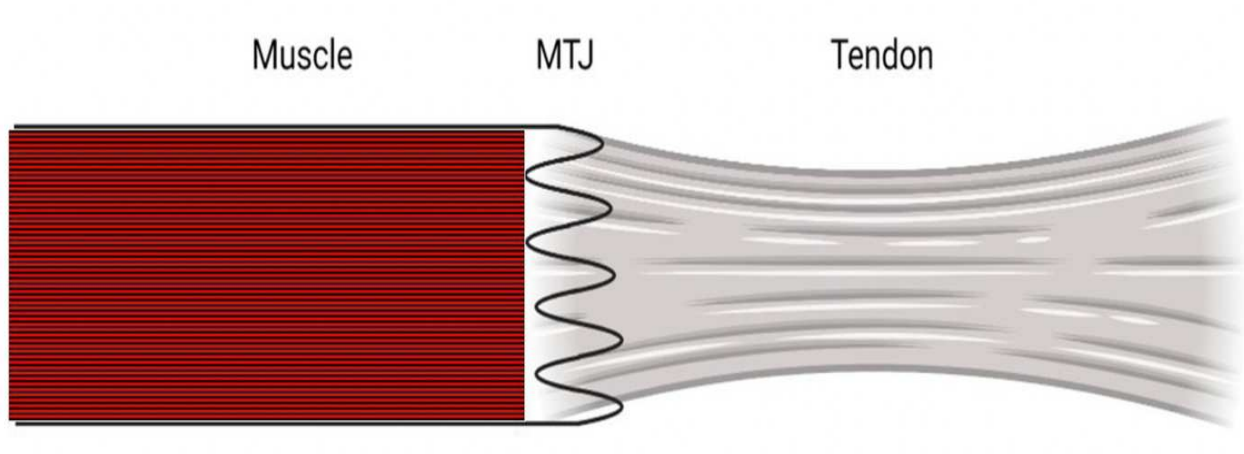


Fig. 2.10. An illustration of the MTJ interface between muscle and tendon (Jakobsen et al., 2022)

2.4.3. THE TRICEPS SURAE MUSCLES

The triceps surae (TS), commonly known as the calf muscles, is comprised of the medial gastrocnemius (MG), lateral gastrocnemius (LG), and soleus (SO) muscles *(Fig. 2.11).* Each muscle contributes fascicles to the AT. The TS are pennate muscles which short fascicles oriented at an oblique angle between the deep and superficial aponeuroses (Chow, 2000). They have a complex connective tissue structure with tendinous tissue and fascia surrounding each muscle, and a common aponeurosis between the MG and LG before fusing with the soleus aponeurosis to form the AT (Blitz and Eliot, 2007, 2008).

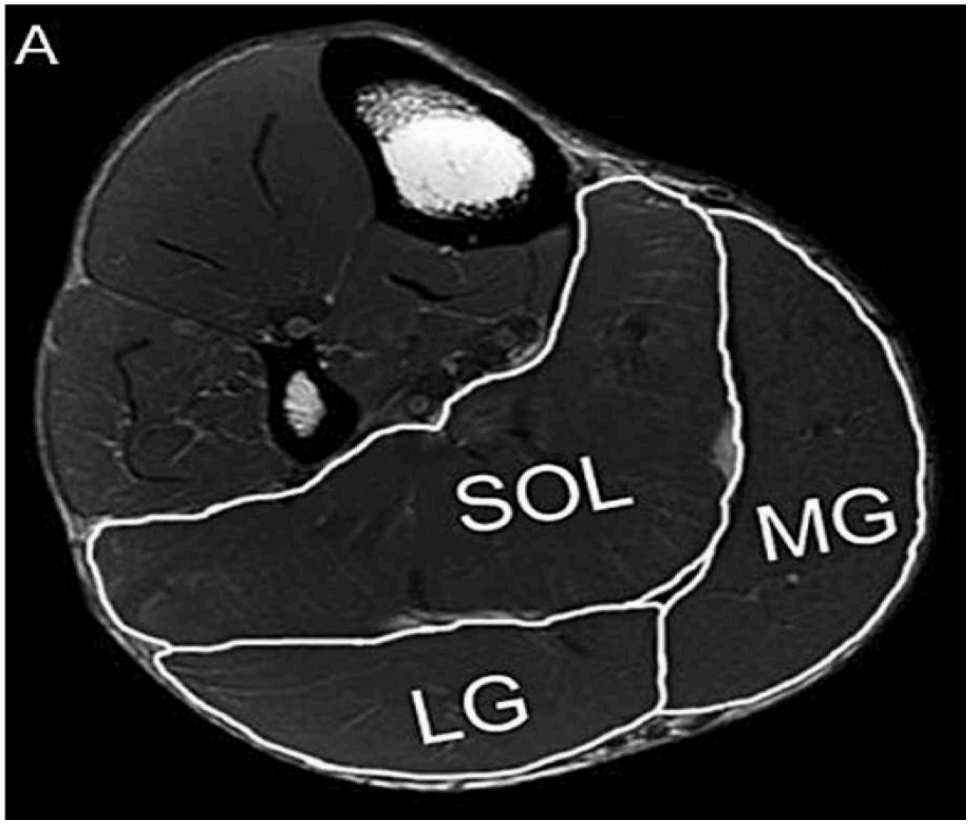


Fig. 2.11. Transverse image of the triceps surae muscles (Kovaks et al., 2021)

The soleus has the greatest muscle volume of the TS (Fukunaga *et al.*, 1996; Albracht *et al.,* 2008) with predominantly type I fibers (Gollnick *et al.*, 1974). It has two proximal tendon origins at the tibia and fibula, which merge distally to form the tendinous arch. The tibial nerve, tibial artery, and veins pass through this arch (Dalmau-Pastor *et al.,* 2014). The soleus has 5 tendinous tissue structures or aponeuroses – the anterior aponeurosis, posterior aponeurosis, medial intramuscular aponeurosis, lateral intramuscular aponeurosis an the central tendon (Hodgson *et al.*, 2007; Balius *et al.*, 2014). It has four compartments which are illustrated in

Figure 2.12, each with its independent nerve supply – the anterior medial and lateral compartments and the posterior medial and lateral compartments (Bolsterlee *et al.*, 2018). The central tendon protrudes in a ridge-like structure from the posterior aponeurosis and splits the medial and lateral compartments of the anterior and posterior compartments. From the proximal end, tendinous tissue with a conical tip gives rise to the anterior aponeurosis. As it runs more distally, the medial and lateral intramuscular aponeurosis emerge, separating the anterior from the posterior compartment (Hodgson *et al.*, 2007). At the distal end, the AT broadens to become the posterior aponeurosis. It merges with the free gastrocnemius aponeurosis to form the AT (Hodgson *et al.*, 2007). The connective tissue structures of the soleus muscle are illustrated in Figure 2.13. The anterior compartment has a unipennate arrangement with a small volume and undergoes more excursion (Bolsterlee *et al.*, 2018). The posterior compartment has a larger volume with multi-pennate fascicle arrangements throughout the distal, mid-portion, and proximal ends (Bolsterlee *et al.*, 2018). The SO is also highly vascularised (Balius *et al.*, 2014) but may have a slower sensory nerve response (Brukner *et al.,* 2018). Anatomical variations of the SO, including a distal accessory region of muscle, an accessory central tendon, or a lack of medial or lateral intramuscular aponeurosis, have been detected (Hodgson *et al.*, 2007; Olewnik *et al.*, 2020; Pedret *et al.*, 2022).

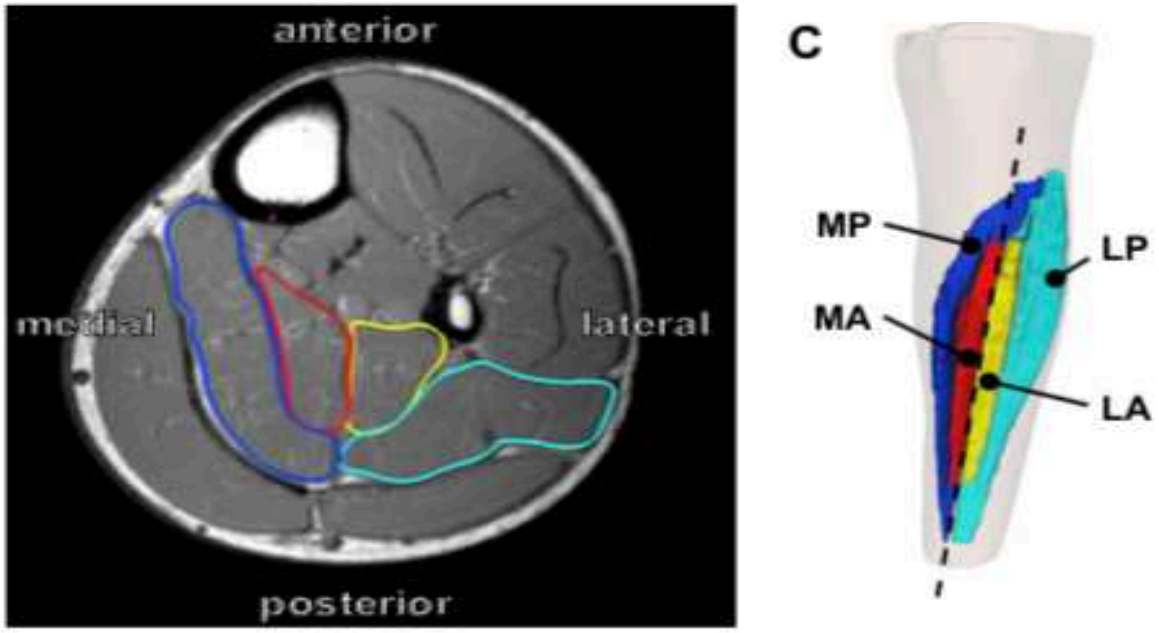


Fig. 2.12. The soleus muscle anatomy illustrating the four compartments (Bolsterlee et al., 2018)

The MG and LG have a unipennate structure where the fascicles have a standard orientation. The MG originates at the medial supracondylar ridge and tubercle of the femur and knee capsule (Dalmau-Pastor *et al.,* 2014). The LG originates at the lateral supracondyle tubercle of the femur and the knee capsule (Dalmau-Pastor *et al.,* 2014). They each have an anterior aponeurosis and a posterior fascia sheet. There is a common aponeurosis between the MG and LG known as the free gastrocnemius aponeurosis or "gastroc run-out," which runs distally and independent of the soleus posterior aponeuroses before fusing to form the AT (Blitz and Eliot, 2007, 2008).

The pennate architecture of the individual calf muscles and their variability across its regions mean that anatomical cross-sectional area is not an accurate reflection of the force capability of the muscles (Fukunaga *et al.*, 1996; Maganaris *et al.*, 2017). Physiological cross-sectional area (PCSA) measures a muscle's cross-section perpendicular to its fibers' orientation. It is directly related to the amount of force a muscle can produce (Albracht *et al.,* 2008). The PCSA of the soleus, with its greater pennation angles and variations across different regions, is 3.5 times that of the MG, which in turn is 2.5 times that of the LG (Fukunaga *et al.*, 1996). The individual force contributions from each muscle will influence AT stress and strain distribution, inter-fascicular shear, and regional mechanical properties (Merry *et al.*, 2022).

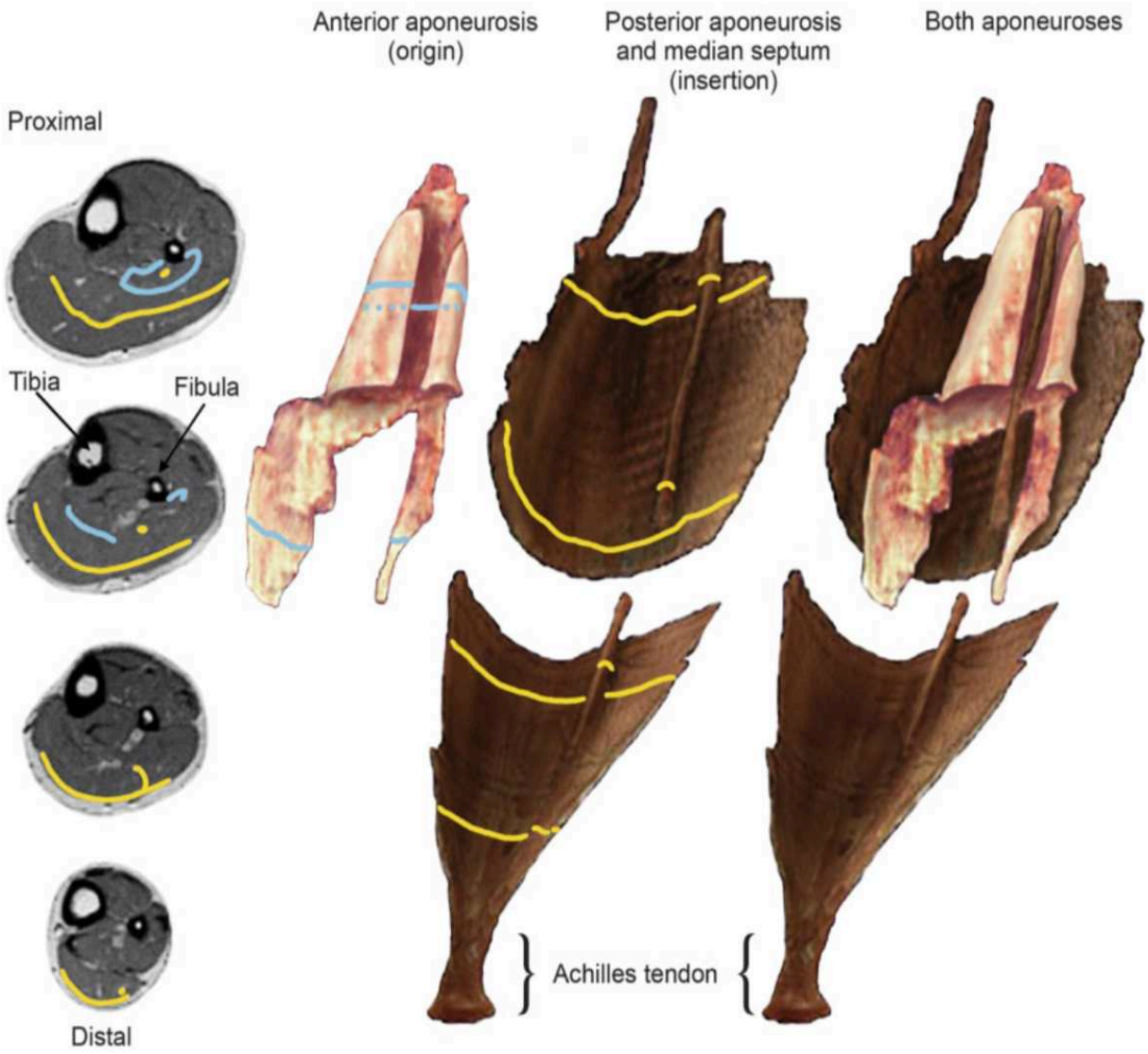


Fig. 2.23. A 3-dimensional dissection image of the aponeurosis structure of the soleus muscle across each region (Hodgson et al., 2007)

3.4.4. THE PLANTARIS

The plantaris is present in 93% of the population (Roche and Calder, 2018) and consists of a small muscle belly with a long tendon *(Fig. 2.14)*. It originates in the knee from the linea aspera and oblique popliteal ligament (Dalmau-Pastor *et al.,* 2014). It then runs distally between the gastrocnemius and soleus muscles before running adjacent to the AT on the medial side

(Dalmau-Pastor *et al.,* 2014). It inserts into the posterior aspect of the calcaneus with some anatomical variations in a small minority of individuals, where it often conjoins with the AT before the calcaneal insertion. The plantaris are densely populated with muscle spindles and are said to act more like a nerve than a mechanical function, giving proprioceptive feedback to the AT (Spang *et al.*, 2014). A thickened plantaris can contribute to Achilles tendinopathy, increasing frictional and compressive loading on the medial side of the AT (Masci *et al.*, 2015).

Fig. 2.14. The plantaris muscle and its long tendon (Dalmau-Pastor et al., 2014; copyright Pau Golanò)

2.5. BIOMECHANICS

2.5.1. ACHILLES TENDON MECHANICS

The AT has three regions on its stress-strain curve *(Fig. 2.15).* The first is the toe region, where strains are less than 2%, which describes the initial crimped pattern of the collagen fibrils and the sliding and rotation of fascicles. The second linear region of the curve represents the stretching of the collagen fibrils under strains greater than 2%, where the tendon displays elastic behaviour by returning to its original length upon the removal of tensile force. This region represents the stiffness of the tendon. The third plastic region under strains of greater than 8% is where microtears occur and, ultimately, a rupture. The tendon does not return to its original length immediately upon load removal in this region. The typical stress required to rupture an AT is around 100 N/mm^2, and the tendon often experiences stresses of up to 70 N/mm^2 (Wren *et al.*, 2001). The tendon fascicles displace non-uniformly under load with differences between superficial fascicles which undergo the least amount of strain, and deep fascicles, which undergo the highest strain (Arndt *et al.*, 2012; Obst *et al.*, 2014). This non-uniform displacement may be a protective mechanism in healthy tendons to manage stress distributions. Fibrils rupture at lower levels of strain well below whole tendon ultimate failure, and the non-uniformity of tendon strain may allow micro ruptures to be contained at the fibril level and facilitate timely healing without a loss of overall function in the tendon (Arndt *et al.*, 2012).

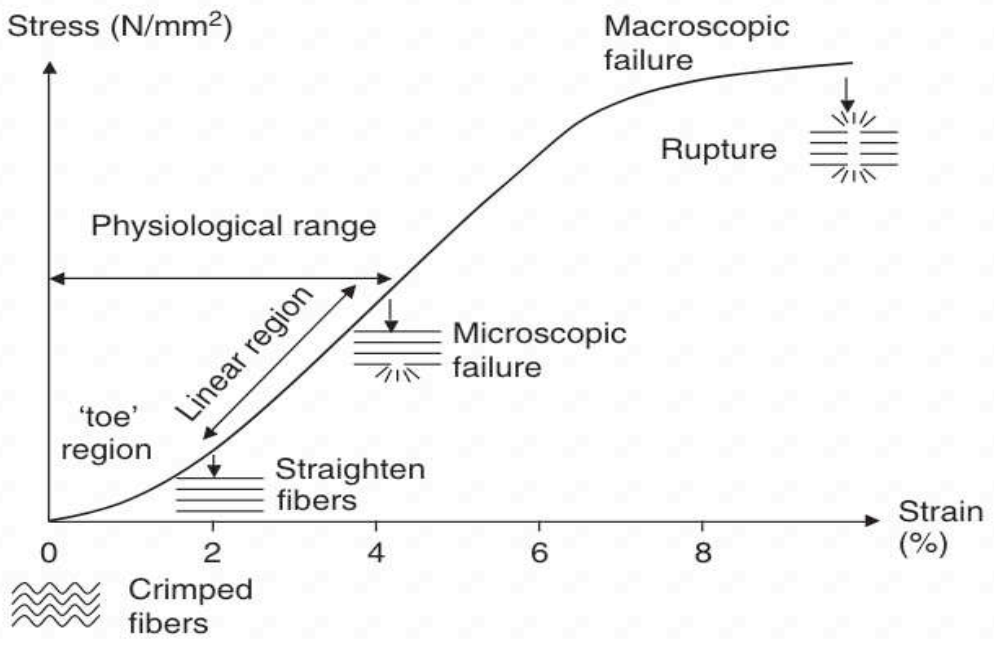


Fig. 2.15. Tendon stress-strain curve illustrating the different regions and impact on collagen fibers (Wang, 2006)

Tendons display transverse isotropic properties, which means that due to their 3D cylindrical geometry with collagen fibrils aligned longitudinally embedded in a matrix, they can withstand forces in that direction, whereas it is weaker and more deformable in a transverse direction (Yin and Elliott, 2004). Tendons also display non-linear properties when force is applied (Beach *et al.,* 2017). This is evident in the toe and initial elastic region of the stress-strain curve, where the crimped collagen fibrils rotate before collagen fascicles stretch (Beach *et al.,* 2017). Tendons do not possess perfect spring properties. They are viscoelastic and display force-relaxation, creep, and hysteresis properties, as illustrated in Figure 2.16 (Wang, 2006; Beach *et al.,* 2017). Viscoelasticity describes how the materials display viscous and elastic characteristics due to the interaction between collagen, water, and ground substances (Wang, 2006). Viscosity measures resistance to flow and is a fluid property. Elasticity is a solid material property that measures the tendon's ability to return to its original shape during unloading. Creep describes how tendon deformation increases under a constant load (Beach *et al.,* 2017). For example, a 1% increase in deformation in the free AT was observed after a 5-km run with no increase in gastrocnemius tendon deformation (Lichtwark *et al.,* 2013). Stress-relaxation describes how stress acting upon the tendon reduces under a constant deformation (Beach *et al.,* 2017). Johnson *et al.* (1994) demonstrated a reduction in stress of between 40-60% when the tendon was subjected to cyclical strains.

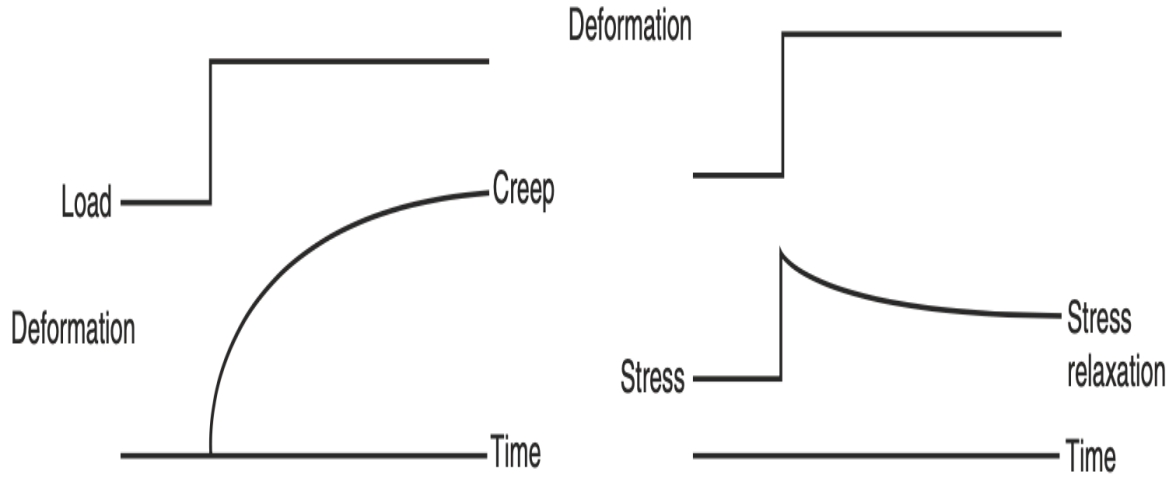


Fig. 2.16. Tendon viscoelastic properties illustrating creep and stress-relaxation behaviour (Beach et al., 2017)

During loading and unloading cycles, some energy converted to heat is lost due to the viscosity of the tendon. This energy loss is known as hysteresis, as illustrated by the area between the loading and unloading curves in Figure 2.17. Higher hysteresis levels mean less energy is released from the tendon during the SSC to propel locomotion. Previous studies have detected hysteresis values of 3 to 38% for the AT, but with a more robust methodology, values closer to 10% appear to be more accurate (Finni *et al.*, 2013; Finni and Lichtwark, 2016).

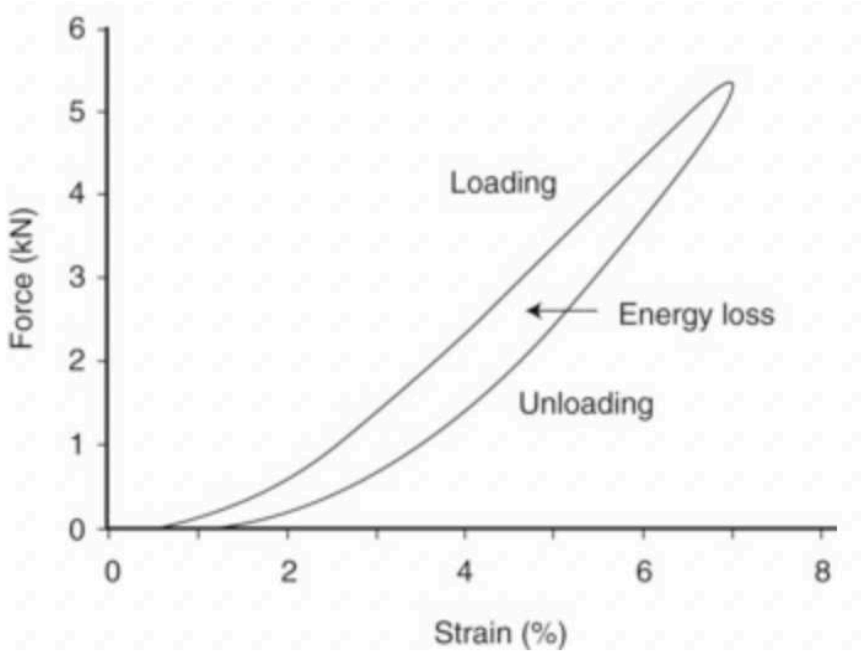


Fig. 2.17. An example of a tendon hysteresis loop (Goodship et al., 1994)

There are regional differences in the orientation of strain in the AT with the mid-portion experiencing longitudinal strain and the proximal region favours transverse strain (Magnusson *et al.*, 2003; Arellano *et al.*, 2019). In one study *(Fig. 2.18)* that performed *in vitro* testing to failure to measure direction of tendon strains, the proximal region of the AT underwent transverse strain during the initial loading phase before longitudinal strain increased a close to failure (Nagelli *et al.*, 2021). One possible conclusion is that an early onset of proximal transverse strains perhaps due to early calf muscle recruitment, may be a protective mechanism against ruptures.

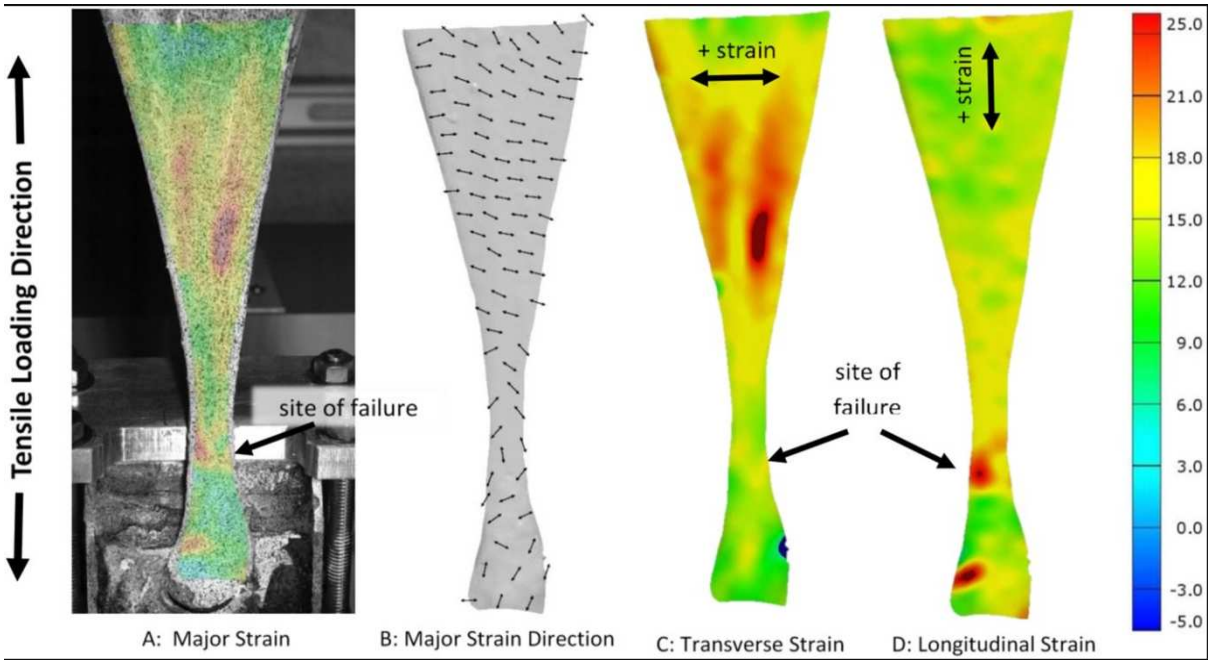


Fig. 2.18. A heat map illustrating regional strain patterns and the impact of transverse and longitudinal strain at the AT failure site (Nagelli et al., 2021)

2.5.2. MUSCLE-TENDON UNIT MECHANICS

Due to the pennate architecture of the triceps surae muscles, fascicles have a narrow region on its force-length-velocity relationship to maximise force and minimise energy cost. A long tendon such as the AT facilitates these conditions as under strain. Optimal AT stiffness enables muscle fascicles to operate on their preferred F-L-V relationship as energy is stored and returned at low energy cost during cyclic actions such as running or repetitive hopping, or more energy returned from the MTU greater than what the muscles fascicles can produce during explosive movements such as jumping or acceleration (Roberts and Azizi, 2011; Lai *et al.*, 2016). Pennate muscles also utilise a gearing mechanism whereby during high-velocity contractions, the muscle belly shortens at a faster speed than muscle fascicles as a result of the rotation of the fascicles, causing the muscle to bulge (Azizi and Roberts, 2009). This action also results in lateral force transmission among neighbouring muscles (Roberts *et al.*, 2019). The same happens in reverse during active lengthening, where fascicles rotate in line with the direction of the force (Azizi and Roberts, 2014). Pennate muscles can adapt their gearing to different levels of contraction speeds (Eng and Roberts, 2018). This gearing mechanism allows the muscle fascicles to maintain their preferred F-L-V relationship to maximise force.

The soleus sarcomeres operate on the ascending limb of its force-length curve close to the plateau region (Rubenson *et al.*, 2012). As locomotion speed increases, the sarcomeres can regulate their shortening velocity to maintain their preferred area on the F-L relationship (Bohm *et al.*, 2019). The conversion of mechanical energy to ATP from the behaviour of the soleus sarcomeres is related to the energy cost (Bohm *et al.*, 2021).

Muscle coordination and knee joint kinematics influence AT loading, due to the joint articulations of the individual muscles and the twisted structure of its sub-tendon fascicles. The MG sub-tendon fascicles with the highest degree of torsion of the TS muscles, have the largest slack length (Arnold and Delp, 2011). Plantarflexion with greater knee flexion creates more tension on the monoarticular SOL, causing greater anterior shear from the biarticular gastrocnemii while the reverse occurs with an extended knee (Bojsen-møller *et al.*, 2018). Similarly, Funaro *et al.* (2022) demonstrated that a heel drop with a flexed knee results in greater strain from the SOL sub-tendon fascicles, whereas a straight leg heel raise and heel drop results in greater strain on the MG sub-tendon fascicles.

2.5.3. RUNNING AND LOWER LIMB BIOMECHANICS

The TS is the biggest force contributor during running, with the highest joint work contribution coming from the ankle (Dorn *et al.,* 2012; Schache *et al.,* 2014; Sanno *et al.*, 2018). The AT experiences forces of up to 8 times bodyweight at steady-state running speeds (*Fig. 2.19*). From jogging to submaximal sprinting speeds, the TS operate close to their maximal force capacity with internal muscle forces from the soleus of 7 times bodyweight at 7 m/s speeds (Dorn *et al.,* 2012). At maximal speeds, force output from the TS declines concomitantly with a decline in effective vertical impulse and a reduction in contact time (Dorn *et al.,* 2012). At these speeds, there is a greater reliance on the tendon's mechanical properties and contribution from the proximal hip musculature during the swing phase (Dorn *et al.,* 2012; Lai *et al.*, 2014). The soleus provides most of the vertical support and acceleration of the centre of mass (Dorn *et al.,* 2012). During the early stages of acceleration from a static start, the soleus offers the most considerable muscle force contributions. The timing of recruitment and F_{peak} differs between the soleus and gastrocnemii muscles (Pandy *et al.*, 2021). The soleus appears to produce its F_{peak} during the mid-stance phase when the centre of mass displacement is greatest, whereas the gastrocnemii become more active during the late stance phase proper to toe-off.

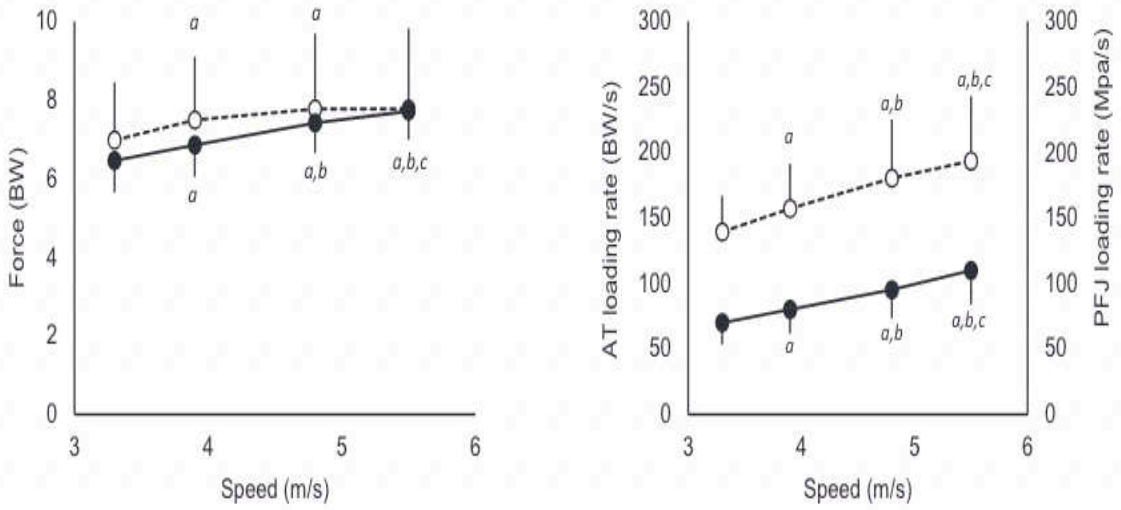


Fig. 2.19. Peak AT forces (solid line) and patellofemoral joint (dotted line) across each speed (A) and (B), peak AT loading rate (solid line) (Starbuck et al., 2021)

AT stiffness - a key determinant of distance running performance (Jones, 2006; Foster and Lucia, 2007; Midgley *et al.,* 2007; Hoogkamer *et al.*, 2016), is associated with running economy (RE) due to the tendon's ability to store more elastic energy during the early stance phase requiring efficient muscle contractions and reduced energy cost (Fletcher *et al.,* 2010; Albracht and Arampatzis, 2013; Rogers, 2017). A 4% improvement in RE correlates with a 1.5-2% performance over a marathon (Kipp *et al.,* 2019). East African athletes have superior RE to Caucasian counterparts and an improved ability to store elastic energy (Kunimasa *et al.*, 2014). A 14-week program of repeated 3-second intensity isometric PF contractions at 90% MVC resulted in a 16% increase in TS T_{peak} and an 11% improvement in AT stiffness with a 4% improvement in RE (Albracht and Arampatzis, 2013). In this study using real-time ultrasound to track MTU tissue mechanics, the calf muscle fascicles operated close to isometric conditions, favouring energy savings as it is more costly for fascicles to shorten at high velocities. During a fatiguing run, elite runners can better maintain their high joint work output from the ankle. In contrast, novice runners shift to greater uptake of joint work at the knee and hip (Sanno *et al.*, 2018). At the tissue level, the AT undergoes higher deformation under fatigue due to creep, which results in increased shortening of the muscle fascicles (Lichtwark and Wilson, 2008; Lichtwark *et al.,* 2013).

The TS MTU is adaptative to the task required by being able to switch between a power amplification, energy conservation, and power attenuation function as illustrated in Figure 2.20 (Roberts and Azizi, 2011). During the initial foot contract in acceleration, there is some concentric behaviour of the soleus fascicles (Lai *et al.*, 2018). The MTU behaves similarly at the tissue level at maximal speed running, where the muscle fascicles undergo quasi-isometric contractions, and the tendon reflects the SSC behaviour of the MTU (Lai *et al.*, 2018).

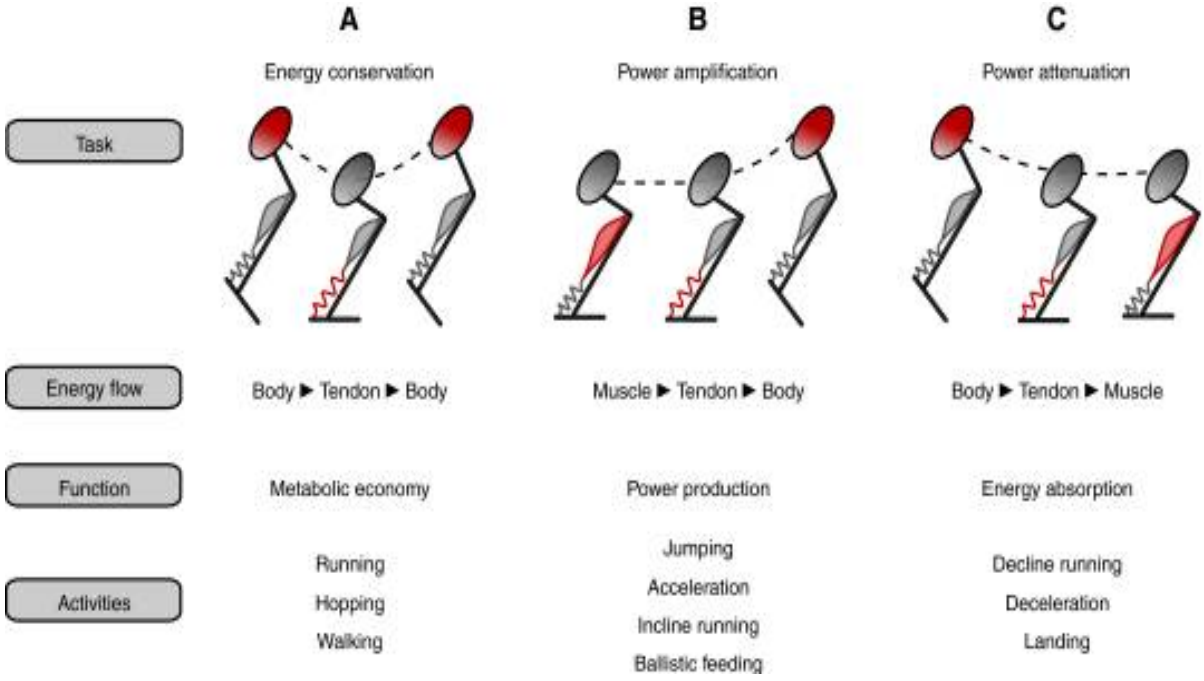


Fig. 2.20. The variable spring function of the MTU (Roberts and Azizi, 2011)

The use of gait-retraining to alter kinetic and kinematic loading patterns to offload injured structures has had some moderate evidence for helping to prevent injuries in recreational runners but limited evidence supporting its use in injury rehabilitation (Doyle *et al*., 2022). There is no clear link between footstrike patterns and running injuries. However, switching from a rearfoot to a mid-to-forefoot strike pattern increase AT loading and contribution from the gastrocnemius, while rearfoot strike patterns increase contribution from the soleus and may be deemed more economical over longer distances (Almonroeder *et al.,* 2013; Yong *et al.*, 2019). Stride frequency and step length have an inverse relationship, whereby manipulating one results in altered loading of some injury-prone anatomical structures (Schubert *et al.,* 2014). Increasing step length requires greater output from the ankle and calf muscles, whereas

increasing step frequency requires increased contribution from the hip flexors and extensor muscles (Dorn *et al.,* 2012).

Several biomechanical variables are associated with lower limb injuries, albeit with limited evidence. Due to a lack of prospective studies, many of these features present with the injury, and it is difficult to identify an actual causative factor. Common kinematic features include a negative shank angle at footstrike, which may increase braking forces, and a contralateral hip drop and knee valgus (Bramah *et al.*, 2018, 2021). Ground reaction force variables such as vertical impact loading rate are associated with running injuries such as plantar fascia pain and tibia bone stress injuries, but not with Achilles tendinopathy (Johnson *et al.*, 2020). There are limited findings on the gait features of runners with Achilles tendinopathy. Greater rearfoot eversion, ankle dorsiflexion, and knee flexion excursions during stance were observed in runners with Achilles tendinopathy compared to uninjured runners (Donoghue *et al.*, 2008). However, a meta-analysis has shown insufficient evidence for foot kinematics as a distinctive feature of tendinopathy (Sancho *et al.*, 2019). Pronation has been attributed to some injuries but with limited evidence. There is poor agreement in the research and among clinicians as to what constitutes "normal," "over -" and "under- "pronation". Increased braking forces have been attributed to Achilles tendinopathy (Lorimer and Hume, 2014), decreased forward transfer of the centre of force throughout the stance phase, and a laterally deviated force distribution under the forefoot at mid-stance (Van Ginckel *et al.*, 2009). Other studies have highlighted altered recruitment patterns of the gluteal muscles on the injured side in runners with Achilles tendinopathy (Sancho *et al.*, 2019).

The cyclic loading patterns on the AT during distance running may contribute to the development of injury due to the accumulated microdamage exceeding the adaptive ability of the tendon (Wren *et al.*, 2003; Edwards, 2018). Higher initial tendon stresses and strain reduced the time to tendon failure throughout a long-distance run, due to a reduction in modulus and an increase in hysteresis (Wren *et al.*, 2003). A ceiling effect for collagen synthesis is reached after 100 loading cycles during a 36-km run *(Fig. 2.21),* suggesting that the tendon cannot further adapt and may result in accumulated tendon damage and the development of pathology (Magnusson *et al.,* 2010). Reported AT strains during running exceed the "optimal zone" of 4.5-7% strain for tendon adaptation (Pizzolato *et al.*, 2019; Arampatzis *et al.,* 2020; Devaprakash *et al.*, 2022), suggesting that running alone may not be a sufficient adaptive stimulus for the AT in the short term. An emerging concept in running biomechanics is the

measurement of soft tissue vibrations. Increased soft tissue vibrations lead to the early onset of neuromuscular fatigue and may contribute to injury risk (Play *et al.,* 2022). Measuring AT vibrations and their effect on collagen degradation and indeed PF muscle coordination, is worthy of investigation.

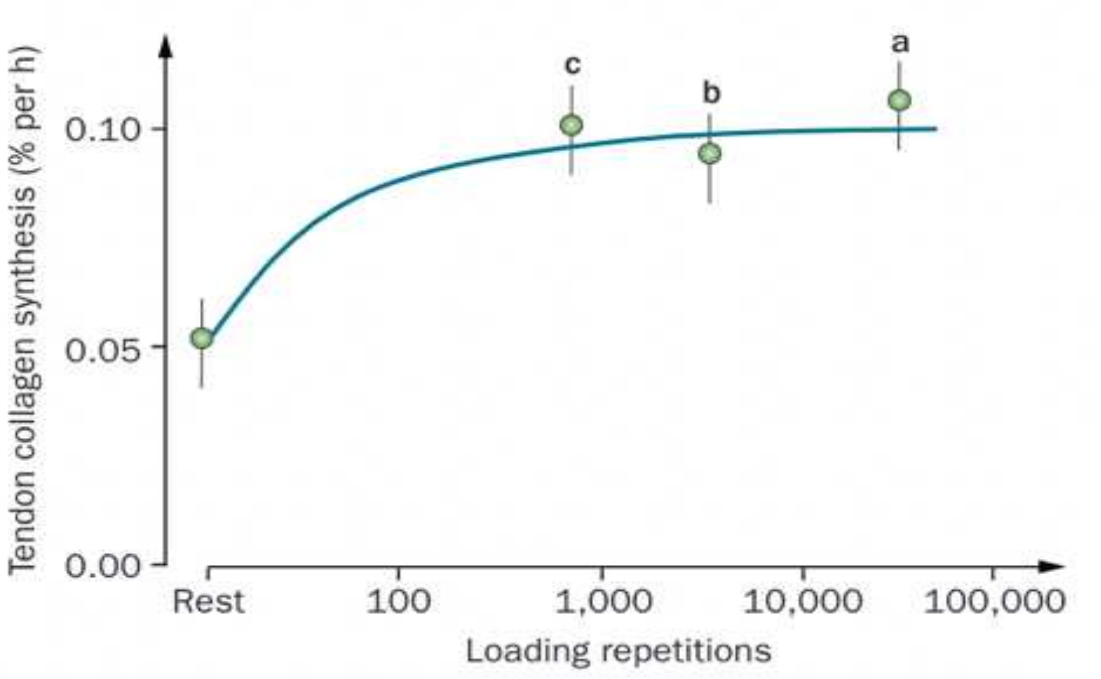


Fig. 2.21. Collagen synthesis response to loading based on the number of loading cycles. The graph shows how long-distance running (b) reaches a ceiling effect of collagen synthesis after 100 loading cycles (Magnusson, 2010)

Considering the multi-factorial nature of running injuries and the interaction between intrinsic and extrinsic risk factors, one cannot attribute causation based on an isolated gait feature. Assessments using coordination variability or joint coupling relationships provides a deeper evaluation of the gait features adopted by injured runners, which may help to direct a rehabilitation program (Baida *et al.*, 2018; Chen *et al.*, 2020). Clustering analysis is another tool that was used in field sports players with athletic groin pain, where subgroups of players with an ankle, knee, or hip joint kinetic strategy emerged during a cut manoeuvre (Franklyn-Miller *et al.*, 2017).

Van Oeveren et al. (2021) proposed a dual axis framework model *(Fig 2.22)* to characterise five different running styles based on some interacting spatiotemporal features, including step

frequency, step length, stance time, flight time, and vertical displacement of the centre of mass. A runner with a "Bounce" style displays a longer flight and short stance time, resulting in a moderate step frequency and larger vertical displacement. A "Push" style requires a long stance and flight time resulting in a low step frequency and sizeable vertical displacement. A "Hop" style involves short stance and flight times, resulting in high step frequency and moderate vertical displacement. A "Stick" characteristic involves a long stance and short flight time resulting in medium frequency and low centre of mass displacement. Finally, a "Sit" feature in the centre which displays greater knee flexion at footstrike with moderate vertical displacement and step frequency. James Wild (Wild *et al.*, 2021) identified four groupings based on their spatiotemporal strategies using a similar clustering analysis on sprint and field sports athletes during the initial acceleration phase. This study highlighted that similar initial acceleration performances could be achieved with different spatiotemporal strategies.

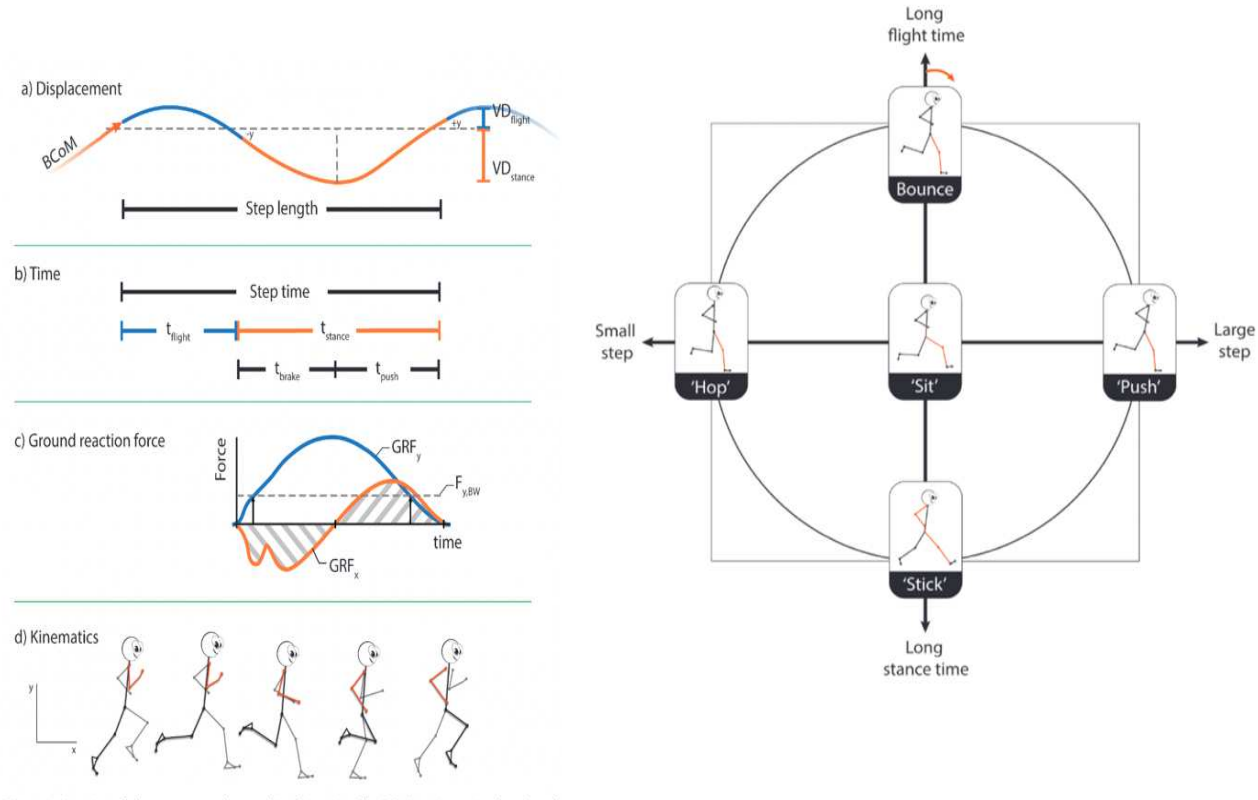


Fig. 2.22. The dual axis framework for sub-categorising running styles based on combined spatiotemporal, kinetic and kinematic features (Van Oeveren 2021)

2.5.4. HOPPING AND LOWER LIMB BIOMECHANICS

Hopping involves a typical stretch-shorting cycle (SSC) mechanism similar to running, where the AT stretches as force is applied from the calf muscles. During repetitive hopping, the calf muscle fascicles maintain isometric conditions as the MTU stretches and shortens, whereas in maximal effort hopping, there is some stretching and shortening of the muscle fascicles, and greater output from the MTU than applied by the muscle (Ishikawa and Komi, 2008; Earp *et al.*, 2011; Roberts and Azizi, 2011; Farris *et al.*, 2016; Aeles and Vanwanseele, 2019). Single-leg vertical hopping is a common clinical test for pain provocation and identifying deficits in lower-limb spring capabilities (Silbernagel *et al.*, 2006, 2007).

Although a single-leg vertical hop exposes the AT tendon to high stresses and strains (Lichtwark, 2005), horizontal and multi-planar hopping add extra loading demands on the tendon with higher loading rates (Gheidi *et al.*, 2018; Baxter *et al.*, 2021). A horizontal hop requires greater joint work contribution from the ankle and muscle force contribution from the soleus muscle (Kotsifaki *et al.,* 2021). Along with the highest AT forces and loading rates observed as outlined above, a horizontal plyometric test may reveal useful information on lower-limb function following an AT injury.

2.5.5. LOWER LIMB STIFFNESS

2.5.5.1. Whole-body stiffness

Stiffness is a measure of the resistance of a body to deformation when force is applied, and it is measured at whole-body, joint, MTU, and tendon levels. The spring-mass model illustrates the centre of mass acting over a linear spring and can describe the global characteristics of running and hopping (Cheng and McMahon, 1976; Blickhan, 1989; Farley and González, 1996). However, quasi-stiffness is a more accurate description due to the non-linear spring behaviour (Latash and Zatsiorski, 1993). Both vertical (K_{vert}) and leg (K_{leg}) stiffness variables demonstrate spring-mass behaviour where the former depicts the vertical orientation of the leg at contact and the latter at ground contact with the leg at an angle (Butler *et al.,* 2003). However, some original studies (Farley and Morgenroth, 1999) lack a clear distinction between the two definitions during vertical hopping tasks using vertical ground reaction force to measure leg stiffness. For non-vertical dominant locomotion, such as running and horizontal plyometric exercises, it may be inaccurate to illustrate leg stiffness using vertical ground reaction forces

and more appropriate to use the resultant leg force vector in the direction of leg compression during the eccentric phase (Coleman *et al.*, 2012).

Global stiffness such as K_{vert} and K_{leg} display spring characteristics regulated at the joint level, through various permutations of agonist and antagonist co-contraction strategies and muscle-tendon unit behaviours (Latash and Zatsiorsky, 1993). Higher leg stiffness values are observed in power-trained athletes compared to endurance runners, which were accounted for by significant differences in the ankle and knee stiffness (Hobara *et al.*, 2008). Similarly, Rabita et al. (2011) observed higher leg stiffness and lower limb explosive qualities in gymnasts compared to runners and controls. However, no correlation between K_{leg} and intrinsic musculotendinous mechanical properties could be determined, suggesting that other factors such as coordination, pre-activation, and stretch reflex amplitudes may contribute significantly to global stiffness properties.

2.5.5.2. Joint stiffness

Joint stiffness is governed by the various MTU's that cross it, as well as passive tissues and neural sub-systems (Latash and Zatsiorski, 1993). The contribution of the ankle (K_{ankle}) and Knee (K_{knee}) joint stiffness varies according to the task and intensity. Sprinters display higher K_{ankle} values than distance runners (Stefanyshyn and Nigg, 1998). Kuitunen *et al.* (2002) reported increased K_{Knee} over increasing speeds while K_{ankle} remained constant. Distance runners with forefoot strike patterns exhibit high K_{knee} values and lower K_{ankle} due to extra joint angular displacement at the ankle and a more flexed knee at foot strike with less room for joint displacement (Hamill *et al.,* 2014). In sprinting, contact times are almost half what distance runners would display, suggesting high-force application to the ground with minimal joint displacements. In bilateral hopping tasks, ankle stiffness accounts for variations in K_{vert}. In a single leg drop jump, Maloney *et al.* (2017) found that K_{ankle} correlated most with K_{vert} and limb compliance, with differences in K_{ankle} observed between stiff and compliant limbs.

Lower limb stiffness is related to factors which underpin athletic performance, such as contact time, stride frequency, running speed and economy (Butler *et al.,* 2003; Brughelli and Cronin, 2008; McMahon *et al.,* 2012). Stiffness impairments are also observed in injured athletes and viewed as a risk factor (Butler *et al.,* 2003; Maquirriain, 2012; Lorimer and Hume, 2016; Gore *et al.*, 2018). Stiffness is measured during running, jumping, and hopping tasks. Vertical

hopping is a commonly-used test to assess stiffness. During a hopping task, lower K_{leg} on the injured limb was observed in runners with Achilles tendinopathy (Maquirriain, 2012). Measuring lower limb stiffness may provide a valuable measure of readiness for return to sport following a lower limb injury, and hop tests are easy to administer and can be performed in a time-efficient manner in a clinical setting.

2.5.5.3. Achilles tendon mechanical and material properties

AT stiffness is a measure of the mechanical properties of the tendon and is calculated by dividing the change in force applied to the tendon by the deformation that occurs in the direction of the applied force and is expressed in N/mm. Young's modulus, a measure of the tendon's material properties, is calculated by dividing the change in tendon stress (AT force/CSA) by the % strain that occurs. Both measurements are calculated in the linear region of the stress-strain curve *(Fig. 2.15)* or a force-deformation curve, respectively. Young's modulus is essentially stiffness normalised to the dimensions of the tendon and is heavily influenced by viscoelastic behaviour, as outlined in section 2.5.1. Stiffness or modulus is measured on a force plate or dynamometer in conjunction with 2D motion capture and real-time ultrasound. The test involves a series of progressive isometric contractions performed for up to 6 seconds, with displacements of the MG MTJ tracked as a surrogate measure of tendon elongation as illustrated in Figure 2.23 (Albracht and Arampatzis 2013; Geremia *et al.,* 2018). Rotations at the subtalar joint are accounted for by placing markers on anatomical points (Fukunaga *et al.,* 2001; Magnusson *et al.,* 2001). PF force is measured and divided by the AT moment arm to calculate AT force.

Shear wave elastography (SWE) has emerged as an alternative measure of tendon material properties (Aubry *et al.*, 2013; Coombes *et al.*, 2018). SWE involves a passive measurement of the speed at which a shear wave propagates through the tissue with higher speeds indicating a higher stiffness. Some limitations exist, which makes it difficult to accurately measure tendon modulus as the speed at which shear wave propagates through tendon tissue often exceeds the machine's capabilities – particularly in dorsiflexed angles. One solution to overcome this is continuous shear wave elastography, where an external stimulus is applied to the tendon enabling a more accurate measurement (Corrigan *et al.*, 2019).

Higher AT stiffness is associated with superior running economy (Rogers, 2017), but the relationship between AT stiffness and sprint performance is unclear. Arampatzis *et al.* (2007) showed greater AT stiffness in sprinters compared to distance runners, but other studies have found no difference or lower levels of AT stiffness in sprinters compared to distance runners (Stenroth *et al.*, 2016; Kubo *et al.*, 2020). Achilles tendinopathy patients present with reduced AT stiffness on their injured limb or when comparing both limbs with healthy controls (Arya and Kulig, 2010; Wang *et al.*, 2012). These deficits in AT stiffness relate to a reduced rate of force development and horizontal hop performance (Wang *et al.*, 2012).

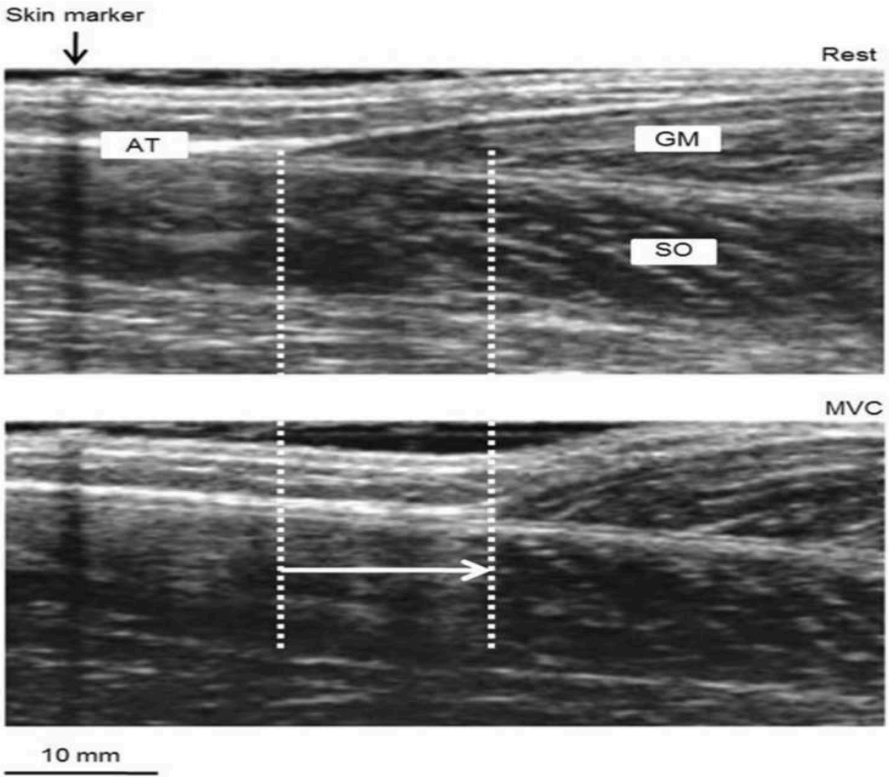


Fig. 2.23. An ultrasound image demonstrating the MTJ of the MG as a reference point to track tendon elongation. The bottom image shows the shortening of the MG as the tendon elongates when force is applied during an isometric plantarflexion contraction (Geremia et al., 2018)

2.5.5.4. Age-related changes to Achilles tendon and calf muscle properties

Achilles tendon injuries are most prevalent in middle-aged populations (van der Vlist *et al.*, 2019; Millar *et al.*, 2021; Xergia *et al.*, 2022). Similarly, calf muscle strain injuries have a higher incidence rate over the age of 30 (Pedret *et al.*, 2015; Green and Pizzari, 2017). Masters

athletes experience a decline in lower limb biomechanical and physiological properties (Willy and Paquette, 2019; Majaj *et al.*, 2020). Age-related changes include reduced AT stiffness, increased AT CSA and reduced PF muscle CSA with shorter, more pennated muscle fascicles (Stenroth *et al.*, 2012; Waugh *et al.*, 2012; Lindemann *et al.*, 2020). However, older sprint-trained athletes appear to preserve their mechanical and morphological properties better than older distance runners (Stenroth *et al.*, 2016), and it has been argued that distance running alone is not a sufficient stimulus for attenuate these age-related declines (Majaj *et al.*, 2020). Numerous studies demonstrated reduced inter-tendon sliding between the deep and superficial layers in ATs of middle-to-older age populations when compared to younger (Clark and Franz, 2021; Slane and Thelen, 2015; Thorpe *et al.* 2013). This may result in repeated localised stress concentrated on the mid-portion of the tendon. A greater number of advanced-glycation end-product cross-links are also observed in an aging population which may reduce the tendon's energy storage capacity and predispose it to injury (Svensson et al. 2016).

Systemic factors such as age-related chronic low-grade inflammation or "inflammaging" may impact how the musculoskeletal system can recover and adapt to exercise (Kunz and Lanza, 2023). It is also relevant to the AT given the emerging evidence of non-resolving inflammation in the development and persistence of tendinopathy as detailed in section 2.6.1.8. The genetic predisposition to spondyloarthriits, cardiovascular disease and other systemic conditions that manifest in an aging population, may add extra confounding factors in the development of Achilles tendon injuries. This was reflected in the inclusion criteria for participants in Studies 3 and 4 where an upper age limit of 45 years old was applied.

2.6 ACHILLES TENDON INJURIES

The three most common Achilles tendon injuries are Achilles tendinopathy, paratenonitis, and Achilles ruptures. The AT can either fully or partially rupture, with a complete rupture most often requiring surgical repair.

2.6.1 ACHILLES TENDINOPATHY

Achilles tendinopathy is the most common Achilles injury and occurs at both the mid-portion of the tendon and at the BJT. The diagnostic term has evolved over the last three decades from tendonitis, describing a typical inflammatory condition, to tendinosis moving away from an inflammatory state to a more degenerative type, to tendinopathy *(Fig. 2.24)*. Tendinopathy is defined as pain and impaired function in the affected tendon during mechanical loading (Scott *et al.*, 2020). Tendinopathy is broadly accepted to be a degenerative condition with many contributing factors (Scott *et al.*, 2020). In recent years, there has been a growing acceptance that inflammatory interactions are present in the pathogenesis of tendinopathy (Rees *et al.,* 2014; Dakin *et al.*, 2017; Millar *et al.,* 2017; Mosca *et al.*, 2018).

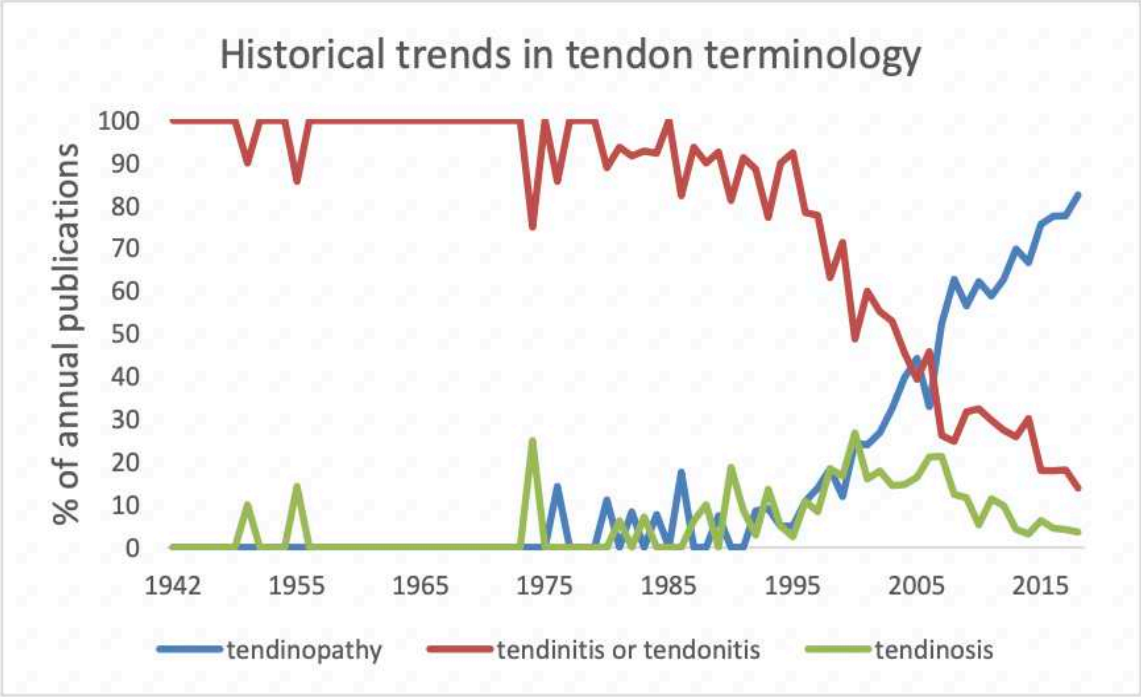


Fig. 2.24. A graph illustrating the historical trends in terminology which has evolved to a commonly accepted as tendinopathy (Scott et al., 2020, ICON consensus statement)

2.6.1.1. Mid-portion Achilles tendinopathy

Mid-portion Achilles tendinopathy occurs between 2-7 cm proximal to the BTJ with local thickening – particularly in chronic presentations (Maffulli *et al.*, 2020; Scott *et al.*, 2020; De Vos *et al.*, 2021). Pain symptoms are usually experienced in this portion of the AT upon palpation and sporting activity (Maffulli *et al.*, 2020; Scott *et al.*, 2020; De Vos *et al.*, 2021).

2.6.1.2. Insertional Achilles tendinopathy

Insertional Achilles tendinopathy occurs within 2 cm of the BJT with pain in that region during palpation and sporting activity (De Vos *et al.*, 2021). Pain may be further exacerbated when loading the tendon into ankle dorsiflexion, causing increased compressional loading. A retrocalcaneal bursitis often accompanies an insertional Achilles tendinopathy. Often, the bursitis can be the primary driver of insertional heel pain without tendinopathy. A small number of patients present with a Haglund's deformity, which is a bone spur in the superolateral side of the calcaneus that can exacerbate pain symptoms due to friction with the heel cup of the shoe over the tendon, with the bone spur protruding from the other side.

2.6.1.3. Epidemiology

Achilles tendinopathy affects 2% of the general population (De Jonge *et al.*, 2011), with two-thirds of patients who present to general practice not active in sports (De Vos *et al.*, 2021). The injury is prevalent in 7-9% of sporting populations, with up to half of elite runners expected to experience it in their lifetime (Kujala *et al.,* 2005). In track and field athletics, it is more prevalent among middle and long-distance runners than sprint, throw and jump athletes, with 25% experiencing bilateral symptoms (Janssen *et al.*, 2018).

2.6.1.4. Risk factors

The complex systems model by Bittencourt et al. (2016) applies to any MSK injury by inputting known risk factors known as the "web of determinants" and taking into account the interaction of a number of these determinants that may lead to an adaptive or injury response *(Fig. 2.25).* Despite limited evidence, risk factors for developing Achilles tendinopathy include reduced PF strength, biomechanical gait features, the experience of ta previous tendinopathy, training in cold weather, consumption of ofloxacin antibiotics, metabolic factors, and alcohol consumption (van der Vlist *et al.*, 2019). Some factors, such as reduced PF strength, may reduce the tendon's capacity to tolerate high loads, while other factors, such as antibiotics,

metabolic profile, or alcohol consumption, may alter the tendon's metabolism to delay recovery with an incomplete remodelling in response to load-induced tissue damage.

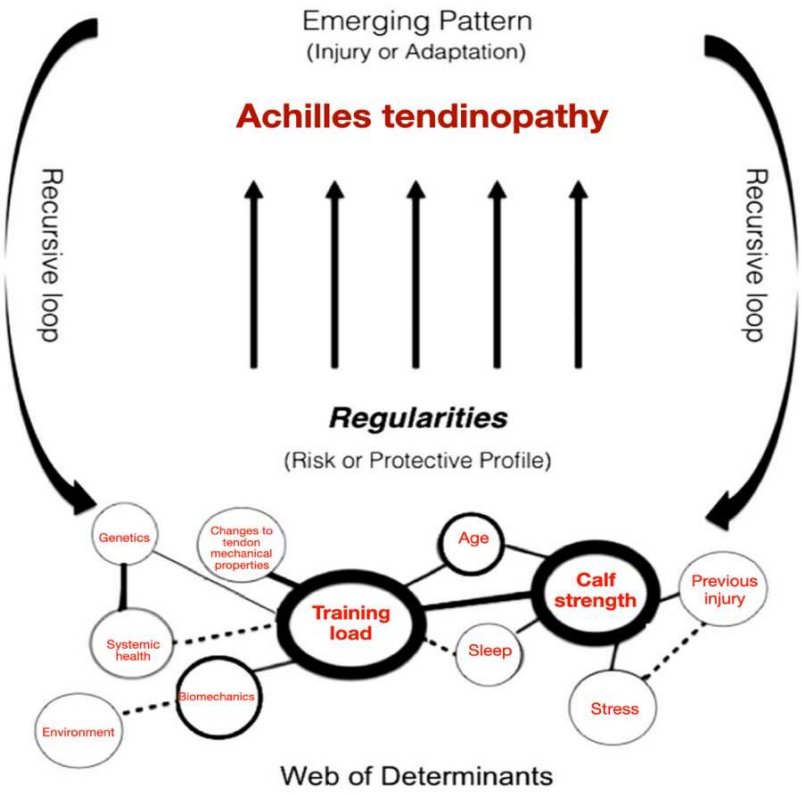


Fig. 2.25. The Complex Systems Model (Bittencourt et al., 2016) adapted for Achilles tendinopathy with a hypothetical interaction of determinants.

2.6.1.5. Pathophysiological models of Achilles tendinopathy

Four models have been proposed to describe the development of tendinopathy. These include:

1. Arnozcky's theory of tendinopathy (Arnoczky *et al.,* 2007)
2. The iceberg model (Abate *et al.*, 2009)
3. The failed healing model (Fu *et al.*, 2010)
4. The continuum model (Cook and Purdam, 2009)

The continuum model by Cook and Purdam (2009) and illustrated in Figure 2.26, is the most widely-used of the four models, to describe the staged progression of tendinopathy from a normal tendon to reactive tendinopathy to chronic degenerative tendinopathy and was subsequently updated to reflect the emerging understanding of inflammatory interactions

(Cook and Purdam, 2009; Cook *et al.*, 2016). Altered tenocyte behaviour with suspected cytokine signalling and increased proteoglycans are observed in reactive tendinopathy. Imaging shows fusiform swelling, but the collagen and matrix structures are largely preserved. As the tendon goes through a further stage of disrepair, it experiences structural changes to its collagen hierarchy, which are not easily reversible. In the degenerative stage, there is further structural destruction, increased type III to type I collagen ratio, increased vascularity, and reduced tolerance to tensile loading.

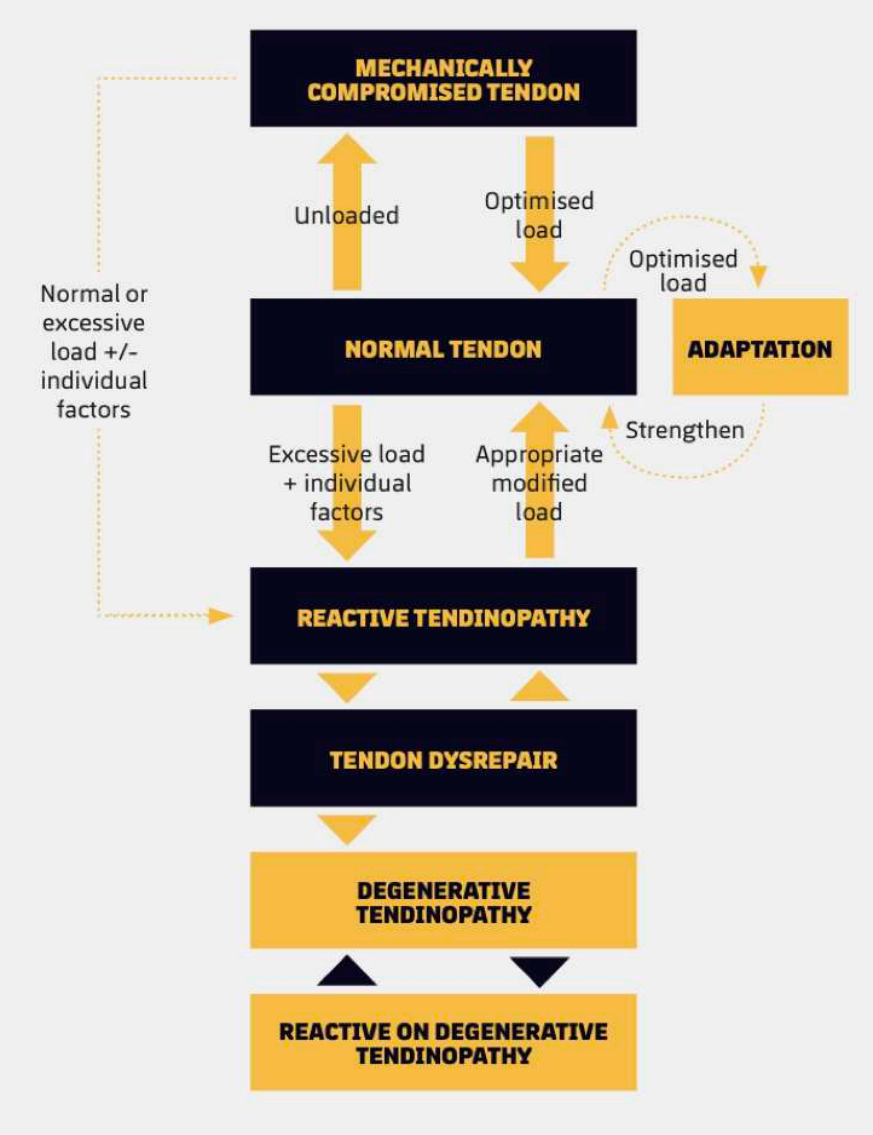


Fig. 2.26. The continuum model of tendinopathy (Cook and Purdam, 2009; copyright Barcelona FC Tendon Guide 2021)

Common pathological features of tendinopathy include:

- Changes in the ECM composition with loss of type I collagen and an increase of type III in the early stages
- Extra ECM proteins are deposited, creating a more fibrocartilaginous environment
- Tenocytes lose their spindle shape to become rounder, more proliferative and metabolically active, and apoptotic
- Ingrowth of blood vessels and nerve fascicles
- A mismatch between matrix metalloproteinases (MMPs), which are markers of ECM degradation, and tissue inhibitors of MMPs (TIMPs)
- Inflammatory interactions
  (Riley, 2008; Magnusson *et al.,* 2010; Ackermann, 2013; Cook *et al.*, 2016; Dakin *et al.*, 2017; Millar *et al.,* 2017)

2.6.1.6. Sub-classifications of Achilles tendinopathy patients

Hanlon et al. (2021) used a mixed modelling approach with 14 variables of interest, including patient characteristics and tendon health factors, to emerge with three subgroups of Achilles tendinopathy: Activity-dominant, psychosocial-dominant, and structure-dominant *(Fig. 2.27).*

1. Activity-dominant

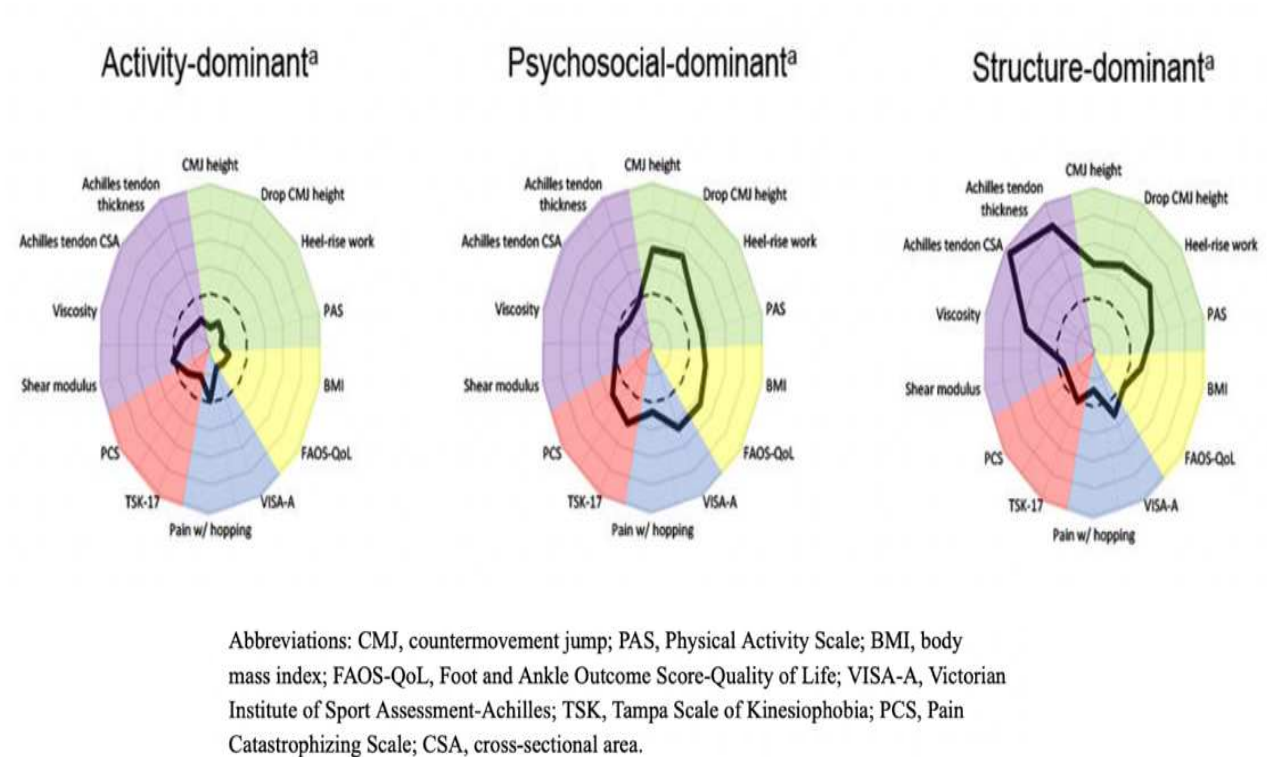
This was the largest subgroup, with participants in the younger age cohort with the highest levels of physical activity, function, and quality of life. Their symptoms were milder, with fewer structural changes visible on imaging. There was more likely to be an overloading mechanism as a primary contributor to the development of their symptoms, and they appeared to respond favourably to exercise therapy and load management.

2. Psychosocial-dominant

This subgroup was predominantly female and had higher levels of obesity. They reported higher pain symptoms and the poorest quality of life with more significant functional impairments. They had increased levels of kinesiophobia and pain catastrophizing scores. However, they had minimal structural changes detected on imaging.

3. Structure-dominant

This was the smallest subgroup but was older, predominantly male, and a high proportion were obese. Patients had the most structural changes with greater AT thickness and CSA on imaging. Of all the subgroups, they had the most significant functional deficits with the lowest heel raise performance, with many unable to complete a single heel raise. They also reported poor quality of life but better than the psychosocial group. This group also had other comorbidities, including diabetes and poorer metabolic health.



Abbreviations: CMJ, countermovement jump; PAS, Physical Activity Scale; BMI, body mass index; FAOS-QoL, Foot and Ankle Outcome Score-Quality of Life; VISA-A, Victorian Institute of Sport Assessment-Achilles; TSK, Tampa Scale of Kinesiophobia; PCS, Pain Catastrophizing Scale; CSA, cross-sectional area.

Fig. 2.27. Radar plots comparing subgroup performances on outcome measures (Hanlon et al., 2021)

2.6.1.7. Biopsychosocial (BPS) model

The BPS model considers the broader psychological, social, and biological factors to understand a patient's medical condition (Borrell-Carrió *et al.,* 2004). Fear, depression, and anxiety are common in a cohort of patients with MSK injuries. These traits can lead to lower self-efficacy culminating in fear avoidance behaviours, pain catastrophizing, and hypervigilance (Borrell-Carrió *et al.,* 2004; Edgar *et al.*, 2022). There is often an accepted

disconnect between pain and pathology on imaging in tendinopathy and an incomplete understanding of the mechanisms that drive pain (Ackermann *et al.*, 2022). The BPS model for tendinopathy *(Fig. 2.28)* provides a framework to screen patients who may fit into this domain and to use techniques to reframe their irrational beliefs around pain, treatment, and the prognosis of their injury (Edgar *et al.*, 2022).

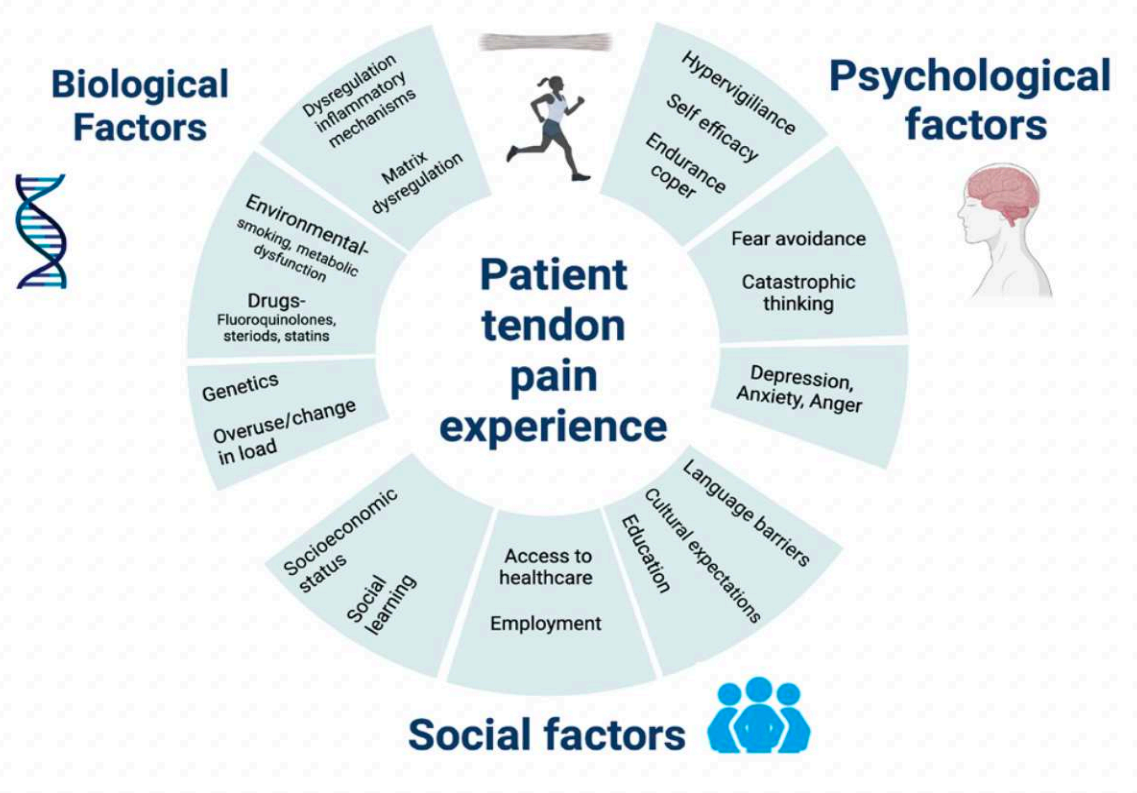


Fig. 2.28. The biopsychosocial model for tendinopathy (Edgar et al., 2022)

2.6.1.8. The role of inflammation

The influence of inflammatory responses in the pathogenesis of tendinopathy has seen a pendulum shift over the last three decades. Most reviews prior to 2011 refuted the presence of an inflammatory component to tendinopathies. However, most of these studies focussed on the presence or absence of neutrophils, as highlighted in Figure 2.29 (Mosca *et al.,* 2018). In the last decade, with the ability to thoroughly investigate cellular and molecular signatures, new evidence emerged demonstrating that elements of an inflammatory response, particularly the interaction between immune cells and resident stromal cells, are part of the process in the development and continuation of tendinopathy (Rees *et al.,* 2013, Millar *et al.,* 2017, Dakin *et al.,* 2018, Mosca *et al.,* 2018).

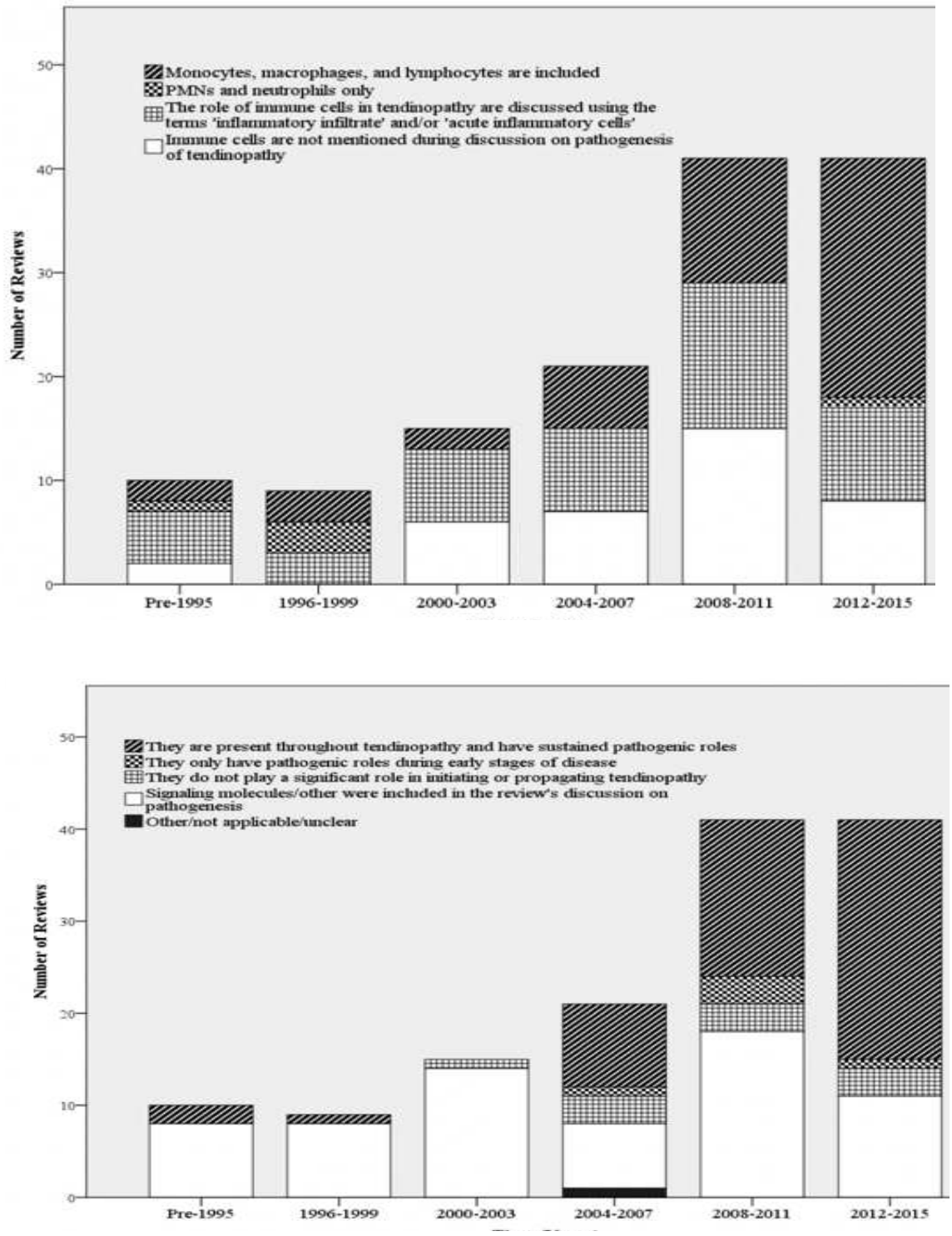


Fig. 2.29. A timeline of studies with a breakdown of different inflammatory markers that were included (top) and a timeline of studies that detected a role for each inflammatory marker in tendinopathy (bottom) (Mosca et al. 2018)

Chronic inflammation features in Achilles tendinopathies and ruptures, albeit with slightly different inflammatory signatures (Dakin *et al.*, 2017). The detection of inflammatory interactions was evident before 2011. In acute Achilles tendinopathy, Backmann *et al.* (1990) observed inflammatory changes in the paratenon co-existing with degenerative changes, while Schubert *et al.* (2005) detected the presence of macrophages and lymphocytes in chronic Achilles tendinopathy (both cited in Rees *et al.,* 2013). There is a growing recognition that tenocytes proliferate and increase their metabolic activity in response to cytokines and growth factors, as part of an inflammatory response (Scott *et al.,* 2007; Millar *et al.,* 2017). Increased macrophages and mast cells levels have been found in pathological tendons compared to healthy tendons (Millar, 2017). Vascular endothelial growth factor (VGEF) – a key regulator for blood vessel formation and produced by macrophages, is primarily responsible for neovascularisation, a key feature in chronic tendinopathies concomitantly with neoinnervation, and contributes to the nociceptive pain response (Rees *et al.,* 2014). Many key inflammatory interactions occur in the earlier stages of tendon microdamage before onset of symptoms (Millar *et al.,* 2017). Substance P is a neuropeptide with pro-inflammatory properties and, when injected experimentally into a tendon, resulted in increased neovascularisation (Rees *et al.,* 2014). Substance P also regulates matrix metalloproteinase-3 (MMP-3), which in turn governs degradation and remodelling of the ECM (Riley, 2005; Fong *et al.*, 2013).

The interaction between immune cells (resident or infiltrating) and resident stromal cells have critical roles in turning a normal inflammatory response in the tissue into a chronic disease such as tendinopathy (Millar *et al.,* 2017; Dakin *et al.,* 2017). There are three cellular compartments involved in the development of inflammation in a tendon *(Fig. 2.30):*

1. The infiltrating compartment includes invading immune cells (T cells, mast cells, and pro-inflammatory (M1) and pro-resolving (M2) macrophages).
2. The immune-sensing compartment includes resident immune cells that sense and respond to tissue damage.
3. The stromal compartment where resident tenocytes reside and are primarily responsible for tissue remodelling and repair (Millar *et al.,* 2017)

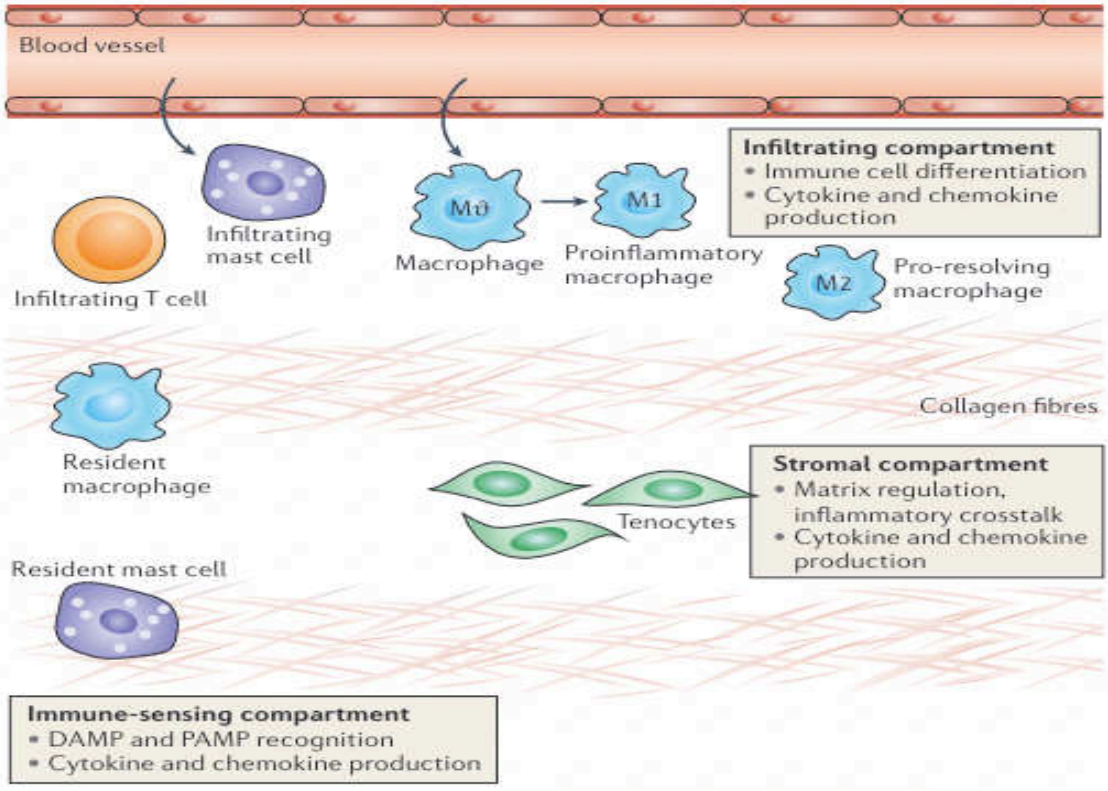


Fig. 2.30. Illustration of 3 compartments of the inflammatory interactions in tendons (Miller et al., 2017)

The immune cells in the infiltrating compartment are recruited when stromal and resident immune cells are activated. The tenocytes secrete cytokines and chemokines due to the presence of cell-surface immune receptors that switch towards an activated inflammatory phenotype. Dakin *et al.* (2017) demonstrated that when compared to healthy tendons, diseased tendon cells previously exposed to tendinopathy possess "stromal memory," making them susceptible to the disease on subsequent exposure *(Fig. 2.31)*. Inflammatory mediators from mast cells regulate collagen synthesis and MMP expression in tenocytes, suggesting that a failed resolution of an inflammatory response to tendon loading may be one possible mechanism in the development of tendinopathy. Similar to treatments for rheumatoid arthritis and arthropathies, there may be a role for pro-inflammatory inhibitors as part of the treatment for some tendinopathies.

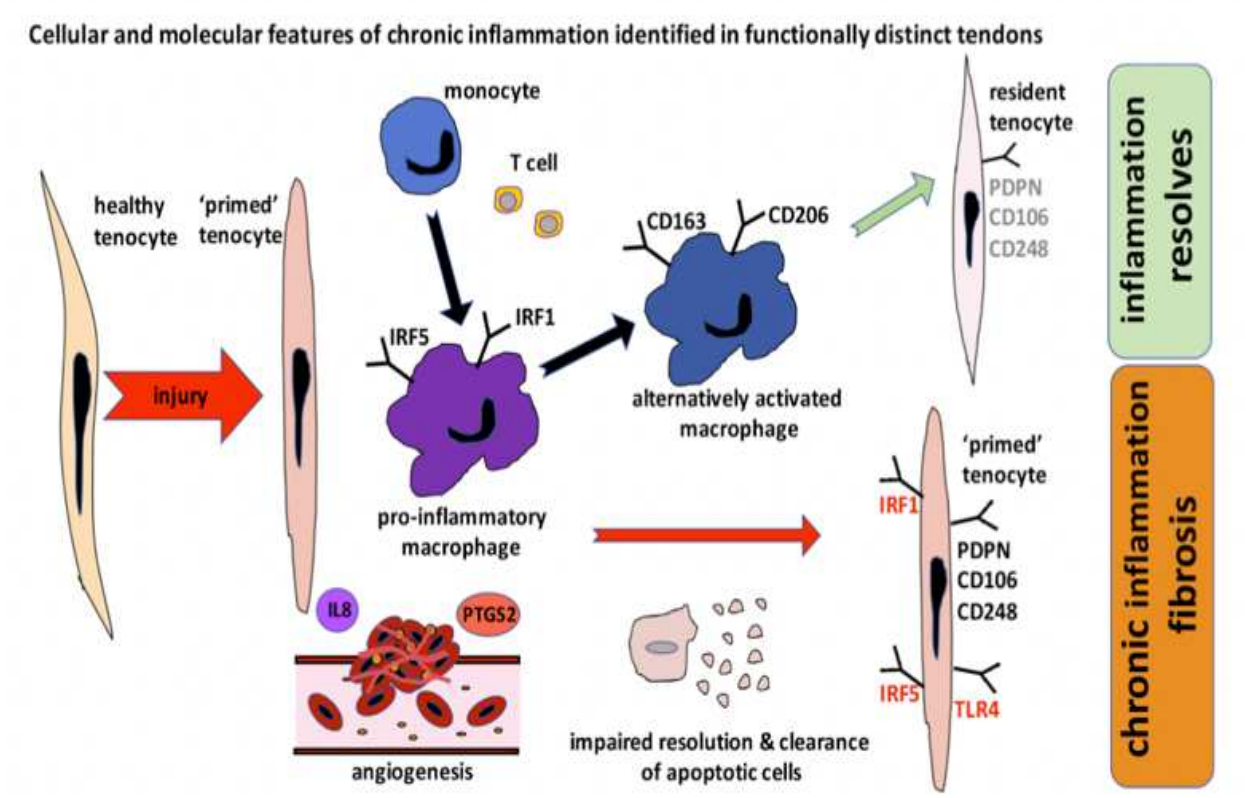


Fig 2.31. Illustration of chronic inflammatory pathways versus resolving inflammatory pathways (Dakin et al., 2017)

Millar *et al.* (2021) proposed a pathophysiological model for tendinopathy taking into account genetic and environmental factors and inflammatory interactions from the immune and stromal cells *(Fig. 2.32).* Pre-clinical tendinopathy develops where pathological changes are present with increased cell activity in response to load but without clinical symptoms. The condition progresses when there is a failure to return to homeostasis or adapt to load. In this early stage of tendinopathy, there is an influx of immune cells, a higher-than-normal level of collagen synthesis, dysfunction of the interfascicular matrix, and increased ground substances and MMPs. In chronic tendinopathy, there is a dysfunction of the stromal cells, which are signalled for inflammatory and degenerative responses, increased oxidative stress, mitochondrial dysfunction, and apoptosis. This pathophysiological condition is difficult to reverse.

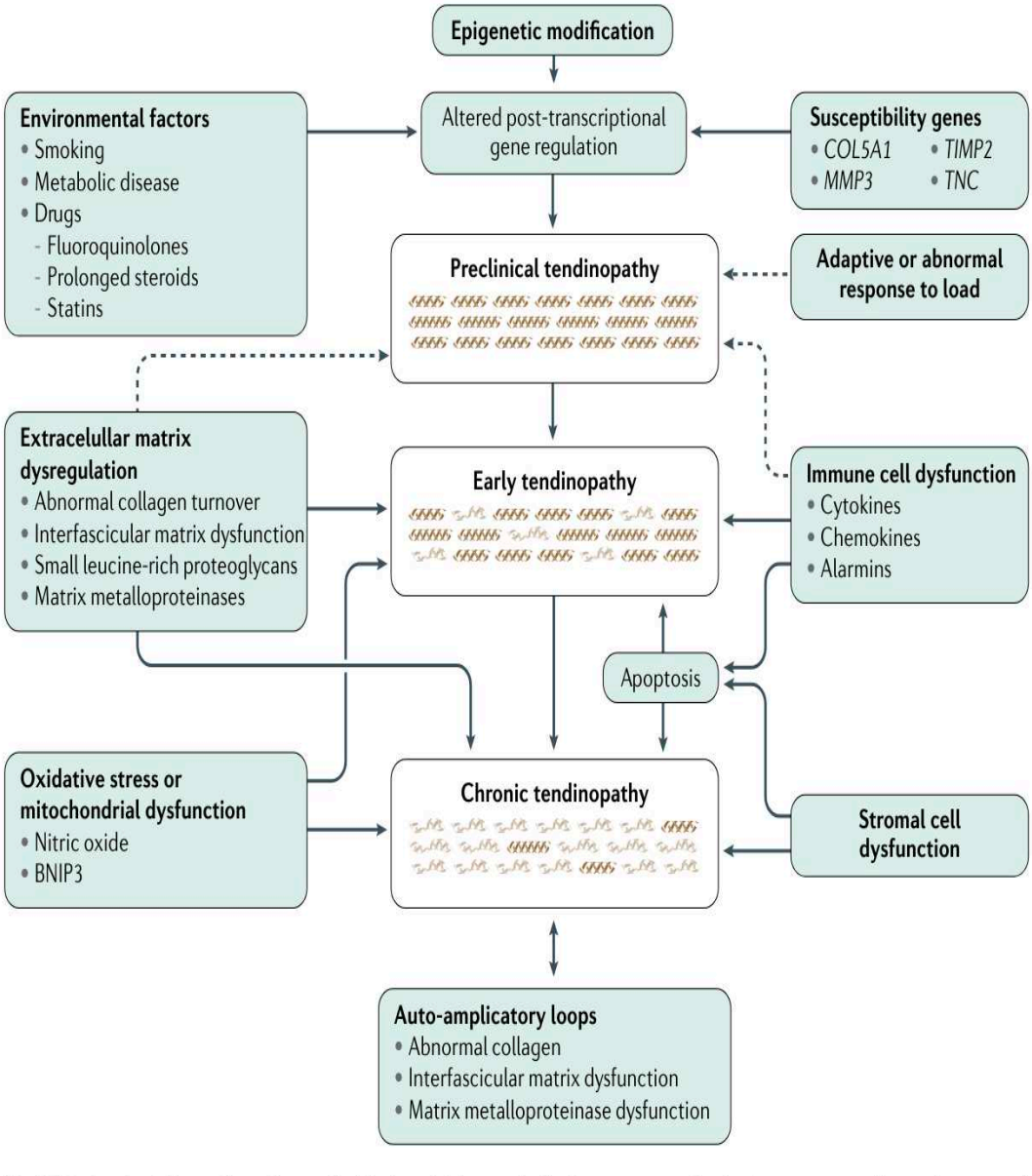


Fig. 2.32. The pathophysiology of tendinopathy (Millar et al. 2021)

2.6.2. PARATENONITIS

Paratenonitis, which also encompasses "peritendinitis," is an overuse injury to the paratenon. Inflammatory cell reactions, extravasation of plasma proteins, and an accumulation of fibrin are observed (Kvist *et al.*, 1987). The resulting metabolic and morphological changes impair the paratenon's ability to glide smoothly over the tendon (Kvist *et al.*, 1987). Frictional loading can provoke pain or prolong the pathology.

2.6.3. ACHILLES TENDON RUPTURES

2.6.3.1. Epidemiology

Achilles tendon ruptures are common injuries in middle-aged and older recreational and elite sporting populations, with an annual incidence rate of 30 per 100,000 person-years rising in recent years. Impairments following a rupture can persist for many years, preventing a high proportion of athletes from returning to their sport at pre-injury levels. In some cases, quality of life can be severely affected. Surgical repair is the most common approach following a rupture, but many patients are managed non-surgically with no difference in outcomes after 12 months. However, a higher incidence of re-ruptures is reported in the conservatively managed cases compared to surgically-repaired (Ochen *et al.*, 2019; Myhrvold *et al.*, 2022). Alarmingly, around 30-40% of high-performing athletes who sustain an AT rupture fail to return to their pre-injury level of performance (Trofa *et al.*, 2017; Yang *et al.*, 2019). Common impairments which can be long-lasting following an AT rupture include reduced power from the ankle and deficits in inner range PF strength, and reduced heel raise height (Willy *et al.*, 2017; Baxter *et al.,* 2019; Hoeffner *et al.*, 2022). Morphological changes that may account for these impairments include an increase in AT slack length and reduced MG fascicle length with an increased pennation angle (Zellers *et al.,* 2016b; Hullfish *et al.,* 2019a, 2019b; Stäudle *et al.*, 2022).

2.6.3.2. Risk factors

A rupture occurs when the tendon reaches a high strain level, resulting in tensile failure. It happens during explosive movements, with the most common mechanisms involving pushing off the rearfoot to accelerate, landing from a jump, foot plant, and changing of direction (Zellers *et al.,* 2016a; Trofa *et al.*, 2017; De la Fuente *et al.*, 2019; Tarantino *et al.*, 2020). In these movements, the ankle undergoes rapid dorsiflexion as the heel is off the ground. There is substantial evidence that pathological tendon changes occur before a rupture (Maffulli *et al.,* 2015). In 2011 following the NFL-enforced "lockout" period, a higher-than-normal incidence of Achilles tendon ruptures was reported during the early pre-season, as illustrated in Figure 2.33 (Myer *et al.*, 2011). It is well-accepted that the Achilles tendon responds negatively to reduced levels of habitual activity and increased loading beyond the tendon's ability to adapt (Magnusson *et al.,* 2010). The increased loading during the 2011 NFL pre-season following the lockout period may have predisposed tendons to a high risk of rupture due to elevated collagen resynthesis and accumulated neuromuscular fatigue. Risk factors include the use of steroids, quinolones, and oral bisphosphonate, the presence of chronic inflammation and

Achilles tendinopathy, spring season, having diabetes, a previous musculoskeletal injury, hypothyroidism or renal failure, as well as genetic factors such as polymorphisms of collagen genes, were reported in a recent systematic review (Xergia *et al.*, 2022).

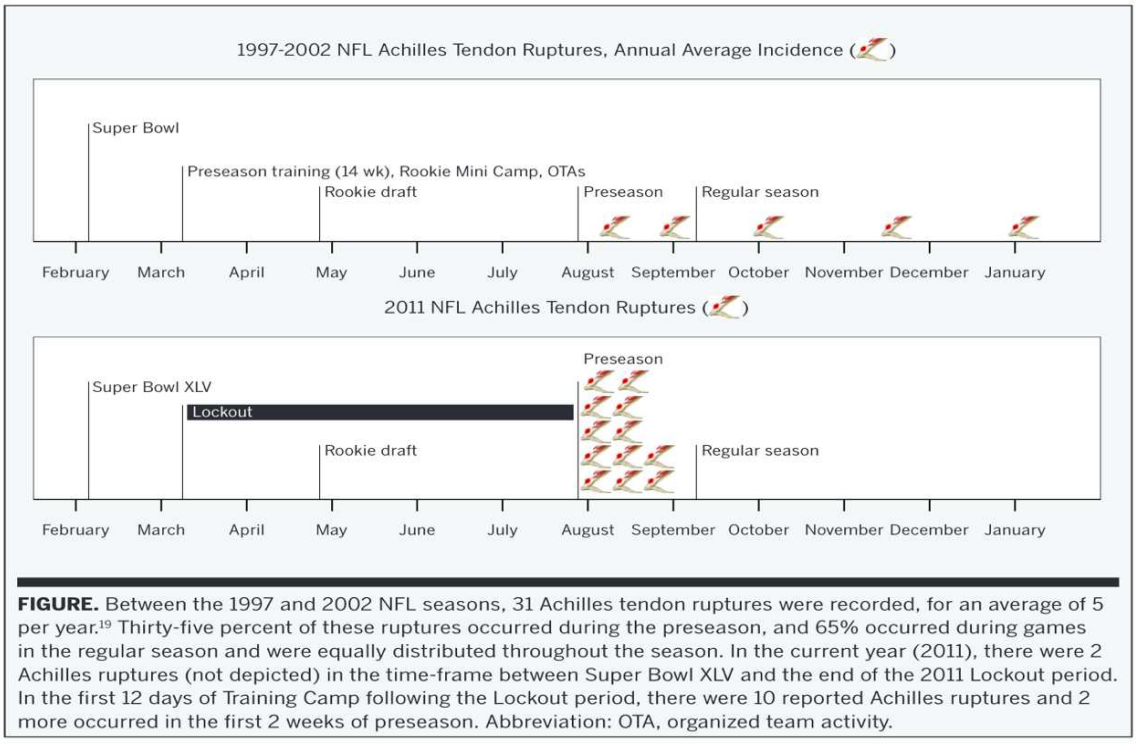


FIGURE. Between the 1997 and 2002 NFL seasons, 31 Achilles tendon ruptures were recorded, for an average of 5 per year.[19] Thirty-five percent of these ruptures occurred during the preseason, and 65% occurred during games in the regular season and were equally distributed throughout the season. In the current year (2011), there were 2 Achilles ruptures (not depicted) in the time-frame between Super Bowl XLV and the end of the 2011 Lockout period. In the first 12 days of Training Camp following the Lockout period, there were 10 reported Achilles ruptures and 2 more occurred in the first 2 weeks of preseason. Abbreviation: OTA, organized team activity.

Figure 2.33. The average incidence of AT ruptures between 1997-2002 over the course of the NFL season (top) and (bottom) the exponential increase in incidences in the 2011 pre-season following the enforced lockout period (Meyer et al. 2011)

2.6.4. DIAGNOSIS OF ACHILLES TENDON INJURIES

2.6.4.1. Differential diagnosis

When a patient presents with mid-portion or insertional Achilles pain, the differential diagnosis includes the following:

- Paratenonitis
- Posterior ankle impingement
- Os trigonum
- Achilles tendon rupture
- Pain from an accessory soleus muscle
- Plantaris-related Achilles pain
- Sural nerve entrapment

- Fat pad irritation
- Inflammatory disease
- Tibialis posterior or flexor hallucis longus tenosynovitis

2.6.4.2. Clinical assessments

Most often accompanied by Imaging, clinical diagnostic tests are used to diagnose Achilles tendinopathy. Swelling and pain on palpation of the mid-portion (2-7 cm proximal to the calcaneus) or AT insertion (within 2 cm of the calcaneus) is a standard indicator of Achilles tendinopathy with 81% specificity and 64% sensitivity (Reiman *et al.*, 2014). Standard clinical pain-provocation tests include a single-leg heel raise and single-leg hop (Silbernagel *et al.*, 2006a; Maffulli *et al.*, 2020). The Royal London Hospital test is also used, where the clinician palpates the localised painful area of the tendon in a neutral ankle position and instructs the patient to dorsiflex and plantarflex actively. If the pain is present on palpation in maximum dorsiflexion and less in plantarflexion, this indicates Achilles tendinopathy with 54% sensitivity and 86% specificity (Reiman *et al.*, 2014). The arc sign can rule out the diagnosis of paratenonitis, whereby a painful nodule is located in the tendon. If the palpable nodule moves from plantarflexion into dorsiflexion, this would suggest a diagnosis of Achilles tendinopathy with 42% sensitivity and 88% specificity (Reiman *et al.*, 2014). However, if the nodule doesn't move, a diagnosis of paratenonitis can be suspected. Plantaris involvement, whereby a thickened plantaris tendon causes friction or compression against the AT during ankle dorsiflexion, would be strongly suspected if there is pain on the medial side of the mid-portion or proximal region of the AT (Masci *et al.*, 2015).

In insertional Achilles tendinopathy, pain is experienced upon palpation of the AT insertion over the posterosuperior aspect of the calcaneus. A diagnosis of enthesopathy would be made where there is an inflammatory disease, and obtaining a past medical history or family history of rheumatoid arthritis or spondyloarthropathy would be necessary (Benjamin *et al.*, 2006). In many cases of insertional AT pain, there is also the presence of retrocalcaneal bursitis, which is palpable between the AT insertion and the superomedial aspect of the calcaneus.

An AT rupture is diagnosed using the Thompson test, where the clinician squeezes the calf muscle, which with an intact tendon would result in plantarflexion. If there is no responsive plantarflexion, an AT rupture is suspected. A noticeable gap in the AT would also be detected.

2.6.4.3. Imaging

Ultrasound (US) imaging is the preferred option for Imaging as it is more affordable and readily available in clinical settings. Magnetic resonance imaging (MRI), the gold standard for diagnostic Imaging, is also used, requiring a referral from a doctor or physiotherapist and is more expensive.

The typical features of Achilles tendinopathy on US or MRI imaging are increased localised thickening measured in the anterior-posterior plane *(Fig. 2.34),* altered structure with an increased white signal on MRI or echogenicity on the US indicating disruption to type I collagen tissue, and presence of neo- or hypervascularisation (De Vos *et al.*, 2021). Ultrasound tissue characterisation (UTC) measures the level of collagen tissue disorganisation and is regularly used for screening athletes who may be at risk for developing tendinopathy (Docking, Cook and Docking, 2016). An x-ray may be used in insertional Achilles tendinopathy cases to detect calcification signs (De Vos *et al.*, 2021).

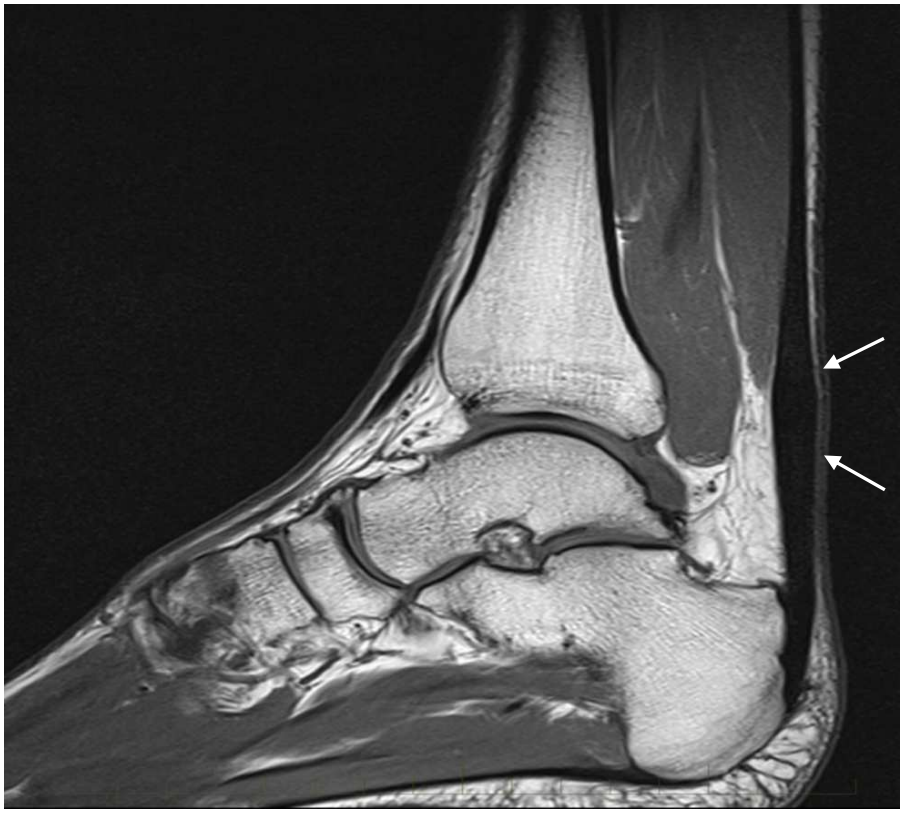


Fig 2.34. MRI of Achilles tendinopathy where mild fusiform thickening is visible in the mid-portion as indicated by the white arrows.

2.6.6.4. Screening

Certain medications can alter collagen metabolism, which may predispose to tendinopathy when combined with other risk factors. Patients with rheumatoid arthritis (RA) or spondyloarthropathy (SpA), diabetes, and cardiovascular disease may also have systemic inflammatory or metabolic factors contributing to the development and persistence of tendinopathy symptoms. Where there is a family history of RA or SpA, it is prudent to complete a blood test to confirm or exclude these broader diagnostic factors. When patients present with Achilles pain, it is prudent to ask them to declare any medication such as statins, a recent course of antibiotics, and whether they use oral contraceptives in the case of females. It is also essential to be vigilant for signs of elevated stress, depression, or anxiety, as this may feed into the biopsychosocial model for tendinopathy and may require pain management support in conjunction with rehabilitation (Edgar *et al.*, 2022).

2.6.5. PATIENT-REPORTED OUTCOME MEASURES (PROMs)

2.6.5.1. VISA-A Questionnaire

The VISA-A questionnaire is a valid, reliable, and easy-to-use outcome measure tool for intervention studies on AT (Robinson *et al.*, 2001; Sigurðsson and Silbernagel, 2022). It consists of eight questions regarding pain and function during daily living and sporting activities. The overall score is between 0-100, where higher scores represent reduced pain and improved function. An improvement of 21 points is typically observed between 2 and 12 weeks of a rehabilitation program (Murphy *et al.*, 2018), with a clinically meaningful change of 14 points reported (Lagas *et al.*, 2021). When comparing it against other PROMs, the authors found that the VISA-A was most responsive over time with scores above 89.5, indicating complete recovery (Sigurðsson and Silbernagel, 2022). Its use has been called into question on its validity in non-sporting populations or where there is a higher level of disability due to the condition (Comins *et al.*, 2021). An example of a VISA-A questionnaire is available in Appendix 7.

2.6.5.2. Global rating of change (GROC)

The GROC questionnaire was designed for a patient to self-assess their improvement or deterioration in pain symptoms following an MSK injury - usually in response to an intervention. The patient rates their changes in symptoms on a Likert scale based on whether they feel better, worse, or the same compared to before they began their intervention. This

questionnaire is often used for long-term follow-up assessments. Refer to Appendix 8 for an example of a GROC questionnaire used in Study 3.

2.6.5.3. Tampa scale of kinesiophobia (TSK)

The TSK was first developed by Miller, Kori, and Todd (1991) as a measure of fear of pain in MSK injury patients. The long form of the TSK has 17 items, each with a 4-point scale to self-assess their fear of movement or physical activity and fear-avoidance behaviours. Higher scores indicate higher levels of kinesiophobia. Patients with Achilles tendinopathy, with the highest levels of kinesiophobia, could not perform more than three single leg heel raises (Chimenti *et al.*, 2021; Hanlon *et al.,* 2021). Refer to Appendix 12 for an example of a TSK questionnaire used in Study 5.

2.6.5.4. Achilles tendon rupture score (ATRS)

The ATRS was designed and validated by Nilsson-Helander *et al.* (2007) as a patient-reported outcome measure after rehabilitation for an AT rupture. It has ten questions where patients rate their responses on a 10-point scale. Caution is advised when using this tool in the first six months post-rupture or before the patient has returned to athletics activity, as the last three items may deflate the score (Hansen *et al.*, 2019). Refer to Appendix 11 for an example of an ATRS questionnaire used in Study 5.

2.6.5.5. Foot and ankle outcome score (FAOS)

The FAOS is one of the most widely-used patient-reported outcome measures for foot and ankle injuries. It was designed in Sweden as an alternative to the knee outcome score with validity and reliability tested on 213 patients (Roos *et al.,* 2001). It contains 42 items across five subsections based on pain, function during daily living, function in sport and physical activity, and quality of life relating to the Foot and ankle, respectively. Refer to Appendix 13 for an example of the FAOS questionnaire used in Study 5.

2.7. PERFORMANCE TESTS

2.7.1. PLANTAR FLEXOR STRENGTH

PF strength deficits are observed between injured and uninjured limbs or when both limbs are compared to healthy controls in patients with Achilles tendinopathy (McAuliffe *et al.*, 2019; O'Neill *et al.,* 2019). PF strength impairments persist for several months and often years in patients who sustain an AT rupture (Chester *et al.*, 2003; Zellers *et al.,* 2016; Hullfish *et al.,* 2019; Khair *et al.*, 2022). PF strength is typically measured using an isometric or IKD test using either a straight knee, a bent knee, or a combination of both. Testing calf strength with a bent knee provides an isolated measure of soleus muscle strength as the biarticular gastrocnemius muscles reduce their force output, whereas the monoarticular soleus maintains or can increase its force output (Arampatzis *et al.*, 2006; Landin *et al.,* 2015; Bojsen-møller *et al.*, 2018). There is a lack of consistency with the protocols used to measure PF strength with various IKD protocols, isometric testing and calf endurance tests. Considering that the muscle force contributions from the PFs are several times body weight, there is a growing need for a surrogate measure of maximal strength where the relative F_{peak} or T_{peak} measured is well above body weight. This would require measuring at slower IKD speeds or an isometric test.

2.7.1.1 Isokinetic (IKD) strength testing

IKD testing measures muscle torque around a joint over a fixed angular speed. An IKD ankle test measures PF T_{peak} during concentric or eccentric actions, usually performed over one or two sets of 5 repetitions following a familiarisation set. The speeds used vary from 30 °/sec to 220 °/sec (Alfredson *et al.*, 1998; O'Neill *et al.,* 2019; McAuliffe *et al.*, 2019), which highlights a lack of consistency when interpreting IKD strength values. McAuliffe (2019), in his systematic review, found that slower IKD speeds can detect greater calf strength deficits in Achilles tendinopathy patients. IKD tests are also performed with a bent knee which, if results in similar strength deficits with knee-straight, may indicate strength deficits predominantly in the soleus muscle (O'Neill *et al.,* 2019).

2.7.1.2 Isometric strength testing

Isometric PF strength has been traditionally measured using an IKD dynamometer and usually when measuring AT mechanical and material properties in conjunction with video motion capture and real-time ultrasonography. Patients perform three maximal voluntary isometric contractions from a neutral or slightly dorsiflexed angle. With the easier availability of force plate technology in recent years, a seated calf isometric test may be a quick and convenient

way to measure calf, and in particular, soleus muscle F_{peak} (Rhodes *et al.*, 2022). However, there is a need to standardise a protocol with fixed knee and ankle angles to measure maximal force from the SO.

2.7.1.3 Calf raise test

This test is used in most clinical settings to assess calf function. The patient is required to stand upright on one leg while lightly using the wall for balance and perform repeated calf raises to maintain consistent heel raise height and concentric-eccentric tempo (Silbernagel *et al.*, 2006; Hébert-Losier *et al.*, 2009; Hébert-Losier and Holmberg, 2013; Baxter *et al.,* 2019). Approximately 30 single-leg calf raises indicate adequate calf endurance in the young to middle-aged population (Hébert-Losier *et al.*, 2017). The Calf Raise application was designed to measure heel raise height and tempo and calculate estimated power using the camera's pixels on a smartphone (Hébert-Losier *et al.*, 2022). Despite the clinical usefulness of this test, it is not a measure of maximal strength and thus may not provide a complete calf strength profile of the patient.

2.7.2. REACTIVE STRENGTH

Similar to PF strength testing, reported hop test protocols for measuring reactive strength qualities vary between drop jumps (Arya and Kulig, 2010; Fouré *et al.,* 2010), repeated hops test (Silbernagel *et al.*, 2006; Maquirriain, 2012; Sancho *et al.*, 2022) and horizontal hops (Firth *et al.*, 2010; Wang *et al.*, 2012). Horizontal hopping exposes the AT to the highest tensile forces and loading rates compared to vertical hopping (Gheidi *et al.*, 2018; Baxter *et al.*, 2021). Therefore it may be valuable to clinicians to examine the reliability and biomechanical features of a horizontal plyometric test and determine its usefulness as a rehabilitation and RTS outcome measure.

2.8 MANAGEMENT OF ACHILLES TENDON INJURIES

2.8.1. TENDON RESPONSE TO EXERCISE

Most studies on tendon adaptations to exercise are based on healthy tendons with few insights into the response of pathological human tendons to exercise at a microscopic level. Tendons respond to a mechanical stimulus by altering their structure, composition, and mechanical and material properties (Wang, 2006). However, adult tendon tissue turnover is slow compared to other bodily tissue (Heinemeier *et al.*, 2013). Increases in mechanical and material property adaptations occur before structural properties such as tendon CSA change in response to heavy resistance training (Geremia *et al.*, 2015, 2018; Wiesinger *et al.*, 2015). Repetitive cyclical loading, such as running, appears to be a lower stimulus for structural and mechanical adaptations. Increases in tendon CSA have been demonstrated in habitual distance runners over five years, while no changes have been found in novice runners after nine months of regular training (Magnusson *et al.,* 2016). Greater tendon stiffness on the dominant leg has been found in long and triple-jump athletes over several seasons (Bohm *et al.*, 2015).

Exercise results in increased secretion of growth factors such as insulin-like growth factors (IGF-1), transforming growth factors β (TGF-β), connective tissue growth factors (CTGF), and protective cytokines such as interleukin-6 (IL-6) (Magnusson *et al.,* 2010). IGF-1 is a crucial regulator of collagen synthesis, and increases in cytokine levels are observed in parallel with collagen synthesis (Magnusson *et al.,* 2010). Exercise also increases cell proliferation and influences immune cell response (Schulze-Tanzil *et al.*, 2022). The ingrown nerve and blood vessels have also been shown to recede in response to exercise (Magnusson *et al.,* 2010). Mechanotransduction describes the conversion of a mechanical stimulus, including tension, shear, and compression, into a biochemical reaction (Lavagnino *et al.*, 2015). The perturbated tenocytes interact with the ECM, resulting in the upregulation of essential matrix proteins. It is not entirely clear how much direct remodelling of injured tissue occurs or whether remodelling occurs in the area around the lesion. The latter uses an analogy of "the doughnut and the hole," where the healthy part of the tendon adapts by laying down more collagen tissue (Docking *et al.,* 2016).

2.8.1.1. Collagen synthesis

Collagen synthesis involves the interaction of MMPs and TRIMPs, as well as pro-inflammatory and pro-resolving inflammatory mediators (Riley, 2005; Jones *et al.*, 2006; Kjaer *et al.*, 2009; Magnusson *et al.,* 2010). In response to high-loading exercise, collagen degradation occurs

initially and peaks within 24 hours, while collagen synthesis peaks between 24-36 hours, with a net collagen synthesis occurring in 48-72 hours (Magnusson *et al.,* 2010). If a regenerating tendon loads beyond its capacity in this 48-72 hour period, it may fail to adapt *(Fig. 2.35)*.

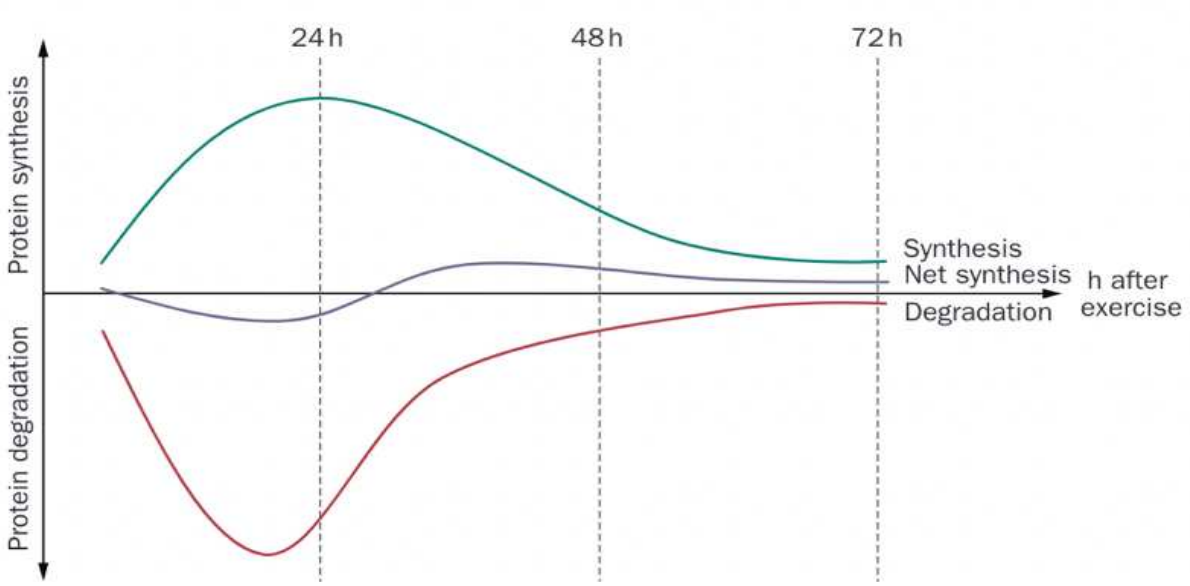


Fig. 2.35. A schematic representation of the time responses of collagen synthesis and degradation in response to exercise (Magnussen et al. 2010)

The stages of collagen synthesis at sub fibril level have been outlined by O'Brien (1997) and Riley (2005) and occur both inside and outside the cell, and is illustrated in Figure 2.36. In the first stage, an mRNA forms for each alpha peptide chain. Pre-procollagen molecules form when the alpha peptide chains are secreted from the nucleus to the cisternae of the cell, where the signal peptide is removed to form procollagen – a precursor to collagen. Hydroxylation of proline and lysine produces hydroxyproline and hydroxylysine, respectively, of which the latter undergo glycosylation. Procollagen alpha chains assemble into a triple helix formation with cleavage of propeptides known as registration peptides at either end. The procollagen relocates to the Golgi apparatus, where it is packaged as secretory vesicles. The procollagen is then secreted into the extra-cellular space, where the registration peptides are removed to form tropocollagen which assembles into collagen fibrils. The fibrils are held together by lysis-oxidase cross-links comprised predominantly of the earlier-formed hydroxylysine.

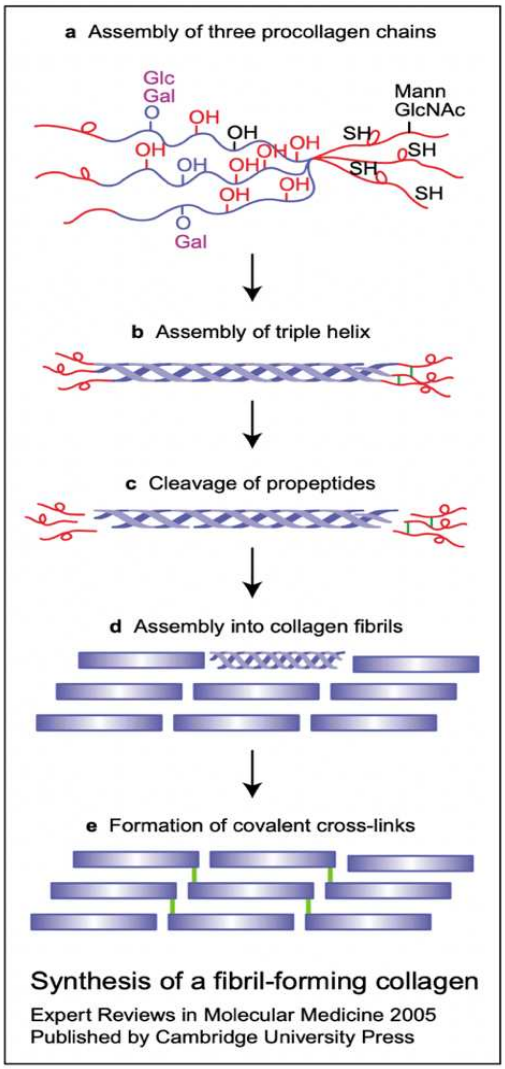


Fig. 2.36. Collagen synthesis at sub-fibril level Riley (2005)

2.8.2. ECCENTRIC EXERCISES

Exercise therapy involving eccentric contractions, defined as the lengthening of the MTU under tension, has been the mainstay of Achilles tendinopathy rehab since the 1980s, based on the research of Stanish et al. (1986). Their six-week program involved exercises performed once per day, beginning with slow contractions and progressing to higher speed contractions, with 44% of participants with chronic Achilles tendinopathy reporting complete resolution of symptoms, with a further 45% reporting satisfactory reduction in symptoms. This program evolved in the 1990s with Alfredson's protocol of high-volume daily eccentric exercises in both knee-extended and knee-flexed positions, which had positive clinical outcomes (Alfredson *et al.*, 1998). The hypothesised mechanism underpinning the positive clinical response to eccentric exercise was the re-organisation of type I collagen fibers and improved

cross-linkage (Mafi *et al.,* 2001). While eccentric exercise was the treatment of choice from the 1980s until the early 2000s, no high-quality studies compared other contraction modes to support its superiority.

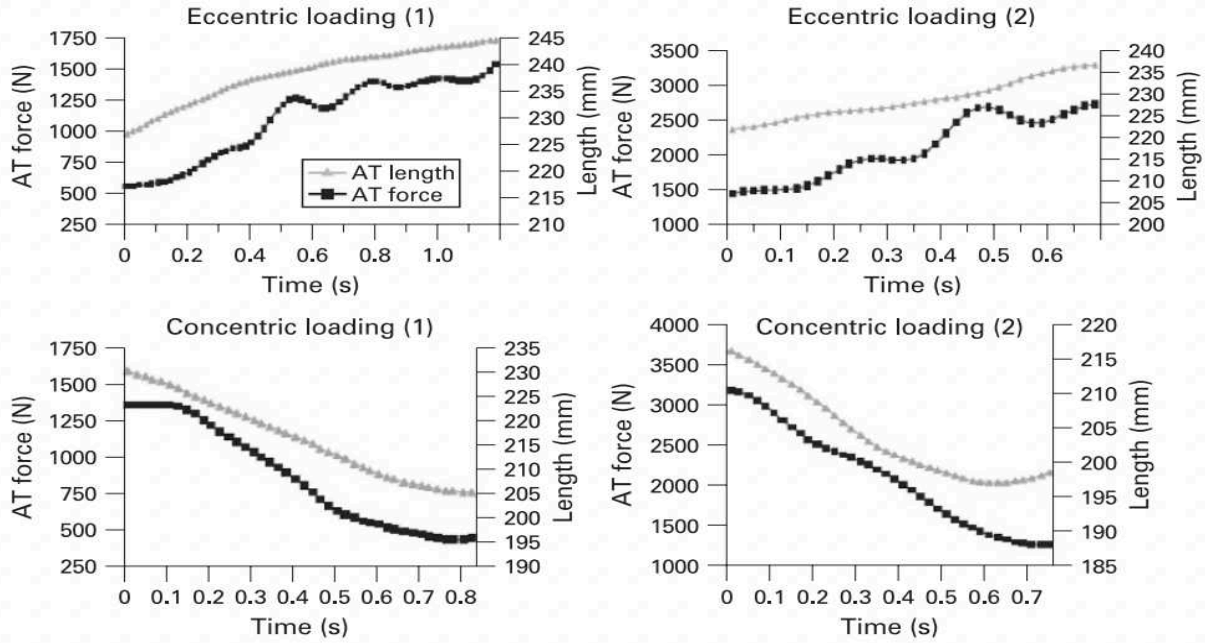


Fig. 2.37. A single-subject example of AT force-time and length-change curves during a heel raise exercise's eccentric and concentric loading phases. No significant difference in force or elongation was observed between concentric or eccentric loading. However, force fluctuations were detected during the eccentric phase (Rees et al., 2008)

2.8.3. HEAVY SLOW RESISTANCE

The use of heavy, slow resistance exercises (HSR) gained prominence in the 2000s when a program performing three calf exercises, three times per week, with prescribed loading intensities of 15RM progressing to 6RM, resulted in similar levels of clinical improvements as Alfredson's protocol, but the former led to greater levels of patient satisfaction (Beyer *et al.*, 2015). Clinical improvements following an HSR program are associated with increased collagen fibril density in patients with patellar tendinopathy (Kongsgaard *et al.*, 2010).

Table 2.2. A summary of evidence-based exercise prescription guidelines in the rehabilitation of Achilles tendinopathy (Merry et al. 2022)

Biomechanical Consideration	Section	Summary Points	Clinical Recommendation
Muscle Contraction Type	Section 4.1	• With a lack of evidence favoring one contraction type [141–143], it does not seem justified to exclusively prescribe eccentric exercises	- Different contraction types can be used to treat AT [a] - Focus on conveying the principles of tendon loading
Load Intensity	Section 4.2	• High-magnitude loading (>70% of MVC [b]) induces greater tendon adaptation in healthy individuals [29,32] • Many AT exercise programs favor bodyweight loading and increase resistance as tolerated (e.g., 5 kg increments in a backpack) [40]	- Increasing load intensity appears to stimulate greater tendon adaptation in healthy individuals - Prioritize high-magnitude loading (as tolerated) and load progression over time
Loading Frequency, Rate, and Duration	Section 4.3	• Evidence pertaining to these factors is limited • Seminal AT rehabilitation programs prioritize 'slow' loading [134–136]	- Not enough existing evidence, though most programs use 'slow' loading frequencies
Exercise Positioning	Section 4.4	• Of the lower limb joint angles, ankle angle appears to most impact Achilles tendon loading as it largely dictates the force through the Achilles tendon [161] and tendon elongation [168] • WB [c] enhances ankle dorsiflexion compared to NWB [d] across knee angles in healthy individuals [164] • Soleus activity is independent of knee angle [153–155]; gastrocnemius is less active in knee flexion [153–155,158]	- Ankle dorsiflexion, knee/hip extension may be most appropriate for AT therapeutic exercise - Excessive dorsiflexion may be irritable to those with insertional AT, and should be avoided, at least in the early stages of rehabilitation - WB positions are widely used within AT rehabilitation, but this may be because WB helps facilitate high-magnitude loading - Loading magnitude should be prioritized over exercise positioning
Exercise Schedule	Section 4.5	• Most studies use 12-week long exercise interventions, though positive results have been found at six weeks [40] • Of 52 RCTs [e], session frequency ranged from two to seven days per week, and two to 14 exercise sessions per week [40] • Of 52 RCTs, sets ranged from 1 to 12, and repetitions ranged from three to 30 [40]	- A 12-week exercise program duration appears most appropriate - Exercise session frequency can vary considerably, and it largely depends on the loading intensity, volume, and tolerability - Sets/repetitions can vary considerably, and they largely depend on the loading intensity and tolerability

[a] AT = Achilles Tendinopathy; [b] MVC = Maximum Voluntary Contraction; [c] WB = Weight-bearing; [d] NWB = Non-weight-bearing; [e] RCTs = Randomized controlled trials.

Isometric exercises using sustained repeated holds over 45 seconds reduced patient pain levels in patellar tendinopathy (Rio *et al.*, 2015). However, contrary findings were shown in patients with Achilles tendinopathy using a similar protocol (O'Neill *et al.*, 2017). Improvements in tendon stiffness in advance of morphological changes in healthy subjects have been found between 6-14 weeks using short repeated isometric contractions at intensities of 90% MVIC *(Fig. 2.38)* (Albracht and Arampatzis, 2013; Bohm *et al.*, 2015; Wiesinger *et al.*, 2015; Arampatzis *et al.,* 2020; Lazarczuk *et al.*, 2022; McMahon, 2022) and after four weeks using a supramaximal eccentric loading protocol at 140% MVIC (Geremia *et al.*, 2018). The tendon strain and force level has been shown to be similar between concentric and eccentric loading phases *(Fig. 2.37)*. However, unique force fluctuations were observed during the eccentric

loading phase, which may be a positive stimulus for AT adaptation (Rees *et al.*, 2008; O'Neill *et al.,* 2015). Performing calf exercises into and out of maximally dorsiflexed ankle angles increases tendon force due to the shorter AT moment arm (Yeh *et al.*, 2021). Loading itself, irrespective of exercise mode appears to be the main factor in achieving positive clinical outcomes in Achilles tendinopathy rehabilitation (Van Der Vlist *et al.*, 2020; Merry *et al.*, 2022). The current evidence suggests that the tendon will respond favourably to calf strength irrespective of contraction mode so long as the load is heavy and slow enough (Bohm *et al.,* 2015; Lazarczuk *et al.*, 2022; McMahon, 2022). Soleus strength deficits are common in runners with Achilles tendinopathy, and bent knee calf raises are often advocated (O'Neill *et al.,* 2019; Sancho *et al.*, 2022). Table 2.2 summarises the evidence-based exercise prescription guidelines for Achilles tendinopathy and Table 2.3 highlights the effects of different types of training on tendon adaptations.

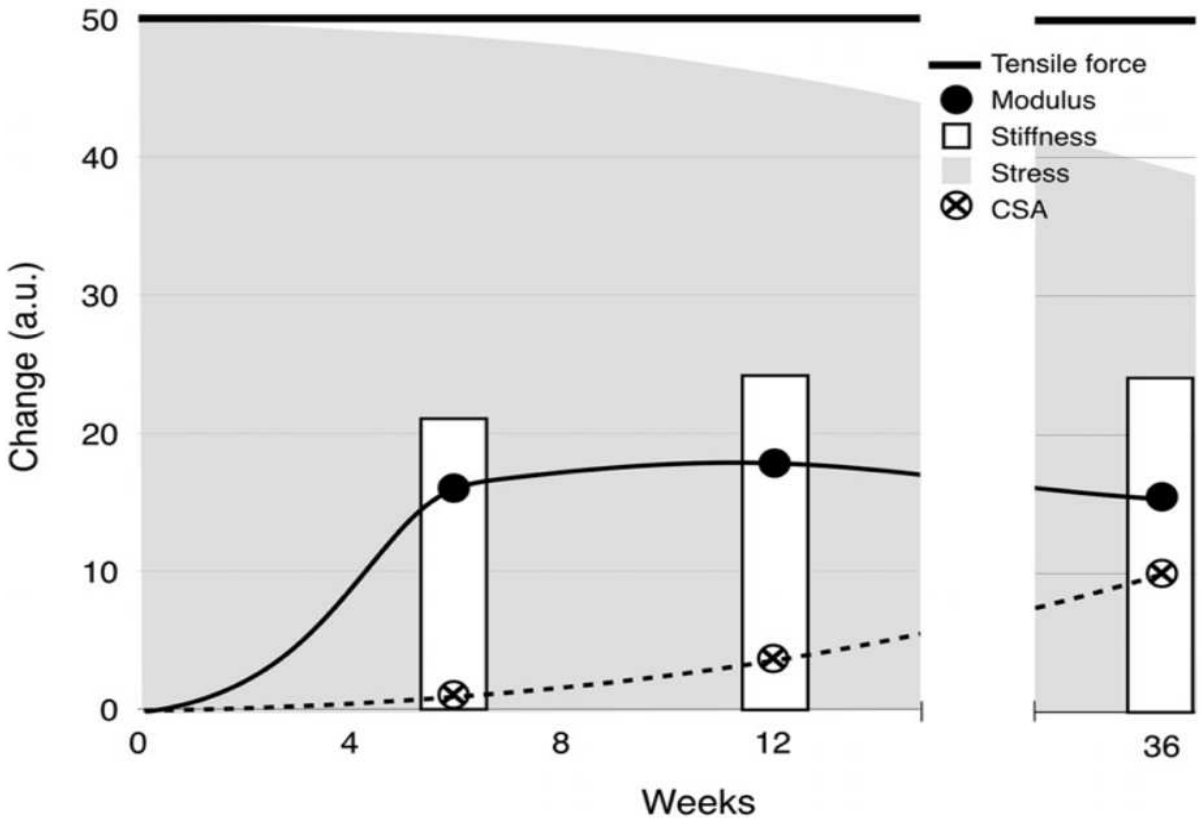
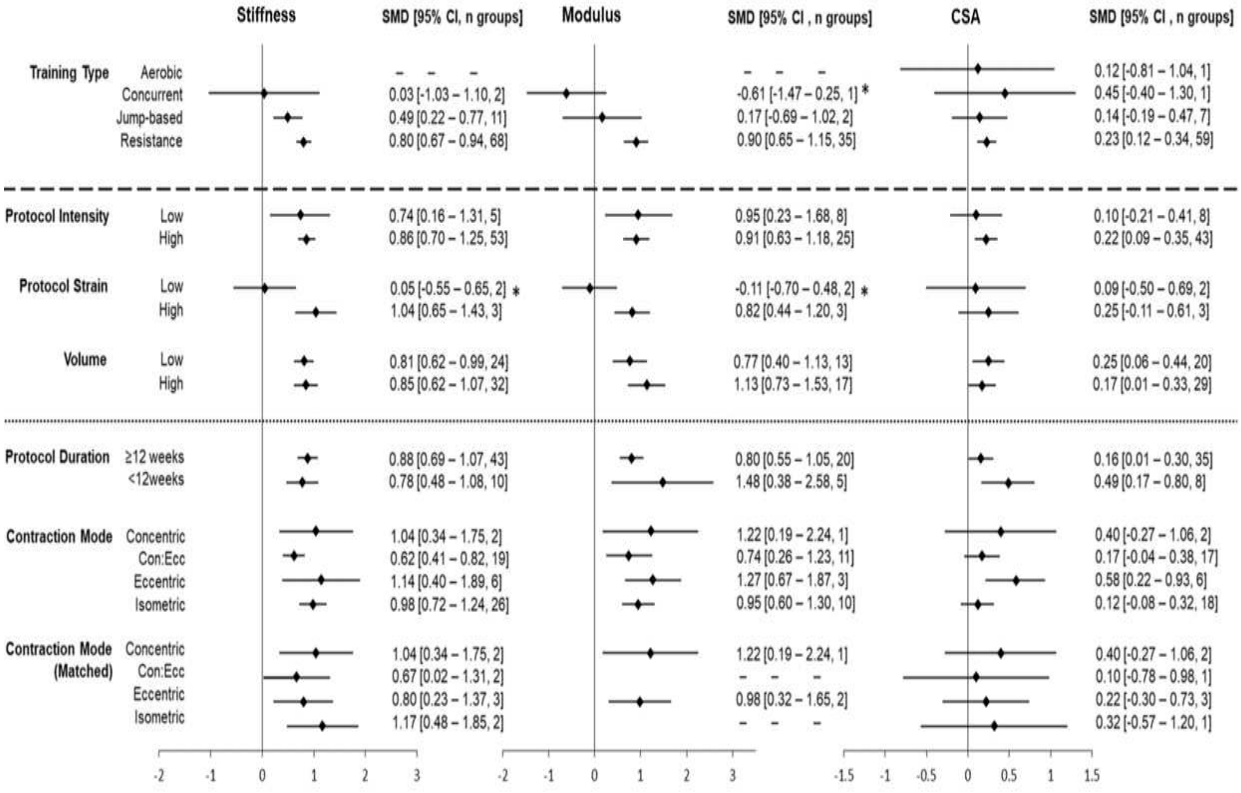


Fig. 2.38. A timeline for kinetic, material and mechanical, and morphological changes in tendons in response to resistance training (Wiesenger et al. 2015)

Table 2.3. Tendon adaptions to different types of training (Lazarczuk et al. 2022)



2.8.4. PLYOMETRIC TRAINING

Plyometric training (PT) involves a stretch-shortening cycle action of the muscle-tendon unit (MTU), where the tendon stores elastic energy upon elongation, and energy return from the MTU is more significant than that applied by muscle contraction. Tendon stiffness is a crucial determinant of plyometric performance, and reductions in AT stiffness impairs both contact time and jump height or distance (Kubo *et al.*, 2007; Arya and Kulig, 2010; Fouré *et al.,* 2010; Wang *et al.*, 2012). Reductions in the single-leg hop for distance (Wang *et al.*, 2012) and leg stiffness during single-leg vertical hopping (Maquirriain, 2012) have been observed on the affected leg in runners with Achilles tendinopathy. Impairments in hop performance have been detected in athletic Achilles tendinopathy patients at one-year follow-up despite a satisfactory resolution of symptoms (Silbernagel *et al.*, 2007b).

There are no advantages to avoiding plyometric exercises at low levels of tolerable pain with Achilles tendinopathy (Silbernagel *et al.*, 2007a; Sancho *et al.*, 2019). In a pilot study on 15 runners with Achilles tendinopathy, 13 reported improved satisfaction levels following plyometric training, coinciding with a 20.65 point improvement in the VISA-A questionnaire

(Sancho *et al.*, 2019). The effect of PT on tendon mechanical properties has been mixed. One study showed a 21% improvement in normalized stiffness (stiffness relative to AT CSA) after a 14-week intervention with no change in the control group. Performing plyometric exercises by controlling knee flexion and over short drop heights increased AT stiffness significantly more than performing them with knee flexion over a ten-week program, with strong correlations between increases in AT stiffness and improvement in jump height over a 20-cm drop jump (Laurent *et al.,* 2020).

2.8.5. REHABILITATION PATHWAYS

Plyometric exercises complement heavy calf resistance exercises and prepare the MTU for the high forces and loading rates of running-based sports (Komi *et al.,* 1992; Gheidi *et al.*, 2018; Baxter *et al.*, 2021). A periodised rehabilitation model progressing from developing strength, energy storage, and energy storage and release qualities to build the necessary capacity to return to sport was proposed by Cook and Docking (2015) and illustrated in Figure 2.39. A rehabilitation pathway that involves a daily exercise program of combined concentric and eccentric exercise, with the addition of plyometric exercises as pain symptoms permit while continuing regular sports activity, has been developed by Silbernagel and Crossley (2015). In this protocol, pain below 3/10 is required to progress to the next level, and an additional unspecified load is recommended as a progression for the calf resistance exercises. To our knowledge, no RCTs exist to compare a pain-guided progression pathway for Achilles tendinopathy rehabilitation with a program guided by functional outcome measures.

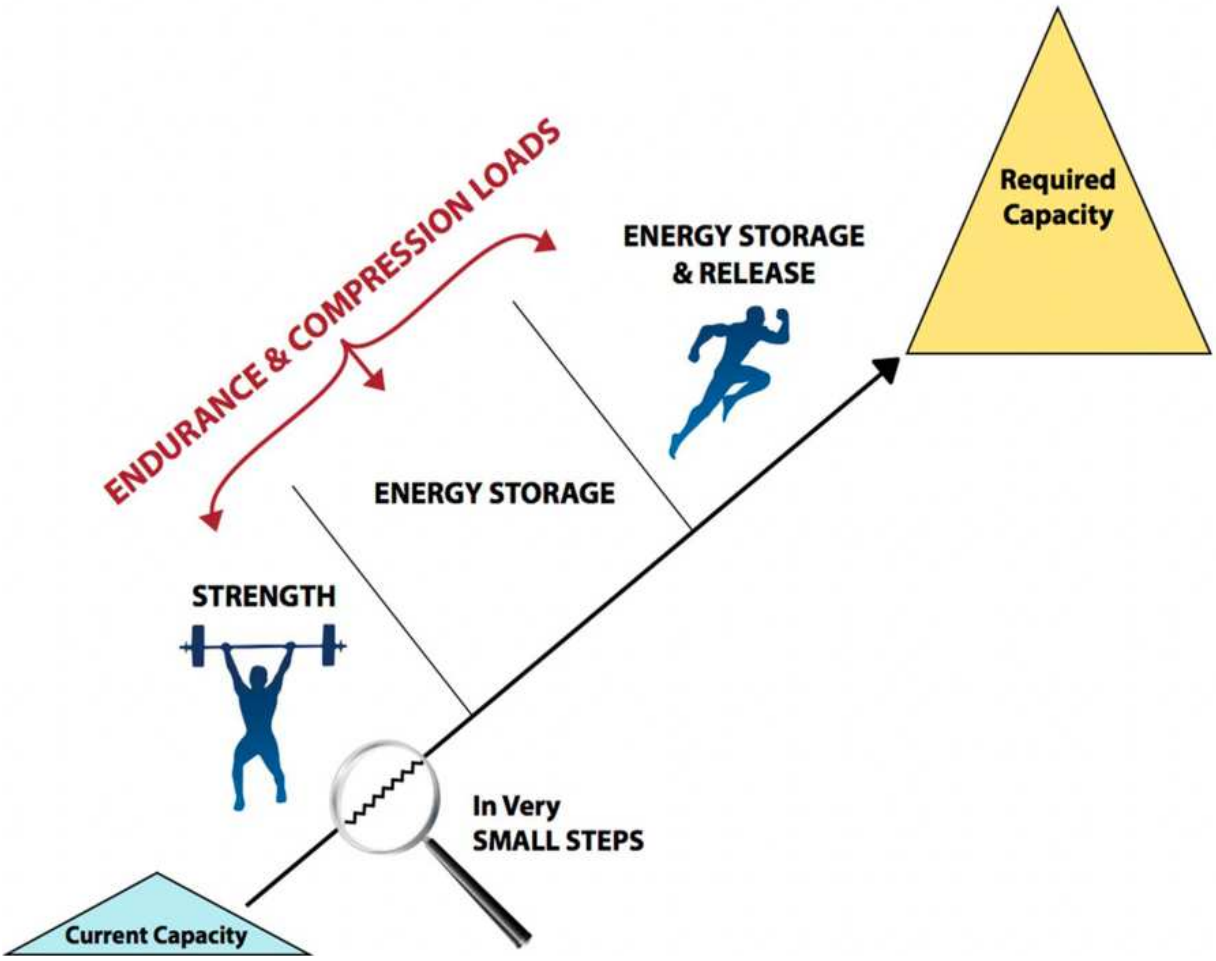


Fig. 2.39. Schematic of progressive tendon rehabilitation pathway where the focus is on improving tendon capacity to levels required to return to sport (Cook and Docking, 2015)

2.8.6. PASSIVE TREATMENTS

Tendinopathies are often managed with adjuncts such as injections (Kearney *et al.*, 2015; Martin *et al.*, 2018), Non-Steroidal Anti-Inflammatory Drugs (NSAIDs) (Riley, 2008; Chimenti *et al.*, 2017), ultrasound (Riley, 2008; Chimenti *et al.*, 2017), shockwave (Rompe *et al.*, 2007; Magnussen, Dunn and Thomson, 2009), laser (Chimenti *et al.*, 2017), iontophoresis (Martin *et al.*, 2018), acupuncture (Zhang *et al.*, 2013), orthotics (Magnussen *et al.,* 2009; Martin *et al.*, 2018), wearing a night splint (De Jonge *et al.*, 2010), vibration and cryotherapy (Romero-Morales *et al.*, 2018), mucopolysaccharides (Balius *et al.*, 2016), topical glyceryl

trinitrate patches (Challoumas *et al.*, 2019), and a wait-and-see approach (Rompe *et al.*, 2007). Many of these treatments lack strong evidence for their effects but are often used as an adjunct to a rehabilitation program. High-volume saline injections are a common therapy used in chronic Achilles tendinopathy conditions. Saline solution is injected into the space between the Kager's fat pad and the paratenon to reduce pain and remove neo-vessels and irregular nerve endings. Many studies have demonstrated significant improvements in clinical symptoms and Visa-A scores (Barker-Davies *et al.*, 2017; Kakkos *et al.*, 2021), but one study (van der Vlist *et al.*, 2020) found no additional benefit when compared to exercise therapy, while another (Nielsen *et al.*, 2020) demonstrated a clinically-meaningful improvement in 33% of chronic Achilles tendinopathy that failed to resolve after a rehabilitation program. ESWT has been used in tendinopathies where the proposed mechanism of altering the nociceptive feedback from the sensory nerve endings (Millar *et al.*, 2021) with moderate evidence for its clinical benefits as an adjunct treatment combined with rehabilitation (Paantjens *et al.*, 2022). Figure 2.40 summarises a best-practice treatment approach for tendinopathy and which passive treatments may have a role in certain circumstances.

2.8.6.1. Potential for biological interventions

A better understanding of the inflammatory processes and variations of collagen genes associated with tendinopathy, provides an opportunity to explore biological interventions that may alter the tenocytes signature from an inflammatory and degenerative type to an anabolic and adaptive state (Riley, 2008; Dean *et al.*, 2017; Millar *et al.,* 2017; Dakin *et al.*, 2018). Inflammatory inhibitor injection therapies are widely used in the management of RA and SpA with successful outcomes and similar injection therapies may be part of the future direction in managing non-resolving tendinopathies (Millar *et al.,* 2017; Millar *et al.*, 2021).

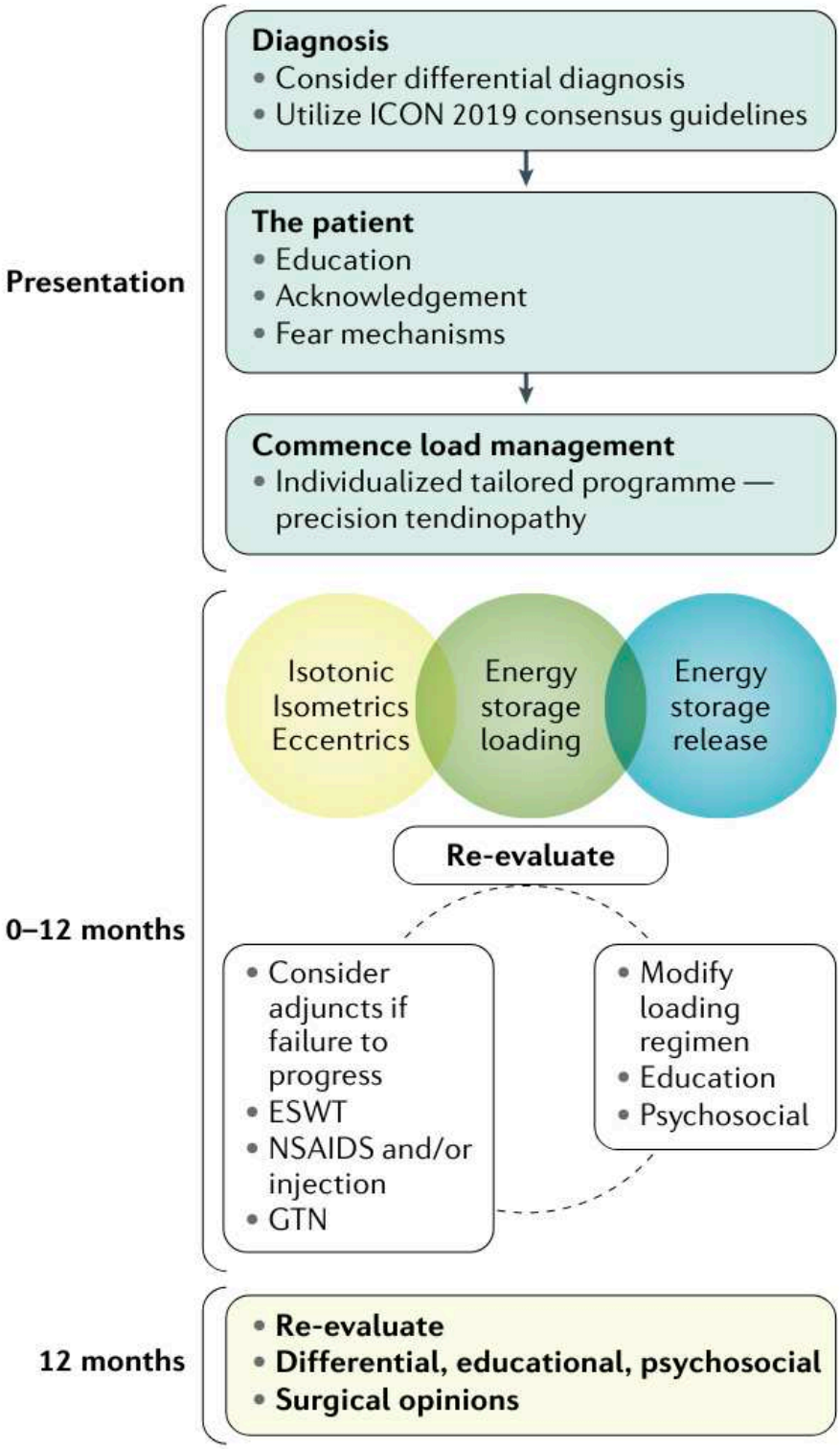


Fig. 2.40. A recommended best-practice patient management flowchart for tendinopathy (Millar et al. 2021)

2.8.7. SURGERY

2.8.6.1. Achilles tendinopathy

Surgical techniques to treat Achilles tendinopathy include scraping, debridement and removal of the plantaris. The latter option is recommended where a thickened plantaris is causing AT pain. AT surgery is usually an option of last resort where rehab has failed over a period of time. Tendon scraping is the least invasive of standard surgical techniques, with reported good outcomes in the 24 months. It involves a local anaesthetic and a small incision and is guided by US (Masci *et al.*, 2020). Peritendinous tissue is scraped to remove abnormal nerve growth and accompanying blood vessels. Tendon debridement involves the removal of degenerative tendon tissue separating the AT from the Kager's fat pad, with good outcomes reported after 12 months (Thermann *et al.*, 2020)

No evidence suggests that surgery is superior to exercise therapy in managing Achilles tendinopathy (Challoumas *et al.*, 2019). Dutch sports medicine guidelines recommend that surgery be considered if the symptoms fail to resolve after six months of rehabilitation involving exercise therapy (De Vos *et al.*, 2021), while other consensus papers recommend at least 12 months (Millar *et al.*, 2020; Millar *et al.*, 2021).

2.8.6.2. Achilles tendon ruptures

A surgical repair of the AT has traditionally been the preferred option following a rupture. However, in recent years, more AT ruptures have been managed conservatively (Zellers *et al.,* 2016b; Ochen *et al.*, 2019; Myhrvold *et al.*, 2022). The risk of re-rupture between a surgical repair and conservative management has decreased from 5-7% to 1.6% (Ochen *et al.*, 2019; Butt *et al.*, 2022). Similar functional outcomes have been observed after six months when comparing surgical versus non-surgical management of a rupture (Myhrvold *et al.*, 2022). Complications from surgical repair include the risk of infection, deep vein thrombosis, and injury to the sural nerve (Ochen *et al.*, 2019).

The standard surgical techniques include an open repair, minimally-invasive repair, and a tendon transfer. An open repair requires a longitudinal incision of 6-8 cm, which is usually on the medial side, to avoid the sural nerve where the skin and paratenon are retracted to apply sutures to the ruptured tendon to repair it (Rosenzweig and Azar, 2009). In most cases, a posterior compartment fasciotomy is performed to release compartment pressure and allow space for internal bleeding. A minimally invasive repair involves a smaller transverse incision

of 2-3 cm, and the proximal AT and fascia are separated to repair the tendon. This technique has reported similar functional outcomes to an open repair with less complication and risk of sural nerve damage (Patel and Kadakia, 2019). A tendon transfer is usually performed on older, less physically active patients or a chronically ruptured AT by transferring a tendon from the flexor hallucis longus to reinforce the AT (Wegrzyn *et al.*, 2010). A more recent surgical technique known as the InternalBrace method is one favoured by elite athletes. This knotless technique involves direct fixation to the calcaneus where MTU length can be set during surgery, and facilitates early mobilisation and return to sport (McWilliam and Mackey, 2016).

2.9 RESEARCH PROBLEM

To date, there have been no objective data measures to progress Achilles tendon rehabilitation besides pain response to exercise, while they have been used to progress rehabilitation in other contexts such as hamstring strain injuries (Mendiguchia *et al.*, 2017; Hickey *et al.*, 2020). Previous investigated rehabilitation programs have focused on a single mode exercise such as eccentric (Stanish *et al.,* 1986; Alfredson *et al.*, 1998) or HSR (Beyer *et al.*, 2015) Comparative studies have shown that one exercise mode is not superior (Beyer *et al.*, 2015; Habets *et al.*, 2021). It is generally accepted that a graded program involving combined exercise modes are recommended to return athletes with Achilles tendinopathy, back to sport (Silbernagel *et al.*, 2007a; Cook and Purdam, 2014; Mascaró *et al.*, 2018). However, outcome measures to progress rehabilitation exercises and return to sport have not been investigated. It is not clear whether improved function through strength and biomechanical impairments, can lead to a reduction in pain in some patients. For athletes who fit the biopsychosocial model of pain, their progress may be needlessly delayed if progression is based purely in pain response. Given the complexity of pain which does not always equate to tissue damage, this concept is worthy of exploration. In addition, there has been a lack of consistency in the protocols utilised for assessing PF and reactive strength (McAuliffe *et al.*, 2019). Force plate technology has become widely available and affordable, enabling the opportunity to standardise isometric strength testing and hop testing protocols. Many AT injury assessments use vertical hopping protocols such as a repeated hop test. Since maximal effort, horizontal hopping results in the highest tendon loading (Gheidi *et al.*, 2018; Baxter *et al.*, 2021), measuring reactive strength in this task may be clinically valuable.

2.9.1. AIMS OF THE THESIS

This thesis explores a criteria-based rehabilitation program for AT injuries in an athletic population. As part of this, we will first test the reliability of a knee-extended isokinetic and seated isometric calf strength test, and a single-leg horizontal plyometric test, with particular relevance to their use as outcome measures in the rehabilitation of AT injuries. We will also investigate the biomechanical features and relationships between joint kinetic and kinematic variables with global stiffness and performance features in the horizontal plyometric test.

The thesis will address these aims across two themes:

- **Theme 1** – Return to play outcome measures to assess lower limb strength, performance, and biomechanical features after an AT injury will be addressed in studies 1 and 2. In study 1, we designed a novel single-leg horizontal plyometric test and evaluated its reliability and biomechanical features. We felt that this type of exercise would provide a useful measure of AT load tolerance to guide rehabilitation progression and RTS decision-making. In study 2, we tested the reliability of F_{peak} seated calf isometric test and T_{peak} and joint angle specific torque in prone knee-extended IKD test at a speed of 30°/sec. We justified the evaluation of the seated calf isometric test due to the emerging use of force plate technology to measure isometric F_{peak} and the necessity to measure calf strength, given the plethora of AT calf muscle injuries in sport. The rationale for assessing the reliability of T_{peak} and joint angle-specific torque was based on the need to assess IKD PF strength reflective of the high force demands of these muscles.

- **Theme 2** - The rehabilitation pathway for AT injuries is governed by assessment outcome measures, which we address in studies 3, 4, and 5. In Study 3, we designed a protocol for a randomised controlled trial (RCT) for a criteria-based rehabilitation program for chronic mid-portion Achilles tendinopathy as we felt that research to date on Achilles tendinopathy rehabilitation programs focused solely on pain response and lacked a focus on functional outcome measures to guide progression and RTS. We compared an intervention (SSC6) designed over two to three sessions per week with a focus on high intensity and achieving strength and hop test targets to govern progression and exercising to a maximal tolerable level of pain with Silbernagel's Achilles tendinopathy rehabilitation program. The VISA-A questionnaire was the primary outcome measure, with secondary outcomes including PF IKD peak torque, vertical and horizontal plyometric features and running biomechanics. We also evaluated adherence and fidelity, as well as longitudinal follow-ups at months 6, 12 and 24 based on VISA-A and GROC scores. The RCT commenced in January 2020 but the impact of Covid-19 from March of that year, greatly impacted recruitment and data collection. It also proved challenging for some participants to adhere to their individualised

rehabilitation program due to limited access to gym-based equipment. Therefore, in Study 4, we reported on the preliminary results of our RCT based on the incomplete number of participants who have so far completed the 12-week intervention. In study 5, we conducted a case report on a gaelic football player who suffered an AT rupture and underwent a surgical repair. We detailed his rehabilitation journey, which followed similar progression guidelines to the protocol for Achilles tendinopathy in study 3, and reported on his subjective and functional testing with a focus on strength and biomechanical features. While this was a different AT injury to a tendinopathy, similar adaptive responses are required to return an athlete to sport following an AT rupture. We sought to test the proof of concept for the criteria-based rehabilitation program for Achilles tendinopathy with another AT injury.

3. THEME 1 - RETURN TO PLAY OUTCOME MEASURES TO ASSESS LOWER LIMB STRENGTH, PERFORMANCE, AND BIOMECHANICAL FEATURES AFTER AN ACHILLES TENDON INJURY

3.1. STUDY 1: A NOVEL SINGLE-LEG HORIZONTAL PLYOMETRIC EXERCISE TASK: RELIABILITY, STIFFNESS AND JOINT MECHANICAL OUTPUTS

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Colin Griffin[1,2], Katherine A J Daniels[2,3], Chris Richter[2], Andrew Franklyn-Miller[2,4], Jean-Benoit Morin[1,5,6]

[1]Université Côte d'Azur, LAMHESS, Nice, France.

[2]Sports Surgery Clinic, Santry Demesne Dublin 9, Ireland

[3]Department of Sport and Exercise Sciences, Manchester Metropolitan University, Manchester, United Kingdom

[4]Centre for Health, Exercise and Sports Medicine, University of Melbourne, Parkville Victoria, Australia

[5]Sports Performance Research Institute New Zealand (SPRINZ), Auckland University of Technology, Auckland, New Zealand

[6]Univ Lyon, UJM-Saint-Etienne, Inter-university Laboratory of Human Movement Biology, EA 7424, F-42023, Saint-Etienne, France

Address for correspondence: Colin Griffin, Sports Medicine department, Sports Surgery Clinic, Santry Demesne Dublin 9, Ireland.
Email: colingriffin@sportssurgeryclinic.com

Key words

Stiffness, Hopping, Performance, Injury, Rehabilitation, Ankle

3.1.1. ABSTRACT

There has been little investigation of horizontal plyometric exercises despite their relevance for athletic performance. The aim of this study was to (i) assess test-retest reliability of biomechanical and performance features in a single-leg horizontal plyometric exercise, (ii) investigate joint stiffness (K_{joint}) and mechanical outputs and their relationship with rebound distance (RD), horizontal reactive strength index (hRSI), leg (K_{leg}) and vertical (K_{vert}) stiffness and (iii) determine how many trials are required to capture a representative mean across different variables. Ten males performed the task over two sessions with 3D motion and force

data captured. Biomechanical and performance features were then extracted. Good-to-excellent reliability was demonstrated for most biomechanical and performance features. K_{ankle} and contact time each correlated with both K_{vert} and K_{leg}. Peak hip joint moment and peak horizontal GRF (hGRF) correlated with RD and hRSI. Joint power and work were highest at the ankle, while joint stiffness was higher at the knee compared to the ankle. A stable correlation with the mean for the majority of variables was reached by the third trial. We propose the use of this test to assess horizontal reactive strength and lower-limb joint mechanical features, using the mean of three trials.

3.1.2. INTRODUCTION

Jumping and hopping exercise tests are commonly used to measure lower limb power, reactive strength and biomechanical qualities that are relevant to performance and recovery after an injury (Bolgla *et al.,* 1997; Butler *et al.,* 2003; McMahon *et al.,* 2012). By performing these tests unilaterally, asymmetries may be identified that can be addressed in a strength and conditioning or rehabilitation program (King *et al.*, 2019). However, less is understood about the biomechanical features of single-leg horizontal plyometric exercises and the extent to which they differ from vertical hopping which may be relevant in performance and rehabilitation settings.

Single leg horizontal hop tests such as a triple-hop have demonstrated good reliability (Bolgla *et al.,* 1997) and are a valid predictor of lower limb strength and power (Hamilton *et al.,* 2008). However, while hop distance has been used as a measure of performance, a deeper evaluation of the biomechanics behind single-hop performance and observed asymmetries may prove useful to researchers, clinicians and coaches. Single leg hop for distance tests, which include a triple-hop, highlighted deficits between an injured and uninjured limb in patients following ACL rupture (Noyes *et al.,* 1991) and ankle instability (Caffrey *et al.*, 2009). The within-limb joint work distribution strategy for horizontal hopping differs from vertical hopping, with vertical demonstrating larger contributions from the knee while horizontal hops exhibit greater contributions from the ankle (Aeles and Vanwanseele, 2019; Davies *et al.,* 2020; Kotsifaki *et al.*, 2021). Significantly impaired horizontal hop performance featured in runners with Achilles tendinopathy accompanied by reduced tendon stiffness, rate of force development and delayed activation of the individual calf muscles (Wang *et al.*, 2012). While vertical hopping is a frequently-used test to measure reactive strength qualities and highlight deficits in lower-limb injuries (Silbernagel *et al.*, 2006; Brazier et al., 2014; King *et al.*, 2019), a horizontal rebound

task may provide deeper insights into ankle function for running-related performance and as an injury rehabilitation outcome measure.

Lower limb stiffness is linked to athletic performance and injury risk (Butler *et al.,* 2003; Maquirriain, 2012; Lorimer *et al.,* 2018). Stiffness can be measured during running, jumping, and hopping tasks. Vertical hopping is a commonly-used test to measure stiffness (Farley and Morgenroth, 1999; Brughelli and Cronin, 2008; Hobara *et al.*, 2009; Kuitunen *et al.,* 2011; Maloney *et al.,* 2017). However, horizontal plyometric exercises develop athletic qualities that are reflected in running, acceleration, agility, and horizontal jumping performance (Dobbs *et al.*, 2015; Kariyama *et al.,* 2017; Moran *et al.*, 2021). Single leg horizontal hopping exposes the Achilles tendon to higher loading rates compared to vertical hopping (Gheidi *et al.*, 2018; Baxter *et al.*, 2021).

Both K_{vert} and K_{leg} is used to measure whole-body stiffness where the former depicts the vertical orientation of the leg at contact and the latter when ground contact is made with the leg at an angle (Butler *et al.,* 2003). However, some original studies (Farley and Morgenroth, 1999) lack a clear distinction between the two definitions during vertical hopping tasks by using vertical ground reaction force to calculate leg stiffness. For non-vertical locomotion such as running and horizontal plyometric exercises, it may be inaccurate to illustrate leg stiffness using vertical ground reaction forces and more appropriate to use the component of the ground reaction force oriented along the leg between the centre of pressure (CoP) under the foot, and the hip during the eccentric phase (Coleman *et al.*, 2012). Measuring lower limb stiffness may provide a useful measure of readiness for return to sport following a lower limb injury.

To our knowledge, horizontal reactive strength index has only been measured in a triple-hop test (Davey *et al.*, 2021; Šarabon *et al.,* 2021), while whole-body and joint stiffness variables have not been extensively investigated, except for the step phase of a triple jump (Perttunen *et al.*, 2000). Other variables such as the orientation of ground reaction force and distribution of peak joint moments, work and powers are also worthy of investigation to identify any compensations an athlete may employ as a result of injury. Despite the clinical utilisation of various single-leg horizontal rebound tasks as an outcome measure for return to performance during injury rehabilitation, knowledge about reactive strength qualities, and variables such as lower limb stiffness, and joint mechanical outputs underpinning hop performance, remain elusive. It is also valuable to determine how many trials are required to obtain a stable

representation of performance in key variables in this task as this may be useful for practitioners to perform in a time efficient manner in a clinical setting and for longitudinal monitoring of athletes in a rehabilitation pathway or throughout the season.

The aims of this study were (i) to assess the test-retest reliability of key biomechanical and performance variables in a single-leg horizontal plyometric exercise task, (ii) to investigate joint stiffness and mechanical outputs and their relationship with rebound distance and vertical stiffness and (iii) to determine how many trials are required to reach the correlation threshold for the group mean across the different variables. We hypothesised that joint stiffness would be highest at the knee due to the maximal effort nature of the task (Hobara *et al.*, 2009; Kuitunen *et al.,* 2011), and joint work and power at the ankle compared to the knee and hip as has been previously identified in a single leg hop for distance task (Aeles and Vanwanseele, 2019; Kotsifaki *et al.*, 2021). Due to the exploratory nature of parts (i) and (iii), no clear hypothesis could be formed.

3.1.3. MATERIALS AND METHODS

Ten healthy male participants were recruited to take part in two testing sessions which were fourteen days apart for nine and sixteen days for one participant. All participants (28.5 ± 5.6 years, height 1.79 ± 0.04 m, body mass 82.4 ± 6.6 kg) regularly performed strength training but were unfamiliar with the protocol at the time of testing. The study was approved by the Sports Surgery Clinic research ethics committee and each participant gave informed written consent prior to testing.

The experimental protocol was identical for the two testing sessions. Each participant completed a standardised warm-up which consisted of a 2-minute jog on the treadmill at 8 km/hr, 10 bodyweight squats, 10 pogo hops in place, and 3 familiarisation trials on each leg. The test required participants to perform a forward hop over two 15-cm hurdles rebounding off a force platform in between, completing 10 alternating trials on each leg *(Fig. 3.1)*. The participants were instructed to keep their hands on their hips and to rebound 'as fast as possible' and 'as far as possible'. The trials were performed in an unshod condition and after each trial, the participants walked back slowly to begin the next trial taking approximately 10 seconds of recovery time. A video demonstration of this test is available here: https://vimeo.com/725287405.

Fig. 3.1.1. The stance phase of the single leg horizontal rebound test

3.1.3.1. Data acquisition

Twelve infrared cameras (200 Hz; Vicon, UK) were used for three-dimensional motion capture synchronised with two force platforms (1000 Hz, AMTI, USA) to measure ground reaction force data. Reflective markers (14 mm diameter) placed on the hallux, lateral malleolus, calcaneus, shank, lateral femoral epicondyle, thigh, anterior superior iliac spine, and posterior superior iliac spine, were used in accordance with the Plug-in-gait model (Vicon, UK) with all segments used to calculate centre of mass (COM) position. Motion and force data were filtered using a fourth-order low pass Butterworth filter with a cut-off frequency of 15Hz. The data were then exported to MATLAB 2015a (Mathworks, USA) for feature extraction. Statistical analysis was performed in R (R Studio (2020), PBC, Boston, MA).

The following variables were calculated in the sagittal plane for both test sessions and reported in Table 1: K_{vert}, K_{leg}, ankle, knee, and hip joint stiffness, ankle, knee, and hip joint moments, powers and total work, rebound distance (RD), vertical, horizontal and leg ground reaction force, and contact time. All kinetic variables were normalised to body mass. RD was calculated as the horizontal distance from the midstance phase on the force plate to the initial landing phase using one of the foot markers for reference. Horizontal reactive strength (hRSI) was calculated by dividing rebound distance by contact time. The stance phase was determined by a vertical ground reaction force threshold of 20 N during contact with the force plates, which detected contact time.

K_{vert} was calculated during the early stance phase, as the ratio of change in vertical ground reaction force (GRF) from the time of initial contact ($_{timpact}$) to vertical COM displacement (ΔCoM) from $_{timpact}$ to maximum CoM displacement ($_{tmax.dis}$) (Blickhan, 1989; McMahon and Cheng, 1990).

$$K_{vert} = force(_{tmax.dis}) – Force(_{timpact})/ CoM(_{tmax.dis}) – CoM(_{timpact})$$

K_{leg} was calculated in the sagittal plane as the ratio of change in leg ground reaction force (F_{leg}) which is the component of the GRF aligned to the leg vector between the CoP and the hip joint centre (HJC), to the change in leg length (ΔLeg) at the shortest leg length ($_{tmin.length}$) during the stance phase, similar to the model proposed by Coleman *et al*., (2012). We measured leg length as the distance from the HJC to the CoP on the force plate surface, in the sagittal plane.

$$K_{leg} = F_{leg}(_{tmin.length}) – F_{leg}(_{timpact}) / \text{Leg length } (_{tmin.length}) – \text{Leg length } (_{timpact})$$

Joint stiffness (K_{ankle}, $K_{knee,}$ and $K_{hip)}$ at the ankle knee, and hip respectively, were calculated in the sagittal plane as the ratio of change in joint moment to change in joint displacement from joint angle at $_{timpact}$ time of maximum joint angular displacement ($_{tmax.dis}$).

$$K_{joint} = \text{ Joint moment } (_{tmax.dis}) – \text{Joint moment } (_{timpact}) / \text{Joint angle } (_{tmax.dis}) – \text{Joint angle } (_{timpact})$$

3.1.3.2. Statistical analysis

Both limbs were analysed for all trials. A two-way mixed intra-class correlation coefficient (ICC) method using absolute agreement was performed using R to examine the test-retest reliability (session 1 to session 2), with p values and 95% confidence intervals reported. ICC threshold values for reliability were interpreted as moderate (ICC > 0.5), good (ICC > 0.75) and excellent (ICC > 0.90). Pearson correlation coefficient analysis was employed using R to determine the correlation between predictor features contact time, stiffness, joint moments, work, powers, and displacements with outcome variables: rebound distance, horizontal reactive strength, and vertical and leg stiffness. Thresholds for interpretation of small (r > 0.1), moderate (r > 0.3), large (r > 0.5) and very large (r > 0.7) correlations using values proposed by Hopkins *et al.*, (2009) were applied and reported where significance was reached ($p < 0.05$). To test for the violation of independence, a linear regression analysis and Durbin-Watson test were then used. Joint stiffness, displacements, moments, work, and powers were compared at the ankle, knee, and hip using one-way repeated measures ANOVA, with significance ($p < 0.05$) and eta squared effect sizes calculated and magnitudes reported using Cohen's thresholds of small ($\eta^2 > 0.01$), medium ($\eta^2 > 0.06$) and large ($\eta^2 > 0.14$) for comparing means (Correll *et al.*, 2019).

To determine the number of trials required to reach the correlation threshold of the group mean, a "true" mean was generated by a simulation using a customized python (3.7) script (pandas 1.4.1, numpy 1.22.2, scipy 1.8.0) where the mean of seven randomly selected trials per session was calculated over 100 iterations and averaged. The mean of n trials (n = 1, 2, .., 10) was then correlated against the true mean to compute a Pearson's correlation coefficient that was used to determine from which trials a true mean representation could be expected, with a correlation threshold set at 0.9 for a nearly perfect fit (Hopkins *et al.*, 2009).

3.1.4. RESULTS

A shaded plot illustrating the mean and standard deviation of vertical and horizontal ground reaction force-time curves during stance phase, are illustrated Figure 3.1.1.

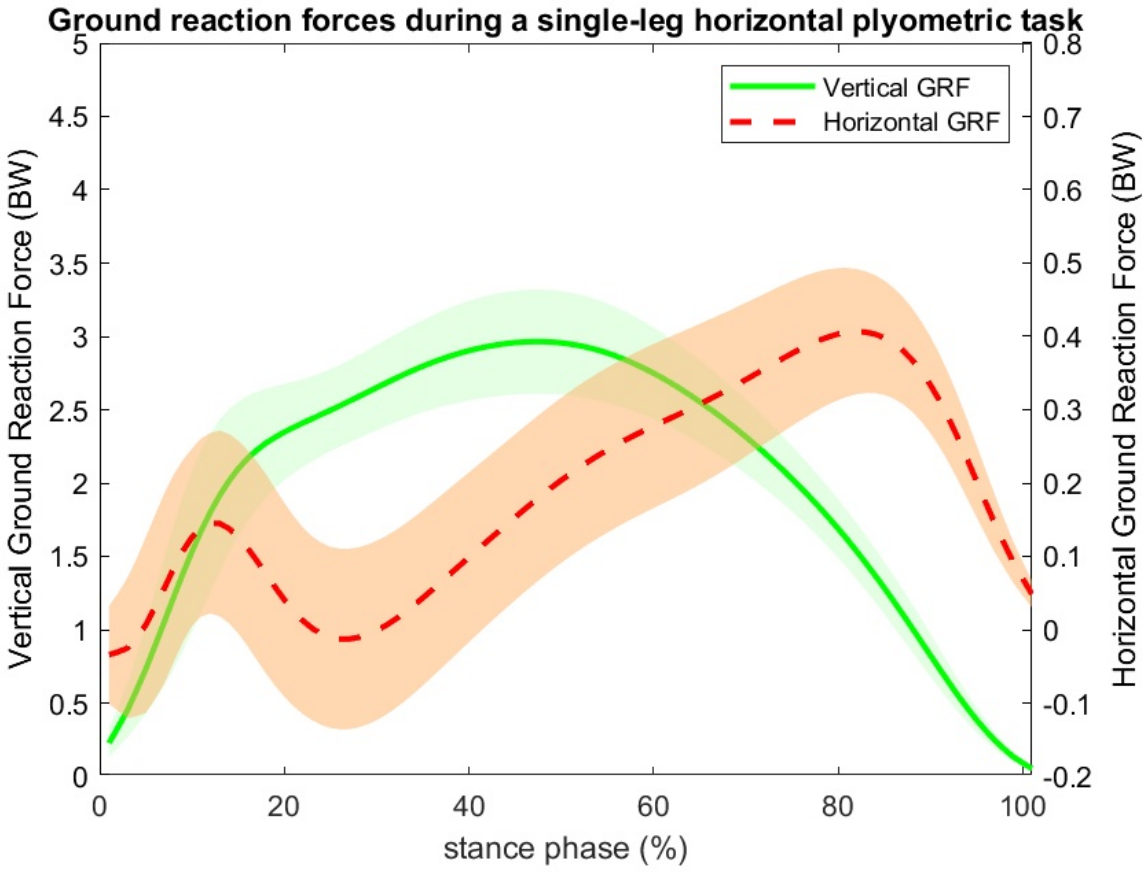

Fig. 3.1.2. ***A shaded plot illustrating the mean and standard deviation of vertical and horizontal ground reaction force during the stance phase***

3.1.4.1. Test-retest reliability

Mean values from all variables for both testing sessions, including confidence intervals and p values, are displayed in Table 3.1.1. The hip joint was maximally flexed at initial contact and demonstrated extension throughout the stance phase and therefore hip joint stiffness could not be calculated using joint stiffness equations. Excellent reliability was demonstrated for vGRF (0.91), and good reliability for hRSI (0.75), rebound distance (0.80), contact time (0.78), F_{leg} (0.86) and peak knee moment (0.89), K_{ankle} (0.81) and K_{knee} (0.75). Moderate reliability was observed for K_{vert} (0.67), K_{leg} (0.61), Δ knee (0.56), hGRF (0.69), ankle (0.53) and hip 0.71) peak moments, and ankle power (0.61) and work (0.56).

Table 3.1.1. Mean values (± SD) and coefficient of variation (CoV) for all variables examined for both testing sessions, ICC (95% CI) and associated p values, standard error of measurement (SEM) and minimal detectable differences.

Variable	*Day 1*	*CoV*	*Day 2*	*CoV*	*ICC (95% CI)*	*p*	*SEM*	*MDD*
Rebound distance (cm)	152.49 ± 30.87	20.24	145.81 ± 34.20	23.45	0.80 (0.72-0.85)	< 0.001	7.44	20.64
Contact time (s)	0.26 ± 0.03	11.54	0.27 ± 0.03	11.11	0.78 (0.70-0.84)	< 0.001	0.01	0.03
Reactive strength index (ms-^{1})	5.94 ± 1.32	22.22	5.50 ± 1.35	24.50	0.75 (0.59-0.81)	< 0.001	0.51	1.41
Peak vertical GRF (N/kg)	29.93 ± 3.54	11.83	29.45 ± 4.08	16.30	0.91 (0.88-0.93)	< 0.001	0.66	1.83
Peak horizontal GRF (N/kg)	4.30 ± 0.93	21.63	4.08 ± 0.99	20.62	0.69 (0.58-0.77)	< 0.001	0.49	1.36
Peak leg force (N/kg)	28.92 ± 3.38	11.69	28.16 ± 4.01	14.28	0.86 (0.80-0.90)	< 0.001	0.99	2.77
Ankle peak joint moment (N·m/kg)	2.91 ± 0.61	20.92	2.94 ± 0.66	22.44	0.53 (0.37-0.65)	< 0.001	0.62	1.73
Knee peak joint moment (N·m/kg)	3.60 ± 0.61	20.96	3.60 ± 0.63	17.50	0.89 (0.86-0.92)	< 0.001	0.16	0.43
Hip peak joint moment (N·m/kg)	3.96 ± 0.81	20.45	4.11 ± 0.95	23.11	0.71 (0.60-0.79)	< 0.001	0.25	0.70
Δ CoM (cm)	12.23 ± 1.93	15.78	12.41 ± 2.31	18.61	0.42 (0.24-0.57)	< 0.001	1.69	4.71
Δ Leg (cm)	15.86 ± 2.82	17.78	16.63 ± 2.31	13.89	0.72 (0.60-0.79)	< 0.001	1.51	4.19
Δ Ankle (deg)	36.57 ± 5.02	13.72	36.26 ± 5.32	14.67	0.49 (0.32-0.62)	< 0.001	4.41	12.21
Δ Knee (deg)	19.97 ± 6.43	32.19	19.52 ± 7.58	13.83	0.56 (0.44-0.68)	< 0.001	4.09	11.34
Vertical stiffness (kN/m/kg)	0.25 ± 0.04	16.00	0.24 ± 0.04	16.67	0.67 (0.55-0.75)	< 0.001	0.02	0.06
Leg stiffness (kN/m/kg)	0.18 ± 0.03	16.67	0.17 ± 0.03	17.64	0.61 (0.44-0.72)	< 0.001	0.02	0.05
Ankle joint stiffness (N·mm/deg/kg)	1.21 ± 0.29	23.97	1.21 ± 0.27	22.31	0.81 (0.74-0.86)	< 0.001	0.01	0.02
Knee joint stiffness (N·mm/deg/kg)	1.68 ± 0.49	29.17	1.74 ± 0.60	34.48	0.75 (0.65-0.82)	< 0.001	0.03	0.08
Ankle peak joint power (W/kg)	20.42 ± 2.78	13.61	18.83 ± 2.86	15.18	0.61 (0.34-0.75)	< 0.001	2.28	6.32
Knee peak joint power (W/kg)	9.69 ± 2.70	27.86	9.63 ± 2.58	26.79	0.37 (0.15-0.53)	0.01	3.07	8.54
Hip peak joint power (W/kg)	12.00 ± 3.67	30.58	13.56 ± 4.05	29.86	0.42 (0.20-0.58)	< 0.001	4.58	12.68
Ankle total joint work (J/kg)	1606.0 ± 375.4	23.37	1577.9 ± 327.5	20.75	0.56 (0.45-0.65)	< 0.001	239.89	664.96
Knee total joint work (J/kg)	693.4 ± 315.6	45.51	688.3 ± 327.5	47.58	0.35 (0.22-0.47)	< 0.001	285.77	792.13
Hip total joint work (J/kg)	1272.4 ± 470.1	36.94	1345.8 ± 466.7	34.67	0.31 (0.22-0.47	< 0.001	467.36	1295.44

Abbreviations: SD: standard deviation; ICC: Intra-class correlation; CI: confidence interval; CoV: coefficient of variation; SEM: standard error of measurement; MDD: minimal detectable difference; GRF ground reaction force; CON; centre of mass

3.1.4.2. Pearson's correlation analysis

Table 3.1.2 shows the Pearson's correlation coefficients for the relationship between the predictor variables and the outcome variables: RD, hRSI, K_{vert} and K_{leg}. At joint level, both K_{ankle} (r = 0.54) and K_{knee} (r = 0.56) had a strong correlation with $K_{vert,}$ while K_{ankle} (r = 0.64) had a large correlation with $K_{leg.}$ Similarly, vGRF had a large correlation with K_{vert} (r = 0.65) and K_{leg} (r = 0.55) as did F_{leg} (r = 0.61 and r = 0.56, respectively). Knee joint angular displacement had a large correlation with K_{vert} (r = -0.50). Hip peak joint moment (r = 0.56) and hGRF (r = 0.66) had a large correlation with hop distance, while hGRF had a similarly large correlation effect with hRSI (r = 0.58). Contact time had a very large correlation (r = -0.77) with K_{vert} and a large correlation (r = -0.67) with K_{leg}.. All of the correlations with a moderate-to-strong interpretation reached significance ($p < 0.001$). However, when the Durbin-Watson test was applied, the assumption of independence was not met (Durbin-Watson statistic <1.0). The correlation plots illustrating large and very large correlations are displayed in Figure 3.1.2, with the different colours of the dots representing each participant.

3.1.4.3. ANOVA Joint mechanical outputs

The differences between the joint mechanical outputs using eta squared effect sizes are reported in Table 3.1.3. The greatest peak joint work occurred at the ankle with a medium effect in comparison to the knee ($\eta^2 = 0.07$) and a small effect in comparison to the hip ($\eta^2 = 0.01$). Similarly, the highest joint powers were observed at the ankle with a medium effect when compared to the knee ($\eta^2 = 0.08$) and a small effect when compared to the hip ($\eta^2 = 0.01$). The highest peak joint moments occurred at the hip with a medium effect compared to the ankle ($\eta^2 = 0.07$) and a small effect when compared to the knee ($\eta^2 = 0.01$). Stiffness values were higher at the knee than at the ankle with a large effect compared to the knee ($\eta^2 = 0.16$), while the largest joint displacements occurred at the ankle with a medium effect in comparison to the knee ($\eta^2 = 0.06$).

3.1.4.4. Correlation with the true mean

The average of all trials for each of the variables across the 2 testing sessions reached a stable correlation with the 'true' mean from trial 3 onwards (r > 0.90) except for ΔCoM and leg length, hip joint moment, ankle and hip joint power, which were achieved from the 4th trial, and hip joint work from the 5th trial onwards. The correlation plots between each trial and the

'true' mean for each variable measured are displayed in Figure 3.1.3. The fluctuations for RD and hRSI on the left limb in the 2nd testing session were accounted for by one participant whose values were significantly lower than the others for some trials.

Table 3.1.2. Pearson correlation coefficient (r values), correlation magnitude thresholds (interpretation) and significance (p values) of contact time and joint mechanical outputs with rebound distance, horizontal reactive strength index, leg stiffness and vertical stiffness for combined testing days

		Rebound distance (mm)			*Reactive strength index (ms^{-1})*			*Vertical stiffness (K_{vert})*			*Leg stiffness (K_{leg})*		
	Mean ± SD	**r**	**Interpretation**	**p**	**r**	**Interpretation**	**p**	**r**	**Interpretation**	**p**	**r**	**Interpretation**	**p**
Contact time (s)	0.26 ± 0.03	0.25	*Small*	< 0.001	-0.21	Small	< 0.001	-0.77	Very Large	< 0.001	-0.67	*Large*	< 0.001
Ground reaction force													
Peak vertical GRF (N/kg)	29.74 ± 3.85	-0.15	*Small*	0.03	0.09	-	0.21	0.65	*Large*	< 0.001	0.55	*Large*	< 0.001
Peak horizontal GRF (N/kg)	4.2 ± 0.97	0.66	*Large*	< 0.001	0.58	Large	< 0.001	0.10	*Small*	0.31	0.08	-	0.14
Peak leg force (N/kg)	28.60 ± 3.75	-0.12	*Small*	0.09	0.11	Small	0.13	0.61	*Large*	< 0.001	0.56	*Large*	< 0.001
Stiffness													
K_{vert} (kN/m/kg)	0.24 ± 0.05	-0.06	-	0.25	0.31	Moderate	< 0.001	-		-	-		-
K_{leg} (kN/m)	0.18 ± 0.04	-0.20	*Small*	< 0.001	0.15	Small	< 0.001	-		-	-		-
K_{ankle} (N·mm/deg)	1.21 ± 0.28	-0.15	*Small*	0.01	0.13	Small	0.04	0.54	*Large*	< 0.001	0.64	*Large*	< 0.001
K_{knee} (N·mm/deg)	1.72 ± 0.54	-0.08	-	0.19	0.19	Small	< 0.001	0.56	*Large*	< 0.001	0.35	*Moderate*	< 0.001
Joint moments													
Ankle peak moment (N·m/kg)	2.93 ± 0.65	-0.20	*Small*	< 0.001	-0.08	-	0.12	0.24	*Small*	< 0.001	0.21	*Small*	< 0.001
Knee peak moment (N·m/kg)	3.60 ± 0.62	-0.13	*Small*	0.01	0.17	Small	0.01	0.45	*Moderate*	<0.001	0.47	*Moderate*	< 0.001
Hip peak moment (N·m/kg)	3.98 ± 0.93	0.56	*Large*	< 0.001	0.49	Moderate	< 0.001	-0.07	-	0.48	-0.28	*Small*	0.007
Joint work													
Ankle total joint work (J/kg)	1591.9 ± 369.1	-0.10	*Small*	0.15	0.07	-	0.31	0.20	*Small*	0.003	0.14	*Small*	0.04
Knee total joint work (J/kg)	690.1 ± 321.5	-0.27	*Moderate*	< 0.001	-0.35	Moderate	< 0.001	-0.13	*Small*	0.07	-0.06	-	0.39
Hip total joint work (J/kg)	1309.1 ± 468.4	0.22	*Small*	0.002	0.13	Small	0.07	-0.13	*Small*	0.06	-0.24	*Small*	< 0.001
Joint powers													
Ankle power (W/kg)	19.43 ± 4.62	0.29	*Small*	< 0.001	0.38	Moderate	< 0.001	0.20	*Small*	0.003	0.22	*Small*	0.005
Knee power (W/kg)	9.96 ± 2.89	0.19	*Small*	< 0.001	0.19	Small	< 0.001	0.06	-	0.34	-0.08	-	0.71
Hip power (W/kg)	13.35 ± 4.78	0.20	*Small*	< 0.001	0.26	Moderate	< 0.001	0.22	*Small*	0.002	-0.15	-	0.03
Global displacements													
Δ CoM (cm)	12.29 ± 1.65	-0.14	*Small*	0.01	-0.25	Moderate	< 0.001	-0.31	*Moderate*	< 0.001	-0.22	*Small*	< 0.001
Δ Leg (cm)	16.30 ± 2.45	0.13	*Small*	0.01	-0.02	-	0.66	-0.23	*Small*	< 0.001	-0.47	*Moderate*	< 0.001
Joint angular displacements													
Δ Ankle (deg)	36.48 ± 5.27	0.11	*Small*	0.04	-0.02	-	0.70	-0.34	*Moderate*	< 0.001	-0.43	*Moderate*	< 0.001
Δ Knee (deg)	19.73 ± 7.07	-0.01	-	0.82	-0.28	Moderate	< 0.001	-0.50	*Large*	< 0.001	-0.38	*Moderate*	< 0.001

Table 3.1.3. Joint mechanical output relationships using eta squared effect size (p values) and their interpretations for each joint variable (larger joint outputs are in the vertical columns) for both testing days.

Joint output variable	η^2 (p)	Interpretation	η^2 (p)	Interpretation
	K_{ankle}			
K_{knee}	0.16 (0.01)	*Large*		
	Δ knee			
Δ ankle	0.06 (0.01)	*Medium*		
	Ankle peak moment		**Knee peak moment**	
Knee peak moment	0.10 (0.01)	*Medium*	-	
Hip peak moment	0.07 (0.01)	*Medium*	0.01 (0.01)	*Small*
	Knee peak power		**Hip peak power**	
Ankle peak power	0.08 (0.01)	*Medium*	0.01 (0.51)	*Small*
Hip peak power	0.02 (0.01)	*Small*	-	
	Knee total joint work		Hip total joint work	
Ankle total joint work	0.07 (0.01)	*Medium*	0.01 (0.41)	*Small*
Hip total joint work	0.01 (0.01)	*Small*	**-**	

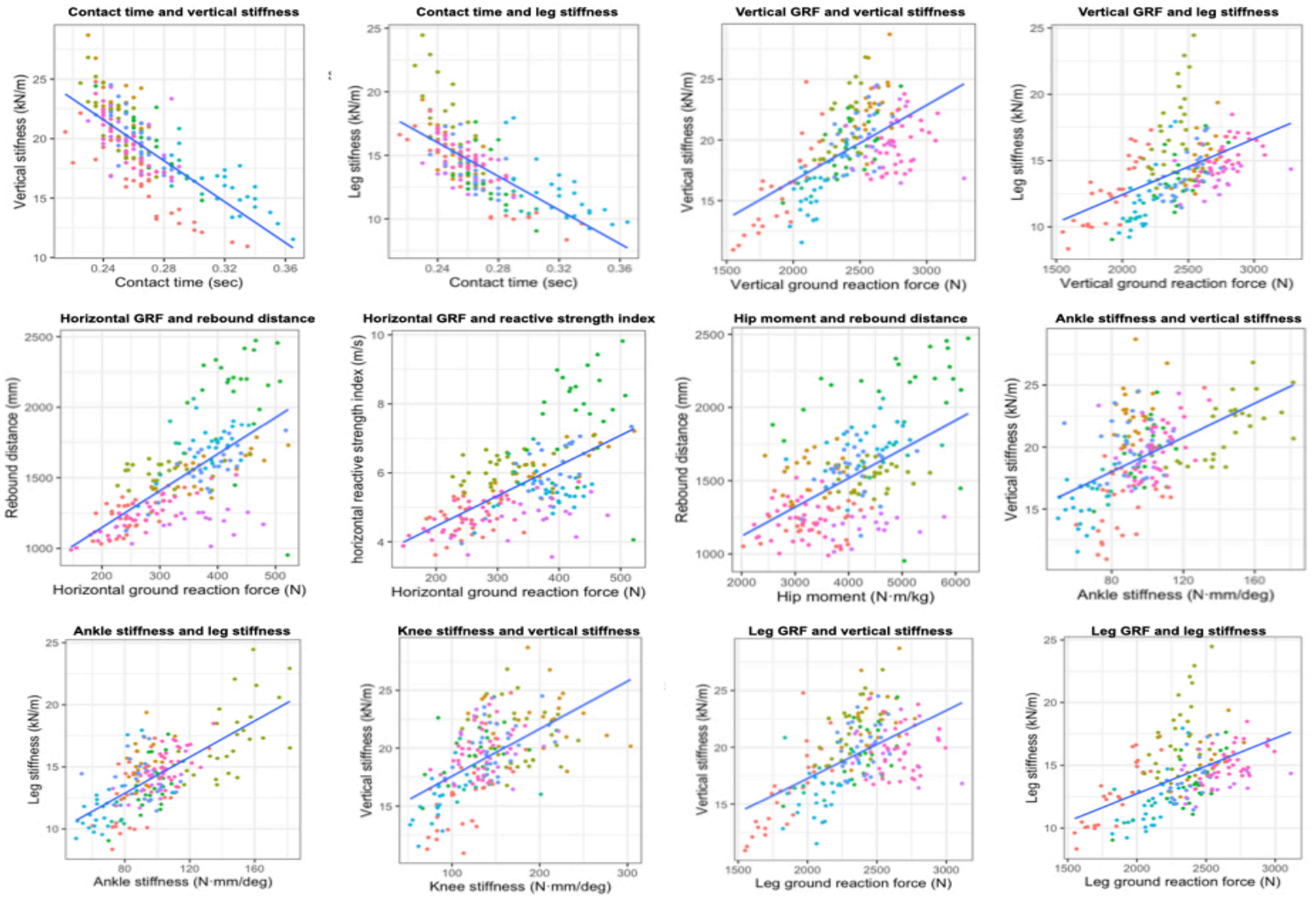

Fig. 3.1.3. Pearson correlation plots for features that demonstrated large to very large correlations. The different colours represent each of the ten participants.

3.1.5. DISCUSSION

3.1.5.1. Reliability

In this study, we established that a single leg horizontal plyometric exercise is a reliable test for measuring key performance variables such as hRSI, rebound distance, and contact time, as well as ground reaction forces, stiffness, and joint kinematic variables. Hop distance has previously demonstrated good reliability during a triple hop test, albeit for a slightly different task to that investigated in this study (Bolgla *et al.,* 1997). A recent study found good reliability for flight time, CT, hRSI and K_{leg} in a triple-hop test (Davey *et al.*, 2021). During double leg vertical hopping, Diggin *et al.* (2016) found good inter- and intraday reliability for K_{leg} and $K_{ankle,}$ while Joseph et al. (Joseph *et al.*, 2013) observed good reliability for K_{vert} but poor reliability for K_{ankle} and K_{knee} during running and hopping tasks. These joint stiffness findings are in contrast with what was observed in our study. One possible reason for this could be due to the acyclic nature of the horizontal rebound compared to high-frequency cyclic tasks like repeated hopping and running where there is an adjustment at joint level to regulate K_{leg} and K_{vert} (Farley *et al.*, 1998; Farley and Morgenroth, 1999).

3.1.5.2. Lower-limb Stiffness

To our knowledge, this is the first study to investigate joint, leg, and whole-body stiffness variables, and joint work and power in a single leg horizontal plyometric exercise. We hypothesised that joint stiffness would be highest at the knee compared to the ankle which was observed in this study and can be attributed to higher peak joint moments occurring at the knee with lower joint angular displacements, in contrast to the ankle. It has previously been reported that the least stiff joint has the largest correlation with vertical stiffness (Maloney *et al.*, 2017). The large correlation we observed between K_{ankle} and K_{vert} and K_{leg} respectively, may partially support this finding. Hobara et al. (2009) demonstrated that K_{knee} accounted for most of the variance in leg stiffness in maximal intensity double leg hopping. However, in this study, knee joint angular displacement had a larger correlation with vertical stiffness than ankle joint angular displacement. Conversely in a similar hopping task, Farley and Morgenroth (1999) found that increases in K_{leg} were accounted for by concurrent increases in K_{ankle} as the rotation of the foot segments contribute more to CoM excursions. The biomechanical nature of the task in this study, where the participants land in knee flexion with less joint angular displacements thereafter compared to the ankle, may suggest a complex interplay between the two joints that contribute to CoM and leg length excursions, and thus regulate K_{vert} and K_{leg}. The leg stiffness values in this study are similar to reported values during running at steady-state speeds (Morin

et al., 2005; Coleman *et al.*, 2012). It must be noted however, that leg stiffness values vary depending on the calculation model used (Coleman *et al.*, 2012) and the type of athlete, with sprinters exhibiting greater k_{leg} than endurance runners (Harrison *et al.,* 2004).

3.1.5.3. Correlation findings

Our results highlighted that contact time had a strong correlation with K_{vert} and $K_{leg.}$ Shorter ground contact times during hopping are also associated with greater AT stiffness (Abdelsattar *et al.,* 2018). Both hip joint moment and hGRF had a large correlation with rebound distance. However, it must be considered that the assumption of independence was not met. Hip extensor strength and horizontal orientation of GRF are key determinants of acceleration performance (Morin *et al.*, 2015), while horizontal jumping has a closer relationship with sprint performance compared to vertical hopping (Dobbs *et al.*, 2015). Performance in a triple jump is associated with vGRF during the braking phase and hGRF during the propulsion phase of the step phase (Perttunen *et al.*, 2000). A recent systematic review concluded that vertical plyometric exercises were found to improve vertical performance only, whereas horizontal plyometric training results in improvements in both vertical and horizontal performance (Moran *et al.*, 2021). These findings may be relevant for running sports and using a horizontal rebound may be a practical way of assessing horizontal plyometric ability.

3.1.5.4. Joint outputs

The dominance of the ankle, knee, and hip varied depending on the joint variable measured. Peak joint moment was highest at the hip, while joint power, work, and angular displacement were highest at the ankle, and the knee displayed greater joint stiffness than the ankle. The highest peak joint power and work at the ankle are in agreement with our hypothesis and other studies during a single-leg horizontal hop or rebound exercise task (Aeles and Vanwanseele, 2019; Kotsifaki *et al.*, 2021). Higher joint work at the ankle compared to the knee and hip are observed in distance running (Novacheck, 1998; Schache *et al.*, 2011) where elite runners maintain higher ankle joint output over a prolonged fatiguing run in comparison to novice runners (Sanno *et al.*, 2018). The highest net joint work and power occurs at the ankle during the early acceleration phase of maximal sprinting (Williams *et al.,* 2017; Schache *et al.,* 2019).

While this study did not measure muscle and tendon loading patterns it may be possible to use findings from previously-reported musculoskeletal modelling techniques based on running and hopping tasks, in conjunction with the joint mechanical outputs from this study, to gain a better

understanding of the muscle contributions to horizontal reactive strength qualities. High pre-activation and braking activity of the vastus lateralis and a peak in medial gastrocnemius EMG activity during the propulsion phase are observed in world-class triple jumpers during the step phase and jump phases (Perttunen *et al.*, 2000). In a single-leg hop for distance, the soleus contributes the largest muscle force during the propulsive phase (Kotsifaki *et al.*, 2021). Previous studies have shown that forward hopping exposes the AT to the higher loading rates compared to vertical hopping (Gheidi *et al.*, 2018; Baxter *et al.*, 2021). Reduced tendon stiffness, delayed muscle activation from the triceps surae and impaired hop for distance performance have been observed in runners with Achilles tendinopathy (Wang *et al.*, 2012). In light of our findings of ankle dominance for joint work and power, a maximal effort horizontal plyometric task may provide a robust assessment of the ankles capacity and athlete's progression following an Achilles injury rehabilitation program. This test is currently being used by the authors of this study as a key outcome measure for an Achilles tendinopathy randomised controlled trial (Griffin *et al.*, 2021).

3.1.5.5. Correlation with the 'true' mean

The correlation threshold was reached after three trials for the majority of the features measured and suggests that averaging three test trials following three familiarisation trials in the warm-up, are sufficient to capture a stable mean value of a measure. These findings are in agreement with test protocols for common jumping or hopping tests which utilise three test trials (King *et al.*, 2019; Davey *et al.*, 2021), while six trials were required for a lateral hurdle hop test (Gore *et al.*, 2016).

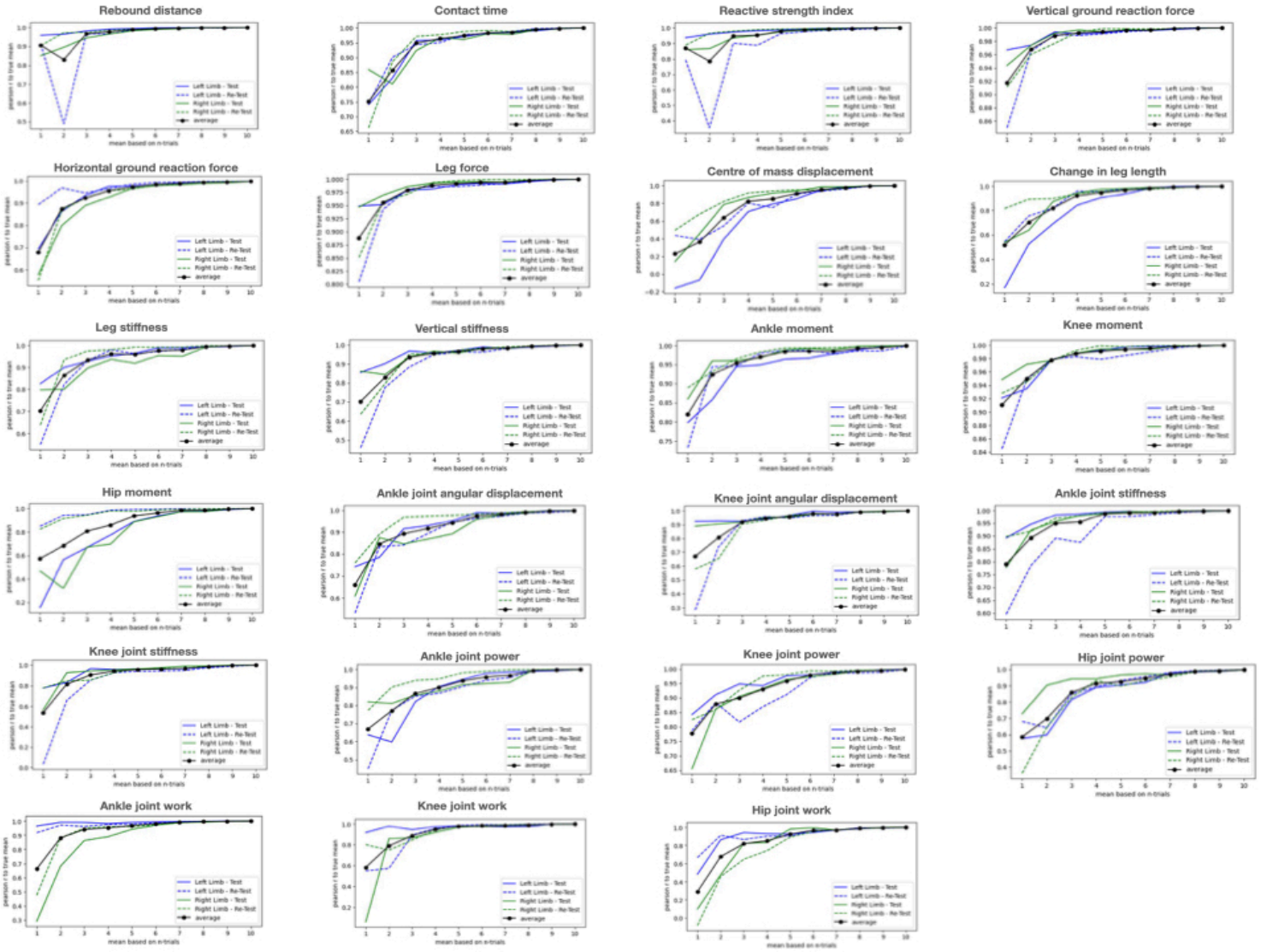

Fig. 3.1.4. The correlation plots between each trial for both testing sessions and the 'true' mean for each feature measured.

3.1.5.6. Limitations

There are some important limitations that should be acknowledged in this study. The reliability of some of the variables with ICC values <0.75 with large confidence intervals, should be interpreted with caution due to the small sample size. This also applied to the correlation analysis as, if the average value for each participant was used, the sample size (n=10) would be too small and therefore, we opted to use all trials for each participant which the Durbin-Watson test revealed to be dependent. The Plug-in-Gait model used assumes the foot acts like a rigid segment and this may overestimate ankle joint power and work by not allowing for rotation of the individual foot segments. This rigid foot model may also under estimate ankle joint stiffness and overestimate displacements by between 45-60% at higher force demands (Kessler *et al.*, 2020). All joint stiffness variables were calculated in the sagittal plane and do not take into consideration the joint displacements and moments that may occur in the frontal and transverse planes. It was not possible to calculate hip joint stiffness using the hip joint angle changes from initial contact to maximum displacement due to the lack of hip flexion during the stance phase. Given that the largest peak joint moments occurred at the hip, the impact of hip joint stiffness in this task may this have been overlooked.

3.1.6. CONCLUSION

Our study demonstrated moderate-to-excellent reliability for performance features such as rebound distance and horizontal reactive strength index, as well as most whole-body and joint kinematic and stiffness features in a single-leg horizontal rebound exercise. We observed large correlations between horizontal ground reaction force and performance features, as well as for contact time, ankle and knee joint stiffness with vertical and leg stiffness. The ankle displayed the highest joint work and power, while the knee showed the highest joint stiffness, and the largest peak joint moment was at the hip. Three familiarisation trials followed by three test trials are sufficient to obtain a stable representation of performance across the majority of variables. We propose the use of this test as a simple way to measure horizontal reactive strength index equivalent to the commonly-used reactive strength index in the drop jump. Considering the highest joint work and power outputs at the ankle coupled with the previously observed muscle calf muscle force contribution and AT loading rates, a horizontal rebound task such as the one used in this study may be a suitable assessment for return to performance following an ankle-related injury.

3.2. STUDY 2: TEST-RETEST RELIABILITY FOR A SEATED CALF ISOMETRIC STRENGTH TEST AND ISOKINETIC PLANTARFLEXOR PEAK AND JOINT ANGLE-SPECIIFC TORQUE

Plan to submit to the Journal of Strength and Conditioning in March 2023

Colin Griffin[1,2], Leigh Ryan[1], Ruth Shaw[1], Jean-Benoit Morin[1,3,4]

[1]Université Côte d'Azur, LAMHESS, Nice, France.

[2]Sports Surgery Clinic, Santry Demesne Dublin 9, Ireland

[3]Sports Performance Research Institute New Zealand (SPRINZ), Auckland University of Technology, Auckland, New Zealand

[4]Univ Lyon, UJM-Saint-Etienne, Inter-university Laboratory of Human Movement Biology, EA 7424, F-42023, Saint-Etienne, France

Address for correspondence: Colin Griffin, Sports Medicine department, Sports Surgery Clinic, Santry Demesne Dublin 9, Ireland.
Email: colingriffin@sportssurgeryclinic.com

3.2.1. ABSTRACT

Muscle strength testing is common practice in performance and rehabilitation settings. The PFs contribute the greatest muscle force of all lower-limb muscles. PF contractions with an extended knee require force from all the PF muscles, but when the knee is flexed close to 90° most of the force comes from the SO muscle. There is little consistency in speeds used to measure IKD strength and force plate testing has become widely available in recent years. This study aimed to assess the reliability of F_{peak} in a seated calf isometric test and PF T_{peak} and joint-angle-specific torque in an IKD test at 30°/sec. Ten participants performed a seated calf isometric test and ankle IKD test over two testing sessions with a time interval of 2-7 days between test. The participants produced force over 5 seconds for 3 repetitions on each leg in the seated calf isometric test with the best repetition for both legs used for analysis. Five trials were performed on each leg over two sets with the mean of the best three repetitions on each leg used for analysis. Good reliability was demonstrated for F_{peak} in the seated calf isometric test (ICC = 0.78; 95% CI: 0.51, 0.91) with mean value of 1209 ± 266.7 N, which equated to 1.66 times body weight. The IKD PF T_{peak} values showed good reliability (ICC = 0.87; 95% CI 0.70, 0.95) for T_{peak} and torque at 10° dorsiflexion (ICC = 0.83; 95% CI: 0.62, 0.93), while torque at 20° plantarflexion revealed moderate reliability (ICC = 0.58; 95% CI: 0.19, 0.81).

Both F_{peak} on a seated calf isometric test and PF T_{peak} on an IKD test at 30°/sec are reliable ways to measure soleus and total PF strength respectively. On the IKD test, PF torque at 10° dorsiflexion is reliable but measuring at 20° plantarflexion is less reliable despite being clinically useful and may require more precision with setting anatomical zero and standardising footwear.

3.2.2. INTRODUCTION

Many practitioners use strength testing to assess a muscle's capacity to return to sport following an injury or to identify the potential to improve performance. IKD dynamometry is the gold standard for measuring muscle torque around a joint. However, with force plate technology becoming more affordable and widely available, many professional sports clubs and clinics use isometric testing to assess F_{peak} in a squat and/or mid-thigh pull.

The most significant force output of lower limb muscles during running, jumping, and acceleration comes from the PFs (Dorn *et al.,* 2012; Hamner and Delp, 2012; Schache *et al.*, 2019; Kipp and Kim, 2020; Kotsifaki *et al.*, 2021). During running, the calf muscles operate close to their maximal capacity at slow to steady-state speeds (Dorn *et al.,* 2012; Kulmala *et al.*, 2016). The soleus muscle is the primary accelerator of the centre of mass in a vertical and horizontal direction (Hamner and Delp, 2012). During ballistic movements such as acceleration or jumping, as well as running, it is the most significant contributor of muscle force ranging from 7 times bodyweight at 4 m/s to 10 m/s during early acceleration (Dorn, Schache and Pandy, 2012; Kipp and Kim, 2020; Kotsifaki *et al.*, 2021; Pandy *et al.*, 2021). The PF muscles have a pennate fiber arrangement making them more suited to slow muscle contractions, favouring high force production (Lichtwark and Wilson, 2008; Farris and Sawicki, 2012; Rubenson *et al.*, 2012; Farris *et al.*, 2016; Bohm *et al.*, 2019). Because the PFs are also comprised predominantly of type I fibers, they can sustain and repeat high-force outputs for extended durations (Gollnick *et al.*, 1974).

PF strength is traditionally measured using isokinetic dynamometry (IKD) but there is a lack of consistency in the protocols used. Many studies have used joint angular velocities of 90°/sec and 225°/sec to measure concentric and eccentric T_{peak} (Alfredson *et al.*, 1998; McAuliffe *et al.*, 2019; O'Neill *et al.,* 2019). Alfredson's rationale for using angular velocities of 90°/sec was that it replicated the ankle joint angular velocity experienced when running (Alfredson *et al.*,

1998). However, many studies using those speeds report T_{peak} values well below 100% body mass, which may not be a reflection of the muscle force demands of several times body weight experienced by the PFs (Alfredson *et al.*, 1998; Dorn *et al.,* 2012; O'Neill *et al.,* 2019). Thus, measuring IKD torque at slow speeds, closer to isometric contractions, may be more indicative of the muscle tissue mechanics experienced during running. Therefore, it may be more valuable to assess at an angular velocity of 30°/sec. No published studies have reported torque at specific joint angles, such as 10° dorsiflexion or 20° plantarflexion. Impairments in heel raise height in a single leg calf raise following an AT rupture is a common observation (Baxter *et al.,* 2019; Hoeffner *et al.*, 2022). Similarly, patients with mid-portion or insertional Achilles tendinopathy often experience pain provocation when producing torque from dorsiflexed angles. The ability to measure torque at specific joint angles may provide a more objective evaluation of the strength deficits at those angles and guide exercise prescription during rehabilitation.

Historically, an IKD is also used to measure isometric PF strength over 5-second contractions (Arampatzis *et al.*, 2006). This protocol measures AT mechanical properties over submaximal contractions (Albracht and Arampatzis, 2013; Geremia *et al.*, 2018). It may be challenging to measure isometric PF F_{peak} on a force plate in standing due to the inability to constrain the contributions from more proximal joints. It is more practical to obtain an isolated measure of PF force by assessing PF F_{peak} in a prone or supine position with uninvolved body segments immobilised. Due to the biarticular function of the gastrocnemius muscles, knee flexion will reduce their force output but will have minimal effect on the monoarticular soleus muscles (Arampatzis *et al.*, 2006). Also, given that the soleus often operates independently from the gastrocnemius in specific tasks (Suzuki *et al.,* 2014; Pandy *et al.*, 2021), measuring its F_{peak} in isolation would help inform strength programming.

Previous studies have assessed the reliability of absolute T_{peak} values in an ankle IKD test at 30°/sec (Chester *et al.*, 2003) and F_{peak} in a seated calf isometric strength test (Rhodes *et al.*, 2022). However, to our knowledge, no studies have assessed the reliability of T_{peak} at 30°/sec in uninjured participants and joint-specific torque values. One study evaluated the reliability of T_{peak} relative to body weight at 90° and 225°/sec respectively, which revealed moderate reliability, whereas absolute T_{peak} showed good reliability (Al-Uzri *et al.*, 2016). We sought to evaluate both a knee-extended IKD and seated isometric protocol for measuring PF strength. While it is possible to measure knee-extended PF strength standing, it requires careful precision to constrain the contribution from the proximal joints and the use of inverse dynamics to

accurately calculate PF torque which may be time-consuming and unfeasible in. a practical setting. IKD is considered the ”gold standard” for assessing muscle torques around a joint, enables a more isolated measure of PF torque. Given the widespread availability of force plate technology, a seated calf isometric test can be easily administered and, with a more knee-flexed angle, provide a relatively isolated measure of soleus force output. The aim of this study was to: (i) test the reliability of relative IKD T_{peak}, as well as torque at 10° dorsiflexion and 20° plantarflexion in an ankle IKD test at 30°/sec and (ii), to test the reliability of absolute and relative F_{peak} in a seated calf isometric test using force plates.

3.2.3. METHODS

Ten healthy participants took part in the ankle IKD test (5 males, 5 females; 23.9 ± 3.2 years, height 172.5 ± 7.3 cm, body mass 74.05 ±7.7 kg) and the seated calf IKD test (7 males, 3 females; 28.2 ±8.1 years, height 176 ± 7.9 cm, body mass 78.1 ±8.6 kg). Two testing sessions were performed for each of the protocols, with a time interval between tests between two and seven days due to participant and lab availability. Six participants (4 males, 2 females) performed both test protocols in the order of the ankle IKD test and then the seated calf isometric test. Each participant regularly performed strength training and had not completed any exhaustive training in the 48 hours before the testing sessions. The SSC research ethics committee approved the study, and each participant provided informed written consent before testing.

3.2.3.1. Ankle IKD test

The participants performed a standardised warm-up of a 3-minute light spin on a wattbike. Before each test session, body mass and height were measured. The test was performed with an extended knee with the participant lying prone on an IKD dynamometer (Cybex Norm, Computer Sports Medicine Inc.) as illustrated in Figure 3.2.2. The monorail and dynamometer angles were set to 45° with the medial malleolus aligned to the centre of the dynamometer's rotation axis. The anatomical zero mark on the dynamometer was used to set a neutral ankle for consistency, and the joint angle range was set between 30° plantarflexion and 20° dorsiflexion. Gravitational torque was measured at 15° plantarflexion, with the participant asked to relax as much as possible, then accounted for so resting torque was set to 0 Nm. The participants performed three sets of 5 trials with one-minute rest between trials. The first set was a familiarisation set where the participants began at 60% effort and increased by 10% each repetition, reaching a maximal effort on each trial and being encouraged to "push hard" through

the entire range. The mean of the best three repetitions for T_{peak} on each limb was calculated and reported along with torque at 10° dorsiflexion and 20° plantarflexion. All torque values were expressed relative to body mass (Nm/kg %). Data were exported and processed in python using a custom-made script.

Fig. 3.2.1. A seated calf isometric test

3.2.3.2. Seated calf isometric test

The participants who performed an ankle IKD test performed the seated calf isometric test after. Those who only performed the isometric test completed a warm-up on the wattbike. The test was performed on a dual force plate platform (Vald Performance, Queensland, Australia; sampled at 1000 Hz). The patient was seated with their forefoot resting on a block from the base of the first metatarsal *(Fig. 3.2.1)*. The force plates were calibrated with the resting weight measured with the foot block on each platform. The knee angle was 90° with ratchet strapping

placed over the quad tendon and aligned with the lateral malleolus. The ankle was in 10° dorsiflexion with the ratchet set tightly to minimise heel displacement. The participant performed three familiarisation trials of 5-second isometric contractions at 80%, 90%, and 95% of perceived maximal efforts, respectively, with a 30-second rest between trials. Following this, they performed three test trials of maximal isometric efforts over 5 seconds with a 1-minute rest in between. This protocol is similar to other studies that have measured maximal isometric PF torque (Albracht and Arampatzis, 2013), isometric mid-thigh pull, and isometric squat (Brady *et al.,* 2018). The best repetition for each limb was used for analysis.

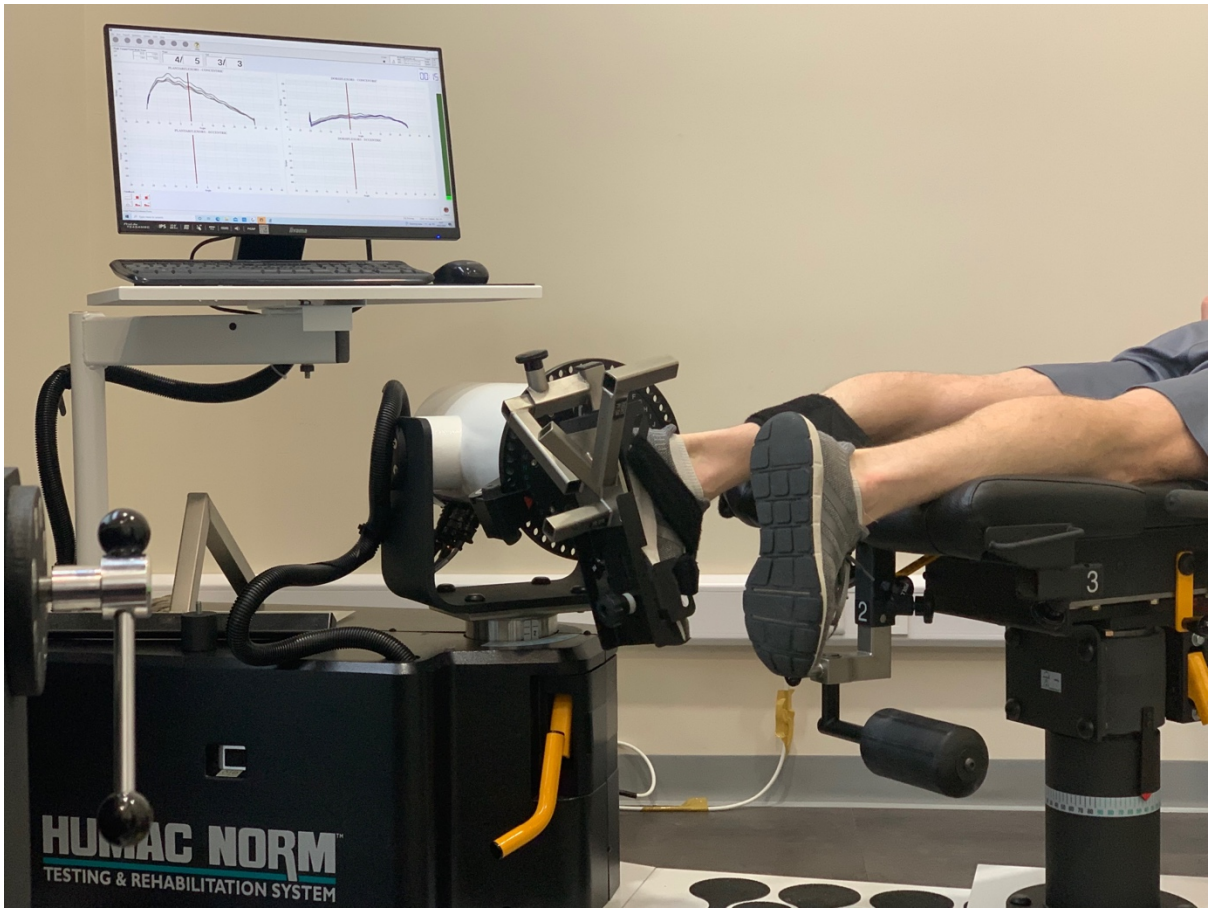

Fig. 3.2.2. The isokinetic plantar flexor test

3.2.3.3. Statistical analysis

Both limbs were analysed for all trials. The data for the two tests were exported to r for statistical analysis. The intra-class correlation was calculated using two-way ANOVA with an absolute agreement to determine the reliability of both test protocols with the coefficient of variability (CoV), standard error of measurement (SEM), and 95% confidence intervals

reported. ICC threshold values for reliability were interpreted as moderate (ICC > 0.5), good (ICC > 0.75), and excellent (ICC > 0.90).

3.2.4. RESULTS

The results of the test-retest reliability for the seated calf isometric test are displayed in Table 3.2.1. This test demonstrated good reliability (ICC = 0.78; 95% CI: 0.51, 0.91). The mean value of the participants was 1209 ± 266.7 N, which equated to 1.66 times body weight. The IKD PF T_{peak} values showed good reliability (ICC = 0.87; 95% CI 0.70, 0.95) for T_{peak} and torque at 10° dorsiflexion (ICC = 0.83; 95% CI: 0.62, 0.93), while torque at 20° plantarflexion revealed moderate reliability (ICC = 0.58; 95% CI: 0.19, 0.81). The results of reliability statistics for the IKD PF test are summarised in Table 3.2.3.

3.2.5. DISCUSSION

This study aimed to test the reliability of F_{peak} in a seated calf isometric strength test using force plates and T_{peak} and joint angle-specific torque in an IKD test at 30°/sec speeds. We demonstrated good reliability for F_{peak} in a seated calf isometric test and T_{peak} and torque at 10° dorsiflexion in the IKD test. We found moderate reliability for torque at 20° plantarflexion. Our findings indicate that an ankle IKD test at 30°/sec is a reliable measure of total PF muscle strength. The seated calf isometric test is reliable for evaluating soleus muscle maximal force. A knee angle close to 90° will affect the force output of the biarticular gastrocnemius muscles (Arampatzis *et al.*, 2006; Lauber et al., 2014).

Table 3.2.1. Seated calf isometric test with the mean, SD and CoV values for the best repetition of F_{peak} (N) for both limbs combined (n=20) for each test and the reliability statistics

	Best repetition (N)						95% confidence intervals		ICC	SEM (N)
	Test 1			*Test 2*						
	Mean (N)	SD	CoV (%)	Mean (N)	SD	CoV (%)	*Upper*	*Lower*		
Peak vertical force for both limbs	1209.4	266.7	21.9	1281.1	271.3	21.2	*0.91*	*0.51*	*0.78*	*121.1*

Table 3.2.2. Prone plantar flexor isokinetic test measuring concentric PF T_{peak} (%BW), torque at 10°dorsiflexion (DF) and 20° plantarflexion (PF) at 30°/sec with an extended knee with the mean, SD and CoV values for the three best repetitions for both limbs combined (n=20) for each test and their reliability statistics

	Mean of the 3 best repetitions (Nm/kg %)						95% confidence intervals		ICC	SEM (Nm/kg %)
	Test 1			*Test 2*						
	Mean (Nm/kg %)	SD	CoV (%)	Mean (Nm/kg %)	SD	CoV (%)	Upper	Lower		
T_{peak} for both limbs	123.8	29.2	23.5	128.2	35.3	27.5	0.95	0.70	0.87	11.7
Torque at 10° DF for both limbs	110.8	28.7	25.9	117.1	27.2	31.8	0.93	0.62	0.83	13.5
Torque at 20° PF for both limbs	56.4	17.1	30.3	58.7	15.1	25.7	0.81	0.19	0.58	10.6

Our ICC values are broadly similar to the only other study that has tested the reliability of a seated calf isometric test, which also found good reliability (ICC = 0.89 on the right leg, 0.79 on the left leg) in 30 elite soccer players (Rhodes *et al.*, 2022). The only slight variation in the protocol used was a bar with a cushioned Airex pad over the knee and a neutral ankle angle of 90°. However, a neutral ankle angle may not facilitate maximal force output from the soleus as this requires more dorsiflexed angles (Manal *et al.,* 2006). Our study used a ratchet strap over the knee, which allowed good tension and comfort. We also set the ankle angle to 10° dorsiflexion to achieve more optimal force-length conditions. Rhodes et al. (2022) used a 3-second protocol instead of 5 seconds in our study. Other studies have used 5-second durations in IMTP, and ISQ tests (Brady et al., 2018). This difference may not be relevant as peak isometric force is usually achieved within the first 3 seconds (Khamoui *et al.*, 2011). Our reliability results align with planta flexor isometric strength assessments using a hand-held dynamometer or IKD (Hébert-Losier and Murray, 2020). ICC values of 0.70 with coefficients of variation less than 15% are accepted as demonstrating good reliability for isometric strength tests (Haff *et al.*, 1997; Brady *et al.,* 2018). Our ICC values are well above 0.70, but our CoV values are above 15%, indicating a higher-than-desired variability between repeated measurements.

The reliability of our IKD values is similar to findings across different speeds elsewhere (Chester *et al.*, 2003; Al-Uzri *et al.*, 2016). Few studies have assessed IKD PF T_{peak} at 30°/sec in a prone position with the knee extended. No studies have measured torque at inner or outer range joint angles. This level of detail may prove helpful to clinicians working with injured athletes or patients to address joint angle-specific deficits. Our findings of moderate reliability for torque at 20° plantarflexion may be explained by the fact that we set the anatomical zero based on the dynamometer settings instead of manually measuring with a goniometer. We did not control for different shoe types. Therefore, it may be possible that shoes with a greater heel stack height than more minimalist shoes would result in discrepancies in actual ankle joint angle when anatomical zero was set and may impact torque at end-range plantarflexion.

Muscle strength testing is widely used in performance and injury rehabilitation settings. Maximal strength using 1RM can be easily assessed, with appropriate safety measures, during compound exercises such as a squat or deadlift with good correlation to isometric values (Haff, 2018, chapter in Comfort *et al.,* 2018). Assessing 1RM may not be practical for evaluating maximal local muscle strength. Therefore isometric testing on a force plate or IKD testing can

provide an accurate and reliable solution where such technology is available. When assessing the PFs, it may be prudent to consider the three muscles which collectively contribute more than 80% of the T_{peak}. The soleus muscle has 3.5 times the force generation capacity of the medial gastrocnemius and is the biggest force producer of the lower limb muscles during jumping and running (Fukunaga *et al.*, 1996; Dorn *et al.,* 2012; Kipp and Kim, 2020; Kotsifaki *et al.*, 2021). Assessing the soleus in isolation and total PF strength may reveal specific strength deficits or whether its proportional strength is adequate, which may be overlooked.

Some limitations should be acknowledged when interpreting the results of this study. The low sample size of ten participants for each protocol underpowers the study. We had mixed gender and athletic ability among the participants. The irregularity of the test-retest time intervals and lack of standardisation of footwear may have contributed to the high CoV's between repeated trials.

3.2.6. CONCLUSION

This study evaluated the reliability of IKD PF peak, joint angle-specific torque, and seated calf isometric F_{peak}. We demonstrated good reliability for F_{peak} in the seated calf isometric test and IKD PF $T_{peak,}$ respectively. In the latter test, we found good reliability for torque at 10° dorsiflexion but only moderate reliability at 20° plantarflexion.

4. THEME 2 - A REHABILITATION PATHWAY FOR ACHILLES TENDON INJURIES GOVERNED BY ASSESSMENT OUTCOME MEASURES

4.1. STUDY 3. A CRITERIA-BASED REHABILITATION PROGRAM FOR CHRONIC MID-PORTION ACHILLES TENDINOPATHY: STUDY PROTOCOL FOR A RANDOMISED CONTROLLED TRIAL

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Colin Griffin[1,2], Katherine Daniels[2,3,5], Caroline Hill[2], Andrew Franklyn-Miller[2,7], Jean-Benoît Morin[1,4,6]

Author affiliations

[1] Université Côte d'Azur, LAMHESS, Nice, France.

[2] Sports Surgery Clinic, Santry Demesne Dublin 9, Ireland

[3] University of Bristol, Queen's School of Engineering, University Walk, Bristol BS81TR, United Kingdom

[4] Sports Performance Research Institute New Zealand (SPRINZ), Auckland University of Technology, Auckland, New Zealand

[5] Department of Sport and Exercise Sciences, Manchester Metropolitan University, Manchester, United Kingdom

[6] Univ Lyon, UJM-Saint-Etienne, Inter-university Laboratory of Human Movement Biology, EA 7424, F-42023, Saint-Etienne, France

[7]Centre for Health, Exercise and Sports Medicine, University of Melbourne, Parkville Victoria, Australia

Address for correspondence: Colin Griffin, Sports Medicine Department, Sports Surgery Clinic, Santry Demesne, Dublin 9, Ireland.
Email: colingriffin@sportssurgeryclinic.com

4.1.1. ABSTRACT

Achilles tendinopathy (AT) is a common overuse injury in running-related sports where patients experience pain and impaired function which can persist. A graded rehabilitation program has been successful in reducing pain and improving function to enable a return to sport. The aim of this study is to compare the effectiveness of a criteria-based rehabilitation program including strength and reactive strength targets, with a previously successful rehabilitation program on changes in pain and function using the Victorian Institute of Sport

Assessment-Achilles (VISA-A) questionnaire. Secondary aims will be to assess changes in calf strength, reactive strength, and lower limb running and forward hop biomechanics over the course of a 12-week rehabilitation program, and long-term follow-up investigations. Sixty eligible participants with chronic mid-portion AT who train in running-based sports will be included in this study. They will be randomly assigned to a group that will follow an evidence-based rehabilitation program of daily exercises with progression guided by symptoms or a group performing 3 high-intensity rehabilitation sessions per week with individualised load targets progressing to reactive strength exercises. Testing will take place at baseline, week 6 and 12. PF T_{peak} will be measured using IKD dynamometry, reactive strength will be measured using a drop jump and lower limb biomechanical variables will be measured during a single leg forward hurdle hop test and treadmill running using 3D motion analysis. Follow-up interviews will take place at 6, 12 and 24 months after beginning the program which will assess patient participation in sport and possible re-injury. This is the first study to propose an individualised criteria-based graded rehabilitation program in patients in with chronic mid-portion Achilles tendinopathy where progression is guided by strength and reactive strength outcome measures. This study will provide a comprehensive assessment of PF strength, reactive strength and lower limb biomechanical variables in running and forward hopping with the VISA-A questionnaire as the primary outcome measure and long term post-intervention follow-up assessments performed.

Trial registration

ClinicalTrials.gov (ID: NCT04384874). Registered retrospectively on April 23rd 2020.

Key words

Achilles tendinopathy, plantar flexor strength, Stiffness, Hopping, Achilles tendon, Injury, Rehabilitation

4.1.2. INTRODUCTION

The Achilles tendon is the largest and strongest tendon in the human body (Harris and Peduto, 2006) and usually withstands very high tensile forces during exercise (Komi, 1990), but is also one of the most commonly injured tendons (Wren *et al.*, 2001). Achilles tendinopathy (AT) affects 2% of the general population (De Jonge *et al.*, 2011), and has an incidence of 7-9% in

running-based sports with a cumulative lifetime incidence of up to 52% among certain athletic populations (Kujala *et al.,* 2005).

Tendinopathy is described as pain and impaired function in the affected tendon (Cook *et al.,* 2002; Khan, 2002; Cook and Purdam, 2009). Over time this may result in reduced physical activity, absenteeism from sport and impaired quality of life (Cook and Purdam, 2009). Histologically and biochemically pathological tendon has been shown to include increased hyper-cellularity, reduced collagen type I and increased type III content, increased proteoglycans and glycosaminoglycans, and blood vessel in-growth (Jones *et al.*, 2006; Riley, 2008). Excessive loading of the tendon is believed to be the primary contributory factor to Achilles tendinopathy (Selvanetti *et al.,* 1997). The fibroblastic cells known as tenocytes within the extracellular matrix are sensitive to mechanical loading and, when the tendon is overloaded, the cells alter the protein composition of the matrix resulting in pathology and reduced capacity for exercise (Kjær *et al.*, 2009).

Patients with AT usually present with pain, swelling and impaired performance of the tendon (Mead *et al.*, 2018), as well as altered function of the PF muscles (Silbernagel *et al.*, 2006; O'Neill *et al.,* 2019; McAuliffe *et al.*, 2019). In a sporting population, training load perturbations such as a rapid increase in training volume, intensity or frequency are said to be common contributory factors (Järvinen *et al.*, 2005). Re-injury rates are high, most likely due to incomplete restoration of muscle-tendon unit function (Silbernagel *et al.*, 2006), and symptoms can persist for a number of years in some cases (Silbernagel *et al.*, 2007b). In an eight-year follow-up study, 20% of patients still experienced impaired physical activity (Knobloch *et al.*, 2008). A failed healing response and degenerative changes are associated with the development of chronic tendinopathy resulting in reduced load capacity and persistent pain symptoms (Cook and Purdam, 2009). This is described by Cook et al. (Cook and Purdam, 2009) in their proposed continuum model involving three stages: reactive tendinopathy, tendon disrepair and degenerative tendinopathy.

Impairments in tendon mechanical properties such as stiffness and Young's modulus have been highlighted in AT (Arya and Kulig, 2010; Child *et al.*, 2010; Wang *et al.*, 2012). Wang et al. (2012) observed reduced stiffness and increased hysteresis of the AT, along with reduced rate of force development of the PF muscles and reduced single-leg horizontal hop performance in symptomatic limbs of patients with AT, compared to the non-symptomatic limb. While one

study found reduced lower limb stiffness in the injured limb of runners with AT during hopping (Maquirriain, 2012), biomechanical variables such as leg and joint stiffness in running and hopping tasks have not been extensively researched in patients with Achilles tendinopathy.

Many passive treatment therapies such as injections (Kearney *et al.*, 2015; Martin *et al.*, 2018), Non-Steroidal Anti-Inflammatory Drugs (NSAIDs) (Riley, 2008; Chimenti *et al.*, 2017), ultrasound (Riley, 2008; Chimenti *et al.*, 2017), shockwave (Rompe *et al.*, 2007; Magnussen *et al.,* 2009), laser (Chimenti *et al.*, 2017), iontophoresis (Martin *et al.*, 2018), acupuncture (Zhang *et al.*, 2013), orthotics (Magnussen *et al.,* 2009; Martin *et al.*, 2018), wearing a night splint (De Jonge *et al.*, 2010), vibration and cryotherapy (Romero-Morales *et al.*, 2018), mucopolysaccharides (Balius *et al.*, 2016), and a wait-and-see approach (Rompe *et al.*, 2007) have been used in the management of AT. However, there is strongest evidence for the use of exercise therapy as the primary treatment option (Cook and Purdam, 2014; Silbernagel and Crossley, 2015; Van Der Vlist *et al.*, 2020). Tendons adapt to exercise as the mechanical perturbation of the inter- and intra-fascicular cells triggers a molecular response signalling an expression of important proteins in the extra-cellular matrix which restore the mechanical properties of the tendon (Lavagnino *et al.*, 2015; Snedeker and Foolen, 2017). Three main modes of exercise have been widely used, each associated with improvements in clinical symptoms to varying degrees, namely: Alfredson's eccentric protocol (Alfredson *et al.*, 1998), Silbernagel's combined concentric-eccentric protocol (Silbernagel and Crossley, 2015) and the heavy-slow resistance (HSR) protocol (Beyer *et al.*, 2015). The Silbernagel protocol *(Table4.1.1)* comprises a combined concentric-eccentric exercise program performed daily, before progressing to plyometric exercises as symptoms permit, with no individualisation of exercise prescription and progression guided solely by pain symptoms on a numeric pain rating scale (NPRS).

Recent evidence suggests that magnitude of loading, irrespective of contraction mode, is the primary stimulus for tendon adaptation (Bohm *et al.,* 2015). Isometric exercises using 5 x 45-second contractions at 70% maximal voluntary contraction (MVC) have been used for early management of tendinopathies with evidence suggesting an analgesic effect (Rio *et al.*, 2015). However, this has been since contested by the findings of (O'Neill *et al.,* 2017). Documented timeframes for rehabilitation interventions vary between 6 weeks to several months with no clear objective measures for return to sport. Patients with AT display impaired reactive strength qualities during hopping tasks and it is recommended to include plyometric training at an

advanced stage of a rehabilitation program to prepare for the stretch-shortening cycle demands of running-based sports (Silbernagel *et al.*, 2007a; Silbernagel and Crossley, 2015). A multi-stage rehabilitation program that includes the combination of strength development and plyometric training may thus be beneficial, but there is a lack of consensus on assessing these qualities to guide exercise prescription and progression through the rehabilitation pathway.

While numerous studies have shown positive clinical improvements and tendon adaptations to exercise (Alfredson *et al.*, 1998; Beyer *et al.*, 2015; Bohm *et al.,* 2015; Silbernagel and Crossley, 2015; Murphy *et al.*, 2018), studies which investigate a periodised return to sport rehabilitation program with load targets and outcome measures for progression, are necessary due to the individualised nature of its initial presentation and diverse timeframes for recovery. The Sports Surgery Clinic (SSC) rehabilitation pathway *(Table4.1.2)* proposed in this study involves six stages of progressive rehabilitation (SSC6) from initial diagnosis and assessment, through developing strength, power and reactive strength, linear and multi-directional running, and return to performance. The existing literature has demonstrated positive clinical outcomes using Silbernagel's rehabilitation program (Silbernagel *et al.*, 2007a; Murphy *et al.*, 2018) and we have selected this a suitable comparative control for this study which involves a graded progression pathway from combined concentric-eccentric exercises to plyometric training (Silbernagel and Crossley, 2015).

Considering the multiple functional impairments experienced by athletes with AT, a battery of kinematic and kinetic tests to investigate PF strength, reactive strength and lower limb biomechanical variables in hopping and running, may provide guidance on exercise prescription, progression through a rehabilitation program and return to sport decision-making. To the best of our knowledge no study has assessed such breadth of athletic qualities affected by AT.

This study will aim to compare the outcome of SSC6, a multi-factorial, individualised criteria-based rehabilitation program with Silbernagel's combined concentric-eccentric program, in physically active participants with chronic mid-portion AT. In addition to the commonly reported outcome measures of VISA-A, as secondary outcome measures we will assess PF strength, reactive strength and lower limb kinematic and kinetics during running and hopping at 6-week intervals during a 12-week rehabilitation program as these have not been reported

previously. We also further aim to investigate the long term effects of rehabilitation programs and achieved outcome measures over a 6, 12 and 24-month follow-up period.

4.1.2.1. Aims

Using the VISA-A questionnaire as the primary outcome measure, the aim of this study is to compare the effectiveness of Silbernagel's daily exercise program with progression guided by pain symptoms, against SSC6's exercise program carried out 3 times per week with specific load targets. We will assess PF strength using an isokinetic measurement, reactive strength based on a drop jump, and lower limb biomechanics during a novel single leg horizontal rebound test and running, and investigate whether changes in these variables over the course of the 12-week rehabilitation program are associated with improved pain and function outcomes using the VISA-A questionnaire when comparing the two rehabilitation programs. We will assess participant satisfaction with their prescribed program, adherence and fidelity using a training diary and perform follow-up interviews at 6, 12 and 24 months to analyse participation in their sport and any potential re-injury rates.

4.1.3. METHODS

4.1.3.1. Study design

This study will be a single-centre, parallel group randomized-control trial. The data collection will take place at the SSC Sports Medicine department at the Sports Surgery Clinic in Dublin. The study protocol has been reported using the Standard Protocol Items: Recommendations for Interventions (SPIRIT) statement guidelines (Appendix 9). The study was approved by the Sports Surgery Clinic's Research Ethics Committee, (Application number: SAREB13/05/19CG/MJ) and registered at ClinicalTrials.gov (ID: NCT04384874).

4.1.3.2. Participants

Adult patients diagnosed with chronic mid-portion AT who participate in running-based sports will be invited to take part in this study. Patients who present to the Sports Surgery Clinic (SSC) with Achilles pain will be seen by a Sport and Exercise medicine physician, their history and clinical examination will be confirmed with magnetic resonance imaging (MRI). If the patient is diagnosed and meets the inclusion criteria, they will be invited to participate in the study and will be given an information sheet to read with a minimum of 24 hours to consider before agreeing by signing a consent form (Appendix 5). Participants will also be recruited externally through adverts on social media channels, emails to coaching contacts and local

sports clubs. Participants who feel they are eligible and meet the inclusion criteria will be referred for examination by a sport and exercise medicine physician at the clinic to confirm diagnosis and eligibility for the study.

4.1.3.3. Inclusion/exclusion criteria

Inclusion criteria

Participants will be eligible for this study if they are aged 18-45 years, perform running-based sports, are diagnosed with mid-portion AT, following a clinical examination by a sports medicine physician and confirmed with MRI, and have been experiencing symptoms for more than 3 months but less than 3 years.

Exclusion criteria

Patients will be ineligible for the study if they have a co-existing lower-limb injury, have had a running-related injury in the previous 12 months, or have had any peritendinous, or intra tendinous Achilles injection in the past 6 months, or previous Achilles surgery (Silbernagel *et al.*, 2007; Murphy *et al.*, 2018; O'Neill *et al.,* 2019).

4.1.3.4. Randomisation and blinding

Participants will be assessed at baseline before being randomly assigned to the intervention group or control group and will follow a prescribed rehabilitation program for 12 weeks. See Table 3 for a summary of the study design. The randomisation will be performed using the online tool www.sealedenvelope.com and the participant will be handed an envelope from an independent observer not involved with the study, containing their respective group allocation number. The principal investigator and training group investigators will be blinded to the group randomisation process, following procedures that have been used in similar studies (Mendiguchia *et al.*, 2017). The participants will be prescribed with an exercise program with video demonstrations of each exercise under the supervision of the investigator in their respective group. The program will be carried out at home or in a local gym in addition to supervised rehabilitation sessions every 2-3 weeks at SSC. Testing will take place again at week 6 and 12. Follow-up interviews will take place at 6, 12 and 24 months after baseline testing. The investigator involved with the testing and follow-up interviews will also be blinded to the group allocation. The primary outcome measure will be changes to the VISA-A questionnaire. Secondary outcome measures will include PF strength, lower limb reactive strength, biomechanics and running gait.

4.1.4. OUTCOME MEASURES AND ASSESSMENTS

4.1.4.1. Investigations

At baseline, week 6 and 12, all participants will be required to complete a VISA-A questionnaire as well as perform IKD testing and 3D motion capture running gait assessment. In addition, hop testing will be performed at week 6 and 12 *(Table4.1.3).* Hop testing is included in the testing battery from week 6 onwards as it is expected some participants with Achilles pain at baseline testing may be fearful of performing hopping tasks or risk of exacerbating their pain, and the data collected may not be an accurate reflection of their capabilities.

4.1.4.2. Primary outcome measure

VISA-A Questionnaire

The VISA-A questionnaire has been shown to be a valid, reliable and easy-to-use outcome measure tool for intervention studies on AT (Robinson *et al.*, 2001). It consists of eight questions regarding pain and function during both daily living and sporting activities. The overall score is between 0-100 where higher scores represent reduced pain and improved function. An improvement of 21 points between 2 and 12 weeks of a rehabilitation program have been typically observed (Murphy *et al.*, 2018). While the VISA-A score will not determine eligibility for inclusion into the study, it will be used to map progress over the course of the rehabilitation program and in the follow-up period. The difference in VISA-A score between both training protocols from baseline testing to the outcome testing at 6 weeks, 12 weeks, 3, 6 and 12 months; will formulate the primary outcome measure for this study.

4.1.4.3. Secondary outcome measures

Isokinetic plantar flexor strength

Reduced PF strength is a common feature in patients with Achilles tendinopathy (Alfredson *et al.*, 1998; Silbernagel *et al.*, 2006; O'Neill *et al.,* 2019; McAuliffe *et al.*, 2019). One prospective study to date established that PF torque below 50 Nm was a risk factor for developing AT (Mahieu, 2006). IKD testing is commonly used to measure PF T_{peak} (Alfredson *et al.*, 1998; O'Neill *et al.,* 2019; McAuliffe *et al.*, 2019).

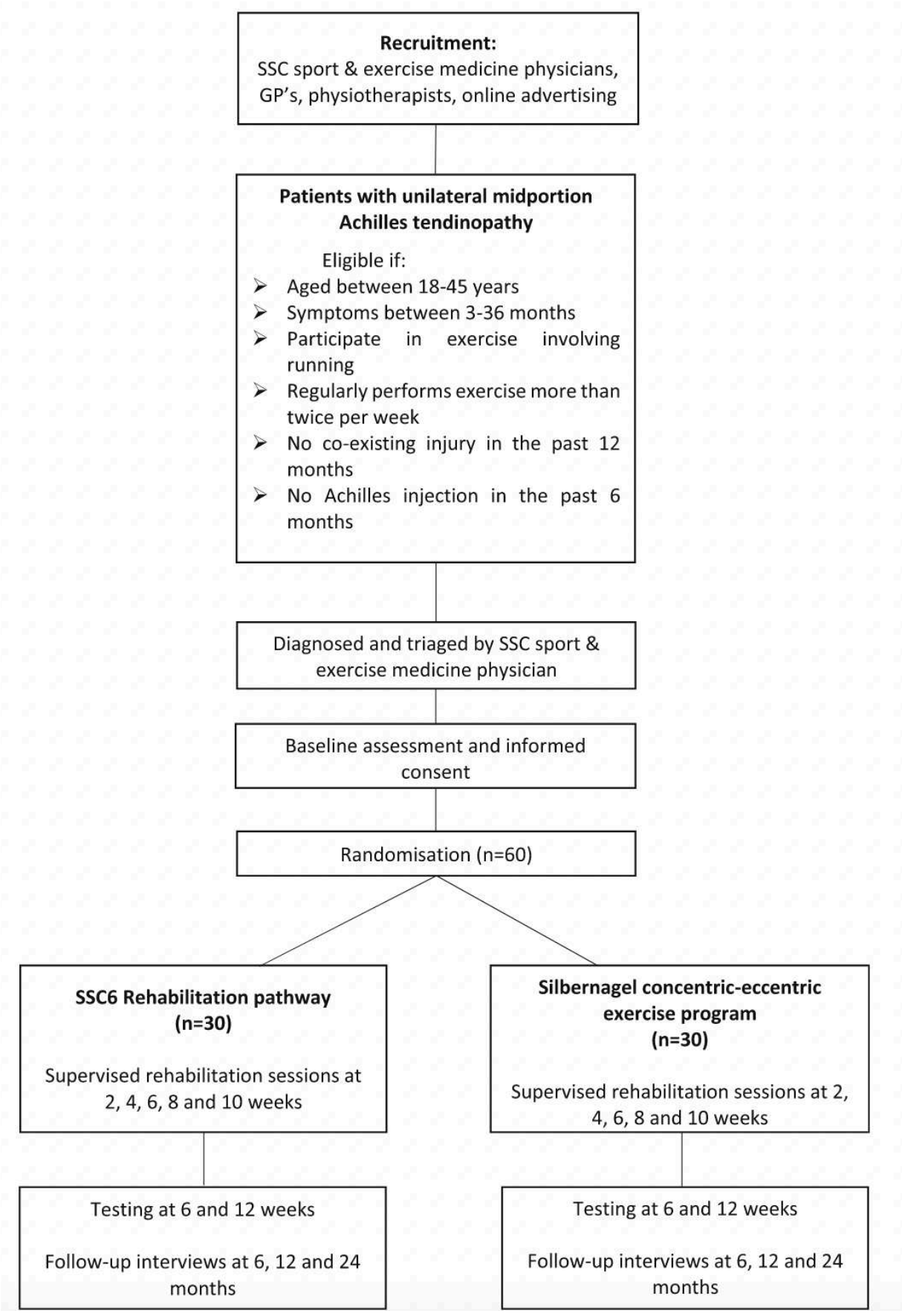


Fig. 4.1.1. Study design flow chart

Two separate protocols will be used for this test. In the first protocol, the participant will lie prone with full knee extension. In the second protocol, the participant will lie supine with 80° knee flexion. When the knee is flexed to greater than 60°, the force contribution of the biarticular gastrocnemius muscles to plantarflexion is reduced and is thus representative of the force produced predominantly by soleus muscle (Arampatzis *et al.*, 2006). If similar PF T_{peak} deficits exist between the two protocols, the identified deficits may thus be attributed to the soleus muscle (O'Neill *et al.,* 2019), which will influence exercise prescription.

The testing will be performed on an IKD (Cybex Norm, Computer Sports Medicine Inc.). In both protocols, the participant will have their foot strapped to a pedal with the centre of axis of rotation aligned with the medial malleolus and a correction for gravity applied. Beginning with their uninjured limb, participants will be asked to perform a warm-up involving 5 sub maximal concentric plantarflexion and dorsiflexion contractions increasing progressively from 60% to 100% of their self-perceived MVC for familiarisation. The participants will then be required to produce a maximal plantarflexion force over 5 repetitions for 2 sets with a 1-minute rest between sets. Verbal encouragement will be provided to produce maximal effort through full range of motion for each repetition. In the second test, the participants will lie in supine position with the knee flexed to 80° in order to specifically test the T_{peak} of the soleus. The same familiarisation protocol, sets and repetitions as the previous test will apply. Both tests will use an angular velocity of 60° per second and operate through an ankle range of between 30° plantarflexion and 20° dorsiflexion. Data will be sampled at 100 and T_{peak} expressed as percentage of body mass (Nm/kg %) will be reported on both limbs. Between-limb asymmetries in T_{peak} will also reported and analysed.

Three-dimensional running gait analysis

Altered running biomechanics and muscle recruitment strategies have been highlighted in runners with AT (Azevedo *et al.*, 2009; Munteanu *et al.*, 2011; Geremia *et al.*, 2015; Ogbonmwan *et al.,* 2018). Using a proprietary three-dimensional optical motion analysis system (Run 3D, Oxford, United Kingdom) the following kinematic and spatiotemporal variables will be measured: contact time, aerial time, stride length, stride frequency and joint angular displacements from initial contact to mid stance phase. Lower limb stiffness will be calculated using a validated equation based on the spring-mass model with running speed, contact time, body mass and leg length as inputs (Morin *et al.*, 2005). The participants will

warm-up by running for between 2-5 minutes on the treadmill at a self-selected speed. Once they report that they are adequately warmed up they will be instructed to run at a speed that they feel they would be comfortable running at a steady pace for 30 minutes. Data will be captured for 30 seconds at a random interval over a 2 minute period and the participants will not be informed about when the data capture begins. For the subsequent tests at weeks 6 and 12, the participants will be required to repeat the same speed for re-analysis.

Hop tests

AT material properties contribute to stretch-shortening cycle performance during hopping and jumping exercises (Kubo *et al.*, 1999; Abdelsattar *et al.,* 2018). Reduced tendon mechanical properties, PF muscle rate of force development and deficits on a single forward hop test have previously been observed in patients with AT (Wang *et al.*, 2012).

The hop tests will take place on two force platforms (AMTI, USA) to measure ground reaction force (GRF) data sampled at 1000 Hz. Ten infrared cameras (200 Hz; Bonita B10/Vero v2.2, Vicon, UK) will be used for three-dimensional motion capture. Reflective markers (14 mm diameter) placed on all relevant anatomical landmarks including the thorax, will be used in accordance with a modified Plug-in-gait model (Vicon, UK) (Marshall *et al.*, 2014), with centre of mass (COM) calculated from all segments. Motion and force data will be filtered using a fourth order zero-lag low pass Butterworth filter with a cut-off frequency of 15 Hz. The data will be exported to MATLAB 2015a (Mathworks, USA) for processing. Participants will perform 3 trials on each test, unshod and with hands placed on iliac crests.

I. Drop jump

Participants will perform both a double leg drop jump (DLDJ) and single leg drop jumps (SLDJ). The participants will complete a standardised warm-up which consists of 10 bodyweight squats, followed by 10 pogo hops in place and 3 familiarisation trials for both. A 30 cm box will be used for the DLDJ and a 20 cm box for the SLDJ. The participant who will be unshod with hands placed on iliac crests, will be required to drop off the box and rebound off the force plate as quickly as possible aiming for maximum jump height. They will be instructed to maintain knee and hip extension during flight phase and where there is visible evidence of knee flexion or a ‘tuck jump’, the trial will be deemed invalid and they will be asked to repeat until a competent trial is achieved. The ground contact phase will be defined by a GRF greater than 20 N and jump height will be calculated from centre of mass

displacement using kinematic data. Reactive strength index (RSI), which is a measure of jump height divided by ground contact time, will be calculated for both the double and single leg drop jump.

II. Single leg hurdle hop

After completing the drop jump tests, participants will be asked to perform a single leg forward hurdle hop test (SLHH). The protocol is detailed in Study 2, but briefly, the test requires that participants to perform a single leg forward hop over two 15-cm hurdles rebounding off the force platform in between, completing 3 trials on each leg. The participants will be instructed to rebound 'as fast as possible' and 'as far as possible', and to attempt to be fully stable on 1 leg upon landing. A video demo of the test is available on this link: https://vimeo.com/725287405. After each trial the participants will walk back slowly to begin the next trial taking approximately 10 seconds recovery time. Hop distance, rebound distance and contact time, as well as key biomechanical variables such as vertical, horizontal and leg ground reaction force, vertical, leg and joint stiffness, joint powers and moments, and joint angular displacements will be calculated using a custom MATLAB script (Mathworks, USA). Hop distance will be calculated as the distance from the initiation of the hop to the initial contact as the participants lands at the end of the hop and rebound distance from the force plate to the landing. Vertical stiffness (K_{vert}) will be calculated at the point of maximum displacement of COM, as the ratio of change in vertical ground reaction force (GRF) to COM displacement:

$$K_{vert} = \Delta Force/\Delta CoM$$

Leg stiffness will be calculated in the sagittal plane as the ratio of change in leg ground reaction force (F_{leg}) to the change in leg length at the shortest leg length during stance phase as previously proposed (Coleman *et al.*, 2012). Leg length is measured as the distance from the hip joint centre to the centre of pressure in the sagittal plane, while F_{leg} is calculated from the resultant GRF magnitude scaled to the leg angle using the trigonometry sine rule.

$$K_{leg} = \Delta F_{leg}/\Delta Leg$$

Joint stiffness (K_{ankle}, K_{knee} and $K_{hip)}$ at the ankle and knee, will be calculated in the sagittal plane as the ratio of change in joint moment to change in joint displacement:

$K_{joint} = \Delta$ moment/Δ angle

A pilot study has previously been carried out on 10 healthy participants prior to the commencement of the Achilles RCT study (Griffin *et al.,* 2018). Good-to-excellent reliability (ICC > 0.75) was found for hop and rebound distance, contact time, knee and ankle joint stiffness, vertical and leg GRF, with moderate reliability (ICC 0.50-0.75) for reactive strength index, vertical and leg stiffness, ankle joint peak power, ankle and knee joint peak moments, and horizontal GRF. In a separate study using the same protocol, 3 trials were sufficient to obtain a stable measure of performance across key variables (Griffin *et al.,* 2018).

Training diary

In order to determine adherence and fidelity with the rehabilitation program and pain response to exercise, each patient will be required to complete a training diary logging their completed running and rehabilitation sessions as well as reporting any pain symptoms using a numerical pain rating scale (NPRS), that will be reviewed at week 6 and returned at week 12. Adherence is defined as the proportion of prescribed exercises completed while fidelity refers to whether the participant completed the prescribed exercises, sets, repetitions and target loads. Participants will be advised to take an extra recovery day between exercise sessions if pain was above 5/10 on the day after a session and to adjust their loads for the subsequent session.

Follow-up interviews

At 6, 12 and 24 months from baseline testing, patients will be required to complete a questionnaire (see Appendix 8) to analyse their participation in their respective sport, document any re-injuries and to obtain patient satisfaction feedback on their respective rehabilitation program. These outcomes will be reported and compared between groups to determine if the rehabilitation program had any significant effect.

Table 4.1.1 Silbernagel's combined concentric-eccentric program

Phase 1: Weeks 1-2

Patient status: Pain and difficulty with all activities, difficulty performing 10 single leg heel raises

Goal: Start to exercise, gain understanding of their injury and of pain monitoring model

Treatment program: Perform exercises every day:

- Pain monitoring model information and advice on exercise activity
- Circulation exercises (moving foot up and down)
- Double leg heel raises standing on the floor (3 x 10-15 repetitions)
- Single leg heel raises standing on the floor (3 x 10)
- Sitting heel raises (3 x 10)
- Eccentric heel raises standing on the floor (3 x 10)

Phase 2: Weeks 2-5

Patient status: Pain with exercise, morning stiffness, pain when performing heel raises

Goal: Start strengthening

Treatment program: Perform exercises every day:

- Double leg heel raises standing on the edge of a step (3 x 15)
- Single leg heel raises standing on the edge of a step (3 x 10)
- Sitting heel raises (3 x 15)
- Eccentric heel raises standing on the edge of a step (3 x 15)
- Quick-rebounding heel raises (3 x 20)

Phase 3: Weeks 3-12 (longer if needed)

Patient status: Tolerates phase 2 exercise program well, no pain at distal portion of tendon, possibly increased or decreased morning stiffness

Goal: Heavier strength training, increase or begin running and/or jumping

Treatment program: Perform exercises every day with heavier load 2-3 times per week

- Single leg heel raises standing on the edge of a step with added weight (3 x 10)
- Sitting heel raises (3 x 15)
- Eccentric heel raises standing on the edge of a step with added weight (3 x 15)
- Quick-rebounding heel raises (3 x 20)
- Plyometric training

Phase 4: Weeks 12- 6 months (longer if needed)

Patient status: Minimal symptoms, morning stiffness but not every day, can participate in sports without difficulty

Goal: Heavier strength training, increase or begin running and/or jumping

Treatment program: Perform exercises every day with heavier load 2-3 times per week

- Single leg heel raises standing on the edge of a step with added weight (3 x 10)
- Eccentric heel raises standing on the edge of a step with added weight (3 x 15)
- Quick-rebounding heel raises (3 x 20)

Table 4.1.2. SSC6 Rehabilitation program

Level 1 *Week 0-3* Entry criteria: Pain >5/10 on SL calf raise	**Kinetic chain** (2 days per week) Box squat 3 x 8 reps @ 10RM Step-up 3 x 8 reps e/s @ 10RM	**Calf Isometrics** (daily) 5 x 45 sec holds @ 60 sec RM)		
Level 2 *Week 0-4* Entry criteria: Pain <5/10 on SL calf raise	**Kinetic chain (2 days per week)** Front squat 4 x 8 reps @ 10RM Or Deadlift 4 x 8 reps @ 10RM Step-up 3 x 8 e/s @ 10RM Or Split squat 3 x 8 reps e/s	**Calf strength** (3 days per week) SL calf raises 4 x 8 reps @ 10RM *~ Begin with dumbbell and shoes off* *~ Aim to through 1st MTPJ and good rearfoot control* Seated SL calf raises 4 x 10 reps @ 12RM *~ Begin with kettlebell on knee and forefoot on a plate*		
Level 3 *Week 3-6* Entry criteria: Pain <4/10 on SL calf raise	**Kinetic chain (2 days per week)** Front squat 4 x 6 reps @ 8RM Or Deadlift 4 x 6 reps @ 8RM Step-up 3 x 6 e/s @ 8RM Or Split squat 3 x 6 each side @ 8RM	**Calf strength** (3 times per week) SL calf raises 4 x 8 reps @ 10RM *~ Progress to a smith machine or barbell using rack for support* *~ Aim for >70% BW* Seated SL calf raises 4 x 10 reps @ 12RM *~ Progress to smith machine or landmine press* *~ Aim for >90% BW*	**Coordination/running technique** Ankling 3 x 10m March 3 x 10m A-skip 3 x 20m	
Level 4 *Week 6-9* Entry criteria: Pain <5/10 for 10 **D**L hops <10% asymmetry in calf IKD tests	**Kinetic chain (2 days per week)** Front squat 4 x 6 reps @ 8RM Or Deadlift 4 x 6 reps @ 8RM Step-up 3 x 6 reps e/s @ 8RM Or Split squat 3 x 6 each side @ 8RM	**Calf strength** (3 times per week) SL calf raises 4 x 8 reps @ 10RM *~ Progress to a smith machine or barbell using rack for support* *~ Aim for >80% BW* Seated SL calf raises 4 x 10 reps @ 12RM *~ Progress to smith machine or landmine press* *~ Aim for >110% BW*	**DL Reactive strength** (2 times per week) DL Pogo hops in-place 4 x 10 (Day 1) *~ Keep knees straight and stiff* *~ Flat foot contacts* *~ Active dorsiflexion during flight phase* DL pogo hops forward 4 x 10 (Day 2) *~ Keep knees straight and stiff* *~ Flat foot contacts* *~ Active dorsiflexion during flight phase*	
Level 5 *Week 9-12* Entry criteria: Pain <4/10 for 10 SL hops Exit criteria: <10% asymmetry in single leg vertical and horizontal RSI	**Kinetic chain (2 days per week)** Front squat 3 x 5 reps @ 7RM Or Deadlift 3 x 5 reps @ 7RM Step-up 3 x 5 reps e/s @ 7RM Or Split squat 3 x 5 each side @ 7RM	**Calf strength** (3 times per week) SL calf eccentric 4 x 8 reps @ 10RM *~ Use a smith machine/leg press/ barbell using rack for support* *~ Up on 2 legs, lower down slowly on 1 over 3 seconds* *~ Aim for >100% BW or equivalent* Seated SL calf raises 4 x 10 reps @ 12RM *~ Progress to smith machine or landmine press* *~ Aim for >110% BW*	**DL Reactive strength** (2 times per week) Drop jump 4 x 4 reps from 20-30cm box *~ Maximum jump height with minimal contact* *~ Minimal knee bend on ground contact* *~ Cue "imagine the floor is hot"*	**SL Reactive strength** (2 times per week) SL pogo hops in-place 4 x 10 e/s (Day 1) SL pogo hops forward 4 x 10 e/s (Day 2)
Level 6 *Week 12-26* Recommended maintenance program	**Kinetic chain (2 days per week)** Front squat 3 x 5 reps @ 7RM Or Deadlift 3 x 5 reps @ 7RM Step-up 3 x 5 reps e/s @ 7RM Or Split squat 3 x 5 each side @ 7RM	**Calf strength** (2 times per week) SL calf isometric 4 x 8 reps x 4 second holds *~ Use a smith machine/leg press/ barbell using rack for support* *~ Up on 2 legs, hold on 1* *~ Aim for >140% BW or equivalent*	**DL Reactive strength** (2 times per week) Drop jump 4 x 5 reps from 20-30cm box	**SL Reactive strength** (2 times per week) SL pogo hops in-place 4 x 12 e/s (Day 1) SL pogo hops forward 4 x 12 e/s (Day 2)

Abbreviations: DL - double leg, SL - single leg, reps - repetitions, e/s - each side, BW - bodyweight, RM - repetition maximum

4.1.5. INTERVENTIONS

Each participant will be prescribed a graded rehabilitation exercise training program which they will perform at home or in a local gym. However, they will present themselves for one supervised session every 2-3 weeks by their respective group investigators to ensure compliance and appropriate progression. The patients following Silbernagel's training program *(Table 4.1.1)* will perform solely calf strength exercises with self-prescribed additional resistance and will progress their exercises based on a NPRS, where there is no greater than a 4/10 pain response during and in the 24 hours following a training session. They will then progress to plyometric exercises as tolerated. The SSC6 group *(Table 4.1.2)* will follow a multifactorial exercise program comprising of bilateral and unilateral kinetic chain strength, calf strength and plyometric training as well as running drills as early as they can tolerate them. Table 4.1.4 highlights the points of difference between to two training interventions. The participants will enter at the highest level where they meet the minimum criteria. For the calf exercises, they will be encouraged to lift a certain percentage of bodyweight in additional resistance and increase weekly. A certain level of pain within tolerable limits will be accepted and participants will be encouraged to increase their resistance loading weekly so long as that pain doesn't increase. Progression to Level 4 of the program will be based on achieving their prescribed exercise load targets and achieving a deficit of less than 10% between injured and uninjured limbs on the IKD strength tests. The reactive strength exercises will be performed at near maximal intensity for a set number of repetitions with good competency and within tolerable pain limits. The participants will progress to Level 5 when they can perform 10 single leg hops with a score of <4/10 on the NPRS and progress from Level 5 when single leg RSI deficits are <10%. Outcome measures will be monitored at the various timepoints and will be tracked according to reported NPRS ratings. In both groups, participants will be permitted to begin running in phase 2 when pain during daily activity is <2/10 but will be advised on periodising their running and rehabilitation exercises throughout the week. Each participant will be provided with a training log in order to monitor training loads. Should an adverse event occur which results in re-injury or a new injury, the participant will be instructed to contact their respective investigator immediately so that they can be examined and their treatment will be adjusted, postponed or discontinued where appropriate. Upon completion of the training intervention, participants in both groups will be given a maintenance training program for 6 months. The design, prescription and reporting of the training intervention meets all of the 16-item checklist requirements in the Consensus on Exercise Reporting Template (CERT) (Slade *et al.*, 2016) which is available in Appendix 10.

4.1.6. STATISTICAL ANALYSIS AND POWER CALCULATION

This study is powered to detect a change of 15 points on the VISA-A questionnaire, similar to previous studies investigating clinical changes after a rehabilitation program (Rompe *et al.,* 2009; Stevens and Tan, 2014). The average reported change in a VISA-A questionnaire after a 12-week intervention is 21 points with a standard deviation 6.6 points (Murphy *et al.*, 2018). Assuming a power of 80% and a two-sided 5% significance level, 25 participants in each group would be required. Allowing for a conservative drop-out rate of 15%, the proposed sample size is 60, with 30 in each group. This number is similar to those used in other high-quality injury rehabilitation RCT studies (Beyer *et al.*, 2015; Mendiguchia *et al.*, 2017).

Statistical analysis will be performed using R (R Studio version 1.2.5). Descriptive statistics will be used for all continuous variables, and means and standard deviations will be reported. Comparisons between both groups at different timepoints will be assessed using Student's independent samples two-tailed t-tests. An intention to treat analysis will be used to test a within-group and between-group change in VISA-A questionnaire score at testing and follow-up timepoints, using a repeated measures Analysis of Covariance (ANCOVA). The primary outcome measure - changes to the VISA-A questionnaire, will the dependent variable, group will the between participants factor and time will be the covariate. Non-parametric equivalents (Matt-Whitney U-Test and Friedman Test respectively) will be used if a Shapiro-Wilk test indicates that the assumption of normality has not been met. A multiple regression analysis will be used to investigate the total variance and the relative weight of each independent variable with changes in VISA-A score as the dependent variable. The independent variables will be changes in PF strength, reactive strength and lower limb biomechanical variables, as well as exercise adherence and fidelity. Effect sizes will be reported using partial eta-squared threshold values of >0.2 (small), >0.5 (moderate), and >0.8 (large). Statistical significance will be accepted at α=0.05.

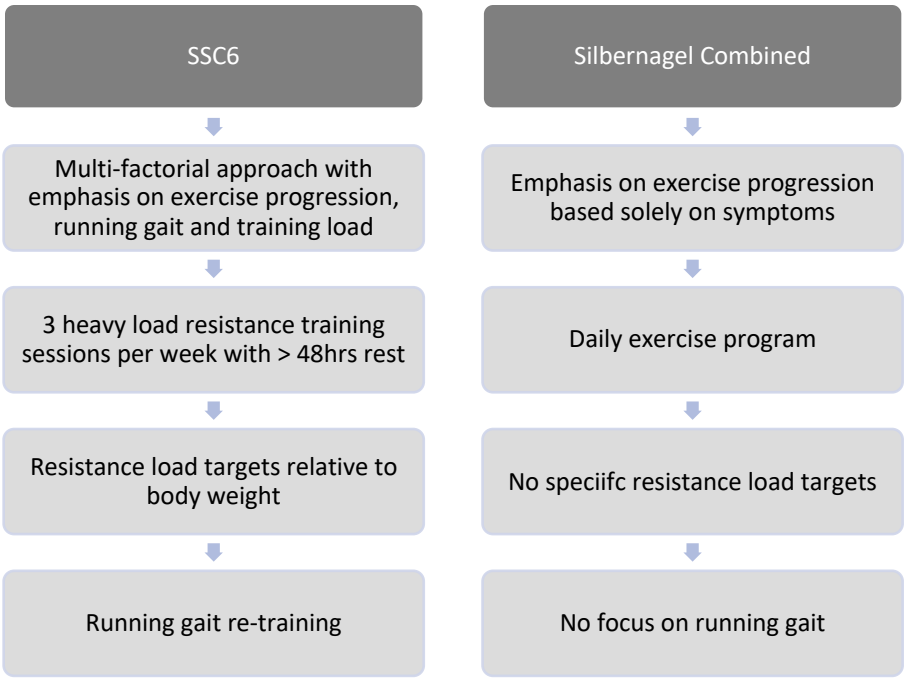
Table 4.1.3. Overview of outcome measures over the course of the study

	Baseline	*Week 6*	*Week 12*	*6 months*	*12 months*	*24 months*
Body mass	X					
Body height	X					
Body mass index	X					
Sport/activity level	X			X	X	X
VISA-A Questionnaire	X	X	X	X	X	X
IKD plantar flexor T_{peak} (knee extension)	X	X	X			
IKD plantar flexor T_{peak} (knee flexion)	X	X	X			
3D running gait analysis	X	X	X			
Double leg drop jump		X	X			
Single leg drop jump		X	X			
Single leg horizontal rebound		X	X			
Exercise compliance		X	X	X		

4.1.7. DISCUSSION

Exercise therapy is widely accepted as the primary treatment option for runners with AT (Kountouris and Cook, 2007; Silbernagel, 2015; Van Der Vlist *et al.*, 2020). Heavy resistance strength exercises targeting the muscle-tendon unit have been shown to increase physiological cross-sectional area and pennation angle in the muscle (Albracht and Arampatzis, 2013) and tendon mechanical and material properties (Bohm *et al.,* 2015; Geremia *et al.*, 2018). This type of loading has resulted in improved clinical outcomes in AT patients (Beyer *et al.*, 2015; Murphy *et al.*, 2018). Plyometric training prepares the muscle tendon unit for high tensile forces and loading rates associated with running based sports (Komi, 1990; Silbernagel, 2015; Baxter *et al.*, 2020). However, there is no clear guidance on how to prescribe and progress the loading for calf strength exercises apart from using pain response to exercise. Only a few studies have investigated running biomechanical features associated with AT with limited evidence for poor control of rearfoot eversion (Donoghue *et al.*, 2008; Munteanu *et al.*, 2011) and reduced leg stiffness on the injured limb (Maquirriain, 2012).

Table 4.1.4. SSC6 Versus Silbernagel's rehabilitation program



An acceptable level of pain symptoms are permitted during AT rehabilitation (Silbernagel *et al.*, 2007a; Cook and Purdam, 2014) and it remains to be explored if a primary focus on achieving strength, reactive strength and biomechanical targets can lead to similar outcomes in reduced timeframes and with lower re-injury rates. This is the first study to propose an individualised, criteria-based graded rehabilitation program in patients in with chronic mid-portion Achilles tendinopathy where progression is guided by strength and reactive strength outcome measures within tolerable pain limits. The participants in our study will undertake a comprehensive assessment of kinematic and kinetic tests to investigate PF strength, reactive strength and lower limb biomechanical variables in hopping and running. We will perform long term evaluations at evaluations at 6, 12 and 24 months to monitor progress, re-injury incidences and sustainability of return to sport and investigate patient satisfaction with their respective rehabilitation exercise programs.

Our study will include a sample of participants who practise running-based sports and are of a particular age profile (age 18-45), have had no injection therapies in the previous 6 months and no co-existing lower limb injuries. Like most studies of similar design, there is a high risk of drop-outs, poor compliance with the respective programs and failure to respond to the follow-

up questionnaires. This will be managed by aiming for a higher number of participants than the study is powered for and maintaining regular communication with the participants.

In summary, this two-arm RCT will compare the effectiveness of a criteria-based rehabilitation program with progression guided by achieving functional outcome measures with an evidenced-based program where progression is guided solely by pain symptoms. The results of this study will provide insights as to whether improved strength, reactive strength and lower limb biomechanics are associated with reduced pain in patients with chronic mid-portion AT and assist clinicians treating this injury to set objective criteria to progress rehabilitation and return to sport.

Trial Status

Recruitment for the trial started in January 2020 and it is anticipated that data collection will be completed in April 2023. As of December 23rd 2022, 28 participants have been included.

4.2. STUDY 4. A CRITERIA-BASED REHABILITATION PROGRAM FOR CHRONIC MID-PORTION ACHILLES TENDINOPATHY: PRELIMINARY RESULTS OF A RANDOMISED CONTROLLED TRIAL

4.2.1. RESULTS

4.2.1.1. Covid-19 pandemic

Recruitment for this study began in January 2020, and seven eligible participants entered the study within the first four weeks. However, the beginning of 2020 saw the emergence of the covid-19 virus, which quickly escalated worldwide. By the middle of March 2020, the virus had firmly taken hold in Ireland, and the government introduced restrictions to contain its spread. These restrictions included the provision of non-essential healthcare and research activities. The Irish public healthcare body - the Health Service Executive (HSE), took control of all private hospitals to support the public health system and to be ready in the case of a national emergency. This contract lasted three months, from the end of March until June 2020. As a result, data collection for the RCT paused during this period and resumed in July 2020. Throughout the remainder of 2020 and 2021, government restrictions of different levels remained in place, which prohibited travelling outside of a 5-km zone, or at lower levels of restrictions, outside of their county boundaries. There were periods when covid-19 cases were extraordinarily high, and people were afraid to travel for fear of contracting the virus. This study was powered for a sample size of 50, with 25 in each group, to detect a significant between-group difference in VISA-A questionnaire outcomes.

4.2.1.2. Recruitment

By the end of November 2022, 28 participants had completed the 12-week program *(Fig. 4.2.1)*. There were sixteen participants in the SSC6 group (34.4 ±7.6 years; 13 males and three females) and 12 in SG (36.8 ±5.7 years; 9 males and three females). The demographic profile and baseline profile of the participants are outlined in Table 4.2.1. Participants were recruited externally through social media advertising and “word of mouth” or as internal patients of the SSC. The investigator contacted participants who reported Achilles pain and expressed interest in being part of the study to cross-check their symptoms and injury history against the inclusion criteria. The interested participants used a pain map provided by the investigator to highlight the location of their symptoms to ensure that there would be a high chance of a positive diagnosis and confirm eligibility. All patients had their diagnosis confirmed by an MRI scan and a clinical examination by a sport and exercise medicine physician at the SSC. All patients,

whether externally recruited or existing patients of the SSC, were required to pay for their MRI scan and the physician's consultation fee. After that, upon entry to the study, all testing and rehabilitation sessions were provided free of charge. Eligible patients were then booked into the lab for their baseline testing and subsequently randomised into their training group following the completion of testing. The assessments, blinding, and randomisation procedures are detailed in Study 4.1. Briefly, running gait and ankle IKD testing using both a straight knee and bent knee protocol at IKD speeds of 60°/sec were performed at baseline and repeated at weeks 6 and 12 with the addition of hop testing. The hop testing involved a double-leg drop jump (DLDJ), a single-leg drop jump (SLDJ) and a single-leg horizontal rebound hop (SLHH). The order of testing remained consistent for each participant at each testing interval, as did the self-selected running speed. The VISA-A questionnaire, the primary outcome measure, was completed at each testing session. Each patient was prescribed a rehabilitation program through an in-house exercise app and advised to log details of each training session conducted on the app. Patients were encouraged to maintain their regular running program as symptoms permitted, and two participants – one in each group, completed a marathon between weeks 6-12 of the program.

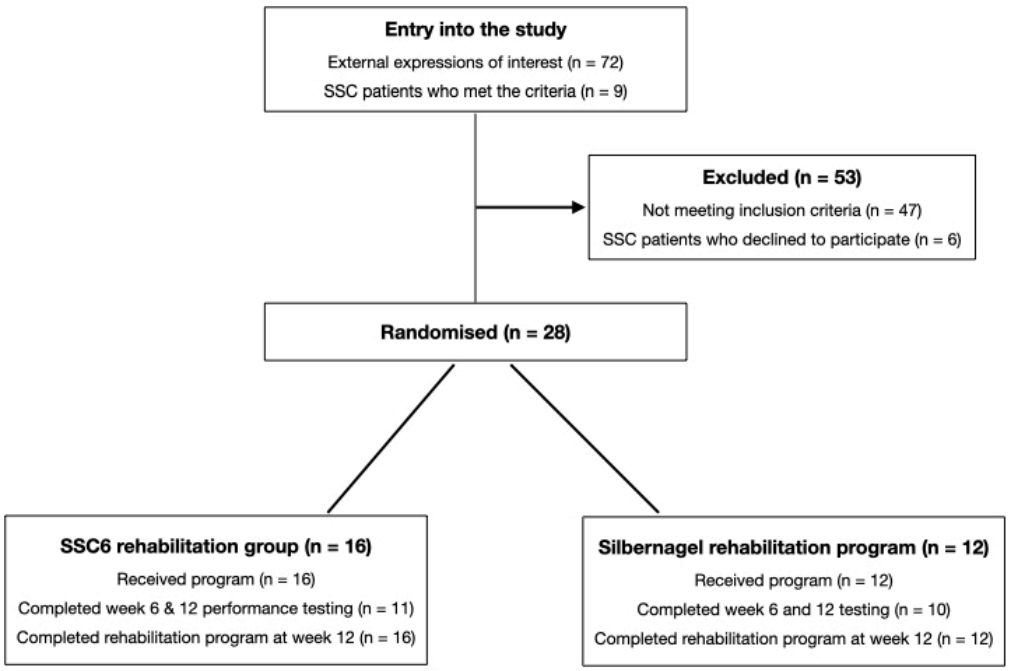


Fig. 4.2.1. Flowchart illustrating the recruitment and group allocation of participants

The seven participants in the study in March 2020 could not complete week 12 testing, with only four able to perform week six testing before the lab closed. This number of omissions from the overall sample size weakened the interpretation of findings for the IKD and hop tests, as well as running biomechanical analysis. The seven patients continued to perform their rehabilitation program for the remainder of the 12 weeks and were asked to complete a VISA-A questionnaire via email at weeks 6 and 12, respectively. With the closure of gyms for several months, and prolonged periods of restricted access, many patients had to perform their rehabilitation program at home with limited equipment. These restrictions would have less impact on the SG protocol as the exercises are more suited to performing at home. However, the SSC6 program required access to weight training equipment – particularly a smith machine to perform heavy-loaded calf exercises.

Table 4.2.1. Demographic profile and baseline characteristics of participants in each group

	SSC6 (n = 16)	***SG (n = 12)***
Age (y)	34.4 ±7.6	36.8 ±5.7
Gender		
Males	13	9
Females	3	3
Body mass (kg)	78.5 ±9.7	75.3 ±12.4
Height (cm)	176.3 ±6.4	176.7 ±7.5
BMI (kg/m^2)	25.3 ±3.0	23.9 ±3.5
Unilateral symptoms (n)	14	9
Bilateral symptoms (n)	2	3
Sport (days per week)	5.4	4.8
Sport (n)		
Track and field athletics	3	2
Distance running	7	7
Gaelic football	3	3
Hurling	2	0
Rugby	1	0
Number of years participating in their sport	17.7 ±7.7	11.8 ±6.4
Duration of symptoms (months)	20.5 ±10.5	17.5 ±7.3
VISA-A	66.4 ±18.8	71.2 ±17.3
PF peak torque KE (% BM)		
Injured leg	109.0 ±25.9	114.3 ±21.1
Uninjured leg	111.6 ±25.4	118.8 ±25.6
PF peak torque KF (%BM)		
Injured leg	95.9 ±23.3	101.6 ±17.6
Uninjured leg	97.2 ±22.4	109.4 ±20.7

4.2.1.3. VISA-A questionnaire

Both groups achieved clinically meaningful changes in their VISA-A scores of 26.27 ±13.71 ($p < 0.001$, ES: 1.78, 95% CI: 0.92, 2.58) for the SSC group and 18.64 ±12.77 (p = 0.007; ES: 1.16; 95% CI: 0.30, 2.03), for SG respectively *(Fig. 4.2.2)*. However, we detected a non-significant medium effect for between-group differences of 9.80 points (p = 0.008; ES: 0.67; 95% CI: -0.10, 1.44). Both groups demonstrated significant changes with large effect sizes in the first six weeks of 19.00 ±12.32 points for SSC6 (p = 0.002; ES 1.28; 95% CI: 0.48, 2.02) and 12.39 ±8.91 points for SG (p = 0.046; ES 0.86; 95% CI: 0.00, 1.66). Similarly, the between-group differences in the first six weeks were non-significant (p = 0.10; ES: 0.63; 95% CI: -0.14,1.40).

4.2.1.4. Performance tests

Both groups experienced minor improvements in T_{peak} values from baseline to week 12 for all tests across both limbs. Large effects with significance were revealed for changes in PF T_{peak} in knee flexion for the injured ($p = 0.05$; ES: 0.95; 95% CI: -0.01, 1.83) and uninjured ($p = 0.04$; ES: 0.97; 95% CI: 0.01, 1.85) leg for SSC6 from week 0-12. However, the between group changes were not significant. LSI was measured but remained between 90-110% for each leg on both testing protocols. Twenty-one participants (SSC: n = 11; SG: n = 10) successfully completed both week 6 hop testing and twenty (SSC: n = 11, SG: n = 9) at week 12. The only significant within-group change was for contact time for SG uninjured group ($p = 0.03$; ES: -1.02; 95% CI: -0.06, -1.0) in the SLDJ, with no other significant changes within and between groups for performance or biomechanical features. The only significant within-group changes in running biomechanical features in the SSC6 group were for flight time on the injured leg from week 0-6 ($p = 0.04$; ES: 0.74; 95% CI: 0.01, 1.47), leg stiffness on the uninjured leg ($p = 0.03$; ES: 0.79; 95% CI: 0.06, 1.52) week 0-6, and for the SG group, maximal hip adduction on the injured leg ($p = 0.03$; ES: 0.94; 95% CI: 0.06, 1.82) from week 0-12, with no significant between-group differences. The changes in VISA-A scores, PF strength and hop performance are summarised in Table 4.2.2, while hop biomechanical features are summarised in Table 4.2.3 and running biomechanical features in Table 4.2.4.

4.2.1.5. Adherence and fidelity

The participants were asked to log their completed rehabilitation sessions in the exercise app containing their program, including sets, reps, and load lifted for each session. The investigator reviewed each participant's logged training sessions after 12 weeks and assessed adherence

and fidelity to the program. The SSC6 group achieved an adherence level of 82.12% ±12.41 with 73.26% ±13.94 for SG. Adherence rates above 70% were deemed satisfactory, consistent with previous studies (Sancho *et al.*, 2019), which both groups surpassed. Fidelity rates were 72.85% ± 17.53 for SSC6 and 67.87% ±14.59 for SG.

The patients were asked to provide feedback and describe their programs' positive and negative aspects. The feedback was mainly positive, with some highlighting their improved knowledge about the injury and how to manage it.

> *"Learning where I have weaknesses; Gaining an understanding of the specific benefits of certain exercises and which particular areas they target; Improving or correcting my technique for certain exercises that I had been doing"* (SSC6, Participant #4)

> *"Daily programme and follow up really made a difference in making sure rehab was undertaken consistently and correctly."* (SG, Participant #6)

Some participants found the SG program challenging to sustain on a daily basis:

> *"Finding time each day was a challenge; Staying motivated each day to perform rehab/prehab is also hard for me when I prefer to be active outdoors"* (SG, Participant #2)

Some participants in the SSC group found it difficult to fully adhere to the program due to the gyms being closed during their 12-week program:

> *"Covid got in the way a lot and closing of gyms didn't help."* (SSC6, Participant #5)

Table 4.2.2. VISA-A scores, plantar flexor isokinetic strength and performance features from double leg drop jump, single leg drop jump and single leg horizontal rebound tests for participants in each group and statistical analysis

	Group	*Baseline*	*6 weeks*	*Δ week 0-6 in raw units*	*Within group statistics, p-value, ES (95% CI)*	*Between group statistics p-value, ES (95% CI)*
VISA-A	SSC6	66.40 ±17.76	84.4 ±11.4	19.00 ±12.32	$p < 0.01$**; ES: 1.28 (0.48, 2.02)	
	SG	71.00 ±17.13	83.33 ±11.3	12.33 ±8.91	$p = 0.05$*; ES: 0.86 (0.00, 1.66)	$p = 0.10$; ES: 0.63 (-0.14, 1.40)
PF peak torque KE (% BM)						
Injured leg	SSC6	109.0 ±25.9	114.0 ±18.7	5.0 ±14.1	$p = 0.49$; ES: 0.27 (-0.50, 1.04)	NS
Uninjured leg		111.6 ±25.4	117.7 ±19.9	6.1 ±17.8	$p = 0.45$; ES: 0.29 (-0.48, 1.06)	NS
LSI (%)		98.4 ±13.2	97.2 ±8.3			
Injured leg	SG	114.3 ±21.1	113.4 ±20.7	-0.9 ±20.2	NS	
Uninjured leg		118.8 ±25.6	124.1 ±23.6	5.3 ±16.1	$p = 0.62$; ES: 0.21 (-0.63, 1.05)	
LSI (%)		99.5 ±17.7	93.2 ±9.1			
PF peak torque KF (% BM)						
Injured leg	SSC6	95.9 ±23.3	109.5 ±25.2	15.6 ±17.6	$p = 0.14$; ES: 0.58 (-0.21, 1.36)	$p = 0.59$; ES: 0.26 (-0.69, 1.18)
Uninjured leg		97.2 ±22.4	105.4 ±20.8	9.2 ±20.7	$p = 0.34$; ES: 0.37 (-0.40, 1.15)	$p = 0.16$; ES: 0.70 (0.01, 1.85)
LSI (%)		100.6 ±15.5	104.0 ±10.9			
Injured leg	SG	101.6 ±23.7	114.4 ±22.9	12.8 ±10.2	$p = 0.27$; ES: 0.47 (-0.38, 1.31)	
Uninjured leg		109.4 ±25.1	117.4 ±20.1	8.0 ±14.3	NS	
LSI (%)		93.1 ±14.3	97.8 ±10.2			
DLDJ						
Jump height (cm)	SSC6	-	21.49 ±6.77	-	-	-
	SG	-	19.97 ±5.79	-	-	-
Contact time (s)	SSC6	-	0.27 ±0.07	-	-	-
	SG	-	0.27 ±0.04	-	-	-
RSI (m/s)	SSC6	-	0.85 ±0.35	-	-	-
	SG	-	0.77 ±0.29	-	-	-
SLDJ						
Jump height (cm)						
Injured leg	SSC6	-	9.76 ±3.49	-	-	-
Uninjured leg		-	10.87 ±3.88	-	-	-

LSI (%)		-	84.8 ±21.50	-	-	-
Injured leg	SG	-	9.06 ±5.03	-	-	-
Uninjured leg		-	9.32 ±3.39	-	-	-
LSI (%)		-	96.32 ±26.8	-	-	-
Contact time (s)						
Injured leg	SSC6	-	0.36 ±0.07	-	-	-
Uninjured leg		-	0.35 ±0.07	-	-	-
LSI (%)		-	89.9 ±11.6	-	-	-
Injured leg	SG	-	0.37 ±0.04	-	-	-
Uninjured leg		-	0.36 ±0.04	-	-	-
LSI (%)		-	98.6 ±11.4	-	-	-
RSI (m/s)						
Injured leg	SSC6	-	0.29 ±0.14	-	-	-
Uninjured leg		-	0.33 ±0.13	-	-	-
LSI (%)		-	93.1 ±11.8	-	-	-
Injured leg	SG	-	0.26 ±0.14	-	-	-
Uninjured leg		-	0.27 ±0.12	-	-	-
LSI (%)		-	98.8 ±18.1	-	-	-
SLHH						
Rebound distance (cm)						
Injured leg	SSC6	-	123.28 ±20.1	-	-	-
Uninjured leg		-	128.77 ±18.7	-	-	-
LSI (%)		-	95.7 ±10.1	-	-	-
Injured leg	SG	-	118.54 ±31.6	-	-	-
Uninjured leg		-	128.21 ±28.5	-	-	-
LSI (%)			92.5 ±7.1			
Contact time (s)						
Injured leg	SSC6	-	0.36 ±0.12	-	-	-
Uninjured leg		-	0.34 ±0.09	-	-	-
LSI (%)		-	105.9 ±9.5	-	-	-

Injured leg	SG	-	0.33 ±0.07	-	-	-
Uninjured leg		-	0.33 ±0.05	-	-	-
LSI (%)			101.1 ±17.6			
RSI (m/s)						
Injured leg	SSC6	-	3.98 ±1.44	-	-	-
Uninjured leg		-	4.18 ±1.47	-	-	-
LSI (%)		-	95.2 ±15.13	-	-	-
Injured leg	SG	-	3.81 ±1.46	-	-	-
Uninjured leg		-	4.14 ±1.21	-	-	-
LSI (%)		-	93.7 ±15.87	-	-	-

Notes:
SSC6: SSC6 training group; SG: Silbernagel group; PF: plantar flexor; KE: knee extended; BM: body mass; KF: knee flexed; LSI: limb symmetry index; DJDJ: double-leg drop jump; RSI: reactive strength index; SLDJ: single-leg drop jump; SLHH: single-leg horizontal rebound hop; ES: effect size; NS: non-significant
Cohen's d effect sizes are used for within group effects. Hedges' g effect sizes are used for between group effects where there are differences in sample size.
Effect sizes are reported where values are >0.2
* Significant ($p < 0.05$); ** Significant ($p < 0.01$)

	Group	Week 12	Δ week 6-12	Within group statistics, p-value, ES (95% CI)	Between group statistics, p-value, ES (95% CI)	Δ week 0-12 in raw units	Within group statistics, p-value, ES (95% CI)	Between group statistics p-value, ES (95% CI)
VISA-A	SSC6	90.4 ±9.85	6.60 ±8.98	*p* = 0.09; ES: 0.62; (-0.11, 1.33)		25.60 ±13.71	*p* < 0.001**; ES: 1.80 (0.92, 2.58)	
	SG	87.67 ±9.47	5.36 ±5.70	*p* = 0.31; ES: 0.43; (-0.40, 1.22)	*p* = 0.44; ES: 0.29 (-0.46, 1.04)	16.47 ±12.77	*p* = 0.01**; ES: 1.20 (0.30, 2.03)	p = 0.08; ES: 0.67 (-0.10, 1.44)
PF peak torque KE (% BM)								
Injured leg	SSC6	116.8 ±22.5	2.8 ±8.2	NS	NS	7.8 ±19.9	*p* = 0.42; ES: 0.35 (-0.53, 1.24)	NS
Uninjured leg		119.6 ±22.3	1.9 ±9.4	NS	NS	8.0 ±16.5	*p* = 0.41; ES: 0.36 (-0.52, 1.25)	NS
LSI (%)		98.2 ±11.5						
Injured leg	SG	119.5 ±20.9	8.0 ±20.7	*p* = 0.50; ES: 0.29 (-0.57, 1.15)	NS	11.4 ±16.6	*p* = 0.55; ES: 0.25 (-0.61, 1.11)	NS
Uninjured leg		121.8 ±21.5	2.2 ±11.5	NS	NS	11.4 ±12.4	*p* = 0.49; ES: 0.29 (-0.57, 1.15)	NS
LSI (%)		97.8 ±10.7						
PF peak torque KF (% BM)								
Injured leg	SSC6	117.8 ±25.1	8.3 ±17.0	*p* = 0.49; ES: 0.31 (-0.58, 1.19)	NS	21.9 ±22.0	*p* = 0.05*; ES: 0.95 (-0.01, 1.83)	*p* = 0.59; ES: 0.26 (-0.69, 1.18)
Uninjured leg		117.3 ±18.6	11.9 ±16.3	*p* = 0.19; ES: 0.59 (-0.31, 1.49)	NS	21.1 ±21.7	*p* = 0.04*; ES: 0.97 (0.01, 1.85)	*p* = 0.16; ES: 0.70 (0.01, 1.85)
LSI (%)		100.1 ±10.8						
Injured leg	SG	118.8 ±24.3	4.4 ±12.5	*NS*	NS	17.2 ±9.8	NS	
Uninjured leg		117.6 ±21.0	0.2 ±6.8	*NS*	NS	8.2 ±17.7	NS	
LSI (%)		101.7 ±17.0						
DLDJ								
Jump height (cm)	SSC6	22.44 ±4.46	0.95	NS	NS	-	-	-
	SG	19.72 ±4.93	-0.02	NS	NS	-	-	-
Contact time (s)	SSC6	0.28 ±0.07	0.01	NS	NS	-	-	-
	SG	0.28 ±0.04	-0.01	NS	NS	-	-	-
RSI (m/s)	SSC6	0.85 ±0.20	0.00	NS	NS	-	-	-
	SG	0.79 ±0.33	0.02	NS	NS	-	-	-
SLDJ								
Jump height (cm)								
Injured leg	SSC6	10.45 ±3.22	0.75	NS	NS	-	-	-
Uninjured leg		11.01 ±3.25	0.14	*NS*	NS	-	-	-
LSI (%)		94.9 ±27.4				-	-	-
Injured leg	SG	9.01 ±4.14	-0.05	NS	NS	-	-	-
Uninjured leg		8.80 ±4.01	-0.52	NS	NS	-	-	-
LSI (%)		102.4 ±21.9				-	-	-

Contact time (s)								
Injured leg	SSC6	0.33 ±0.06	-0.03	NS	NS	-	-	-
Uninjured leg		0.28 ±0.07	-0.07	*p* = 0.03*; ES: -1.02 (-0.06, -1.0)	NS	-	-	-
LSI (%)		117.9 ±12.2				-	-	-
Injured leg	SG	0.34 ±0.04	-0.03	NS; ES: -0.71 (-1.69, 0.27)	NS	-	-	-
Uninjured leg		0.34 ±0.05	-0.02	NS	NS	-	-	-
LSI (%)		99.8 ±10.7				-	-	-
RSI (m/s)								
Injured leg	SSC6	0.33 ±0.12	0.04	NS	NS	-	-	-
Uninjured leg		0.34 ±0.13	0.01	NS	NS	-	-	-
LSI (%)		97.2 ±19.5				-	-	-
Injured leg	SG	0.28 ±0.17	0.02	NS	NS	-	-	-
Uninjured leg		0.27 ±0.15	0.00	NS	NS	-	-	-
LSI (%)		103.7 ±13.8				-	-	-
SLHH								
Rebound distance (cm)								
Injured leg	SSC6	125.02 ±23.82	1.64	NS	NS	-	-	-
Uninjured leg		120.31 ±32.95	-8.46	*NS*	NS	-	-	-
LSI (%)		103.9 ±5.2				-	-	-
Injured leg	SG	115.32 ±20.01	-3.22	NS	NS	-	-	-
Uninjured leg		121.14 ±21.86	-7.07	NS	NS	-	-	-
LSI (%)		95.2 ±14.7						
Contact time (s)								
Injured leg	SSC6	0.30 ±0.05	-0.06	NS	NS	-	-	-
Uninjured leg		0.30 ±0.05	-0.04	NS	NS	-	-	-
LSI (%)		99.9 ±5.0				-	-	-
Injured leg	SG	0.32 ±0.06	-0.01	NS	NS	-	-	-
Uninjured leg		0.32 ±0.07	-0.01	NS	NS	-	-	-
LSI (%)		99.8 ±12.6						
RSI (m/s)								
Injured leg	SSC6	4.35 ±1.16	0.37	NS	NS	-	-	-
Uninjured leg		4.14 ±1.47	-0.04	NS	NS	-	-	-
LSI (%)		105.1 ±6.1				-	-	-
Injured leg	SG	3.71 ±0.93	-0.10	NS	NS	-	-	-
Uninjured leg		4.00 ±1.0	-0.14	NS	NS	-	-	-
LSI (%)		92.8 ±17.9				-	-	-

Notes:
SSC6: SSC6 training group; SG: Silbernagel group; PF: plantar flexor; KE: knee extended; BM: body mass; KF: knee flexed; LSI: limb symmetry index; DJDJ: double-leg drop jump; RSI: reactive strength index; SLDJ: single-leg drop jump; SLHH: single-leg horizontal rebound hop; ES: effect size; NS: non-significant
Hedges' g effect sizes are used for between group effects where there are differences in sample size.
Effect sizes are reported where values are >0.2
* Significant ($p < 0.05$), ** Significant ($p < 0.01$)

Table 4.2.3. Biomechanical features and statistical analysis for single-leg drop jump and single-leg horizontal rebound test in weeks 6 and 12

	Group	*Week 6*	*Week 12*	*Δ week 6-12*	*Within group statistics, p-value, ES (95% CI)*	*Between group statistics, p-value, ES (95% CI)*
SLDJ						
Vertical stiffness (kN/m)						
Injured leg	SSC6	12.59 ±3.09	13.46 ±2.96	0.87	NS	NS
Uninjured leg		12.68 ±2.96	13.13 ±3.72	*0.45*	NS	NS
Injured leg	SG	12.71 ±3.38	14.29 ±3.49	1.58	NS	NS
Uninjured leg		13.00 ±3.63	14.52 ±3.78	1.52	NS	NS
Leg stiffness (kN/m)						
Injured leg	SSC6	12.05 ±2.88	12.87 ±2.89	0.82	NS	NS
Uninjured leg		12.36 ±2.44	12.95 ±3.55	0.59	NS	NS
Injured leg	SG	12.43 ±3.14	13.53 ±3.22	1.10	NS	NS
Uninjured leg		12.66 ±3.67	13.53 ±3.49	0.87	NS	NS
Ankle joint stiffness (N·mm/deg)						
Injured leg	SSC6	68.43 ±18.29	76.39 ±19.32	7.96	NS	NS
Uninjured leg		75.08 ±17.32	79.50 ±23.18	4.42	NS	NS
Injured leg	SG	61.41 ±13.23	69.86 ±14.99	8.45	NS; ES: 0.57 (-0.40, 1.54)	NS
Uninjured leg		68.56 ±14.77	74.14 ±21.19	5.58	NS	NS
Knee joint stiffness (N·mm/deg)						
Injured leg	SSC6	78.41 ±33.6	95.25 ±32.15	16.84	NS; ES: 0.50 (-0.43, 1.40)	NS
Uninjured leg		83.04 ±30.2	99.77 ±33.59	18.73	NS; ES: 0.51 (-0.41, 1.42)	NS
Injured leg	SG	68.82 ±27.71	99.42 ±44.16	30.62	NS; ES: 0.80 (-0.19, 1.79)	NS
Uninjured leg		61.42 ±25.11	91.01 ±32.95	29.59	NS; ES: 0.97 (-0.04, 1.97)	NS
Ankle peak joint power (W/kg)						
Injured leg	SSC6	14.22 ±3.09	15.37 ±4.16	1.15	NS	NS
Uninjured leg		15.91 ±3.67	15.57 ±4.16	-0.34	NS	NS
Injured leg	SG	13.81 ±3.31	13.39 ±4.53	-0.42	NS	NS
Uninjured leg		13.28 ±2.28	14.07 ±3.84	0.79	NS	NS
Knee peak joint power (W/kg)						
Injured leg	SSC6	8.04 ±2.56	8.93 ±3.07	0.89	NS	NS
Uninjured leg		8.03 ±3.18	8.58 ±4.25	0.55	NS	NS
Injured leg	SG	7.54 ±2.56	8.21 ±2.74	0.67	NS	NS
Uninjured leg		7.25 ±2.23	8.75 ±2.02	1.50	NS; ES: 0.67 (-0.31, 1.65)	NS

Hip peak joint power (W/kg)						
Injured leg	SSC6	5.44 ±2.49	4.92 ±2.17	-0.52	NS	NS
Uninjured leg		4.92 ±2.42	6.54 ±4.88	1.62	NS	NS
Injured leg	SG	5.64 ±1.74	5.57 ±3.79	-0.07	NS	NS
Uninjured leg		5.25 ±1.69	5.17 ±2.53	-0.08	NS	NS

	Group	***Week 6***	***Week 12***	***Δ week 6-12***	***Within group statistics, p-value, ES (95% CI)***	***Between group statistics, p-value, ES (95% CI)***
SLHH						
Vertical stiffness (kN/m)						
Injured leg	SSC6	16.11 ±4.45	17.97 ±5.76	1.86	NS	NS
Uninjured leg		15.90 ±4.69	17.25 ±5.09	*1.35*	NS	NS
Injured leg	SG	17.09 ±4.83	16.80 ±5.68	-0.29	NS	NS
Uninjured leg		17.61 ±6.07	17.72 ±6.95	0.11	NS	NS
Leg stiffness (kN/m)						
Injured leg	SSC6	11.77 ±3.12	13.75 ±3.85	1.98	NS; ES: 0.54 (-0.35, 1.43)	NS
Uninjured leg		12.50 ±3.87	13.29 ±3.73	0.79	NS	NS
Injured leg	SG	11.96 ±4.33	12.55 ±4.47	0.59	NS	NS
Uninjured leg		13.42 ±5.52	13.33 ±5.95	-0.09	NS	NS
Ankle joint stiffness (N·mm/deg)						
Injured leg	SSC6	70.41 ±22.69	79.76 ±24.39	9.35	NS	NS
Uninjured leg		82.55 ±30.19	92.29 ±21.59	10.74	NS	NS
Injured leg	SG	78.67 ±43.01	76.72 ±30.41	-1.95	NS	NS
Uninjured leg		84.85 ±41.29	86.93 ±41.29	2.08	NS	NS
Knee joint stiffness (N·mm/deg)						
Injured leg	SSC6	142.28 ±68.02	162.40 ±91.73	20.12	NS	NS
Uninjured leg		141.32 ±75.69	164.24 ±83.36	22.92	NS	NS
Injured leg	SG	129.35 ±73.50	136.32 ±83.33	6.97	NS	NS
Uninjured leg		127.59 ±86.81	182.93 ±117.20	55.34	NS; ES: 0.51 (-0.45, 1.48)	NS

Ankle peak joint power (W/kg)						
Injured leg	SSC6	16.82 ±3.68	16.93 ±3.85	0.11	NS	NS
Uninjured leg		17.61 ±3.95	15.47 ±6.67	-2.14	NS	NS
Injured leg	SG	14.95 ±3.06	12.62 ±5.08	-2.33	NS; ES: -0.54 (-1.5, 0.43)	NS
Uninjured leg		15.96 ±3.69	13.45 ±5.84	-2.51	NS	NS
Knee peak joint power (W/kg)						
Injured leg	SSC6	7.69 ±3.01	8.27 ±3.64	0.58	NS	NS
Uninjured leg		7.81 ±3.75	7.51 ±3.71	-0.30	NS	NS
Injured leg	SG	7.40 ±2.55	6.61 ±3.31	-0.79	NS	NS
Uninjured leg		7.56 ±2.67	7.20 ±2.92	-0.36	NS	NS
Hip peak joint power (W/kg)						
Injured leg	SSC6	7.25 ±1.73	9.17 ±3.21	1.92	NS; ES: 0.69 (-0.29, 1.67)	NS
Uninjured leg		7.63 ±2.91	8.70 ±3.19	1.07	NS	NS
Injured leg	SG	10.42 ±5.94	8.87 ±3.61	-1.55	NS	NS
Uninjured leg		10.38 ±5.86	10.20 ±6.22	-0.18	NS	NS

Notes:
SSC6: SSC6 training group; SG: Silbernagel group; PF: plantar flexor; KE: knee extended; BM: body mass; KF: knee flexed; LSI: limb symmetry index; DJDJ: double-leg drop jump; RSI: reactive strength index; SLDJ: single-leg drop jump; SLHH: single-leg horizontal rebound hop; ES: effect size; NS: non-significant
Hedges' g effect sizes are used for between group effects where there are differences in sample size.
Effect sizes are reported where values are >0.5
* Significant ($p < 0.05$), ** Significant ($p < 0.01$)

Table 4.2.4 Running biomechanical features and statistical analysis

Biomechanical features	**Group**	**Baseline**	**Week 6**	**Δ 0-6 weeks**	**Within group statistics, p-value, ES (95% CI)**	**Week 12**	**Δ 6-12 weeks**	**Within group statistics, p-value, ES (95% CI)**	**Δ 0-12 weeks**	**Within group statistics, p-value, ES (95% CI)**
Contact time (s)										
Injured leg	SSC6	0.277 ±0.04	0.272 ±0.03	-0.005	NS	0.272 ±0.04	-0.000	NS	-0.005	NS
Uninjured leg		0.278 ±0.04	0.267 ±0.03	-0.011	NS	0.276 ±0.04	0.009	NS	-0.002	NS
Injured leg	SG	0.281 ±0.06	0.274 ±0.05	-0.007	NS	0.246 ±0.06	-0.028	NS	-0.035	NS
Uninjured leg		0.277 ±0.06	0.275 ±0.06	0.002	NS	0.249 ±0.04	-0.026	NS	-0.028	NS
Flight time (s)										
Injured leg	SSC6	0.405 ±0.05	0.418 ±0.04	0.013	NS	0.415 ±0.04	0.001	NS	-0.010	NS
Uninjured leg		0.407 ±0.04	0.434 ±0.03	0.027	p = 0.04; ES: 0.74; (0.01, 1.47)	0.422 ±0.03	-0.012	NS	0.015	NS
Injured leg	SG	0.437 ±0.07	0.448 ±0.05	0.011	NS	0.442 ±0.03	-0.006	NS	0.005	NS
Uninjured leg		0.441 ±0.07	0.449 ±0.05	0.008	NS	0.445 ±0.02	-0.004	NS	0.004	NS
Duty factor										
Injured leg	SSC6	0.406 ±0.05	0.395 ±0.04	-0.011	NS	0.396 ±0.05	0.001	NS	-0.010	NS
Uninjured leg		0.406 ±0.05	0.381 ±0.05	-0.025	NS	0.396 ±0.05	0.015	NS	-0.010	NS
Injured leg	SG	0.392 ±0.08	0.455 ±0.23	0.063	NS	0.354 ±0.05	-0.101	NS; ES: -0.58 (-1.44, 0.27)	-0.038	NS; ES: -0.55 (-1.40, 0.30)
Uninjured leg		0.386 ±0.08	0.453 ±0.23	0.067	NS	0.360 ±0.04	-0.093	NS; ES: -0.54 (-1.39, 0.31)	-0.026	NS
Leg stiffness (kN/m)										
Injured leg	SSC6	8.75 ±0.27	9.33 ±2.25	0.58	NS	9.21 ±1.29	-0.12	NS	0.46	NS; ES: 0.50 (-0.23, 1.20)
Uninjured leg		8.91 ±0.52	9.89 ±1.65	0.98	p = 0.03; ES: 0.79 (0.06, 1.52)	9.51 ±1.16	-0.38	NS	0.60	NS; ES: 0.66 (-0.07, 1.38)
Injured leg	SG	7.45 ±2.38	8.82 ±3.27	1.37	NS	7.33 ±0.60	-1.49	NS; ES: -0.61 (-1.46, 0.25)	-0.12	NS
Uninjured leg		7.52 ±2.46	9.02 ±3.57	1.50	NS	8.23 ±0.60	-0.79	NS	0.71	NS
CoM excursion (mm)	SSC6	115.9 ±20.8	117.2 ±19.9	±19.9	NS	115.4 ±22.1	-1.80	NS	-0.50	NS
	SG	111.7 ±18.6	107.6 ±23.0	-4.10	NS	117.2 ±19.9	9.60	NS	5.50	NS
Cadence (SPM)	SSC6	171.7 ±9.60	171.4 ±6.90	-0.30	NS	173.5 ±9.50	2.10	NS	1.80	NS
	SG	167.7 ±10.90	171.1 ±13.10	3.40	NS	173.8 ±13.00	2.70	NS	6.10	NS

Eversion excursion during stance (deg)										
Injured leg	SSC6	12.9 ±5.1	14.6 ±5.6	1.7	NS	13.8 ±3.7	-0.8	NS	0..9	NS
Uninjured leg		15.8 ±4.1	16.2 ±5.4	0.4	NS	15.6 ±6.1	-0.6	NS	-0.2	NS
Injured leg	SG	16.3 ±5.2	17.1 ±5.5	0.8	NS	16.1 ±4.5	-1.0	NS	-0.2	NS
Uninjured leg	SG	16.5 ±5.3	18.7 ±5.3	2.2	NS	18.5 ±4.6	-0.2	NS	2.0	NS
Eversion velocity during stance (deg/s)										
Injured leg	SSC6	296.9 ±172	340.9 ±224	224.0	NS	290.3 ±92	-50.6	NS	-6.6	NS
Uninjured leg		328.1 ±143	335.6 ±148	7.5	NS	320.4±170	-15.2	NS	-7.7	NS
Injured leg	SG	351.9 ±153	358.7 ±128	6.8	NS	334.6 ±80	-24.1	NS	-17.3	NS
Uninjured leg		369.5 ±155	391.2 ±167	21.7	NS	367.8 ±143	-23.4	NS	-1.7	NS
Time of max eversion during stance (% gait)										
Injured leg	SSC6	13.8 ±4.1	15.2 ±6.5	1.4	NS	13.2 ±4.8	-2.0	NS	-0.6	NS
Uninjured leg		13.9 ±4.1	13.8 ±3.9	-0.1	NS	13.8 ±3.9	0.0	NS	-0.1	NS
Injured leg	SG	14.2 ±4.9	14.5 ±4.8	0.3	NS	14.3 ±4.1	-0.2	NS	0.1	NS
Uninjured leg		14.1 ±4.4	13.7 ±3.8	-0.4	NS	14.3 ±3.1	0.6	NS	0.2	NS
Max dorsiflexion during stance (deg)										
Injured leg	SSC6	27.3 ±4.3	27.6 ±3.1	0.3	NS	28.9 ±3.8	1.3	NS	1.6	NS
Uninjured leg		26.2 ±3.5	27.1 ±3.9	0.9	NS	27.9 ±3.7	0.8	NS	1.7	NS
Injured leg	SG	25.3 ±2.9	24.9 ±2.9	-0.4	NS	24.9 ±2.8	-0.4	NS	0.1	NS
Uninjured leg		24.5 ±4.1	24.9 ±3.6	0.4	NS	25.6 ±4.0	0.7	NS	1.1	NS
Max knee flexion during stance (deg)										
Injured leg	SSC6	51.3 ±10.6	53.9 ±4.2	2.6	NS	54.6 ±5.3	0.7	NS	3.3	NS
Uninjured leg		51.2 ±10.0	53.6 ±6.1	2.4	NS	52.1 ±4.8	-1.5	NS	0.9	NS
Injured leg	SG	53.3 ±3.9	49.3 ±7.6	-4.0	NS; ES: -0.64 (-1.49, 0.22)	49.7 ±8.3	0.4	NS	-3.6	NS; ES: -0.53 (-1.38, 0.32)
Uninjured leg		53.8 ±6.3	51.8 ±9.8	-2.0	NS	53.3 ±5.5	1.5	NS	-0.5	NS
Max hip adduction (deg)										
Injured leg	SSC6	9.3 ±7.3	6.5 ±4.9	-2.8	NS	7.7 ±4.5	1.2	NS	-1.6	NS
Uninjured leg		6.0 ±6.9	10.2 ±6.2	4.2	NS; ES: 0.62 (-0.10, 1.34)	5.4 ±5.3	-4.8	NS; ES: -0.81 (-1.55, -0.07)	-0.6	NS
Injured leg	SG	4.6 ±3.4	10.1 ±10.0	0.1	NS	9.0 ±5.4	-1.1	NS	4.4	$P = 0.03$; ES: 0.94 (0.06, 1.82)
Uninjured leg		7.5 ±6.6	5.4 ±6.8	-2.1	NS	8.4 ±4.4	3.0	NS; ES: 0.50 (-0.35, 1.35)	0.9	NS

Max hip internal rotation (deg)										
Injured leg	SSC6	15.7 ±5.5	14.6 ±8.6	-1.1	NS	17.9 ±6.7	3.3	NS	2.2	NS
Uninjured leg		14.4 ±6.8	10.5 ±8.7	-3.9	NS; ES: 0-0.50 (-1.20, 0.23)	9.7 ±6.4	-0.8	NS	-4.7	NS; ES: -0.69 (-1.42, 0.03)
Injured leg	SG	12.3 ±11.1	15.4 ±5.2	3.1	NS	12.5 ±6.0	-2.9	NS; ES: -0.50 (-1.35, 0.35)	0.2	NS
Uninjured leg		12.0 ±12.3	13.4 ±6.4	1.4	NS	12.9 ±6.4	-0.5	NS	0.9	NS
Pelvic obliquity (deg)										
Injured leg	SSC6	4.9 ±3.4	4.5 ±2.2	-0.4	NS	5.8 ±2.6	1.3	NS; ES: 0.53 (-0.20, 1.25)	2.2	NS
Uninjured leg		5.6 ±4.1	6.1 ±4.3	0.5	NS	3.3 ±2.0	-2.8	NS; ES: -0.81 (-1.56, -0.07)	-2.3	NS; ES: -0.69 (-1.41, 0.04)
Injured leg	SG	5.2 ±3.1	5.5 ±2.3	0.3	NS	5.5 ±3.7	0.0	NS	0.2	NS
Uninjured leg		6.2 ±3.6	4.8 ±3.0	-1.4	NS	5.2 ±2.8	0.4	NS	-1.0	NS

Notes:
SSC6: SSC6 training group; SG: Silbernagel group; PF: plantar flexor; KE: knee extended; BM: body mass; KF: knee flexed; LSI: limb symmetry index; DJDJ: double-leg drop jump; RSI: reactive strength index; SLDJ: single-leg drop jump; SLHH: single-leg horizontal rebound hop; ES: effect size; NS: non-significant
Hedges' g effect sizes are used for between group effects where there are differences in sample size.
Effect sizes are reported where values are >0.5
* Significant ($p < 0.05$), ** Significant ($p < 0.01$)

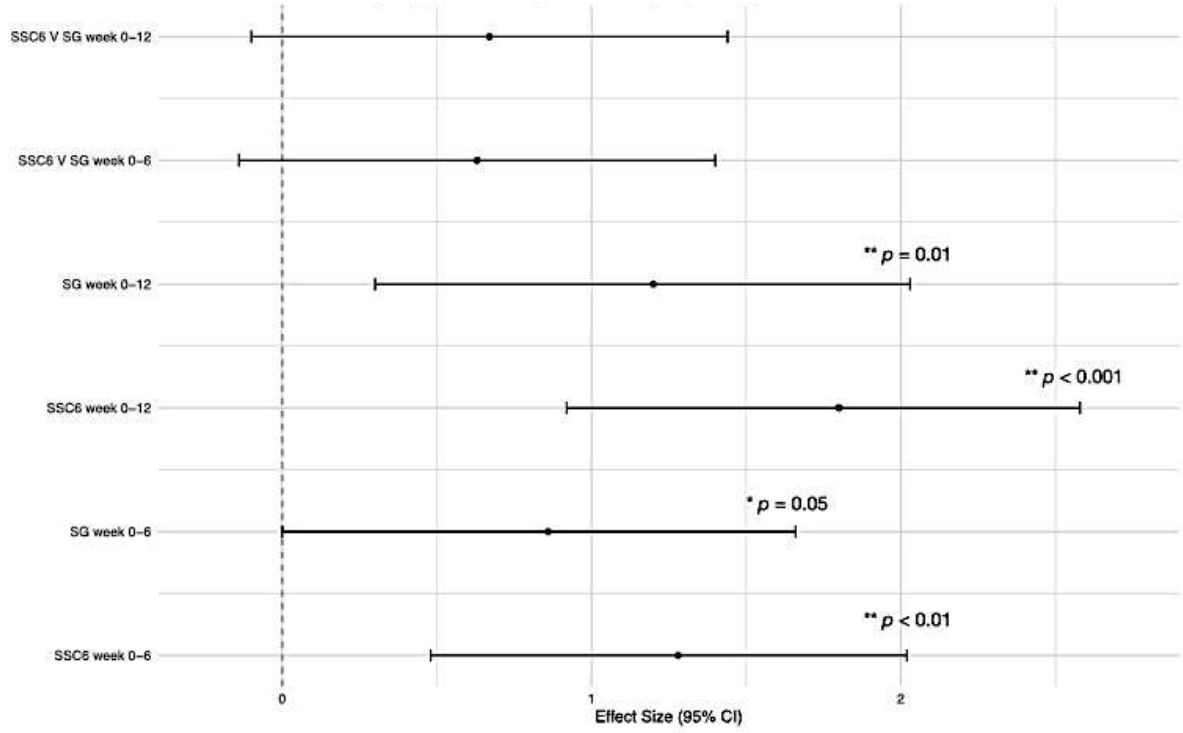


Fig. 4.2.2. Between-group (SSC6 V SG) and within-group effect sizes and 95% confidence intervals for changes in VISA-A scores between weeks 0-6 and week 6-12

4.2.2. DISCUSSION

4.2.2.1. VISA-A outcomes

Both groups recorded favourable VISA-A questionnaire changes above clinically meaningful improvements of 14 points (Lagas *et al.*, 2021). The average reported improvement is 21 points (Murphy *et al.*, 2018), with scores above 89.5 indicating complete recovery (Sigurðsson and Silbernagel, 2022) - both of which SSC6 surpassed, but without reaching significance over SG. A larger sample size is required for our findings to better determine significance for the difference in improvements. The baseline VISA-A scores for both groups, which were marginally lower for SSC6, were higher than baseline scores recorded in other similar studies (Silbernagel *et al.*, 2007a; Beyer *et al.*, 2015). One reason for this may be that this was a more athletic population with a narrower age profile of 18 to 45 compared to other studies with an upper age limit of 60 to 65 years (Alfredson *et al.*, 1998; Silbernagel *et al.*, 2007a; Habets *et al.*, 2021; Sancho *et al.*, 2022). We wanted to keep the upper age limit to 45 to avoid confounding the baseline VISA-A scores due to age-related comorbidities that can increase pain and disability associated with Achilles tendinopathy (Svensson *et al.*, 2016; Hanlon *et al.,*

2021). The narrower age limit in our study also excluded many older recreationally-active Achilles tendinopathy patients who attended the SSC for treatment. Some participants who played field sports and reported severe pain and disability during their peak competitive season entered the study in the offseason when symptoms were somewhat reduced and thus may have reported higher baseline VISA-A scores.

4.2.2.2. Plantar flexor peak torque

There were no significant differences between injured and uninjured limbs between groups in this study, with both groups demonstrating improvements in both IKD testing protocols. The SSC6 group achieved significant improvements in PF torque in both limbs over the 12 weeks, but this was not significantly greater than improvements found in SG. Previous studies highlighted significant calf strength deficits in runners with Achilles tendinopathy (Alfredson *et al.*, 1998; Silbernagel *et al.*, 2007b; O'Neill *et al.,* 2019; Sancho *et al.*, 2022). However, O'Neill et al. (2019) found that PF T_{peak} in knee-extended and knee-flexed IKD test protocols in both limbs was significantly lower when compared to healthy controls (O'Neill *et al.,* 2019). While the author's IKD test speeds did not match the 60°/sec speeds used in this study, the concentric T_{peak} values relative to body mass at 90°/sec in one of the protocols were well below the values we obtained. In a similar study comparing runners with Achilles tendinopathy and healthy controls, Sancho (2022) observed PF strength and hop performance impairments. In that study, the mean baseline VISA-A scores were 56% with an average age of 47 years, which were markedly different from the baseline characteristics of the participants in our study. The mean age of participants was 42 years, with a baseline VISA-A score of 59%. In light of the findings in our study with a younger age profile and higher baseline VISA-A score, it may be helpful to investigate whether VISA-A scores correlate with PF strength and, indeed, hop performance.

4.2.2.3. Hop tests

In this study, we performed hop tests at weeks 6 and 12 and found no significant deficits or changes in biomechanical and performance features in either group. Previous studies detected impairments in hop performance and reduced leg stiffness in runners with Achilles tendinopathy (Silbernagel *et al.*, 2007b; Maquirriain, 2012; Wang *et al.*, 2012; Sancho *et al.*, 2022). Reduced AT stiffness is a common finding in runners with Achilles tendinopathy (Arya

and Kulig, 2010; Wang *et al.*, 2012), which can negatively impact horizontal hop distance (Wang *et al.*, 2012) and affect stretch-shortening cycle behaviour during hopping (Debenham *et al.*, 2016; Abdelsattar *et al.,* 2018). We observed the largest increase in VISA-A outcomes in the first six weeks and therefore, participants may have had reduced pain and improved function by the time they performed hop tests for the first time. When designing this study, we decided not to perform hop testing at baseline as we felt that higher levels of pain, kinesiophobia, and dysfunction could inflate the magnitude of improvement in hop performance.

4.2.2.4. Running biomechanics

We detected limited significant between-limb within-group differences and no between-group differences, with no substantial changes throughout the 12-week program within the current sample size. Running gait features associated with Achilles tendinopathy is an under-researched area. A limited number of studies have detected running gait features such as poor pronation control, altered knee joint kinematics, and muscle recruitment patterns (Donoghue *et al.*, 2008; Azevedo *et al.*, 2009; Munteanu *et al.*, 2011; Sancho *et al.*, 2019). Our small sample size that successfully completed all three testing sessions, may not be sufficient to detect any meaningful changes with large effect sizes or significance. A deeper level of waveform analysis during stance phase and evaluation of joint or segment coupling relationships may be worthy of exploration which was not possible with the methods used in our study.

4.2.2.5. Adherence and fidelity

Adherence rates above 70% are deemed satisfactory, consistent with previous studies (Sancho *et al.*, 2019), which both groups surpassed. The fidelity rates, which is a measure of the percentage of sets and reps completed as prescribed, were accounted for by the SSC6 group not being able to access the gym during periods of covid-19 restrictions and for the SG group not performing the exercises daily as prescribed.

4.2.3. CONCLUSION

In this preliminary set of results, we observed greater improvements in VISA-A scores in the SSC6 group compared to SG, with the most substantial changes occurring in the first six weeks. Both groups improved their PF T_{peak} over the 12 weeks in knee-extended and knee-flexed

testing protocols, with the SSC achieving significant increases in the latter protocol. A smaller proportion of the participants completed the hop testing at weeks 6 and 12, with no observed trends detected thus far. The large improvements in VISA-A scores despite no significant or consistent biomechanical changes in the hop tests and running assessments, may suggest other factors account for clinical improvements. Both groups achieved satisfactory levels of adherence and fidelity but the impact of covid-19 and the closure of gyms affected the SSC6 group more due to the type of exercises and loading prescribed. This study will continue until we reach our *a priori* sample size of 25 in each group.

4.2.4 PERSCECTIVES

After designing this protocol and at the time of submitting this thesis, are in the process of testing it in Study 4, we felt that elements of it could be applied to other AT injuries such as a peratenonitis or an AT rupture. In the case of a rupture, where alterations to the AT and PF muscles exists which result in reduced MTU capacity and lower-limb biomechanical impairments, a criteria-based graded rehabilitation program is also recommended. Therefore, when an opportunity presented during the preparation of this thesis to conduct a case report on an athlete who sustained an AT rupture with a surgical repair performed, it seemed logical to apply the principles of the protocol presented in Study 3, to this case.

4.3. STUDY 5. REHABILITATION AND BIOMECHANICAL EVALUATION AFTER AN ACHILLES TENDON REPAIR: A CASE REPORT

Plan to submit to Journal Orthopaedic & Sports Physical Therapy (JOSPT) Cases in February 2023

Colin Griffin[1,2], Leigh Ryan[2], Enda King[2,3], Jean-Benoit Morin[1,4,5]

[1]Université Côte d'Azur, LAMHESS, Nice, France.
[2]Sports Surgery Clinic, Santry Demesne Dublin 9, Ireland
[3]Rehabilitation Department, Aspetar Orthopaedic and Sports Medicine Hospital, Doha, Qatar
[4]Sports Performance Research Institute New Zealand (SPRINZ), Auckland University of Technology, Auckland, New Zealand
[5]Univ Lyon, UJM-Saint-Etienne, Inter-university Laboratory of Human Movement Biology, EA 7424, F-42023, Saint-Etienne, France

Address for correspondence: Colin Griffin, Sports Medicine Department, Sports Surgery Clinic, Santry Demesne Dublin 9, Ireland.

Email: colingriffin@sportssurgeryclinic.com

4.3.1. ABSTRACT

AT ruptures which are surgically repaired or managed non-surgically, can lead to long-term lower limb performance and biomechanical impairments due to morphological changes in the tendon and PF muscles. A 35-year-old gaelic football player sustained an AT rupture during team training early in the pre-season following a lockdown period during the covid pandemic. The mechanism of injury was a back-step acceleration after landing from a jump during the warm-up. The patient underwent a surgical repair within four days. The patient achieved significant improvements in all patient-reported outcome scores (PROMS), strength and biomechanical assessments over 36 weeks. However, a persistent limb-symmetry index (LSI) remained for PF torque at 20° plantarflexion on ankle IKD testing. The patient achieved an acceptable level of symmetry in PF T_{peak} with knee extension and seated calf peak isometric

force after 36 weeks, but a 60% LSI in inner range PF torque remained. A reduction in ankle joint power and a concurrent increase in knee joint power during a vertical hop and hip joint power in a horizontal hop was identified on the injured limb using 3D biomechanical assessment.

Key words: Achilles tendon rupture, rehabilitation, biomechanics, muscle strength testing

4.3.2. BACKGROUND

Achilles tendon ruptures are common in middle-aged and older recreational and elite sporting populations, with an annual incidence rate of around 30 events per 100,000 persons (Myhrvold *et al.*, 2022; Xergia *et al.*, 2022). Impairments can persist for many years, preventing a high proportion of athletes from returning to the sport to pre-injury levels (Trofa *et al.*, 2017; Yang *et al.*, 2019; Hoeffner *et al.*, 2022). Surgical repair is traditionally favoured, but many cases are managed non-surgically with no difference in following outcomes after 12 months (Myhrvold *et al.*, 2022). However, conservatively-managed patients report a marginally higher re-rupture rate compared to surgically-repaired (Ochen *et al.*, 2019; Myhrvold *et al.*, 2022).

A rupture occurs when the tendon reaches a high strain level, resulting in tensile failure (Wren *et al.*, 2003; Nagelli *et al.*, 2021, 2022). These incidents arise during explosive movements such as pushing off the rearfoot to accelerate, landing from a jump and changing direction (Trofa *et al.*, 2017; De la Fuente *et al.*, 2019; Tarantino *et al.*, 2020). In these movements, the ankle experiences rapid dorsiflexion as the heel is off the ground. There is evidence of pathological changes in the tendon preceding the rupture (Maffulli *et al.,* 2015; Xergia *et al.*, 2022).

During the Covid-19 pandemic, various governments imposed restrictions which periodically prohibited collective training for team sports. Following the resumption of team training and shorter compacted seasons in some sports, many sports medicine experts expressed concerns about the high risk of injuries as training loads increased. Achilles ruptures were one such injury considering the precedence following the 2011 NFL “lockout” period where a higher-than-normal incidence of AT ruptures occurred during the early pre-season (Myer *et al.*, 2011).

4.3.3. CASE PRESENTATION

The patient was a 35-year-old male inter-county gaelic football player who suffered a rupture to his right AT during the first week of pre-season training following the resumption of collective team training. The injury occurred during the warm-up, where he attempted to push off his rear foot to accelerate after landing from a jump. Upon reflection, he reported an occasional feeling of right calf "tightness" in the months before the rupture and, in the past, experienced mild Achilles tendinopathy symptoms.

4.3.4. DIFFERENTIAL DIAGNOSIS

The diagnosis of a tendon rupture was unequivocal in this case. The Thompson test is the primary clinical diagnostic tool whereby the patient lies in a prone position and the clinician squeezes the calf muscle with no visible plantarflexion indicating a complete AT rupture. An MRI scan may be used to confirm the diagnosis and rule out damage to neighbouring structures.

4.3.5. TREATMENT

The patient had a surgical repair of his AT four days after the rupture in his local hospital. He was placed in a cast for six weeks, despite a boot being the preferred option to facilitate early mobilisation. After a review with his surgeon six weeks post-surgery, the cast was removed and replaced with an AirCast walker boot with three heel wedges removing one heel wedge each week, to be fully weight-bearing at a neutral ankle angle at week nine, and to mobilise without the boot from week 10. The patient supplemented with collagen and vitamin C from week 6 to support tendon remodelling and aimed for a daily protein intake of protein of 2-2.5 grams per kilogram of body mass split evenly across 4 to 5 doses to preserve muscle mass and support hypertrophic response to exercise.

The patient presented to the Sports Surgery Clinic on week 7 to begin his rehabilitation. We observed significant visible atrophy of the calf muscles on his injured leg. We initially focused on exercises to improve the recruitment of foot, ankle, hip, hamstring and quad musculature, and calf muscles *(Fig. 4.3.1)*. The patient removed the boot for the lower limb exercises, which were done non-weight-bearing and with the ankle in plantigrade to protect the repair and avoid tendon elongation. We added blood flow restriction to the injured leg with the occlusion cuff placed around the upper thigh. We also included kinetic chain exercises such as a box squat performed with the boot on and then progressed to front squats, deadlifts, and split squats and step-ups for single-leg progressions throughout the rehabilitation pathway.

The patient was fully weight-bearing without the boot at week ten but displayed a stiff walking gait on his injured leg, which we addressed immediately with coordination drills. We progressed the foot and calf exercises to fully weight-bearing and into a neutral ankle. We then loaded into full dorsiflexion for the seated calf raises and actively sought to restore ADF range of motion with anterior-posterior glides. We included a double leg calf raise with the toes pointing outwards to target hypertrophy of the medial gastrocnemius muscle *(Fig. 4.3.2).* This exercise progressed to standing on a block to work into dorsiflexion to increase fascicle length with single-leg progressions *(Fig. 4.3.3)*. From week 20, the calf exercises involved single-leg isometric holds for four sets of 5 repetitions of 5-second holds aiming for 100% bodyweight of external load on the smith machine and standing single-leg seated calf raises through the full range of dorsiflexion with 110% bodyweight of load *(Fig. 4.3.4).*

We introduced low-level plyometric exercises beginning with band-assisted pogo hops. These progressed to full weight-bearing pogo hops and drop jumps. Single-leg plyometrics began with rearfoot hops, advancing to single-leg pogo hops, forward and medial and lateral hop variations, and intensified with box rebounds and mini hurdle hops *(Fig 4.3.4).* The patient returned to running on week 19, beginning with short repeated tempo runs over 30-second durations. Volume was increased over the six weeks aiming to cover 2.5km of moderate-speed running. We introduced speed development runs over 40-60m at week 24, acceleration preparation at week 26 utilising loaded prowler marches and bounds to support, and multi-directional running at week 28 *(Fig. 4.3.5).*

Rehab program week 8

	Exercise	Load	Sets x reps
1	SL clamshell	Blue mini band	3 x 12 e/s
2	Prone hamstring curl ISO	Black mini band	3 x 4 x 10 sec e/s
3	Seated band-resisted toe flexion	Black theraband	3 x 15 e/s
4	Band-resisted ankle inversion	Black theraband	3 x 12 e/s
5	Band-resisted ankle eversion	Black theraband	3 x 12 e/s
6	Box squat	15-20kg KB	3 x 15
7	SL prone inner range calf pulses (injured leg)	Black strength band	4 x 20
8	SL calf raises (uninjured leg)	12-15kg DB	3 x 10
9	Seated inner range calf raises (injured leg)	15-20kg	4 x 15
10	Leg extensions	17RM	3 x 15

Fig. 4.3.1. A sample rehabilitation session during week 8

Rehab program week 12

	Exercise	Load	Sets x reps
1	SL crab band	Black mini band	3 x 12 e/s
2	Prone hamstring curl ISO	Black mini band	3 x 4 x 10 sec e/s
3	Standing band-resisted toe flexion	Black theraband	3 x 15 e/s
4	SL RDL	10kg in opposite hand	3 x 8 e/s
5	Penguin taps	BW	3 x 20 sec
6	Front box squat	10RM	4 x 8
7	Standing band-assisted calf ISOs	Black strength band	4 x 4 x 10 sec
8	SL calf raises (uninjured leg)	20-25kg DB	3 x 10
9	DL calf raises with toes pointing out	17RM	3 x 15
10	Seated calf raises from neutral ankle	30kg	4 x 15
11	Hamstring curls	14RM	3 x 12
12	Leg extensions	14RM	3 x 12

Fig. 4.3.2. A sample rehabilitation session during week 12

Rehab program week 18

	Exercise	Load	Sets x reps
1	SL crab band	Black mini band	3 x 12 e/s
2	Standing band-resisted toe flexion with heel raise	Black theraband	3 x 15 e/s
3	SL RDL	10kg in opposite hand	3 x 8 e/s
4	Penguin bounds	BW	3 x 20 sec
5	A-skip	BW	3 x 20m
6	Rearfoot pogo hops (injured leg)	BW	3 x 12
7	DL pogo hops	BW	4 x 15
8	Back squat	8RM	4 x 6
9	Step-up	8RM	3 x 8 e/s
10	SL calf raises*	12RM	12RM
11	DL full range calf raises with toes pointing out	17RM	3 x 15
12	Seated full range calf raises	14RM	4 x 12
13	SL band-assisted inner range ISOs (injured leg)	Black strength band	2 x 4 x 15 sec

* On the injured leg the patient began with bodyweight loading and progressed to added load with a dumbbell

Fig. 4.3.3. A sample rehabilitation session during week 18

Rehab program week 25

	Exercise	Load	Sets x reps
1	SL crab band	Black mini band	3 x 12 e/s
2	Penguin bounds	BW	3 x 20 sec
5	A-skip	BW	3 x 20m
6	DL pogos	BW	2 x 15
7	DL drop jump (30cm)	BW	4 x 4
8	SL forward hops	BW	3 x 12 e/s
9	SL medial & lateral hops	BW	3 x 12 e/s
10	SL calf ISO	>70% BW	4 x 5 x 5 sec
11	SL full range calf raises with toes pointing out	14RM	3 x 12
12	Seated full range calf raises	>100% BW	4 x 8 e/s
13	SL inner range ISOs (injured leg)	BW	2 x 4 x 15 sec

SL - single leg; DL - double leg; e/s - each side; RM - repetition maximum; ISO - isometric; DB - dumbbell; KB - kettlebell

Fig. 4.3.4. A sample rehabilitation session during week 25

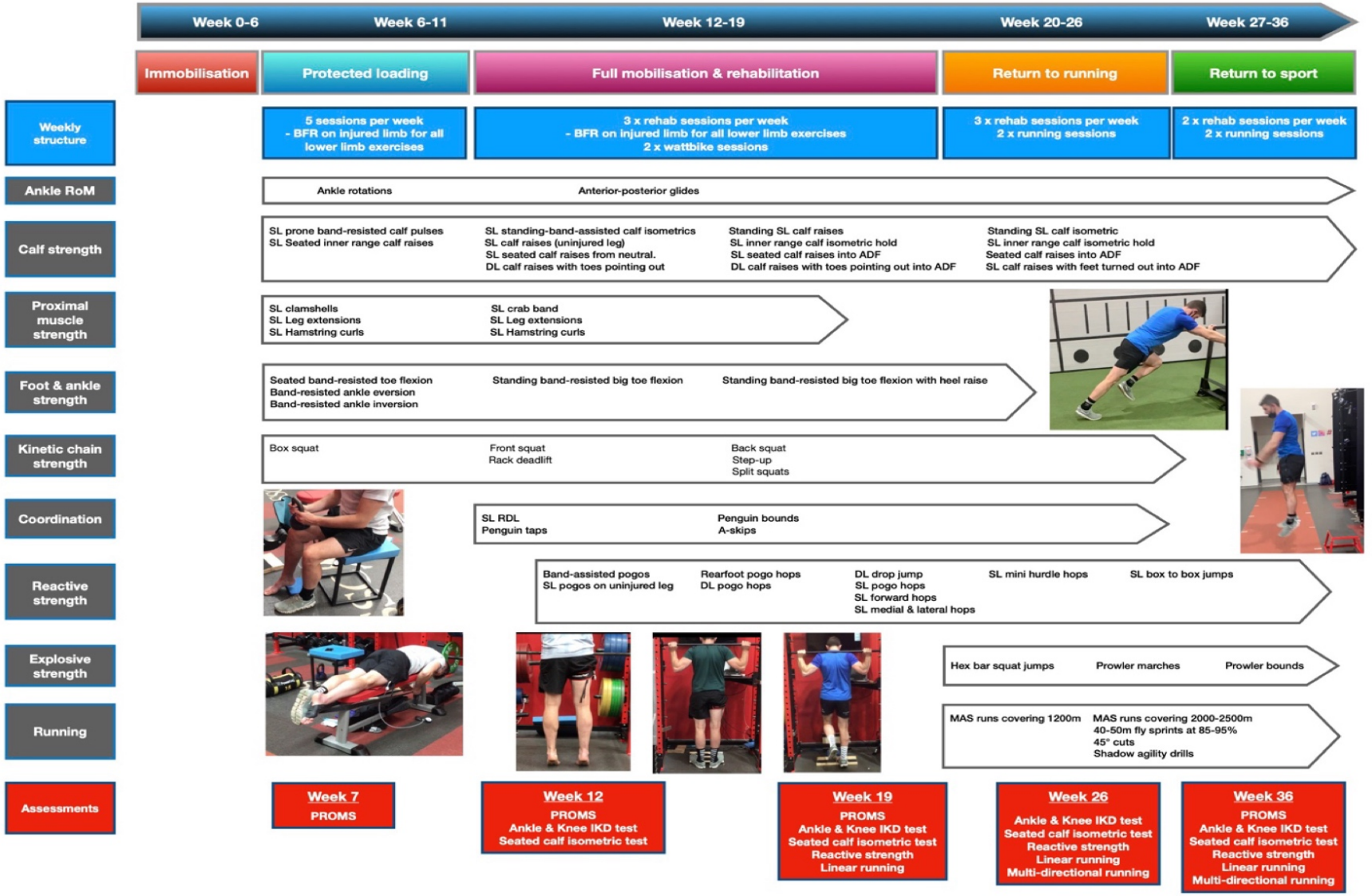


Fig. 4.3.5. A summary of the rehabilitation pathway and assessments over the course of a 36-week recovery following an AT repair

4.3.6. OUTCOME AND FOLLOW-UP

The patient completed three patient-reported outcome score (PROMS) questionnaires – the AT rupture score (ATRS), the foot and ankle outcome score (FAOS) and the Tampa scale of kinesiophobia (TSK), at weeks 7, 12, 9, 26 and 36 post-surgery. At the 36-week follow-up, the patient recorded near-maximum scores for ATRS and FAOS and a favourable reduction of 16 points in the TSK questionnaire *(Fig. 4.3.6)*.

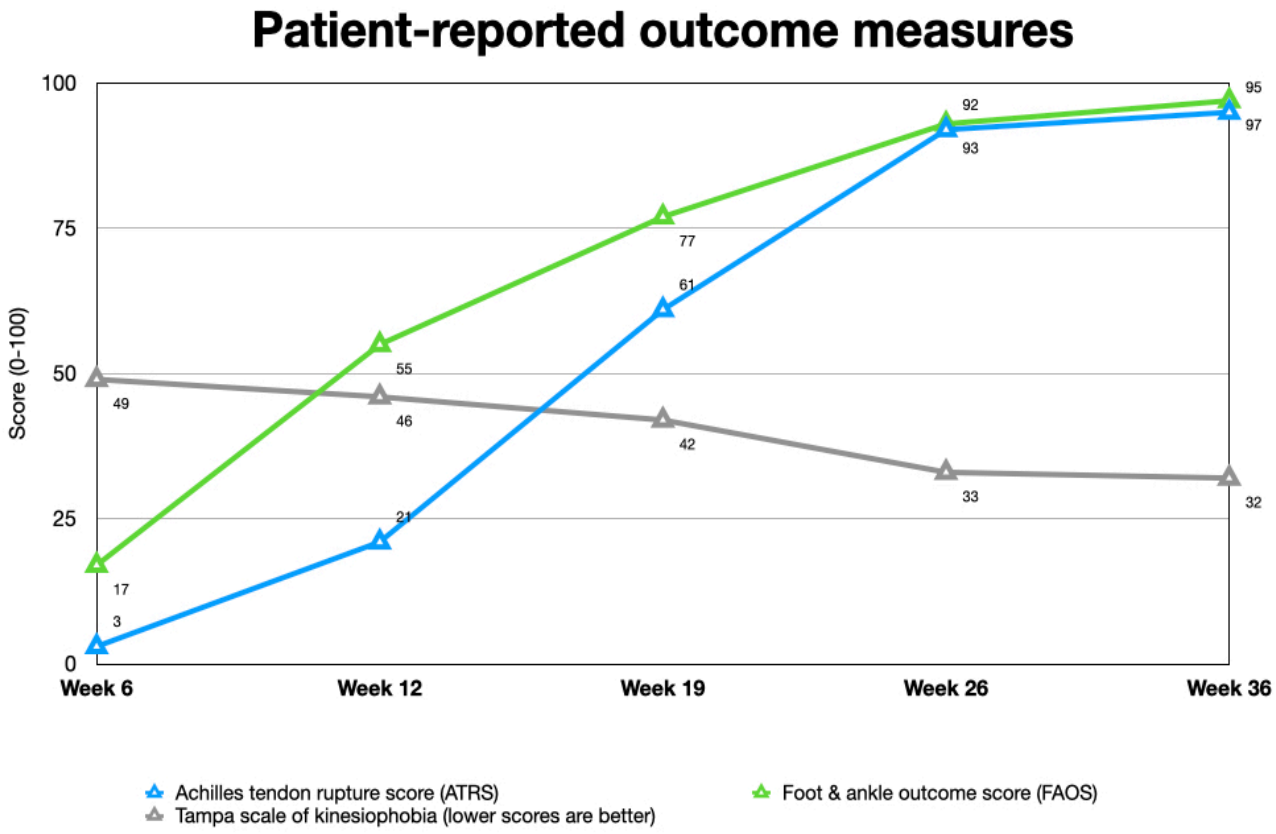


Fig. 4.3.6. Patient-reported outcome measures (PROMs) recorded at weeks 6, 12, 19, 26 and 36 during the patient's rehabilitation program

Table 4.3.1. A summary of lower limb strength testing at weeks 12, 19, 26 and 36.

	Week 12			***Week 19***			***Week 26***			***Week 36***		
	Injured	**Uninjured**	**LSI (%)**	**Injured**	**Uninjured**	**LSI (%)**	**Injured**	**Uninjured**	**LSI (%)**	**Injured**	**Uninjured**	**LSI (%)**
ADF (cm)	3	16	19	6	16	38	10	16	63	14	16	88
Ankle IKD (30°/sec)												
PF peak torque (Nm/kg %)	100	162	62	126	174	72	133	196	68	133	171	78
PF torque at 10° DF (Nm/kg %)	96	157	61	123	165	75	128	173	74	131	161	81
PF torque at 20° PF (Nm/kg %)	30	64	47	41	85	48	51	100	51	45	75	60
DF peak torque (Nm/kg %)	39	39	100	43	39	110	43	39	110	49	41	120
Knee IKD (60°/sec)												
Knee extension peak torque (Nm/kg %)	238	186	83	277	298	93	289	307	95	-	-	-
Knee flexion peak torque (Nm/kg %)	143	167	86	170	197	86	172	182	95	-	-	-
Seated calf isometric test												
Peak vertical force (% body mass)	96	136	71	119	176	68	141	190	74	162	199	81

Table 4.3.2. A summary of performance features for DLDJ, SLDJ and SLHH at weeks 19, 26 and 36.

	Week 19			***Week 26***			***Week 36***		
	Injured	**Uninjured**	**LSI (%)**	**Injured**	**Uninjured**	**LSI (%)**	**Injured**	**Uninjured**	**LSI (%)**
DLDJ									
Jump height (cm)		21.9			24.0			30.0	
Contact time (s)		0.35			0.27			0.27	
RSI (m/s)		0.62			0.89			1.13	
SLDJ									
Jump height (cm)	10.3	15.3	67	11.2	15.8	71	11.5	15.6	74
Contact time (s)	0.34	0.34	100	0.32	0.32	101	0.31	0.31	98
RSI (m/s)	0.37	0.53	68	0.35	0.50	70	0.38	0.50	76
SLHH									
Rebound distance (cm)	102.2	154.4	66	153.4	172.2	89	169.3	180.8	94
Contact time (s)	0.26	0.25	104	0.28	0.29	97	0.26	0.29	90
RSI (m/s)	3.92	6.16	64	5.46	5.93	92	6.50	6.21	105

Table 4.3.3. Linear running biomechanical features at weeks 19, 26 and 36

	Injured	**Uninjured**	**LSI (%)**	**Injured**	**Uninjured**	**LSI (%)**	**Injured**	**Uninjured**	**LSI (%)**
Pelvic tilt during stance (deg)	20.4	20.1	101	20.2	21.8	93	12.4	13.4	93
Peak knee flexion during stance (deg)	46.9	54.5	86	49.3	53.8	92	59.1	61.6	96
Peak ankle dorsiflexion during stance (deg)	22.3	28.3	82	22.7	27.9	81	31.8	32.5	98
Eversion excursion during stance (deg)	14.9	14.1	106	22.6	22.0	103	18.8	17.8	106
Vertical excursion of centre of mass (mm)	112.8	112.8	100	105.8	105.8	100	105.5	105.5	100
Contact time (s)	0.25	0.25	100	0.20	0.20	100	0.22	0.21	105
Flight time (s)	0.44	0.43	102	0.44	0.43	102	0.41	0.42	98
Duty factor	0.36	0.37	97	0.31	0.32	97	0.35	0.33	109
Leg stiffness (kN/m)	11.83	11.42	104	13.78	12.61	109	11.0	11.9	92

The first performance assessment took place in week 12, which included a knee and ankle IKD test at 30°/sec and 60°/sec speeds, respectively, where relative torque values were measured (Nm/kg %), a seated calf isometric test where peak force was measured as percentage bodyweight, and a knee-to-wall in a split lunge position to measure ankle dorsiflexion (ADF) range of motion. The ankle IKD test highlighted a T_{peak} LSI of 61% and a 49% for PF torque at 20° plantarflexion, while the seated calf isometric test revealed a 71% F_{peak} LSI. At the end of the rehab pathway, there were considerable bilateral improvements in both IKD and isometric tests. The T_{peak} LSI on the ankle IKD was increased to 81% compared to 61% at week 12, with a 40% torque deficit persisting at 20° plantarflexion. The patient displayed an LSI of 83% for knee extensor T_{peak} and 85% for knee flexor T_{peak} on the knee IKD at week 12. Still, bilateral values were close to accepted normative values of 260% and 160% bodyweight, respectively, for knee extensors and flexors. These scores improved sufficiently at week 26, with complete symmetry achieved in knee extensor and flexor torques *(Table 4.3.1).*

We assessed vertical and horizontal reactive strength qualities for the first time in week 19 using a double-leg drop jump, single-leg drop jump, and single-leg horizontal rebound. The hop tests revealed a 70% LSI for jump height on the single-leg drop jump and a 66% LSI for rebound distance on a single-leg horizontal rebound *(Table 4.3.2).* The joint kinetic evaluation showed a considerable reduction in ankle joint power with increased knee joint power in the drop jump, with increased hip joint power output in the horizontal rebound, on the injured compared to the uninjured leg *(Fig. 4.3.7 and 4.3.8).* Ankle joint stiffness was higher on the injured leg but this was due to considerably reduced joint angular displacement with a lower peak joint moment which improved over the course of the rehabilitation program *(Table 4.3.4 and 4.3.5).*

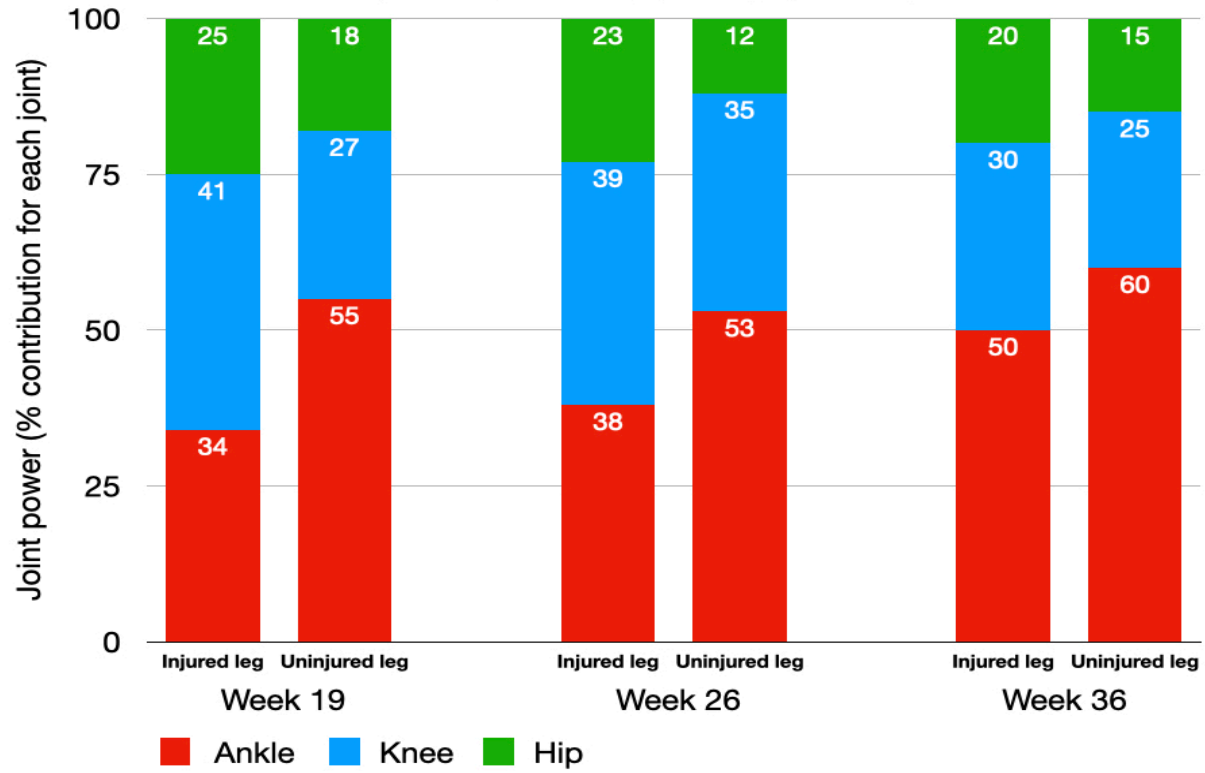


Fig. 4.3.7. Joint power contribution from the ankle, knee and hip for a SLDJ at weeks 19, 26 and 36 for both injured and uninjured limbs

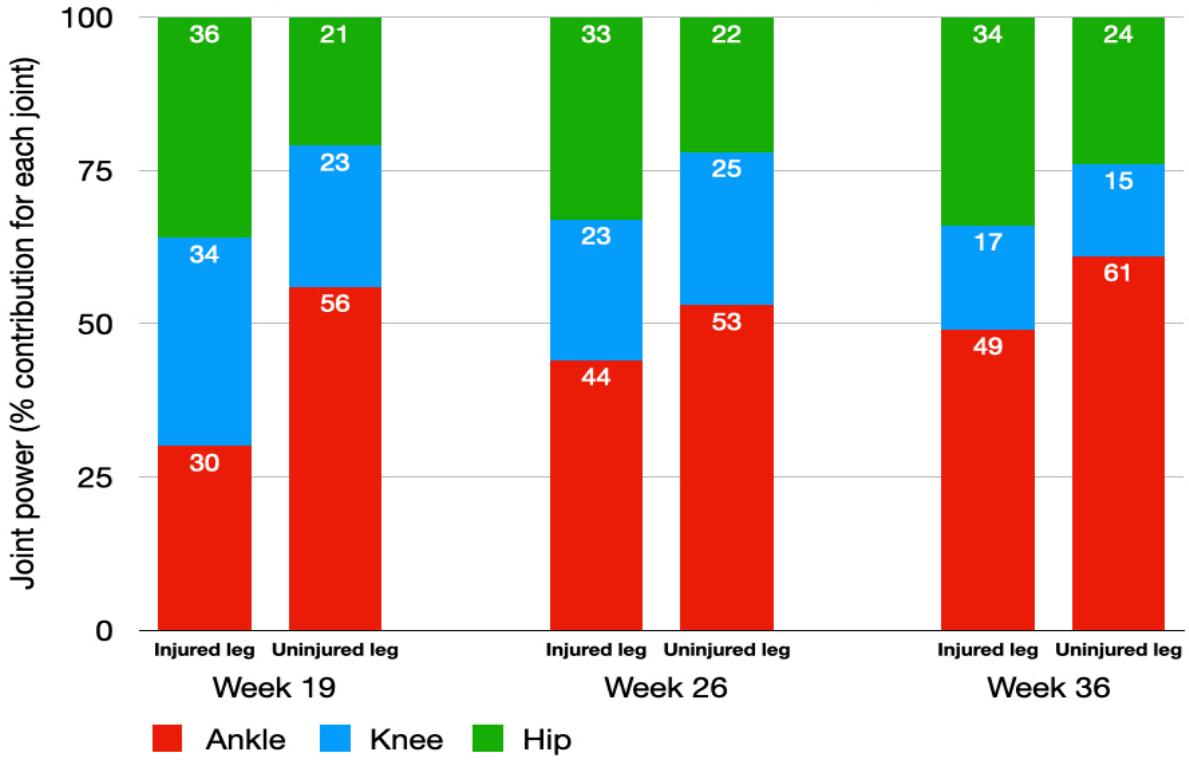


Fig. 4.3.8. Joint power contribution from the ankle, knee and hip for a SLHH at weeks 19, 26 and 36 for both injured and uninjured limbs

We assessed running gait at week 19, which revealed symmetry for all kinematic and spatiotemporal variables and leg stiffness, except for peak dorsiflexion during the stance phase, which was lower on the injured leg but regained symmetry at week 36 *(Table 4.3.3)*. Leg stiffness was estimated from body mass, speed, leg length, flight and contact time (Morin *et al.*, 2005). We assessed multi-directional running at weeks 26 and 36 using a planned and unplanned 45° cut. Ankle joint power was reduced for both cuts on the injured limb at week 36 but increased to become symmetrical with the uninjured limb at week 36 *(Fig. 4.3.9)*. At week 36, cutting times were faster from the injured leg in both tests, with bilateral improvements compared to week 26 *(Fig. 4.3.10)*.

Table 4.3.4 Joint moments, angular displacements, stiffness and leg stiffness for a single leg drop jumps at weeks 19, 26 and 36

	Week 19			***Week 26***			***Week 36***		
	Injured	**Uninjured**	**LSI (%)**	**Injured**	**Uninjured**	**LSI (%)**	**Injured**	**Uninjured**	**LSI(%)**
SLDJ									
Ankle peak joint moment (Nm)	2589	2706	96	2724	3801	72	3627	3749	87
Knee peak joint moment (Nm)	1970	3510	56	2986	3668	81	2711	2754	98
Hip peak joint moment	3753	3649	103	4183	3037	137	3484	3108	112
Δ ankle (deg)	16.4	43.2	38	30.3	44.7	67	39.5	44.5	89
Δ knee (deg)	36.3	38.6	94	32.8	30.3	108	27.4	32.4	85
Δ hip (deg)	38.1	38.6	99	13.8	4.2	323	10.9	8.8	124
K_{ankle} *(Nm/deg)*	110.3	82.2	134	88.4	84.3	105	82.2	83.9	98
K_{knee} *(Nm/deg)*	69.9	66.9	104	102.8	144.6	71	114.7	106.4	108
K_{hip} *(Nm/deg)*	79.3	76.2	104	136.1	267.9	51	199.1	188.1	106
K_{leg} *(kN/m)*	11.2	11.8	95	12.2	13.7	89	15.7	12.6	125

Table 4.3.5 Joint moments, angular displacements, stiffness and leg stiffness for a single leg horizontal rebound at weeks 19, 26 and 36

	Week 19			***Week 26***			***Week 36***		
	Injured	**Uninjured**	**LSI (%)**	**Injured**	**Uninjured**	**LSI (%)**	**Injured**	**Uninjured**	**LSI (%)**
SLHH									
Ankle peak joint moment (Nm)	3074	3125	98	2580	3509	74	3294	3877	85
Knee peak joint moment (Nm)	1466	3171	46	2778	3442	81	2265	2265	109
Hip peak joint moment	3863	4057	95	4985	4356	114	4229	4017	105
Δ ankle (deg)	12.2	32.4	38	16.6	39.0	43	28.5	39.6	72
Δ knee (deg)	20.4	20.4	100	17.5	19.1	91	12.6	10.9	115
Δ hip (deg)	31.5	38.7	81	-13.4	-15.5	86	-15.2	-17.7	86
K_{ankle} *(Nm/deg)*	31.5	38.7	81	155.4	90.0	172	111.1	96.2	116
K_{knee} *(Nm/deg)*	114.1	97.5	117	162.4	180.2	90	170.6	183.5	93
K_{leg} *(kN/m)*	7.7	8.2	94	21.1	13.3	159	20.2	14.5	139

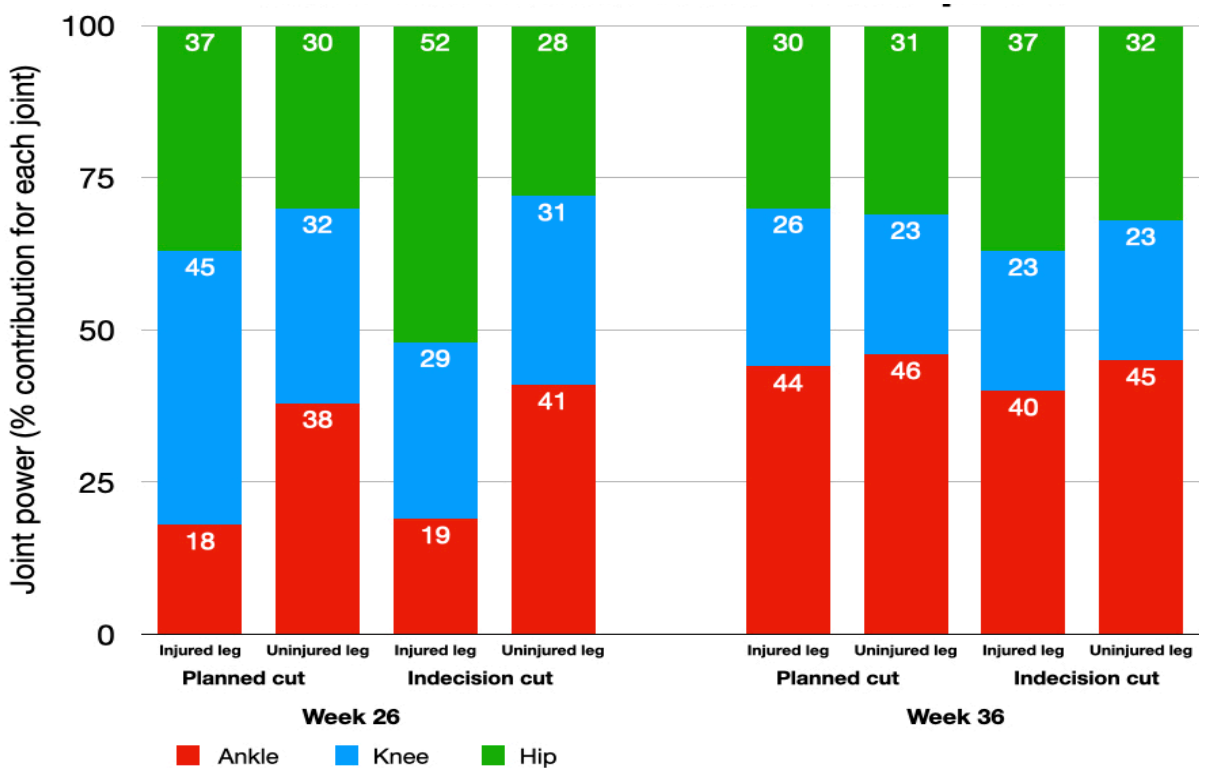


Fig. 4.3.9. Joint power contribution from the ankle, knee and hip for a planned and indecision cut at weeks 26 and 36 for both injured and uninjured limbs

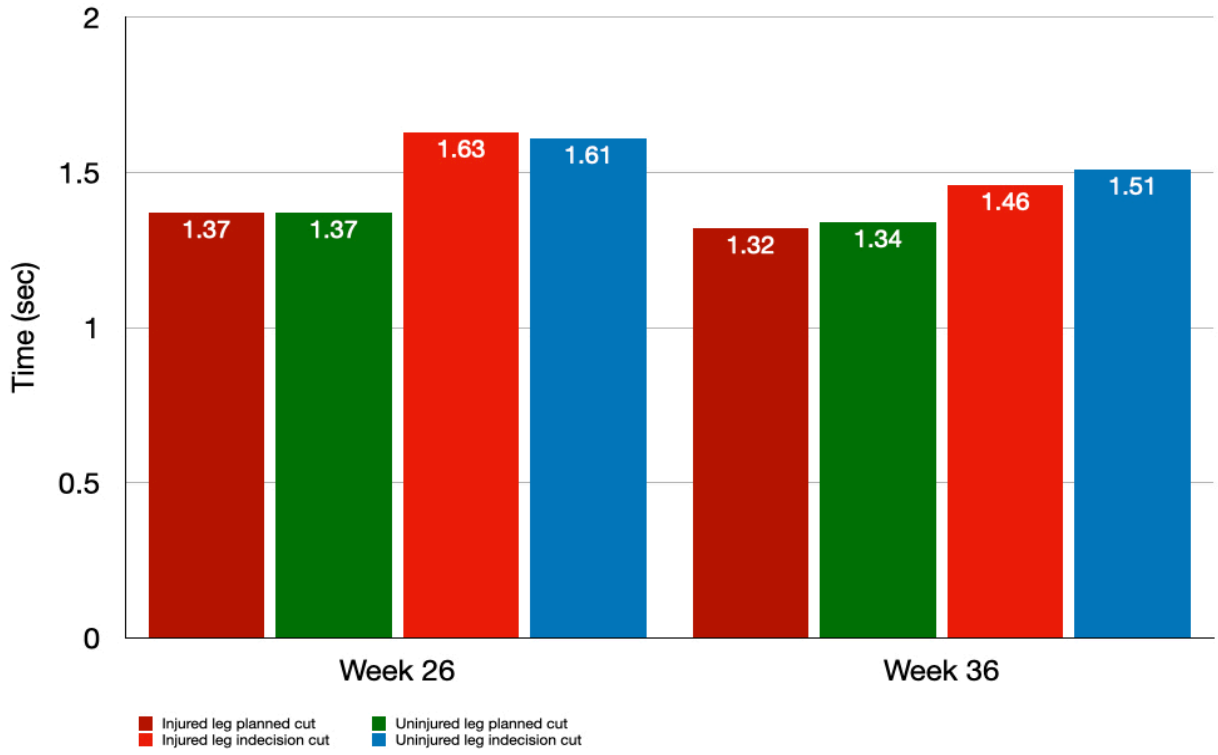


Fig. 4.3.10. Times for planned and indecision cuts for both injured and uninjured leg at week 26 and 36.

4.3.7. DISCUSSION

This study provided a unique opportunity to apply the protocol for Achilles tendinopathy rehabilitation in Study 3, to the rehabilitation of an athlete who had an AT repair following a rupture. In doing so, this study fitted into Theme 2 of this thesis with outcome measures for PF strength and SLHH from the first theme applied. Two key findings emerged from this case report. The first was the LSI for PF strength which took 36 weeks to surpass 80%. However, a significant deficit in T_{peak} persisted at the end of the 36-week pathway. T_{peak} occurred in greater ADF on the injured limb. The second finding was the reduction in ankle joint power in the vertical and horizontal hop tests and during a 45° cut manoeuvre.

An Achilles rupture, regardless of undergoing surgical repair or non-surgical management, results in morphological adaptions to the tendon and PF muscles. The tendon's resting length increases and the medial gastrocnemius muscle fascicles shorten and become more pennated (Zellers *et al.,* 2016b; Hullfish *et al.,* 2019a; Hoeffner *et al.*, 2022). These architectural changes underpin the inability to achieve full weight-bearing heel raise height on the injured limb and reduced ankle propulsive power (Hullfish *et al.,* 2019b; Hoeffner *et al.*, 2022). The medial gastrocnemius muscle appears to experience the most morphological changes after a rupture. This may be due to the loss of torsion in the fibers it contributes to the AT (van Gils *et al.,* 1996). We sought to address this by targeting the medial gastrocnemius with a hypertrophy stimulus with the feet turned out and progressed to allowing the ankle to load into full dorsiflexion to add an eccentric stimulus to increase fascicle length (Franchi *et al.*, 2017; Geremia *et al.*, 2019; Nunes *et al.*, 2020).

This study observed similar deficits in IKD plantarflexion T_{peak} in the seated calf isometric test, suggesting that the soleus accounted for overall PF strength deficits (O'Neill *et al.,* 2019). The ongoing sizeable inner range plantarflexion strength deficits may be explained by atrophy and altered architecture of the medial gastrocnemius muscle resulting in a shift towards a more narrow region in its force-length relationship due to a loss in sarcomeres in series (Hullfish *et al.,* 2019). Also, it affects the muscle sarcomeres' force-velocity relationship, where the architecture becomes less suited for high shortening velocities, thus negatively impacting the ankle joint power (Lieber and Ward, 2011). Willy et al. (2017) observed a reduction in ankle joint power and increased kinetic loading at the knee in runners following an AT rupture. Our study demonstrated increased knee joint power during vertical single-leg drop jumps on the injured limb and increased hip joint power in the single-leg horizontal rebound. Visually,

during single-leg horizontal plyometric exercises, we observed the patient landing in greater hip flexion on his injured side and relying on hip extension for propulsion. During vertical hopping, there was more knee flexion during stance on his injured limb and less ankle dorsiflexion. The lower-limb strength and biomechanical impairments observed in this study are common findings with AT ruptures. The joint angle torque deficits during IKD testing and ankle joint power impairments highlighted with 3D biomechanical assessment provide more detail into the potential underlying factors.

4.3.8. LEARNING POINTS

- Asymmetries in IKD PF T_{peak} with knee extension and seated calf isometric force were similar at each assessment, indicating a loss of soleus force generation capacity following an AT rupture.
- Inner-range PF strength deficits reported following an AT rupture were quantified by measuring joint angle torque on an ankle IKD test.
- Lower-limb biomechanical impairments, such as reduced ankle joint power, were identified with 3D motion capture and force plate measurements during a single-leg drop jump, horizontal rebound, and cutting manoeuvre.

5. GENERAL DISCUSSION

5.1. SUMMARY OF THE MAIN FINDINGS OF THE THESIS

This thesis sought to evaluate the rehabilitation of AT injuries using a biomechanical assessment approach to guide exercise progression and return to sport. The thesis centred around two themes - the first around assessments in studies 1 and 2, and the second around rehabilitation in studies 3, 4 and 5. We tested the reliability and biomechanical features of some critical performance diagnostic tests to govern rehabilitation and return to sport following AT injuries. We conducted a randomised controlled trial to investigate a criteria-based rehabilitation program for chronic mid-portion Achilles tendinopathy and to apply a similar pathway for a case report for a player with an AT surgical repair following a rupture.

In ***Study 1,*** we designed a novel horizontal single-leg plyometric exercise test and evaluated its reliability and biomechanical features. We identified the need to assess horizontal reactive strength qualities to complement the existing knowledge of vertical reactive strength. Emerging evidence suggested that higher joint kinetic outputs come from the ankle and higher tendon loading than vertical hops. We felt this would provide a valuable assessment tool following AT and ankle injuries. We demonstrated moderate-to-excellent reliability for rebound distance, horizontal reactive strength and most key performance and biomechanical features. Our analysis revealed that the highest joint work and power occurred at the ankle, with greater joint stiffness at the knee than the ankle and higher peak joint moments at the hip. We investigated the relationships between spatiotemporal and joint biomechanical features with performance and whole-body stiffness. We found significant correlations between horizontal ground reaction force with rebound distance and reactive strength index. Contact time and ankle and knee joint stiffness correlated strongly with vertical and leg stiffness. Due to the novel nature of this test, we evaluated how many trials are required to obtain a stable measure of performance and found that three trials per leg following three familiarisation trials are sufficient. We applied this novel test as a critical rehabilitation outcome measure in conjunction with vertical drop jump tests in Studies 3, 4 and 5.

In ***Study 2***, we assessed the reliability of a seated calf isometric F_{peak}, IKD T_{peak}, and joint angle-specific torque at 30°/sec speed with knee-extended. In our Achilles randomised-controlled trial in studies 3 and 4, we performed IKD tests with both knee-flexed and knee extended at speeds of 60°/sec. Following this, we re-evaluated our protocols as we felt that 60°/sec was too high to gain a measure reflective of maximal calf muscle strength. Another consideration was that many professional sports clubs, institutes and training centres use force

platform technology. The critical role of PFs, particularly the soleus, as the most significant lower limb force contributor for running and jumping strengthened the need for a reliable and robust means of assessing its strength. We also sought to evaluate the reliability of an IKD test at 30°/sec with an extended knee, as previous studies have used much higher speeds which may reflect the joint angular velocity of running but not the high muscle torque demands of running. Considering the often observed joint angle-specific PF strength deficits following specific injuries, we felt it would be valuable to measure torque at 10° dorsiflexion and 20° plantarflexion and evaluate its reliability. Our study demonstrated good reliability for peak vertical force in the seated calf isometric test and PF T_{peak} and torque at 10°dorsiflexion in the IKD test. However, we only found moderate reliability for torque at 20° plantarflexion. We used these two tests in our case-control study of a player who had an AT repair following a rupture in ***Study 5***.

In ***Study 3***, we designed a study protocol for a randomised controlled trial for a criteria-based rehabilitation program for chronic mid-portion Achilles tendinopathy. Many rehabilitation programs use pain symptoms in response to exercise to guide the progression of exercises and return to sport. There is a lack of knowledge about using biomechanical changes and strength targets to progress through the phases of rehabilitation and inform return to sport decision-making. We trialled an intervention (SSC6) designed over two to three sessions per week with a focus on high intensity and achieving strength and hop test targets to govern progression and exercising to a maximal tolerable level of pain. Our control group (SG) followed Silbernagel's highly-regarded Achilles tendinopathy rehabilitation program. We used the VISA-A questionnaire as our primary outcome measure and compared responses within and between groups while assessing PF IKD strength, vertical and horizontal hops, and running biomechanics over a 12-week intervention with adherence and fidelity monitored. The patients would also be required to complete 6, 12 and 24-month follow-ups through an online questionnaire. This study was registered on ClinicalTrials.gov and peer-reviewed and published in BMC Musculoskeletal Disorders journal.

In ***Study 4***, we reported on the preliminary results of our RCT. We have had 28 participants complete our trial thus far, below our powered sample size of fifty. Both groups experienced significant improvements in their VISA-A questionnaire scores over 12 weeks, with most of these improvements achieved in the first six weeks. The SSC6 group experienced a superior improvement of 9 points compared to SG, but this between-group difference did not reach

significance (p = 0.08). The SCC6 group achieved significant gains in IKD T_{peak} with knee-flexed over the 12 weeks, but the between-group changes were insignificant. This finding may be due to participants in the SSC6 group displaying inferior soleus strength prescribed with high-intensity strength exercises targeting that muscle. There were no meaningful changes in hop test scores or running biomechanics over the 12 weeks with this sample size.

In ***Study 5***, we worked with an inter-county gaelic football player who sustained an AT rupture during pre-season training and had a subsequent repair. Throughout a 9-month rehabilitation program, we collected PROMs, strength, reactive strength and lower limb biomechanical data at regular intervals. We used this data to guide our rehabilitation. The main findings from this case report were the persistent deficits in PF T_{peak} and torque at 20° plantarflexion, which were identified by the ankle IKD test at 30°/sec, as well as reduced ankle joint power during the single leg hop tests.

5.2. PRACTICAL APPLICATIONS

Theme 1 of this thesis showed that the biomechanical features of a novel horizontal plyometric test are reliable and that the ankle is the dominant joint for peak power and work. When combined with existing knowledge on the soleus muscle force contribution and higher AT loading rates, this clinically-useful test may reveal impairments in ankle joint output and provide a useful outcome measure in rehabilitating ankle, AT, and calf-related injuries. F_{peak} in a seated calf isometric test, which represents a measure of maximal soleus strength, is reliable. With force plate technology more affordable and widely available in recent years, this test can be performed time-efficiently. We used a rachet strapping over the knee, which allowed the participant to find a comfortable position to produce maximal force. Where IKD testing is available, measuring at a speed of 30°/sec is also reliable for T_{peak} and torque at 10° dorsiflexion with PF torque scores averaging well above 100% bodyweight. We recommend wearing more minimalist shoes for this test which may help set a more accurate anatomical zero and achieve a more reliable measure of torque at 20° plantarflexion.

In ***Theme 2***, we found that a criteria-based rehabilitation program focussed on two-to-three high-intensity sessions per week led to superior improvements in VISA-A questionnaire scores – particularly in the first six weeks, but did not reach significance with our sample size. Athletic or time-restricted Achilles tendinopathy patients can achieve significant improvements with a

more high-intensity and outcome-focused rehabilitation program based around tow-to-three sessions per week. Therefore, a daily schedule of exercises focussed on pain response to progress may not be necessary or advantageous.

The use of performance testing and lower-limb biomechanical evaluation of running, change of direction, and vertical and horizontal hopping revealed distinct deficits and functional impairments in a patient who had an AT repair following a rupture. These detections helped to guide the direction of rehabilitation.

5.3. LIMITATIONS

One of the main limitations of the findings of our thesis was the relatively small sample sizes in our reliability studies and randomised controlled trial. Ideally, a sample size of thirty would be required to power a reliability study adequately. As outlined in Study 4, the impact of covid-19 from March 2020 was another limitation as it profoundly affected our ability to recruit participants for the RCT at specific periods and led to lower levels of adherence and fidelity for the SSC6 group when gyms were closed. In hindsight, it would have been valuable to assess hops at baseline in study 4.1 and determine whether improved performance related to the changes in VISA-A scores in the first six weeks. We opted against hop testing at baseline as we felt that pain and potential kinesiophobia would augment any lower limb biomechanical impairments and injured limb performance deficits and inflate the level of improvements between week 0-6. However, given that the largest improvements in VISA-A outcome measures occurred between week 0-6, and the higher baseline VISA-A scores than reported in other studies, an assessment of vertical and horizontal hop performance and function from the beginning may have provided valuable insights. The small sample sizes in Study 4 hinder our ability to obtain any meaningful interpretations from the hop test and running analysis. Another limitation in the findings of our thesis was the angular velocities used in Study 4 for IKD testing. When designing the protocol we selected 60°/sec for both knee-extended and knee-flexed protocols. Upon reflection we felt that slower angular velocities such as 30°/sec would be more meaningful as a higher number of participants would achieve peak torque values of greater than 100% body mass – more representative of the muscle forces experienced during running. We tested the reliability of this angular velocity in Study 3 along with seated calf isometric peak force to evaluate soleus maximal strength and applied this in the AT repair case report in Study 5.

5.4. FUTURE DIRECTIONS

The findings of this thesis ought to be applied in conjunction with existing knowledge and new evidence relating to Achilles tendinopathy. An individualised program for Achilles tendinopathy is necessary given the multi-factorial nature of the pathology. This first requires a comprehensive profiling to help identify the main factors relating to their pathology development and to individualise their treatment plan. There is emerging evidence for non-resolving inflammatory processes and genetic variations of collagen for chronic cases, which may predispose specific cohorts (Dean *et al.*, 2017; Millar *et al.,* 2017; Dakin *et al.*, 2018; Mosca *et al.*, 2018). The addition of biological interventions to a rehabilitation program may prove valuable in the future for chronic cases which fail to resolve to rehabilitation in a reasonable timeframe (Millar *et al.*, 2021). It is also critical to identify patients who fit the biopsychosocial model and to provide further support on dealing with the psychosocial aspects of their pain (Edgar *et al.*, 2022). As evident in this thesis, some patients may present with a reasonable level of calf strength and hop test performance and display sound running gait features. Identifying the most likely driving force behind the development of pathology and symptoms is key.

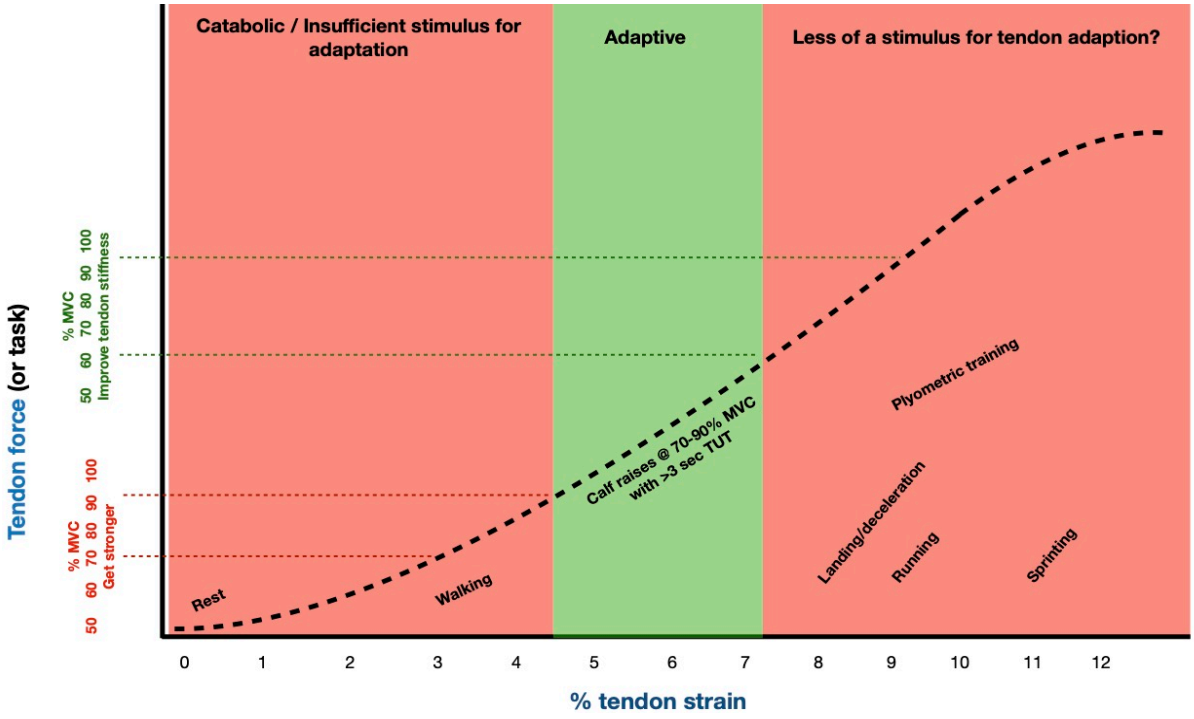


Fig. 5. An illustration of the tendon loading based on various exercise tasks and a hypothetical example of the % MVC required by two individuals to achieve strains of 4.5-7% for positive tendon adaptations. (Adapted from Pizzolato et al., 2019; Arampatzis, Mersmann and Bohm, 2020; Devaprakash et al., 2022; Lazarczuk et al., 2022; McMahon, 2022)

The future direction of individualised programming will most likely target levels of strain to achieve a positive tendon adaptive response as illustrated in Figure 5. The ability to measure tendon strain in response to the force applied from the PFs may enable clinicians to individualise the loading of calf strength exercises to achieve an adaptive strain of 4.5-7% (Pizzolato *et al.*, 2019; Arampatzis *et al.,* 2020). For some athletes with high levels of calf strength, this may mean working at a lower percentage of maximal voluntary contraction (Arampatzis *et al.,* 2020). In contrast, others lacking in calf strength may initially need a more hypertrophy stimulus to develop the force required to achieve those strain zones (Arampatzis *et al.,* 2020). Given the individualised loading patterns of the three key PF muscles and the alterations following tendinopathy, it may be pertinent to measure the morphological properties of each muscle to determine if one muscle needs more of a stimulus over the other muscles. For example, the lateral gastrocnemius muscle appears to suffer the biggest loss of neural drive in a cohort of patients with Achilles tendinopathy (Crouzier *et al.*, 2019; Fernandes *et al.*, 2022). Even though it has the smallest volume and PCSA of the three muscles, it may still upset the loading balance in the AT with differential strain patterns (Arndt *et al.*, 2012; Slane and Thelen, 2014). By assessing this level of detail, an extra layer of precision can be applied to rehabilitating AT injuries.

5.5. CONCLUSION

This thesis contributed new perspectives on the management of AT injuries and the reliability of performance testing. This was achieved despite the small sample sizes and the impact of the covid-19 pandemic at critical stages of the data collection. The findings of our thesis are most relevant to recreational and elite sports people with AT injuries, given our participants' sporting and age profiles. We demonstrated good reliability for measuring plantar maximal strength in two tests and performance and biomechanical features for a single-leg horizontal plyometric exercise. The findings of these tests informed the rehabilitation of a football player who underwent an AT repair following a rupture. In our randomised controlled trial, we found that a criteria-based rehabilitation program performed two-to-three times per week while exercising to a maximal level of tolerable pain resulted in a greater increase in VISA-A questionnaire scores – which is a gold standard clinical outcome measure. However, due to our small sample size at the time of submission, completing the trial with the necessary number of participants is warranted for full conclusions about significance level.

6. BIBLIOGRAPHY

6.1 REFERENCES

Abate, M., Silbernagel, K.G., Siljeholm, C., Di Iorio, A., De Amicis, D., Salini, V., Werner, S., and Paganelli, R. (2009) 'Pathogenesis of tendinopathies: inflammation or degeneration?', *Arthritis Research & Therapy*, 11(3), p. 235. Available at: https://doi.org/10.1186/ar2723.

Abdelsattar, M., Konrad, A. and Tilp, M. (2018) 'Relationship between achilles tendon stiffness and ground contact time during drop jumps', *Journal of Sports Science and Medicine*, 17(2), pp. 223–228.

Ackermann, P.W. (2013) 'Neuronal regulation of tendon homoeostasis'. Available at: https://doi.org/10.1111/iep.12028.

Ackermann, P.W., Alim, M., Pejler, G. and Peterson, M. (2022) 'Tendon pain – what are the mechanisms behind it?', *Scandinavian Journal of Pain*. Available at: https://doi.org/10.1515/sjpain-2022-0018.

Aeles, J. and Vanwanseele, B. (2019) 'Do Stretch-Shortening Cycles Really Occur in the Medial Gastrocnemius? A Detailed Bilateral Analysis of the Muscle-Tendon Interaction During Jumping', *Front. Physiol*, 10, p. 1504. Available at: https://doi.org/10.3389/fphys.2019.01504.

Ahmed, I.M. Lagopoulos, M., McConnell, P., Soames, R. W., and Sefton, G. K. (1998) 'Blood supply of the Achilles tendon', *Journal of Orthopaedic Research*, 16(5), pp. 591–596. Available at: https://doi.org/10.1002/jor.1100160511.

Albracht, K. and Arampatzis, A. (2013) 'Exercise-induced changes in triceps surae tendon stiffness and muscle strength affect running economy in humans', *European Journal of Applied Physiology*, 113(6), pp. 1605–1615. Available at: https://doi.org/10.1007/s00421-012-2585-4.

Albracht, K., Arampatzis, A. and Baltzopoulos, V. (2008) 'Assessment of muscle volume and physiological cross-sectional area of the human triceps surae muscle in vivo', *Journal of Biomechanics*, 41(10), pp. 2211–2218. Available at: https://doi.org/10.1016/j.jbiomech.2008.04.020.

Alfredson, H. Pietilä, T., Jonsson, P., and Lorentzon, R. (1998) 'Heavy-Load Eccentric Calf Muscle Training For the Treatment of Chronic Achilles Tendinosis', *Am J Sports Med*, 26(3), pp. 360–366.

Almonroeder, T., Willson, J.D. and Kernozek, T.W. (2013) 'The effect of foot strike pattern on achilles tendon load during running', *Annals of Biomedical Engineering*, 41(8), pp. 1758–1766. Available at: https://doi.org/10.1007/s10439-013-0819-1.

Al-Uzri, M., O'Neill, S., Watson, P., and Kelly, C. (2016) 'Reliability of isokinetic dynamometry of the plantarflexors in knee flexion and extension', *Physiotherapy Practice and Research*, 38(1), pp. 49–57. Available at: https://doi.org/10.3233/PPR-160084.

Apaydin, N. Bozkurt, M., Loukas, M., Vefali, H., Tubbs, R. S., and Esmer, A. F. (2009) 'Relationships of the sural nerve with the calcaneal tendon: an anatomical study with surgical and clinical implications', *Surgical and Radiologic Anatomy*, 31(10), pp. 775–780. Available at: https://doi.org/10.1007/s00276-009-0520-0.

Arampatzis, A. Karamanidis, K., Stafilidis, S., Morey-Klapsing, G., DeMonte, G., and Brüggemann, G. P. (2006) 'Effect of different ankle- and knee-joint positions on gastrocnemius medialis fascicle length and EMG activity during isometric plantar flexion', *Journal of Biomechanics*, 39(10), pp. 1891–1902. Available at: https://doi.org/10.1016/j.jbiomech.2005.05.010.

Arampatzis, A. Karamanidis, K., Morey-Klapsing, G., De Monte, G., and Stafilidis, S. (2007) 'Mechanical properties of the triceps surae tendon and aponeurosis in relation to intensity of sport activity', *Journal of Biomechanics*, 40(9), pp. 1946–1952. Available at: https://doi.org/10.1016/j.jbiomech.2006.09.005.

Arampatzis, A., Mersmann, F. and Bohm, S. (2020) 'Individualized Muscle-Tendon Assessment and Training', *Frontiers in Physiology*, 11, p. 723. Available at: https://doi.org/10.3389/fphys.2020.00723.

Arellano, C.J. Konow, N., Gidmark, N. J., and Roberts, T. J. (2019) 'Evidence of a tunable biological spring : elastic energy storage in aponeuroses varies with transverse strain in vivo', pp. 3–8.

Arndt, A. Bengtsson, A. S., Peolsson, M., Thorstensson, A., and Movin, T. (2012) 'Non-uniform displacement within the Achilles tendon during passive ankle joint motion', *Knee Surgery, Sports Traumatology, Arthroscopy*, 20(9), pp. 1868–1874. Available at: https://doi.org/10.1007/s00167-011-1801-9.

Arnoczky, S.P., Lavagnino, M. and Egerbacher, M. (2007) 'The mechanobiological aetiopathogenesis of tendinopathy: is it the over-stimulation or the under-stimulation of tendon cells?', *International Journal of Experimental Pathology*, 88(4), pp. 217–226. Available at: https://doi.org/10.1111/j.1365-2613.2007.00548.x.

Arnold, E.M. and Delp, S.L. (2011) 'Fibre operating lengths of human lower limb muscles during walking', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 366(1570), pp. 1530–1539. Available at: https://doi.org/10.1098/rstb.2010.0345.

Arya, S. and Kulig, K. (2010) 'Tendinopathy alters mechanical and material properties of the Achilles tendon', *Journal of Applied Physiology*, 108(3), pp. 670–675. Available at: https://doi.org/10.1152/japplphysiol.00259.2009.

Aubry, S. Risson, J. R., Kastler, A., Barbier-Brion, B., Siliman, G., Runge, M., and Kastler, B. (2013) 'Biomechanical properties of the calcaneal tendon in vivo assessed by transient shear wave elastography', *Skeletal Radiology*, 42(8), pp. 1143–1150. Available at: https://doi.org/10.1007/s00256-013-1649-9.

Azevedo, L.B. Lambert, M. I., Vaughan, C. L., O'Connor, C. M., and Schwellnus, M. P. (2009) 'Biomechanical variables associated with Achilles tendinopathy in runners', *British Journal of Sports Medicine* [Preprint]. Available at: https://doi.org/10.1136/bjsm.2008.053421.

Azizi, E. and Roberts, T.J. (2009) 'Biaxial strain and variable stiffness in aponeuroses', *Journal of Physiology*, 587(17), pp. 4309–4318. Available at: https://doi.org/10.1113/jphysiol.2009.173690.

Azizi, E. and Roberts, T.J. (2014) ‘Geared up to stretch : pennate muscle behavior during active lengthening’, pp. 376–381. Available at: https://doi.org/10.1242/jeb.094383.

Baar, K. (2019) ‘Stress Relaxation and Targeted Nutrition to Treat Patellar Tendinopathy’, *International Journal of Sport Nutrition and Exercise Metabolism*, 29(4), pp. 453–457. Available at: https://doi.org/10.1123/ijsnem.2018-0231.

Baida, S.R., Gore, S. J., Franklyn-Miller, A. D., and Moran, K. A. (2018) ‘Does the amount of lower extremity movement variability differ between injured and uninjured populations? A systematic review’, *Scandinavian Journal of Medicine and Science in Sports*, 28(4), pp. 1320–1338. Available at: https://doi.org/10.1111/sms.13036.

Balius, R., Rodas, G., Pedret, C., Capdevila, L., Alomar, X., and Bong, D. A. (2014) ‘Soleus muscle injury: sensitivity of ultrasound patterns’, *Skeletal Radiology*, 43(6), pp. 805–812. Available at: https://doi.org/10.1007/s00256-014-1856-z.

Balius, R. Álvarez, G., Baró, F., Jiménez, F., Pedret, C., Costa, E., and Martínez-Puig, D. (2016) ‘A 3-Arm Randomized Trial for Achilles Tendinopathy: Eccentric Training, Eccentric Training Plus a Dietary Supplement Containing Mucopolysaccharides, or Passive Stretching Plus a Dietary Supplement Containing Mucopolysaccharides’, *Current Therapeutic Research*, 78, pp. 1–7. Available at: https://doi.org/10.1016/j.curtheres.2016.11.001.

Barker-Davies, R.M., Nicol, A., McCurdie, I., Watson, J., Baker, P., Wheeler, P., Fong, D., Lewis, M., and Bennett, A. N. (2017) ‘Study protocol: a double blind randomised control trial of high volume image guided injections in Achilles and patellar tendinopathy in a young active population’, *BMC Musculoskeletal Disorders*, 18(1), pp. 1–12. Available at: https://doi.org/10.1186/s12891-017-1564-7.

Baxter, J. R., Corrigan, P., Hullfish, T. J., O'Rourke, P., and Silbernagel, K. G. (2021) ‘Exercise Progression to Incrementally Load the Achilles Tendon’, *Medicine and Science in Sports and Exercise*, 53(1), pp. 124–130. Available at: https://doi.org/10.1249/MSS.0000000000002459.

Baxter, J.R., Farber, D.C. and Hast, M.W. (2019) ‘Plantarflexor fiber and tendon slack length are strong determinates of simulated single-leg heel raise height’, *Journal of Biomechanics*, 86, pp. 27-33. Available at: https://doi.org/10.1016/j.jbiomech.2019.01.035.

Beach, Z.M., Gittings, D.J. and Soslowsky, L.J. (2017) ‘Tendon Biomechanics’, in G.L. Canata, P. d’Hooghe, and K.J. Hunt (eds) *Muscle and Tendon Injuries: Evaluation and Management*. Berlin, Heidelberg: Springer, pp. 15–22. Available at: https://doi.org/10.1007/978-3-662-54184-5_2.

Benjamin, M., Toumi, H., Ralphs, J. R., Bydder, G., Best, T. M., and Milz, S. (2006) ‘Where tendons and ligaments meet bone: attachment sites ('entheses’) in relation to exercise and/or mechanical load’, *Journal of Anatomy*, 208(4), pp. 471–490. Available at: https://doi.org/10.1111/j.1469-7580.2006.00540.x.

Beyer, R., Kongsgaard, M., Hougs Kjær, B., Øhlenschlæger, T., Kjær, M., and Magnusson, S. P. (2015) ‘Heavy slow resistance versus eccentric training as treatment for achilles tendinopathy: A randomized controlled trial’, *American Journal of Sports Medicine*, 43(7), pp. 1704–1711. Available at: https://doi.org/10.1177/0363546515584760.

Bjur, D., Alfredson, H. and Forsgren, S. (2005) 'The innervation pattern of the human Achilles tendon: studies of the normal and tendinosis tendon with markers for general and sensory innervation', *Cell and Tissue Research*, 320(1), pp. 201–206. Available at: https://doi.org/10.1007/s00441-004-1014-3.

Blickhan, R. (1989) 'The spring-mass model for running and hopping', *Journal of Biomechanics*, pp. 1217–1227. Available at: https://doi.org/10.1016/0021-9290(89)90224-8.

Blitz, N.M. and Eliot, D.J. (2007) 'Anatomical Aspects of the Gastrocnemius Aponeurosis and Its Insertion: A Cadaveric Study', *Journal of Foot and Ankle Surgery*, 46(2), pp. 101–108. Available at: https://doi.org/10.1053/j.jfas.2006.11.003.

Blitz, N.M. and Eliot, D.J. (2008) 'Anatomical Aspects of the Gastrocnemius Aponeurosis and its Muscular Bound Portion: A Cadaveric Study-Part II', *Journal of Foot and Ankle Surgery*, 47(6), pp. 533–540. Available at: https://doi.org/10.1053/j.jfas.2008.08.006.

Bohm, S., Mersmann, F., Marzilger, R., Schroll, A., and Arampatzis, A. (2015) 'Asymmetry of Achilles tendon mechanical and morphological properties between both legs', *Scandinavian Journal of Medicine and Science in Sports*, 25(1), pp. e124–e132. Available at: https://doi.org/10.1111/sms.12242.

Bohm, S., Mersmann, F., Santuz, A., and Arampatzis, A. (2019) 'The force–length–velocity potential of the human soleus muscle is related to the energetic cost of running', *Proceedings of the Royal Society B: Biological Sciences*, 286(1917), p. 20192560. Available at: https://doi.org/10.1098/rspb.2019.2560.

Bohm, S., Mersmann, F., Santuz, A., and Arampatzis, A. (2021) 'Enthalpy efficiency of the soleus muscle contributes to improvements in running economy', *Proceedings of the Royal Society B: Biological Sciences*, 288(1943), p. 20202784. Available at: https://doi.org/10.1098/rspb.2020.2784.

Bohm, S., Mersmann, F. and Arampatzis, A. (2015) 'Human tendon adaptation in response to mechanical loading: a systematic review and meta-analysis of exercise intervention studies on healthy adults', *Sports Medicine - Open*, 1(1). Available at: https://doi.org/10.1186/s40798-015-0009-9.

Bojsen-Møller, J., Hansen, P., Aagaard, P., Svantesson, U., Kjaer, M., & Magnusson, S. P. (2018) 'Differential displacement of the human soleus and medial gastrocnemius aponeuroses during isometric plantar flexor contractions in vivo', pp. 1908–1914. Available at: https://doi.org/10.1152/japplphysiol.00084.2004.

Bolsterlee, B., Finni, T., D'Souza, A., Eguchi, J., Clarke, E. C., and Herbert, R. D. (2018) 'Three-dimensional architecture of the whole human soleus muscle in vivo', *PeerJ*, 6, p. e4610. Available at: https://doi.org/10.7717/peerj.4610.

Borrell-Carrió, F., Suchman, A.L. and Epstein, R.M. (2004) 'The Biopsychosocial Model 25 Years Later: Principles, Practice, and Scientific Inquiry', *Annals of Family Medicine*, 2(6), pp. 576–582. Available at: https://doi.org/10.1370/afm.245.

Brady, C., Harrison, A. and Comyns, T. (2018) 'A review of the reliability of biomechanical variables produced during the isometric mid-thigh pull and isometric squat and the reporting

of normative data', *Sports Biomechanics*, 19, pp. 1–25. Available at: https://doi.org/10.1080/14763141.2018.1452968.

Bramah, C., Preece, S. J., Gill, N., and Herrington, L. (2018) 'Is There a Pathological Gait Associated With Common Soft Tissue Running Injuries ?', *The American Journal of Sports Medicine*, 46(12), pp. 3023–3031. Available at: https://doi.org/10.1177/0363546518793657.

Bramah, C., Preece, S. J., Gill, N., and Herrington, L. (2021) 'Kinematic Characteristics of Male Runners With a History of Recurrent Calf Muscle Strain Injury', *International Journal of Sports Physical Therapy*, 16(3), pp. 732–740. Available at: https://doi.org/10.26603/001C.22971.

Brazier, J., Bishop, C. and Simons, C. (2014) 'Lower Extremity Stiffness: Effects on Performance and Injury and Implications for Training', *Strenght and Conditioning Journal*, 36(5), pp. 103–112.

Brughelli, M. and Cronin, J. (2008) 'A review of research on the mechanical stiffness in running and jumping: Methodology and implications', *Scandinavian Journal of Medicine and Science in Sports*, 18(4), pp. 417–426. Available at: https://doi.org/10.1111/j.1600-0838.2008.00769.x.

Brukner, P. and Connell, D. (2016) '"Serious thigh muscle strains": beware the intramuscular tendon which plays an important role in difficult hamstring and quadriceps muscle strains', *British Journal of Sports Medicine*, 50(4), pp. 205–208. Available at: https://doi.org/10.1136/bjsports-2015-095136.

Brukner, P., Cook, J.L. and Purdam, C.R. (2018) 'Does the intramuscular tendon act like a free tendon?', *British Journal of Sports Medicine*, 52(19), pp. 1227–1228. Available at: https://doi.org/10.1136/bjsports-2017-098834.

Butler, R.J., Crowell, H.P. and Davis, I.M. (2003) 'Lower extremity stiffness: implications for performance and injury', *Clinical Biomechanics*, 18(6), pp. 511–517. Available at: https://doi.org/10.1016/S0268-0033(03)00071-8.

Challoumas, D., Clifford, C., Kirwan, P., and Millar, N. L. (2019) 'How does surgery compare to sham surgery or physiotherapy as a treatment for tendinopathy? A systematic review of randomised trials', *BMJ Open Sport & Exercise Medicine*, 5(1), p. e000528. Available at: https://doi.org/10.1136/bmjsem-2019-000528.

Challoumas, D., Kirwan, P. D., Borysov, D., Clifford, C., McLean, M., and Millar, N. L. (2019) 'Topical glyceryl trinitrate for the treatment of tendinopathies: a systematic review', *British Journal of Sports Medicine*, 53(4), pp. 251–262. Available at: https://doi.org/10.1136/bjsports-2018-099552.

Charvet, B., Ruggiero, F. and Le Guellec, D. (2012) 'The development of the myotendinous junction. A review', *Muscles, Ligaments and Tendons Journal*, 2(2), pp. 53–63.

Chen, T. L., Wong, D. W., Wang, Y., Tan, Q., Lam, W. K., and Zhang, M. (2020). Changes in segment coordination variability and the impacts of the lower limb across running mileages in half marathons: Implications for running injuries. *Journal of sport and health science*, *11*(1), 67–74. https://doi.org/10.1016/j.jshs.2020.09.006

Chen, T. M., Rozen, W. M., Pan, W. R., Ashton, M. W., Richardson, M. D., and Taylor, G. I. (2009) 'The arterial anatomy of the Achilles tendon: Anatomical study and clinical implications', *Clinical Anatomy*, 22(3), pp. 377–385. Available at: https://doi.org/10.1002/ca.20758.

Cheng, G.C. and Mcmahon, T.A. (1976) 'McMahon 1990 - The mechanics of running how does stiffness couple with speed.pdf', *J Biomech*, pp. 65-78.

Chester, R., Costa, M. L., Shepstone, L., and Donell, S. T. (2003) 'Reliability of Isokinetic Dynamometry in Assessing Plantarflexion Torque Following Achilles Tendon Rupture', *Foot & Ankle International*, 24(12), pp. 909–915. Available at: https://doi.org/10.1177/107110070302401207.

Child, S., Bryant, A. L., Clark, R. A., and Crossley, K. M. (2010) 'Mechanical properties of the achilles tendon aponeurosis are altered in athletes with achilles tendinopathy', *American Journal of Sports Medicine*, 38(9), pp. 1885–1893. Available at: https://doi.org/10.1177/0363546510366234.

Chimenti, R. L., Cychosz, C. C., Hall, M. M., and Phisitkul, P. (2017) 'Current Concepts Review Update: Insertional Achilles Tendinopathy', *Foot and Ankle International*, 38(10), pp. 1160–1169. Available at: https://doi.org/10.1177/1071100717723127.

Chimenti, R. L., Post, A. A., Silbernagel, K. G., Hadlandsmyth, K., Sluka, K. A., Moseley, G. L., and Rio, E. (2021) 'Kinesiophobia Severity Categories and Clinically Meaningful Symptom Change in Persons With Achilles Tendinopathy in a Cross-Sectional Study: Implications for Assessment and Willingness to Exercise', *Frontiers in Pain Research*, 2. Available at: https://www.frontiersin.org/articles/10.3389/fpain.2021.739051 (Accessed: 11 October 2022).

Chow, R. (2000) 'Sonographic studies of human soleus and gastrocnemius muscle architecture : gender variability', pp. 236–244.

Clark, W. H., & Franz, J. R. (2021). Age-related changes to triceps surae muscle-subtendon interaction dynamics during walking. Scientific reports, 11(1), 21264. https://doi-org.proxy.unice.fr/10.1038/s41598-021-00451-y

Coleman, D. R., Cannavan, D., Horne, S., and Blazevich, A. J. (2012) 'Leg stiffness in human running: Comparison of estimates derived from previously published models to direct kinematic-kinetic measures', *Journal of Biomechanics*, 45(11), pp. 1987–1991. Available at: https://doi.org/10.1016/j.jbiomech.2012.05.010.

Comins, J., Siersma, V., Couppe, C., Svensson, R. B., Johansen, F., Malmgaard-Clausen, N. M., and Magnusson, S. P. (2021) 'Assessment of content validity and psychometric properties of VISA-A for Achilles tendinopathy', *PLOS ONE*. Edited by A. Rushton, 16(3), p. e0247152. Available at: https://doi.org/10.1371/journal.pone.0247152.

Cook, J. L., Rio, E., Purdam, C. R., and Docking, S. I. (2016) 'Revisiting the continuum model of tendon pathology: What is its merit in clinical practice and research?', *British Journal of Sports Medicine*, 50(19), pp. 1187–1191. Available at: https://doi.org/10.1136/bjsports-2015-095422.

Cook, J.L. and Docking, S.I. (2015) ‘Rehabilitation will increase the “capacity” of your - insert musculoskeletal tissue here. Defining “tissue capacity”: A core concept for clinicians’, *British Journal of Sports Medicine*, 49(23), pp. 1484–1485. Available at: https://doi.org/10.1136/bjsports-2015-094849.

Cook, J.L., Khan, K.M. and Purdam, C. (2002) ‘Achilles tendinopathy’, *Manual Therapy*, 7(3), pp. 121–130. Available at: https://doi.org/10.1054/math.2002.0458.

Cook, J.L. and Purdam, C.R. (2009) ‘Is tendon pathology a continuum? A pathology model to explain the clinical presentation of load-induced tendinopathy’, *British Journal of Sports Medicine*, 43(6), pp. 409–416. Available at: https://doi.org/10.1136/bjsm.2008.051193.

Cook, J.L. and Purdam, C.R. (2014) ‘The challenge of managing tendinopathy in competing athletes’, *British Journal of Sports Medicine*, 48(7), pp. 506–509. Available at: https://doi.org/10.1136/bjsports-2012-092078.

Coombes, B. K., Tucker, K., Vicenzino, B., Vuvan, V., Mellor, R., Heales, L., Nordez, A., and Hug, F. (2018) ‘Achilles and patellar tendinopathy display opposite changes in elastic properties: A shear wave elastography study’, *Scandinavian Journal of Medicine and Science in Sports*, 28(3), pp. 1201–1208. Available at: https://doi.org/10.1111/sms.12986.

Corrigan, P., Zellers, J. A., Balascio, P., Silbernagel, K. G., and Cortes, D. H. (2019) ‘Quantification of Mechanical Properties in Healthy Achilles Tendon Using Continuous Shear Wave Elastography: A Reliability and Validation Study’, *Ultrasound in Medicine and Biology*, 45(7), pp. 1574–1585. Available at: https://doi.org/10.1016/j.ultrasmedbio.2019.03.015.

Crouzier, M., Tucker, K., Lacourpaille, L., Doguet, V., Fayet, G., Dauty, M., and Hug, F. (2019) ‘Force-sharing within the Triceps Surae’, *Medicine & Science in Sports & Exercise*, (10), p. 1. Available at: https://doi.org/10.1249/mss.0000000000002229.

Dakin, S. G., Buckley, C. D., Al-Mossawi, M. H., Hedley, R., Martinez, F. O., Wheway, K., Watkins, B., and Carr, A. J. (2017) ‘Persistent stromal fibroblast activation is present in chronic tendinopathy’, *Arthritis Research and Therapy*, 19(1), pp. 1–11. Available at: https://doi.org/10.1186/s13075-016-1218-4.

Dakin, S. G., Newton, J., Martinez, F. O., Hedley, R., Gwilym, S., Jones, N., Reid, H. A. B., Wood, S., Wells, G., Appleton, L., Wheway, K., Watkins, B., and Carr, A. J. (2018) ‘Chronic inflammation is a feature of Achilles tendinopathy and rupture’, *British Journal of Sports Medicine*, 52(6), pp. 359–367. Available at: https://doi.org/10.1136/bjsports-2017-098161.

Dalmau-Pastor, M., Fargues-Polo, B., Jr, Casanova-Martínez, D., Jr, Vega, J., and Golanó, P. (2014). Anatomy of the triceps surae: a pictorial essay. *Foot and ankle clinics*, *19*(4), 603–635. https://doi.org/10.1016/j.fcl.2014.08.002

Davey, K., Read, P., Coyne, J., Jarvis, P., Turner, A., Brazier, J., Šarabon, N., Jordan, M.J., and Bishop, C. (2021) ‘An Assessment of the Hopping Strategy and Inter-Limb Asymmetry during the Triple Hop Test: A Test–Retest Pilot Study’, *Symmetry*, 13(10), p. 1890. Available at: https://doi.org/10.3390/sym13101890.

Davies, W.T., Myer, G.D. and Read, P.J. (2020) 'Is It Time We Better Understood the Tests We are Using for Return to Sport Decision Making Following ACL Reconstruction? A Critical Review of the Hop Tests', *Sports Medicine*, 50(3), pp. 485–495. Available at: https://doi.org/10.1007/s40279-019-01221-7.

De Jonge, S., de Vos, R. J., Van Schie, H. T., Verhaar, J. A., Weir, A., and Tol, J. L. (2010) 'One-year follow-up of a randomised controlled trial on added splinting to eccentric exercises in chronic midportion Achilles tendinopathy', *British Journal of Sports Medicine*, 44(9), pp. 673–677. Available at: https://doi.org/10.1136/bjsm.2008.052142.

De la Fuente, C., Ramirez-Campillo, R., Gallardo-Fuentes, F., Alvarez, C., Bustamante, C., Henríquez, H., and Carpes, F. P. (2022). Pattern analysis of a complete Achilles tendon rupture suffered during high jump preparation in an official national-level athletic competition. *Sports biomechanics*, *21*(3), 312–322. Available at: https://doi.org/10.1080/14763141.2019.1651897.

De Vos, R. J., van der Vlist, A. C., Zwerver, J., Meuffels, D. E., Smithuis, F., van Ingen, R., van der Giesen, F., Visser, E., Balemans, A., Pols, M., Veen, N., den Ouden, M., and Weir, A. (2021) 'Dutch multidisciplinary guideline on Achilles tendinopathy', *Br J Sports Med*, *55*(20), pp. 1125–1134. Available at: https://doi.org/10.1136/bjsports-2020-103867.

Dean, B. J. F., Dakin, S. G., Millar, N. L., and Carr, A. J. (2017) 'Review: Emerging concepts in the pathogenesis of tendinopathy', *The Surgeon*, 15(6), pp. 349–354. Available at: https://doi.org/10.1016/j.surge.2017.05.005.

Debenham, J. R., Travers, M. J., Gibson, W., Campbell, A., and Allison, G. T. (2016) 'Achilles tendinopathy alters stretch shortening cycle behaviour during a sub-maximal hopping task', *Journal of Science and Medicine in Sport*, 19(1), pp. 69–73. Available at: https://doi.org/10.1016/j.jsams.2014.11.391.

Devaprakash, D., Graham, D. F., Barrett, R. S., Lloyd, D. G., Obst, S. J., Kennedy, B., Adams, K. L., Kiely, R. J., Hunter, A., Vlahovich, N., Pease, D. L., Shim, V. B., Besier, T. F., Zheng, M., Cook, J. L., and Pizzolato, C. (2022) 'Free Achilles tendon strain during selected rehabilitation, locomotor, jumping, and landing tasks', *Journal of Applied Physiology* [Preprint]. Available at: https://doi.org/10.1152/japplphysiol.00662.2021.

Dobbs, C. W., Gill, N. D., Smart, D. J., & McGuigan, M. R. (2015) 'Relationship Between Vertical and Horizontal Jump Variables and Muscular Performance in Athletes', *The Journal of Strength & Conditioning Research*, 29(3), pp. 661–671. Available at: https://doi.org/10.1519/JSC.0000000000000694.

Docking, S. I., and Cook, J. (2016). Pathological tendons maintain sufficient aligned fibrillar structure on ultrasound tissue characterization (UTC). *Scandinavian journal of medicine & science in sports*, *26*(6), pp. 675–683. Available at: https://doi.org/10.1111/sms.12491.

Donoghue, O. A., Harrison, A. J., Coffey, N., & Hayes, K. (2008) 'Functional data analysis of running kinematics in Chronic Achilles tendon injury', *Medicine and Science in Sports and Exercise*, 40(7), pp. 1323–1335. Available at: https://doi.org/10.1249/MSS.0b013e31816c4807.

Dorn, T.W., Schache, A.G. and Pandy, M.G. (2012) 'Muscular strategy shift in human running: dependence of running speed on hip and ankle muscle performance', *Journal of Experimental Biology*, 215(11), pp. 1944–1956. Available at: https://doi.org/10.1242/jeb.064527.

Earp, J. E., Kraemer, W. J., Cormie, P., Volek, J. S., Maresh, C. M., Joseph, M., and Newton, R. U. (2011) 'Influence of muscle-tendon unit structure on rate of force development during the squat, countermovement, and drop jumps', *Journal of Strength and Conditioning Research*, 25(2), pp. 340–347. Available at: https://doi.org/10.1519/JSC.0b013e3182052d78.

Edama, M., Kubo, M., Onishi, H., Takabayashi, T., Inai, T., Yokoyama, E., Hiroshi, W., Satoshi, N., and Kageyama, I. (2015) 'The twisted structure of the human Achilles tendon', *Scandinavian Journal of Medicine and Science in Sports*, 25(5), pp. e497–e503. Available at: https://doi.org/10.1111/sms.12342.

Edgar, N., Clifford, C., O'Neill, S., Pedret, C., Kirwan, P., and Millar, N. L. (2022) 'Biopsychosocial approach to tendinopathy', *BMJ Open Sport & Exercise Medicine*, 8(3), p. e001326. Available at: https://doi.org/10.1136/bmjsem-2022-001326.

Edwards, W.B. (2018) 'Modeling Overuse Injuries in Sport as a Mechanical Fatigue Phenomenon'. Available at: https://doi.org/10.1249/JES.0000000000000163.

Eng, C.M. and Roberts, T.J. (2018) 'Aponeurosis influences the relationship between muscle gearing and force', *Journal of applied physiology (Bethesda, Md. : 1985)*, 125(2), pp. 513–519. Available at: https://doi.org/10.1152/japplphysiol.00151.2018.

Farley, C.T. and González, O. (1996) 'Leg stiffness and stride frequency in human running', *Journal of Biomechanics*, 29(2), pp. 181–186. Available at: https://doi.org/10.1016/0021-9290(95)00029-1.

Farley, C.T. and Morgenroth, D.C. (1999) 'Leg stiffness primarily depends on ankle stiffness during human hopping', *Journal of Biomechanics* [Preprint]. Available at: https://doi.org/10.1016/S0021-9290(98)00170-5.

Farris, D. J., Lichtwark, G. A., Brown, N. A., and Cresswell, A. G. (2016) 'The role of human ankle plantar flexor muscle-tendon interaction and architecture in maximal vertical jumping examined in vivo', *Journal of Experimental Biology*, 219(4), pp. 528–534. Available at: https://doi.org/10.1242/jeb.126854.

Farris, D.J. and Sawicki, G.S. (2012) 'Human medial gastrocnemius force-velocity behavior shifts with locomotion speed and gait', *Proceedings of the National Academy of Sciences*, 109(3), pp. 977–982. Available at: https://doi.org/10.1073/pnas.1107972109.

Fernandes, G. L., Orssatto, L. B. R., Sakugawa, R. L., and Trajano, G. S. (2022). Lower motor unit discharge rates in gastrocnemius lateralis, but not in gastrocnemius medialis or soleus, in runners with Achilles tendinopathy: a pilot study. *European journal of applied physiology*, 1–11. Advance online publication. Available at: https://doi.org/10.1101/2022.05.05.22274750.

Fernandes, G. L., Orssatto, L. B. R., Shield, A. J., and Trajano, G. S. (2022) 'Runners with mid-portion Achilles tendinopathy have greater triceps surae intracortical inhibition than

healthy controls', *Scandinavian Journal of Medicine & Science in Sports*, 32(4), pp. 728–736. Available at: https://doi.org/10.1111/sms.14111.

Finni, T., Peltonen, J., Stenroth, L., and Cronin, N. J. (2013) 'Viewpoint: On the hysteresis in the human Achilles tendon', *Journal of Applied Physiology*, 114(4), pp. 515–517. Available at: https://doi.org/10.1152/japplphysiol.01005.2012.

Finni, T. and Lichtwark, G.A. (2016) 'Rise of the tendon research', *Scandinavian Journal of Medicine and Science in Sports*, 26(9), pp. 992–994. Available at: https://doi.org/10.1111/sms.12731.

Firth, B. L., Dingley, P., Davies, E. R., Lewis, J. S., and Alexander, C. M. (2010) 'The Effect of Kinesiotape on Function, Pain, and Motoneuronal Excitability in Healthy People and People With Achilles Tendinopathy', *Clinical Journal of Sport Medicine*, 20(6), pp. 416–421. Available at: https://doi.org/10.1097/JSM.0b013e3181f479b0.

Fletcher, J.R., Esau, S.P. and MacIntosh, B.R. (2010) 'Changes in tendon stiffness and running economy in highly trained distance runners', *European Journal of Applied Physiology*, 110(5), pp. 1037–1046. Available at: https://doi.org/10.1007/s00421-010-1582-8.

Fong, G., Backman, L. J., Hart, D. A., Danielson, P., McCormack, B., and Scott, A. (2013) 'Substance P Enhances Collagen Remodeling and MMP-3 Expression By Human Tenocytes', *Journal of orthopaedic research : official publication of the Orthopaedic Research Society*, 31(1), pp. 91–98. Available at: https://doi.org/10.1002/jor.22191.

Foster, C. and Lucia, A. (2007) 'The Forgotten Factor in Elite Performance', *Sports Med*, p. 4. Available at: https:// doi.org/10.2165/00007256-200737040-00011

Fouré, A., Nordez, A. and Cornu, C. (2010) 'Plyometric training effects on Achilles tendon stiffness and dissipative properties', *Journal of Applied Physiology*, 109(3), pp. 849–854. Available at: https://doi.org/10.1152/japplphysiol.01150.2009.

Franchi, M. V., Reeves, N. D., & Narici, M. V. (2017) 'Skeletal Muscle Remodeling in Response to Eccentric vs . Concentric Loading : Morphological , Molecular , and Metabolic Adaptations', 8(July), pp. 1–16. Available at: https://doi.org/10.3389/fphys.2017.00447.

Francis, P., Whatman, C., Sheerin, K., Hume, P., and Johnson, M. I. (2019) 'The Proportion of Lower Limb Running Injuries by Gender, Anatomical Location and Specific Pathology: A Systematic Review', *Journal of sports science and medicine*, *18*(1), pp. 21–31.

Franklyn-Miller, A., Richter, C., King, E., Gore, S., Moran, K., Strike, S., and Falvey, E. C. (2017) 'Athletic groin pain (part 2): a prospective cohort study on the biomechanical evaluation of change of direction identifies three clusters of movement patterns', *British Journal of Sports Medicine*, 51(5), pp. 460–468. Available at: https://doi.org/10.1136/bjsports-2016-096050.

Fu, S. C., Rolf, C., Cheuk, Y. C., Lui, P. P., and Chan, K. M. (2010) 'Deciphering the pathogenesis of tendinopathy: a three-stages process', *BMC Sports Science, Medicine and Rehabilitation*, 2(1), p. 30. Available at: https://doi.org/10.1186/1758-2555-2-30.

Fukunaga, T., Roy, R. R., Shellock, F. G., Hodgson, J. A., and Edgerton, V. R. (1996) 'Specific tension of human plantar flexors and dorsiflexors', *Journal of Applied Physiology*, 80(1), pp. 158–165. Available at: https://doi.org/10.1152/jappl.1996.80.1.158.

Funaro, A., Shim, V., Crouzier, M., Mylle, I., & Vanwanseele, B. (2022). Subject-Specific 3D Models to Investigate the Influence of Rehabilitation Exercises and the Twisted Structure on Achilles Tendon Strains. *Frontiers in Bioengineering and Biotechnology*, *10*, 914137. https://doi-org/10.3389/fbioe.2022.914137

Geremia, J. M., Bobbert, M. F., Casa Nova, M., Ott, R. D., Lemos, F.deA., Lupion, R.deO., Frasson, V. B., and Vaz, M. A. (2015) 'The structural and mechanical properties of the Achilles tendon 2 years after surgical repair', *Clinical Biomechanics*, 30(5), pp. 485–492. Available at: https://doi.org/10.1016/j.clinbiomech.2015.03.005.

Geremia, J. M., Baroni, B. M., Bobbert, M. F., Bini, R. R., Lanferdini, F. J., and Vaz, M. A. (2018) 'Effects of high loading by eccentric triceps surae training on Achilles tendon properties in humans', *European Journal of Applied Physiology*, *118*(8), pp. 1725–1736. Available at: https://doi.org/10.1007/s00421-018-3904-1.

Geremia, J. M., Baroni, B. M., Bini, R. R., Lanferdini, F. J., de Lima, A. R., Herzog, W., and Vaz, M. A. (2019) 'Triceps Surae Muscle Architecture Adaptations to Eccentric Training', *Frontiers in Physiology*, 10. Available at: https://doi.org/10.3389/fphys.2019.01456.

Gheidi, N., Kernozek, T. W., Willson, J. D., Revak, A., and Diers, K. (2018) 'Achilles tendon loading during weight bearing exercises', *Physical Therapy in Sport*, 32, pp. 260–268. Available at: https://doi.org/10.1016/j.ptsp.2018.05.007.

Van Gils, C.C., Steed, R.H. and Page, J.C. (1996) 'Torsion of the human achilles tendon', *The Journal of Foot and Ankle Surgery*, 35(1), pp. 41–48. Available at: https://doi.org/10.1016/S1067-2516(96)80011-1.

Gollnick, P. D., Sjödin, B., Karlsson, J., Jansson, E., & Saltin, B. (1974) 'Human soleus muscle: A comparison of fiber composition and enzyme activities with other leg muscles', *Pflügers Archiv European Journal of Physiology*, 348(3), pp. 247–255. Available at: https://doi.org/10.1007/BF00587415.

Goodship, A.E., Birch, H.L. and Wilson, A.M. (1994) 'The Pathobiology and Repair of Tendon and Ligament Injury', *Veterinary Clinics of North America: Equine Practice*, 10(2), pp. 323–349. Available at: https://doi.org/10.1016/S0749-0739(17)30359-0.

Gore, S. J., Franklyn-Miller, A., Richter, C., Falvey, E. C., King, E., and Moran, K. (2018) 'Is stiffness related to athletic groin pain?', *Scandinavian Journal of Medicine & Science in Sports*, 28(6), pp. 1681–1690. Available at: https://doi.org/10.1111/sms.13069.

Green, B. and Pizzari, T. (2017) 'Calf muscle strain injuries in sport: a systematic review of risk factors for injury', *Scandinavian Journal of Medicine and Science in Sports* [Preprint]. Available at: https://doi.org/10.1136/bjsports-2016-097177.

Griffin, C., Richter, C., Franklyn-Miller, A., Morin J.B. (2018) 'A novel single-leg hurdle hop exercise: test-retest reliability of vertical stiffness, contact time, ground reaction force, total

hop distance and rebound distance'. *World Congress of Biomechanics* [Conference presentation]

Griffin, C., Richter, C., Franklyn-Miller, A., Morin, J.B. (2018) 'The number of trials required to obtain a true representation of biomechanical features extracted during a single leg hurdle hop exercise'. *European College of Sports Science* [Conference Presentation]

Griffin, C., Daniels, K., Hill, C., Franklyn-Miller, A., and Morin, J. B. (2021). A criteria-based rehabilitation program for chronic mid-portion Achilles tendinopathy: study protocol for a randomised controlled trial. *BMC musculoskeletal disorders*, *22*(1), 695. https://doi.org/10.1186/s12891-021-04553-6

Habets, B., van Cingel, R. E. H., Backx, F. J. G., van Elten, H. J., Zuithoff, P., and Huisstede, B. M. A. (2021) 'No Difference in Clinical Effects When Comparing Alfredson Eccentric and Silbernagel Combined Concentric-Eccentric Loading in Achilles Tendinopathy: A Randomized Controlled Trial', *Orthopaedic Journal of Sports Medicine*, 9(10), p. 232596712110312. Available at: https://doi.org/10.1177/23259671211031254.

Haff, G.G., Stone, M.H., O'bryant, H.S., Harman, E.A., Dinan, C., Johnson, R.L., and Han, K.H. (1997). Force-Time Dependent Characteristics of Dynamic and Isometric Muscle Actions. *Journal of Strength and Conditioning Research, 11*, 269–272.

Hamill, J., Gruber, A.H. and Derrick, T.R. (2014) 'Lower extremity joint stiffness characteristics during running with different footfall patterns', *European Journal of Sport Science* [Preprint]. Available at: https://doi.org/10.1080/17461391.2012.728249.

Hamner, S.R. and Delp, S.L. (2012) 'Muscle contributions to fore-aft and vertical body mass center accelerations over a range of running speeds', *Journal of Biomechanics*, pp. 1–8. Available at: https://doi.org/10.1016/j.jbiomech.2012.11.024.

Hanlon, S.L., Pohlig, R.T. and Silbernagel, K.G. (2021) 'Beyond the Diagnosis: Using Patient Characteristics and Domains of Tendon Health to Identify Latent Subgroups of Achilles Tendinopathy', *Journal of Orthopaedic & Sports Physical Therapy*, pp. 1–28. Available at: https://doi.org/10.2519/jospt.2021.10271.

Hansen, M.S., Helander, K.N., Karlsson, J., and Barfod, K.W. (2019) '20 The Achilles tendon total rupture score should be used with caution the first 6 months after injury', *British Journal of Sports Medicine*, 53(Suppl 1), pp. A7–A8. Available at: https://doi.org/10.1136/bjsports-2019-scandinavianabs.20.

Harper, S. E., Roembke, R. A., Zunker, J. D., Thelen, D. G., and Adamczyk, P. G. (2020) 'Wearable Tendon Kinetics', *Sensors*, 20(17), p. 4805. Available at: https://doi.org/10.3390/s20174805.

Harris, C.A. and Peduto, A.J. (2006) 'Achilles tendon imaging', *Australasian Radiology*, 50(6), pp. 513–525. Available at: https://doi.org/10.1111/j.1440-1673.2006.01622.x.

Harrison, A.J., Keane, S.P. and Coglan, J. (2004) 'Force-velocity relationship and stretch-shortening cycle function in sprint and endurance athletes', *Journal of Strength and Conditioning Research*, 18(3), pp. 473–479. Available at: https://doi.org/10.1519/13163.1.

Hasani, F., Vallance, P., Haines, T., Munteanu, S. E., and Malliaras, P. (2021) 'Are Plantarflexor Muscle Impairments Present Among Individuals with Achilles Tendinopathy and Do They Change with Exercise? A Systematic Review with Meta-analysis', *Sports Medicine - Open 2021 7:1*, 7(1), pp. 1–18. Available at: https://doi.org/10.1186/S40798-021-00308-8.

Hébert-Losier, K., Schneiders, A. G., Newsham-West, R. J., and Sullivan, S. J. (2009) 'Scientific bases and clinical utilisation of the calf-raise test', *Physical Therapy in Sport*, 10(4), pp. 142–149. Available at: https://doi.org/10.1016/j.ptsp.2009.07.001.

Hébert-Losier, K., Wessman, C., Alricsson, M., and Svantesson, U. (2017) 'Updated reliability and normative values for the standing heel-rise test in healthy adults', *Physiotherapy*, 103(4), pp. 446–452. Available at: https://doi.org/10.1016/j.physio.2017.03.002.

Hébert-Losier, K., Ngawhika, T. M., Gill, N., and Balsalobre-Fernandez, C. (2022) 'Validity, reliability, and normative data on calf muscle function in rugby union players from the Calf Raise application', *Sports Biomechanics*, pp. 1–22. Available at: https://doi.org/10.1080/14763141.2022.2118158.

Hébert-Losier, K. and Holmberg, H.C. (2013) 'Biomechanics of the heel-raise test performed on an incline in two knee flexion positions', *Clinical Biomechanics*, 28(6), pp. 664–671. Available at: https://doi.org/10.1016/j.clinbiomech.2013.06.004.

Hébert-Losier, K. and Murray, L. (2020) 'Reliability of centre of pressure, plantar pressure, and plantar-flexion isometric strength measures: A systematic review', *Gait & Posture*, 75, pp. 46–62. Available at: https://doi.org/10.1016/j.gaitpost.2019.09.027.

Heinemeier, K. M., Schjerling, P., Heinemeier, J., Magnusson, S. P., and Kjaer, M. (2013) 'Lack of tissue renewal in human adult Achilles tendon is revealed by nuclear bomb 14C', *The FASEB Journal*, 27(5), pp. 2074–2079. Available at: https://doi.org/10.1096/fj.12-225599.

Heinemeier, K. M., Schjerling, P., Øhlenschlæger, T. F., Eismark, C., Olsen, J., and Kjær, M. (2018) 'Carbon-14 bomb pulse dating shows that tendinopathy is preceded by years of abnormally high collagen turnover', *The FASEB Journal*, 32(9), pp. 4763–4775. Available at: https://doi.org/10.1096/fj.201701569R.

Hickey, J. T., Timmins, R. G., Maniar, N., Rio, E., Hickey, P. F., Pitcher, C. A., Williams, M. D., and Opar, D. A. (2020) 'Pain-Free Versus Pain-Threshold Rehabilitation Following Acute Hamstring Strain Injury: A Randomized Controlled Trial', *Journal of Orthopaedic & Sports Physical Therapy*, 50(2), pp. 91–103. Available at: https://doi.org/10.2519/jospt.2020.8895.

Hobara, H., Kimura, K., Omuro, K., Gomi, K., Muraoka, T., Iso, S., and Kanosue, K. (2008) 'Determinants of difference in leg stiffness between endurance- and power-trained athletes', *Journal of Biomechanics*, 41(3), pp. 506–514. Available at: https://doi.org/10.1016/j.jbiomech.2007.10.014.

Hobara, H., Muraoka, T., Omuro, K., Gomi, K., Sakamoto, M., Inoue, K., and Kanosue, K. (2009) 'Knee stiffness is a major determinant of leg stiffness during maximal hopping',

Journal of Biomechanics, 42(11), pp. 1768–1771. Available at: https://doi.org/10.1016/J.JBIOMECH.2009.04.047.

Hodgson, J. A., Finni, T., Lai, A. M., Edgerton, V. R., and Sinha, S. (2007) 'Influence of Structure on the Tissue Dynamics of the Human Soleus Muscle Observed in MRI Studies During Isometric Contractions', *Journal of Morphology*, 268(February), pp. 254–274. Available at: https://doi.org/10.1002/jmor.

Hoeffner, R., Svensson, R.B., Bjerregaard, N., Kjær, M., and Magnusson, S.P. (2022) 'Persistent Deficits after an Achilles Tendon Rupture: A Narrative Review', *Translational Sports Medicine*. Edited by S. Egginton, 2022, pp. 1–7. Available at: https://doi.org/10.1155/2022/7445398.

Hoogkamer, W., Kipp, S., Spiering, B. A., and Kram, R. (2016) 'Altered Running Economy Directly Translates to Altered Distance-Running Performance', *Medicine & Science in Sports & Exercise*, 48(11), pp. 2175–2180. Available at: https://doi.org/10.1249/MSS.0000000000001012.

Hullfish, T.J., O'Connor, K.M. and Baxter, J.R. (2019a) 'Gastrocnemius fascicles are shorter and more pennate throughout the first month following acute Achilles tendon rupture', *PeerJ*, 7(4), p. e6788. Available at: https://doi.org/10.7717/peerj.6788.

Hullfish, T.J., O'Connor, K.M. and Baxter, J.R. (2019b) 'Medial gastrocnemius muscle remodeling correlates with reduced plantarflexor kinetics 14 weeks following Achilles tendon rupture', *Journal of Applied Physiology*, 127(4), pp. 1005–1011. Available at: https://doi.org/10.1152/japplphysiol.00255.2019.

Ishikawa, M. and Komi, P.V. (2008) 'Muscle Fascile and Tendon Behavior During Human Locomotion Revisited', *Exerc.Sport Sci.Rev.*, pp. 193–199.

Janssen, I., van der Worp, H., Hensing, S., and Zwerver, J. (2018) 'Investigating Achilles and patellar tendinopathy prevalence in elite athletics', *Research in sports medicine (Print)*, 26(1), pp. 1–12. Available at: https://doi.org/10.1080/15438627.2017.1393748.

Järvinen, T. A., Kannus, P., Maffulli, N., and Khan, K. M. (2005) 'Achilles tendon disorders: Etiology and epidemiology', *Foot and Ankle Clinics*, 10(2), pp. 255–266. Available at: https://doi.org/10.1016/j.fcl.2005.01.013.

Johnson, C. D., Tenforde, A. S., Outerleys, J., Reilly, J., and Davis, I. S. (2020) 'Impact-Related Ground Reaction Forces Are More Strongly Associated With Some Running Injuries Than Others', *American Journal of Sports Medicine*, 48(12), pp. 3072–3080. Available at: https://doi.org/10.1177/0363546520950731.

Johnson, G. A., Tramaglini, D. M., Levine, R. E., Ohno, K., Choi, N. Y., & Woo, S. L. (1994). Tensile and viscoelastic properties of human patellar tendon. *Journal of Orthopaedic Research : Official publication of the Orthopaedic Research Society*, *12*(6), 796–803. https://doi-org/10.1002/jor.1100120607

Jones, A.M. (2006) 'The Physiology of the World Record Holder for the Women's Marathon', *International Journal of Sports Science & Coaching*, 1(2), pp. 101–116. Available at: https://doi.org/10.1260/174795406777641258.

Jones, G. C., Corps, A. N., Pennington, C. J., Clark, I. M., Edwards, D. R., Bradley, M. M., Hazleman, B. L., and Riley, G. P. (2006) 'Expression profiling of metalloproteinases and tissue inhibitors of metalloproteinases in normal and degenerate human Achilles tendon', *Arthritis and Rheumatism*, 54(3), pp. 832–842. Available at: https://doi.org/10.1002/art.21672.

de Jonge, S., van den Berg, C., de Vos, R. J., van der Heide, H. J., Weir, A., Verhaar, J. A., Bierma-Zeinstra, S. M., & Tol, J. L. (2011) 'Incidence of midportion Achilles tendinopathy in the general population', *British Journal of Sports Medicine*, 45(13), pp. 1026–1028. Available at: https://doi.org/10.1136/bjsports-2011-090342.

Kakkos, G. A., Klontzas, M. E., Koltsakis, E., & Karantanas, A. H. (2021) 'US-guided high-volume injection for Achilles tendinopathy', *Journal of Ultrasonography*, 21(85), pp. e127–e133. Available at: https://doi.org/10.15557/JoU.2021.0021.

Kannus, P. (2000) 'Structure of the tendon connective tissue: Tendon connective tissue structure', *Scandinavian Journal of Medicine & Science in Sports*, 10(6), pp. 312–320. Available at: https://doi.org/10.1034/j.1600-0838.2000.010006312.x.

Kariyama, Y., Hobara, H. and Zushi, K. (2017) 'Differences in take-off leg kinetics between horizontal and vertical single-leg rebound jumps', *Sports Biomechanics*, 16(2), pp. 187–200. Available at: https://doi.org/10.1080/14763141.2016.1216160.

Kearney, R. S., Parsons, N., Metcalfe, D., & Costa, M. L. (2015) 'Injection therapies for Achilles tendinopathy', *Cochrane Database of Systematic Reviews*, 2015(5). Available at: https://doi.org/10.1002/14651858.CD010960.pub2.

Khair, R. M., Stenroth, L., Cronin, N. J., Reito, A., Paloneva, J., & Finni, T. (2022) 'Muscle-tendon morphomechanical properties of non-surgically treated Achilles tendon 1-year post-rupture', *Clinical Biomechanics*, 92, p. 105568. Available at: https://doi.org/10.1016/j.clinbiomech.2021.105568.

Khamoui, A. V., Brown, L. E., Nguyen, D., Uribe, B. P., Coburn, J. W., Noffal, G. J., & Tran, T. (2011) 'Relationship Between Force-Time and Velocity-Time Characteristics of Dynamic and Isometric Muscle Actions', *The Journal of Strength & Conditioning Research*, 25(1), pp. 198–204. Available at: https://doi.org/10.1519/JSC.0b013e3181b94a7b.

Khan, K.M. (2002) 'Time to abandon the "tendinitis" myth', *Bmj*, 324(7338), pp. 626–627. Available at: https://doi.org/10.1136/bmj.324.7338.626.

King, E., Richter, C., Franklyn-Miller, A., Wadey, R., Moran, R., and Strike, S. (2019) 'Back to Normal Symmetry? Biomechanical Variables Remain More Asymmetrical Than Normal During Jump and Change-of-Direction Testing 9 Months After Anterior Cruciate Ligament Reconstruction', *The American Journal of Sports Medicine*, 47(5), pp. 1175–1185. Available at: https://doi.org/10.1177/0363546519830656.

Kipp, K. and Kim, H. (2020) 'Relative contributions and capacities of lower extremity muscles to accelerate the body's center of mass during countermovement jumps', *Computer Methods in Biomechanics and Biomedical Engineering*, 23(12), pp. 914–921. Available at: https://doi.org/10.1080/10255842.2020.1772764.

Kipp, S., Kram, R. and Hoogkamer, W. (2019) 'Extrapolating Metabolic Savings in Running: Implications for Performance Predictions', *Frontiers in Physiology*, 10. Available at: https://www.frontiersin.org/articles/10.3389/fphys.2019.00079 (Accessed: 18 October 2022).

Kjaer, M., Langberg, H., Heinemeier, K., Bayer, M. L., Hansen, M., Holm, L., Doessing, S., Kongsgaard, M., Krogsgaard, M. R., and Magnusson, S. P. (2009) 'From mechanical loading to collagen synthesis, structural changes and function in human tendon', *Scandinavian Journal of Medicine and Science in Sports*, 19(4), pp. 500–510. Available at: https://doi.org/10.1111/j.1600-0838.2009.00986.x.

Knobloch, K., Schreibmueller, L., Longo, U. G., and Vogt, P. M. (2008) 'Eccentric exercises for the management of tendinopathy of the main body of the Achilles tendon with or without an AirHeel Brace. A randomized controlled trial. B: Effects of compliance', *Disability and Rehabilitation*, 30(20–22), pp. 1692–1696. Available at: https://doi.org/10.1080/09638280701785676.

Knudsen, A. B., Larsen, M., Mackey, A. L., Hjort, M., Hansen, K. K., Qvortrup, K., Kjaer, M., and Krogsgaard, M. R. (2015) 'The human myotendinous junction: An ultrastructural and 3D analysis study: The human myotendinous junction', *Scandinavian Journal of Medicine & Science in Sports*, 25(1), pp. e116–e123. Available at: https://doi.org/10.1111/sms.12221.

Komi, P. V. (1990) 'Relevance of in vivo force measurements to human biomechanics', *Journal of Biomechanics*, 23(SUPPL. 1). Available at: https://doi.org/10.1016/0021-9290(90)90038-5.

Komi, P.V., Fukashiro, S. and Järvinen, M. (1992) 'Biomechanical loading of Achilles tendon during normal locomotion.', *Clinics in sports medicine*, 11(3), pp. 521–31.

Kongsgaard, M., Qvortrup, K., Larsen, J., Aagaard, P., Doessing, S., Hansen, P., Kjaer, M., and Magnusson, S. P. (2010) 'Fibril Morphology and Tendon Mechanical Properties in Patellar Tendinopathy', *American Journal of Sports Medicine*, 38(4), pp. 749–756. Available at: https://doi.org/10.1177/0363546509350915.

Kotsifaki, A., Korakakis, V., Whiteley, R., Van Rossom, S., and Jonkers, I. (2020) 'Measuring only hop distance during single leg hop testing is insufficient to detect deficits in knee function after ACL reconstruction: a systematic review and meta-analysis', *Br J Sports Med*, 54, pp. 139–153. Available at: https://doi.org/10.1136/bjsports-2018-099918.

Kotsifaki, A., Korakakis, V., Graham-Smith, P., Sideris, V., and Whiteley, R. (2021). Vertical and Horizontal Hop Performance: Contributions of the Hip, Knee, and Ankle. *Sports health*, *13*(2), 128–135. https://doi.org/10.1177/1941738120976363

Kountouris, A. and Cook, J. (2007) 'Rehabilitation of Achilles and patellar tendinopathies', *Best Practice and Research: Clinical Rheumatology*, 21(2), pp. 295–316. Available at: https://doi.org/10.1016/j.berh.2006.12.003.

Kubo, K., Kawakami, Y., and Fukunaga, T. (1999) 'Influence of elastic properties of tendon structures on jump performance in humans Influence of elastic properties of tendon structures on jump performance in humans', *Journal of applied physiology (Bethesda, Md. : 1985)*, 87, pp. 2090–2096.

Kubo, K., Morimoto, M., Komuro, T., Tsunoda, N., Kanehisa, H., and Fukunaga, T.(2007) 'Influences of tendon stiffness, joint stiffness, and electromyographic activity on jump performances using single joint', *European Journal of Applied Physiology*, 99(3), pp. 235–243. Available at: https://doi.org/10.1007/s00421-006-0338-y.

Kuitunen, S., Komi, P. V and Kyrolainen, H. (2002) 'Knee and ankle joint stiffness in sprint running', 34(1), pp. 166–173.

Kuitunen, S., Ogiso, K. and Komi, P.V. (2011) 'Leg and joint stiffness in human hopping', *Scandinavian Journal of Medicine & Science in Sports*, 21(6), pp. e159–e167. Available at: https://doi.org/10.1111/j.1600-0838.2010.01202.x.

Kujala, U.M., Sarna, S. and Kaprio, J. (2005) 'Cumulative incidence of achilles tendon rupture and tendinopathy in male former elite athletes', *Clinical Journal of Sport Medicine*, 15(3), pp. 133–135. Available at: https://doi.org/10.1097/01.jsm.0000165347.55638.23.

Kulmala, J. P., Korhonen, M. T., Ruggiero, L., Kuitunen, S., Suominen, H., Heinonen, A., Mikkola, A., and Avela, J. (2016) 'Walking and running require greater effort from the ankle than the knee extensor muscles', *Medicine and Science in Sports and Exercise*, 48(11), pp. 2181–2189. Available at: https://doi.org/10.1249/MSS.0000000000001020.

Kunimasa, Y., Sano, K., Oda, T., Nicol, C., Komi, P. V., Locatelli, E., Ito, A., and Ishikawa, M. (2014) 'Specific muscle-tendon architecture in elite Kenyan distance runners: Achilles tendon moment arm for Kenyan runners', *Scandinavian Journal of Medicine & Science in Sports*, 24(4), pp. e269–e274. Available at: https://doi.org/10.1111/sms.12161.

Kunz, H. E., & Lanza, I. R. (2023). Age-associated inflammation and implications for skeletal muscle responses to exercise. Experimental Gerontology, 177, 112177. https://doi-org/10.1016/j.exger.2023.112177

Kvist, M., Józsa, L., Järvinen, M. J., and Kvist, H. (1987) 'Chronic achilles paratenonitis in athletes: a histological and histochemical study', *Pathology*, 19(1), pp. 1–11. Available at: https://doi.org/10.3109/00313028709065127.

Lagas, I. F., van der Vlist, A. C., van Oosterom, R. F., van Veldhoven, P. L. J., Reijman, M., Verhaar, J. A. N., and de Vos, R. J. (2021) 'Victorian Institute of Sport Assessment-Achilles (VISA-A) Questionnaire—Minimal Clinically Important Difference for Active People With Midportion Achilles Tendinopathy: A Prospective Cohort Study', *Journal of Orthopaedic & Sports Physical Therapy*, 51(10), pp. 510–516. Available at: https://doi.org/10.2519/jospt.2021.10040.

Lai, A., Schache, A. G., Lin, Y. C., and Pandy, M. G. (2014) 'Tendon elastic strain energy in the human ankle plantar-flexors and its role with increased running speed', pp. 3159–3168. Available at: https://doi.org/10.1242/jeb.100826.

Lai, A., Schache, A. G., Brown, N. A., and Pandy, M. G. (2016). Human ankle plantar flexor muscle-tendon mechanics and energetics during maximum acceleration sprinting. *Journal of the Royal Society, Interface*, *13*(121), 20160391. https://doi.org/10.1098/rsif.2016.0391

Lai, A. K. M., Lichtwark, G. A., Schache, A. G., and Pandy, M. G. (2018) 'Differences in in vivo muscle fascicle and tendinous tissue behavior between the ankle plantarflexors during

running', *Scandinavian Journal of Medicine and Science in Sports* [Preprint], (March). Available at: https://doi.org/10.1111/sms.13089.

Landin, D., Thompson, M. and Reid, M. (2015) 'Knee and Ankle Joint Angles Influence the Plantarflexion Torque of the Gastrocnemius', *Journal of Clinical Medicine Research*, 7(8), p. 602. Available at: https://doi.org/10.14740/JOCMR2107W.

Langberg, Bülow, and Kjær (1998) 'Blood flow in the peritendinous space of the human Achilles tendon during exercise', *Acta Physiologica Scandinavica*, 163(2), pp. 149–153. Available at: https://doi.org/10.1046/j.1365-201X.1998.00361.x.

Latash, M.L. and Zatsiorsky, V.M. (1993) 'Joint stiffness: Myth or reality?', *Human Movement Science* [Preprint]. Available at: https://doi.org/10.1016/0167-9457(93)90010-M.

Lauber, B., Lichtwark, G.A. and Cresswell, A.G. (2014) 'Reciprocal activation of gastrocnemius and soleus motor units is associated with fascicle length change during knee flexion', *Physiological Reports*, 2(6). Available at: https://doi.org/10.14814/phy2.12044.

Lavagnino, M., Wall, M. E., Little, D., Banes, A. J., Guilak, F., and Arnoczky, S. P. (2015) 'Tendon Mechanobiology: Current knowledge and Future Research Opportunities', *J Orthop Res*, 33(6), pp. 813–822. Available at: https://doi.org/10.1002/jor.22871.Tendon.

Lazarczuk, S. L., Maniar, N., Opar, D. A., Duhig, S. J., Shield, A., Barrett, R. S., and Bourne, M. N. (2022) 'Mechanical, Material and Morphological Adaptations of Healthy Lower Limb Tendons to Mechanical Loading: A Systematic Review and Meta-Analysis', *Sports Medicine 2022*, pp. 1–25. Available at: https://doi.org/10.1007/S40279-022-01695-Y.

Lichtwark, G.A. (2005) 'In vivo mechanical properties of the human Achilles tendon during one-legged hopping', *Journal of Experimental Biology*, 208(24), pp. 4715–4725. Available at: https://doi.org/10.1242/jeb.01950.

Lichtwark, G.A., Cresswell, A.G. and Newsham-West, R.J. (2013) 'Effects of running on human Achilles tendon length–tension properties in the free and gastrocnemius components', *Journal of Experimental Biology*, 216(23), pp. 4388–4394. Available at: https://doi.org/10.1242/jeb.094219.

Lichtwark, G.A. and Wilson, A.M. (2008) 'Optimal muscle fascicle length and tendon stiffness for maximising gastrocnemius efficiency during human walking and running', *Journal of Theoretical Biology*, 252(4), pp. 662–673. Available at: https://doi.org/10.1016/j.jtbi.2008.01.018.

Lieber, R.L. and Ward, S.R. (2011) 'Skeletal muscle design to meet functional demands', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 366(1570), pp. 1466–1476. Available at: https://doi.org/10.1098/rstb.2010.0316.

Lindemann, I., Coombes, B. K., Tucker, K., Hug, F., and Dick, T. J. M. (2020) 'Age-related differences in gastrocnemii muscles and Achilles tendon mechanical properties in vivo', *Journal of Biomechanics*, 112, p. 110067. Available at: https://doi.org/10.1016/j.jbiomech.2020.110067.

Lorimer, A. and Hume, P. (2014) 'Achilles Tendon Injury Risk Factors Associated with Running', *Sports medicine (Auckland, N.Z.)*, 44. Available at: https://doi.org/10.1007/s40279-014-0209-3.

Lorimer, A.V. and Hume, P.A. (2016) 'Stiffness as a Risk Factor for Achilles Tendon Injury in Running Athletes', *Sports Medicine*, 46(12), pp. 1921–1938. Available at: https://doi.org/10.1007/s40279-016-0526-9.

Maffiuletti, N. A., Aagaard, P., Blazevich, A. J., Folland, J., Tillin, N., and Duchateau, J. (2016) 'Rate of force development: physiological and methodological considerations', *European Journal of Applied Physiology*, 116(6), pp. 1091–1116. Available at: https://doi.org/10.1007/S00421-016-3346-6.

Maffulli, N., Longo, U. G., Kadakia, A., and Spiezia, F. (2020) 'Achilles tendinopathy', *Foot and Ankle Surgery*, 26(3), pp. 240–249. Available at: https://doi.org/10.1016/j.fas.2019.03.009.

Maffulli, N., Via, A.G. and Oliva, F. (2015) 'Chronic Achilles Tendon Disorders', *Clinics in Sports Medicine*, 34(4), pp. 607–624. Available at: https://doi.org/10.1016/j.csm.2015.06.010.

Maganaris, C. N., Baltzopoulos, V., Ball, D., and Sargeant, A. J. (2017) 'In vivo specific tension of human skeletal muscle', *Journal of Applied Physiology*, 90(3), pp. 865–872. Available at: https://doi.org/10.1152/jappl.2001.90.3.865.

Magnussen, R.A., Dunn, W.R. and Thomson, A.B. (2009) 'Nonoperative treatment of midportion achilles tendinopathy: A systematic review', *Clinical Journal of Sport Medicine*, 19(1), pp. 54–64. Available at: https://doi.org/10.1097/JSM.0b013e31818ef090.

Magnusson, S. P., Hansen, P., Aagaard, P., Brønd, J., Dyhre-Poulsen, P., Bojsen-Moller, J., and Kjaer, M. (2003) 'Differential strain patterns of the human gastrocnemius aponeurosis and free tendon, in vivo', *Acta Physiologica Scandinavica*, 177(2), pp. 185–195. Available at: https://doi.org/10.1046/j.1365-201X.2003.01048.x.

Magnusson, S.P., Heinemeier, K.M. and Kjaer, M. (2016) 'Collagen Homeostasis and Metabolism', in P.W. Ackermann and D.A. Hart (eds) *Metabolic Influences on Risk for Tendon Disorders*. Cham: Springer International Publishing (Advances in Experimental Medicine and Biology), pp. 11–25. Available at: https://doi.org/10.1007/978-3-319-33943-6_2.

Magnusson, S.P., Langberg, H. and Kjaer, M. (2010) 'The pathogenesis of tendinopathy: Balancing the response to loading', *Nature Reviews Rheumatology*, 6(5), pp. 262–268. Available at: https://doi.org/10.1038/nrrheum.2010.43.

Mahieu, N.N. (2006) 'Intrinsic Risk Factors for the Development of Achilles Tendon Overuse Injury: A Prospective Study', *American Journal of Sports Medicine* [Preprint]. Available at: https://doi.org/10.1177/0363546505279918.

Majaj, R. M., Powell, D. W., Weiss, L. W., and Paquette, M. R.(2020) 'Ankle kinetics and plantarflexor morphology in older runners with different lifetime running exposures', *Human Movement Science*, 72. Available at: https://doi.org/10.1016/j.humov.2020.102660.

Maloney, S. J., Richards, J., Nixon, D. G. D., Harvey, L. J., and Fletcher, I. M. (2017) 'Vertical stiffness asymmetries during drop jumping are related to ankle stiffness asymmetries', *Scandinavian Journal of Medicine and Science in Sports*, 27(6), pp. 661–669. Available at: https://doi.org/10.1111/sms.12682.

Manal, K., Roberts, D.P. and Buchanan, T.S. (2006) 'Optimal Pennation Angle of the Primary Ankle Plantar and Dorsiflexors: Variations with Sex, Contraction Intensity, and Limb', *Journal of Applied Biomechanics*, 22(4), pp. 255–263. Available at: https://doi.org/10.1123/jab.22.4.255.

Maquirriain, J. (2012) 'Leg stiffness changes in athletes with achilles tendinopathy', *International Journal of Sports Medicine*, 33(7), pp. 567–571. Available at: https://doi.org/10.1055/s-0032-1304644.

Marshall, B. M., Franklyn-Miller, A. D., King, E. A., Moran, K. A., Strike, S. C., and Falvey, É. C. (2014) 'Biomechanical Factors Associated With Time to Complete a Change of Direction Cutting Maneuver', *Journal of Strength and Conditioning Research*, 28(10), pp. 2845–2851. Available at: https://doi.org/10.1519/JSC.0000000000000463.

Martin, R. L., Chimenti, R., Cuddeford, T., Houck, J., Matheson, J. W., McDonough, C. M., Paulseth, S., Wukich, D. K., and Carcia, C. R. (2018). Achilles Pain, Stiffness, and Muscle Power Deficits: Midportion Achilles Tendinopathy Revision 2018. *The Journal of orthopaedic and sports physical therapy*, *48*(5), A1–A38. https://doi.org/10.2519/jospt.2018.0302

Mascaro, A., Cos, M.A., Morral, A., Roig, A., Purdam, C., and Cook, J. (2018) 'Load management in tendinopathy: Clinical progression for Achilles and patellar tendinopathy', *Apunts Medicina de l'Esport*, 53(197), pp. 19–27. Available at: https://doi.org/10.1016/j.apunts.2017.11.005.

Masci, L., Spang, C., van Schie, H. T., and Alfredson, H. (2015) 'Achilles tendinopathy—do plantaris tendon removal and Achilles tendon scraping improve tendon structure? A prospective study using ultrasound tissue characterisation', *BMJ Open Sport & Exercise Medicine*, 1(1), p. e000005. Available at: https://doi.org/10.1136/bmjsem-2015-000005.

Masci, L., Alfredson, H., Neal, B., and Wynter Bee, W. (2020) 'Ultrasound-guided tendon debridement improves pain, function and structure in persistent patellar tendinopathy: short term follow-up of a case series', *BMJ Open Sp Ex Med*, 6, p. 803. Available at: https://doi.org/10.1136/bmjsem-2020-000803.

McAuliffe, S., Tabuena, A., McCreesh, K., O'Keeffe, M., Hurley, J., Comyns, T., Purtill, H., O'Neill, S., and O'Sullivan, K. (2019) 'Altered Strength Profile in Achilles Tendinopathy: A Systematic Review and Meta-Analysis', *Journal of Athletic Training*, 54(8), pp. 889–900. Available at: https://doi.org/10.4085/1062-6050-43-18.

McMahon, G. (2022) 'No Strain, No Gain? The Role of Strain and Load Magnitude in Human Tendon Responses and Adaptation to Loading', *Journal of Strength and Conditioning Research*, Publish Ahead of Print. Available at: https://doi.org/10.1519/JSC.0000000000004288.

McMahon, J.J., Comfort, P. and Pearson, S. (2012) 'Lower Limb Stiffness', *Strength & Conditioning Journal*, 34(6), pp. 94–101. Available at: https://doi.org/10.1519/SSC.0b013e3182781b4e.

McNeilly, C. M., Banes, A. J., Benjamin, M., and Ralphs, J. R. (1996) 'Tendon cells in vivo form a three-dimensional network of cell processes linked by gap junctions.', *Journal of Anatomy*, 189(Pt 3), pp. 593–600.

McWilliam, J.R., Mackay, G. (2016) 'The Internal Brace for Midsubstance Achilles Ruptures'. *Foot & Ankle International*, 37(7), pp. 794-800. doi:10.1177/1071100716653373

Mead, M. P., Gumucio, J. P., Awan, T. M., Mendias, C. L., and Sugg, K. B.(2018) 'Pathogenesis and management of tendinopathies in sports medicine', *Translational Sports Medicine*, 1(1), pp. 5–13. Available at: https://doi.org/10.1002/tsm2.6.

Mendiguchia, J., Martinez-Ruiz, E., Edouard, P., Morin, J. B., Martinez-Martinez, F., Idoate, F., and Mendez-Villanueva, A. (2017) 'A Multifactorial, Criteria-based Progressive Algorithm for Hamstring Injury Treatment', *Medicine and Science in Sports and Exercise*, 49(7), pp. 1482–1492. Available at: https://doi.org/10.1249/MSS.0000000000001241.

Merry, K., Napier, C., Waugh, C. M., and Scott, A. (2022) 'Foundational Principles and Adaptation of the Healthy and Pathological Achilles Tendon in Response to Resistance Exercise: A Narrative Review and Clinical Implications', *Journal of Clinical Medicine*, 11(16), p. 4722. Available at: https://doi.org/10.3390/jcm11164722.

Midgley, A.W., McNaughton, L.R. and Jones, A.M. (2007) 'Training to Enhance the Physiological Determinants of Long-Distance Running Performance: Can Valid Recommendations be Given to Runners and Coaches Based on Current Scientific Knowledge?', *Sports Medicine*, 37(10), pp. 857–880. Available at: https://doi.org/10.2165/00007256-200737100-00003.

Millar, N. L., Silbernagel, K. G., Thorborg, K., Kirwan, P. D., Galatz, L. M., Abrams, G. D., Murrell, G. A. C., McInnes, I. B., and Rodeo, S. A. (2021) 'Tendinopathy', *Nature Reviews Disease Primers*, 7(1), p. 1. Available at: https://doi.org/10.1038/s41572-020-00234-1.

Millar, N.L., Murrell, G.A.C. and Kirwan, P. (2020) 'Time to put down the scalpel? The role of surgery in tendinopathy', *British Journal of Sports Medicine*, 54(8), pp. 441–442. Available at: https://doi.org/10.1136/bjsports-2019-101084.

Millar, N.L., Murrell, G.A.C. and McInnes, I.B. (2017) 'Inflammatory mechanisms in tendinopathy – towards translation', *Nature Reviews Rheumatology*, 13(2), pp. 110–122. Available at: https://doi.org/10.1038/nrrheum.2016.213.

Miller, R.P., Kori, S.H. and Todd, D.D. (1991) 'The Tampa Scale: a Measure of Kinisophobia', *The Clinical Journal of Pain*, 7(1), p. 51.

Moran, J., Ramirez-Campillo, R., Liew, B., Chaabene, H., Behm, D. G., García-Hermoso, A., Izquierdo, M., and Granacher, U. (2021) 'Effects of Vertically and Horizontally Orientated Plyometric Training on Physical Performance: A Meta-analytical Comparison', *Sports Medicine*, 51(1), pp. 65–79. Available at: https://doi.org/10.1007/s40279-020-01340-6.

Morin, J. B., Dalleau, G., Kyröläinen, H., Jeannin, T., and Belli, A. (2005) 'A simple method for measuring stiffness during running', *Journal of Applied Biomechanics*, 21(2), pp. 167–180. Available at: https://doi.org/10.1123/jab.21.2.167.

Mosca, M. J., Rashid, M. S., Snelling, S. J., Kirtley, S., Carr, A. J., and Dakin, S. G. (2018) 'Trends in the theory that inflammation plays a causal role in tendinopathy: a systematic review and quantitative analysis of published reviews', *BMJ Open Sport — Exercise Medicine*, 4(1), p. e000332. Available at: https://doi.org/10.1136/bmjsem-2017-000332.

Munteanu, S. E., and Barton, C. J. (2011) 'Lower limb biomechanics during running in individuals with achilles tendinopathy: a systematic review', *Journal of Foot and Ankle Research*, 4(1), p. 15. Available at: https://doi.org/10.1186/1757-1146-4-15.

Murphy, M., Travers, M., Gibson, W., Chivers, P., Debenham, J., Docking, S., and Rio, E. (2018) 'Rate of Improvement of Pain and Function in Mid-Portion Achilles Tendinopathy with Loading Protocols: A Systematic Review and Longitudinal Meta-Analysis', *Sports Medicine*, 48(8), pp. 1875–1891. Available at: https://doi.org/10.1007/s40279-018-0932-2.

Myer, G. D., Faigenbaum, A. D., Cherny, C. E., Heidt, R. S., Jr, and Hewett, T. E. 2011) 'Did the NFL Lockout Expose the Achilles Heel of Competitive Sports?', *Journal of Orthopaedic & Sports Physical Therapy*, 41(10), pp. 702–705. Available at: https://doi.org/10.2519/jospt.2011.0107.

Myhrvold, S. B., Brouwer, E. F., Andresen, T. K. M., Rydevik, K., Amundsen, M., Grün, W., Butt, F., Valberg, M., Ulstein, S., and Hoelsbrekken, S. E. (2022). Nonoperative or Surgical Treatment of Acute Achilles' Tendon Rupture. *The New England journal of medicine*, *386*(15), 1409–1420. https://doi.org/10.1056/NEJMoa2108447

Nagelli, C. V., Hooke, A., Quirk, N., Padilla, C. L. D., Hewett, T. E., Griensven, M. van, Coenen, M., Berglund, L., Evans, C. H., and Müller, S. A. (2021) 'Mechanical and possible auxetic properties of human Achilles tendon during in vitro testing to failure'. bioRxiv, p. 2021.09.09.459526. Available at: https://doi.org/10.1101/2021.09.09.459526.

Nagelli, C. V., Hooke, A., Quirk, N., De Padilla, C. L., Hewett, T. E., van Griensven, M., Coenen, M., Berglund, L., Evans, C. H., and Müller, S. A. (2022). Mechanical and strain behaviour of human Achilles tendon during in vitro testing to failure. *European cells & materials*, *43*, 153–161. https://doi.org/10.22203/eCM.v043a12

Nielsen, T. G., Miller, L. L., Mygind-Klavsen, B., and Lind, M. (2020) 'The effect of high-volume image-guided injection in the chronic non-insertional Achilles tendinopathy: a retrospective case series', *Journal of Experimental Orthopaedics*, 7(1), p. 45. Available at: https://doi.org/10.1186/s40634-020-00264-4.

Nilsson-Helander, K., Thomeé, R., Silbernagel, K. G., Thomeé, P., Faxén, E., Eriksson, B. I., and Karlsson, J. (2007) 'The Achilles Tendon Total Rupture Score (ATRS): Development and Validation', *The American Journal of Sports Medicine*, 35(3), pp. 421–426. Available at: https://doi.org/10.1177/0363546506294856.

Nordenholm, A., Nilsson, N., Senorski, E. H., Helander, K. N., Westin, O., and Olsson, N. (2022) 'Patients with chronic Achilles tendon rupture have persistent limitations in patient-reported function and calf muscle function one year after surgical treatment – a case series',

Journal of Experimental Orthopaedics, 9(1), p. 15. Available at: https://doi.org/10.1186/s40634-022-00451-5.

Nunes, J. P., Costa, B. D. V., Kassiano, W., Kunevaliki, G., Castro-E-Souza, P., Rodacki, A. L. F., Fortes, L. S., and Cyrino, E. S. (2020) 'Different foot positioning during calf training to induce portion-specific gastrocnemius muscle hypertrophy', *Journal of Strength and Conditioning Research*, (April), p. (minor revisions-submitted 24/02/2020).

O'Brien, M. (1997) 'Structure and metabolism of tendons', *Scandinavian Journal of Medicine & Science in Sports*, 7(2), pp. 55–61. Available at: https://doi.org/10.1111/j.1600-0838.1997.tb00119.x.

O'Brien, M. (2005) 'The Anatomy of the Achilles Tendon', *Foot and Ankle Clinics*, 10(2), pp. 225–238. Available at: https://doi.org/10.1016/j.fcl.2005.01.011.

Obst, S. J., Renault, J. B., Newsham-West, R., and Barrett, R. S. (2014) 'Three-dimensional deformation and transverse rotation of the human free Achilles tendon in vivo during isometric plantarflexion contraction', *Journal of Applied Physiology*, 116(4), pp. 376–384. Available at: https://doi.org/10.1152/japplphysiol.01249.2013.

Ochen, Y., Beks, R. B., van Heijl, M., Hietbrink, F., Leenen, L. P. H., van der Velde, D., Heng, M., van der Meijden, O., Groenwold, R. H. H., and Houwert, R. M. (2019) 'Operative treatment versus nonoperative treatment of Achilles tendon ruptures: systematic review and meta-analysis', *BMJ*, 364, p. 5120. Available at: https://doi.org/10.1136/bmj.k5120.

Van Oeveren, B. T., de Ruiter, C. J., Beek, P. J., and van Dieën, J. H. (2021) 'The biomechanics of running and running styles: a synthesis', *Sports Biomechanics*, pp. 1–39. Available at: https://doi.org/10.1080/14763141.2021.1873411.

Ogbonmwan, I., Kumar, B.D. and Paton, B. (2018) 'New lower-limb gait biomechanical characteristics in individuals with Achilles tendinopathy: A systematic review update', *Gait & Posture*, 62, pp. 146–156. Available at: https://doi.org/10.1016/j.gaitpost.2018.03.010.

Olewnik, Ł., Zielinska, N., Paulsen, F., Podgórski, M., Haładaj, R., Karauda, P., and Polguj, M. (2020) 'A proposal for a new classification of soleus muscle morphology', *Annals of Anatomy*, 232, p. 151584. Available at: https://doi.org/10.1016/j.aanat.2020.151584.

O'Neill, S., Barry, S. and Watson, P. (2019) 'Plantarflexor strength and endurance deficits associated with mid-portion Achilles tendinopathy: The role of soleus', *Physical Therapy in Sport*, 37, pp. 69–76. Available at: https://doi.org/10.1016/j.ptsp.2019.03.002.

O'Neill, S., Radia, J., Bird, K., Rathleff, M. S., Bandholm, T., Jorgensen, M., & Thorborg, K. (2017) 'P23: Acute sensory and motor response to 45-seconds heavy isometric holds for the plantar flexors in patients with Achilles tendinopathy', *Online Journal of Rural Nursing & Health Care*, 17(1), pp. SS20–SS20. Available at: https://doi.org/10.1007/S00167-018-5050-Z.

O'Neill, S., Watson, P.J. and Barry, S. (2015) 'Why Are Eccentric Exercises Effective for Achilles Tendinopathy?', *International journal of sports physical therapy*, 10(4), pp. 552–62.

Paantjens, M. A., Helmhout, P. H., Backx, F. J. G., van Etten-Jamaludin, F. S., and Bakker, E. W. P. (2022) 'Extracorporeal Shockwave Therapy for Mid-portion and Insertional Achilles

Tendinopathy: A Systematic Review of Randomized Controlled Trials', *Sports Medicine - Open*, 8(1), p. 68. Available at: https://doi.org/10.1186/s40798-022-00456-5.

Pandy, M. G., Lai, A. K. M., Schache, A. G., and Lin, Y. C. (2021) 'How muscles maximize performance in accelerated sprinting', *Scandinavian Journal of Medicine and Science in Sports*, 31(10), pp. 1882–1896. Available at: https://doi.org/10.1111/SMS.14021.

Patel, M.S. and Kadakia, A.R. (2019) 'Minimally Invasive Treatments of Acute Achilles Tendon Ruptures', *Foot and Ankle Clinics*, 24(3), pp. 399–424. Available at: https://doi.org/10.1016/j.fcl.2019.05.002.

Pedret, C., Rodas, G., Balius, R., Capdevila, L., Bossy, M., Vernooij, R. W., and Alomar, X. (2015) 'Return to Play After Soleus Muscle Injuries', *Orthopaedic Journal of Sports Medicine*, 3(7). Available at: https://doi.org/10.1177/2325967115595802.

Pedret, C., Rupérez, F., Mechó, S., Balius, R., and Rodas, G. (2022) 'Anatomical Variability of the Soleus Muscle: A Key Factor for the Prognosis of Injuries?', *Sports Medicine*, pp. s40279-022-01731–x. Available at: https://doi.org/10.1007/s40279-022-01731-x.

Pękala, P. A., Henry, B. M., Pękala, J. R., Piska, K., and Tomaszewski, K. A. (2017) 'The Achilles tendon and the retrocalcaneal bursa: An anatomical and radiological study', *Bone & Joint Research*, 6(7), pp. 446–451. Available at: https://doi.org/10.1302/2046-3758.67.BJR-2016-0340.R1.

Pizzolato, C., Lloyd, D. G., Zheng, M. H., Besier, T. F., Shim, V. B., Obst, S. J., Newsham-West, R., Saxby, D. J., and Barrett, R. S. (2019) 'Finding the sweet spot via personalised Achilles tendon training: The future is within reach', *British Journal of Sports Medicine*, 53(1), pp. 11–12. Available at: https://doi.org/10.1136/bjsports-2018-099020.

Play, M. C., Trama, R., Millet, G. Y., Hautier, C., Giandolini, M., & Rossi, J. (2022). Soft Tissue Vibrations in Running: A Narrative Review. Sports Medicine - Open, 8(1), 131. https://doi-org/10.1186/s40798-022-00524-w

Rees, J. D., Lichtwark, G. A., Wolman, R. L., and Wilson, A. M. (2008) 'The mechanism for efficacy of eccentric loading in Achilles tendon injury; an in vivo study in humans', *Rheumatology*, 47(10), pp. 1493–1497. Available at: https://doi.org/10.1093/rheumatology/ken262.

Rees, J.D., Stride, M. and Scott, A. (2014) 'Tendons – time to revisit inflammation', *British Journal of Sports Medicine*, 48(21), pp. 1553–1557. Available at: https://doi.org/10.1136/bjsports-2012-091957.

Reeves, N.D. and Cooper, G. (2017) 'Is human Achilles tendon deformation greater in regions where cross-sectional area is smaller?' Available at: https://doi.org/10.1242/jeb.157289.

Reiman, M., Burgi, C., Strube, E., Prue, K., Ray, K., Elliott, A., and Goode, A. (2014) 'The Utility of Clinical Measures for the Diagnosis of Achilles Tendon Injuries: A Systematic Review With Meta-Analysis', *Journal of Athletic Training*, 49(6), pp. 820–829. Available at: https://doi.org/10.4085/1062-6050-49.3.36.

Rhodes, D., Jeffery, J., Brook-Sutton, D., and Alexander, J. (2022) 'Test-Retest Reliability of the Isometric Soleus Strength Test in Elite Male Academy Footballers', *International Journal of Sports Physical Therapy*, 17(2). Available at: https://doi.org/10.26603/001c.31047.

Riley, G. (2005) 'Chronic tendon pathology: molecular basis and therapeutic implications', *Expert Reviews in Molecular Medicine*, 7(5), pp. 1–25. Available at: https://doi.org/10.1017/S1462399405008963.

Riley, G. (2008) 'Tendinopathy - From basic science to treatment', *Nature Clinical Practice Rheumatology*, 4(2), pp. 82–89. Available at: https://doi.org/10.1038/ncprheum0700.

Rio, E., Kidgell, D., Purdam, C., Gaida, J., Moseley, G. L., Pearce, A. J., and Cook, J. (2015) 'Isometric exercise induces analgesia and reduces inhibition in patellar tendinopathy', *British Journal of Sports Medicine*, 49(19), pp. 1277–1283. Available at: https://doi.org/10.1136/bjsports-2014-094386.

Jakobsen, J. R., Mackey, A. L., Koch, M., Imhof, T., Hannibal, J., Kjaer, M., and Krogsgaard, M. R. (2022) 'Larger interface area at the human myotendinous junction in type 1 compared to type 2 muscle fibers', *Scandinavian Journal of Medicine & Science in Sports*, n/a(n/a). Available at: https://doi.org/10.1111/sms.14246.

Roberts, T. J., Eng, C. M., Sleboda, D. A., Holt, N. C., Brainerd, E. L., Stover, K. K., Marsh, R. L., and Azizi, E. (2019) 'The Multi-Scale, Three-Dimensional Nature of Skeletal Muscle Contraction', *Physiology*, 34(6), pp. 402–408. Available at: https://doi.org/10.1152/physiol.00023.2019.

Roberts, T.J. and Azizi, E. (2011) 'Flexible mechanisms: the diverse roles of biological springs in vertebrate movement', *The Journal of Experimental Biology*, 214(3), pp. 353–361. Available at: https://doi.org/10.1242/jeb.038588.

Robinson, J. M., Cook, J. L., Purdam, C., Visentini, P. J., Ross, J., Maffulli, N., Taunton, J. E., Khan, K. M., and Victorian Institute Of Sport Tendon Study Group (2001) 'The VISA-A questionnaire : a valid and reliable index of the clinical severity of Achilles tendinopathy The VISA-A questionnaire : a valid and reliable index of the clinical severity of Achilles tendinopathy', *Sports Medicine*, pp. 335–341. Available at: https://doi.org/10.1136/bjsm.35.5.335.

Roche, A.J. and Calder, J.D.F. (2018) 'Disorders of the Tendo Achillis', in A. Robinson, J.W. Brodsky, and J.P. Negrine (eds) *Core Topics in Foot and Ankle Surgery*. 1st edn. Cambridge University Press, pp. 264–281. Available at: https://doi.org/10.1017/9781108292399.016.

Rogers, S. A., Whatman, C. S., Pearson, S. N., and Kilding, A. E. (2017) 'Assessments of Mechanical Stiffness and Relationships to Performance Determinants in Middle-Distance Runners', *International Journal of Sports Physiology and Performance*, 10(7), pp. 888–896. Available at: https://doi.org/10.1123/ijspp.2014-0539.

Romero-Morales, C., Martín-Llantino, P. J., Calvo-Lobo, C., Beltran-Alacreu, H., López-López, D., Sánchez-Gómez, R., and Rodríguez-Sanz, D. (2018) 'Effectiveness of Eccentric Exercise and a Vibration or Cryotherapy Program in Enhancing Rectus Abdominis Muscle Thickness and Inter-Rectus Distance in Patients with Chronic Mid-Portion Achilles

Tendinopathy: A Randomized Clinical Trial', *International Journal of Medical Sciences*, 15(14), pp. 1764–1770. Available at: https://doi.org/10.7150/ijms.28656.

Rompe, J. D., Nafe, B., Furia, J. P., and Maffulli, N. (2007) 'Eccentric loading, shock-wave treatment, or a wait-and-see policy for tendinopathy of the main body of tendo Achillis: a randomized controlled trial.', *The American journal of sports medicine*, 35(3), pp. 374–83. Available at: https://doi.org/10.1177/0363546506295940.

Rompe, J.D., Furia, J. and Maffulli, N. (2009) 'Eccentric loading versus eccentric loading plus shock-wave treatment for midportion achilles tendinopathy: A randomized controlled trial', *American Journal of Sports Medicine*, 37(3), pp. 463–470. Available at: https://doi.org/10.1177/0363546508326983.

Roos, E.M., Brandsson, S. and Karlsson, J. (2001) 'Validation of the foot and ankle outcome score for ankle ligament reconstruction', *Foot & Ankle International*, 22(10), pp. 788–794. Available at: https://doi.org/10.1177/107110070102201004.

Rosenzweig, S. and Azar, F.M. (2009) 'Open Repair of Acute Achilles Tendon Ruptures', *Foot and Ankle Clinics*, 14(4), pp. 699–709. Available at: https://doi.org/10.1016/j.fcl.2009.07.002.

Rubenson, J., Pires, N. J., Loi, H. O., Pinniger, G. J., and Shannon, D. G. (2012). On the ascent: the soleus operating length is conserved to the ascending limb of the force-length curve across gait mechanics in humans. *The Journal of experimental biology*, *215*(Pt 20), 3539–3551. https://doi.org/10.1242/jeb.070466

Sancho, I., Malliaras, P., Barton, C., Willy, R. W., and Morrissey, D. (2019) 'Biomechanical alterations in individuals with Achilles tendinopathy during running and hopping: A systematic review with meta-analysis', *Gait & Posture*, 73, pp. 189–201. Available at: https://doi.org/10.1016/j.gaitpost.2019.07.121.

Sancho, I., Morrissey, D., Willy, R. W., Barton, C., and Malliaras, P. (2019) 'Education and exercise supplemented by a pain-guided hopping intervention for male recreational runners with midportion Achilles tendinopathy: A single cohort feasibility study', *Physical Therapy in Sport*, 40, pp. 107–116. Available at: https://doi.org/10.1016/j.ptsp.2019.08.007.

Sancho, I., Morrissey, D., Willy, R. W., Tayfur, A., Lascurain-Aguirrebeña, I., Barton, C., and Malliaras, P. (2022) 'Recreational runners with Achilles tendinopathy have clinically detectable impairments: A case-control study', *Physical Therapy in Sport*, 55, pp. 241–247. Available at: https://doi.org/10.1016/J.PTSP.2022.05.002.

Sanno, M., Willwacher, S., Epro, G., and Brüggemann, G. P. (2018) 'Positive work contribution shifts from distal to proximal joints during a prolonged run', *Medicine and Science in Sports and Exercise*, 50(12), pp. 2507–2517. Available at: https://doi.org/10.1249/MSS.0000000000001707.

Šarabon, N., Kozinc, Ž. and Bishop, C. (2021) 'Comparison of Vertical and Horizontal Reactive Strength Index Variants and Association With Change of Direction Performance', *Journal of Strength and Conditioning Research*, Publish Ahead of Print. Available at: https://doi.org/10.1519/JSC.0000000000004193.

Schache, A. G., Lai, A. K. M., Brown, N. A. T., Crossley, K. M., and Pandy, M. G. (2019) 'Lower-limb joint mechanics during maximum acceleration sprinting', *Journal of Experimental Biology*, 222(22). Available at: https://doi.org/10.1242/jeb.209460.

Schache, A.G., Dorn, T.W. and Pandy, M.G. (2014) *Lower-Limb Muscular Strategies for Increasing Running Speed*.

Schubert, A., Kempf, J. and Heiderscheit, B. (2014) 'Influence of Stride Frequency and Length on Running Mechanics: A Systematic Review', *Sports health*, 6, pp. 210–217. Available at: https://doi.org/10.1177/1941738113508544.

Schulze-Tanzil, G. G., Delgado-Calcares, M., Stange, R., Wildemann, B., and Docheva, D. (2022) 'Tendon healing: a concise review on cellular and molecular mechanisms with a particular focus on the Achilles tendon', *Bone & Joint Research*, 11(8), pp. 561–574. Available at: https://doi.org/10.1302/2046-3758.118.BJR-2021-0576.R1.

Scott, A., Squier, K., Alfredson, H., Bahr, R., Cook, J. L., Coombes, B., de Vos, R. J., Fu, S. N., Grimaldi, A., Lewis, J. S., Maffulli, N., Magnusson, S. P., Malliaras, P., Mc Auliffe, S., Oei, E. H. G., Purdam, C. R., Rees, J. D., Rio, E. K., Gravare Silbernagel, K., Speed, C., … Zwerver, J. (2020) 'ICON 2019: International Scientific Tendinopathy Symposium Consensus: Clinical Terminology', *British Journal of Sports Medicine*, 54(5), pp. 260–262. Available at: https://doi.org/10.1136/bjsports-2019-100885.

Selvanetti, A., Cipolla, M. and Puddu, G. (1997) 'Overuse tendon injuries: Basic science and classification', *Operative Techniques in Sports Medicine*, 5(3), pp. 110–117. Available at: https://doi.org/10.1016/S1060-1872(97)80031-7.

Sigurðsson, H.B. and Silbernagel, K.G. (2022) 'Is the VISA-A Still Seaworthy, or Is It in Need of Maintenance?', *Orthopaedic Journal of Sports Medicine*, 10(8), p. 23259671221108950. Available at: https://doi.org/10.1177/23259671221108950.

Silbernagel, K. G., Gustavsson, A., Thomeé, R., and Karlsson, J. (2006) 'Evaluation of lower leg function in patients with Achilles tendinopathy', *Knee Surgery, Sports Traumatology, Arthroscopy*, 14(11), pp. 1207–1217. Available at: https://doi.org/10.1007/s00167-006-0150-6.

Silbernagel, K. G., Thomeé, R., Eriksson, B. I., and Karlsson, J. (2007a) 'Continued sports activity, using a pain-monitoring model, during rehabilitation in patients with achilles tendinopathy: A randomized controlled study', *American Journal of Sports Medicine*, 35(6), pp. 897–906. Available at: https://doi.org/10.1177/0363546506298279.

Silbernagel, K. G., Thomeé, R., Eriksson, B. I., and Karlsson, J. (2007b) 'Full symptomatic recovery does not ensure full recovery of muscle-tendon function in patients with Achilles tendinopathy', *British Journal of Sports Medicine*, 41(4), pp. 276–280. Available at: https://doi.org/10.1136/bjsm.2006.033464.

Silbernagel, K.G. and Crossley, K.M. (2015) 'A Proposed Return-to-Sport Program for Patients With Midportion Achilles Tendinopathy: Rationale and Implementation', *Journal of Orthopaedic & Sports Physical Therapy*, 45(11), pp. 876–886. Available at: https://doi.org/10.2519/jospt.2015.5885.

Slade, S. C., Dionne, C. E., Underwood, M., Buchbinder, R., Beck, B., Bennell, K., Brosseau, L., Costa, L., Cramp, F., Cup, E., Feehan, L., Ferreira, M., Forbes, S., Glasziou, P., Habets, B., Harris, S., Hay-Smith, J., Hillier, S., Hinman, R., Holland, A., … White, C. (2016) 'Consensus on exercise reporting template (Cert): Modified delphi study', *Physical Therapy*, 96(10), pp. 1514–1524. Available at: https://doi.org/10.2522/ptj.20150668.

Slane, L.C. and Thelen, D.G. (2014) 'Non-uniform displacements within the Achilles tendon observed during passive and eccentric loading', *Journal of Biomechanics*, 47(12), pp. 2831-2835. Available at: https://doi.org/10.1016/j.jbiomech.2014.07.032.

Snedeker, J.G. and Foolen, J. (2017) 'Tendon injury and repair – A perspective on the basic mechanisms of tendon disease and future clinical therapy', *Acta Biomaterialia* [Preprint]. Available at: https://doi.org/10.1016/j.actbio.2017.08.032.

Spang, C., Alfredson, H., Harandi, V.M., and Forsgren, S. (2014) '97 Richly Innervated Tissue In Between The Plantaris And Achilles Tendon In Achilles Tendinopathy', *British Journal of Sports Medicine*, 48(Suppl 2), pp. A63–A63. Available at: https://doi.org/10.1136/bjsports-2014-094114.96.

Stanish, W.D., Rubinovich, R.M. and Curwin, S. (1986) 'Eccentric exercise in chronic tendinitis.', *Clinical orthopaedics and related research*, (208), pp. 65–8.

Starbuck, C., Bramah, C., Herrington, L., and Jones, R. (2021) 'The effect of speed on Achilles tendon forces and patellofemoral joint stresses in high-performing endurance runners', *Scandinavian Journal of Medicine & Science in Sports*, 31(8), pp. 1657–1665. Available at: https://doi.org/10.1111/sms.13972.

Stäudle, B., Seynnes, O., Laps, G., Brüggemann, G. P., and Albracht, K. (2022) 'Altered Gastrocnemius Contractile Behavior in Former Achilles Tendon Rupture Patients During Walking', *Frontiers in Physiology*, 13. Available at: https://doi.org/10.3389/fphys.2022.792576.

Stefanyshyn, D.J. and Nigg, B.M. (1998) 'Dynamic Angular Stiffness of the Ankle Joint during Running and Sprinting', *Journal of Applied Biomechanics*, 14(3), pp. 292–299. Available at: https://doi.org/10.1123/jab.14.3.292.

Stenroth, L., Peltonen, J., Cronin, N. J., Sipilä, S., and Finni, T. (2012) 'Age-related differences in Achilles tendon properties and triceps surae muscle architecture in vivo', *Journal of Applied Physiology*, 113(10), pp. 1537–1544. Available at: https://doi.org/10.1152/japplphysiol.00782.2012.

Stenroth, L., Cronin, N. J., Peltonen, J., Korhonen, M. T., Sipilä, S., and Finni, T. (2016) 'Triceps surae muscle-tendon properties in older endurance- and sprint-trained athletes', *Journal of Applied Physiology*, 120(1), pp. 63–69. Available at: https://doi.org/10.1152/japplphysiol.00511.2015.

Stevens, M. and Tan, C.-W. (2014) 'Effectiveness of the Alfredson Protocol Compared With a Lower Repetition-Volume Protocol for Midportion Achilles Tendinopathy: A Randomized Controlled Trial', *Journal of Orthopaedic & Sports Physical Therapy*, 44(2), pp. 59–67. Available at: https://doi.org/10.2519/jospt.2014.4720.

Stilwell, D.L. (1957) 'The innervation of tendons and aponeuroses', *American Journal of Anatomy*, 100(3), pp. 289–317. Available at: https://doi.org/10.1002/aja.1001000302.

Suzuki, T., Chino, K. and Fukashiro, S. (2014) 'Gastrocnemius and soleus are selectively activated when adding knee extensor activity to plantar flexion', *Human Movement Science*, 36, pp. 35–45. Available at: https://doi.org/10.1016/j.humov.2014.04.009.

Svensson, R. B., Heinemeier, K. M., Couppé, C., Kjaer, M., and Magnusson, S. P. (2016) 'Effect of aging and exercise on the tendon', *Journal of Applied Physiology*, 121(6), pp. 1353–1362. Available at: https://doi.org/10.1152/japplphysiol.00328.2016.

Szaro, P., Witkowski, G., Smigielski, R., Krajewski, P., and Ciszek, B. (2009) 'Fascicles of the adult human Achilles tendon - An anatomical study', *Annals of Anatomy*, 191(6), pp. 586–593. Available at: https://doi.org/10.1016/j.aanat.2009.07.006.

Tarantino, D., Palermi, S., Sirico, F., and Corrado, B. (2020) 'Achilles tendon rupture: Mechanisms of injury, principles of rehabilitation and return to play', *Journal of Functional Morphology and Kinesiology*, 5(4). Available at: https://doi.org/10.3390/jfmk5040095.

Theobald, P., Benjamin, M., Nokes, L., and Pugh, N. (2005) 'Review of the vascularisation of the human Achilles tendon', *Injury*, 36(11), pp. 1267–1272. Available at: https://doi.org/10.1016/j.injury.2005.02.012.

Thermann, H., Fischer, R., Gougoulias, N., Cipollaro, L., and Maffulli, N. (2020) 'Endoscopic debridement for non-insertional Achilles tendinopathy with and without platelet-rich plasma', *Journal of Sport and Health Science* [Preprint]. Available at: https://doi.org/10.1016/j.jshs.2020.06.012.

Trofa, D. P., Miller, J. C., Jang, E. S., Woode, D. R., Greisberg, J. K., & Vosseller, J. T. (2017) 'Professional Athletes' Return to Play and Performance After Operative Repair of an Achilles Tendon Rupture'. Available at: https://doi.org/10.1177/0363546517713001.

Trotter, J.A., Eberhard, S. and Samora, A. (1983) 'Structural connections of the muscle-tendon junction', *Cell Motility*, 3(5), pp. 431–438. Available at: https://doi.org/10.1002/cm.970030511.

Vaishya, R., Agarwal, A. K., Azizi, A. T., and Vijay, V. (2016) 'Haglund's Syndrome: A Commonly Seen Mysterious Condition', *Cureus*, 8(10), p. e820. Available at: https://doi.org/10.7759/cureus.820.

Van Ginckel, A., Thijs, Y., Hesar, N. G., Mahieu, N., De Clercq, D., Roosen, P., and Witvrouw, E. (2009) 'Intrinsic gait-related risk factors for Achilles tendinopathy in novice runners: A prospective study', *Gait & Posture*, 29(3), pp. 387–391. Available at: https://doi.org/10.1016/j.gaitpost.2008.10.058.

Van der Vlist, A. C., Breda, S. J., Oei, E. H. G., Verhaar, J. A. N., and de Vos, R. J. (2019) 'Clinical risk factors for Achilles tendinopathy: a systematic review', *British Journal of Sports Medicine*, 53(21), pp. 1352–1361. Available at: https://doi.org/10.1136/bjsports-2018-099991.

Van der Vlist, A. C., van Oosterom, R. F., van Veldhoven, P. L. J., Bierma-Zeinstra, S. M. A., Waarsing, J. H., Verhaar, J. A. N., and de Vos, R. J. (2020) 'Effectiveness of a high

volume injection as treatment for chronic Achilles tendinopathy: randomised controlled trial', *BMJ*, 370, p. m3027. Available at: https://doi.org/10.1136/bmj.m3027.

Waggett, A. D., Ralphs, J. R., Kwan, A. P., Woodnutt, D., and Benjamin, M. (1998) 'Characterization of collagens and proteoglycans at the insertion of the human achilles tendon', *Matrix Biology*, 16(8), pp. 457–470. Available at: https://doi.org/10.1016/S0945-053X(98)90017-8.

Wang, H. K., Lin, K. H., Su, S. C., Shih, T. T., and Huang, Y. C. (2012) 'Effects of tendon viscoelasticity in Achilles tendinosis on explosive performance and clinical severity in athletes', *Scandinavian Journal of Medicine and Science in Sports*, 22(6), pp. 1–9. Available at: https://doi.org/10.1111/j.1600-0838.2012.01511.x.

Wang, J.H.C. (2006) 'Mechanobiology of tendon', *Journal of Biomechanics*, 39(9), pp. 1563–1582. Available at: https://doi.org/10.1016/j.jbiomech.2005.05.011.

Ward, E. R., Andersson, G., Backman, L. J., and Gaida, J. E. (2016) 'Fat pads adjacent to tendinopathy: more than a coincidence?', *British Journal of Sports Medicine*, 50(24), pp. 1491–1492. Available at: https://doi.org/10.1136/bjsports-2016-096174.

Waugh, C. M., Blazevich, A. J., Fath, F., and Korff, T. (2012) 'Age-related changes in mechanical properties of the Achilles tendon', *Journal of Anatomy*, 220(2), pp. 144–155. Available at: https://doi.org/10.1111/j.1469-7580.2011.01461.x.

Webb, J., Moorjani, N. and Radford, M. (2000) 'Anatomy of the sural nerve and its relation to the Achilles Tendon', *Foot & Ankle International*, 21(6), pp. 475–477. Available at: https://doi.org/10.1177/107110070002100604.

Wegrzyn, J., Luciani, J. F., Philippot, R., Brunet-Guedj, E., Moyen, B., and Besse, J. L. (2010) 'Chronic Achilles tendon rupture reconstruction using a modified flexor hallucis longus transfer', *International Orthopaedics*, 34(8), pp. 1187–1192. Available at: https://doi.org/10.1007/s00264-009-0859-1.

Wiesinger, H. P., Kösters, A., Müller, E., and Seynnes, O. R. (2015) 'Effects of Increased Loading on In Vivo Tendon Properties: A Systematic Review', *Systematic Review. Med. Sci. Sports Exerc*, 47(9), pp. 1885–1895. Available at: https://doi.org/10.1249/MSS.0000000000000603.

Wild, J. J., Bezodis, I. N., North, J. S., and Bezodis, N. E. (2021) 'Characterising initial sprint acceleration strategies using a whole-body kinematics approach', *Journal of Sports Sciences* [Preprint]. Available at: https://doi.org/10.1080/02640414.2021.1985759/FORMAT/EPUB.

Willy, R. W., Brorsson, A., Powell, H. C., Willson, J. D., Tranberg, R., and Silbernagel, K.G. (2017) 'Elevated Knee Joint Kinetics and Reduced Ankle Kinetics Are Present during Jogging and Hopping after Achilles Tendon Ruptures', *American Journal of Sports Medicine*, 45(5), pp. 1124–1133. Available at: https://doi.org/10.1177/0363546516685055.

Wren, T. A., Yerby, S. A., Beaupré, G. S., and Carter, D. R. (2001) 'Mechanical properties of the human achilles tendon', *Clinical Biomechanics*, 16(3), pp. 245–251. Available at: https://doi.org/10.1016/S0268-0033(00)00089-9.

Wren, T. A., Lindsey, D. P., Beaupré, G. S., & Carter, D. R. (2003) 'Effects of Creep and Cyclic Loading on the Mechanical Properties and Failure of Human Achilles Tendons', *Annals of Biomedical Engineering*, 31(6), pp. 710–717. Available at: https://doi.org/10.1114/1.1569267.

Xergia, S. A., Tsarbou, C., Liveris, N. I., Hadjithoma, M., and Tzanetakou, I. P. (2022) 'Risk factors for Achilles tendon rupture: an updated systematic review', *The Physician and Sportsmedicine*, pp. 1–11. Available at: https://doi.org/10.1080/00913847.2022.2085505.

Yang, J., Hodax, J. D., Machan, J. T., Krill, M. K., Lemme, N. J., Durand, W. M., Hoffman, J. T., Hewett, T. E., and Owens, B. D. (2019) 'Factors Affecting Return to Play After Primary Achilles Tendon Tear: A Cohort of NFL Players', *Orthopaedic Journal of Sports Medicine*, 7(3). Available at: https://doi.org/10.1177/2325967119830139.

Yeh, C. H., Calder, J. D., Antflick, J., Bull, A. M. J., and Kedgley, A. E. (2021) 'Maximum dorsiflexion increases Achilles tendon force during exercise for midportion Achilles tendinopathy', *Scandinavian Journal of Medicine and Science in Sports* [Preprint]. Available at: https://doi.org/10.1111/SMS.13974.

Yin, L., & Elliott, D. M. (2004). A biphasic and transversely isotropic mechanical model for tendon: application to mouse tail fascicles in uniaxial tension. *Journal of Biomechanics*, *37*(6), 907–916. https://doi-org/10.1016/j.jbiomech.2003.10.007

Yong, J. R., Dembia, C. L., Silder, A., Jackson, R. W., Fredericson, M., and Delp, S. L. (2019) 'Foot strike pattern during running alters muscle-tendon dynamics of the gastrocnemius and the soleus', *bioRxiv preprint*, pp. 1–25. Available at: https://doi.org/10.1038/s41598-020-62464-3.

Zellers, J.A., Carmont, M.R. and Grävare Silbernagel, K. (2016a) 'Return to play post-Achilles tendon rupture: a systematic review and meta-analysis of rate and measures of return to play', *British Journal of Sports Medicine*, 50(21), pp. 1325–1332. Available at: https://doi.org/10.1136/bjsports-2016-096106.

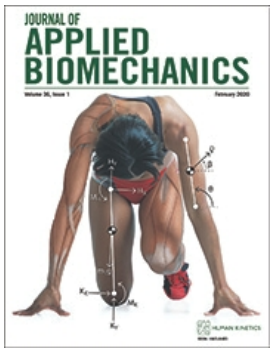
Zellers, J.A., Cortes, D.H. and Silbernagel, K.G. (2016b) 'From acute Achilles tendon rupture to return to play - a case report evaluating recovery of tendon structure, mechanical properties, clinical and functional outcomes.', *International journal of sports physical therapy*, 11(7), pp. 1150–1159.

Zhang, B. M., Zhong, L. W., Xu, S. W., Jiang, H. R., and Shen, J. (2013) 'Acupuncture for chronic Achilles tendinopathy: A randomized controlled study', *Chinese Journal of Integrative Medicine*, 19(12), pp. 900–904. Available at: https://doi.org/10.1007/s11655-012-1218-4.

7. APPENDICES

APPENDIX 1: (THEME 1, STUDY 1) STUDY 1 MANUSCRIPT SUBMITTED TO THE JOURNAL OF APPLIED BIOMECHANICS

Journal of Applied Biomechanics



A novel single-leg horizontal plyometric exercise task: reliability, stiffness and joint mechanical outputs

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A novel single-leg horizontal plyometric exercise task: reliability, stiffness and joint mechanical outputs

Colin Griffin[1,2], Katherine A J Daniels[2,3], Chris Richter[2], Andrew Franklyn-Miller[2,4], Jean-Benoit Morin[1,5,6]

[1]Université Côte d'Azur, LAMHESS, Nice, France.

[2]Sports Surgery Clinic, Santry Demesne Dublin 9, Ireland

[3]Department of Sport and Exercise Sciences, Manchester Metropolitan University, Manchester, United Kingdom

[4]Centre for Health, Exercise and Sports Medicine, University of Melbourne, Parkville Victoria, Australia

[5]Sports Performance Research Institute New Zealand (SPRINZ), Auckland University of Technology, Auckland, New Zealand

[6]Univ Lyon, UJM-Saint-Etienne, Inter-university Laboratory of Human Movement Biology, EA 7424, F-42023, Saint-Etienne, France

Address for correspondence: Colin Griffin, Sports Medicine department, Sports Surgery Clinic, Santry Demesne Dublin 9, Ireland.

Email: colingriffin@sportssurgeryclinic.com

Key words

Stiffness, Hopping, Performance, Injury, Rehabilitation, Ankle

Abstract

There has been little investigation of horizontal plyometric exercises despite their relevance for athletic performance. The aim of this study was to (i) assess test-retest

reliability of biomechanical and performance features in a single-leg horizontal plyometric exercise, (ii) investigate joint stiffness (K_{joint}) and mechanical outputs and their relationship with rebound distance (RD), horizontal reactive strength index (hRSI), leg (K_{leg}) and vertical (K_{vert}) stiffness and (iii) determine how many trials are required to capture a representative mean across different variables. Ten males performed the task over two sessions with 3D motion and force data captured. Biomechanical and performance features were then extracted. Good-to-excellent reliability was demonstrated for most biomechanical and performance features. K_{ankle} and contact time each correlated with both K_{vert} and K_{leg}. Peak hip joint moment and peak horizontal GRF (hGRF) correlated with RD and hRSI. Joint power and work were highest at the ankle, while joint stiffness was higher at the knee compared to the ankle. A stable correlation with the mean for the majority of variables was reached by the third trial. We propose the use of this test to assess horizontal reactive strength and lower-limb joint mechanical features, using the mean of three trials.

(Abstract word count 197)

Introduction

Jumping and hopping exercise tests are commonly used to measure lower limb power, reactive strength and biomechanical qualities that are relevant to performance and recovery after an injury (Bolgla *et al.,* 1997; Butler *et al.,* 2003; McMahon *et al.,* 2012). By performing these tests unilaterally, asymmetries may be identified that can be addressed in a strength and conditioning or rehabilitation program (King *et al.*, 2019). However, less is understood about the biomechanical features of single-leg horizontal plyometric exercises and the extent to which they differ from vertical hopping which may be relevant in performance and rehabilitation settings.

Single leg horizontal hop tests such as a triple-hop have demonstrated good reliability (Bolgla *et al.,* 1997) and are a valid predictor of lower limb strength and power (Hamilton *et al.,* 2008). However, while hop distance has been used as a measure of performance, a deeper evaluation of the biomechanics behind single-hop performance and observed asymmetries may prove useful to researchers, clinicians and coaches. Single leg hop for distance tests, which include a triple-hop, highlighted deficits between an injured and uninjured limb in patients following ACL rupture (Noyes *et al.,* 1991) and ankle instability (Caffrey *et al.*, 2009). The within-limb joint work distribution strategy for horizontal hopping differs from vertical hopping, with vertical demonstrating larger contributions from the knee while horizontal hops exhibit greater contributions from the ankle (Aeles and Vanwanseele, 2019; Davies *et al.,* 2020; Kotsifaki *et al.*, 2021). Significantly impaired horizontal hop performance featured in runners with Achilles tendinopathy accompanied by reduced tendon stiffness, rate of force development and delayed activation of the individual calf muscles (Wang *et al.*, 2012). While vertical hopping is a frequently-used test to measure reactive strength qualities and highlight deficits in lower-limb injuries (Silbernagel *et al.*, 2006; Brazier et al., 2014; King *et al.*, 2019), a horizontal rebound task may provide deeper insights into ankle function for running-related performance and as an injury rehabilitation outcome measure.

Lower limb stiffness is linked to athletic performance and injury risk (Butler *et al.,* 2003; Maquirriain, 2012; Lorimer *et al.,* 2018). Stiffness can be measured during running, jumping, and hopping tasks. Vertical hopping is a commonly-used test to measure stiffness (Farley and Morgenroth, 1999; Brughelli and Cronin, 2008; Hobara et al., 2009; Kuitunen *et al.,* 2011; Maloney *et al.,* 2017). However, horizontal plyometric exercises

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develop athletic qualities that are reflected in running, acceleration, agility, and horizontal jumping performance (Dobbs *et al.*, 2015; Kariyama *et al.,* 2017; Moran *et al.*, 2021). Single leg horizontal hopping exposes the Achilles tendon to higher loading rates compared to vertical hopping (Gheidi *et al.*, 2018; Baxter *et al.*, 2021).

Both K_{vert} and K_{leg} is used to measure whole-body stiffness where the former depicts the vertical orientation of the leg at contact and the latter when ground contact is made with the leg at an angle (Butler *et al.,* 2003). However, some original studies (Farley and Morgenroth, 1999) lack a clear distinction between the two definitions during vertical hopping tasks by using vertical ground reaction force to calculate leg stiffness. For non-vertical locomotion such as running and horizontal plyometric exercises, it may be inaccurate to illustrate leg stiffness using vertical ground reaction forces and more appropriate to use the component of the ground reaction force oriented along the leg between the centre of pressure (CoP) under the foot, and the hip during the eccentric phase (Coleman *et al.*, 2012). Measuring lower limb stiffness may provide a useful measure of readiness for return to sport following a lower limb injury.

To our knowledge, horizontal reactive strength index has only been measured in a triple-hop test (Davey *et al.*, 2021; Šarabon *et al.,* 2021), while whole-body and joint stiffness variables have not been extensively investigated, except for the step phase of a triple jump (Perttunen *et al.*, 2000). Other variables such as the orientation of ground reaction force and distribution of peak joint moments, work and powers are also worthy of investigation to identify any compensations an athlete may employ as a result of injury. Despite the clinical utilisation of various single-leg horizontal rebound tasks as an outcome measure for return to performance during injury rehabilitation, knowledge

about reactive strength qualities, and variables such as lower limb stiffness, and joint mechanical outputs underpinning hop performance, remain elusive. It is also valuable to determine how many trials are required to obtain a stable representation of performance in key variables in this task as this may be useful for practitioners to perform in a time efficient manner in a clinical setting and for longitudinal monitoring of athletes in a rehabilitation pathway or throughout the season.

The aims of this study were (i) to assess the test-retest reliability of key biomechanical and performance variables in a single-leg horizontal plyometric exercise task, (ii) to investigate joint stiffness and mechanical outputs and their relationship with rebound distance and vertical stiffness and (iii) to determine how many trials are required to reach the correlation threshold for the group mean across the different variables. We hypothesised that joint stiffness would be highest at the knee due to the maximal effort nature of the task (Hobara *et al.*, 2009; Kuitunen *et al.,* 2011), and joint work and power at the ankle compared to the knee and hip as has been previously identified in a single leg hop for distance task (Aeles and Vanwanseele, 2019; Kotsifaki *et al.*, 2021). Due to the exploratory nature of parts (i) and (iii), no clear hypothesis could be formed.

Materials and methods

Ten healthy male participants were recruited to take part in two testing sessions which were fourteen days apart for nine and sixteen days for one participant. All participants (28.5 ± 5.6 years, height 1.79 ± 0.04 m, body mass 82.4 ± 6.6 kg) regularly performed strength training but were unfamiliar with the protocol at the time of testing. The study was approved by the Sports Surgery Clinic research ethics committee and each participant gave informed written consent prior to testing.

129

130 The experimental protocol was identical for the two testing sessions. Each participant
131 completed a standardised warm-up which consisted of a 2-minute jog on the treadmill
132 at 8 km/hr, 10 bodyweight squats, 10 pogo hops in place, and 3 familiarisation trials
133 on each leg. The test required participants to perform a forward hop over two 15-cm
134 hurdles rebounding off a force platform in between, completing 10 alternating trials on
135 each leg. The participants were instructed to keep their hands on their hips and to
136 rebound 'as fast as possible' and 'as far as possible'. The trials were performed in an
137 unshod condition and after each trial, the participants walked back slowly to begin the
138 next trial taking approximately 10 seconds of recovery time. A video demonstration of
139 this test is available in supplementary material in Appendix A.

140

141 *Data acquisition*

142 Twelve infrared cameras (200Hz; Vicon, UK) were used for three-dimensional motion
143 capture synchronised with two force platforms (1000Hz, AMTI, USA) to measure
144 ground reaction force data. Reflective markers (14 mm diameter) placed on the hallux,
145 lateral malleolus, calcaneus, shank, lateral femoral epicondyle, thigh, anterior superior
146 iliac spine, and posterior superior iliac spine, were used in accordance with the Plug-
147 in-gait model (Vicon, UK) with all segments used to calculate centre of mass (COM)
148 position. Motion and force data were filtered using a fourth-order low pass Butterworth
149 filter with a cut-off frequency of 15Hz. The data were then exported to MATLAB 2015a
150 (Mathworks, USA) for feature extraction. Statistical analysis was performed in R (R
151 Studio (2020), PBC, Boston, MA).

152

153 The following variables were calculated in the sagittal plane for both test sessions and
154 reported in table 1: K_{vert}, K_{leg}, ankle, knee, and hip joint stiffness, ankle, knee, and hip
155 joint moments, powers and total work, rebound distance (RD), vertical, horizontal and
156 leg ground reaction force, and contact time. All kinetic variables were normalised to
157 body mass. RD was calculated as the horizontal distance from the midstance phase
158 on the force plate to the initial landing phase using one of the foot markers for
159 reference. Horizontal reactive strength (hRSI) was calculated by dividing rebound
160 distance by contact time. The stance phase was determined by a vertical ground
161 reaction force threshold of 20 N during contact with the force plates, which detected
162 contact time.
163
164 K_{vert} was calculated during the early stance phase, as the ratio of change in vertical
165 ground reaction force (GRF) from the time of initial contact ($_{timpact}$) to vertical COM
166 displacement (ΔCoM) from $_{timpact}$ to maximum CoM displacement ($_{tmax.dis}$) (Blickhan,
167 1989; McMahon and Cheng, 1990).
168
169 $K_{vert} = force(_{tmax.dis}) – Force(_{timpact})/ CoM(_{tmax.dis}) – CoM(_{timpact})$
170
171 K_{leg} was calculated in the sagittal plane as the ratio of change in leg ground reaction
172 force (F_{leg}) which is the component of the GRF aligned to the leg vector between the
173 CoP and the hip joint centre (HJC), to the change in leg length (ΔLeg) at the shortest
174 leg length ($_{tmin.length}$) during the stance phase, similar to the model proposed by
175 Coleman *et al*., (2012). We measured leg length as the distance from the HJC to the
176 CoP on the force plate surface, in the sagittal plane.
177

$K_{leg} = F_{leg}(t_{min.length}) – F_{leg}(t_{impact}) / \text{Leg length } (t_{min.length}) – \text{Leg length } (t_{impact})$

Joint stiffness (K_{ankle}, $K_{knee,}$ and $K_{hip)}$ at the ankle knee, and hip respectively, were calculated in the sagittal plane as the ratio of change in joint moment to change in joint displacement from joint angle at t_{impact} time of maximum joint angular displacement ($t_{max.dis}$).

$K_{joint} = \text{Joint moment } (t_{max.dis}) – \text{Joint moment } (t_{impact}) / \text{Joint angle } (t_{max.dis}) – \text{Joint angle } (t_{impact})$

***** Insert Figure 1 *****

Statistical analysis

Both limbs were analysed for all trials. A two-way mixed intra-class correlation coefficient (ICC) method using absolute agreement was performed using R to examine the test-retest reliability (session 1 to session 2), with p values and 95% confidence intervals reported. ICC threshold values for reliability were interpreted as moderate (ICC > 0.5), good (ICC > 0.75) and excellent (ICC > 0.90). Pearson correlation coefficient analysis was employed using R to determine the correlation between predictor features contact time, stiffness, joint moments, work, powers, and displacements with outcome variables: rebound distance, horizontal reactive strength, and vertical and leg stiffness. Thresholds for interpretation of small (r > 0.1), moderate (r > 0.3), large (r > 0.5) and very large (r > 0.7) correlations using values proposed by Hopkins et al., (2009) were applied and reported where significance was reached (p < 0.05). Joint stiffness, displacements, moments, work, and powers were compared at

the ankle, knee, and hip using one-way repeated measures ANOVA, with significance ($p < 0.05$) and eta squared effect sizes calculated and magnitudes reported using Cohen's thresholds of small ($\eta^2 > 0.01$), medium ($\eta^2 > 0.06$) and large ($\eta^2 > 0.14$) for comparing means (Correll *et al.*, 2019).

To determine the number of trials required to reach the correlation threshold of the group mean, a "true" mean was generated by a simulation using a customized python (3.7) script (pandas 1.4.1, numpy 1.22.2, scipy 1.8.0) where the mean of seven randomly selected trials per session was calculated over 100 iterations and averaged. The mean of n trials (n = 1, 2, .., 10) was then correlated against the true mean to compute a Pearson's correlation coefficient that was used to determine from which trials a true mean representation could be expected, with a correlation threshold set at 0.9 for a nearly perfect fit (Hopkins *et al.*, 2009).

***** Insert Table 1 *****

Results

A shaded plot illustrating the mean and standard deviation of vertical and horizontal ground reaction force-time curves during stance phase, are illustrated Figure 1.

Test-retest reliability

Mean values from all variables for both testing sessions, including confidence intervals and p values, are displayed in table 1. The hip joint was maximally flexed at initial contact and demonstrated extension throughout the stance phase and therefore hip joint stiffness could not be calculated using joint stiffness equations. Excellent

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228 reliability was demonstrated for vGRF (0.91), and good reliability for hRSI (0.75),
229 rebound distance (0.80), contact time (0.78), F_{leg} (0.86) and peak knee moment (0.89),
230 K_{ankle} (0.81) and K_{knee} (0.75).. Moderate reliability was observed for K_{vert} (0.67), K_{leg}
231 (0.61), Δ knee (0.56), hGRF (0.69), ankle (0.53) and hip 0.71) peak moments, and
232 ankle power (0.61) and work (0.56).
233
234 ***** Insert Table 2 *****
235
236 *Pearson's correlation analysis*
237 Table 2 shows the Pearson's correlation coefficients for the relationship between the
238 predictor variables and the outcome variables: RD, HRSI, K_{vert} and K_{leg}. At joint level,
239 both K_{ankle} (r = 0.54) and K_{knee} (r = 0.56) had a strong correlation with $K_{vert,}$ while K_{ankle}
240 (r = 0.64) had a large correlation with $K_{leg.}$ Similarly, vGRF had a large correlation with
241 K_{vert} (r = 0.65) and K_{leg} (r = 0.55) as did F_{leg} (r = 0.61 and r = 0.56 respectively). Knee
242 joint angular displacement had a large correlation with K_{vert} (r = 0-.50). Hip peak joint
243 moment (r = 0.56) and hGRF (r = 0.66) had a large correlation with hop distance, while
244 hGRF had a similarly large correlation effect with hRSI (r = 0.58). Contact time had a
245 very large correlation (r = -0.77) with K_{vert} and a large correlation (r = -0.67) with K_{leg}.
246 The correlation plots illustrating large and very large correlations are displayed in
247 Figure 2, with the different colours of the dots representing each participant.
248
249 ***** Insert Figure 2 *****
250 ***** Insert Table 3 *****
251
252 *ANOVA Joint mechanical outputs*

The differences between the joint mechanical outputs using eta squared effect sizes are reported in Table 3. The greatest peak joint work occurred at the ankle with a medium effect in comparison to the knee (η^2 = 0.07) and a small effect in comparison to the hip (η^2 = 0.01). Similarly, the highest joint powers were observed at the ankle with a medium effect when compared to the knee (η^2 = 0.08) and a small effect when compared to the hip (η^2 = 0.01). The highest peak joint moments occurred at the hip with a medium effect compared to the ankle (η^2 = 0.07) and a small effect when compared to the knee (η^2 = 0.01). Stiffness values were higher at the knee than at the ankle with a large effect compared to the knee (η^2 = 0.16), while the largest joint displacements occurred at the ankle with a medium effect in comparison to the knee (η^2 = 0.06).

***** Insert Figure 3 *****

Correlation with the true mean

The average of all trials for each of the variables across the 2 testing sessions reached a stable correlation with the 'true' mean from trial 3 onwards (r > 0.90) except for ΔCoM and leg length, hip joint moment, ankle and hip joint power, which were achieved from the 4th trial, and hip joint work from the 5th trial onwards. The correlation plots between each trial and the 'true' mean for each variable measured are displayed in Figure 3. The fluctuations for RD and hRSI on the left limb in the 2nd testing session were accounted for by one participant whose values were significantly lower than the others for some trials.

Discussion and implications

Reliability

In this study, we established that a single leg horizontal plyometric exercise is a reliable test for measuring key performance variables such as hRSI, rebound distance, and contact time, as well as ground reaction forces, stiffness, and joint kinematic variables. Hop distance has previously demonstrated good reliability during a triple hop test, albeit for a slightly different task to that investigated in this study (Bolgla *et al.,* 1997). A recent study found good reliability for flight time, CT, hRSI and K_{leg} in a triple-hop test (Davey *et al.*, 2021). During double leg vertical hopping, Diggin ***et al.*** (2016) found good inter- and intraday reliability for K_{leg} and $K_{ankle,}$ while Joseph et al. (Joseph *et al.*, 2013) observed good reliability for K_{vert} but poor reliability for K_{ankle} and K_{knee} during running and hopping tasks. These joint stiffness findings are in contrast with what was observed in our study. One possible reason for this could be due to the acyclic nature of the horizontal rebound compared to high-frequency cyclic tasks like repeated hopping and running where there is an adjustment at joint level to regulate K_{leg} and K_{vert} (Farley *et al.*, 1998; Farley and Morgenroth, 1999).

Lower-limb Stiffness

To our knowledge, this is the first study to investigate joint, leg, and whole-body stiffness variables, and joint work and power in a single leg horizontal plyometric exercise. We hypothesised that joint stiffness would be highest at the knee compared to the ankle which was observed in this study and can be attributed to higher peak joint moments occurring at the knee with lower joint angular displacements, in contrast to the ankle. It has previously been reported that the least stiff joint has the largest correlation with vertical stiffness (Maloney *et al.*, 2017). The large correlation we observed between K_{ankle} and K_{vert} and K_{leg} respectively, may partially support this

303 finding. Hobara et al. (2009) demonstrated that K_{knee} accounted for most of the
304 variance in leg stiffness in maximal intensity double leg hopping. However, in this
305 study, knee joint angular displacement had a larger correlation with vertical stiffness
306 than ankle joint angular displacement. This may be due to the biomechanical nature
307 of the task where the participants land in knee flexion and where further knee flexion
308 during stance influences vertical centre of mass displacements. The leg stiffness
309 values in this study are similar to reported values during running at steady-state
310 speeds (Morin *et al.*, 2005; Coleman *et al.*, 2012). It must be noted however, that leg
311 stiffness values vary depending on the calculation model used (Coleman *et al.*, 2012)
312 and the type of athlete, with sprinters exhibiting greater k_{leg} than endurance runners
313 (Harrison *et al.,* 2004).
314
315 *Correlation findings*
316 Our results highlighted that contact time had a strong correlation with K_{vert} and $K_{leg.}$
317 Shorter ground contact times during hopping are also associated with greater Achilles
318 tendon stiffness (Abdelsattar *et al.,* 2018). Both hip joint moment and hGRF had a large
319 correlation with rebound distance. Hip extensor strength and horizontal orientation of
320 GRF are key determinants of acceleration performance (Morin *et al.*, 2015), while
321 horizontal jumping has a closer relationship with sprint performance compared to
322 vertical hopping (Dobbs *et al.*, 2015). Performance in a triple jump is associated with
323 vGRF during the braking phase and hGRF during the propulsion phase of the step
324 phase (Perttunen *et al.*, 2000). A recent systematic review concluded that vertical
325 plyometric exercises were found to improve vertical performance only, whereas
326 horizontal plyometric training results in improvements in both vertical and horizontal
327 performance (Moran *et al.*, 2021). These findings may be relevant for running sports

and using a horizontal rebound may be a practical way of assessing horizontal plyometric ability.

Joint outputs

The dominance of the ankle, knee, and hip varied depending on the joint variable measured. Peak joint moment was highest at the hip, while joint power, work, and angular displacement were highest at the ankle, and the knee displayed greater joint stiffness than the ankle. The highest peak joint power and work at the ankle are in agreement with our hypothesis and other studies during a single-leg horizontal hop or rebound exercise task (Aeles and Vanwanseele, 2019; Kotsifaki *et al.*, 2021). Higher joint work at the ankle compared to the knee and hip are observed in distance running (Novacheck, 1998; Schache *et al.*, 2011) where elite runners maintain higher ankle joint output over a prolonged fatiguing run in comparison to novice runners (Sanno *et al.*, 2018). The highest net joint work and power occurs at the ankle during the early acceleration phase of maximal sprinting (Williams *et al.,* 2017; Schache *et al.,* 2019).

While this study did not measure muscle and tendon loading patterns it may be possible to use findings from previously-reported musculoskeletal modelling techniques based on running and hopping tasks, in conjunction with the joint mechanical outputs from this study, to gain a better understanding of the muscle contributions to horizontal reactive strength qualities. High pre-activation and braking activity of the vastus lateralis and a peak in medial gastrocnemius EMG activity during the propulsion phase are observed in world-class triple jumpers during the step phase and jump phases (Perttunen *et al.*, 2000). In a single-leg hop for distance, the soleus contributes the largest muscle force during the propulsive phase (Kotsifaki *et al.*, 2021).

353 Previous studies have shown that forward hopping exposes the Achilles tendon to the
354 higher loading rates compared to vertical hopping (Gheidi *et al.*, 2018; Baxter *et al.*,
355 2021). Reduced tendon stiffness, delayed muscle activation from the triceps surae and
356 impaired hop for distance performance have been observed in runners with Achilles
357 tendinopathy (Wang *et al.*, 2012). In light of our findings of ankle dominance for joint
358 work and power, a maximal effort horizontal plyometric task may provide a robust
359 assessment of the ankles capacity and athlete's progression following an Achilles
360 injury rehabilitation program. This test is currently being used by the authors of this
361 study as a key outcome measure for an Achilles tendinopathy randomised controlled
362 trial (Griffin *et al.*, 2021).
363
364 *Correlation with the 'true' mean*
365 The correlation threshold was reached after three trials for the majority of the features
366 measured and suggests that averaging three test trials following three familiarisation
367 trials in the warm-up, are sufficient to capture a stable mean value of a measure.
368 These findings are in agreement with test protocols for common jumping or hopping
369 tests which utilise three test trials (King *et al.*, 2019; Davey *et al.*, 2021), while six trials
370 were required for a lateral hurdle hop test (Gore *et al.*, 2016).
371
372 *Limitations*
373 There are some important limitations that should be acknowledged in this study. The reliability
374 of some of the variables with ICC values <0.75 with large confidence intervals, should be
375 interpreted with caution due to the small sample size. The Plug-in-Gait model used assumes
376 the foot acts like a rigid segment and this may overestimate ankle joint power and work by not
377 allowing for rotation of the individual foot segments. This rigid foot model may also under

estimate ankle joint stiffness and overestimate displacements by between 45-60% at higher force demands (Kessler *et al.*, 2020). All joint stiffness variables were calculated in the sagittal plane and do not take into consideration the joint displacements and moments that may occur in the frontal and transverse planes. It was not possible to calculate hip joint stiffness using the hip joint angle changes from initial contact to maximum displacement due to the lack of hip flexion during the stance phase. Given the largest peak joint moments occurred at the hip, the impact of hip joint stiffness in this task may this have been overlooked.

Conclusion

Our study demonstrated moderate-to-excellent reliability for performance features such as rebound distance and horizontal reactive strength index, as well as most whole-body and joint kinematic and stiffness features in a single-leg horizontal rebound exercise. We observed large correlations between horizontal ground reaction force and performance features, as well as for contact time, ankle and knee joint stiffness with vertical and leg stiffness. The ankle displayed the highest joint work and power, while the knee showed the highest joint stiffness, and the largest peak joint moment was at the hip. Three familiarisation trials followed by three test trials are sufficient to obtain a stable representation of performance across the majority of variables. We propose the use of this test as a simple way to measure horizontal reactive strength index equivalent to the commonly-used reactive strength index in the drop jump. Considering the highest joint work and power outputs at the ankle coupled with the previously observed muscle calf muscle force contribution and Achilles tendon loading rates, a horizontal rebound task such as the one used in this study may be a suitable assessment for return to performance following an ankle-related injury.

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Declaration of interests

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References

Abdelsattar, M., Konrad, A. and Tilp, M. (2018) "Relationship between Achilles Tendon Stiffness and Ground Contact Time during Drop Jumps," *Journal of sports science & medicine*, 17(2), pp. 223–228. Available at: http://www.ncbi.nlm.nih.gov/pubmed/29769823.

Aeles, J. and Vanwanseele, B. (2019) "Do Stretch-Shortening Cycles Really Occur in the Medial Gastrocnemius? A Detailed Bilateral Analysis of the Muscle-Tendon Interaction During Jumping," *Frontiers in Physiology*, 10, p. 1504. Available at: https://doi.org/10.3389/fphys.2019.01504.

Baxter, J.R. Corrigan, P., Hullfish, T.J., O'Rourke, P. and Silbernagel, K.G. (2021) "Exercise Progression to Incrementally Load the Achilles Tendon," *Medicine and Science in Sports and Exercise*, 53(1), pp. 124–130. Available at: https://doi.org/10.1249/MSS.0000000000002459.

Blickhan, R. (1989) "The spring-mass model for running and hopping," *Journal of Biomechanics*, pp. 1217–1227. Available at: https://doi.org/10.1016/0021-9290(89)90224-8.

Bolgla, L.A. and Keskula, D.R. (1997) "Reliability of Lower Extremity Functional Performance Tests," *Journal of Orthopaedic & Sports Physical Therapy*, 26(3), pp. 138–142. Available at: https://doi.org/10.2519/jospt.1997.26.3.138.

Brazier, J., Bishop, C. and Simons, C. (2014) 'Lower Extremity Stiffness: Effects on Performance and Injury and Implications for Training', *Strenght and Conditioning Journal*, 36(5), pp. 103–112. Available at: https:doi.org/10.1519/JSC.0000000000002283.

Brughelli, M. and Cronin, J. (2008) "A review of research on the mechanical stiffness in running and jumping: Methodology and implications," *Scandinavian Journal of Medicine and Science in Sports*, 18(4), pp. 417–426. Available at: https://doi.org/10.1111/j.1600-0838.2008.00769.x.

441 Butler, R.J., Crowell, H.P. and Davis, I.M. (2003) "Lower extremity stiffness: implications
442 for performance and injury," *Clinical Biomechanics*, 18(6), pp. 511–517. Available at:
443 https://doi.org/10.1016/S0268-0033(03)00071-8.
444
445 Caffrey, E. Docherty, C.L., Schrader, J. and Klossner, J. (2009) "The Ability of 4 Single-
446 Limb Hopping Tests to Detect Functional Performance Deficits in Individuals With
447 Functional Ankle Instability," *Journal of Orthopaedic & Sports Physical Therapy*, 39(11),
448 pp. 799–806. Available at: https://doi.org/10.2519/jospt.2009.3042.
449
450 Coleman, D.R. Cannavan, D., Horne, S. and Blazevich, A.J. (2012) "Leg stiffness in human
451 running: Comparison of estimates derived from previously published models to direct
452 kinematic-kinetic measures," *Journal of Biomechanics*, 45(11), pp. 1987–1991. Available at:
453 https://doi.org/10.1016/j.jbiomech.2012.05.010.
454
455 Correll, J. Mellinger, C., McClelland, G.H. and Judd, C.M. (2019) "Avoid Cohen's 'Small',
456 'Medium', and 'Large' for Power Analysis," *Trends in Cognitive Sciences*, 24(3), pp. 200–
457 207. Available at: https://doi.org/10.1016/j.tics.2019.12.009.
458
459 Davey, K., Read, P., Coyne, J., Jarvis, P., Turner, A., Brazier, J., Šarabon, N., Jordan, M.J.
460 and Bishop, C. (2021) "An Assessment of the Hopping Strategy and Inter-Limb Asymmetry
461 during the Triple Hop Test: A Test–Retest Pilot Study," *Symmetry*, 13(10), p. 1890.
462 Available at: https://doi.org/10.3390/sym13101890.
463
464 Davies, W.T., Myer, G.D. and Read, P.J. (2020) "Is It Time We Better Understood the Tests
465 We are Using for Return to Sport Decision Making Following ACL Reconstruction? A
466 Critical Review of the Hop Tests," *Sports Medicine*, 50(3), pp. 485–495. Available at:
467 https://doi.org/10.1007/s40279-019-01221-7.
468
469 Diggin, D., Anderson, R. and Harrison, A.J. (2016) "An Examination of the True Reliability
470 of Lower Limb Stiffness Measures During Overground Hopping.," *Journal of Applied*
471 *Biomechanics*, 32(3), pp. 278–286. Available at: https://doi.org/10.1123/jab.2015-0210.
472
473 Dobbs, C.W. *et al.* (2015) 'Relationship Between Vertical and Horizontal Jump Variables
474 and Muscular Performance in Athletes', *The Journal of Strength & Conditioning Research*,
475 29(3), pp. 661–671. Available at: https://doi.org/10.1519/JSC.0000000000000694.
476
477 Dorn, T.W., Schache, A.G. and Pandy, M.G. (2012) "Muscular strategy shift in human
478 running: dependence of running speed on hip and ankle muscle performance," *Journal of*
479 *Experimental Biology*, 215(11), pp. 1944–1956. Available at:
480 https://doi.org/10.1242/jeb.064527.
481
482 Farley, C.T. Houdijk, H.H., Van Strien, C. and Louie, M. (1998) "Mechanism of leg stiffness
483 adjustment for hopping on surfaces of different stiffnesses.," *Journal of Applied Physiology*.
484 85(3), pp. 1044-1055. Available at: http://doi.org/10.1152/jappl.1998.85.3.1044.
485
486 Farley, C.T. and Morgenroth, D.C. (1999) "Leg stiffness primarily depends on ankle stiffness
487 during human hopping," *Journal of Biomechanics*. 32(3), pp. 267-273. Available at:
488 https://doi.org/10.1016/S0021-9290(98)00170-5.
489

Gheidi, N., Kernozek, T.W., Willson, J.D., Revak, A. and Diers, K. (2018) "Achilles tendon loading during weight bearing exercises," *Physical Therapy in Sport*, 32, pp. 260–268. Available at: https://doi.org/10.1016/j.ptsp.2018.05.007.

Gore, S.J., Marshall, B.M., Franklyn-Miller, A.D., Falvey, E.C. and Moran, K.A. (2016) "The number of trials required to obtain a representative movement pattern during a hurdle hop exercise," *Journal of Applied Biomechanics*, 32(3), pp. 295–300. Available at: https://doi.org/10.1123/jab.2015-0121.

Griffin, C., Daniels, K.A., Hill, C., Franklyn-Miller, A.D. and Morin, J.B. (2021) "A criteria-based rehabilitation program for chronic mid-portion Achilles tendinopathy: study protocol for a randomised controlled trial," *BMC Musculoskeletal Disorders*, 22(1), p. 695. Available at: https://doi.org/10.1186/S12891-021-04553-6.

Hamilton, R.T., Shultz, S.J., Schmitz, R.J. and Perrin, D.H. (2008) "Triple-Hop Distance as a Valid Predictor of Lower Limb Strength and Power," *Journal of Athletic Training*, 43(2), pp. 144–151. Available at: https://doi.org/10.4085/1062-6050-43.2.144.

Harrison, A.J., Keane, S.P. and Coglan, J. (2004) 'Force-velocity relationship and stretch-shortening cycle function in sprint and endurance athletes', *Journal of Strength and Conditioning Research*, 18(3), pp. 473–479. Available at: https://doi.org/10.1519/13163.1.

Hobara, H., Muraoka, T., Omuro, K., Gomi, K., Sakamoto, M., Inoue, K. and Kanosue, K. (2009) "Knee stiffness is a major determinant of leg stiffness during maximal hopping," *Journal of Biomechanics*, 42(11), pp. 1768–1771. Available at: https://doi.org/10.1016/J.JBIOMECH.2009.04.047.

Hopkins, W.G., Marshall, S.W., Batterham, A.M. and Hanin, J. (2009) "Progressive statistics for studies in sports medicine and exercise science," *Medicine and Science in Sports and Exercise*, 41(1), pp. 3–12. Available at: https://doi.org/10.1249/MSS.0b013e31818cb278.

Joseph, C.W., Bradshaw, E.J., Kemp, J. and Clark, R.A. (2013) "The Interday Reliability of Ankle, Knee, Leg, and Vertical Musculoskeletal Stiffness During Hopping and Overground Running," *Journal of Applied Biomechanics*, 29(4), pp. 386–394. Available at: https://doi.org/10.1123/jab.29.4.386.

Kariyama, Y., Hobara, H. and Zushi, K. (2017) "Differences in take-off leg kinetics between horizontal and vertical single-leg rebound jumps," *Sports Biomechanics*, 16(2), pp. 187–200. Available at: https://doi.org/10.1080/14763141.2016.1216160.

Kessler, S.E., Lichtwark, G.A., Welte, L.K.M., Rainbow. M.J. and Kelly, L.A. (2020) "Regulation of foot and ankle quasi-stiffness during human hopping across a range of frequencies," *Journal of Biomechanics*, 108, p. 109853. Available at: https://doi.org/10.1016/j.jbiomech.2020.109853.

King, E., Franklyn-Miller, A., Wadey, R., Moran, R. and Strike, S. (2019) "Back to Normal Symmetry? Biomechanical Variables Remain More Asymmetrical Than Normal During

539 Jump and Change-of-Direction Testing 9 Months After Anterior Cruciate Ligament
540 Reconstruction," *The American Journal of Sports Medicine*, 47(5), pp. 1175–1185. Available
541 at: https://doi.org/10.1177/0363546519830656.
542
543 Kipp, K. and Kim, H. (2020) "Relative contributions and capacities of lower extremity
544 muscles to accelerate the body's center of mass during countermovement jumps," *Computer*
545 *Methods in Biomechanics and Biomedical Engineering*, 23(12), pp. 914–921. Available at:
546 https://doi.org/10.1080/10255842.2020.1772764.
547
548 Kotsifaki, A., Korakakis, V., Graham-Smith, P., Sideris, V. and Whiteley, R. (2021)
549 "Vertical and Horizontal Hop Performance: Contributions of the Hip, Knee, and Ankle,"
550 13(2), pp. 128–135. Available at: https://doi.org/10.1177/1941738120976363.
551
552 Kuitunen, S., Ogiso, K. and Komi, P. V. (2011) "Leg and joint stiffness in human hopping,"
553 *Scandinavian Journal of Medicine & Science in Sports*, 21(6), pp. e159–e167. Available at:
554 https://doi.org/10.1111/j.1600-0838.2010.01202.x.
555
556 Lorimer, A. V., Keogh, J.W.L. and Hume, P.A. (2018) "Using stiffness to assess injury risk:
557 comparison of methods for quantifying stiffness and their reliability in triathletes," *PeerJ*, 6,
558 p. e5845. Available at: https://doi.org/10.7717/peerj.5845.
559
560 Maloney, S.J., Richards, J., Nixon, D.G.D., Harvey, L.J. and Fletcher, I.M. (2017) "Vertical
561 stiffness asymmetries during drop jumping are related to ankle stiffness asymmetries,"
562 *Scandinavian Journal of Medicine and Science in Sports*, 27(6), pp. 661–669. Available at:
563 https://doi.org/10.1111/sms.12682.
564
565 Maquirriain, J. (2012) "Leg stiffness changes in athletes with achilles tendinopathy,"
566 *International Journal of Sports Medicine*, 33(7), pp. 567–571. Available at:
567 https://doi.org/10.1055/s-0032-1304644.
568
569 McMahon, J.J., Comfort, P. and Pearson, S. (2012) "Lower Limb Stiffness," *Strength &*
570 *Conditioning Journal*, 34(6), pp. 94–101. Available at:
571 https://doi.org/10.1519/SSC.0b013e3182781b4e.
572
573 McMahon, T.A. and Cheng, G.C. (1990) "The mechanics of running: How does stiffness
574 couple with speed?," *Journal of Biomechanics*, 23(SUPPL. 1), pp. 65–78. Available at:
575 https://doi.org/10.1016/0021-9290(90)90042-2.
576
577 Moran, J., Ramirez-Campillo, R., Liew, B., Chaabene, H., Behm, D.G., García-Hermoso, A.,
578 Izquierdo, M. and Granacher, U. (2021) "Effects of Vertically and Horizontally Orientated
579 Plyometric Training on Physical Performance: A Meta-analytical Comparison," *Sports*
580 *Medicine*, 51(1), pp. 65–79. Available at: https://doi.org/10.1007/s40279-020-01340-6.
581
582 Morin, J.B., Dalleau, G., Kyröläinen, H., Jeannin, T. and Belli, A. (2005) "A simple method
583 for measuring stiffness during running," *Journal of Applied Biomechanics*, 21(2), pp. 167–
584 180. Available at: https://doi.org/10.1123/jab.21.2.167.
585
586 Morin, J.B., Gimenez, P., Edouard, P., Arnal, P., Jiménez-Reyes, P., Samozino, P., Brughelli,
587 M. and Mendiguchia, J. (2015) "Sprint acceleration mechanics: The major role of hamstrings

588 in horizontal force production," *Frontiers in Physiology*, 6(DEC). Available at:
589 https://doi.org/10.3389/fphys.2015.00404.
590
591 Nagahara, R., Naito, H., Miyashiro, K., Morin, J.B. and Zushi, K. (2014) "Traditional and
592 ankle-specific vertical jumps as strength-power indicators for maximal sprint acceleration,"
593 *The Journal of sports medicine and physical fitness*, 54(6), pp. 691–699. Available at:
594 https://pubmed.ncbi.nlm.nih.gov/24739258/.
595
596 Novacheck, T.F. (1998) "The biomechanics of running", *Gait and Posture*. 7(1), pp. 77-95.
597 Available at: https://doi.org/10.1016/S0966-6362(97)00038-6.
598
599 Noyes, F.R., Barber, S.D. and Mangine, R.E. (1991) "Abnormal lower limb symmetry
600 determined by function hop tests after anterior cruciate ligament rupture," *The American*
601 *Journal of Sports Medicine*, 19(5), pp. 513–518. Available at:
602 https://doi.org/10.1177/036354659101900518.
603
604 Pandy, M.G., Lai, A.K.M., Schache, A.G. and Lin, Y.C. (2021) "How muscles maximize
605 performance in accelerated sprinting," *Scandinavian Journal of Medicine and Science in*
606 *Sports*, 31(10), pp. 1882–1896. Available at: https://doi.org/10.1111/SMS.14021.
607
608 Perttunen, J., Kyrolainen, H., Komi, P.V and Heinonen, A. (2000) "Biomechanical loading in
609 the triple jump," *Journal of Sports Sciences*, 18(5), pp. 363–370. Available at:
610 https://doi.org/10.1080/026404100402421.
611
612 Sanno, M., Willwacher, S., Epro, G. and Brüggemann, G.P. (2018) "Positive work
613 contribution shifts from distal to proximal joints during a prolonged run," *Medicine and*
614 *Science in Sports and Exercise*, 50(12), pp. 2507–2517. Available at:
615 https://doi.org/10.1249/MSS.0000000000001707.
616
617 Šarabon, N., Kozinc, Ž. and Bishop, C. (2021) 'Comparison of Vertical and Horizontal
618 Reactive Strength Index Variants and Association With Change of Direction Performance',
619 *Journal of Strength and Conditioning Research*, Publish Ahead of Print. Available at:
620 https://doi.org/10.1519/JSC.0000000000004193.
621
622 Schache, A.G., Blanch, P.D., Dorn, T,W., Brown, N.A., Rosemond, D. and Pandy, M.G.
623 (2011) "Effect of Running Speed on Lower Limb Joint Kinetics," *Medicine & Science in*
624 *Sports & Exercise*, 43(7), p. 1260. Available at:
625 https://doi.org/10.1249/MSS.0b013e3182084929.
626
627 Schache, A.G., Lai, A.K.M., Brown, N.A.T., Crossley, K.M. and Pandy, M.G. (2019)
628 "Lower-limb joint mechanics during maximum acceleration sprinting," *Journal of*
629 *Experimental Biology*, 222(22). Available at: https://doi.org/10.1242/jeb.209460.
630
631 Silbernagel, K.G. *et al.* (2006) 'Evaluation of lower leg function in patients with Achilles
632 tendinopathy', *Knee Surgery, Sports Traumatology, Arthroscopy*, 14(11), pp. 1207–1217.
633 Available at: https://doi.org/10.1007/s00167-006-0150-6.

634 Wang, H.K., Lin, K.H., Su, S.C., Shih, T.T. and Huang, Y.C. (2012) "Effects of tendon
635 viscoelasticity in Achilles tendinosis on explosive performance and clinical severity in

athletes," *Scandinavian Journal of Medicine and Science in Sports*, 22(6), pp. 1–9. Available at: https://doi.org/10.1111/j.1600-0838.2012.01511.x.

Williams, D.S.B., Cole, J.H. and Powell, D.W. (2017) "Lower Extremity Joint Work During Acceleration, Deceleration, and Steady State Running," *Journal of Applied Biomechanics*, 33(1), pp. 56–63. Available at: https://doi.org/10.1123/jab.2016-0063.

Figure legends

Figure 1. A shaded plot illustrating the mean and standard deviation of vertical and horizontal ground reaction force during stance phase

Figure 2. Pearson correlation plots for featured that demonstrated large to very large correlations.

Figure 3. The correlation plots between each trial for both testing sessions and the 'true' mean for each featured measured.

Appendix A. Supplementary material

Link to a video demonstrating the single leg horizontal rebound test:

https://vimeo.com/725287405

Table 1. Mean values (± SD) for all variables examined for both testing sessions, ICC (95% CI) and associated p values

Variable	*Day 1*	*Day 2*	*ICC (95% CI)*	*p*
Rebound distance (cm)	152.49 ± 30.87	145.81 ± 34.20	0.80 (0.72-0.85)	< 0.001
Contact time (s)	0.26 ± 0.03	0.27 ± 0.03	0.78 (0.70-0.84)	< 0.001
Reactive strength index (ms-^{1})	5.94 ± 1.32	5.50 ± 1.35	0.75 (0.59-0.81)	< 0.001
Peak vertical GRF (N/kg)	29.93 ± 3.54	29.45 ± 4.08	0.91 (0.88-0.93)	< 0.001
Peak horizontal GRF (N/kg)	4.30 ± 0.93	4.08 ± 0.99	0.69 (0.58-0.77)	< 0.001
Peak leg force (N/kg)	28.92 ± 3.38	28.16 ± 4.01	0.86 (0.80-0.90)	< 0.001
Ankle peak joint moment (N·m/kg)	2.91 ± 0.61	2.94 ± 0.66	0.53 (0.37-0.65)	< 0.001
Knee peak joint moment (N·m/kg)	3.60 ± 0.61	3.60 ± 0.63	0.89 (0.86-0.92)	< 0.001
Hip peak joint moment (N·m/kg)	3.96 ± 0.81	4.11 ± 0.95	0.71 (0.60-0.79)	< 0.001
Δ CoM (cm)	12.23 ± 1.93	12.41 ± 2.31	0.42 (0.24-0.57)	< 0.001
Δ Leg (cm)	15.86 ± 2.82	16.63 ± 2.31	0.72 (0.60-0.79)	< 0.001
Δ Ankle (deg)	36.57 ± 5.02	36.26 ± 5.32	0.49 (0.32-0.62)	< 0.001
Δ Knee (deg)	19.97 ± 6.43	19.52 ± 7.58	0.56 (0.44-0.68)	< 0.001
Vertical stiffness (kN/m/kg)	0.25 ± 0.04	0.24 ± 0.04	0.67 (0.55-0.75)	< 0.001
Leg stiffness (kN/m/kg)	0.18 ± 0.03	0.17 ± 0.03	0.61 (0.44-0.72)	< 0.001
Ankle joint stiffness (N·mm/deg/kg)	1.21 ± 0.29	1.21 ± 0.27	0.81 (0.74-0.86)	< 0.001
Knee joint stiffness (N·mm/deg/kg)	1.68 ± 0.49	1.74 ± 0.60	0.75 (0.65-0.82)	< 0.001
Ankle peak joint power (W/kg)	20.42 ± 2.78	18.83 ± 2.86	0.61 (0.34-0.75)	< 0.001
Knee peak joint power (W/kg)	9.69 ± 2.70	9.63 ± 2.58	0.37 (0.15-0.53)	0.01
Hip peak joint power (W/kg)	12.00 ± 3.67	13.56 ± 4.05	0.42 (0.20-0.58)	< 0.001
Ankle total joint work (J/kg)	1606.0 ± 375.4	1577.9 ± 327.5	0.56 (0.45-0.65)	< 0.001
Knee total joint work (J/kg)	693.4 ± 315.6	688.3 ± 327.5	0.35 (0.22-0.47)	< 0.001
Hip total joint work (J/kg)	1272.4 ± 470.1	1345.8 ± 466.7	0.31 (0.22-0.47	< 0.001

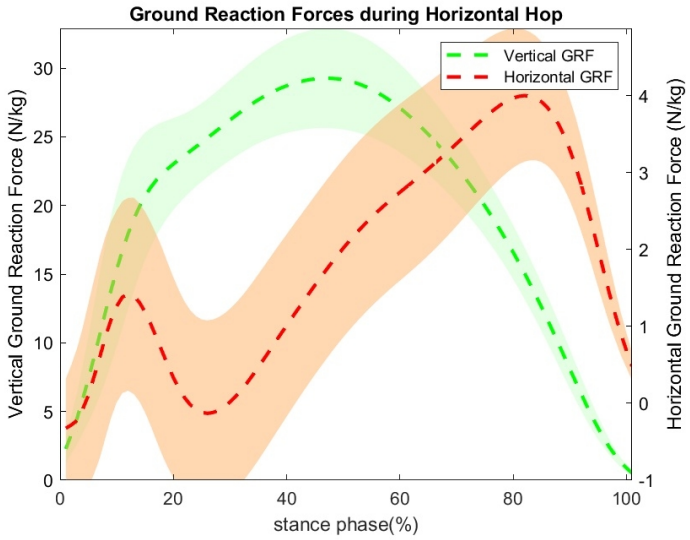
Abbreviations: SD standard deviation; ICC Intra-class correlation; CI confidence interval; GRF ground reaction force

Table 2. Pearson correlation coefficient (r values), correlation magnitude thresholds (interpretation) and significance (p values) of contact time and joint mechanical outputs with rebound distance, horizontal reactive strength index, leg stiffness and vertical stiffness for combined testing days

		Rebound distance (mm)			*Reactive strength index (ms-1)*			*Vertical stiffness (K_{vert})*			*Leg stiffness (K_{leg})*		
	Mean ± SD	**r**	**Interpretation**	**p**	**r**	**Interpretation**	**p**	**r**	**Interpretation**	**p**	**r**	**Interpretation**	**p**
Contact time (s)	0.26 ± 0.03	0.25	*Small*	< 0.001	-0.21	Small	< 0.001	-0.77	Very Large	< 0.001	-0.67	*Large*	< 0.001
Ground reaction force													
Peak vertical GRF (N/kg)	29.74 ± 3.85	-0.15	*Small*	0.03	0.09	-	0.21	0.65	*Large*	< 0.001	0.55	*Large*	< 0.001
Peak horizontal GRF (N/kg)	4.2 ± 0.97	0.66	*Large*	< 0.001	0.58	Large	< 0.001	0.10	*Small*	0.31	0.08	-	0.14
Peak leg force (N/kg)	28.60 ± 3.75	-0.12	*Small*	0.09	0.11	Small	0.13	0.61	*Large*	< 0.001	0.56	*Large*	< 0.001
Stiffness													
K_{vert} (kN/m/kg)	0.24 ± 0.05	-0.06	-	0.25	0.31	Moderate	< 0.001	-		-	-		-
K_{leg} (kN/m)	0.18 ± 0.04	-0.20	*Small*	< 0.001	0.15	Small	< 0.001	-		-	-		-
K_{ankle} (N·mm/deg)	1.21 ± 0.28	-0.15	*Small*	0.01	0.13	Small	0.04	0.54	*Large*	< 0.001	0.64	*Large*	< 0.001
K_{knee} (N·mm/deg)	1.72 ± 0.54	-0.08	-	0.19	0.19	Small	< 0.001	0.56	*Large*	< 0.001	0.35	*Moderate*	< 0.001
Joint moments													
Ankle peak moment (N·m/kg)	2.93 ± 0.65	-0.20	*Small*	< 0.001	-0.08	-	0.12	0.24	*Small*	< 0.001	0.21	*Small*	< 0.001
Knee peak moment (N·m/kg)	3.60 ± 0.62	-0.13	*Small*	0.01	0.17	Small	0.01	0.45	*Moderate*	<0.001	0.47	*Moderate*	< 0.001
Hip peak moment (N·m/kg)	3.98 ± 0.93	0.56	*Large*	< 0.001	0.49	Moderate	< 0.001	-0.07	-	0.48	-0.28	*Small*	0.007
Joint work													
Ankle total joint work (J/kg)	1591.9 ± 369.1	-0.10	*Small*	0.15	0.07	-	0.31	0.20	*Small*	0.003	0.14	*Small*	0.04
Knee total joint work (J/kg)	690.1 ± 321.5	-0.27	*Moderate*	< 0.001	-0.35	Moderate	< 0.001	-0.13	*Small*	0.07	-0.06	-	0.39
Hip total joint work (J/kg)	1309.1 ± 468.4	0.22	*Small*	0.002	0.13	Small	0.07	-0.13	*Small*	0.06	-0.24	*Small*	< 0.001
Joint powers													
Ankle power (W/kg)	19.43 ± 4.62	0.29	*Small*	< 0.001	0.38	Moderate	< 0.001	0.20	*Small*	0.003	0.22	*Small*	0.005
Knee power (W/kg)	9.96 ± 2.89	0.19	*Small*	< 0.001	0.19	Small	< 0.001	0.06	-	0.34	-0.08	-	0.71
Hip power (W/kg)	13.35 ± 4.78	0.20	*Small*	< 0.001	0.26	Moderate	< 0.001	0.22	*Small*	0.002	-0.15	-	0.03
Global displacements													
Δ CoM (cm)	12.29 ± 1.65	-0.14	*Small*	0.01	-0.25	Moderate	< 0.001	-0.31	*Moderate*	< 0.001	-0.22	*Small*	< 0.001
Δ Leg (cm)	16.30 ± 2.45	0.13	*Small*	0.01	-0.02	-	0.66	-0.23	*Small*	< 0.001	-0.47	*Moderate*	< 0.001
Joint angular displacements													
Δ Ankle (deg)	36.48 ± 5.27	0.11	*Small*	0.04	-0.02	-	0.70	-0.34	*Moderate*	< 0.001	-0.43	*Moderate*	< 0.001
Δ Knee (deg)	19.73 ± 7.07	-0.01	-	0.82	-0.28	Moderate	< 0.001	-0.50	*Large*	< 0.001	-0.38	*Moderate*	< 0.001

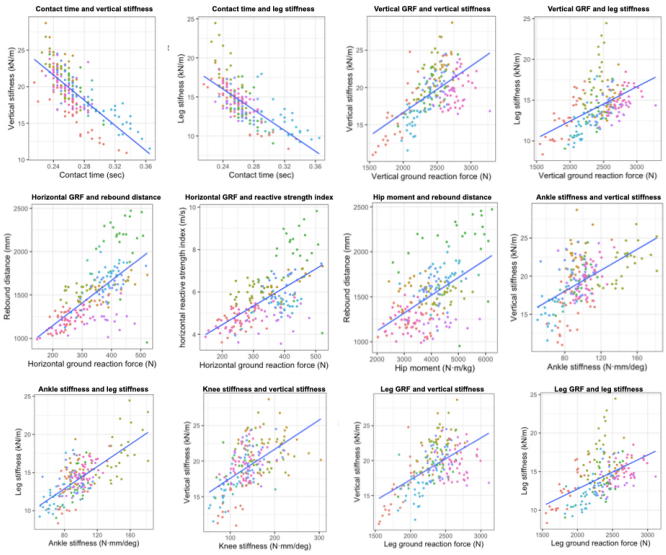
Table 3. Joint mechanical output relationships using eta squared effect size (p values) and their interpretations for each joint variable (larger joint outputs are in the vertical columns) for both testing days.

Joint output variable	η^2 (p)	Interpretation	η^2 (p)	Interpretation
	K_{ankle}			
K_{knee}	0.16 (0.01)	*Large*		
	Δ knee			
Δ ankle	0.06 (0.01)	*Medium*		
	Ankle peak moment		**Knee peak moment**	
Knee peak moment	0.10 (0.01)	*Medium*	-	
Hip peak moment	0.07 (0.01)	*Medium*	0.01 (0.01)	*Small*
	Knee peak power		**Hip peak power**	
Ankle peak power	0.08 (0.01)	*Medium*	0.01 (0.51)	*Small*
Hip peak power	0.02 (0.01)	*Small*	-	
	Knee total joint work		Hip total joint work	
Ankle total joint work	0.07 (0.01)	*Medium*	0.01 (0.41)	*Small*
Hip total joint work	0.01 (0.01)	*Small*	-	



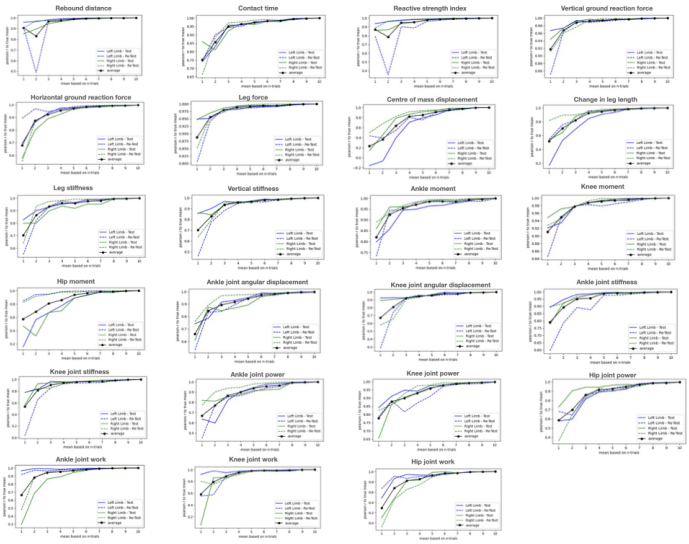
A shaded plot illustrating the mean and standard deviation of vertical and horizontal ground reaction force during stance phase

148x111mm (150 x 150 DPI)



Pearson correlation plots for featured that demonstrated large to very large correlations

361x270mm (72 x 72 DPI)



The correlation plots between each trial for both testing sessions and the 'true' mean for each featured measured

361x270mm (72 x 72 DPI)

630x340mm (144 x 144 DPI)

Human Kinetics, 1607 N Market St, Champaign, IL 61825

APPENDIX 2: (THEME 2, STUDY 3) STUDY 3 MANUSCRIPT PUBLISHED IN BMC MUSCULOSKELETAL DISORDERS JOURNAL

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BMC Musculoskeletal Disorders

STUDY PROTOCOL Open Access

A criteria-based rehabilitation program for chronic mid-portion Achilles tendinopathy: study protocol for a randomised controlled trial

Colin Griffin[1,2*], Katherine Daniels[2,3,4], Caroline Hill[2], Andrew Franklyn-Miller[2,5] and Jean-Benoît Morin[1,6,7]

Abstract

Background: Achilles tendinopathy (AT) is a common overuse injury in running-related sports where patients experience pain and impaired function which can persist. A graded rehabilitation program has been successful in reducing pain and improving function to enable a return to sport. The aim of this study is to compare the effectiveness of a criteria-based rehabilitation program including strength and reactive strength targets, with a previously successful rehabilitation program on changes in pain and function using the Victorian Institute of Sport Assessment-Achilles (VISA-A) questionnaire. Secondary aims will be to assess changes in calf strength, reactive strength, and lower limb running and forward hop biomechanics over the course of a 12-week rehabilitation program, and long-term follow-up investigations.

Methods: Sixty eligible participants with chronic mid-portion AT who train in running-based sports will be included in this study. They will be randomly assigned to a group that will follow an evidence-based rehabilitation program of daily exercises with progression guided by symptoms or a group performing 3 high-intensity rehabilitation sessions per week with individualised load targets progressing to reactive strength exercises. Testing will take place at baseline, week 6 and 12. Plantar flexor peak torque will be measured using isokinetic dynamometry, reactive strength will be measured using a drop jump and lower limb biomechanical variables will be measured during a single leg forward hurdle hop test and treadmill running using 3D motion analysis. Follow-up interviews will take place at 6, 12 and 24 months after beginning the program which will assess patient participation in sport and possible re-injury.

Discussion: This is the first study to propose an individualised criteria-based graded rehabilitation program in patients in with chronic mid-portion Achilles tendinopathy where progression is guided by strength and reactive strength outcome measures. This study will provide a comprehensive assessment of plantar flexor strength, reactive strength and lower limb biomechanical variables in running and forward hopping with the VISA-A questionnaire as the primary outcome measure and long term post-intervention follow-up assessments performed.

Trial registration: ClinicalTrials.gov (ID: NCT04384874). Registered retrospectively on April 23rd 2020.

Keywords: Achilles tendinopathy, Plantar flexor strength, Stiffness, Hopping, Achilles tendon, Injury, Rehabilitation

* Correspondence: colingriffin@sportssurgeryclinic.com
[1]Université Côte d'Azur, LAMHESS, Nice, France
[2]Sports Surgery Clinic, Santry Demesne, Dublin 9, Ireland
Full list of author information is available at the end of the article

Background

The Achilles tendon is the largest and strongest tendon in the human body [1] and usually withstands very high tensile forces during exercise [2], but is also one of the most commonly injured tendons [3]. Achilles tendinopathy (AT) affects 2% of the general population [4], and has an incidence of 7–9% in running-based sports with a cumulative lifetime incidence of up to 52% among certain athletic populations [5].

Tendinopathy is described as pain and impaired function in the affected tendon [6–8]. Over time this may result in reduced physical activity, absenteeism from sport and impaired quality of life [8]. Histologically and biochemically pathological tendon has been shown to include increased hyper-cellularity, reduced collagen type I and increased type III content, increased proteoglycans and glycosaminoglycans, and blood vessel in-growth [9, 10]. Excessive loading of the tendon is believed to be the primary contributory factor to Achilles tendinopathy [11]. The fibroblastic cells known as tenocytes within the extracellular matrix are sensitive to mechanical loading and, when the tendon is overloaded, the cells alter the protein composition of the matrix resulting in pathology and reduced capacity for exercise [12].

Patients with AT usually present with pain, swelling and impaired performance of the tendon [13], as well as altered function of the plantar flexor muscles [14–16]. In a sporting population, training load perturbations such as a rapid increase in training volume, intensity or frequency are said to be common contributory factors [17]. Re-injury rates are high, most likely due to incomplete restoration of muscle-tendon unit function [18], and symptoms can persist for a number of years in some cases [19]. In an eight-year follow-up study, 20% of patients still experienced impaired physical activity [20]. A failed healing response and degenerative changes are associated with the development of chronic tendinopathy resulting in reduced load capacity and persistent pain symptoms [8]. This is described by Cook et al. [8] in their proposed continuum model involving three stages: reactive tendinopathy, tendon disrepair and degenerative tendinopathy.

Impairments in tendon mechanical properties such as stiffness and Young's modulus have been highlighted in AT [21–23]. Wang et al. (2012) observed reduced stiffness and increased hysteresis of the Achilles tendon, along with reduced rate of force development of the plantar flexor muscles and reduced single leg horizontal hop performance in symptomatic limbs of patients with AT, compared to the non-symptomatic limb. While one study found reduced lower limb stiffness in the injured limb of runners with AT during hopping [24], biomechanical variables such as leg and joint stiffness in running and hopping tasks have not been extensively researched in patients with Achilles tendinopathy.

Many passive treatment therapies such as injections [25, 26], Non-Steroidal Anti-Inflammatory Drugs (NSAIDs) [10, 27], ultrasound [10, 27], shockwave [28, 29], laser [27], iontophoresis [25], acupuncture [30], orthotics [25, 29], wearing a night splint [31], vibration and cryotherapy [32], mucopolysaccharides [33], and a wait-and-see approach [28] have been used in the management of AT. However, there is strongest evidence for the use of exercise therapy as the primary treatment option [34–36]. Tendons adapt to exercise as the mechanical perturbation of the inter- and intra-fascicular cells triggers a molecular response signalling an expression of important proteins in the extra-cellular matrix which restore the mechanical properties of the tendon [37, 38]. Three main modes of exercise have been widely used, each associated with improvements in clinical symptoms to varying degrees, namely: Alfredson's eccentric protocol [39], Silbernagel's combined concentric-eccentric protocol [36] and the Heavy Slow Resistance protocol [40]. The Silbernagel protocol [see Table 1] comprises a combined concentric-eccentric exercise program performed daily, before progressing to plyometric exercises as symptoms permit, with no individualisation of exercise prescription and progression guided solely by pain symptoms on a numeric pain rating scale (NPRS).

Recent evidence suggests that magnitude of loading, irrespective of contraction mode, is the primary stimulus for tendon adaptation [41]. Isometric exercises using 5 × 45 s contractions at 70% maximal voluntary contraction (MVC) have been used for early management of tendinopathies with evidence suggesting an analgesic effect [42]. However, this has been since contested by the findings of O'Neill et al. [43]. Documented timeframes for rehabilitation interventions vary between 6 weeks to several months with no clear objective measures for return to sport. Patients with AT display impaired reactive strength qualities during hopping tasks and it is recommended to include plyometric training at an advanced stage of a rehabilitation program to prepare for the stretch-shortening cycle demands of running-based sports [19, 36]. A multi-stage rehabilitation program that includes the combination of strength development and plyometric training may thus be beneficial, but there is a lack of consensus on assessing these qualities to guide exercise prescription and progression through the rehabilitation pathway.

While numerous studies have shown positive clinical improvements and tendon adaptations to exercise [36, 39–41, 44], studies which investigate a periodised return to sport rehabilitation program with load targets and outcome measures for progression, are necessary due to the individualised nature of its initial presentation and

Table 1 Silbernagel's combined concentric-eccentric program

Phase 1: Weeks 1–2
Patient status: Pain and difficulty with all activities, difficulty performing 10 single leg heel raises
Goal: Start to exercise, gain understanding of their injury and of pain monitoring model
Treatment program: Perform exercises every day:
• Pain monitoring model information and advice on exercise activity
• Circulation exercises (moving foot up and down)
• Double leg heel raises standing on the floor (3 × 10–15 repetitions)
• Single leg heel raises standing on the floor (3 × 10)
• Sitting heel raises (3 × 10)
• Eccentric heel raises standing on the floor (3 × 10)
Phase 2: Weeks 2–5
Patient status: Pain and difficulty with all activities, difficulty performing 10 single leg heel raises
Goal: Start to exercise, gain understanding of their injury and of pain monitoring model
Treatment program: Perform exercises every day:
• Pain monitoring model information and advice on exercise activity
• Circulation exercises (moving foot up and down)
• Double leg heel raises standing on the floor (3 × 10–15 repetitions)
• Single leg heel raises standing on the floor (3 × 10)
• Sitting heel raises (3 × 10)
• Eccentric heel raises standing on the floor (3 × 10)
Patient status: Pain with exercise, morning stiffness, pain when performing heel raises
Goal: Start strengthening
Treatment program: Perform exercises every day:
• Double leg heel raises standing on the edge of a step (3 × 15)
• Single leg heel raises standing on the edge of a step (3 × 10)
• Sitting heel raises (3 × 15)
• Eccentric heel raises standing on the edge of a step (3 × 15)
• Quick-rebounding heel raises (3 × 20)
Phase 3: Weeks 3–12 (longer if needed)
Patient status: Tolerates phase 2 exercise program well, no pain at distal portion of tendon, possibly increased or decreased morning stiffness
Goal: Heavier strength training, increase or begin running and/or jumping
Treatment program: Perform exercises every day with heavier load 2–3 times per week
• Single leg heel raises standing on the edge of a step with added weight (3 × 10)
• Sitting heel raises (3 × 15)
• Eccentric heel raises standing on the edge of a step with added weight (3 × 15)
• Quick-rebounding heel raises (3 × 20)
• Plyometric training
Phase 4: Weeks 12–6 months (longer if needed) **Patient status:** Minimal symptoms, morning stiffness but not every day, can participate in sports without difficulty
Goal: Heavier strength training, increase or begin running and/or jumping
Treatment program: Perform exercises every day with heavier load 2–3 times per week
• Single leg heel raises standing on the edge of a step with added weight (3 × 10)
• Eccentric heel raises standing on the edge of a step with added weight (3 × 15)
• Quick-rebounding heel raises (3 × 20)

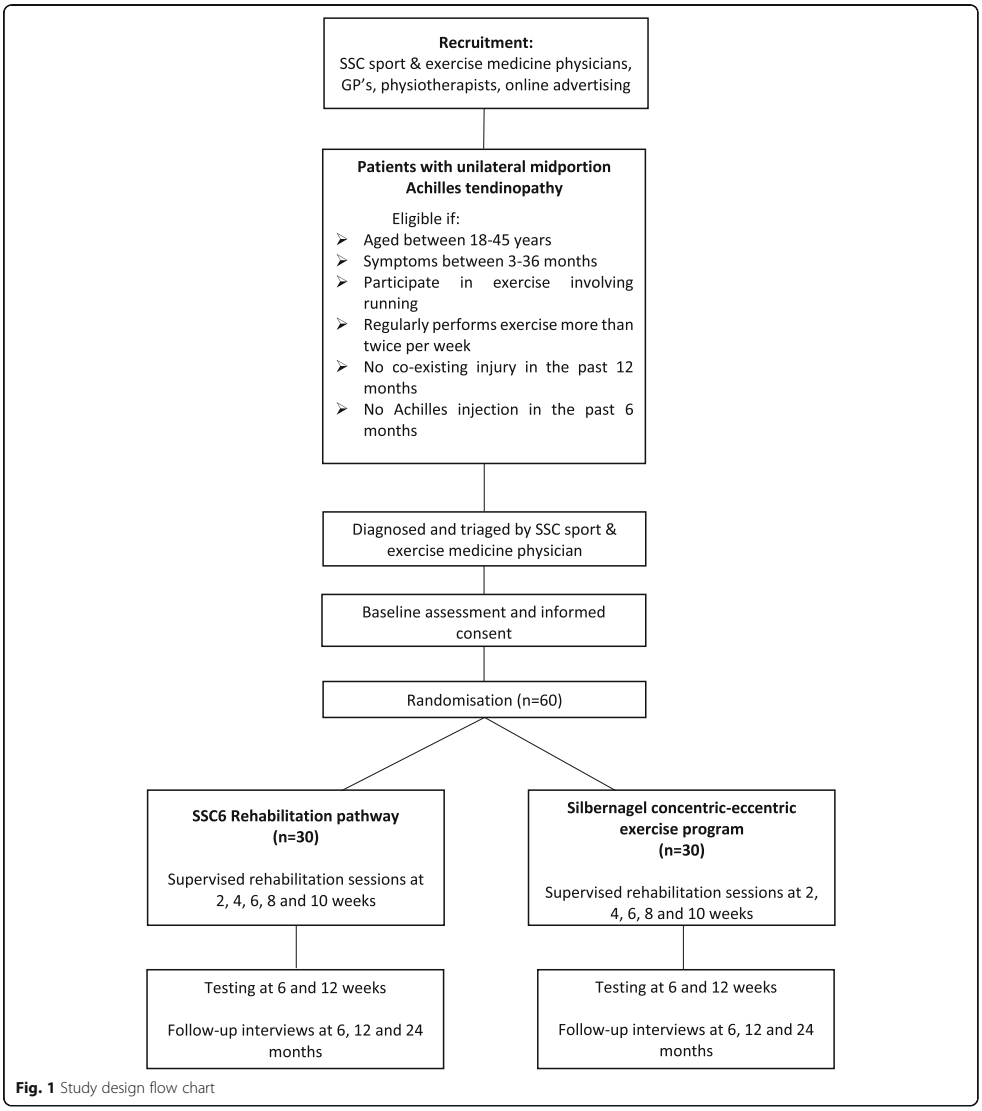

Fig. 1 Study design flow chart

diverse timeframes for recovery. The Sports Surgery Clinic (SSC) rehabilitation pathway [see Table 2] proposed in this study involves 6 stages of progressive rehabilitation (SSC6) from initial diagnosis and assessment, through developing strength, power and reactive strength, linear and multi-directional running, and return to performance. The existing literature has demonstrated positive clinical outcomes using Silbernagel's rehabilitation program [18, 44] and we have selected this a suitable comparative control for this study which involves a graded progression pathway from combined concentric-eccentric exercises to plyometric training [36].

Considering the multiple functional impairments experienced by athletes with AT, a battery of kinematic and

Table 2 SSC6 Rehabilitation program

Level 1 ***Week 0–3*** **Entry criteria:** **Pain > 5/10 on SL calf raise**	**Kinetic chain (2 days per week)** **Box squat 3 × 8 reps @ 10RM** **Step-up 3 × 8 reps e/s @ 10RM**	**Calf Isometrics (daily)** **5 × 45 s holds @ 60 s RM)**		
Level 2 *Week 0–4* Entry criteria: Pain < 5/10 on SL calf raise	**Kinetic chain (2 days per week)** Front squat 4 × 8 reps @ 10RM Or Deadlift 4 × 8 reps @ 10RM Step-up 3 × 8 e/s @ 10RM Or Split squat 3 × 8 reps e/s	**Calf strength** (3 days per week) SL calf raises 4 × 8 reps @ 10RM *~ Begin with dumbbell and shoes off* *~ Aim to through 1st MTPJ and good rearfoot control* Seated SL calf raises 4 × 10 reps @ 12RM *~ Begin with kettlebell on knee and forefoot on a plate*		
Level 3 *Week 3–6* Entry criteria: Pain < 4/10 on SL calf raise	**Kinetic chain (2 days per week)** Front squat 4 × 6 reps @ 8RM Or Deadlift 4 × 6 reps @ 8RM Step-up 3 × 6 e/s @ 8RM Or Split squat 3 × 6 each side @ 8RM	**Calf strength** (3 times per week) SL calf raises 4 × 8 reps @ 10RM *~ Progress to a smith machine or barbell using rack for support* *~ Aim for > 70% BW* Seated SL calf raises 4 × 10 reps @ 12RM *~ Progress to smith machine or landmine press* *~ Aim for > 90% BW*	**Coordination/running technique** Ankling 3 × 10 m March 3 × 10 m A-skip 3 × 20 m	
Level 4 *Week 6–9* Entry criteria: Pain < 5/10 for 10 DL hops < 10% asymmetry in calf isokinetic tests	**Kinetic chain (2 days per week)** Front squat 4 × 6 reps @ 8RM Or Deadlift 4 × 6 reps @ 8RM Step-up 3 × 6 reps e/s @ 8RM Or Split squat 3 × 6 each side @ 8RM	**Calf strength** (3 times per week) SL calf raises 4 × 8 reps @ 10RM *~ Progress to a smith machine or barbell using rack for support* *~ Aim for > 80% BW* Seated SL calf raises 4 × 10 reps @ 12RM *~ Progress to smith machine or landmine press* *~ Aim for > 110% BW*	**DL Reactive strength** (2 times per week) DL Pogo hops in-place 4 × 10 (Day 1) *~ Keep knees straight and stiff* *~ Flat foot contacts* *~ Active dorsiflexion during flight phase* DL pogo hops forward 4 × 10 (Day 2) *~ Keep knees straight and stiff* *~ Flat foot contacts* *~ Active dorsiflexion during flight phase*	
Level 5 *Week 9–12* Entry criteria: Pain < 4/10 for 10 SL hops Exit criteria: < 10% asymmetry in single leg vertical and horizontal RSI	**Kinetic chain (2 days per week)** Front squat 3 × 5 reps @ 7RM Or Deadlift 3 × 5 reps @ 7RM Step-up 3 × 5 reps e/s @ 7RM Or Split squat 3 × 5 each side @ 7RM	**Calf strength** (3 times per week) SL calf eccentric 4 × 8 reps @ 10RM *~ Use a smith machine/leg press/ barbell using rack for support* *~ Up on 2 legs, lower down slowly on 1 over 3 s* *~ Aim for > 100% BW or equivalent* Seated SL calf raises 4 × 10 reps @ 12RM *~ Progress to smith machine or landmine press* *~ Aim for > 110% BW*	**DL Reactive strength** (2 times per week) Drop jump 4 × 4 reps from 20 to 30 cm box *~ Maximum jump height with minimal contact* *~ Minimal knee bend on ground contact* *~ Cue "imagine the floor is hot"*	**SL Reactive strength** (2 times per week) SL pogo hops in-place 4 × 10 e/s (Day 1) SL pogo hops forward 4 × 10 e/s (Day 2)
Level 6 *Week 12–26* Recommended maintenance program	**Kinetic chain (2 days per week)** Front squat 3 × 5 reps @ 7RM Or Deadlift 3 × 5 reps @ 7RM Step-up 3 × 5 reps e/s @ 7RM	**Calf strength** (2 times per week) SL calf isometric 4 × 8 reps × 4 s holds *~ Use a smith machine/leg press/ barbell using rack for support* *~ Up on 2 legs, hold on 1* *~ Aim for > 140% BW or equivalent*	**DL Reactive strength** (2 times per week) Drop jump 4 × 5 reps from 20 to 30 cm box	**SL Reactive strength** (2 times per week) SL pogo hops in-place 4 × 12 e/s (Day 1) SL pogo hops forward 4 × 12 e/s (Day 2)

Table 2 SSC6 Rehabilitation program *(Continued)*

Level 1 ***Week 0–3*** **Entry criteria:** **Pain > 5/10 on SL calf raise**	**Kinetic chain (2 days per week)** **Box squat 3 × 8 reps @ 10RM** **Step-up 3 × 8 reps e/s @ 10RM**	**Calf Isometrics (daily)** **5 × 45 s holds @ 60 s RM)**
	Or Split squat 3 × 5 each side @ 7RM	

Abbreviations: DL - double leg, SL - single leg, reps - repetitions, e/s - each side, BW - bodyweight, RM - repetition maximum

kinetic tests to investigate plantar flexor strength, reactive strength and lower limb biomechanical variables in hopping and running, may provide guidance on exercise prescription, progression through a rehabilitation program and return to sport decision-making. To the best of our knowledge no study has assessed such breadth of athletic qualities affected by AT.

This study will aim to compare the outcome of SSC6, a multi-factorial, individualised criteria-based rehabilitation program with Silbernagel's combined concentric-eccentric program, in physically active participants with chronic mid-portion AT. In addition to the commonly reported outcome measures of VISA-A, as secondary outcome measures we will assess plantar flexor strength, reactive strength and lower limb kinematic and kinetics during running and hopping at 6-week intervals during a 12-week rehabilitation program as these have not been reported previously. We also further aim to investigate the long term effects of rehabilitation programs and achieved outcome measures over a 6, 12 and 24-month follow-up period.

Aims

Using the VISA-A questionnaire as the primary outcome measure, the aim of this study is to compare the effectiveness of Silbernagel's daily exercise program with progression guided by pain symptoms, against SSC6's exercise program carried out 3 times per week with specific load targets. We will assess plantar flexor strength using isokinetic dynamometry, reactive strength based on a drop jump, and lower limb biomechanics during a novel single leg horizontal rebound test and running, and investigate whether changes in these variables over the course of the 12-week rehabilitation program are associated with improved pain and function outcomes using the VISA-A questionnaire when comparing the two rehabilitation programs. We will assess participant satisfaction with their prescribed program, adherence and fidelity using a training diary and perform follow-up interviews at 6, 12 and 24 months to analyse participation in their sport and any potential re-injury rates.

Methods

Study design

This study will be a single-centre, parallel group randomized-control trial. The data collection will take place at the SSC Sports Medicine department at the Sports Surgery Clinic in Dublin. The study protocol has been reported using the Standard Protocol Items: Recommendations for Interventions (SPIRIT) statement guidelines [Available in supplementary files]. The study was approved by the Sports Surgery Clinic's Research Ethics Committee, (Application number: SAREB13/05/19CG/MJ) and registered at ClinicalTrials.gov (ID: NCT04384874).

Participants

Adult patients diagnosed with chronic mid-portion AT who participate in running-based sports will be invited to take part in this study. Patients who present to the Sports Surgery Clinic (SSC) with Achilles pain will be seen by a Sport and Exercise medicine physician, their history and clinical examination will be confirmed with magnetic resonance imaging (MRI). If the patient is diagnosed and meets the inclusion criteria, they will be invited to participate in the study and will be given an information sheet to read with a minimum of 24 h to consider before agreeing by signing a consent form [Additional file 2: Appendix 2]. Participants will also be recruited externally through adverts on social media channels, emails to coaching contacts and local sports clubs. Participants who feel that they are eligible and meet the inclusion criteria will be referred for examination by a sport and exercise medicine physician at the clinic to confirm diagnosis and eligibility for the study.

Inclusion/exclusion criteria

Inclusion criteria

Participants will be eligible for this study if they are aged 18–45 years, perform running-based sports, are diagnosed with mid-portion AT, following a clinical examination by a sports medicine physician and confirmed with MRI, and have been experiencing symptoms for more than 3 months but less than 3 years.

Exclusion criteria

Patients will be ineligible for the study if they have a co-existing lower-limb injury, have had a running-related injury in the previous 12 months, or have had any peritendinous, or intra tendinous Achilles injection in the past 6 months, or previous Achilles surgery [15, 18, 44].

Randomisation and blinding

Participants will be assessed at baseline before being randomly assigned to the intervention group or control group and will follow a prescribed rehabilitation program for 12 weeks. See Table 3 for a summary of the study design. The randomisation will be performed using the online tool www.sealedenvelope.com and the participant will be handed an envelope from an independent observer not involved with the study, containing their respective group allocation number. The principal investigator and training group investigators will be blinded to the group randomisation process. These procedures have been used in similar studies [45]. The participants will be prescribed with an exercise program with video demonstrations of each exercise under the supervision of the investigator in their respective group. The program will be carried out at home or in a local gym in addition to supervised rehabilitation sessions every 2–3 weeks at SSC. Testing will take place again at week 6 and 12. Follow-up interviews will take place at 6, 12 and 24 months after baseline testing. The investigator involved with the testing and follow-up interviews will also be blinded to the group allocation. The primary outcome measure will be changes to the VISA-A questionnaire. Secondary outcome measures will include plantar flexor strength, lower limb reactive strength, biomechanics and running gait.

Outcome measures and assessments

Investigations

At baseline, week 6 and 12, all participants will be required to complete a VISA-A questionnaire as well as perform isokinetic testing and 3D motion capture running gait assessment. In addition, hop testing will be performed at week 6 and 12 [see Table 3]. Hop testing is included in the testing battery from week 6 onwards as it is expected some participants with Achilles pain at baseline testing may be fearful of performing hopping tasks or risk of exacerbating their pain, and the data collected may not be an accurate reflection of their capabilities.

Primary outcome measure

VISA-A questionnaire

The VISA-A questionnaire has been shown to be a valid, reliable and easy-to-use outcome measure tool for intervention studies on AT [46]. It consists of eight questions regarding pain and function during both daily living and sporting activities. The overall score is between 0 and 100 where higher scores represent reduced pain and improved function. An improvement of 21 points between 2 and 12 weeks of a rehabilitation program have been typically observed [44]. While the VISA-A score will not determine eligibility for inclusion into the study, it will be used to map progress over the course of the rehabilitation program and in the follow-up period. The difference in VISA-A score between both training protocols from baseline testing to the outcome testing at 6 weeks, 12 weeks, 3, 6 and 12 months; will formulate the primary outcome measure for this study.

Secondary outcome measures

Isokinetic plantar flexor strength

Reduced plantar flexor strength is a common feature in patients with Achilles tendinopathy [14–16, 39]. One

Table 3 Overview of outcome measures over the course of the study

	Baseline	Week 6	Week 12	6 months	12 months	24 months
Body mass	X					
Body height	X					
Body mass index	X					
Sport/activity level	X			X	X	XX
VISA-A Questionnaire	X	X	X	X	X	X
Isokinetic plantar flexor peak torque (knee extension)	X	X	X			
Isokinetic plantar flexor peak torque (knee flexion)	X	X	X			
3D running gait analysis	X	X	X			
Double leg drop jump		X	X			
Single leg drop jump		X	X			
Single leg horizontal rebound		X	X			
Exercise compliance		X	X	X		

prospective study to date established that plantar flexor torque below 50 Nm was a risk factor for developing AT [47]. Isokinetic testing is commonly used to measure plantar flexor peak torque [15, 16, 39].

Two separate protocols will be used for this test. In the first protocol, the participant will lie prone with full knee extension. In the second protocol, the participant will lie supine with 80° knee flexion. When the knee is flexed to greater than 60°, the force contribution of the biarticular gastrocnemius muscles to plantarflexion is reduced, and is thus representative of the force produced predominantly by soleus muscle [48]. If similar plantar flexor peak torque deficits exist between the two protocols, the identified deficits may thus be attributed to the soleus muscle [15] which will influence exercise prescription.

The testing will be performed on a isokinetic dynamometer (Cybex Norm, Computer Sports Medicine Inc.). In both protocols, the participant will have their foot strapped to a pedal with the centre of axis of rotation aligned with the medial malleolus and a correction for gravity applied. Beginning with their uninjured limb, participants will be asked to perform a warm-up involving 5 sub maximal concentric plantarflexion and dorsiflexion contractions increasing progressively from 60 to 100% of their self-perceived MVC for familiarisation. The participants will then be required to produce a maximal plantarflexion force over 5 repetitions for 2 sets with a 1 min rest between sets. Verbal encouragement will be provided to produce maximal effort through full range of motion for each repetition. In the second test, the participants will lie in supine position with the knee flexed to 80° in order to specifically test the peak torque of the soleus. The same familiarisation protocol, sets and repetitions as the previous test will apply. Both tests will use an angular velocity of 60° per second and operate through an ankle range of between 30° plantarflexion and 20° dorsiflexion. Data will be sampled at 100 and peak torque expressed as percentage of body mass (Nm/kg %) will be reported on both limbs. Between-limb asymmetries in peak torque will also reported and analysed.

Three-dimensional running gait analysis

Altered running biomechanics and muscle recruitment strategies have been highlighted in runners with AT [49–52]. Using a proprietary three-dimensional optical motion analysis system (Run 3D, Oxford, United Kingdom) the following kinematic and spatiotemporal variables will be measured: contact time, aerial time, stride length, stride frequency and joint angular displacements from initial contact to mid stance phase. Lower limb stiffness will be calculated using a validated equation based on the spring-mass model with running speed, contact time, body mass and leg length as inputs [53]. The participants will warm-up by running for between 2 and 5 min on the treadmill at a self-selected speed. Once they report that they are adequately warmed up they will be instructed to run at a speed that they feel they would be comfortable running at a steady pace for 30 min. Data will be captured for 30 s at a random interval over a 2 min period and the participants will not be informed about when the data capture begins. For the subsequent tests at week 6 and 12, the participants will be required to repeat the same speed for re-analysis.

Hop tests

Achilles tendon material properties contribute to stretch shortening cycle performance during hopping and jumping exercises [54, 55]. Reduced tendon mechanical properties, plantar flexor muscle rate of force development and deficits on a single forward hop test have previously been observed in patients with AT [23].

The hop tests will take place on two force platforms (AMTI, USA) to measure ground reaction force (GRF) data sampled at 1000 Hz. Ten infrared cameras (200 Hz; Bonita B10/Vero v2.2, Vicon, UK) will be used for three-dimensional motion capture. Reflective markers (14 mm diameter) placed on all relevant anatomical landmarks including the thorax, will be used in accordance with a modified Plug-in-gait model (Vicon, UK) [56], with centre of mass (COM) calculated from all segments. Motion and force data will be filtered using a fourth order zero-lag low pass Butterworth filter with a cut-off frequency of 15 Hz. The data will be exported to MATLAB 2015a (Mathworks, USA) for processing. Participants will perform 3 trials on each test, unshod and with hands placed on iliac crests.

Drop jump Participants will perform both a double leg drop jump (DLDJ) and single leg drop jumps (SLDJ). The participants will complete a standardised warm-up which consists of 10 bodyweight squats, followed by 10 pogo hops in place and 3 familiarisation trials for both. A 30 cm box will be used for the DLDJ and a 20 cm box for the SLDJ. The participant who will be unshod with hands placed on iliac crests, will be required to drop off the box and rebound off the force plate as quickly as possible aiming for maximum jump height. They will be instructed to maintain knee and hip extension during flight phase and where there is visible evidence of knee flexion or a 'tuck jump', the trial will be deemed invalid and they will be asked to repeat until a competent trial is achieved. The ground contact phase will be defined by a GRF greater than 20 N and jump height will be calculated from centre of mass displacement using kinematic data. Reactive strength index (RSI), which is a measure

of jump height divided by ground contact time, will be calculated for both the double and single leg drop jump.

Single leg hurdle hop After completing the drop jump tests, participants will be asked to perform a single leg forward hurdle hop test (SLHH). The test requires that participants to perform a single leg forward hop over two 15 cm hurdles rebounding off the force platform in between, completing 3 trials on each leg. The participants will be instructed to rebound 'as fast as possible' and 'as far as possible', and to attempt to be fully stable on 1 leg upon landing. After each trial the participants will walk back slowly to begin the next trial taking approximately 10 s recovery time. Hop distance, rebound distance and contact time, as well as key biomechanical variables such as vertical, horizontal and leg ground reaction force, vertical, leg and joint stiffness, joint powers and moments, and joint angular displacements will be calculated using a custom MATLAB script (Mathworks, USA). Hop distance will be calculated as the distance from the initiation of the hop to the initial contact as the participants lands at the end of the hop and rebound distance from the force plate to the landing. Vertical stiffness (K_{vert}) will be calculated at the point of maximum displacement of COM, as the ratio of change in vertical ground reaction force (GRF) to COM displacement:

$$K_{vert} = \Delta Force/\Delta CoM$$

Leg stiffness will be calculated in the sagittal plane as the ratio of change in leg ground reaction force (F_{leg}) to the change in leg length at the shortest leg length during stance phase as previously proposed [57]. Leg length is measured as the distance from the hip joint centre to the centre of pressure in the sagittal plane, while F_{leg} is calculated from the resultant GRF magnitude scaled to the leg angle using the trigonometry sine rule.

$$K_{leg} = \Delta F_{leg}/\Delta Leg$$

Joint stiffness (K_{ankle}, K_{knee} and $K_{hip)}$ at the ankle and knee, will be calculated in the sagittal plane as the ratio of change in joint moment to change in joint displacement:

$$K_{joint} = \Delta \text{ moment}/\Delta \text{ angle}$$

A pilot study has previously been carried out on 10 healthy participants prior to the commencement of the Achilles RCT study [58]. Good-to-excellent reliability (ICC > 0.75) was found for hop and rebound distance, contact time, knee and ankle joint stiffness, vertical and leg GRF, with moderate reliability (ICC 0.50–0.75) for reactive strength index, vertical and leg stiffness, ankle joint peak power, ankle and knee joint peak moments, and horizontal GRF. In a separate study using the same protocol, 3 trials were sufficient to obtain a stable measure of performance across key variables [59].

Training diary

In order to determine adherence and fidelity with the rehabilitation program and pain response to exercise, each patient will be required to complete a training diary logging their completed running and rehabilitation sessions as well as reporting any pain symptoms using a numerical pain rating scale (NPRS), that will be reviewed at week 6 and returned at week 12. Adherence is defined as the proportion of prescribed exercises completed while fidelity refers to whether the participant completed the prescribed exercises, sets, repetitions and target loads. Participants will be advised to take an extra recovery day between exercise sessions if pain was above 5/10 on the day after a session and to adjust their loads for the subsequent session.

Follow-up interviews

At 6, 12 and 24 months from baseline testing, patients will be required to complete a questionnaire [see Additional file 1: Appendix 1] to analyse their participation in their respective sport, document any re-injuries and to obtain patient satisfaction feedback on their respective rehabilitation program. These outcomes will be reported and compared between groups to determine if the rehabilitation program had any significant effect (Fig. 1).

Interventions

Each participant will be prescribed a graded rehabilitation exercise training program which they will perform at home or in a local gym. However, they will present themselves for one supervised session every 2–3 weeks by their respective group investigators to ensure compliance and appropriate progression. The patients following Silbernagel's training program [see Table 1] will perform solely calf strength exercises with self-prescribed additional resistance and will progress their exercises based on a NPRS, where there is no greater than a 4/10 pain response during and in the 24 h following a training session. They will then progress to plyometric exercises as tolerated. The SSC6 group [see Table 2] will follow a multifactorial exercise program comprising of bilateral and unilateral kinetic chain strength, calf strength and plyometric training as well as running drills as early as they can tolerate them. The participants will enter at the highest level where they meet the minimum criteria. For the calf exercises, they will be encouraged to lift a certain percentage of bodyweight in additional resistance and increase weekly. A certain level of pain within tolerable limits will be accepted and participants will be encouraged to increase their resistance loading weekly so

long as that pain doesn't increase. Progression to Level 4 of the program will be based on achieving their prescribed exercise load targets and achieving a deficit of less than 10% between injured and uninjured limbs on the isokinetic strength tests. The reactive strength exercises will be performed at near maximal intensity for a set number of repetitions with good competency and within tolerable pain limits. The participants will progress to Level 5 when they can perform 10 single leg hops with a score of < 4/10 on the NPRS and progress from Level 5 when single leg RSI deficits are < 10%. Outcome measures will be monitored at the various timepoints and will be tracked according to reported NPRS ratings. In both groups, participants will be permitted to begin running in phase 2 when pain during daily activity is < 2/10 but will be advised on periodising their running and rehabilitation exercises throughout the week. Each participant will be provided with a training log in order to monitor training loads. Should an adverse event occur which results in re-injury or a new injury, the participant will be instructed to contact their respective investigator immediately so that they can be examined and their treatment will be adjusted, postponed or discontinued where appropriate. Upon completion of the training intervention, participants in both groups will be given a maintenance training program for 6 months. The design, prescription and reporting of the training intervention meets all of the 16-item checklist requirements in the Consensus on Exercise Reporting Template (CERT) [60] [Available in supplementary files].

See Tables 1 and 2 for an example of the exercise programs, and Table 4 for the points of difference between to two training interventions.

Statistical analysis and power calculation

This study is powered to detect a change of 15 points on the VISA-A questionnaire, similar to previous studies investigating clinical changes after a rehabilitation program [61, 62]. The average reported change in a VISA-A questionnaire after a 12-week intervention is 21 points with a standard deviation 6.6 points [44]. Assuming a power of 80% and a two-sided 5% significance level, a total of 25 participants in each group would be required. Allowing for a conservative drop-out rate of 15%, the proposed total sample size is 60, with 30 in each group. This number is similar to those used in other high quality injury rehabilitation RCT studies [40, 45].

Statistical analysis will be performed using R (R Studio version 1.2.5). Descriptive statistics will be used for all continuous variables, and means and standard deviations will be reported. Comparisons between both groups at different timepoints will be assessed using Student's independent samples two-tailed t-tests. An intention to treat analysis will be used to test a within-group and between-group change in VISA-A questionnaire score at testing and follow-up timepoints, using a repeated measures Analysis of Covariance (ANCOVA). The primary outcome measure - changes to the VISA-A questionnaire, will the dependent variable, group will the between participants factor and time will be the covariate.

Table 4 SSC6 Versus Silbernagel's rehabilitation program.

SSC6	Silbernagel Combined
Multi-factorial approach with emphasis on exercise progression, running gait and training load	Emphasis on exercise progression based solely on symptoms
3 heavy load resistance training sessions per week with >48hrs rest	Daily exercise program
Resistance load targets relative to body weight	No speciifc resistance load targets
Running gait re-training	No focus on running gait

Non-parametric equivalents (Matt-Whitney U-Test and Friedman Test respectively) will be used if a Shapiro-Wilk test indicates that the assumption of normality has not been met. A multiple regression analysis will be used to investigate the total variance and the relative weight of each independent variable with changes in VISA-A score as the dependent variable. The independent variables will be changes in plantar flexor strength, reactive strength and lower limb biomechanical variables, as well as exercise adherence and fidelity. Effect sizes will be reported using partial eta squared threshold values of > 0.2 (small), > 0.5 (moderate), and > 0.8 (large). Statistical significance will be accepted at $\alpha = 0.05$.

Discussion

Exercise therapy is widely accepted as the primary treatment option for runners with AT [35, 36, 63]. Heavy resistance strength exercises targeting the muscle-tendon unit have been shown to increase physiological cross-sectional area and pennation angle in the muscle [64] and tendon mechanical and material properties [41, 65]. This type of loading has resulted in improved clinical outcomes in AT patients [40, 44]. Plyometric training prepares the muscle tendon unit for high tensile forces and loading rates associated with running based sports [2, 36, 66]. However, there is no clear guidance on how to prescribe and progress the loading for calf strength exercises apart from using pain response to exercise. Only a few studies have investigated running biomechanical features associated with AT with limited evidence for poor control of rearfoot eversion [50, 67] and reduced leg stiffness on the injured limb [24].

An acceptable level of pain symptoms are permitted during AT rehabilitation [18, 34] and it remains to be explored if a primary focus on achieving strength, reactive strength and biomechanical targets can lead to similar outcomes in reduced timeframes and with lower reinjury rates. This is the first study to propose an individualised, criteria-based graded rehabilitation program in patients in with chronic mid-portion Achilles tendinopathy where progression is guided by strength and reactive strength outcome measures within tolerable pain limits. The participants in our study will undertake a comprehensive assessment of kinematic and kinetic tests to investigate plantar flexor strength, reactive strength and lower limb biomechanical variables in hopping and running. We will perform long term evaluations at evaluations at 6, 12 and 24 months to monitor progress, reinjury incidences and sustainability of return to sport and investigate patient satisfaction with their respective rehabilitation exercise programs.

Our study will include a sample of participants who practise running-based sports and are of a particular age profile (age 18–45), have had no injection therapies in the previous 6 months and no co-existing lower limb injuries. Like most studies of similar design, there is a high risk of drop-outs, poor compliance with the respective programs and failure to respond to the follow-up questionnaires. This will be managed by aiming for a higher number of participants than the study is powered for and maintaining regular communication with the participants.

In summary, this two-arm RCT will compare the effectiveness of a criteria-based rehabilitation program with progression guided by achieving functional outcome measures with an evidenced-based program where progression is guided solely by pain symptoms. The results of this study will provide insights as to whether improved strength, reactive strength and lower limb biomechanics are associated with reduced pain in patients with chronic mid-portion AT and assist clinicians treating this injury to set objective criteria to progress rehabilitation and return to sport.

Trial status

Recruitment for the trial started in January 2020 and it is anticipated that data collection will be completed in April 2023. As of November 9th 2020, 18 participants have been included.

Abbreviations

ANCOVA: Analysis of covariance; AT: Achilles tendinopathy; CERT: Consensus on Exercise Reporting Template; COM: centre of mass; DLDJ: double leg drop jump; GRF: ground reaction force; ICC: intraclass correlation; K: stiffness; MRI: magnetic resonance image; MVC : maximal voluntary contraction; NPRS: numerical pain rating scale; NSAID: non-steroidal anti-inflammatory drug; RCT: randomised controlled trial; RSI: reactive strength index; SLDJ: single leg drop jump; SLHH: single leg hurdle hop; SPIRIT: Standard Protocol Items: Recommendations for Interventional Trials; SSC: Sports Surgery Clinic; VISA-A: Victorian Institute of Sports Assessment - Achilles

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12891-021-04553-6.

Additional file 1. Appendix 1: Follow-up questionnaire at 6 months.
Additional file 2. Appendix 2: Consent form.

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Related articles

None declared.

Authors' contributions

CG, AFM and JBM devised the study design and protocol, and CG is leading the coordination of the study and investigations. KD provided biomechanical lab, statistical and data analysis support. CG and CH are investigators for respective training groups. CG wrote the manuscript and all authors provided feedback, input and final approval.

Authors' information

CG is a strength and conditioning coach specialising in the rehabilitation of lower limb injuries at the Sports Surgery Clinic in Dublin and is a PhD

student affiliated to the Laboratory of Human Movement Science (LAMHESS) at Université Côte d'Azur in France.
KD is a Senior Lecturer in biomechanics at the Department of Sport and Exercise Sciences in Manchester Metropolitan University and was formerly manager of the biomechanics laboratory at the Sports Surgery Clinic in Dublin (2015–2020).
CH is a physiotherapist at the Sports Surgery Clinic in Dublin.
AFM is a sport and exercise medicine physician and Director of Sports Medicine at the Sports Surgery Clinic in Dublin.
JBM is a Professor at Université Jean Monnet, Saint-Etienne, France and previously at the Laboratory of Human Movement Science (LAMHESS) at Université Côte d'Azur in France (2014–2020).

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Availability of data and materials
Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Ethical approval was obtained by the Sports Surgery Clinic Research and Ethics Committee (Approval number: SAREB13/05/19CG/MJ). Participants will sign written informed consent prior to taking part in the study.

Consent for publication
Not applicable.

Competing interests
None declared.

Author details
[1]Université Côte d'Azur, LAMHESS, Nice, France. [2]Sports Surgery Clinic, Santry Demesne, Dublin 9, Ireland. [3]University of Bristol, Queen's School of Engineering, University Walk, Bristol BS81TR, UK. [4]Department of Sport and Exercise Sciences, Manchester Metropolitan University, Manchester, UK. [5]Centre for Health, Exercise and Sports Medicine, University of Melbourne, Parkville, Victoria, Australia. [6]Sports Performance Research Institute New Zealand (SPRINZ), Auckland University of Technology, Auckland, New Zealand. [7]Univ Lyon, UJM-Saint-Etienne, Inter-university Laboratory of Human Movement Biology, EA 7424, F-42023 Saint-Etienne, France.

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References

1. Harris CA, Peduto AJ. Achilles tendon imaging. Australas Radiol. 2006;50(6):513–25. https://doi.org/10.1111/j.1440-1673.2006.01622.x.
2. Komi P V. Relevance of in vivo force measurements to human biomechanics. J Biomech. 1990;23(SUPPL. 1):23–34.
3. Wren TAL, Yerby SA, Beaupré GS, Carter DR. Mechanical properties of the human achilles tendon. Clin Biomech. 2001;16(3):245–51. https://doi.org/10.1016/S0268-0033(00)00089-9.
4. De Jonge S, Van Den Berg C, De Vos RJ, Van Der Heide HJL, Weir A, Verhaar JAN, et al. Incidence of midportion Achilles tendinopathy in the general population. Br J Sports Med. 2011;45(13):1026–8. https://doi.org/10.1136/bjsports-2011-090342.
5. Kujala UM, Sarna S, Kaprio J. Cumulative incidence of achilles tendon rupture and tendinopathy in male former elite athletes. Clin J Sport Med. 2005;15(3):133–5. https://doi.org/10.1097/01.jsm.0000165347.55638.23.
6. Cook JL, Khan KM, Purdam C. Achilles tendinopathy. Man Ther. 2002;7(3):121–30. https://doi.org/10.1054/math.2002.0458.
7. Khan KM. Time to abandon the "tendinitis" myth. Bmj [Internet]. 2002;324(7338):626–7. Available from:. https://doi.org/10.1136/bmj.324.7338.626.
8. Cook JL, Purdam CR. Is tendon pathology a continuum? A pathology model to explain the clinical presentation of load-induced tendinopathy. Br J Sports Med. 2009;43(6):409–16. https://doi.org/10.1136/bjsm.2008.051193.
9. Jones GC, Corps AN, Pennington CJ, Clark IM, Edwards DR, Bradley MM, et al. Expression profiling of metalloproteinases and tissue inhibitors of metalloproteinases in normal and degenerate human Achilles tendon. Arthritis Rheum. 2006;54(3):832–42. https://doi.org/10.1002/art.21672.
10. Riley G. Tendinopathy - from basic science to treatment. Nat Clin Pract Rheumatol. 2008;4(2):82–9. https://doi.org/10.1038/ncprheum0700.
11. Selvanetti A, Cipolla M, Puddu G. Overuse tendon injuries: basic science and classification. Oper Tech Sports Med [Internet]. 1997;5(3):110–7. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1060187297800317. https://doi.org/10.1016/S1060-1872(97)80031-7.
12. Kjær M, Langberg H, Heinemeier K, Bayer ML, Hansen M, Holm L, et al. From mechanical loading to collagen synthesis, structural changes and function in human tendon. Scand J Med Sci Sport. 2009;19(4):500–10. https://doi.org/10.1111/j.1600-0838.2009.00986.x.
13. Mead MP, Gumucio JP, Awan TM, Mendias CL, Sugg KB. Pathogenesis and management of tendinopathies in sports medicine. Transl Sport Med [Internet]. 2018;1(1):5–13. Available from:. https://doi.org/10.1002/tsm2.6.
14. Silbernagel KG, Gustavsson A, Thomeé R, Karlsson J. Evaluation of lower leg function in patients with Achilles tendinopathy. Knee Surg Sport Traumatol Arthrosc. 2006;14(11):1207–17. https://doi.org/10.1007/s00167-006-0150-6.
15. O'Neill S, Barry S, Watson P. Plantarflexor strength and endurance deficits associated with mid-portion Achilles tendinopathy: the role of soleus. Phys Ther Sport [internet]. 2019;37:69–76. Available from: https://doi.org/10.1016/j.ptsp.2019.03.002.
16. McAuliffe S, Tabuena A, McCreesh K, O'Keeffe M, Hurley J, Comyns T, et al. Altered Strength Profile in Achilles Tendinopathy: A Systematic Review and Meta-Analysis. J Athl Train. 2019;54(8):889–900.
17. Järvinen TAH, Kannus P, Maffulli N, Khan KM. Achilles tendon disorders: etiology and epidemiology. Foot Ankle Clin. 2005;10(2):255–66. https://doi.org/10.1016/j.fcl.2005.01.013.
18. Silbernagel KG, Thomeé R, Eriksson BI, Karlsson J. Continued sports activity, using a pain-monitoring model, during rehabilitation in patients with achilles tendinopathy: a randomized controlled study. Am J Sports Med. 2007;35(6):897–906. https://doi.org/10.1177/0363546506298279.
19. Silbernagel KG, Thomeé R, Eriksson BI, Karlsson J. Full symptomatic recovery does not ensure full recovery of muscle-tendon function in patients with Achilles tendinopathy. Br J Sports Med. 2007;41(4):276–80. https://doi.org/10.1136/bjsm.2006.033464.
20. Knobloch K, Schreibmueller L, Longo UG, Vogt PM. Eccentric exercises for the management of tendinopathy of the main body of the Achilles tendon with or without an AirHeel™ brace. A randomized controlled trial. B: effects of compliance. Disabil Rehabil. 2008;30(20–22):1692–6. https://doi.org/10.1080/09638280701785676.
21. Arya S, Kulig K. Tendinopathy alters mechanical and material properties of the Achilles tendon. J Appl Physiol [Internet]. 2010;108(3):670–5. Available from:. https://doi.org/10.1152/japplphysiol.00259.2009.
22. Child S, Bryant AL, Clark RA, Crossley KM. Mechanical properties of the achilles tendon aponeurosis are altered in athletes with achilles tendinopathy. Am J Sports Med. 2010;38(9):1885–93. https://doi.org/10.1177/0363546510366234.
23. Wang HK, Lin KH, Su SC, Shih TTF, Huang YC. Effects of tendon viscoelasticity in Achilles tendinosis on explosive performance and clinical severity in athletes. Scand J Med Sci Sport. 2012;22(6):1–9.
24. Maquirriain J. Leg stiffness changes in athletes with achilles tendinopathy. Int J Sports Med. 2012;33(7):567–71. https://doi.org/10.1055/s-0032-1304644.
25. Martin RL, Chimenti R, Cuddeford Tyler, Houck J, Matheson JW, Mcdonough CM, et al. Clinical Practice Guidelines Achilles Pain, Stiffness, and Muscle Power Deficits: Midportion Achilles Tendinopathy Revision 2018 SUMMARY OF RECOMMENDATIONS. J Orthop Sport Phys Ther [Internet]. 2018 [cited 2020];48(5):1–38. Available from: www.jospt.org
26. Kearney RS, Parsons N, Metcalfe D, Costa ML. Injection therapies for Achilles tendinopathy [Internet]. Vol. 2015, Cochrane Database of Systematic Reviews. John Wiley and Sons Ltd; 2015 [cited 2020 Jul 29]. Available from: https://doi.org/10.1002/14651858.CD010960.pub2/full
27. Chimenti RL, Cychosz CC, Hall MM, Phisitkul P. Current Concepts Review Update: Insertional Achilles Tendinopathy. Foot Ankle Int [Internet]. 2017 [cited 2020 Jul 29];38(10):1160–1169. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5956523/
28. Rompe JD, Nafe B, Furia JP, Maffulli N. Eccentric loading, shock-wave treatment, or a wait-and-see policy for tendinopathy of the main body of tendo Achillis: a randomized controlled trial. Am J Sports Med [Internet].

2007 Mar 30 [cited 2020 Jul 29];35(3):374–383. Available from: http://www.ncbi.nlm.nih.gov/pubmed/17244902.
29. Magnussen RA, Dunn WR, Thomson AB. Nonoperative treatment of midportion achilles tendinopathy: a systematic review. Clin J Sport Med. 2009;19(1):54–64. https://doi.org/10.1097/JSM.0b013e31818ef090.
30. Zhang BM, Zhong LW, Xu SW, Jiang HR, Shen J. Acupuncture for chronic achilles tendnopathy: A randomized controlled study. Chin J Integr Med [Internet]. 2013 [cited 2020 Jul 29];19(12):900–904. Available from: https://doi.org/10.1007/s11655-012-1218-4
31. De Jonge S, De Vos RJ, Van Schie HTM, Verhaar JAN, Weir A, Tol JL. One-year follow-up of a randomised controlled trial on added splinting to eccentric exercises in chronic midportion Achilles tendinopathy. Br J Sports Med [Internet]. 2010 [cited 2020 Jul 29];44(9):673–677. Available from: https://bjsm.bmj.com/content/44/9/673
32. Romero-Morales C, Martín-Llantino PJ, Calvo-Lobo C, Beltran-Alacreu H, López-López D, Sánchez-Gómez R, et al. Effectiveness of eccentric exercise and a vibration or cryotherapy program in enhancing rectus abdominis muscle thickness and inter-rectus distance in patients with chronic mid-portion Achilles tendinopathy: a randomized clinical trial. Int J Med Sci [Internet]. 2018;15(14):1764–70. Available from: http://www.medsci.org/v15p1764.htm. https://doi.org/10.7150/ijms.28656.
33. Balius R, Álvarez G, Baró F, Jiménez F, Pedret C, Costa E, et al. A 3-Arm Randomized Trial for Achilles Tendinopathy: Eccentric Training, Eccentric Training Plus a Dietary Supplement Containing Mucopolysaccharides, or Passive Stretching Plus a Dietary Supplement Containing Mucopolysaccharides. Curr Ther Res [Internet]. 2016;78:1–7 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0011393X16300716.
34. Cook JL, Purdam CR. The challenge of managing tendinopathy in competing athletes. Br J Sports Med. 2014;48(7):506–9. https://doi.org/10.1136/bjsports-2012-092078.
35. Vlist AC Van Der, Winters M, Weir A, Ardern CL, Vos J De, Welton NJ, et al. Which treatment is most effective for patients with Achilles tendinopathy ? A living systematic review with network meta- analysis of 29 randomised controlled trials. 2020;45(11):1–8.
36. Silbernagel KG. A Proposed Return-to-Sport Program for Patients With Midportion Achilles Tendinopathy: Rationale and Implementation. J Orthop Sports Phys Ther. 2015;45(11):876-86. Available from: www.jospt.org
37. Lavagnino M, Wall ME, Little D, Banes AJ, Guilak F, Arnoczky SP. Tendon Mechanobiology: current knowledge and future research opportunities. J Orthop Res. 2015;33(6):813–22. https://doi.org/10.1002/jor.22871.
38. Snedeker JG, Foolen J. Tendon injury and repair – A perspective on the basic mechanisms of tendon disease and future clinical therapy. Acta Biomaterialia. 2017;63:18-36.
39. Alfredson H, Pietila T, Jonsson P, Lorentzon R. Heavy-load eccentric calf muscle training for the treatment of chronic Achilles tendinosis. Am J Sport Med [Internet]. 1998;26(3):360–6. Available from: http://ajs.sagepub.com/content/26/3/360.short. https://doi.org/10.1177/03635465980260030301.
40. Beyer R, Kongsgaard M, Hougs Kjær B, Øhlenschlæger T, Kjær M, Magnusson SP. Heavy slow resistance versus eccentric training as treatment for achilles tendinopathy: a randomized controlled trial. Am J Sports Med. 2015;43(7):1704–11. https://doi.org/10.1177/0363546515584760.
41. Bohm S, Mersmann F, Arampatzis A. Human tendon adaptation in response to mechanical loading: a systematic review and meta-analysis of exercise intervention studies on healthy adults. Sport Med - Open. 2015;1(1):1-7.
42. Rio E, Kidgell D, Purdam C, Gaida J, Moseley GL, Pearce AJ, et al. Isometric exercise induces analgesia and reduces inhibition in patellar tendinopathy. Br J Sports Med. 2015;49(19):1277–83. https://doi.org/10.1136/bjsports-2014-094386.
43. O'Neill S, Radia J, Bird K, Rathleff MS, Bandholm T, Jorgensen M, et al. P23: acute sensory and motor response to 45-seconds heavy isometric holds for the plantar flexors in patients with Achilles tendinopathy. Online J Rural Nurs Heal Care [Internet]. 2017;17(1):SS20–0. Available from:. https://doi.org/10.1007/s00167-018-5050-z.
44. Murphy M, Travers M, Gibson W, Chivers P, Debenham J, Docking S, et al. Rate of Improvement of Pain and Function in Mid-Portion Achilles Tendinopathy with Loading Protocols: A Systematic Review and Longitudinal Meta-Analysis. Sport Med [Internet]. 2018 15 [cited 2018 Sep 10];48(8):1875–1891. Available from: https://doi.org/10.1007/s40279-018-0932-2
45. Mendiguchia J, Martinez-Ruiz E, Edouard P, Morin JB, Martinez-Martinez F, Idoate F, et al. A multifactorial, criteria-based progressive algorithm for hamstring injury treatment. Med Sci Sports Exerc. 2017;49(7):1482–92. https://doi.org/10.1249/MSS.0000000000001241.
46. Robinson JM, Cook JL, Purdam C, et al. The VISA-A questionnaire: a valid and reliable index of the clinical severity of Achilles tendinopathy. Br J Sports Med. 2001;35:335-41.
47. Mahieu NN. Intrinsic risk factors for the development of Achilles tendon overuse injury: a prospective study. Am J Sports Med. 2006;34(2):226–35. https://doi.org/10.1177/0363546505279918.
48. Arampatzis A, Karamanidis K, Stafilidis S, Morey-Klapsing G, DeMonte G, Brüggemann GP. Effect of different ankle- and knee-joint positions on gastrocnemius medialis fascicle length and EMG activity during isometric plantar flexion. J Biomech. 2006;39(10):1891–902. https://doi.org/10.1016/j.jbiomech.2005.05.010.
49. Azevedo LB, Lambert MI, Vaughan CL, O'Connor CM, Schwellnus MP. Biomechanical variables associated with Achilles tendinopathy in runners. Br J Sports Med. 2009;43(4):288-92.
50. Munteanu SE, Barton CJ, Hootman J, Macera C, Ainsworth B, Addy C, et al. Lower limb biomechanics during running in individuals with achilles tendinopathy: a systematic review. J Foot Ankle Res [Internet]. 2011;4(1):15. Available from: https://doi.org/10.1186/1757-1146-4-15
51. Geremia JM, Bobbert MF, Casa Nova M, Ott RD, De Aguiar LF, De Oliveira LR, et al. The structural and mechanical properties of the Achilles tendon 2 years after surgical repair. Clin Biomech [Internet]. 2015;30(5):485–92. Available from:. https://doi.org/10.1016/j.clinbiomech.2015.03.005.
52. Ogbonmwan I, Kumar BD, Paton B. New lower-limb gait biomechanical characteristics in individuals with Achilles tendinopathy: A systematic review update. Gait Posture [Internet]. 2018 May [cited 2018 Sep 10];62:146–156. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0966636218301425
53. Morin JB, Dalleau G, Kyröläinen H, Jeannin T, Belli A. A simple method for measuring stiffness during running. J Appl Biomech. 2005;21(2):167–80. https://doi.org/10.1123/jab.21.2.167.
54. Kubo K, Kawakami Y, Fukunaga T, James RS, Navas CA, Herrel A. Influence of elastic properties of tendon structures on jump performance in humans influence of elastic properties of tendon structures on jump performance in humans. J Appl Physiol. 1999;87(6):2090–6. https://doi.org/10.1152/jappl.1999.87.6.2090.
55. Abdelsattar M, Konrad A, Tilp M. Relationship between achilles tendon stiffness and ground contact time during drop jumps. J Sport Sci Med. 2018;17(2):223–8.
56. Marshall BM, Franklyn-Miller AD, King EA, Moran KA, Strike SC, Falvey ÉC. Biomechanical Factors Associated With Time to Complete a Change of Direction Cutting Maneuver. J Strength Cond Res [Internet]. 2014 1 [cited 2020 Nov 7];28(10):2845–2851. Available from: http://journals.lww.com/00124278-201410000-00019
57. Coleman DR, Cannavan D, Horne S, Blazevich AJ. Leg stiffness in human running: comparison of estimates derived from previously published models to direct kinematic-kinetic measures. J Biomech [Internet]. 2012;45(11):1987–91. Available from:. https://doi.org/10.1016/j.jbiomech.2012.05.010.
58. Griffin C, Richter C, Franklyn-Miller A, Morin JB. A novel single-leg hurdle hop exercise: test-retest reliability of vertical stiffness, contact time, ground reaction force, total hop distance and rebound distance. World Congress of Biomechanics [Conference presentation]. 2018.
59. Griffin C, Richter C, Franklyn-Miller A, Morin JB. The number of trials required to obtain a true representation of biomechanical features extracted during a single leg hurdle hop exercise. European College of Sports Science [Conference Presentation]. 2018.
60. Slade SC, Dionne CE, Underwood M, Buchbinder R, Beck B, Bennell K, et al. Consensus on exercise reporting template (Cert): modified delphi study. Phys Ther. 2016;96(10):1514–24. https://doi.org/10.2522/ptj.20150668.
61. Rompe JD, Furia J, Maffulli N. Eccentric loading versus eccentric loading plus shock-wave treatment for midportion achilles tendinopathy: a randomized controlled trial. Am J Sports Med. 2009;37(3):463–70. https://doi.org/10.1177/0363546508326983.
62. Stevens M, Tan C-W. Effectiveness of the Alfredson protocol compared with a lower repetition-volume protocol for Midportion Achilles tendinopathy: a randomized controlled trial. J Orthop Sport Phys Ther [Internet]. 2014;44(2):59–67. Available from:. https://doi.org/10.2519/jospt.2014.4720.
63. Kountouris A, Cook J. Rehabilitation of Achilles and patellar tendinopathies. Best Pract Res Clin Rheumatol. 2007;21(2):295–316. https://doi.org/10.1016/j.berh.2006.12.003.

64. Albracht K, Arampatzis A. Exercise-induced changes in triceps surae tendon stiffness and muscle strength affect running economy in humans. Eur J Appl Physiol. 2013;113(6):1605–15. https://doi.org/10.1007/s00421-012-2585-4.
65. Geremia JM, Manfredini B, Maarten B, Bobbert F, Rico R, Juner F, et al. Effects of high loading by eccentric triceps surae training on Achilles tendon properties in humans. Eur J Appl Physiol [Internet]. Eur J Appl Physiol. 2018;118(8):1725-36. Available from: https://doi.org/10.1007/s00421-018-3904-1
66. Baxter JR, Corrigan P, Hullfish TJ, O'Rourke P, Silbernagel KG. Exercise Progression to Incrementally Load the Achilles Tendon. Med Sci Sports Exerc. 2021;53(1):124-30. https://doi.org/10.1249/MSS.0000000000002459.
67. Donoghue OA, Harrison AJ, Coffey N, Hayes K. Functional data analysis of running kinematics in chronic Achilles tendon injury. Med Sci Sports Exerc. 2008;40(7):1323–35. https://doi.org/10.1249/MSS.0b013e31816c4807.

Publisher's Note

Appendix 3. ORAL ABSTRACT PRESENTED AT THE 2018 EUROPEAN COLLEGE OF SPORTS SCIENCE CONFERENCE

THE NUMBER OF TRIALS REQUIRED TO OBTAIN A TRUE REPRESENTATION OF BIOMECHANICAL FEATURES EXTRACTED DURING A SINGLE LEG HURDLE HOP EXERCISE

Griffin, C[1,2]., Richter, C[2]., Franklyn-Miller A[2]., Morin JB[1].

1. University of Nice Sophia Antipolis, Nice, France
2. Sports Surgery Clinic, Dublin, Ireland

INTRODUCTION:
Lower extremity stiffness has been linked to running performance and injury risk[1] with various hopping tests used to measure stiffness[2]. However, it is unclear how many trials are required for a forward hop exercise. The aim of this study was to determine the number of trials required to obtain a true representation of the biomechanical variables in a single leg hurdle hop.

METHODS:
Ten recreationally active males participated in 2 testing sessions 14 days apart involving a standardised warm-up including 3 familiarisation trials on each limb, before performing a forward hop over two 15cm hurdles, rebounding off a force platform in between. The participants completed 10 trials on each limb unshod with their arms akimbo, and were instructed to rebound 'as fast and as far as possible'. Ten infrared cameras (250Hz; Vicon, UK) synchronised with two force platforms (1000Hz, AMTI, USA) were used to capture reflective markers placed at the pelvis (reference for centre of mass [COM]) and ground reaction forces (GRF). Motion and GRF data were filtered using a fourth order low pass Butterworth filter. Vertical stiffness (Kvert), peak GRF, contact time (CT), total hop distance from the start of the hop to the landing position (HD), and rebound distance from the force platform to the landing position (RD), were calculated and examined. Kvert was calculated as the ratio of GRF at the lowest CoM, to CoM displacement. A 'true' mean was generated by a simulation where the mean of 7 randomly selected trials were calculated over 100 iterations and averaged. A correlation was used to judge from which trial a true representation could be expected, with a correlation threshold set at 0.9.

RESULTS:
All trials for the variables of peak GRF, RD and HD demonstrated high correlations for both testing sessions from trial 3. While CT fluctuated within the first session, it demonstrated a high correlation in the second session from trial 3. Correlation of Kvert fluctuated over both sessions, while it reached its highest correlation (r=0.7) also at trial 3 in both sessions.

CONCLUSION:
This study suggestes that 3 trials may be optimal to obtain a true representation for all measured variables in a single leg forward hurdle hop exercise. The low correlation (r=0.7) of Kvert and CT in the latter trials may be indicative of fatigue, movement variability or may not be a reliable variable to obtain a representative measure. Overall, the single leg hurdle hop exercise test may be a convenient clinical tool for lower limb injury rehabilitation requiring less trials to be performed.

REFERENCES:
1. Butler, R.J., Crowell, H.P. Davis, I.M., 2003. CLIN BIOMECH, 18(6), pp.511-517.
2. Brughelli, M. Cronin, J., 2008. SCAND J MED SCI SPOR 18(4), pp.417-426.

APPENDIX 4. POSTER PRESENTATION AT THE 2018 WORLD CONGRESS OF BIOMECHANICS

A novel single-leg hurdle hop exercise: test-retest reliability of vertical stiffness, contact time ground reaction force, total hop distance and rebound distance

Griffin, C[1,2]., Richter, C[2]., Franklyn-Miller A[2]., Morin JB[1].

1. Université Côte d'Azur, Nice, France
2. Sports Surgery Clinic, Dublin, Ireland

Background

- Lower extremity stiffness is linked to performance and injury risk in running-based sports[1].
- Various hopping tests have been used to measure stiffness and reflect the mechanical demands of running[2].

Aim — To test the reliability of a single leg hurdle hop test

Methods

9 recreationally active male subjects → Standardized warm-up including 3 familiarization trials → Subjects were unshod with hands on hips → SL hop over 2 15cm hurdles rebounding off a force plate in between → Instructed to rebound 'as fast as possible' and 'as far as possible' → 2 testing sessions 14 days apart

3D motion analysis (Vicon, UK) → Plug-in-Gait model → 2 force platforms (1000Hz, AMTI, USA) → Processed in MATLAB (Mathworks, USA)

- The **dominant leg** was chosen for analysis.
- **K_{vert} = ratio of pGRF:ΔCOM** (calculated at the point of maximum COM displacement)
- **K_{vert}, contact time (CT), GRF, total hop distance** from the start of the jump to the landing **(HD),** and the **rebound distance** from the force plate to landing **(RD)** were compared between the first 5 (**phase 1**) and second 5 (**phase 2**) trials from the first testing session.

Data analysis
- Paired 2-tailed students *t* test between phase 1 and phase 2
- A 2-way mixed Intraclass Correlation Coefficient (ICC) for test-retest reliability

Results

- No significant difference for K_{vert} , CT and peak GRF (all p>0.27) was found when comparing phase 1 to phase 2.
- HD and RD were greater during phase 2.
- Phase 1 data selected for the test-retest reliability.
- **K_{vert} showed moderate reliability** between sessions, while **good reliability was demonstrated for CT, peak GRF, HD and RD**, as shown in Table 1.

Table 1. Mean ± SD of K_{vert}, contact time, peak GRF, hop distance and rebound distance and determination of reliability during the hurdle hop task using the dominant limb

Variables	Day 1	Day 2	ICC	Reliability
Kvert (kN/m)	18.73 ± 2.07	18.03 ± 2.40	0.571	Moderate
Contact time (s)	0.27 ± 0.02	0.28 ± 0.03	0.812	Good
Peak GRF (N)	2516 ± 276.12	2435 ± 269.72	0.933	Good
Hop distance (mm)	1540 ± 302.06	1531 ± 288.73	0.996	Good
Rebound distance (mm)	1105 ± 189.28	1083 ± 184.42	0.996	Good

Conclusions

- Moderate-to-good reliability for the test and may be a useful clinical tool using 5 trials.
- Considering that hop distances increased without any significant changes in K_{vert}, CT and GRF observed, future prospective studies should investigate the contributions of knee and ankle joint stiffness to K_{vert} and orientation of GRF to hop distance.

References

1. Butler, R.J., Crowell, H.P. and Davis, I.M., 2003. CLIN BIOMECH, 18(6), pp.511-517.
2. Brughelli, M. and Cronin, J., 2008. SCAND J MED SCI SPOR 18(4), pp.417-426.

@colingriffin

Contact: colingriffin50k@gmail.com

APPENDIX 5. THEME 2 (STUDY3)

Unit C10, Gulliver's Retail Park,
Northwood,
Santry,
Dublin 9

www.sportssurgeryclinic.com

A new multi-factorial, individualised rehabilitation program for chronic mid-portion Achilles tendinopathy

Consent to take part in this research study

- I [print name] …… voluntarily agree to participate in this research study.
- I understand that even if I agree to participate now, I can withdraw at any time up to two weeks after my last testing session. If I withdraw from the study but still wish to continue my treatment, I will be charged for my physiotherapy sessions at our regular rate thereafter.
- I have had the purpose and nature of the study explained to me in writing and I have had the opportunity to ask questions about the study and given a minimum of 24 hours to consider taking part.
- I understand that participation involves partaking in a guided exercise program and making myself available for 3 testing sessions that may each last up to 2 hours over a 12-week period, and to be available for a brief interview at 6, 12 and 24 months upon completion of the study.
- I understand that if I were to miss any of the three scheduled testing sessions, I would no longer be eligible for the study.
- I understand that if I inform the researcher that I am at risk of injury or harm, they may have to refer me to a sport and exercise medicine physician or physiotherapist at the Sports Surgery Clinic who may decide that I am no longer suitable to continue with this study.
- I understand that signed consent forms, original video recordings and all data collected will be retained in the Sports Surgery Clinic under password protection for up to 3 years and only accessible to the principal investigators and research staff. After this period the data will be destroyed by the principal investigator.
- I understand that under the freedom of information legislation I am entitled to access the information I have provided at any time while it is in storage as specified above.
- I understand that I am free to contact any of the people involved in the research to seek further clarification and information.

Signature of research participant

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Signature of participant Date

Signature of researcher

---------- ----------
Signature of researcher Date

APPENDIX 6: (THEME 2, STUDY 3)

A new multi-factorial, individualised rehabilitation program for chronic mid-portion Achilles tendinopathy

Participant Information Sheet

30/09/2019

Thank you very much for taking time to consider participating in this research project. We are looking for eligible subjects to take part in a research study conducted by Mr Colin Griffin under the direction of Dr Andrew Franklyn-Miller at SSC Sports Medicine. Please read the following paragraphs, which should explain the research in greater detail.

What is the purpose of the study?

Achilles tendinopathy is common in sports and physical activities that involves running, jumping or hopping. It can result in reduced ability to exercise, participate in sport and affect quality of life. It can persist for several months and often many years. Exercise therapy using resistance training has been shown to help reduce pain and increase function in patients with Achilles tendinopathy. Progression of exercise according to symptoms is recommended. However, the effects of an individualised rehabilitation program guided by achieving strength training targets, biomechanical changes and performance targets on clinical outcomes for patients with Achilles tendinopathy has not been extensively investigated.

The purpose of this study is to investigate if a comprehensive rehabilitation program with criteria for progression is more effective than a commonly-used rehabilitation protocol for Achilles tendinopathy.

Why I have been invited to take part?

You have been invited to take part as you been diagnosed with mid-portion Achilles tendinopathy and therefore you have been deemed a potentially suitable candidate to participate in the study.

Do I have to take part?

Taking part in research is always optional. We will describe the study and go through the information sheet with you. You will be required to take at least 24 hours to consider taking part. Please feel free to take the information sheet home with you and discuss your participation with your friends and family. If you agree to take part, we will then ask you to sign a consent form. You are free to withdraw from the study at any time up to two weeks after the last testing session without giving a reason. After this time, all data will be processed and reported on. You can withdraw by contacting the principal investigator and any information collected from you will be destroyed immediately and not used in the study. Withdrawal from the study will not affect the standard of care you receive. You may still continue your treatment with us and will be charged as normal for subsequent physiotherapy appointments.

What will happen to me if I take part?

All suitable participants will be invited for three testing sessions at 6-week intervals and where possible, supervised rehabilitation exercise sessions at the Sports Medicine Department, Sports Surgery Clinic, Gulliver's Retail Park, Northwood Avenue, Santry, Dublin 9. The tests will include, running gait assessment, strength testing and performance tests.

The schedule of testing is as follows:

Testing session 1 – week 0 (approx. 90 minutes)

1. Completion of a questionnaire on pain symptoms and your ability to partake in physical activity.
2. Measurement of plantar flexor strength on an isokinetic dynamometer
3. Assessment of your running gait on a treadmill with 3D motion capture.
4. Following the initial assessment, you will be randomised into one of two training groups where you will then be provided with an training program under the supervision of a strength and conditioning coach or physiotherapist. You will be required to attend rehabilitation sessions at the SSC every 2 weeks for 12 weeks.

Testing session 2 – week 6 (approx. 2 hours)

1. Completion of a questionnaire on pain symptoms and your ability to partake in physical activity.
2. Measurement of plantar flexor strength on an isokinetic dynamometer
3. Assessment of your running gait on a treadmill with 3D motion capture.
4. Measurement of lower limb jumping and hopping performance using force plates and 3D motion capture.

Testing session 3 – week 12 (approx. 2 hours)

1. Completion of a questionnaire on pain symptoms and your ability to partake in physical activity.
2. Measurement of plantar flexor strength on an isokinetic dynamometer
3. Assessment of your running gait on a treadmill with 3D motion capture.
4. Measurement of lower limb jumping and hopping performance using force plates and 3D motion capture.

Follow-up interviews (approx.. 15 mins)

- Follow-up interviews will take place at 6 months and 12 months after completing the program.
- This will involve a telephone interview with a number of questions relating to your injury status, current level of sporting activity and feedback on the rehabilitation program.

If you miss any of the three scheduled testing sessions, you will no longer be eligible for the study. You may still continue your treatment and will be charged as normal for subsequent physiotherapy appointments.

What do I need to wear?

You will be required to wear shorts and to remove your shirt for part 3-4 of testing to allow us to place data capture markers directly on the skin. If you are a female participant it would be advisable to wear a crop top for these two tests. For the isokinetic strength testing in part 2, we would ask that you wear shoes with a thin sole to minimise movements of the foot. You should also wear your regular running shoes for the running gait analysis and performance tests.

How long will my part in the study last?

Each visit to SSC for testing will last approximately 2 hours. Any additional supervised rehabilitation sessions will last 30 minutes. The rehabilitation program will last approximately 12 weeks depending on outcomes achieved. You will then be advised on a maintenance program for a further 12 weeks which you will be required to perform independently. At 6 and 12 months you will be contacted via email, telephone or post for completion of follow-up questionnaires.

What are the possible benefits in taking part?

Taking part in the study will enable you to avail of a comprehensive investigation and rehabilitation to help you achieve the best outcome from your injury and a reduced risk of re-injury.

What are the possible disadvantages and risks of taking part?

There is a small chance you may feel some tendon and muscle soreness that can last up to 48 hours, however this is normal following exercise and nothing to be concerned about.

In any testing programme there is a risk of injury. Care has been taken in the design of the tests to apply no more load than required or encountered in normal training. If you feel pain, or cannot complete the testing, please tell your staff member who will cease the testing. There is always the risk in any training exercise of an acute injury. While we minimise these risks as much as possible you should understand that injury could occur. Should injury occur, testing will be terminated. A sport and exercise medicine physician or physiotherapist at the Sports Surgery Clinic will then assess the injury and advise in its treatment.

Will my data and personal details be safe?

Your signed consent forms, original video recordings and all data collected will be retained in the Sports Surgery Clinic under password protection for up to 3 years and only accessible to the principal investigators and research staff. After this period the data will be destroyed by the principal investigator. Under the freedom of information act, you are entitled to access the information provided at any time while it is in storage as specified above

Will there be any costs incurred on my part?

You will have to be diagnosed by a Sport and Exercise Medicine Physician at the Sports Surgery Clinic and will have to pay the consultation fee of €250. You will also be required to have an MRI scan. If you have health insurance, you should check with your provider to see if your MRI scan will be covered. This will be your only cost. All testing and supervised rehabilitation sessions are free of charge. In total the services you will be availing of will have an estimated value of €1100 over the duration of the study.

Will taking part be kept confidential?

Yes. You will be allocated a study number and all staff not directly involved with your care will know you by this study number only. All of the collected information and all investigation results will be stored on a password-protected computer, which can only be accessed by investigators using unique usernames and passwords. When the results of the study are reported, individuals that have taken part will not be identified in any way.

Who has reviewed this study?

All research at the Sports Surgery Clinic is reviewed by an independent group of people, called a Research Ethics Committee, to protect your interests. The study has been reviewed and approved by the Sports Surgery Clinic Research Ethics Committee

Contact details and further information?

If you have any questions about the study or regarding your potential eligibility you can contact:

Dr Andy Franklyn-Miller – Principal Investigator for this study

Email: sportsmedicine@sportssurgeryclinic.com
Telephone: 01 5262030

Mr Colin Griffin – PhD candidate who is responsible for the co-ordination all testing procedures:

Email: ColinGriffin@sportssurgeryclinic.com
Telephone: 0863742059

Who can I contact if I wish to make a complaint about any aspect of the study?

You can contact Emer Agnew, Complaints Officer, Sports Surgery Clinic, Santry Dublin 9:

Email: emeragnew@sportssurgeryclinic.com
Telephone: 015262060

What happens at the end of the study?

It is anticipated that the results of the study will be published in a peer reviewed journal as well as being presented at relevant conferences. All information from your individual assessments will be fully anonymised and confidential so people will not be able to identify you personally from the information.

APPENDIX 7: (THEME 2, STUDY 3 & 4)

The VISA-A questionnaire: An index of the severity of Achilles tendinopathy

IN THIS QUESTIONNAIRE, THE TERM PAIN REFERS SPECIFICALLY TO PAIN IN THE ACHILLES TENDON REGION

1. For how many minutes do you have stiffness in the Achilles region on first getting up?

100 mins ☐☐☐☐☐☐☐☐☐☐ 0 mins

0 1 2 3 4 5 6 7 8 9 10

POINTS ☐

2. Once you are warmed up for the day, do you have pain when stretching the Achilles tendon fully over the edge of a step? (keeping knee straight)

strong severe pain ☐☐☐☐☐☐☐☐☐☐ no pain

0 1 2 3 4 5 6 7 8 9 10

POINTS ☐

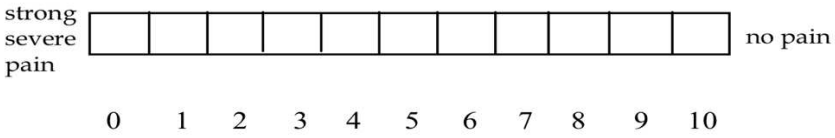
3. After walking on flat ground for 30 minutes, do you have pain within the next 2 hours? (If unable to walk on flat ground for 30 minutes because of pain, score 0 for this question).

strong severe pain ☐☐☐☐☐☐☐☐☐☐ no pain

0 1 2 3 4 5 6 7 8 9 10

POINTS ☐

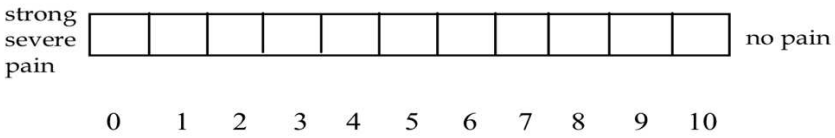
4. Do you have pain walking downstairs with a normal gait cycle?



POINTS

□

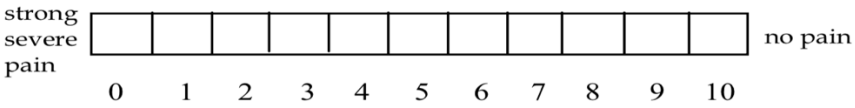
5. Do you have pain during or immediately after doing 10 (single leg) heel raises from a flat surface?



POINTS

□

6. How many single leg hops can you do without pain?



POINTS

□

7. Are you currently undertaking sport or other physical activity?

			POINTS
0	□	Not at all	
4	□	Modified training ± modified competition	□
7	□	Full training ± competition but not at same level as when symptoms began	
10	□	Competing at the same or higher level as when symptoms began	

8. Please complete **EITHER A, B or C** in this question.

- If you have **no pain while undertaking Achilles tendon loading sports** please complete **Q8a only**.
- If you have **pain while undertaking Achilles tendon loading sports but it does not stop you from completing the activity**, please complete **Q8b only**.
- If you have **pain that stops you from completing Achilles tendon loading sports**, please complete **Q8c only**.

A. If you have **no pain** while undertaking **Achilles tendon loading sports**, for how long can you train/practise?

NIL	1-10 mins	11-20 mins	21-30mins	>30 mins
□	□	□	□	□
0	7	14	21	30

POINTS

□

OR

B. If you have some pain while undertaking **Achilles tendon loading sport**, but it

does not stop you from completing your training/practice for how long can you train/practise?

NIL	1-10 mins	11-20 mins	21-30mins	>30 mins	POINTS
□	□	□	□	□	□
0	7	14	21	30	

OR

C. If you have **pain that stops you** from completing your training/practice in **Achilles tendon loading sport**, for how long can you train/practise?

NIL	1-10 mins	11-20 mins	21-30mins	>30 mins	POINTS
□	□	□	□	□	□
0	2	5	7	10	

TOTAL SCORE (/100) □ %

APPENDIX 8: (THEME 2, STUDY 3)

Follow-up questionnaire at 6 months

1. How would you rate your satisfaction with the rehabilitation program?

Poor	Moderate	Good	Excellent
☐	☐	☐	☐

2. Are you likely to continue with the exercise program for the foreseeable future?

Very unlikely	Unlikely	Possibly	Very likely
☐	☐	☐	☐

3. What was your average weekly training hours over the following timepoints:

Immediately prior to commencing the study? ☐

Over the 12 weeks of the rehabilitation program? ☐

From week 12-26? ☐

4. Since beginning your rehabilitation program, how would you describe the change (if any) in Activity Limitations, Symptoms, Emotions, and Overall Quality Of Life related to your Achilles tendon injury?

No change (or condition has got worse)	☐ 1
Almost the same, hardly any change at all	☐ 2
A little better, but no noticeable change	☐ 3
Somewhat better, but the change has not made any real difference	☐ 4
Moderately better, and a slight but noticeable change	5 ☐
Better, and a definite improvement that has made a real and worthwhile difference	☐ 6
A great deal better, and a considerable improvement that has made all the difference	☐ 7

5. Can you describe the positive aspects (if any) about your rehabilitation program (open question)?

6. Can you describe any negative aspects about your rehabilitation program (open question)?

APPENDIX 9: (THEME 2, STUDY 3)

SPIRIT 2013 Checklist: Recommended items to address in a clinical trial protocol and related documents*

Section/item	**Item No.**	**Description**	**Section and page number on which item is reported**
Administrative information			
Title	1	Descriptive title identifying the study design, population, interventions, and, if applicable, trial acronym	Title, page 1
Trial registration	2a	Trial identifier and registry name. If not yet registered, name of intended registry	Trial registration, page 3
	2b	All items from the World Health Organization Trial Registration Data Set	N/A
Protocol version	3	Date and version identifier	N/A
Funding	4	Sources and types of financial, material, and other support	Declarations, Funding, page 22
Roles and responsibilities	5a	Names, affiliations, and roles of protocol contributors	Authors' contribution, page 21 & 22 Authors' information, page 22

	5b	Name and contact information for the trial sponsor	Funding, page 21
	5c	Role of study sponsor and funders, if any, in study design; collection, management, analysis, and interpretation of data; writing of the report; and the decision to submit the report for publication, including whether they will have ultimate authority over any of these activities	Funding, page 21
	5d	Composition, roles, and responsibilities of the coordinating centre, steering committee, endpoint adjudication committee, data management team, and other individuals or groups overseeing the trial, if applicable (see Item 21a for data monitoring committee)	N/A
Introduction			
Background and rationale	6a	Description of research question and justification for undertaking the trial, including summary of relevant studies (published and unpublished) examining benefits and harms for each intervention	Background, page 3,4,5 & 6 Aims, page 7
	6b	Explanation for choice of comparators	Background, page 6 & 7
Objectives	7	Specific objectives or hypotheses	Aims, page 7
Trial design	8	Description of trial design including type of trial (eg, parallel group, crossover, factorial, single group), allocation ratio, and framework (eg, superiority, equivalence, noninferiority, exploratory)	Methods, study design, page 8
Methods: Participants, interventions, and outcomes			
Study setting	9	Description of study settings (eg, community clinic, academic hospital) and list of countries where data will be collected. Reference to where list of study sites can be obtained	Methods, page 8
Eligibility criteria	10	Inclusion and exclusion criteria for participants. If applicable, eligibility criteria for study centres and individuals who will perform the interventions (eg, surgeons, psychotherapists)	Methods 8,9

Interventions	11a	Interventions for each group with sufficient detail to allow replication, including how and when they will be administered	Randomisation and blinding, page 9; Interventions, page 16 &17, Table 1, page 32; Table 2, page 33,
	11b	Criteria for discontinuing or modifying allocated interventions for a given trial participant (eg, drug dose change in response to harms, participant request, or improving/worsening disease)	Interventions, page 17
	11c	Strategies to improve adherence to intervention protocols, and any procedures for monitoring adherence (eg, drug tablet return, laboratory tests)	Training diary, page 15, Interventions, page 16
	11d	Relevant concomitant care and interventions that are permitted or prohibited during the trial	Interventions, page 17
Outcomes	12	Primary, secondary, and other outcomes, including the specific measurement variable (eg, systolic blood pressure), analysis metric (eg, change from baseline, final value, time to event), method of aggregation (eg, median, proportion), and time point for each outcome. Explanation of the clinical relevance of chosen efficacy and harm outcomes is strongly recommended	Primary outcome measure, page 10; Secondary outcome measures, page 11,12,13,14 & 15
Participant timeline	13	Time schedule of enrolment, interventions (including any run-ins and washouts), assessments, and visits for participants. A schematic diagram is highly recommended (see Figure)	Figure 1, page 34
Sample size	14	Estimated number of participants needed to achieve study objectives and how it was determined, including clinical and statistical assumptions supporting any sample size calculations	Statistical analysis and power calculation, page 17
Recruitment	15	Strategies for achieving adequate participant enrolment to reach target sample size	Participants, page 8
Methods: Assignment of interventions (for controlled trials)			
Allocation:			

Sequence generation	16a	Method of generating the allocation sequence (eg, computer-generated random numbers), and list of any factors for stratification. To reduce predictability of a random sequence, details of any planned restriction (eg, blocking) should be provided in a separate document that is unavailable to those who enrol participants or assign interventions	Randomisation and blinding, page 9
Allocation concealment mechanism	16b	Mechanism of implementing the allocation sequence (eg, central telephone; sequentially numbered, opaque, sealed envelopes), describing any steps to conceal the sequence until interventions are assigned	Randomisation and blinding, page 9
Implementation	16c	Who will generate the allocation sequence, who will enrol participants, and who will assign participants to interventions	Randomisation and blinding, page 9
Blinding (masking)	17a	Who will be blinded after assignment to interventions (eg, trial participants, care providers, outcome assessors, data analysts), and how	Randomisation and blinding, page 9
	17b	If blinded, circumstances under which unblinding is permissible, and procedure for revealing a participant's allocated intervention during the trial	N/A
Methods: Data collection, management, and analysis			
Data collection methods	18a	Plans for assessment and collection of outcome, baseline, and other trial data, including any related processes to promote data quality (eg, duplicate measurements, training of assessors) and a description of study instruments (eg, questionnaires, laboratory tests) along with their reliability and validity, if known. Reference to where data collection forms can be found, if not in the protocol	Primary outcome measure, page 10; Secondary outcome measures, page 10,11,12,13,14,15 & 16
	18b	Plans to promote participant retention and complete follow-up, including list of any outcome data to be collected for participants who discontinue or deviate from intervention protocols	Training diary page 15; Follow-up interviews, page 16

Data management	19	Plans for data entry, coding, security, and storage, including any related processes to promote data quality (eg, double data entry; range checks for data values). Reference to where details of data management procedures can be found, if not in the protocol	Data management procedures are documented on the Ethics application form (ref: PORPM_9102_CSS_RGOC) which is available upon request
Statistical methods	20a	Statistical methods for analysing primary and secondary outcomes. Reference to where other details of the statistical analysis plan can be found, if not in the protocol	Statistical analysis and power calculation, page 18
	20b	Methods for any additional analyses (eg, subgroup and adjusted analyses)	Statistical analysis and power calculation, page 18
	20c	Definition of analysis population relating to protocol non-adherence (eg, as randomised analysis), and any statistical methods to handle missing data (eg, multiple imputation)	N/A
Methods: Monitoring			
Data monitoring	21a	Composition of data monitoring committee (DMC); summary of its role and reporting structure; statement of whether it is independent from the sponsor and competing interests; and reference to where further details about its charter can be found, if not in the protocol. Alternatively, an explanation of why a DMC is not needed	N/A
	21b	Description of any interim analyses and stopping guidelines, including who will have access to these interim results and make the final decision to terminate the trial	Interventions, page 17
Harms	22	Plans for collecting, assessing, reporting, and managing solicited and spontaneously reported adverse events and other unintended effects of trial interventions or trial conduct	Interventions, page 17
Auditing	23	Frequency and procedures for auditing trial conduct, if any, and whether the process will be independent from investigators and the sponsor	N/A
Ethics and dissemination			

Research ethics approval	24	Plans for seeking research ethics committee/institutional review board (REC/IRB) approval	Methods, Study design, page 8
Protocol amendments	25	Plans for communicating important protocol modifications (eg, changes to eligibility criteria, outcomes, analyses) to relevant parties (eg, investigators, REC/IRBs, trial participants, trial registries, journals, regulators)	N/A
Consent or assent	26a	Who will obtain informed consent or assent from potential trial participants or authorised surrogates, and how (see Item 32)	Participants, page 8
	26b	Additional consent provisions for collection and use of participant data and biological specimens in ancillary studies, if applicable	N/A
Confidentiality	27	How personal information about potential and enrolled participants will be collected, shared, and maintained in order to protect confidentiality before, during, and after the trial	N/A (outlined in Ethics application form)
Declaration of interests	28	Financial and other competing interests for principal investigators for the overall trial and each study site	Declarations, page 21
Access to data	29	Statement of who will have access to the final trial dataset, and disclosure of contractual agreements that limit such access for investigators	N/A
Ancillary and post-trial care	30	Provisions, if any, for ancillary and post-trial care, and for compensation to those who suffer harm from trial participation	N/A
Dissemination policy	31a	Plans for investigators and sponsor to communicate trial results to participants, healthcare professionals, the public, and other relevant groups (eg, via publication, reporting in results databases, or other data sharing arrangements), including any publication restrictions	N/A
	31b	Authorship eligibility guidelines and any intended use of professional writers	N/A
	31c	Plans, if any, for granting public access to the full protocol, participant-level dataset, and statistical code	N/A
Appendices			

Informed consent materials	32	Model consent form and other related documentation given to participants and authorised surrogates	Appendix 2, page
Biological specimens	33	Plans for collection, laboratory evaluation, and storage of biological specimens for genetic or molecular analysis in the current trial and for future use in ancillary studies, if applicable	N/A

*It is strongly recommended that this checklist be read in conjunction with the SPIRIT 2013 Explanation & Elaboration for important clarification on the items. Amendments to the protocol should be tracked and dated.

APPENDIX 10: (THEME 2, STUDY 3)

CERT ✓ *C*onsensus on *E*xercise *R*eporting *T*emplate

A checklist for what to include when reporting exercise programs

Section/topic	Item	Checklist item	Location** (Section, page)
WHAT: materials	1	Detailed description of the type of exercise equipment (e.g. weights, exercise equipment such as machines, treadmill, bicycle ergometer etc)	Randomisation and blinding, page 9; Interventions, page 16
WHO: provider	2	Detailed description of the qualifications, teaching/supervising expertise, and/or training undertaken by the exercise instructor	Randomisation and blinding, page 9; Authors information, page 22
	3	Describe whether exercises are performed individually or in a group	Interventions, page 16
	4	Describe whether exercises are supervised or unsupervised and how they are delivered	Randomisation and blinding, page 9;
	5	Detailed description of how adherence to exercise is measured and reported	Secondary outcome measures, Training diary, page 15
	6	Detailed description of motivation strategies	N/A

	7a	Detailed description of the decision rule(s) for determining exercise progression	Interventions, page 16 & 17
	7b	Detailed description of how the exercise program was progressed	Interventions, page 16 & 17
	8	Detailed description of each exercise to enable replication (e.g. photographs, illustrations, video etc)	Randomisation and blinding, page 9;
	9	Detailed description of any home program component (e.g. other exercises, stretching etc)	Randomisation and blinding, page 9;
	10	Describe whether there are any non-exercise components (e.g. education, cognitive behavioural therapy, massage etc)	Interventions, page 16 & 17
	11	Describe the type and number of adverse events that occurred during exercise	Interventions, page 17
WHERE: location	12	Describe the setting in which the exercises are performed	Randomisation and blinding, page 9;
WHEN, HOW MUCH: dosage	13	Detailed description of the exercise intervention including, but not limited to, number of exercise repetitions/sets/sessions, session duration, intervention/program duration etc	Table 1, page 32; Table 2, page 33
TAILORING: what, how	14	Describe whether the exercises are generic (one size fits all) or tailored whether tailored to the individual	Interventions, page 16 & 17; Table 1, page 32; Table 2, page 33

	14b	Detailed description of how exercises are tailored to the individual	Interventions, page 16 & 17; Table 1, page 32; Table 2, page 33
	15	Describe the decision rule for determining the starting level at which people commence an exercise program (such as beginner, intermediate, advanced etc)	Interventions, page 16 & 17; Table 1, page 32; Table 2, page 33
HOW WELL: planned, actual	16a	Describe how adherence or fidelity to the exercise intervention is assessed/measured	Secondary outcome measures, Training diary, page 15;
	16b	Describe the extent to which the intervention was delivered as planned	Secondary outcome measures, Training diary, page 15;

The CERT Checklist is designed for reporting details of an exercise intervention. The CERT Checklist should be used in conjunction with a reporting checklist appropriate for the study type e.g. the CONSORT Statement (www.consort-statement.org) for randomised controlled trials, the SPIRIT Statement (www.spirit-statement.org) for a clinical trial protocol. For further guidance regarding reporting guidelines please consult the EQUATOR network (www.equator-network.org)

** Authors – please use N/A if an item is not applicable

APPENDIX 11: (THEME 2, STUDY 5)

ATRS

(Achilles Tendon Total Rupture Score)

Today's Date: ____/____/_____ Date of Birth____/____/_____

Name:_____

All questions refer to your limitations/difficulties related to your injured Achilles tendon.
Answer every question by grading your limitations/symptoms from 0-10.
Remember (0= Major limitations and 10= No limitations).

Please circle the number that matches your level of limitation

1. Are you limited due to decreased strength in the calf/Achilles tendon/foot?

0 1 2 3 4 5 6 7 8 9 10 (No limitations)

2. Are you limited due to fatigue in the calf/Achilles tendon/foot?

0 1 2 3 4 5 6 7 8 9 10 (No limitations)

3. Are you limited due to stiffness in the calf/Achilles tendon/foot?

0 1 2 3 4 5 6 7 8 9 10 (No limitations)

4. Are you limited due to pain in the calf/Achilles tendon/foot?

0 1 2 3 4 5 6 7 8 9 10 (No limitations)

5. Are you limited during activities of daily living?

0 1 2 3 4 5 6 7 8 9 10 (No limitations)

6. Are you limited when walking on uneven surfaces?

0 1 2 3 4 5 6 7 8 9 10 (No limitations)

7. Are you limited when walking quickly up the stairs or up a hill?

0 1 2 3 4 5 6 7 8 9 10 (No limitations)

8. Are you limited during activities that include running?

0 1 2 3 4 5 6 7 8 9 10 (No limitations)

9. Are you limited during activities that include jumping?

0 1 2 3 4 5 6 7 8 9 10 (No limitations)

10. Are you limited in performing hard physical labour?

0 1 2 3 4 5 6 7 8 9 10 (No limitations

Thank you very much for completing all the questions in this questionnaire.

APPENDIX 12: (THEME 2, STUDY 5)

Tampa Scale for Kinesiophobia
(Miller , Kori and Todd 1991)

1 = strongly disagree
2 = disagree
3 = agree
4 = strongly agree

1. I'm afraid that I might injury myself if I exercise	1	2	3	4
2. If I were to try to overcome it, my pain would increase	1	2	3	4
3. My body is telling me I have something dangerously wrong	1	2	3	4
4. My pain would probably be relieved if I were to exercise	1	2	3	4
5. People aren't taking my medical condition seriously enough	1	2	3	4
6. My accident has put my body at risk for the rest of my life	1	2	3	4
7. Pain always means I have injured my body	1	2	3	4
8. Just because something aggravates my pain does not mean it is dangerous	1	2	3	4
9. I am afraid that I might injure myself accidentally	1	2	3	4
10. Simply being careful that I do not make any unnecessary movements is the safest thing I can do to prevent my pain from worsening	1	2	3	4
11. I wouldn't have this much pain if there weren't something potentially dangerous going on in my body	1	2	3	4
12. Although my condition is painful, I would be better off if I were physically active	1	2	3	4
13. Pain lets me know when to stop exercising so that I don't injure myself	1	2	3	4
14. It's really not safe for a person with a condition like mine to be physically active	1	2	3	4
15. I can't do all the things normal people do because it's too easy for me to get injured	1	2	3	4
16. Even though something is causing me a lot of pain, I don't think it's actually dangerous	1	2	3	4
17. No one should have to exercise when he/she is in pain	1	2	3	4

APPENDIX 13: (THEME 2, STUDY 5)

FAOS FOOT & ANKLE SURVEY

Today's date: _____ Date of birth: _____

Name: _____

INSTRUCTIONS: This survey asks for your view about your foot/ankle. This information will help us keep track of how you feel about your foot/ankle and how well you are able to do your usual activities.
Answer every question by ticking the appropriate box, only one box for each question. If you are unsure about how to answer a question, please give the best answer you can.

Symptoms
These questions should be answered thinking of your foot/ankle symptoms during the **last week**.

S1. Do you have swelling in your foot/ankle?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S2. Do you feel grinding, hear clicking or any other type of noise when your foot/ankle moves?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S3. Does your foot/ankle catch or hang up when moving?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S4. Can you straighten your foot/ankle fully?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

S5. Can you bend your foot/ankle fully?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

Stiffness
The following questions concern the amount of joint stiffness you have experienced during the **last week** in your foot/ankle. Stiffness is a sensation of restriction or slowness in the ease with which you move your joints.

S6. How severe is your foot/ankle stiffness after first wakening in the morning?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

S7. How severe is your foot/ankle stiffness after sitting, lying or resting **later in the day**?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Pain

P1. How often do you experience foot/ankle pain?

Never	Monthly	Weekly	Daily	Always
□	□	□	□	□

What amount of foot/ankle pain have you experienced the **last week** during the following activities?

P2. Twisting/pivoting on your foot/ankle

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

P3. Straightening foot/ankle fully

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

P4. Bending foot/ankle fully

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

P5. Walking on flat surface

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

P6. Going up or down stairs

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

P7. At night while in bed

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

P8. Sitting or lying

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

P9. Standing upright

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

Function, daily living

The following questions concern your physical function. By this we mean your ability to move around and to look after yourself. For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your foot/ankle.

A1. Descending stairs

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A2. Ascending stairs

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your foot/ankle.

A3. Rising from sitting

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A4. Standing

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A5. Bending to floor/pick up an object

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A6. Walking on flat surface

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A7. Getting in/out of car

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A8. Going shopping

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A9. Putting on socks/stockings

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A10. Rising from bed

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A11. Taking off socks/stockings

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A12. Lying in bed (turning over, maintaining foot/ankle position)

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A13. Getting in/out of bath

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A14. Sitting

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A15. Getting on/off toilet

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your foot/ankle.

A16. Heavy domestic duties (moving heavy boxes, scrubbing floors, etc)

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A17. Light domestic duties (cooking, dusting, etc)

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

Function, sports and recreational activities

The following questions concern your physical function when being active on a higher level. The questions should be answered thinking of what degree of difficulty you have experienced during the **last week** due to your foot/ankle.

SP1. Squatting

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

SP2. Running

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

SP3. Jumping

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

SP4. Twisting/pivoting on your injured foot/ankle

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

SP5. Kneeling

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

Quality of Life

Q1. How often are you aware of your foot/ankle problem?

Never	Monthly	Weekly	Daily	Constantly
□	□	□	□	□

Q2. Have you modified your life style to avoid potentially damaging activities to your foot/ankle?

Not at all	Mildly	Moderatly	Severely	Totally
□	□	□	□	□

Q3. How much are you troubled with lack of confidence in your foot/ankle?

Not at all	Mildly	Moderately	Severely	Extremely
□	□	□	□	□

Q4. In general, how much difficulty do you have with your foot/ankle?

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

Thank you very much for completing all the questions in this questionnaire.

Questionnaire and User's Guide can be downloaded from: www.koos.nu