Ankle osteoarthritis and its treatments : impact on foot and ankle biomechanics

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Arthrose de cheville et ses traitements : impact sur la biomécanique du pied et de la cheville

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Résumé court

L'arthrose de cheville est une dégénérescence progressive du cartilage caractérisée par une douleur et une incapacité fonctionnelle importante. Cependant, bien que la marche soit améliorée suite à une arthrodèse ou à une prothèse totale de cheville, les patients présentent toujours une altération de la fonction du membre inférieur. Afin d'améliorer notre compréhension des déficiences fonctionnelles associées à cette pathologie et à ces traitements chirurgicaux connexes, une revue systématique de la littérature a été réalisée. Celle-ci démontre un manque de caractérisation de cette pathologie dans les études d'analyse de marche. Cela signifie que les conséquences fonctionnelles sont difficiles à définir sans tenir compte des changements morphologiques et structurels du pied liés à l’arthrose. Par conséquent, des groupes homogènes de patients ont été recrutés sur base de l’étiologie de l’arthrose et de la présence de déformations concomittantes. L’analyse cinétique des articulations intrinsèques du pied chez ces patients a montré que les altérations de la fonction n’étaient pas limitées à la cheville douloureuse, mais affectaient également les articulations adjacentes du pied. De plus, les déformations du pied associées à l’arthrose de cheville influencent la mécanique du pied durant la marche. Enfin, une étude pilote a été réalisée pour donner une première évaluation de la prothèse totale de cheville sur la performance biomécanique des patients souffrant d'arthrose. Nos résultats ont révélé que la mécanique de la cheville après prothèse ressemble à celle des chevilles saines mais que leurs performances biomécaniques restent diminuées par rapport à des sujets asymptomatiques.

Mot clés :

Biomécanique ; Arthrose de cheville ; Marche ; Prothèse totale de cheville

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Résumé long

L'arthrose de cheville est une maladie chronique caractérisée par une dégénérescence progressive des articulations, une douleur et une incapacité importante. Ainsi, environ 1 % de la population adulte au monde vit avec une arthrose symptomatique de la cheville.[1,4,7]

L'objectif de ce projet de doctorat est d'étudier la biomécanique du pied chez des patients souffrant d'arthrose de cheville à l'aide d'une plateforme d'examen clinique avancée composée d'un système d'analyse du mouvement, de mesures de forces et des pressions plantaires.

En complément, une première évaluation a été fournie sur la façon dont la mise en place d'une prothèse totale de cheville est bénéfique pour la performance biomécanique des patients souffrant d'arthrose post-traumatique de la cheville.

La fonction physique évaluée chez les patients souffrant d'arthrose de cheville à l'aide du questionnaire SF-36 rempli par les patients était équivalente ou supérieure à celle des patients atteints d'insuffisance rénale terminale, d'insuffisance cardiaque congestive ou de douleurs au niveau des vertèbres cervicales.[1,4,7] A noter que les patients souffrant d'arthrose de cheville sont généralement plus jeunes que ceux qui souffrent d'arthrose du genou ou de la hanche.[1,7] L'allongement probable de la durée de vie, associé à la diminution importante de la qualité de vie, majore l'effet profondément néfaste de l'arthrose de cheville sur l'incapacité fonctionnelle des patients.[4] Cependant, bien que la marche soit améliorée suite à une arthrodèse ou à une prothèse totale de cheville par rapport à leur situation préopératoire, les patients présentent toujours une altération de la fonction du membre inférieur.[2,3,5,8]

Mesurer et documenter les résultats de ces interventions chirurgicales est un processus complexe : la première question est de savoir quel point de vue des résultats, patient ou chirurgien, doit être exploré. En effet, de nos jours, il existe de plus en plus de données probantes utilisant des mesures rapportées par les patients pour évaluer les résultats de prothèse totale de la cheville ou d'arthrodèses tibio-talo-calcanéennes et tibio-taliennes, reconnaissant l'importance d'appréhender le ressenti du patient à l'égard de sa chirurgie. Toutefois, l'évaluation des résultats déclarés par les patients n'est pas suffisamment affinée pour rendre compte de leur état de rétablissement et de leur capacité à s'adapter aux limitations fonctionnelles prévues ou imprévues suite à leur chirurgie.

Par conséquent, la première partie du présent projet de doctorat vise à présenter une première tentative d'évaluation et à comparer des résultats chirurgicaux après une prothèse totale de la cheville, une arthrodèse tibio-talo-calcanéenne et une arthrodèse tibio-talienne en analysant la perception du patient sur son sentiment de rétablissement (Chapitre 2).

Ainsi, les données probantes ont montré que près de la moitié des patients ont fait état de meilleurs résultats postopératoires, sans symptômes résiduels, quel que soit le type de chirurgie pratiquée. Cela signifie également que la seconde moitié des patients souffrent encore de déficiences fonctionnelles et de limitations dans leurs activités de la vie quotidienne.

Afin d'améliorer notre compréhension des déficiences fonctionnelles associées à l'arthrose de cheville et aux traitements chirurgicaux connexes, la deuxième partie de ce projet de doctorat consiste à présenter une analyse quantitative de la crédibilité scientifique et de l'utilité clinique des connaissances actuelles concernant l'évaluation de l'effet biomécanique lors de la mise en place d'une prothèse totale de la cheville et des arthrodèses de cheville sur les patients atteints d'arthrose de cheville au stade terminal (Chapitre 3).

Par ailleurs, même si l'arthrose de cheville est, dans une large mesure, liée à une altération de la marche,[6] la revue systématique de la littérature et la méta-analyse effectuées dans le cadre de ce projet de doctorat ont montré que le nombre d'études qualitatives et prospectives sur l'analyse de la marche chez cette population est limité. En effet, il semble que l'évaluation objective de la marche ne soit pas suffisamment intégrée dans l'évaluation et la prise en charge de l'arthrose de cheville. Par conséquent, les informations sur le comportement du pied chez ces patients avant et après traitement chirurgical font défaut. Cependant, nous avons également constaté qu'il existe un manque de caractérisation de l'arthrose de cheville dans les études d'analyse de la marche. Cela signifie que les conséquences fonctionnelles sont difficiles à définir sans tenir compte des changements morphologiques et structurels du pied associés à l'arthrose de cheville.

Par conséquent, le présent projet de doctorat a mis au point une plateforme d'examen clinique avancée qui englobe certains défis et avantages liés à la combinaison d'un système de capture de mouvement, d'une plateforme de force et d'une plateforme de pression plantaire. Dès lors, l'intégration de ces dispositifs nous a permis de créer un modèle cinétique du pied à quatre segments permettant d'estimer la génération ou l'absorption des puissances articulaires au niveau du pied et de la cheville durant la marche.

Le présent projet a complété la distribution intrinsèque de la puissance des articulations du pied par une variable "simple" qui encapsule une relation angulaire 3D entre les vecteurs du moment et les vecteurs de la vitesse angulaire d'une même articulation, dans le but de traduire les données cinétiques en une mesure "simple" de la fonction des articulations du pied pendant la marche (Chapitre 4). Cette première estimation du comportement cinétique des multiples articulations du pied a révélé qu'elles adoptent une configuration ″stalibilized-resistive″ pendant la majeure partie de la phase d'appui de la marche.

À notre connaissance, aucune recherche antérieure n'a été effectuée chez des patients souffrant d'arthrose de cheville à l'aide d'un modèle cinématique et cinétique de pied à quatre segments. Cette approche a le potentiel de montrer des comportements cinématiques et cinétiques qu'un modèle du pied représenté par un seul segment rigide masquerait ainsi que de donner des informations supplémentaires sur la fonction de l'avant-pied en mesurant la cinématique et la cinétique des articulations de Chopart et de Lisfranc (Chapitres 5 et 6).

De plus, le présent projet s'est intéressé au manque de caractérisation de l'arthrose de cheville et des déformations ostéoarticulaires associées, identifiées grâce à notre revue systématique de la littérature, et a incorporé des variables radiologiques statiques et dynamiques. Par conséquent, l'un des premiers objectifs du projet était de classer les patients en différents groupes en fonction de l'étiologie de leur arthrose de cheville. Ainsi, l'étiologie la plus courante observée chez les patients recrutés était l'arthrose post-traumatique de cheville. Ce sous-type d'arthrose de cheville survient le plus souvent suite aux fractures et à l'instabilité chronique de cheville. Comme la nature du traumatisme est différente pour ces deux étiologies, on peut s'attendre à ce que les deux sous-types d'arthrose post-traumatique de cheville présentent une mécanique du pied différente pendant la marche. Étonnamment, nous n'avons trouvé aucune différence significative dans les angles et les moments articulaires du pied entre les deux groupes pathologiques.

Cependant, l'exploration de la cinétique des articulations intrinsèques du pied des deux sous-groupes par rapport aux sujets asymptomatiques a révélé que l'altération de la mécanique du pied n'était pas limitée à la cheville douloureuse, mais touchait également les articulations voisines du pied, comme les articulations de Lisfranc et la première métatarso-phalangienne.

Nous pensons également que l'absence de différences observées dans les angles et les moments articulaires du pied entre les deux groupes pathologiques pourrait s'expliquer par la présence de déformations concomitantes du pied et de la cheville associées à l'arthrose de cheville pouvant affecter la mécanique intrinsèque du pied et de l'articulation de la cheville pendant la marche. Par conséquent, le présent projet a étudié l'effet des déformations ostéoarticulaires du pied et de la cheville mesurées radiologiquement sur la cinématique et la cinétique des articulations du pied et de la cheville chez des patients souffrant d'arthrose post-traumatique de cheville.

Ainsi, d'après les radiographies standards dites « en charge », les patients ont été classés en trois groupes de déformation ostéoarticulaire du pied et de la cheville (cavus, planus et neutre). Cette nouvelle approche du profilage des patients a alors révélé trois résultats clés :

1) nos données semblent fournir d'autres preuves de l'interrelation entre la structure du pied et les modifications de la mécanique du pied ;
2) le groupe d’arthrose de cheville présentant une déformation ostéoarticulaire de type cavus tente de réduire la déformation varisante intra-articulaire de la cheville au niveau des articulations du Chopart et du Lisfranc ;
3) aucune différence significative des angles et des moments articulaires n'a été observée entre le groupe atteint d'arthrose ayant des déformations ostéoarticulaires de type pied plat et le groupe atteint d'arthrose sur pied normo axé.

Dès lors, ces résultats indiquent que la désaxation de l'arrière-pied et de la cheville, tel qu’évalué sur un plan radiographique, influence la mécanique du pied pendant la marche chez les patients souffrant d'arthrose post-traumatique de la cheville.

Enfin, une étude pilote (Chapitre 7) a été réalisée pour donner une première évaluation de la façon dont la prothèse totale de cheville est bénéfique pour la performance biomécanique des patients souffrant d'arthrose post-traumatique de la cheville. Nous avons donc étudié l'effet de la prothèse totale de cheville sur les angles, les moments et la puissance de l'articulation de la cheville à l'aide d'un modèle cinématique et cinétique de pied à un et plusieurs segments. Nos résultats ont révélé que la mécanique de la cheville après prothèse totale ressemble à celle des chevilles saines, mais que leur performance biomécanique en termes d'angles et de moments articulaires reste réduite par rapport aux sujets témoins asymptomatiques.

De plus, nous avons constaté que le choix de modèle du pied peut modifier l'interprétation clinique pour évaluer si une intervention chirurgicale comme la prothèse totale de cheville est bénéfique ou non à la performance biomécanique d'un patient. Par conséquent, il est important sur le plan clinique d'évaluer la cinématique et la cinétique de l'articulation de la cheville à l'aide d'une approche de modélisation multi-segments du pied.

En conclusion, ce projet de doctorat vise à contribuer à une meilleure compréhension de la (patho) mécanique de l'arthrose de cheville par le développement d’une plateforme d'examen clinique avancée. L'intégration de tous les dispositifs composant cette dernière nous a permis de créer un modèle cinématique et cinétique du pied à quatre segments, fournissant des informations précieuses pour le raisonnement et l'interprétation cliniques futurs. Nous sommes convaincus que la combinaison d'une telle plateforme d'examen clinique avancée en association avec des informations cliniques et radiographiques nous aidera à mieux comprendre le complexe biomécanique du pied et de la cheville.

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Ankle osteoarthritis and its treatments : impact on foot and ankle biomechanics

Abstract

Ankle osteoarthritis is a degenerative joint disease characterized by significant pain and disability. Although gait is improved after surgery, patients still experience impaired lower limb function. Therefore, this doctoral project compared outcomes following common surgical procedures for ankle osteoarthritis by analyzing patients' perception of recovery. Evidence showed that half of the patients were still experiencing functional impairments after surgery. To increase our understanding of functional impairment experienced by these patients, a meta-analysis was performed to assess the biomechanical effects of total ankle replacement and ankle arthrodesis during gait. It showed that characterization of ankle osteoarthritis is lacking in gait studies and that functional consequences are difficult to define without considering the morphological and structural changes associated with this pathology. Therefore, homogenous study groups of patients were recruited based on the aetiology of ankle osteoarthritis and the presence of concomitant foot deformities. Analyzing the kinetics of the intrinsic foot joints of ankle osteoarthritis patients revealed that the impairment in foot mechanics was not restricted to the painful ankle joint, but also affected neighboring foot joints. Further evidence showed that malalignment of the hindfoot and the ankle does indeed influence foot mechanics during gait. Finally, a pilot study providing a first estimation of how total ankle replacement benefits the biomechanical performance of patients, revealed that ankle mechanics after surgery resembles that of unaffected ankles, but remain impaired compared to control subjects.

Keywords :

Biomechanics ; Ankle osteoarthritis; Walking ; Total ankle replacement

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Foreword

This doctoral project was initiated by Dr. Thibaut Leemrijse, Dr. Jean-Luc Besse, Prof. Laurence Chèze and Paul-André Deleu with a view to achieving a broader and more meaningful picture of the functional health of patients that are treated surgically for foot and ankle pathologies. For many years, the orthopaedic foot and ankle surgeons of the Foot & Ankle Institute (Brussels) and Dr. Jean-Luc Besse (Hospices Civils de Lyon) have had a strong commitment to clinical and translational research. One of the main research interests of both research groups is the surgical management of ankle osteoarthritis. Currently the two most common surgical procedures for ankle osteoarthritis are total ankle replacement and ankle arthrodesis. Although both procedures show good short- and mid-term outcome results, several complications have been reported in long-term studies. Therefore, to improve patient care, both research teams proposed the present research project. This project fits within the work of a larger interdisciplinary and multi-centric research group on foot and ankle biomechanics.

During the last three years, as a part-time PhD student, I had the privilege to initiate the present multicenter study in two foot and ankle research centers (Lyon and Brussels). This PhD manuscript presents the preliminary results of this long-term on-going interdisciplinary and multi-center project. It represents also the successful collaboration of multiple disciplines (i.e., podiatrist, orthopaedic surgeons, engineers) required to grasp the complexity of ankle osteoarthritis.

This thesis dissertation is written in English. However, in accordance to the internal rules and regulations of the Doctoral School, a thesis written in English requires a short and a long summary in French in the preliminary pages. In addition, the first chapter of this thesis dissertation describing the anatomy of the foot and ankle was also written in French.

General introduction

Osteoarthritis of the ankle is a common chronic disorder characterized by progressive joint degeneration, significant pain and disability, affecting approximately 1% of the world's adult population living with symptomatic ankle osteoarthritis.[1,10,16,23,30] Post-traumatic ankle osteoarthritis accounts for up to 79.5% of all cases of ankle osteoarthritis.[7,31] This fraction with post-traumatic aetiology is far greater in the ankle compared to the knee or the hip.[7] Numerous clinical and epidemiologic studies of patients suffering from ankle osteoarthritis have identified previous trauma as the most common aetiology.[31,36] Post-traumatic ankle osteoarthritis may be secondary to ankle-related fractures (post-fracture) and to chronic ankle instability (post-sprain).[31] Evidence suggests that post-fracture ankle osteoarthritis results either from irreversible cartilage damage which occurs at the time of the fracture, or from chronic cartilage overloading which occurs as a result of post-fracture articular incongruity. The evidence also suggests that post-sprain ankle osteoarthritis results from pathological cartilage overloading due to chronic joint instability.[22] Less common causes of ankle osteoarthritis are rheumatoid arthritis, hemochromatosis, haemophilia, neuropathic arthropathy, primary osteoarthritis, post-infectious arthritis, clubfoot deformity and avascular necrosis of the talus.[35,36]

The degree of self-reported physical impairment in patients with isolated ankle joint osteoarthritis using the SF-36 questionnaire was equivalent to or worse than that of patients with end-stage hip osteoarthritis, end-stage kidney disease or congestive heart failure.[1,16,30] The disability related to end-stage ankle osteoarthritis can represent a considerable economic burden for both society and the individual patient.[15] Recently, a Canadian study reported an employment rate of 56% in patients, younger than 55 years affected by end-stage ankle osteoarthritis, much lower than the expected employment rate of 79.2% of an age-matched population.

Significant biomechanical impairment of the entire foot and lower limb has been reported in patients suffering from post-traumatic ankle osteoarthritis.[32,37] Their gait is asymmetric and characterized by a decreased walking speed, a decreased stride length and a reduced mobility of the ankle joint complex.[38] They also seem to adopt an antalgic walking strategy to prevent shear loading through their painful joint.[38]

The surgical management of ankle osteoarthritis is generally reserved for failed medical management (i.e. assistive devices, physiotherapy, orthotics, viscosupplementation) where functional disability affects a patient's quality of life.[29] Currently, the "gold standard" surgical treatment is ankle arthrodesis, which provides good pain relief and a relatively well-documented long-term survivalship.[11,13,18,34,35] However, ankle arthrodesis leads to deficits in work and leisure activities and to adjacent joint degeneration,[4,9,14,24,39] thought to be a consequence of altered mechanical loads as a result of the change in function of the ankle.[4,5,9,14] These disadvantages have encouraged the use of motion-sparing procedures such as total ankle replacement, the potential benefits of which are conserving the existing pre-operative ankle range of motion, improving gait and protecting the adjacent joints[6,8,20], although the last of these has not yet been proven.[26] Despite these persuasive arguments in favour of a total ankle replacement rather than an ankle arthrodesis, long-term clinical and radiological results of total ankle replacement are not as satisfactory as those of total hip and knee replacements.[8]

Although the biomechanical performance was improved after successful total ankle replacement and ankle arthrodesis compared to their pre-operative situation, patients are still experienced impaired lower leg function.[8,12,18,24,26] Recently, Pinsker and colleagues (2016) used advancing patient-reported outcome measures to assess if patients who had undergone a total ankle replacement and ankle arthrodesis could cope with ongoing residual deficits.[24] Even though most patients reported positive post-operative outcomes, only 15% perceived themselves as having no residual deficits.[24] This means that 85% of these patients have to make compensatory functional adaptations to remain capable of performing basic activities of daily living. These compensations are known as accessory offending motion hypermobility, which takes the path of least resistance of motion and is an underlying characteristic of degenerative joint disease.[17] Studies showed secondary postoperative arthritic changes in the ipsilateral adjacent joints, with most degeneration occurring in the subtalar joint, followed by the midtarsal joints.[9,33] This is the result of tissue trauma caused by repeated compensatory movements during activities of daily living. When these arthritic changes become symptomatic, additional surgical procedures will be required, exacerbating the functional deficiencies.[19] Unfortunately, these secondary functional limitations and compensatory adaptations and their impact on structures of neighboring joints during activities of daily living have been little studied.

Nowadays, there exists a growing body of evidence using patient-reported outcome measures to evaluate the outcome of total ankle replacement and ankle arthrodesis and describing levels of function from the patient's perspective.[3,25,27] However, they largely neglect whether patients are coping with ongoing limitations.[25] In contrast, three-dimensional gait analysis is the state of the art for measuring simultaneously lower limb joint kinematics and kinetics during activities of the daily living. Two narrative reviews of the literature show that three-dimensional gait analysis has a great potential for assessing the biomechanical performance of a surgical intervention such as total ankle replacement and ankle arthrodesis aimed at improving function in the foot and lower limb.[2,21]

To provide a more detailed and objective description of foot and lower limb function during activities of daily living, quantitative measurements are needed. Quantitative evaluations such as three-dimensional movement analysis during gait have been used to functionally evaluate patients before and after a total ankle replacement and ankle arthrodesis in the literature.[2,21,28] A major drawback, however, is the oversimplification of foot mechanics neglecting the complex interaction between forefoot, midfoot, hindfoot and ankle. The simplified representation of the foot as a single functional segment is still widely used to assess the impact of ankle osteoarthritis and the effect of total ankle replacement and ankle arthrodesis. This could lead potentially to clinical misinterpretations of how a therapeutic intervention benefits or degrades the biomechanical performance of patients as the estimated changes simply reflect methodological errors inherent in modelling the foot as a single conventional rigid segment.[40] Consequently, information on foot behavior in patients suffering from ankle osteoarthritis before and after their surgical treatment is lacking. However, it may also be argued that characterization of ankle osteoarthritis is lacking in gait analysis studies. This means that functional consequences are difficult to define without considering the morphological and structural changes associated with the ankle osteoarthritis.

Therefore, the present doctoral project aims at enhancing the clinical understanding of ankle osteoarthritis (foot dynamics) by integrating three tools (three dimensional multi-segment foot model, ground reaction force and plantar pressure measurements). The integration of these tools makes it possible to enhance interpretation of a clinical complex phenomenon such as ankle osteoarthritis. It allowed us to create a four-segment kinematic and kinetic foot model to better characterize the functional consequences of ankle osteoarthritis on the multiple joint of the foot. This doctoral project, in our opinion, enables detection of complex pathomechanical pathways associated with ankle osteoarthritis which, once determined, may become important diagnostic and treatment tools to improve patient care.

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Aim of the doctoral project

The combined assessment of intrinsic foot joint angles, moments and power during walking in patients suffering from ankle osteoarthritis is assumed to be of clinical interest, however, this is not yet clearly defined and originates mainly from the anecdotal experience. The aim of this doctoral project was to combine different methodologies in an advanced clinical examination platform and to explore the potential clinical usefulness. Interpretation of the results provided by the platform, should always consider the morphological and structural changes associated with the ankle osteoarthritis. It is hypothesized that the use of the platform will contribute to a better understanding of foot and ankle biomechanics in patients suffering from ankle osteoarthritis. This was investigated in a survey study, a critical analysis of the literature and clinical studies.

The aim of the survey study was to provide a first assessment and comparison of surgical outcomes following total ankle replacement, tibio-talo-calcaneal, and tibiotalar arthrodeses by capturing patients' perception of their feeling of recovery. The question "Are you better ?" is of primary importance for a clinician, giving the patient's a critical appraisal of the patient on the effect of their surgical treatment.

The critical analysis of the literature addressed a number of methodological considerations associated with the development of the advanced clinical examination platform.

The specific objectives and questions of this critical analysis of the literature were:

1) To explore the existing literature on ankle osteoarthritis and its surgical treatments
2) To explore how inclusion criteria were defined for ankle osteoarthritis
3) To explore how concomitant foot and ankle deformities associated with ankle osteoarthritis were assessed
4) To investigate if a single rigid foot model or a multi-segment foot model was used
5) To determine whether total ankle replacement patients maintain or improve their pre-operative dorsi-/plantarflexion ankle motion during gait?
6) Do total ankle replacement and ankle arthrodesis patients improve their foot mechanics relative to their pre-operative state?

Subsequently, the development of the advanced clinical examination platform to assess the foot and ankle biomechanics of patients suffering from ankle osteoarthritis was initiated. The specific objectives of the development of the platform were:

1) The integration and synchronization in time and in space of a motion capture system, a force plate and a plantar pressure plate, identical in 2 different locations (Lyon & Brussels) to initiate a multi-center study
2) The development of an in-house made Matlab© program. Due to the multi-dimensional feature of the integrated measurement protocol, a program that allows handling of the crucial clinical parameters was developed. An innovative step in our in-house made Matlab© program was the development of a multi-segment kinematic and kinetic foot model.

Finally, the possible value of the advanced clinical examination platform in increasing the clinical insight in foot biomechanics of patients suffering from ankle osteoarthritis was assessed. The specific objectives and hypotheses of this clinical part were :

1) To estimate the intrinsic foot joint kinematics and kinetics using a four-segment foot model as well as characterizing the three-dimensional angular relationship between the joint moment and the joint angular velocity vectors, in an attempt to provide a “simple” measure of the function of intrinsic foot joints during gait
2) To compare the foot kinematics and kinetics of patients suffering from post-fracture ankle osteoarthritis to patients suffering from post-sprain ankle osteoarthritis. In supplement, each pathologic group was individually compared to an asymptomatic group of peer-matched control subjects.
3) To investigate the effect of ankle and hindfoot malalignment on the gait kinematics and kinetics of multiple joints of the foot and ankle complex in patients suffering from post-traumatic ankle osteoarthritis
4) To investigate the effect of total ankle replacement on the ankle joint angles, moments and power assessed with a one-segment and multi-segment kinematic and kinetic foot models
5) To compare the outcome difference in ankle joint angles, moments and power from preoperative to postoperative condition between the two modelling approaches in patients treated surgically by a total ankle replacement.

Chapter 1 : “Notions d’anatomie du pied et de la cheville”

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INTRODUCTION

Nous avons naturellement tendance à envisager les choses que nous ne connaissons pas en faisant des analogies avec celles que nous connaissons et que nous comprenons.

Il est logique de penser que la roue tourne autour d'un axe ; comme il semble facile de comprendre que la cheville permet un mouvement de flexion extension et l'image d'une charnière nous vient alors à l'esprit. Cependant, les forces axiales que subit la région talonnière lors de chaque pas doivent se transformer en énergie, sans aucune lésion tissulaire, pour nous permettre de quitter l'avant pied et les orteils sous une forme propulsive.

Il est donc utile d'avoir une bonne représentation de l'anatomie du pied et de la cheville afin de mieux en comprendre les notions biomécaniques et ses explorations décrites dans ce projet de doctorat.

Sous le terme « anatomie » nous évoquerons successivement et très succinctement les structures osseuses, ligamentaires et tendineuses. Nous mettrons volontairement de côté des éléments aussi essentiels que les structures vasculaires, artérielles ou veineuses, la peau et son tissu sous-cutané. De même, la description des éléments neurologiques ne sera pas abordée.

Les structures articulaires sont recouvertes par des zones cartilagineuses qui représentent des surfaces de glissement. Le cartilage est donc soumis à des contraintes et tout excès risque d'entraîner une détérioration de cette surface de glissement et finalement, voir apparaître l'arthrose.

Quant à elles, les structures ligamentaires réunissent entres elles les différentes pièces osseuses et donnent passivement la rigidité et la stabilité à notre structure anatomique. Là aussi, tout excès de contrainte, par défaut d'axe ou d'alignement, peut être à l'origine d'une faillite du système et sera révélé par une laxité articulaire. Ce mécanisme de laxité peut expliquer lui aussi les phénomènes d'arthrose par perte de congruence des surfaces articulaires.

Les structures tendineuses sont actives et permettent d'animer le pied et la cheville, elles génèrent donc le mouvement. Les muscles à l'origine de chaque tendon sont définis comme extrinsèques lorsque leur corps est situé en dehors du pied c'est à dire dans la jambe et sont principalement propulseurs. Les intrinsèques sont situés à l'intérieur du pied entre le calcanéus et leur point d'insertion tendineuse ; ils sont alors plutôt stabilisateurs. Les forces qui animent les tendons doivent idéalement être synchronisées et harmonieuses lors du déroulement du pas au risque de provoquer un déséquilibre.

ANATOMIE GENERALE

Globalement, on définit différentes régions au niveau du pied et de la cheville. On considère comme « cheville », la région tibio-talienne caractérisée par l'extrémité distale du tibia et de la malléole fibulaire (malléole externe) et le talus (anciennement appelé astragale). Cette région est privée de toutes insertions tendineuses. Cette véritable pince s'appuie sur la surface articulaire du talus, qui lui-même s'assoie sur le calcanéus, os de la région talonnière.

Entre ces os, talien et calcanéen, existe deux zones articulaires ; la postérieure est appelée articulation sous talienne proprement dite et l'antérieure se prolonge au niveau de l'articulation dite de Chopart à laquelle participe l'os naviculaire situé plus antérieurement. L'ensemble de ces structures osseuses sont reliées par un système ligamentaire complexe et forment les structures osseuses de la région de l'arrière-pied.

La partie du « médio-pied » est caractérisée par la présence osseuse de l'os naviculaire situé en avant de la tête talienne. Le cuboïde est comme son nom l'indique, de forme cubique situé à la partie antérieure du calcanéus et en relation latérale et plantaire par rapport à l'os naviculaire.

Les trois cunéiformes sont situés à la partie antérieure du naviculaire. Le 3^{e} cunéiforme a lui aussi une relation articulaire latérale avec la partie supérieure du cuboïde.

L'articulation transverse dite de « Lisfranc » délimite antérieurement le médio-pied à « l'avant pied » qui est formé de cinq métatarsiens relativement parallèles à la suite desquels se prolongent les orteils composés de deux phalanges au niveau du premier rayon et de trois phalanges au niveau des petits orteils.

MOUVEMENT DU PIED ET DE LA CHEVILLE

La forme de chaque os détermine la création de mouvements complexes qui ne sont jamais des rotations ou des translations pures mais toujours une combinaison des deux.

Le mouvement de la cheville pourrait être considéré comme un des plus simples au niveau de l'arrière-pied. Cependant, il semble difficile de le définir comme un cylindre autour d'un axe de rotation comme on peut le retrouver au niveau d'une charnière. En effet, l'articulation de la cheville, d'un point de vue ostéologique et syndesmologique, est une articulation essentielle pour la fonction de flexion dorsale et plantaire du pied par rapport à la jambe. Le talus est un os clé de la jonction entre le pilon tibial et les articulations de l'arrière-pied. L'extrémité distale du tibia appelée également pilon tibial comprend une surface articulaire supérieure et une surface sur la malléole médiale. Cette surface articulaire est complétée latéralement par la malléole fibulaire pour former la pince bi-malléolaire qui est une structure dynamique. Elle s'appuie sur l'os talien, dont on peut différencier le corps et le col, et est caractérisée par la présence de surfaces articulaires multiples que ce soit sur sa partie supérieure en rapport avec la pince bi-malléolaire ou sur sa partie inférieure en rapport avec la surface articulaire du calcanéus. Cette région représente le corps. La partie antérieure de l'os considérée comme le col se termine par une tête elle aussi recouverte d'une surface articulaire en relation avec la concavité de l'os naviculaire.

Les relations articulaires de la cheville entre le pilon tibial et le talus ne sont pas cylindriques mais variables et l'analogie doit plutôt être faite par rapport à un segment tronconique définissant cependant un mouvement dont le centre rotatoire n'est pas fixe. De plus, la forme antéro-postérieure de la surface articulaire du talus n'est pas parallèle et se trouve plus large dans la partie antérieure que postérieure. Ceci oblige la pince bi-malléolaire à s'ouvrir lors des mouvements de flexion dorsale et de se refermer lors des mouvements de flexion plantaire. Ce jeu dynamique de la pince bi-malléolaire est autorisé par les mouvements complexes de l'articulation syndesmotique située entre le tibia et la malléole fibulaire qui est elle-même stabilisée par les ligaments syndesmotiques qui autorisent de fins mouvements de rotation-ascension de la malléole fibulaire lors des mouvements de flexion-extension de la cheville.

L'anatomie de l'articulation sous talienne est elle aussi complexe à évoquer. Comme souligné précédemment, il existe des surfaces articulaires situées entre le talus et le calcanéus délimitées par un puissant ligament inter-osseux qui a été comparé à une haie élevée entre les deux secteurs articulaires. Le calcanéus, au niveau de sa structure osseuse, est lui-même défini par la tubérosité que représente la partie postérieure saillante du talon, et le site d'insertion du puissant tendon calcanéen (Achille). L'os se prolonge ensuite par son apophyse antérieure en relation avec le cuboïde et médialement une apophyse de soutien asymétrique appelé *sustentaculum tali*, région qui participe au soutien de la tête talienne. Cette morphologie, totalement asymétrique, présente de multiples variantes morphologiques qui expliquent parfaitement le polymorphisme que l'on peut retrouver au niveau des formes de l'arrière-pied. Une région talonnière déformée latéralement, ou en dehors, caractérisera ce qu'on appelle un valgus de l'arrière-pied et à l'inverse, une déformation médiale ou en dedans, caractérisera le varus de l'arrière-pied. Ces déformations relatives de l'arrière-pied accentueront ou pas le porte-à-faux qui caractérise la structure architecturale de l'arrière-pied. Il est probable que les formes de rayon de courbure articulaire favorisent une stabilité ou une instabilité rotatoire plus ou moins importante entre le talus et le calcanéus. Une insuffisance de soutien au niveau du *sustentaculum tali* favorisera l'instabilité de la tête talienne qui aura tendance à caractériser un pied plat et inversement la superposition de l'os talien au-dessus du calcanéus caractérisera le morphotype de pied creux. On comprend immédiatement que le démembrement de morphotype de pied ou de structure osseuse que ce soit par l'anatomie palpatoire, par l'analyse des radiographies ou du CT-scanner, aura un impact fondamental sur la biomécanique du pied et inversement.

D'un point de vue grossièrement biomécanique, on comprendra que la résultante de force du tendon calcanéen sera modifiée sur l'ensemble du pied et de la cheville lorsqu'il existe une désaxation ou un défaut d'alignement de l'arrière-pied en valgus ou en varus. Les rétractions tendino-musculaires que l'on peut retrouver au niveau du triceps qui anime ce tendon calcanéen, elles aussi, auront un impact positif ou négatif sur les mouvements articulaires de l'arrière-pied et du médio-pied.

Au niveau ligamentaire, un puissant système unit les différentes malléoles aux os de l'arrière-pied. Au niveau médial ou interne, on retrouve une structure fondamentale appelée ligament collatéral médial qui stabilise intimement la malléole médiale à la face interne du talus sur ses fibres profondes et le *sustentaculum tali* sur ses fibres superficielles. Ce ligament se prolonge antérieurement jusqu'au bord médial du naviculaire et complète, sous forme de hamac, le soutien de la tête talienne en prolongeant le sustentaculum tali dans sa région plantaire. Cette partie ligamentaire plus communément appelée « *spring ligament* » sera très souvent retrouvée comme déficiente lorsqu'il existe une déformation en pied plat.

Au niveau latéral de la cheville, il existe également un complexe ligamentaire caractérisé par trois ligaments principaux, un faisceau antérieur entre la malléole fibulaire et le talus, un faisceau moyen entre la malléole fibulaire et le calcanéus, et un faisceau postérieur lui aussi talo-fibulaire. Ces structures stabilisatrices passives seront elles aussi plus ou moins sollicitées en fonction de l'alignement présent ou absent au niveau de l'arrière-pied.

Comme déjà évoqué pour le tendon calcanéen, les structures tendineuses extrinsèques glissent dans des gouttières para malléolaires postérieures latérales et médiales à l'arrière-pied. Les tendons fibulaires sont situés dans la partie latérale de la cheville et s'insèrent sur la partie haute de la fibula et de la membrane inter-osseuse au sein de la jambe. Ils se réfléchissent au niveau de la malléole fibulaire et participent donc indirectement aux mouvements de celle-ci lors de la flexion-extension de la cheville. Ils se terminent respectivement au niveau de la base du cinquième métatarsien pour le fibulaire court et à la base du premier métatarsien pour le fibulaire long. Ils se distinguent autour du tubercule latéral du calcanéus qui sera lui aussi un point de repère important lors de la palpation de sa structure osseuse. De plus, ils ont une relation intime avec les structures ligamentaires latérales dont ils pondèrent la tension lors des mouvements de la cheville et de l'arrière-pied.

Dans la partie médiale de la cheville, on retrouve le tendon du tibial postérieur qui termine son insertion sur le bord interne ou médial du naviculaire et participe dès lors à la stabilité de l'arche médiale du pied. Sa gaine répond, elle aussi intimement sous sa face profonde, aux fibres superficielles du complexe ligamentaire médial et donc au *spring ligament*. Le tendon fléchisseur de l'hallux semble également un vecteur fonctionnel non équivoque. Il est issu de la face postérieure de la jambe et après s'être réfléchi sur le bord postérieur du talus, il glisse sous la partie plantaire du *sustentaculum tali*. A ce niveau, lors de sa contraction, il exerce une force dynamique d'élévation de cette apophyse calcanéenne médiale. Il entraîne ou stabilise dès lors indirectement un mouvement de valgus au niveau de la tubérosité calcanéenne. Son insertion se termine au niveau de la base de la phalange distale du gros orteil sur laquelle il génère une force de propulsion fondamentale lors de la phase terminale du pas.

L'articulation sous talienne antéro-médiale est en continuité avec la surface articulaire de la tête talienne s'opposant à la concavité articulaire du naviculaire. Elle est renforcée, comme nous avons pu le voir, par la gaine et le tendon du tibial postérieur. Il existe donc anatomiquement, au niveau sous talien, une articulation individualisée en postérieur et une articulation antéro-médiale poly-articulaire où interviennent d'importants ligaments de soutien (*spring ligament*) en continuité avec la concavité naviculaire qui reçoit la tête du talus. Cette région anatomique appelée communément articulation de Chopart représente la jonction entre les os dit de « l'arrière-pied » et ceux du « médio-pied ». Si la description anatomique en est relativement simple, son examen clinique et son exploration mécanique semblent beaucoup plus compliqués. Elle participe de façon évidente à la jonction et à la transmission des forces axiales de la jambe vers la partie antérieure du pied dont l'avant-pied est caractérisé par sa palette métatarsienne où l'on retrouve uniquement des forces de propulsion.

Le segment du médio-pied dont la mobilité du Chopart est difficile à évaluer cliniquement présente relativement peu de mobilité et il existe, à l'opposé de la surface articulaire avec le talus au niveau du naviculaire, une surface articulaire qui reçoit la base des trois os cunéiformes. Ces trois surfaces reçoivent le nom de ligne innominée. Il n'existe sur cette interligne pratiquement aucune mobilité reconnue. Le 3^{e} cunéiforme par contre, oppose en direction latérale et plantaire, une surface articulaire avec le cuboïde où là aussi des mouvements peu décrits se rencontrent.

La partie distale des surfaces articulaires des cunéiformes et du cuboïde s'oppose aux bases des cinq métatarsiens au niveau d'une ligne transverse appelée communément articulation de Lisfranc.

Le clavier métatarsien est caractérisé par une mobilité franche entre le premier cunéiforme et la base du premier métatarsien. Cette articulation cunéo-métatarsienne du premier rayon présente des mouvements composites de flexion-adduction, extension-abduction d'une dizaine de degré et participe de façon formelle à la stabilité de l'arche médiale du pied. Cette articulation est renforcée par de puissants ligaments plantaires entre les cunéiformes et la base du premier métatarsien. Sur la base de cette dernière, au niveau plantaire s'insère le tendon terminal du tendon long fibulaire qui, après s'être déroulé sur la face latérale du pied, se réfléchit sur la gouttière cuboïdienne pour traverser ensuite la voûte plantaire. Son action franche est celui d'un stabilisateur de la base du premier métatarsien avec un mouvement de flexion du premier rayon.

La base du 2^{e} et du 3^{e} métatarsien s'enclave de façon rigide stable avec son cunéiforme respectif. Latéralement, le 4^{e} et le 5^{e} métatarsien s'opposent à la surface articulaire du cuboïde avec un secteur de mobilité de 20 à 30°en flexion-extension. Sur la base du 5^{e} métatarsien, on décrit la styloïde métatarsienne qui est elle aussi un élément palpatoire essentiel du bord latéral du pied et le site d'insertion du tendon terminal du court fibulaire.

Dans la région dite de l'avant-pied, la palette métatarsienne se termine par des surfaces articulaires de type condylienne qui s'appuient sur une structure capsulo-ligamentaire fondamentale appelée la plaque plantaire. Les plaques plantaires sont des structures fibro-cartilagineuses en forme de hamac en continuité intime avec la partie plantaire des bases phalangiennes des différents orteils. La structure la plus développée est la plaque plantaire du premier rayon dans laquelle s'insère les os sésamoïdiens afin d'en renforcer sa structure et d'y permettre l'insertion des différents muscles intrinsèques qui stabilisent partiellement le premier rayon.

Lors de la phase de propulsion, il est communément admis que les têtes métatarsiennes roulent au sein de ces plaques plantaires en maintenant, lorsqu'il n'existe pas d'anomalie anatomique, les orteils plaqués en appui au niveau du sol. Ces plaques plantaires sont reliées de façon intime à un réseau fibreux en continuité évidente avec l'aponévrose plantaire et la peau et qui fait le lien rigide et plantaire entre les structures de l'avant-pied et de l'arrière-pied. On voudrait décrire plus loin cette région d'amortissement-cisaillement dont les relations sont intimes par ce réseau fibreux à la structure cutanée et entrelacé du tissu graisseux noyé d'éléments veineux ; mais nous nous le sommes interdit dans l'introduction.

L'aponévrose plantaire est donc une structure fondamentale divisée en trois composants : un médial, un central et un latéral. L'aponévrose est une structure rigide peu déformable insérée sur la tubérosité du calcanéus qui s'étend progressivement en éventail pour s'insérer au niveau des différentes structures fibro-cartilagineuses de l'avant-pied dont principalement les plaques plantaires. Son rôle est fondamental dans la stabilité du pied et évite grossièrement l'effondrement de la structure osseuse en arche lors de sa mise en contrainte par le poids du corps.

Ce mécanisme est renforcé par l'ensemble des muscles intrinsèques du pied, bien présent au niveau du premier rayon sous forme de court fléchisseur, d'abducteur et d'adducteur de l'hallux. Les muscles interosseux sont de courtes structures musculaires insérées entre les métatarsiens qui se terminent sur les bases des premières phalanges des orteils. On retrouve également les courts fléchisseurs qui donnent un effet de flexion de la phalange par rapport à l'articulation métatarso-phalangienne.

CONCLUSION

Ce survol extrêmement simplifié et rapide de la richesse de l'anatomie du pied et de la cheville nous évoque toute la complexité de cet organe proprioceptif qui nous permet d'effectuer des performances décrites comme simples lors de la marche mais beaucoup plus complexes lors de la course, du sport ou de l'adaptation sur des terrains irréguliers. Le but n'est pas de donner une description structurée de l'anatomie mais uniquement d'en survoler les caractéristiques complexes et intriquées qui justifient la mise en œuvre d'examen et d'analyse paracliniques extrêmement sophistiqués afin de pouvoir comprendre et déterminer au mieux la fonction relative de chacun de ses segments ou régions.

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Chapter 2 : Long-term patient's perceived recovery and satisfaction after total ankle replacement, tibio-talar, and tibio-talo-calcaneal arthrodesis

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ABSTRACT

Background: Total ankle replacement (TAR), tibio-talo-calcaneal (TTC), and tibiotalar (TT) arthrodeses are common surgical procedures used to treat end-stage ankle osteoarthritis. Patient-reported outcome measures (PROMS) are increasingly used to evaluate these surgeries. However, they lack at capturing patients' perceived recovery state and ability to cope with potential functional limitations. Therefore, this study aimed at evaluating and comparing the postoperative surgical outcome of TAR, TTC, and TT arthrodeses by considering 3 PROMS, satisfaction rate and a self-reported perceived recovery state.

Methods: This study consisted of a cross-sectional survey aiming at retrospectively analyzing patient postoperative satisfaction and PROMS (FAOS, FFI and SF-12) following TAR (n = 51), TTC (n = 51) and TT (n =50). In addition, each patient was asked to classify himself in one of the following self-reported perceived recovery statements: 'Recovered-Resolved' (better with no symptoms or residual effects); 'Recovered-Not Resolved' (better with some residual effects); 'Not Recovered' (not better). Comparisons were performed between surgeries and between patients' perceived recovery groups.

Results: Almost 50% of the patients reported themselves in the 'Recovered-Resolved' group. Recovered-Resolved group showed higher patient satisfaction and PROMS scores compared to Recovered-Not Resolved and to Not Recovered groups. However, TAR group did not show higher satisfaction and better PROMS scores compared to the two arthrodesis groups. Finally, no difference in distribution of patients' perceived recovery state was observed between the surgeries.

Conclusion: Almost half of the patients reported better postoperative outcomes with no symptoms or residual effects independent of the type of the surgery that was performed.

BACKGROUND

Ankle osteoarthritis is a progressive and degenerative joint disease. The etiology of osteoarthritis is frequently posttraumatic or secondary to chronic ankle instability which can be associated with a malalignment of the hindfoot.[7,9] It is characterised by severe pain, loss of autonomy, functional limitations, diminished health-related quality of life, and, in later stages, an inability to perform daily tasks.[1,14,23] Saltzman et al. (2006) have measured the degree of physical impairment in patients suffering from ankle osteoarthritis, end-stage kidney disease and congestive heart failure using the SF-36.[22] They showed that the degree of physical impairment in these different groups were similar suggesting that suffering from ankle osteoarthritis can be considered as a severe disabling medical problem.[22] Currently, tibiotalar arthrodesis, tibio-talo-calcaneal arthrodesis and total ankle replacement are the three common surgical solutions proposed for end-stage debilitating ankle osteoarthritis. Both procedures aim at removing pain and maintaining a satisfactory function of the lower limb.[15]

Measuring and documenting the outcome of these surgical procedures is a complicated process. The first question that needs to be addressed is whose perspective (patient versus surgeon) of outcomes should be explored. From a clinical point of view, the most common methods of assessment of surgical procedures for end-stage ankle osteoarthritis are clinical range of motion, radiographic measurements, alignment and quantitative data such as three-dimensional gait analysis.[17] In contrast, patient's definition of surgical outcome will vary from a patient to another and will be based on personal issues that are pertinent to him such as resuming physical activities or pain relief. Nowadays, there exists a growing body of evidence using patient-reported outcome measures (PROMS) to evaluate the outcome of total ankle replacement (TAR), tibio-talo-calcaneal (TTC), and tibiotalar (TT) arthrodeses recognizing the importance of capturing the patient's perspective of his surgery.[2,19,26,28] However, these PROMS are not sufficiently fine-tuned to capture patients' perceived recovery state and ability to cope with the expected and or un-expected potential functional limitations after their surgery. When assessing surgical outcome, surgeons should wonder which impairment and limitation does the patient experience and whether the patient will be able to adapt and perform his desired daily activities after surgery. In fact, discrepancies may be observed between the clinical and radiographic results and the actual patient satisfaction.

Recently, Pinsker et al. (2016) evaluated both ankle arthroplasty and arthrodesis by comparing PROMS (using the SF-12, the EuroQol-5, the SMFA and the AOS scores) to the self-reported patient-perceived recovery state regarding residual impairments and limitations.[19] They showed a concordance between the results of the different outcome measures and the self-reported patient-perceived recovery state despite a non-homogeneous distribution between TAR (n = 85) and TT arthrodesis (n = 15).

Therefore, the present study aimed at evaluating and comparing the surgical outcome of TAR, TTC, and TT arthrodeses by considering 3 PROMS (SF-12, FAOS and FFI), a general satisfaction percentage, and a self-reported classification measuring whether the patient can cope with ongoing symptoms or limitations [i.e.: 1. Recovered-Resolved (R-R); 2. Recovered, not Resolved (R-NR); 3. Not Recovered (NR)]. Three hypotheses were tested in this study. First, it was expected that R-R patients would obtain high satisfaction scores and present no or low difficulties in performing activities of daily living (ADL), that R-NR patients would have midrange satisfaction and difficulties in performing ADLs, and that NR patients would report low satisfaction and high difficulties in performing ADLs. Secondly, TAR patients would report higher satisfaction, and no or lower difficulties in performing ADLs compared to TT or TTC patients. Finally, it was expected that R-R group would be composed of a majority of TAR patients.

MATERIALS & METHODS

Study Design and Sampling

Participants in this study were all operated in the same hospital by 2 senior orthopaedic foot and ankle surgeons between April 2010 and March 2017. Patients were eligible to take part in this study if they had (1) undergone TAR, TTC or TT for post-fracture ankle osteoarthritis (PF OA), ankle osteoarthritis due to chronic ankle instability (Insta OA) and idiopathic ankle osteoarthritis (Idiop OA), (2) a minimum of 12 months follow-up, (3) 18 years of age or older and (4) the ability to complete the requested survey. Patients suffering from inflammatory arthritis (lupus, haemochromatosis, rheumatoid arthritis), diabetic osteoarthropathy and neurological diseases were excluded from this study. The rationale for this exclusion criteria is that differences in issues of importance have been found between foot surgery patients with and without rheumatoid arthritis.[24] Based on these criteria, potential eligible patients were contacted by phone. Criteria to take part in this study were explained and consent was obtained prior to the study. A survey was then sent to them for completion. The study was approved by the local ethics committee.

Survey Content

Demographic items: Patients were asked to provide demographic data including age, gender, height, weight, and actual or last professional occupation which was classified as physical (farmer, plumber, ...) or sedentary (secretary, accountant, ...) activity (Table 2.1).

Self-reported Recovery State: Patients were then asked to select one of the three statements that best described their self-perceived recovery state.[3,19] Patients classified themselves as 'Recovered-Resolved' (R-R) [i.e.: I'm better with no symptoms or residual effects], 'Recovered, Not Resolved' (R-NR) [i.e.: I'm better but I experience some residual effect. Nevertheless, I have figured out ways to avoid them or can cope/live with them] and 'Not Recovered' (NR) [i.e.: I'm not better at this point in time].

Satisfaction: Overall satisfaction was evaluated postoperatively based on 3 items: (1) ability to perform daily activities; (2) symptom relief defined by the fact that the ankle can be forgotten; and (3) decreased physical pain. Patients were asked to rate these items on a 5-point scale (i.e.: 0 = very dissatisfied; 1 = dissatisfied; 2 = neither satisfied nor dissatisfied; 3 = satisfied, as expected; 4= very satisfied, better than expected).[3,24]

Functional Status: To assess functional abilities, patients were asked postoperatively to complete the Foot Functional Index (FFI) which is a reliable and valid scale to evaluate the effectiveness of a treatment in patients with conditions affecting the foot and ankle.[5,20,25] This score was rated by postoperative TAR and TT patients as the most likely to change due to surgery compared to frequently used PROMS such as AOS, AOFAS, LEFS, WOMAC and SFMA.[18] The Foot Function Index is scored from 0 to 100, with a lower score representing a better outcome. In addition, the FFI was completed by 3 additional criteria from the Foot and Ankle Outcome Scale (FAOS) relating to symptoms (swelling and stiffness) and pain frequency.[8,21] The FAOS is scored from 0 to 100, with a higher score representing better scores.

Health Status: To measure health-related quality of life, patients completed postoperatively the Short Form-12 version (SF-12). This questionnaire consisted of twelve questions measuring 8 health domains to assess physical and mental health.[11,14,27] High scores represent better mental and physical health. SF-12 was found to be a satisfactory psychometrical tool for the assessment of health-related quality of life in patients suffering from end-stage ankle osteoarthritis and their related surgical treatments.[12,14,16] Moreover, the physical component of SF-12 is strongly correlated with the physical component of the SF-36 which is well supported by evidence of reliability, validity, and responsiveness for patients suffering from ankle osteoarthritis.[12,14]

Statistical Analysis

The skewness and kurtosis scores were calculated and compared to the results of the ShapiroWilk tests to determine whether the variables were normally distributed. If discrepancies were found between the results for the same variable, data was plotted to make an informed decision about the (non-) normality of the data. Depending on the data distribution, the one-way ANOVA test (normal distribution) or the Kruskal-Wallis test (non-normal distribution) were used to determine if there were any statistical difference for each variable between the 3 surgical procedures and the 3 self-reported recovery groups. In the case of normal distribution, if a significant difference was found for a variable between the 3 surgical procedure groups, the Gabriel's post hoc test was used to indicate groups' differences as group sizes were slightly unequal [i.e.: TAR (n = 51) ; TTC (n = 51) ; TT (n = 50)]. However, in the case of normal distribution, if a significant difference was found for a variable between the 3 recovery groups, Games-Howell's post hoc test was performed to detect groups' differences as sample sizes were unequal [i.e.: R-R (n = 75) ; R-NR (n = 62) ; NR (n = 15)]. In the case of non-normal distribution, if a significant difference was found between groups, Dunn's post hoc test was carried out on each pair of groups. To test the third hypothesis in this study, Pearson's chi square test was used to determine if there is a significant association between the self-reported recovery state and the surgical procedure groups. Statistical significance was set at $P \leq .05$ and the SPSS Statistics software (Version 25) was used to analyse data (SPSS Inc., Chicago, Illinois, USA).

RESULTS

Sample Description

Searching the foot and ankle registry of our department identified two hundred fourteen eligible patients. Inspection of the visit notes allowed us to exclude 24 participants due to death (n=3) and invalid contact details (n=21). In addition, two participants refused to participate in the study. Of the 188 participants who consented to participate, 152 participants (TAR n=51;

TTC n=51; TT n=50) completed and responded accurately to the questionnaire, representing 80% valid response rate.

The final sample (n= 152; 51.3% female) had a mean age of 62.5 ± 12 years (mean±SD) and had a mean body mass index of 28.5 ± 5.5 kg/m^2. The preoperative diagnosis was post-fracture osteoarthritis (PF OA) in 107 (70.4%) ankles, osteoarthritis due to chronic ankle instability (Insta OA) in 30 (19.7%) ankles and idiopathic osteoarthritis (Idiop OA) in 15 (9.9%) ankles (Table 2.1 & 2.2). Professional activities were classified as sedentary in 63.8% of the participants. The mean postoperative follow-up duration was 46 ± 20.8 months (Tables 2.1 & 2.2).

Sample Description by Recovery Group

There was a significant difference in patient's age between the self-reported recovery groups [$F(2, 149) = 8.23$, $P < .001$, $\omega = 0.29$] ; R-R group was significantly older than the R-NR group ($P = .002$) and the NR group ($p = .009$). No statistical difference was found for age between the R-NR group and the NR group. There was also no significant difference in BMI [$H(2) = 3.38$, $P = .184$] and in follow-up duration [$H(2) = .154$, $P = .926$] between recovery groups (Table 2.1). No significant association was observed between the preoperative diagnosis and the self-reported recovery groups (χ^2 (4) = 2.78, $P = .596$).

Sample Description by Surgical Procedure

There was a significant difference in patients' age between the surgical procedures [$F(2, 149) = 12.08$, $P < .001$, $\omega = .36$]; TT patients were significantly younger than TAR ($p < .001$) and TTC patients ($P = .028$) (Table 2.2). No significant difference in BMI was observed between the three types of interventions [$H(2) = 5.44$, $P = .066$]. However, there was a significant difference in follow-up duration between the different types of surgery [$H(2) = 17.49$, $P < .001$] ; TAR patients had a significant longer follow-up duration (55.7 ± 21.3) than TTC patients (44.5 ± 21.3; $P = .025$, $r = .21$), and TT patients (37.7 ± 15.5; $P < .001$, $r = .33$) (Table 2.2). A significant association was found between the preoperative diagnosis and the types of surgical procedures (χ^2 (4) = 17.07, $P = .002$).

Table 2-1 : Demographic description by recovery group[a]

	R-R (n=75 ; 49.3%)	R-NR (n=62 ; 40.8%)	NR (n=15 ; 9.9%)	Total Sample (n = 152 ; 100%)
Gender (n, % F)	33 (44%)	33 (53.2%)	12 (80%)	78 (51.3%)
Age (Y) *,***	66.3 ± 10.8 (36-85)	59.3 ± 12.6 (30-85)	57.1 ± 9.6 (42-72)	62.5 ± 12 (30-85)
Prof (n, % Sed)	48 (64%)	37 (59.7%)	12 (80%)	97 (63.8%)
BMI	27.9 ± 4.7	29.5 ± 6.3	27.2 ± 5.52	28.5 ± 5.51
Follow-up (months)	46.5 ± 20.9 (13-96)	45.5 ± 21.1 (14-93)	45.9 ± 20.5 (13-68)	46.0 ± 20.8 (13-96)
Pre-operative diagnosis				
PF OA (n, %)	50 (66.7%)	45 (72.6%)	12 (80%)	107 (70.4%)
Insta. OA (n, %)	17 (22.7%)	10 (16.1%)	3 (20%)	30 (19.7%)
Idiop. OA (n, %)	8 (10.7%)	7 (11.3%)	0 (0%)	15 (9.9%)

*Abbreviations: *, significant difference between R-R and R-NR ; ***, significant difference between R-R and NR ; R-R, Recovered- Resolved ; R-NR , Recovered, Not Resolved ; NR, Not Recovered ; F, female ; Y, year ; Prof, profession ; Sed, Sedentary ; BMI, Body Mass Index ; M, Months ; PF OA, Post-Fracture Ankle Osteoarthritis ; Insta. OA, Ankle osteoarthritis due to chronic ankle instability ; Idiop OA, Idiopathic ankle osteoarthritis. [a]Unless otherwise stated, values refer to mean ± standard deviation (range).*

Table 2-2 : Demographic description by surgical procedure[a]

	TAR (n=51)	TTC (n=51)	TT (n=50)	Total Sample (n = 152)
Gender (n, % W.)	29 (56.9%)	22 (43.1%)	27 (54%)	78 (51,3%)
Age (Y) **, ***	67.8 ± 11.2 (41-85)	62.7 ± 10.3 (38-81)	56.9 ± 12 (30-83)	62.5 ± 12 (30-85)
Prof (n, % Sed)	37 (72.5%)	29 (56.9%)	31 (62%)	97 (63.8%)
BMI	28.3 ± 4.4	29.91 ± 6.6	27.2 ± 5.0	28.48 ± 5.5
Follow-up (months) *, ***	55.7 ± 21.3 (16-96)	44.5 ± 21.3 (13-90)	37.7 ± 15.5 (13-66)	46 ± 20.8 (13-96)
Pre-operative diagnosis				
PF OA (n, %)	42 (82.4%)	27 (52.9%)	38 (76%)	107 (70.4%)
Insta. OA (n, %)	3 (5.8%)	19 (37.3%)	8 (16%)	30 (19.7%)
Idiop. OA (n, %)	6 (11.8%)	5 (9.8%)	4 (8%)	15 (9.9%)

*Abbreviations: *, significant difference between TAR and TTC arthrodesis ; **, significant difference between TTC and TT arthrodesis ; ***, significant difference between TAR and TT arthrodesis ; TAR, Total Ankle Replacement ; TTC, Tibio-talo-Calcaneal arthrodesis ; TT, Tibiotalar arthrodesis ; F, female ; Y, year ; Prof, profession ; Sed, Sedentary ; BMI: Body Mass Index ; M, Months ; PF OA, Post-Fracture Ankle Osteoarthritis ; Insta. OA, Ankle Osteoarthritis due to chronic Ankle Instability ; Idiop OA, Idiopathic Ankle Osteoarthritis. [a]Unless otherwise stated, values refer to mean ± standard deviation (range).*

Difference in Health-Related Outcome Measures Across Recovery Groups

Satisfaction: There was a significant difference in satisfaction score between the self-reported recovery groups [$H(2) = 107.85$, $P < .001$]; R-R group had overall a higher satisfaction rate compared to R-NR group ($P < .001$, $r = .68$) and to NR group ($P < .001$, $r = .66$). R-NR group showed also higher satisfaction rate than NR group ($P = .008$, $r = .24$) (Table 2.3 & Figure 2.1).

Functional status: There was a significant difference between the recovery groups in FAOS score [$H(2) = 61.002$, $P < .001$]; planned comparison showed that R-R group had a higher FAOS score compared to R-NR group ($P < .001$, $r = .55$) and NR group ($P < .001$, $r = .45$). A significant difference was also found in FFI score between the recovery groups [$H(2) = 88.58$, $P < .001$]; significant differences were observed between R-R and R-NR ($P < .001$, $r = -.63$), R-R and NR ($P < .001$, $r = -.59$), and R-NR and NR groups ($P = .029$, $r = -.21$) with lower scores achieved by R-R patients, followed by R-NR and NR patients.

Health Status: Significant differences were found in the SF-12 PC [$F(2, 149) = 39.48$, $P < .001$, $\omega = .58$] and in the SF-12 MC [$F(2, 149) = 23.21$, $P < .001$, $\omega = .48$] between the self-reported recovery groups. Games-Howell post-hoc tests revealed that there were highly significant differences between every self-reported recovery group for both SF-12 sub-scores ($P < .001$). P-value only differed between R-NR and NR groups for the SF-12 MC ($P = .002$) (Table 2.3 & Figure 2.1).

In agreement with the first hypothesis, the three recovery groups displayed postoperatively a logical gradient of satisfaction, FFI, SF-12 PC and SF-12 MC scores (except for the FAOS) with the better results achieved by R-R patients, followed by R-NR and NR patients (Table 2.3).

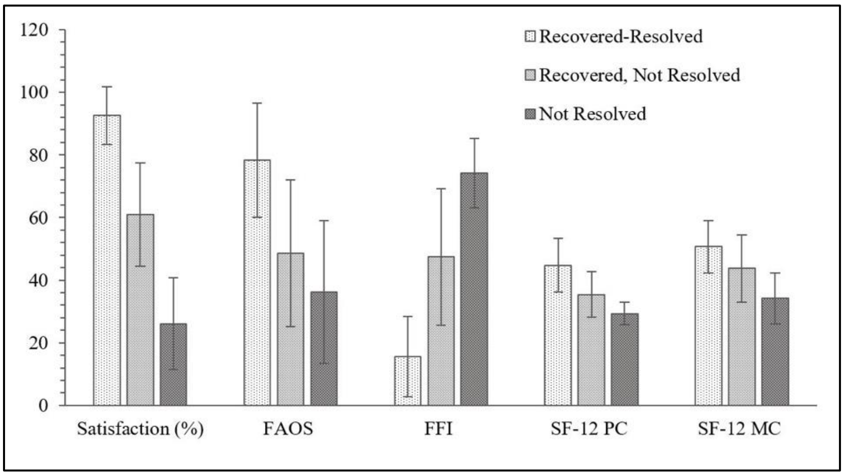

Figure 2.1 : Satisfaction & health-related outcome measures by recovery group

Table 2-3 : Description of surgical procedure groups and outcome measures by recovery group[a]

	R-R (n=75)	R-NR (n=62)	NR (n=15)	Total Sample (n = 152)
TAR	31 (41.3%)	17 (27.4%)	3 (20%)	51 (33.6%)
TTC	24 (32%)	23 (37.1%)	4 (26.7%)	51 (33.6%)
TT	20 (26.7%)	22 (35.5%)	8 (53.3%)	50 (32.9%)
Satisfaction *,**,***	92.6% ± 9.2	60.9% ± 16.5	26.1% ± 14.7	73.1% ± 25.3
FAOS *,***	78.4 ±18.3	48.5 ± 23.5	36.3 ± 22.8	62.0 ± 266
FFI *,**,***	15.6 ± 12.8	47.4 ± 21.9	74.2 ± 111	34.4 ± 26.2
SF-12 PC *,**,***	44.7 ± 8.5	35.4 ± 7.3	29.4 ± 3.5	39.4 ± 9.4
SF-12 MC *,**,***	50.7 ± 8.3	43.7 ± 10.7	34.2 ± 8.1	46.2 ± 10.6

*Abbreviations: *, significant difference between R-R and R-NR ; **, significant difference between R-NR and NR ; ***, significant difference between R-R and NR ; R-R, Recovered- Resolved ; R-NR , Recovered, Not Resolved ; NR, Not Recovered ; TAR, Total Ankle Replacement ; TTC, Tibio-talo-Calcaneal arthrodesis ; TT, Tibiotalar arthrodesis ; FAOS, Foot and Ankle Outcome Score ; FFI, Functional Foot Index ; SF-12, Short Form-12 ; PC, Physical Component ; MC, Mental Component.*

[a]Unless otherwise stated, values refer to mean ± standard deviation (range).

Difference in Health-Related Outcome Measures Across Surgical Procedure Groups

Satisfaction: There was a significant difference between the three different surgical procedures in satisfaction score [$H(2) = 9.09$, $P = .011$]. TAR patients were significantly more satisfied than TT patients ($P = .009$, $r = .24$). In contrast, TAR patients showed no significantly higher satisfaction rates compared to TTC patients. One could also observe a trend in mean satisfaction score decreasing gradually between the TAR (80.7% ± 22.5), the TTC (71.3% ± 26.9) and the TT (67.2% ± 24.9) groups (Table 2.4 & Figure 2.2).

Functional Status: There was no significant difference in the FAOS score between the surgical procedures [$H(2) = 3.96$, $P = .14$]. However, TAR patients seem to score better at the FAOS score (67.3 ± 18.9) than TTC patients (63.5 ± 27.4) and TT arthrodesis (55.2 ± 31.1). Planned comparisons indicated a significant difference [$H(2) = 7.74$, $P = .021$] in FFI scores between the three surgical procedure groups. TAR patients showed a lower FFI score compared to TT patients ($P = .02$, $r = -.23$).

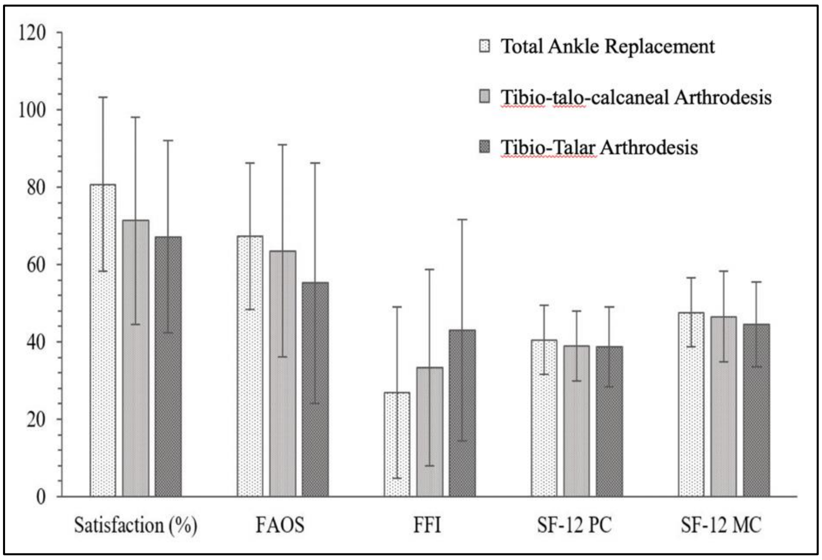

Figure 2.2 : Outcome measures by surgical procedure

Health Status: No significant difference was observed between the different surgical procedures in SF-12 PC [$H(2) = 1.53$, $P = .465$] and SF-12 MC scores [$F(2, 149) = 1.13$, $P = .33$]. However, results displayed a gradual decrease for both scores between the three surgical procedure groups with better results achieved by TAR patients, followed by TTC patients and TT patients (Table 2.4 & Fig. 2).

Therefore, the second hypothesis was not demonstrated as almost none of the above described results were significant. However, a general trend can be observed as TAR patients showed better PROMS scores and satisfaction results compared to TTC and TT patients.

Table 2-4 : Description of recovery group and outcome measures by surgical procedure[a]

	TAR (n=51)	TTC (n=51)	TT (n=50)	Total Sample (n = 152)
R-R (n, %)	31 (60.8%)	24 (47.1%)	20 (40%)	75 (49.3%)
R, NR (n, %)	17 (33.3%)	23 (45.1%)	22 (44%)	62 (40.8%)
NR (n, %)	3 (5.9%)	4 (7.8%)	8 (16%)	15 (9.9%)
Satisfaction ***	80.7% ± 22.5	71.3% ± 26.9	67.2% ± 24.9	73.1% ± 25.3
FAOS	67.3 ± 18.9	63.5 ± 27.4	55.2 ± 31.1	62.0 ± 26.6
FFI ***	27.0 ± 22.2	33.3 ± 25.4	43.1 ± 28.6	34.4 ± 26.2
SF-12 PC[b]	40.5 ± 8.9	39.0 ±9.0	38.7 ± 10.4	39.4 ± 9.4
SF-12 MC[c]	47.6 ± 8.9	46.6 ± 11.7	44.47 ± 11.0	46.2 ± 10.6

Abbreviation: ***, significant difference between TAR and TT arthrodesis ; TAR, Total Ankle Replacement ; TTC, Tibio-talo-Calcaneal arthrodesis ; TT, Tibiotalar arthrodesis ; R-R, Recovered- Resolved ; R,NR , Recovered, Not Resolved ; NR, Not Recovered ; FAOS, Foot and Ankle Outcome Score ; FFI, Functional Foot Index ; SF-12, Short Form-12 ; PC, Physical Component ; MC, Mental Component.
[a]Unless otherwise stated, values refer to mean ± standard deviation (range).

Association between Surgical Procedures and Recovery Groups

There was no significant association between the types of surgery and the recovery groups (χ^2 (4) = 6.28, P = .18) meaning that the last hypothesis of this study was not demonstrated. However, it appeared that R-R group was composed of a higher number of TAR patients. In contrast, half of the NR group was composed of TT patients. (Figure 2.3).

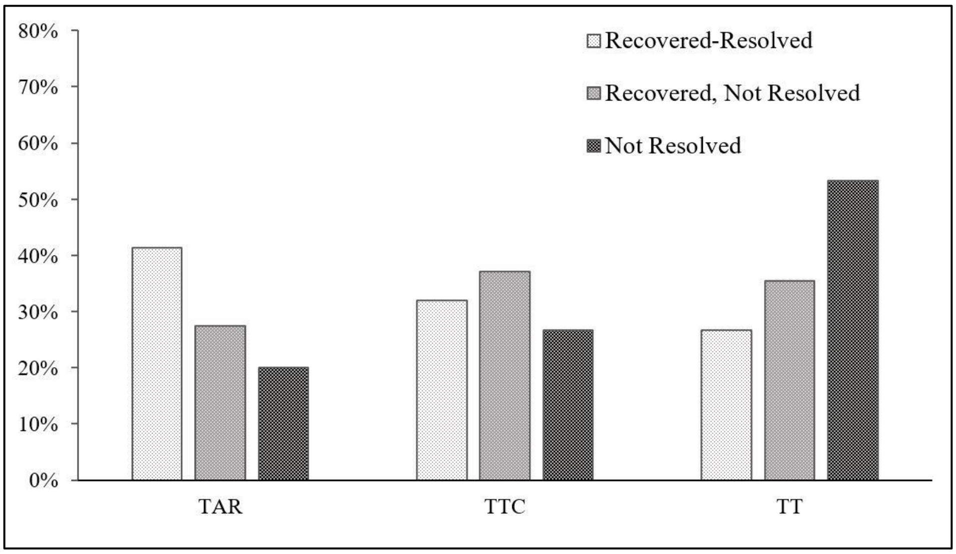

Figure 2.3 : Surgical procedures by recovery group

DISCUSSION

This study aimed at assessing the surgical outcomes of three common procedures (TAR, TTC, and TT) to treat end-stage ankle osteoarthritis by attempting to capture patients' perception of their sense of recovery. As expected, there was a concordance between the patient's self-reported recovery state, satisfaction, and PROMS scores. However, no clear difference in outcome scores was found to favour a surgical procedure over another.

The present study has attempted to emphasize the importance of patient satisfaction and self-reported recovery state while evaluating surgical outcome. In contrast to traditional outcome measures of a surgical procedure, patients' recovery state is not only reflected in changes or resolution of the state of a disease (end-stage ankle osteoarthritis), but could also be described as an adjustement to the way of life or an adaptation to live with the disorder.[4] In addition, the perception of recovery is highly contextualized and influenced by many factors such as age, the ability to resume work or to cope with functional limitations, carefully selecting and resuming leisure activities, and many others.[4,17] This indicates that two patients could mean different things while saying that they have recovered from their surgery. Therefore, it is essential that health professionals understand the full impact of a disease on a patient's life in order to completely understand what recovery means for him following surgery while evaluating surgical outcomes.

Three main hypotheses were tested in this study. Our first hypothesis is in agreement with previous evidence as a concordance was demonstrated between the patients' self-reported recovery state, satisfaction, and PROMS scores.[19] Interestingly, a notable difference in the distribution of participants in the three self-reported recovery groups was found compared to the findings of Pinsker et al. (2016). In contrast to their results, the percentage of 'Recovered-Resolved' patients (50%) was three times higher in the present study. A possible explanation might be that patients received a more thorough explanation prior to surgery about potential functional limitations related to their surgery, and therefore, might adapt better their functional expectations prior to surgery decreasing the risk of becoming disappointed. Consequently, they might cope better with their recovery state and potential functional limitations experienced postoperatively. The authors strongly believe that capturing patients' expectations and functional issues prior to surgery is a key element to obtain effective surgical outcomes.[2] However, it is difficult to develop questions that appropriately capture patients' expectations in all clinical conditions; the "one measure for all" approach adopted by many may not be appropriate as issues of importance differs from one patient to another.

Secondly, it was not demonstrated that the TAR group would obtain a higher satisfaction percentage and no or limited difficulties in performing ADLs compared to TTC and TT groups (except for satisfaction and FFI scores between TAR and TT groups). In fact, from a surgical point of view, it was expected that TAR group would have better PROMS scores than TTC and TT groups as TAR is a motion-sparing surgery. Surprisingly, our results revealed that preserving ankle motion does not statistically increase patient satisfaction and PROMS scores. Nonetheless, a general trend can be observed as overall, TAR patients seem to have better satisfaction and PROMS scores compared to TTC and TT patients. However, this trend can potentially be explained by the mean age of each surgical group. TAR patients (67.8 ± 11.2) were older than TT (56.9 ± 12) and TTC patients (62.7 ± 10.3). Studies have already demonstrated that satisfaction following a surgery increases with age.[2,6,23] Consequently, one could argue that better results can be observed in TAR patients as they were older than TTC and TT patients.

The third hypothesis was also not demonstrated. No statistical difference was found suggesting that a higher number of TAR patients would classify themselves as 'Recovered-

Resolved' (R-R) group compared to TT and TTC patients. Based on these results, one may conclude that the motion sparing procedure is not more likely to result in a 'Recovered-Resolved' self-reported recovery state over the two types of arthrodesis procedures. However, a general trend can be observed, and it appears that there were more TAR patients in the R-R group and a higher number of TT patients in the NR group. This trend can be explained by various factors including age and expectations. In fact, TT patients were younger than the two other groups, meaning that they might have more difficulties in adapting their behaviours and daily activities. This resilient behaviour to adapt at a younger age was described by Baltes's (1990) theory of selective optimization with compensation (SOC).[3] His theory is related to strategies to cope with age-related changes such as '*selecting fewer, but important goals, pursue these goals in an optimized way, and by doing so, apply adequate compensatory means to overcome internal or external barriers*'.[10] In this perspective, patient's expectations are adjusted to permit the subjective experience of satisfaction. Based on this theory, one could argue that older patients can more easily adopt these strategies in contrast to younger patients, who could be more resilient to changes. Moreover, in their study, Gignac, Cott & Badley (2002) have shown that older adults with osteoarthritis used more often compensation strategies (i.e.: '*efforts to meet goals by new means'*) in contrast to younger adults who tend to use optimization strategies (i.e.: '*efforts to augment or enrich one's reserves in order to continue functioning').*[13] Therefore, these differences in strategies to cope with changes will impact their sense of limitations and satisfaction following surgery. Furthermore, our results showed that R-R patients were older than R-NR patients (P = .002), and NR patients (P = .009). One may therefore conclude that the results of the present study agreed well with previous studies demonstrating the relationship between age and satisfaction following surgery.[2,6,23]

Another explanation might be that patients who underwent a TTC arthrodesis in contrast to TT arthrodesis had lower functional expectations. Ajis et al. (2013) have reported that fewer TT patients met their desired activity level after surgery compared to TTC patients. They also found that TT patients were also much more likely to attribute their unmet level of activity to their operated ankle compared to TTC patients.[2] Evidence suggested that patients who underwent TTC arthrodesis must go through a longer period of convalescence and might therefore consider their surgery more 'seriously' as the TT arthrodesis is extended to the subtalar joint. Consequently, it might be easier for them to meet their expectations following surgery in contrast to patients who underwent TT arthrodesis.[2] The present results provide further evidence that TT patients had lower satisfaction rates and PROMS score which appeared to be mostly prevalent in the 'Not-Recovered' group.

One of the strengths of this study was the ability to include and analyse the surgical indications, which were divided into 3 groups: post-fracture ankle osteoarthritis, ankle osteoarthritis due to chronic ankle instability, and idiopathic ankle osteoarthritis. Results have shown that there were no significant associations between the patient-perceived recovery state and the surgical indications (P = .596), which excludes the idea that surgical outcomes were influenced by preoperative diagnosis discrepancies.

This study has some limitations. First, the present study was a retrospective study with the limitation that no PROMS scores were collected prior to surgery. Second, one might argue that the high level of satisfaction in this study could potentially be explained by a biased sample selection underlying that unsatisfied patients would not agree to engage in this study. However, only 2 patients have explicitly refused to take part in the study. Finally, PROMS were composed of closed questions forcing patients to give an answer that does not accurately represent their opinion. However, this shortcoming was partially tackled by being able to classify themselves in one of the three self-perceived recovery statements.

CONCLUSION

This study provides a first attempt in assessing and comparing surgical outcomes following TAR, TTC, and TT arthrodeses by capturing patients' perception of their sense of recovery. An unexpected finding was that R-R group was not exclusively composed of TAR patients. Evidence suggests that patients with a TT or a TTC arthrodesis could also classify themselves as '*being better with no residual limitations*'. However, to obtain a positive surgical outcome, it appears that it is crucial to improve the patient - doctor communication, especially with younger patients. They have higher expectations prior to surgery and different ways of coping with functional limitations than older patients. Consequently, a patient's concerns and expectations should be considered prior to surgery in order to meet the patient's expectations and to avoid patient's misconceptions of surgical outcomes.

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Chapter 3 : Change in gait biomechanics after total ankle replacement and ankle arthrodesis: a systematic review and meta-analysis

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ABSTRACT

Background: The aim of this systematic review with meta-analysis was to determine the change in gait biomechanics after total ankle replacement and ankle arthrodesis for end-stage osteoarthritis.

Methods: Electronic databases were searched up until May 2019. Peer-reviewed journal studies including adult participants suffering from end-stage ankle osteoarthritis and reporting pre- and post-operative kinematics, kinetics and spatio-temporal effects of total ankle replacement and ankle arthrodesis during walking were included. Seventeen suitable studies were identified and assessed according to methodological and biomechanical qualities. Meta-analysis was performed by calculating the effect size using standard mean differences between pre- and post-operative gait status.

Findings: Seventeen studies with a total of 883 patients were included. Meta-analysis revealed a significant improvement in lower limb kinematics, kinetics and spatio-temporal parameters after total ankle replacement. However, no significant effect on maximum ankle plantarflexion, knee and hip range of motion and cadence was found for fixed-bearing prosthesis. Improvement in gait biomechanics after ankle arthrodesis was limited to ankle moment, hip range of motion and walking speed.

Interpretation**:** The currently available evidence base of research papers evaluating changes in gait biomechanics after total ankle replacement and ankle arthrodesis is limited by a lack of prospective research, low sample sizes and heterogeneity in the patho-etiology of ankle osteoarthritis. Following total ankle replacement for end-stage ankle osteoarthritis, improvements were demonstrated for spatio-temporal, kinematic and kinetic gait patterns compared to the pre-operative measrures. Improvements in gait mechanics after ankle arthrodesis were limited to walking speed, ankle moment and hip range of motion.

Keywords**:** Osteoarthritis; Ankle replacement; Arthroplasty; Arthrodesis; Gait Analysis; Biomechanics

INTRODUCTION

Osteoarthritis (OA) of the ankle is a common chronic disorder characterized by progressive joint degeneration, significant pain and disability, with approximately 1% of the world's adult population living with symptomatic ankle OA.[1,14,21,33,42] Currently, the "gold standard" surgical treatment is ankle arthrodesis (AA), which provides good pain relief and a relatively well-documented long-term survivalship of AA.[15,16,23,46,47] However, AA leads to deficits in work and leisure activities and to adjacent joint degeneration,[4,12,20,34,53] thought to be a consequence of altered mechanical loads as a result of the change in function of the ankle.[4,6,12,20] These disadvantages have encouraged the use of motion-sparing procedures such as total ankle replacement (TAR), the potential benefits of which are conserving the existing pre-operative ankle range of motion (RoM), improving gait and protecting the adjacent joints[5,10,27], although the latter has not yet been proven.[35]

Three-dimensional gait analysis (3DGA) is the state of the art of measuring lower limb joint kinematics and kinetics simultaneously during activities of the daily living. Three narrative reviews of the literature showed that 3DGA has considerable potential for evaluating functional outcomes of TAR and AA aimed at improving function at the foot and lower limb.[3,29,36] However, these papers did not assess the treatment effect of the procedures, which raises questions regarding the evidence supporting the biomechanical value of TAR and AA in patients suffering from end-stage ankle OA. The relative advantages of TAR versus AA continue to be one of the most debated topics in foot and ankle surgery. Do TAR patients maintain or improve their pre-operative dorsi-/plantarflexion ankle motion during gait? Do TAR and AA patients improve their foot mechanics relative to their pre-operative state? The debate also continues as to which ankle prosthesis design should be used to provide the best clinical outcome, the evidence from the TAR group overall being unclear. The objective of this review is to present a quantitative assessment of the scientific credibility and clinical utility of the present knowledge regarding the assessment of the biomechanical effect of TAR and AA in patients suffering from end-stage ankle OA.

METHODS

The systematic review protocol was developed in accordance to the guidelines provided by the Preferred Reporting of Systematic Reviews and Meta-Analysis (PRISMA) Statement.[30] The protocol for the review was registered in the International Prospective register for Systematic Reviews (PROSPERO; registration no. CRD42018110053).

Search strategy

The Population, Intervention, Comparison and Outcome (PICO) framework was used to define the search strategy. The following databases were searched from inception: Cochrane Library, PubMed and Web of Science (via ISI Web of Knowledge) (until May 2019). The three main groups of keywords covering all MeSH terms and keywords related to "ankle osteoarthritis", "biomechanical and locomotion metrics" and "ankle arthrodesis / ankle prosthesis" were used in this review (example for PubMed in Figure 3.1). Databases were searched by two reviewers, with agreement required on the number of search hits achieved before screening was initiated. References and abstracts of studies were stored alphabetically using the reference management software Mendeley (Elsevier, Netherlands). Additional relevant papers were found by examining the reference lists of papers identified in the initial searches. Duplicate references sourced from different electronic searches were removed. The inclusion and exclusion process was performed by two reviewers (JLB & PAD) based on the title and abstract of the identified papers. A full-text evaluation was undertaken if the title and abstract did not provide adequate information. A consensus meeting was held to resolve any areas of disagreement between reviewers, and the opinion of a 3rd reviewer (AN) was sought if a consensus was not reached. To affirm the inclusion of all eligible studies, one reviewer (PAD) subsequently manually screened the reference lists of all included articles.

Eligibility criteria

Studies published in English as full papers were eligible for inclusion in this review when they met the following criteria: 1) participants were adults aged ≥18 years undergoing primary TAR and AA; 2) ankle OA was the principal indicator for surgical intervention; 3) studies reported at least pre-operative and post-operative gait data; 4) a minimum of 12 months follow-up providing evidence of any pre- to post-operative changes in gait;[2,50] 5) the use of non-invasive/in-vivo 3DGA using a motion capture system to collect at least joint kinematic data based on the trajectories of skin-mounted markers.); and 6) the participants were able to perform the given task unaided. Studies including participants with a history of other major medical conditions affecting gait or previous surgery (e.g. neuromuscular diseases, revision lower limb arthroplasty, etc.) were not eligible for inclusion. Letters, conference proceedings, case reports, cadaveric studies, bone pin (invasive) studies, abstracts and reviews were excluded from the review.

	Concept #1	Concept #2	Concept #3
	AND		AND
MeSH terms	”Ankle Osteoarthritis”	”Locomotion” OR “Biomechanical Phenomena” OR “Mechanics” OR “Mechanical Phenomena”	“Ankle Prosthesis” OR “Ankle Arthrodesis”
Title / Abstract	Ankle osteoarthritis OR arthritis	Motion OR movement OR locomot* OR kinematic* OR kinetic* OR dynamic* OR load* OR biomech* mechanic* OR moment* OR angle* OR rotation* OR force*	“Ankle prosthesis” OR “total ankle replacement” OR “total ankle arthroplasty” OR “ankle arthrodesis” OR “ankle fusion”

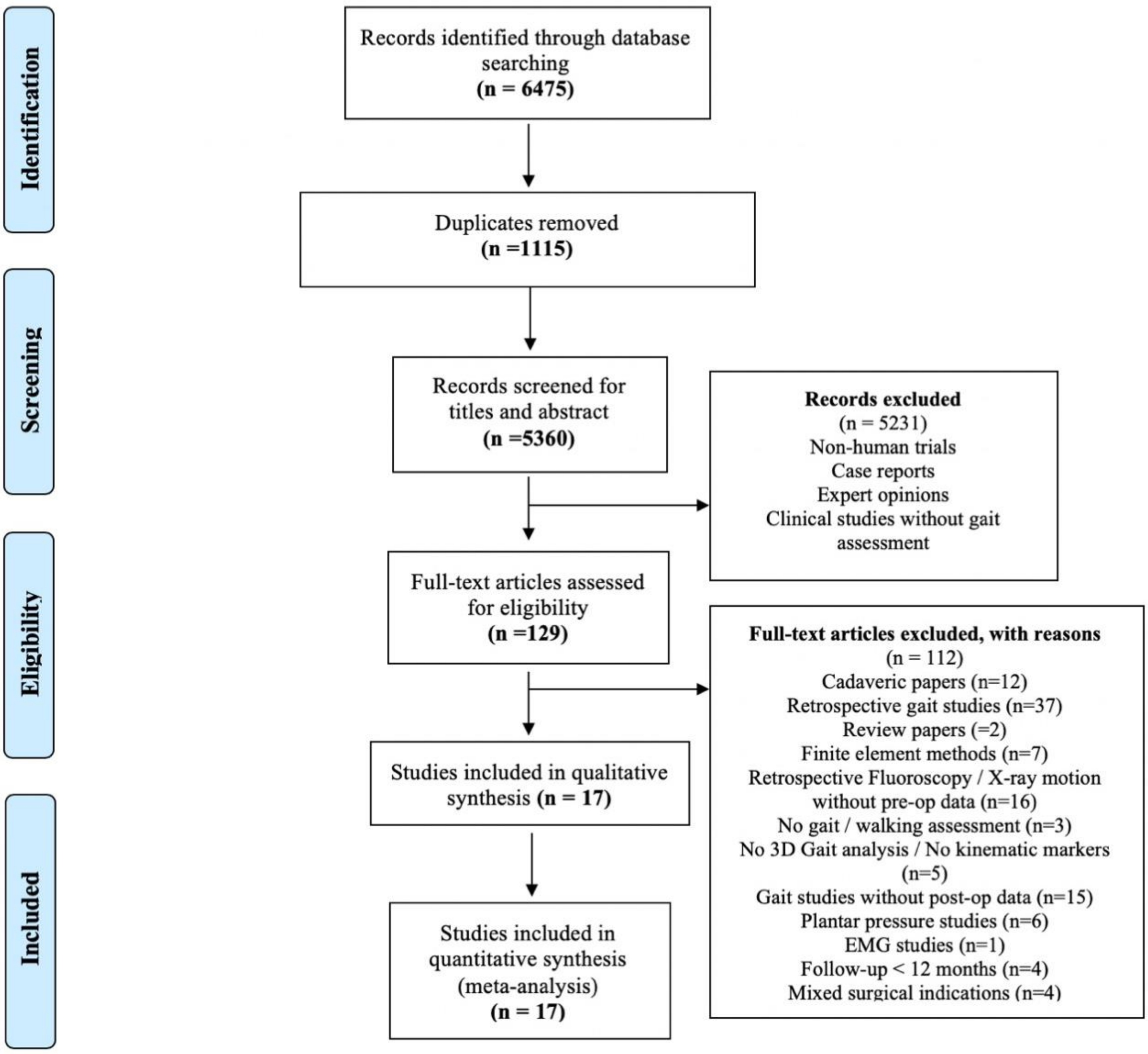


Figure 3.1 : Pubmed search strategy & flow diagram of search results

Methodological quality assessment

A modified version of the Downs and Black Quality Index was used to evaluate the methodological quality of the selected papers.[17] The methodological quality of the papers was assessed using a subset of the data extracted to gauge both internal and external validity. Two reviewers (PAD, LC) independently evaluated the quality of each study, and any discrepancies were resolved during a consensus meeting. The opinion of a 3rd reviewer (AN) was sought if a consensus could not be reached. The modified version of the Downs and Black Quality Index[17] is scored out of 26, with higher scores indicating higher-quality studies. The studies were ranked using the following classifications: "high quality" (HQ) having scores greater than 21; "moderate quality" (MQ) having scores between 17 and 21; "fair quality" (FQ) having scores between14 and 17 and "poor quality" (PQ) having scores lower than 14.[13] A Kappa inter-rater agreement test (Kappa (*K*) statistic) was used to evaluate the agreement between the two reviewers (PAD and LC). The *K* value was interpreted as follows: scores < 0.20 rated as Poor, scores between 0.21-0.40 rated as Fair, scores between 0.41-0.60 rated as Moderate, scores between 0.61-0.80 rated as Good, and scores between 0.81-1.00 rated as Very good. Studies rated as "poor quality" were excluded from the systematic review.

Outcome measures and data extraction

A data-extraction file created in Cochrane Review Manager (RevMan, V.5, Cochrane Collaboration, Oxford, UK) was used to extract numerical data from all studies by two reviewers (PAD & AN). Once completed, one of the two reviewers compared the original data with the extracted data to verify that the data were extracted accurately from the studies included in the meta-analysis. The primary outcome measures for this review were spatiotemporal, kinematic and kinetic parameters reported during level walking. Means and standard deviations (SD) for all gait variables relating to the affected ankle were extracted for pre-operative and the final post-operative assessments in order to determine the long term effect of surgery on gait function, as functional recovery can take 6 to 12 months. To assist the interpretation of findings, one investigator (PAD) extracted data regarding study design, participant characteristics and publication details.[50]

Data synthesis and analysis

Where adequate data were reported, means and standard deviations (SDs) of the following gait variables were used to calculate standardized mean differences (SMD and 95% confidence intervals) between pre- and post-operative assessments using Cochrane Review Manager (V.5) (RevMan, V.5, Cochrane Collaboration, Oxford, UK): ankle RoM, maximal ankle dorsiflexion and plantarflexion angle, maximal ankle moment, maximal ankle power, knee RoM, hip RoM, walking speed, cadence, stance duration and step length. When means and SDs were not reported by the authors estimations were made using the methodology described by Wan et al. and medians and interquartile ranges used.[51] Meta-analyses were performed by calculating the effect size using the standardized mean differences, and a random-effects model. Interpretation of SMD magnitude was based on previous recommendations, where SMD values were considered large (> 1.2), medium (0,6-1,2) or small (< 0,6). No significant differences were considered to have been identified from the meta-analysis when the 95% confidence interval was exceeded 0 ($P < 0.05$). When appropriate data (e.g. means and SDs) were not provided in the publication, authors were contacted with a request to provide additional data. In the case of non-response, the variables were recorded as "not reported" and excluded for further analysis.[26] Forest plots were produced using Cochrane Review Manager (V.5) to facilitate the interpretation of SMD values and their respective 95% Confidence Interval (CI). Results of studies were pooled if adequate homogeneity was found to occur in terms of research design and outcome measures. The level of statistical heterogeneity for pooled data was tested by using a chi-squared test and I^2 statistics.[25] Heterogeneity was defined as high (>75%), moderate (50-75%), and low (25-50%).[25] When adequate data were reported in the same international system of units, mean differences (MD and 95% confidence intervals) between pre- and post-operative time points were calculated.

Evidence-based recommendations

Based on the previous publication of van Tulder et al. (2003), levels of evidence were assigned for each variable of interest, based on the statistical outcomes and methodological quality of the included studies.[48]

Levels of evidence-based recommendations (van Tulder et al., 2003) are :

- ***Strong evidence*** derived from three or more studies, including a minimum of two high quality (HQ) studies that are statistically homogenous; may be associated with a statistically significant or non-significant pooled results.
- ***Moderate evidence*** was based on statistically significant pooled results derived from multiple studies that are statistically heterogeneous, including at least one high quality study (HQ); or from multiple moderate quality (MQ) or fair quality (FQ) studies which are statistically homogenous.
- ***Limited evidence*** was based on results from one high quality study (HQ) or multiple moderate (MQ) or fair quality (FQ) studies that are statistically heterogeneous.
- ***Very limited evidence*** was based on results from one fair quality study (FQ).
- ***No evidence*** was based on pooled results insignificant and derived from multiple studies regardless of quality that are statistically heterogeneous.

RESULTS

Review selection and identification

Details of the search results and the process of inclusion and exclusion are shown in Figure 1. A total of 6475 citations were retrieved from the electronic database search. After applying the eligibility criteria and searching reference lists, 129 references were identified as being eligible for full-text review based on their title and abstract. Of these, 112 papers were subsequently excluded, the main reasons for exclusion being cadaveric studies, finite element studies and studies without preoperative gait data. Seventeen papers were included for final review.

Quality assessment

The Downs and Black scale checklist scores ranged from 9 to 23 of a possible 26 (Appendix file 1). Of the 17 studies included, 2 had a score lower than 14 (rated as “poor quality”).[9,19] One study was rated as high-quality scoring between 26 and 22,[39] and two studies were rated as “moderate quality” scoring between 18 and 21.[11,37] Twelve studies were rated as “fair quality” scoring between 14 and 17.[5,6,8,22,24,27,32,38,40,41,44,45] The Kappa inter-rater agreement value, including the assessment of the 17 studies, was 0.747 (95% CI 0682 to 0.813). indicating a good agreement between the two reviewers (PAD and LC). Of the 17 papers, 14 were case series studies, 1 was a prospective cohort study and 2 were retrospective studies (Table 3.1)

Table 3-1 : Study and patient characteristics (NA : not applicable, NR : not reported, SD : standard deviation, FB : Fixed-bearing, MB : Mobile-bearing; Ankle prostheses : Salto Talaris® (Integra Life Sciences, USA), INBONE (Wright Medical Technology, USA); STAR™ (Stryker, Orthopaedics, USA) ; Agility (Depuys Synthes USA), Hintegra (Integra, US); AES (Ankle Evolutive System, Transystem, France), BOX (Bologna-Oxford,,Finsbury, UK), Mobility (Depuy, UK).

Author (Year)	Study Design	Sample size (M/F ratio)			Mean age, SD (years)			Sub-type Ankle OA	Type of Prosthesis	Biomechanical Model	Foot as 1 segment	Walking speed	Joints	Plane	Follow-up	Quality score
		TAR	AA	CTRL	TAR	AA	CTRL									
Segal Cl Biomech 2018[37]	Case series	20 (8/12)	13 (10/3)	NA	59.9 ± 8.7	53.4 ± 9.8	NA	NR	FB (Agility / Salto Talaris)	Plug-in Gait	Yes	Self-selected	Ankle, Knee, Hip	Sagittal	37	17
Brodsky FAI 2017[38]	Case series	76 (28/48)	NA	NA	61.1 ± 10.3	NA	NA	PT 42 / 7 RA / 27 PM	MB (STAR)	Modified Helen Hayes market set	Yes	Self-Selected	Ankle, Knee, Hip	Sagittal	12.8	16
Tenenbaum FAS 2017[39]	Case series	Old : 21 (8/13)	NA	NA	74.6 ± 3.4	NA	NA	NR	MB (STAR)	Modified Helen Hayes market set	Yes	Self-Selected	Ankle, Knee, Hip	Sagittal	27,4	15
		Young : 21 (4/17)	NA	NA	55.4 ± 2.8	NA	NA	NR							26,2	
Queen CORR 2017[34]	Case series	FB : 15 (7/8)	NA	NA	61 ± 13	NA	NA	NR	FB (Salto Talaris)	Modified Helen Hayes market set	Yes	Self-Selected	Ankle, Knee, Hip	Sagittal	12	23
		MB : 18 (4/14)	NA	NA	65 ± 9	NA	NA	NR	MB (STAR)						12	
Brodsky BJJ 2016[16]	Case series	NA	20 (10/10)	NA	NA	58.95 ± 14.8	NA	PT 12 / PM 8	NR	Modified Helen Hayes market set	Yes	Self-Selected	Ankle, Knee, Hip	Sagittal	24	15
Grier G&P 2016[40]	Case series	Neutral : 32 (NR)	NA	NA	63.5 ± 9.6	NA	NA	NR	FB & MB (INBONE / Salto Talaris / STAR)	Modified Helen Hayes market set	Yes	Self-Selected	Ankle, Knee, Hip	Frontal	24	15
		Varus : 38 (NR)	NA	NA	61.6 ± 7.7	NA	NA	NR	FB & MB (INBONE / Salto Talaris / STAR)						24	
		Valgus : 23 (NR)	NA	NA	64.6 ± 11.0	NA	NA	NR	FB & MB (INBONE / Salto Talaris / STAR)						24	

Caravaggi Cl Biomech 2015[1]	Retrospective cohort study	10 (5/5)	NA	20 (11/9)	55 (range 36 to 70)	NA	28 (range 23 to 36)	NR	MB (BOX)	IOR LLM 2007	Yes	Self-Selected	Ankle, Knee, Hip	3D	60	12
Queen FAI 2014[41]	Case series	TAL : 22 (NR)	NA	NA	62.5 ± 11.1	NA	NA	PT 19 / PM 3	FB & MB (INBONE / Salto Talaris / STAR)	Modified Helen Hayes market set	Yes	Self-Selected	Ankle, Knee, Hip	Sagittal	12	14
		GSR : 37 (NR)	NA	NA	60.7 ± 9.5	NA	NA	PT 29 / PM 4 / Other 2	FB & MB (INBONE / Salto Talaris / STAR)						12	
		TAR : 170 (NR)	NA	NA	64.0 ± 9.4	NA	NA	PT 136 / PM 24 / Other 7	FB & MB (INBONE / Salto Talaris / STAR)						12	
Queen JBJS 2014[42]	Case series	FB : 41 (NR)	NA	NA	63.8 ± 9.0	NA	NA	NR	FB (Salto Talaris)	Modified Helen Hayes market set	Yes	Self-Selected	Ankle, Knee, Hip	Sagittal	24	16
		MB 49 (NR)	NA	NA	62.4 ± 10.9	NA	NA	NR	MB (STAR)						24	
Queen Cl Biomech 2014[43]	Case series	78 (46/32)	NA	NA	63.6 ± 9.0	NA	NA	NR	FB & MB (Salto Talaris / STAR)	Modified Helen Hayes market set	Yes	Self-Selected	Ankle, Knee, Hip	Sagittal	24	17
Choi FAI 2013[35]	Case series	21 (5/16)	NA	NA	69 ± 6.9	NA	NA	PT 12 / PM 8 / HEMA 1	FB (Salto Talaris)	Plug-in Gait	Yes	Self-Selected	Ankle, Knee, Hip	Sagittal	37,2	18
Flavin FAI 2013[2]	Case series	14 (5/9)	14 (3/11)	NA	56.9 ± 8.6	60.7 ± 16.3	NA	17 PT, 4 PM, 4 CAI, 4 PT + CAI	MB (STAR)	Milwaukee Foot Model	No	Self-selected	Ankle, Hindfoot	Sagittal, Frontal	12	12
Queen FAI 2012[36]	Case series	51 (27/24)	NA	NA	65.0 ± 8.3	NA	NA	NR	FB (INBONE / Salto Talaris)	Modified Helen Hayes market set	Yes	Self-selected	Ankle	Sagittal	24	20

Hahn FAI 2012[44]	Case series	9 (4/5)	9 (6/3)	NA	53.9 ± 8.7	62.7 ± 10.7	NA	NR	NR	Plug-in Gait	Yes	Self-Selected	Ankle, Knee, Hip	Sagittal	12	16
Brodsky JBJS 2011[18]	Case series	50 (10/40)	NA	NA	60.8 ± 11.1	NA	NA	PT & PM 47 / RA 3	MB (STAR)	Modified Helen Hayes market set	Yes	Self-Selected	Ankle, Knee, Hip	Sagittal	49	15
Ingrosso G&P 2009[17]	Retrospective cohort	10 (8/2)	NA	20 (11/9)	57.4 ± NR	NA	27.9 ± NR	PT 9 / PSOA 1	MB (BOX)	IOR LLM 2007	Yes	Self-Selected	Ankle, Knee, Hip	3D	12	16
Valderrabano Cl Biomech 2007[47]	Prospective cohort	15 (6/9)	NA	15 (6/9)	53.3 ± NR	NA	52.9 ± NR	PT 15	MB (Hintegra)	Helen Hayes marker set	Yes	Self-Selected	Ankle, Knee, Hip	3D	12	16

Sample selection, composition and description

Study details including sample sizes, participant demographics and type of prosthesis used are shown in Table 3.1. The number of participants ranged from 9 to 229 in the 17 studies. Gender male:female ratio was not reported in 3 studies. The subtype of OA was reported in 8 of the 17 studies. The characterization of the investigated ankle OA describing the subtype of ankle OA and its associated osteo-articular deformity was poorly described in 14 studies. Post-traumatic ankle OA was the most common aetiology reported by subjects in all of the included studies. Only one study reported the radiographic severity of ankle OA prior to surgery.[49] The most common intervals between intervention and follow up were 12 and 24 months (range: 12 to 49 months).

Study procedures related to gait specific measurement protocol

Conventional marker setups and lower limb models available with the Motion Capture systems were most commonly used for gait data acquisition, and kinematic and kinetic computation (Table 3.1). The foot was modelled in most of the studies as a single rigid element, except for the study of Flavin (2013). Variables relating to the mechanical behaviour of the lower limb were limited to the sagittal plane in 12 of the included studies.

Outcome measures

A summary of findings for each gait variable in the meta-analysis is shown in Table 3.2 & 3.3 and Supplementary Materials (cfr Appendix) with detailed information of the magnitude of effects and the strength of evidence provided below.

Ankle dorsi- / plantarflexion RoM

Based on the overall pooled SMD from 11 studies totalling 280 participants, moderate evidence indicated an increase in ankle RoM after the implantation of TAR (SMD: 0.68, 95%CI 0.51 to 0.85) with a MD of 3.20° (95%CI 2.44-3.96)(Figure 3.2). Mobile-bearing TAR showed similar improvements in ankle RoM to the fixed-bearing TAR (Table 3.3).[5,8,9,11,19,24,27,39,45,50]

There was limited evidence of no change in ankle dorsi-/plantarflexion RoM after an AA in the 17 studies (Figure 3.2).[6,19,24]

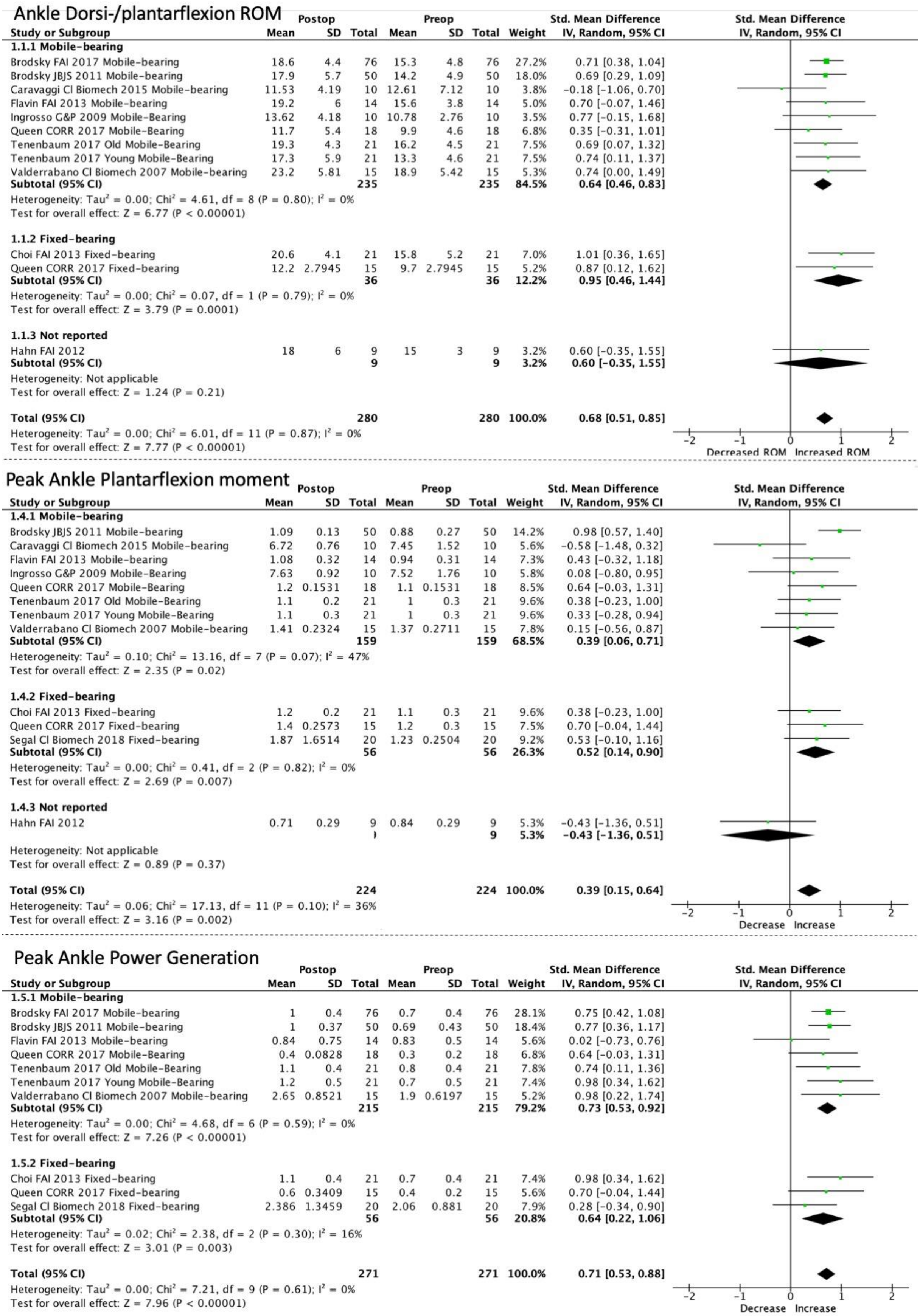
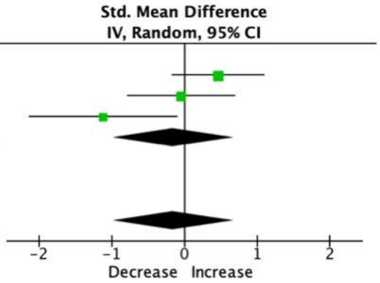


Figure 3.2 : The change in gait parameters (Ankle Dorsi-/Plantar-flexion RoM, Peak Ankle Plantarflexion Moment, Peak Ankle Power Generation) following total ankle replacement (TAR global, Mobile-bearing prosthesis and Fixed-bearing prosthesis) compared to pre-operative status

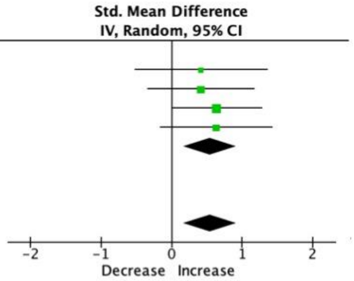
Ankle Dorsi-/plantarflexion ROM

Study or Subgroup	Postop Mean	Postop SD	Postop Total	Preop Mean	Preop SD	Preop Total	Weight	Std. Mean Difference IV, Random, 95% CI
2.1.3 Fusion								
Brodsky BJJ 2016 Fusion	14.87	3.7432	20	13.1	3.7432	20	37.5%	0.46 [−0.17, 1.09]
Flavin FAI 2013 Fusion	15	2.2	14	15.2	5.6	14	34.6%	−0.05 [−0.79, 0.70]
Hahn FAI 2012 Fusion	15	2	9	18	3	9	27.9%	−1.12 [−2.13, −0.11]
Subtotal (95% CI)			**43**			**43**	**100.0%**	**−0.16 [−0.99, 0.68]**
Heterogeneity: $Tau^2 = 0.38$; $Chi^2 = 6.81$, df = 2 (P = 0.03); $I^2 = 71\%$								
Test for overall effect: Z = 0.37 (P = 0.71)								
Total (95% CI)			**43**			**43**	**100.0%**	**−0.16 [−0.99, 0.68]**
Heterogeneity: $Tau^2 = 0.38$; $Chi^2 = 6.81$, df = 2 (P = 0.03); $I^2 = 71\%$								
Test for overall effect: Z = 0.37 (P = 0.71)								



Peak Ankle Plantarflexion moment

Study or Subgroup	Postop Mean	Postop SD	Postop Total	Preop Mean	Preop SD	Preop Total	Weight	Std. Mean Difference IV, Random, 95% CI	Year
2.4.3 Fusion									
Hahn FAI 2012 Fusion	0.8	0.19	9	0.71	0.22	9	16.3%	0.42 [−0.52, 1.35]	2012
Flavin FAI 2013 Fusion	1.11	0.32	14	0.96	0.38	14	25.5%	0.41 [−0.34, 1.16]	2013
Brodsky BJJ 2016 Fusion	1.11	0.3227	20	0.9	0.3227	20	35.3%	0.64 [0.00, 1.27]	2016
Segal Cl Biomech 2018 Fusion	1.323	0.3102	13	1.124	0.2996	13	22.9%	0.63 [−0.16, 1.42]	2018
Subtotal (95% CI)			**56**			**56**	**100.0%**	**0.54 [0.17, 0.92]**	
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 0.32$, df = 3 (P = 0.96); $I^2 = 0\%$									
Test for overall effect: Z = 2.81 (P = 0.005)									
Total (95% CI)			**56**			**56**	**100.0%**	**0.54 [0.17, 0.92]**	
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 0.32$, df = 3 (P = 0.96); $I^2 = 0\%$									
Test for overall effect: Z = 2.81 (P = 0.005)									



Peak Ankle Power Generation

Study or Subgroup	Postop Mean	Postop SD	Postop Total	Preop Mean	Preop SD	Preop Total	Weight	Std. Mean Difference IV, Random, 95% CI
2.5.3 Fusion								
Brodsky BJJ 2016 Fusion	0.7	0.4195	20	0.5	0.4195	20	42.1%	0.47 [−0.16, 1.10]
Flavin FAI 2013 Fusion	0.66	0.34	14	0.56	0.49	14	30.1%	0.23 [−0.51, 0.97]
Segal Cl Biomech 2018 Fusion	2.387	1.6701	13	1.952	1.0688	13	27.8%	0.30 [−0.47, 1.07]
Subtotal (95% CI)			**47**			**47**	**100.0%**	**0.35 [−0.06, 0.76]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 0.25$, df = 2 (P = 0.88); $I^2 = 0\%$								
Test for overall effect: Z = 1.68 (P = 0.09)								
Total (95% CI)			**47**			**47**	**100.0%**	**0.35 [−0.06, 0.76]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 0.25$, df = 2 (P = 0.88); $I^2 = 0\%$								
Test for overall effect: Z = 1.68 (P = 0.09)								

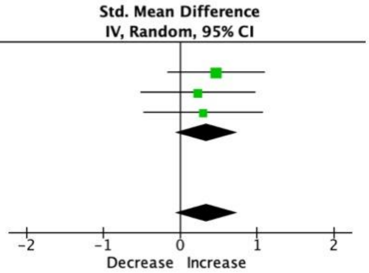


Figure 3.3 : The change in all gait parameters (Ankle Dorsi-/Plantar-flexion RoM, Peak Ankle Plantarflexion Moment, Peak Ankle Power Generation) following ankle arthrodesis compared to pre-operative status.

Maximum ankle dorsiflexion angle

8 studies reported moderate evidence of an increase in ankle dorsiflexion angle after the implantation of a TAR (SMD: 0.37, 95%CI 0.14 to 0.59) with a MD of 1.72° (95%CI 0.70-2.73).[8,9,11,19,27,37,44,45] Fixed-bearing TAR showed similar improvements in ankle dorsiflexion angle to the mobile-bearing TAR (Table 3.3).[11,37,44]

Limited evidence indicated no change in ankle dorsiflexion angle after an AA.[6,19,44]

Maximum ankle plantarflexion angle

Moderate evidence indicated an increase in ankle plantarflexion angle after implantation of a TAR (SMD: 0.37, 95%CI 0.14 to 0.60) with a MD of 2.03° (95%CI 1.07-2.99).[8,9,11,19,27,39,44,45] Six studies[8,9,19,27,39,45] analysing mobile-bearing prostheses reported moderate evidence of an increase in ankle plantarflexion angle after implantation (SMD: 0.38, 95%CI 0.06 to 0.71) with a MD of 2.18° (95%CI 0.78-3.58). However, pooled data of studies analysing fixed-bearing prostheses showed moderate evidence of no increase or decrease in ankle plantarflexion RoM after surgery.[11,37,44]

Limited evidence of no change in ankle plantarflexion angle after an AA.[6,19,44]

Peak plantarflexion ankle moment

Based on the pooled SMD from 10 studies totalling 224 participants, there was moderate evidence of an increase in peak plantarflexion ankle moment (SMD: 0.39, 95%CI 0.15 to 0.64) after TAR (Table 3.2 & 3.3, Figure 3.2).[5,9,11,19,24,27,39,44,45,50] No MD could be given for studies analysing mobile-bearing prostheses as two of the studies[9,27] normalized the data by a length measurement as well as a weight measurement.

There was moderate evidence of an increase in ankle moment after an AA (SMD: 0.54, 95%CI 0.17 to 0.92) with a MD of 0.16 N.m/kg (95%CI 0.05 to 0.27)(Figure 3.3).[6,19,24,44]

Table 3-2 : Summary findings for gait parameters. Change from pre-operative to post-operative status and quality of the evidence related to Standard Mean Difference (SMD) : A : Total ankle replacement : pre-operative versus post-operative; B ; Ankle arthrodesis : pre-operative versus post-operative (NA: Not applicable, MD : mean difference, deg: degrees, HQ: High quality, MQ : Moderate Quality, FQ : Fair quality)

A. Total ankle replacement : pre-operative versus post-operative

Variables	SMD/ MD	Mean	Lower 95% CI	Higher 95% CI	I^2	Overall effect	Evidence	Quality studies	Effect
Ankle RoM (deg)	SMD	0.68	0.51	0.85	0	*P* <0.00001	Moderate	HQ (Queen et al., 2017); MQ (Choi et al.,2013), FQ (Valderrabano et al., 2007; Ingrosso et al., 2009; Brodsky et. al., 2011; Hahn et al., 2012; Tenenbaum et al., 2017; Brodsky et al., 2017), PQ (Flavin et al., 2013; Caravaggi et al., 2015)	Medium
	MD	3.20	2.44	3.96	0	*P* <0.00001			
Ankle DF RoM (deg)	SMD	0.37	0.14	0.59	27	*P* <0.001	Moderate	MQ (Queen et al., 2012; Choi et al., 2013), FQ (Ingrosso et al., 2009; Tenenbaum et al., 2017; Brodsky et al., 2017; Segal et al., 2018), PQ (Flavin et al., 2013; Caravaggi et al., 2015)	Small
	MD	1.72	0.70	2.73	32	*P* =0.0009			
Ankle PF RoM (deg)	SMD	0.37	0.14	0.60	25	*P* =0.001	Moderate	HQ (Queen et al., 2017), MQ (Choi et al., 2013), FQ (Ingrosso et al., 2009; Tenenbaum et al., 2017; Brodsky et al., 2017; Segal et al., 2018), PQ (Flavin et al., 2013; Caravaggi et al., 2015)	Small
	MD	2.03	1.07	2.99	11	*P* <0.0001			
Ankle Moment (N.m/kg)	SMD	0.39	0.15	0.64	36	*P* =0.002	Moderate	HQ (Queen et al., 2017), MQ (Choi et al., 2013), FQ (Valderrabano et al., 2007; Ingrosso et al., 2009; Brodsky et. al., 2011; Tenenbaum et al., 2017; Segal et al., 2018), PQ (Flavin et al., 2013; Caravaggi et al., 2015)	Small
	MD	NA	NA	NA	NA	NA			
Ankle Power (W/kg)	SMD	0.71	0.53	0.88	0	*P* <0.00001	Moderate	HQ (Queen et al., 2017), MQ (Choi et al., 2013), FQ (Valderrabano et al., 2007; Brodsky et. al., 2011; Tenenbaum et al., 2017; Brodsky et al., 2017; Segal et al., 2018), PQ (Flavin et al., 2013)	Medium
	MD	0.28	0.18	0.38	51	*P* <0.00001			
Knee RoM (deg)	SMD	0.37	0.04	0.70	43	*P* =0.03	Moderate	MQ (Choi et al., 2013), FQ (Brodsky et. al., 2011; Hahn et al., 2012; Tenenbaum et al., 2017; Segal et al., 2018)	Small
	MD	2.92	0.17	5.67	55	*P* =0.04			
Hip RoM (deg)	SMD	0.62	0.38	0.86	0	*P* <0.00001	Moderate	MQ (Choi et al., 2013), FQ (Brodsky et. al., 2011; Hahn et al., 2012; Tenenbaum et al., 2017; Segal et al., 2018)	Medium
	MD	3.90	2.33	5.46	9	*P* <0.00001			
Walking speed (m/s)	SMD	1.02	0.85	1.19	35	*P* <0.00001	Moderate	HQ (Queen et al., 2017), MQ (Queen et al., 2012; Choi et al., 2013), FQ (Valderrabano et al., 2007; Ingrosso et al., 2009; Brodsky et. al., 2011; Hahn et al., 2012; Queen et al., 2014; Grier et al., 2016; Tenenbaum et al., 2017; Brodsky et al., 2017; Segal et al., 2018), PQ (Flavin et al., 2013; Caravaggi et al., 2015)	Medium
	MD	0.23	0.19	0.27	55	*P* <0.00001			
Cadence (steps/min)	SMD	0.66	0.45	0.87	15	*P* <0.00001	Moderate	MQ (Choi et al., 2013),FQ (Valderrabano et al., 2007; Brodsky et. al., 2011; Hahn et al., 2012; Tenenbaum et al., 2017; Brodsky et al., 2017; Segal et al., 2018), PQ (Flavin et al., 2013)	Medium
	MD	8.14	6.03	10.25	2	*P* <0.00001			
Stance Duration (%)	SMD	-0.35	-0.55	-0.15	0	*P* =0.0005	Moderate	MQ (Queen et al., 2012; Choi et al., 2013), FQ (Valderrabano et al., 2007; Ingrosso et al., 2009; Brodsky et. al., 2011; Tenenbaum et al., 2017), PQ (Caravaggi et al., 2015)	Small
	MD	-0.01	-0.62	0	3	*P* =0.001			
Step Length (m)	SMD	0.75	0.98	26	26	*P* <0.00001	Moderate	MQ (Queen et al., 2012; Choi et al., 2013), FQ (Valderrabano et al., 2007; Tenenbaum et al., 2017; Brodsky et al., 2017; Segal et al., 2018), PQ (Flavin et al., 2013)	Medium
	MD	NA	NA	NA	NA	NA			

B. Ankle arthrodesis: pre-operative versus post-operative

Variables	SMD / MD	Mean	Lower 95% CI	Higher 95% CI	I2	Overall effect	Evidence	Quality studies	Effect
Ankle RoM (deg)	SMD	-0.16	-0.99	0.68	71	*P* = 0.71	Limited	FQ (Hahn et al., 2012; Brodsky et al., 2016), PQ (Flavin et al., 2013)	No effect
	MD	-0.49	-3.48	2.51	75	*P* = 0.75			
Ankle DF RoM (deg)	SMD	0.64	-0.42	1.70	83	*P* = 0.24	Limited	FQ (Brodsky et al., 2016, Segal et al., 2018), PQ (Flavin et al., 2013)	No effect
	MD	3.64	-2.23	9.51	87	*P* = 0.22			
Ankle PF RoM (deg)	SMD	-0.11	-1.20	0.97	85	*P* = 0.84	Moderate	FQ (Brodsky et al., 2016, Segal et al., 2018), PQ (Flavin et al., 2013)	No effect
	MD	-0.54	-7.45	6.38	87	*P* = 0.88			
Ankle Moment (N.m/kg)	SMD	0.54	0.17	0.92	0	*P* = 0.005	Moderate	FQ (Hahn et al., 2012; Brodsky et al., 2016, Segal et al., 2018), PQ (Flavin et al., 2013)	Small
	MD	0.16	0.05	0.27	0	*P* = 0.004			
Ankle Power (W/kg)	SMD	0.35	-0.06	0.76	0	*P* = 0.09	Moderate	FQ (Brodsky et al., 2016, Segal et al., 2018), PQ (Flavin et al., 2013)	No effect
	MD	0.17	-0.03	0.36	0	*P* = 0.09			
Knee RoM (deg)	SMD	0.34	-0.09	0.77	0	*P* = 0.12	Moderate	FQ (Hahn et al., 2012; Brodsky et al., 2016, Segal et al., 2018)	No effect
	MD	1.43	-0.53	3.38	0	*P* = 0.15			
Hip RoM (deg)	SMD	0.89	0.44	1.34	0	*P* <0.0001	Moderate	FQ (Hahn et al., 2012; Brodsky et al., 2016, Segal et al., 2018)	Medium
	MD	4.77	2.54	7.00	0	*P* = 0.0001			
Walking speed (m/s)	SMD	0.76	0.37	1.15	0	*P* <0.0001	Moderate	FQ (Hahn et al., 2012; Brodsky et al., 2016, Segal et al., 2018), PQ (Flavin et al., 2013)	Medium
	MD	0.17	0.09	0.24	0	*P* <0.00001			
Cadence (steps/min)	SMD	0.30	-0.07	0.68	0	*P* = 0.11	Moderate	FQ (Hahn et al., 2012; Brodsky et al., 2016, Segal et al., 2018), PQ (Flavin et al., 2013)	No effect
	MD	3.05	-0.24	6.34	0	*P* = 0.07			
Stance Duration (%)	SMD	-0.20	-0.83	0.42	NA	NA	Very Limited	FQ (Brodsky et al., 2016)	No effect
	MD	0	-0.01	0.01	NA	NA			
Step Length (m)	SMD	0.13	-0.84	1.10	0.79	*P* = 0.79	Limited	FQ (Brodsky et al., 2016, Segal et al., 2018), PQ (Flavin et al., 2013)	No effect
	MD	0.03	-0.05	0.11	0.43	*P* = 0.43			

Maximal ankle power

The overall pooled SMD from 8 studies totalling 271 participants showed moderate evidence that patients exhibited an improvement in ankle power generation after TAR compared to pre-operative levels (SMD: 0.71, 95%CI 0.53 to 0.88) with a MD of 0.28 W/kg (95%CI 0.18 to 0.38) (Table 3.2 & 3.3, Figure 3.2).[5,8,11,19,39,44,45,50] Three studies indicated moderate evidence that ankle power did not change after an AA (Figure 3.3).[6,19,44]

Knee flexion/extension RoM

There was moderate evidence that patients with a TAR exhibited an improvement in knee flexion/extension RoM after implantation (SMD: 0.37, 95%CI 0.04 to 0.70) of a MD 2.92° (95%CI 0.17 to 5.67).[5,11,24,44,45] Two studies[5,45] showed limited evidence of an improvement in knee flexion/extension RoM after implantation of a mobile-bearing ankle prosthesis (SMD: 0.61, 95%CI 0.29 to 0.91) with a MD of 4.87° (95%CI 1.29 to 8.26). Two studies using fixed-bearing ankle prostheses showed moderate evidence that there was no difference between pre- and post-operative knee flexion/extension RoM.[39,44]

Three studies indicated moderate evidence that knee flexion/extension RoM did not change after an AA.[6,24,44]

Hip Flexion/Extension RoM

The papers provided moderate evidence that patients with a TAR exhibited an improvement in hip flexion/extension RoM after implantation (SMD: 0.62, 95%CI 0.38 to 0.86) with a MD of 3.90° (95%CI 2.33 to 5.46).[5,11,24,44,45] The meta-analysis indicated evidence of moderate heterogeneity between studies analysing fixed-bearing prostheses ($I^2 = 62\%$), which was not the case for mobile-bearing prostheses and yielded no significant difference between pre- and post-operative conditions (SMD: 0.55, 95%CI -0.17 to 1.28).[39,44]

There was moderate evidence of an increase in hip flexion/extension RoM after an AA (SMD: 0.89, 95%CI 0.44 to 1.34) with a MD of 4.77° (95%CI 2.54 to 7.00).[6,24,44]

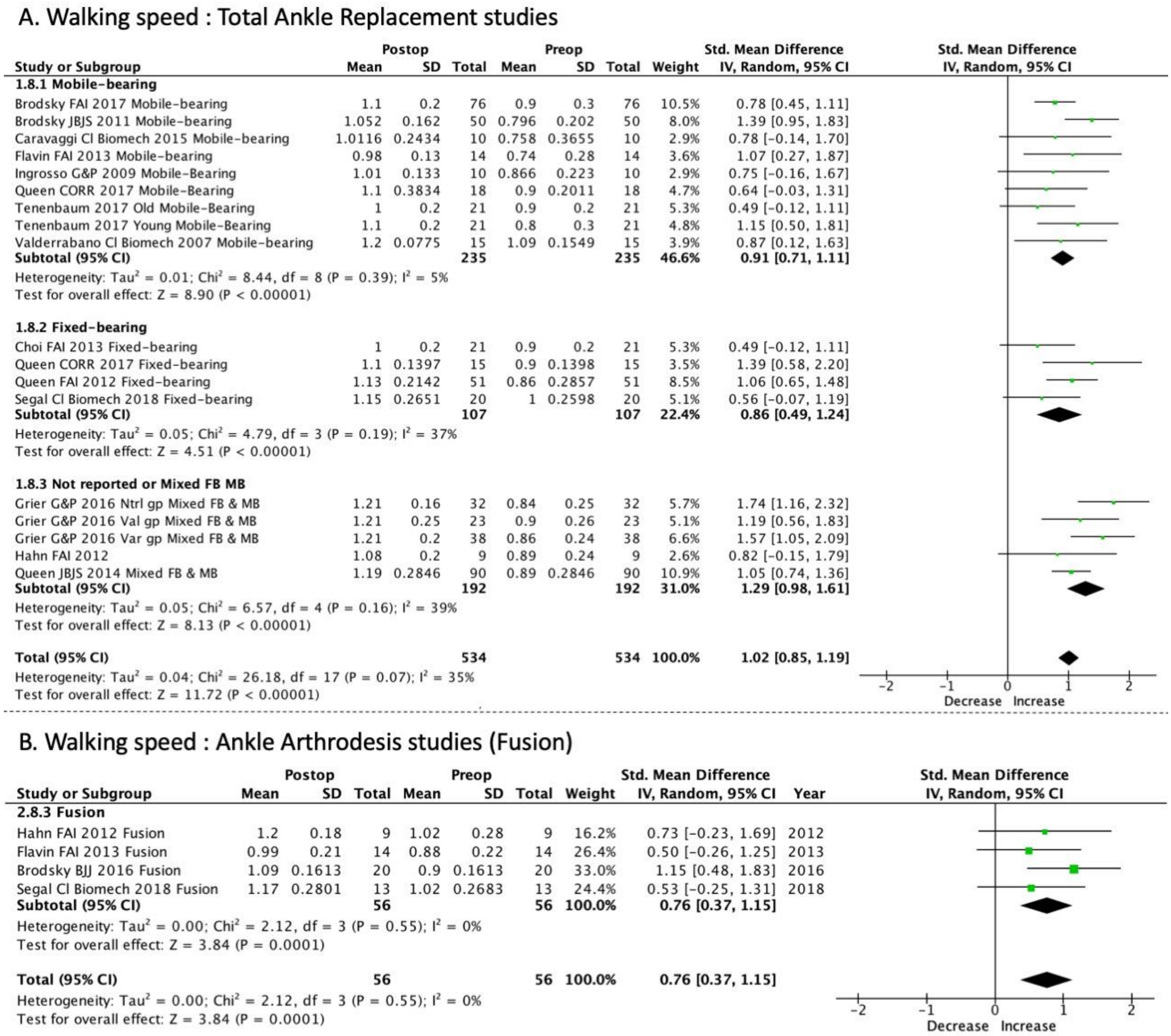


Figure 3.4 : The change in walking speed following total ankle replacement and ankle arthrodesis compared to pre-operative status

Walking speed

Fourteen studies totalling 534 participants reported moderate evidence that patients with a TAR exhibited an increase in walking speed after surgery (Table 3.2 & 3.3, Figure 3.4) (SMD: 1.02, 95%CI 0.85 to 1.19) with a MD of 0.23 m/s (95%CI 0.19 to 0.27).[5,8,9,11,19,22,24,27,37,39,41,44,45,50] Four studies reported moderate evidence of an increase in walking speed after an AA (SMD: 0.76, 95%CI 0.37 to 1.15) with a MD of 0.17 m/s (95%CI 0.09 to 0.24))(Figure 3.4).[6,19,24,44]

Cadence

Based on the overall pooled SMD of 8 studies totalling 247 participants, there was moderate evidence that patients with a TAR exhibited an increase in cadence after implantation (SMD: 0.66, 95%CI 0.45 to 0.87) with a MD of 8.14 steps/min (95%CI 6.03 to 10.25).[5,8,11,19,24,44,45,50] In contrast to the data for mobile-bearing prostheses, the meta-analysis yielded no significant difference in the cadence after implantation of a fixed-bearing ankle prosthesis.[11,44]

There was moderate evidence that cadence did not change after an AA.[6,19,24,44]

Stance duration (% of the gait cycle)

Based on a total of 7 studies totalling 199 participants, moderate evidence was found that patients exhibited a decrease in stance duration after the implantation of ankle prosthesis regardless of the type of prosthesis that was implanted (Table 3.2 & 3.3) (SMD: -0.35, 95%CI -0.55 to -0.15 and MD -0.01%, 95%CI -0.02 to 0.00).[5,9,11,27,37,45,50]

One study reported very limited evidence that stance duration did not change after an AA.[6]

Step Length

Moderate evidence was demonstrated that patients with a TAR exhibited an increase in step length after implantation (SMD: 0.75, 95%CI 0.52 to 0.98).[8,11,19,37,44,45,50] No MD could be established as one study[37] normalized step length by the height of the subjects. The meta-analysis indicated evidence of moderate heterogeneity between studies analysing fixed-bearing prostheses (I^2 = 62%), in contrast to that for mobile-bearing prostheses, and yielded a significant difference between pre- and post-operative conditions (SMD: 0.84, 95%CI 0.32 to 1.36).[11,37,44] Four studies indicated moderate evidence of an increase in step length after implantation of a mobile-bearing ankle prosthesis (SMD: 0.66, 95%CI 0.42 to 0.90) with a MD of 0.06m (95%CI 0.02 to 0.09).[8,19,45,50]

Limited evidence was demonstrated for no change in step length after an AA.[6,44]

Table 3-3 : Summary findings for gait parameters. Change from pre-operative to post-operative status and quality of the evidence related to Standard Mean Difference (SMD) : A : Mobile-bearing, B) Fixed-bearing. (NA: Not applicable, MD : mean difference, deg: degrees, HQ: High quality, MQ : Moderate Quality, FQ : Fair quality)

A. Mobile-bearing total ankle replacement									
Variables	**SMD/ MD**	**Mean**	**Lower 95% CI**	**Higher 95% CI**	**I^2**	**Overall effect**	**Evidence**	**Quality studies**	**Effect**
Ankle RoM (deg)	SMD	0.64	0.46	0.83	0	P< 0.00001	Moderate	HQ (Queen et al., 2017), FQ (Valderrabano et al., 2007; Ingrosso et al., 2009; Brodsky et. al., 2011; Tenenbaum et al., 2017; Brodsky et al., 2017), PQ (Flavin et al., 2013; Caravaggi et al., 2015)	Medium
	MD	3.32	2.32	4.07	0	P< 0.00001			
Ankle DF RoM (deg)	SMD	0.23	0.01	0.046	0	*P* =0.04	Moderate	FQ (Ingrosso et al., 2009; Tenenbaum et al., 2017; Brodsky et al., 2017), PQ (Flavin et al., 2013; Caravaggi et al., 2015)	Small
	MD	1.3	-0.02	2.61	22	*P* =0.05			
Ankle PF RoM (deg)	SMD	0.38	0.06	0.71	46	*P* =0.02	Moderate	HQ (Queen et al., 2017), FQ (Ingrosso et al., 2009; Tenenbaum et al., 2017; Brodsky et al., 2017), PQ (Flavin et al., 2013; Caravaggi et al., 2015)	Small
	MD	2.18	0.78	3.58	31	*P* =0.002			
Ankle Moment (N.m/kg)	SMD	0.39	0.06	0.71	47	*P* =0.02	Moderate	HQ(Queen et al., 2017), FQ (Valderrabano et al., 2007; Ingrosso et al., 2009; Brodsky et. al., 2011; Tenenbaum et al., 2017), PQ (Flavin et al., 2013; Caravaggi et al., 2015)	Small
	MD	NA	NA	NA	NA	NA			
Ankle Power (W/kg)	SMD	0.73	0.53	0.92	0	P< 0.00001	Moderate	HQ(Queen et al., 2017) FQ (Valderrabano et al., 2007; Brodsky et. al., 2011; Tenenbaum et al., 2017; Brodsky et al., 2017), PQ (Flavin et al., 2013)	Medium
	MD	0.28	0.15	0.41	64	P< 0.00001			
Knee RoM (deg)	SMD	0.60	0.29	0.91	7	*P* =0.0001	Limited	FQ (Brodsky et. al., 2011; Tenenbaum et al., 2017)	Medium
	MD	4.78	1.29	8.26	48	*P* =0.007			
Hip RoM (deg)	SMD	0.69	0.39	0.99	0	P< 0.00001	Limited	FQ (Brodsky et. al., 2011; Tenenbaum et al., 2017)	Medium
	MD	4.58	2.70	6.45	0	P< 0.00001			
Walking speed (m/s)	SMD	0.91	0.71	1.11	5	P< 0.00001	Moderate	HQ (Queen et al., 2017), FQ (Valderrabano et al., 2007; Ingrosso et al., 2009; Brodsky et. al., 2011; Tenenbaum et al., 2017; Brodsky et al., 2017), PQ (Flavin et al., 2013; Caravaggi et al., 2015)	Medium
	MD	0.19	0.14	0.24	30	P< 0.00001			
Cadence (steps/min)	SMD	0.75	0.49	1.02	31	P< 0.00001	Moderate	FQ (Valderrabano et al., 2007; Brodsky et. al., 2011; Tenenbaum et al., 2017; Brodsky et al., 2017), PQ (Flavin et al., 2013)	Medium
	MD	8.63	5.91	11.34	26	P< 0.00001			
Stance Duration (%)	SMD	-0.30	-0.55	-0.05	0	*P* =0.02	Moderate	FQ (Valderrabano et al., 2007; Ingrosso et al., 2009; Brodsky et. al., 2011; Tenenbaum et al., 2017) , PQ (Caravaggi et al., 2015)	Small
	MD	-0.01	-0.02	0	10	*P* =0.03			
Step Length (m)	SMD	0.66	0.42	0.90	0	*P*< 0.00001	Limited	FQ (Valderrabano et al., 2007; Tenenbaum et al., 2017; Brodsky et al., 2017), PQ (Flavin et al., 2013)	Medium
	MD	0.06	0.02	0.09	59	*P* =0.0007			

B. Fixed-bearing total ankle replacement									
Variables	SMD/ MD	Mean	Lower 95% CI	Higher 95% CI	I^2	Overall effect	Evidence	Quality studies	Effect
Ankle RoM	SMD	0.95	0.46	1.44	0	*P* =0.0001	Moderate	HQ (Queen et al., 2017); MQ (Choi et al.,2013)	Medium
	MD	3.42	1.21	5.63	41	*P* =0.002			
Ankle DF RoM	SMD	0.55	0.07	1.03	56	*P* =0.02	Limited	MQ (Queen et al., 2012; Choi et al., 2013), FQ (Segal et al., 2018)	Small
	MD	2.21	0.66	3.76	41	*P* =0.005			
Ankle PF RoM	SMD	0.27	-0.11	0.64	0	*P* =0.16	Moderate	HQ (Queen et al., 2017); MQ (Choi et al., 2013); FQ (Segal et al., 2018)	No effect
	MD	1.29	-0.39	2.96	11	*P* <0.0001			
Ankle Moment (N.m/kg)	SMD	0.52	0.14	0.90	0	*P*=0.007	Moderate	HQ (Queen et al., 2017); MQ (Choi et al., 2013); FQ (Segal et al., 2018)	Small
	MD	0.16	0.02	0.30	15	*P*=0.03			
Ankle Power (W/kg)	SMD	0.64	0.22	1.06	16	*P*=0.003	Moderate	HQ (Queen et al., 2017); MQ (Choi et al., 2013); FQ (Segal et al., 2018)	Medium
	MD	0.28	0.13	0.43	0	*P*=0.0002			
Knee RoM	SMD	-0.07	-0.50	0.37	0	*P* =0.77	Moderate	MQ (Choi et al., 2013); FQ (Segal et al., 2018)	No effect
	MD	-0.43	-3.49	2.63	0	*P* =0.78			
Hip RoM	SMD	0.55	-0.17	1.28	62	*P* =0.13	Limited	MQ (Choi et al., 2013); FQ (Segal et al., 2018)	No effect
	MD	3.42	-1.57	8.41	74	*P* =0.18			
Walking speed (m/s)	SMD	0.86	0.49	1.24	37	*P* <0.00001	Moderate	HQ (Queen et al., 2017); MQ (Queen et al., 2012; Choi et al., 2013); FQ (Segal et al., 2018)	Medium
	MD	0.19	0.12	0.26	39	*P* <0.00001			
Cadence (steps/min)	SMD	0.45	0.01	0.89	0	*P* =0.05	Moderate	MQ (Choi et al., 2013); FQ (Segal et al., 2018)	No effect
	MD	6.01	0.26	11,77	0	*P* =0.04			
Stance Duration (%)	SMD	-0.45	-0.78	-0.12	0	*P* =0.007	Moderate	MQ (Queen et al., 2012; Choi et al., 2013),	Small
	MD	-0.01	-0.02	0	0	*P* =0.009			
Step Length (m)	SMD	0.84	0.32	1.36	62	*P* =0.001	Limited	MQ (Queen et al., 2012; Choi et al., 2013), FQ (Segal et al., 2018)	Medium
	MD	NA	NA	NA	NA	NA			

DISCUSSION

This systematic review aimed to synthesise previous research evaluating the biomechanical effect of TAR and AA in patients suffering from end-stage ankle OA. There is currently limited to moderate evidence that all spatio-temporal variables are improved following TAR irrespective of the type of prosthesis implanted. Segal (2018) suggested that TAR patients improved their walking speed by increasing their cadence.[44] In contrast, very limited to moderate evidence was shown by the systematic review that there is no improvement in spatio-temporal variables after an AA except for walking speed.

The main advantage of TAR over AA is the conservation of the existing pre-operative ankle RoM.[5,10,27] Data pooling of ankle kinematics showed a medium effect (3.20°) in increasing the dorsi-/plantarflexion RoM of the replaced ankle, using skin markers to assess motion. This methodology may well have resulted in an over-estimation of bone motion due to soft tissue artefact.[31,52] The increase in RoM found could also be attributed to accessory offending motion hypermobility of the adjacent foot joints in studies where the foot was considered to be one rigid segment (Table 3.2). There was moderate evidence that experimental errors or natural gait variability could account for only a small increase in RoM for dorsiflexion (1.72°) and for plantarflexion (2.03°) during gait.[43] In the light of these results, it seems that TAR does increase the pre-operative ankle RoM. In contrast, a reduced ankle RoM should be an expected outcome for AA. Although the ankle joint is fused, four studies reported the ankle dorsi- and/or plantarflexion RoM.[7,19,24,44] The movements reported in these studies could be due to the rigid foot model used in the studies, the motion reported not being due to true ankle RoM, but the resulting compensation of the neighbouring joints. Future prospective studies evaluating TAR or AA should therefore use a 3D multi-segment foot model to avoid erroneus motion data relating of the surgical effects on foot mechanics.

A second advantage of TAR over AA is the protection of the adjacent and non-adjacent joints.[5,10,27] Conventional gait models were used in all the studies included in this review, allowing the evaluation of function of the neighbouring joints (i.e. hip, knee) pre and post surgery (Table 3.1). Twelve of the seventeen studies limited their analysis to the affected joint without considering the entirety of the lower kinetic chain. From a biomechanical point of view, such consideration is an important facet of any procedure since the segments of the lower limb are a linked system.[18,28] Moderate evidence was found indicating that TAR patients increase their flexion-extension RoM at the knee and the hip post-operatively.[5,11,24,44,45] In contrast, the evidence suggests that arthrodesis patients show no post-operatively change in knee RoM, but an increase (4.77°) in hip RoM. This would seem to reinforce the notion that patients suffering from the ankle OA compensate more at the hip than at the knee for reduced ankle RoM.[44] Future studies should combine 3D lower limb models with 3D multi-segment foot models to enhance our understanding of the functional compensatory adaptations occurring at the neighbouring joints after TAR and AA.

Moderate evidence was found that all ankle kinetic variables are improved following TAR. Increase in peak plantar flexion moment and ankle power generation is a good indicator of an improvement in the ability to use the foot to propel forward and an increase in the strength of the calf muscles.[27] AA studies demonstrated moderate evidence of an increase in ankle dorsiflexion moment. However, there was also moderate evidence of a lack of effect on the generation of ankle power during gait.

During the past decade, development of TAR design has resulted in two major types: mobile-bearing implants, where the polyethylene meniscal bearing is free to slide on both tibial and talar articular surface components fixed to the bones, and fixed-baring implants, where the meniscal bearing is fixed to the tibial component.[29] Unfortunately, there is a paucity of randomized trial studies which analyse differences in gait mechanics in patients with a fixed- versus mobile-bearing TAR. Only one study[39] considered this topic, and revealed no difference in outcomes between the two implant types. Pooled data from trials testing the two types of prosthesis individually showed limited differences in gait mechanics after TAR using the two implant designs (Table 3.3), the differences possible being the result of experimental error or natural gait variability.[43]

There were of course limitations associated with the studies included in this review. The methodological quality assessment of the studies allowed the identification of several methodological limitations, such as the absence of outcome measurer blinding and reporting of methodological validity. Moreover, the categorisation of ankle OA was limited and non-specific in most of the studies. The heterogeneity in the patho-etiology of ankle OA means that the functional consequences are difficult to define without considering the morphological and structural changes associated with the ankle OA, thereby making it difficult to generate meaningful pooled results for specific ankle OA sub-types. Only one study[50] included in the review had an intervention group composed exclusively of post-traumatic ankle OA. In contrast to the global TAR results, patients suffering from post-traumatic ankle OA showed no evidence of an effect of TAR on peak plantarflexion moment, stance duration or step length. Future studies should clearly define the sub-type of end-stage ankle OA and their associated osteoarticular deformity. In the absence of this information, caution should be exercised when considering results generated by pooled data. A further limitation of the review was the lack of access to data generated or analysed in several of the papers. Where necessary authors were contacted with a request to provide additional data. Unfortunately, none of our requests were met, decreasing the number of studies and participants included in the meta-analysis.

CONCLUSION

Current research evaluating changes in gait biomechanics after TAR and AA is limited by a lack of prospective research, low sample sizes and heterogeneity in the patho-etiology of ankle OA. Meta-analysis revealed a significant increase in lower limb kinematics, kinetics and spatio-temporal parameters after total ankle replacement. Improvement in gait variables after ankle arthrodesis was limited to ankle moment, hip range of motion and walking speed. Future studies should combine 3D lower limb models with 3D multi-segment foot models to enhance our understanding of the functional compensatory adaptations of the neighbouring joints after TAR and AA.

Supplementary Materials Description

Supplementary materials can be found in the Appendix section

Supplementary material 1: Results of modified Downs and Black scale

Supplementary material 2**:** The change in gait parameters (Ankle Dorsiflexion RoM, Ankle Plantarflexion RoM) following total ankle replacement (TAR global, Mobile-bearing prosthesis and Fixed-bearing prosthesis) compared to pre-operative status

Supplementary material 3**:** The change in gait parameters (Knee and Hip RoM) following total ankle replacement (TAR global, Mobile-bearing prosthesis and Fixed-bearing prosthesis) compared to pre-operative status

Supplementary material 4**:** The change in spatio-temporal parameters (Cadence, Stance Duration, Step Length) following total ankle replacement (TAR global, Mobile-bearing prosthesis and Fixed-bearing prosthesis) compared to pre-operative status

Supplementary material 5**:** The change in all gait parameters (Ankle Dorsiflexion RoM, Ankle Plantarflexion RoM, Knee and Hip RoM) following ankle arthrodesis compared to pre-operative status.

Supplementary material 6**:** The change in spatio-temporal parameters (Cadence, Stance Duration, Step Length)) following ankle arthrodesis compared to pre-operative status

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Chapter 4 : Intrinsic foot joints adapt a stabilized-resistive configuration during the stance phase

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ABSTRACT

Background**:** This study evaluated the 3D angle between the joint moment and the joint angular velocity vectors at the Ankle, Chopart, Lisfranc and First Metatarso-phalangeal joints, and investigated if these joints are predominantly driven or stabilized during gait.

Methods**:** The participants were 20 asymptomatic subjects. A four-segment kinetic foot model was used to calculate and estimate intrinsic foot joint moments, powers and angular velocities during gait. 3D angles between the joint moment and the joint angular velocity vectors were calculated for the Ankle, Chopart, Lisfranc, and First Metatarso-phalangeal joints. When the 3D vectors were approximately aligned the moment was considered to result in propulsion (angle <60°) or resistance (angle >120°) at the joint. When the 3D vectors are approximately orthogonal (angle close to 90°), the moment was considered to stabilize the joint.

Results: The results showed that the four intrinsic joints of the foot are never fully propelling, resisting or being stabilized, but are instead subject to a combination of the three effects during the majority of the stance phase of gait. However, the results also show that during pre-swing all four of the joints are subject to moments that result purely in propulsion. At heel off, the propulsive configuration appears for the Lisfranc joint first at terminal stance, then for the other foot joints at pre-swing in the following order: Ankle joint, Chopart joint and First Metatarso-Phalangeal joint.

Conclusions**:** Intrinsic foot joints adopt a stabilized-resistive configuration during the majority of the stance phase, with the exception of pre-swing during which all joints were found to adopt a propulsive configuration. The notion of stabilization, resistance and propulsion should be further investigated in subjects with foot and ankle disorders.

Keywords : Foot kinetics, Multi-segment foot, Inverse dynamics, walking

Adequate measurement of the complex intrinsic movement of the foot and ankle complex during walking has been impeded for decades by the simplified representation of foot as a single functional segment.[11] The development of three-dimensional (3D) multi-segment foot models partially tackled this major shortcoming of the established 3D lower limb models and showed their clinical value through the detection of intrinsic foot mobility impairments [11]. During the last decade, foot and ankle biomechanics were essentially described through the kinematics of the gait cycle as determined from cadaver, invasive bone pins, biplanar videoradiography and non-invasive surface marker studies, and plantar pressure measurements.[22,23,31–33] Recently, multi-segment kinetic foot models have received increasing attention in methodological and clinical studies providing new insights into how the intrinsic joints of the foot can have individual power distributions.[2,4,10,41] While kinematic multi-segment foot models can demonstrate the motion of the various intrinsic joints of the foot, establishing the kinetics of these joints represent a new series of challenges: definition of inter-segment joint centers, estimation of segmental shear forces and definition of segment inertial properties.[10] Despite these technical and methodological challenges, joint moments and powers have been able to provide new insights into the dynamic contribution of the Chopart and Lisfranc joints during gait, and new mechanisms of foot dysfunction in specific foot and ankle pathologies.[10,14,39]

Based on the literature, kinetic analysis of intrinsic foot joints seems to be a valuable way for uncovering the role of foot and ankle during locomotion. However, the clinical interpretation of joint power remains an area of debate and not without controversies in the field of biomechanics. Although subject to challenge, joint power has been reported separately for the frontal, sagittal and transverse planes, which has revealed inconsistent results at the ankle.[1,5,15] The scientific community has also associated joint power with muscle action and energy transfer.[12,18,19] However, their link with joint power has been widely criticized in the literature.[12,18,19] The difficulty is largely in the attribution of energy transfer (e.g. storage in elastic structures, muscle action) and in the allocation of forces to the agonist-antagonist and multi-joint muscles.[12,41] The nature of the foot and ankle further increases the complexity of interpretation by the fact that, compared to the other major joints of the lower limb, intrinsic foot joints share common ligament and muscle tendon structures. Further analysis integrating in-vivo medical imaging[37] with musculo-skeletal models[43] would be required to shed light on the contribution of each of the anatomical structures to foot and ankle function. It is therefore proposed that the joint power be supplemented by an angle ($\alpha_{M\omega}$) which encapsulates a 3D angular relationship between the joint moment (**M**) and the joint angular velocity (**ω**) vectors, in an attempt to translate kinetic data into a "simple" functional relationship expressed in an accessible format applicable to the lower limb joints (ankle, knee, hip)[12] When the 3D vectors **M** and **ω** are aligned (0° or 180°), the moment results in propulsion or resistance. When the 3D vectors **M** and **ω** are orthogonal (90°), the moment stabilizes the joint.[12] The 3D angle $\alpha_{M\omega}$ between the joint moment (**M**) and the joint angular velocity (**ω**) revealed that the ankle joint generally adapts a resistive configuration (at midstance) followed by a propulsive configuration (at pre-swing) in healthy adults.

Based on current knowledge on the estimation of foot joint kinetics, this study proposes to expand the calculation of $\alpha_{M\omega}$ to a four-segment kinetic foot model. Our hypothesis is that intrinsic foot joints are only partially propelling, resisting or stabilized due to the complex contributions of intrinsic and extrinsic foot muscles, ligaments and multiple joint surfaces. Therefore, the objective of this study was to analyse $\alpha_{M\omega}$ at the Chopart, Lisfranc and first metatarso-phalangeal joints during the stance phase of gait and to investigate if these joints are predominantly propelling, resisting or stabilized. Angle $\alpha_{M\omega}$ was also computed at the ankle joint with the foot considered to be a multi-segment system and a single segment for comparison.

METHODS

Subjects

Twenty asymptomatic adult subjects participated in the study (male/female ratio 14/6; age : 45.35 ± 11.97 ; height, 1.75 ± 0.08; weight : 75.5 ± 9.13; BMI : 24.62 ± 2.50; walking speed 1.39 ± 0.15). Participants were included if 1) they were able to walk barefooted independently, without support, 2) they had no history of orthopaedic, neurological or musculoskeletal problems affecting their gait. All participants were volunteers and signed the informed consent approved by the local ethical committee (B200-2017-061).

Protocol

The simultaneous assessment of kinematics, kinetics, and plantar pressure measurements of each subject was achieved through the use of an advanced clinical examination platform combining a motion capture system, a force plate and a plantar pressure plate. The motion capture system consisted of 8 Miqus cameras (Qualysis, Göteborg Sweden) to capture the kinematic data (200Hz) of the participant while walking over a 10 meters walkway at a self-selected speed.[6] In the middle of the walkway, a Footscan® pressure plate (dimensions 0.5m x 0.4m, 4096 sensors, 2.8 sensors per cm^2, RSscan International, Paal, Belgium) was mounted upon a custom made AMTI-force plate (dimensions 0.5 x 0.4m, Advanced Mechanical Technology, Inc., Watertown, MA, US). The force plate was custom-made to fit the surface dimensions of the plantar pressure plate. This set-up allowed for the detection of specific gait events as well as for a continuous calibration of the pressure plate with the force plate using a Footscan® 3D interface box (RSscan International, Paal, Belgium). Data from the pressure and force plates were measured at a sampling rate of 200Hz. The integration and synchronization of the three different hardware devices was achieved through the use of a Miqus Sync unit interface (Qualysis, Göteborg Sweden).

Thirty-two 8mm retro-reflective markers were mounted over anatomical landmarks according to the Instituto Orthopedico Rizzoli 3D multi-segment foot model (RFM).[23] The skin markers were mounted using double-sided adhesive tape. After maker placement, the participants were asked to walk barefoot, at a self-selected speed until five valid trials were recorded. A trial was considered valid when the following criteria were met: 1) walking speed was within predetermined boundaries, 2) no visual adjustment was made in gait pattern to contact the pressure plate and 3) a clear contact with the pressure plate.[8] All marker trajectories were computed by Qualysis Tracking Manager 2.16 (Qualysis, Göteborg Sweden).

Data analysis

Inter-segment 3D rotations were calculated according to an adapted version of Instituto Orthopedico Rizzoli 3D multi-segment foot model developed by Deschamps et al. (2017) (IOR-4Segment-model 1) following ISB recommendations, where dorsiflexion/plantarflexion (sagittal plane) is defined as rotation about the medio-lateral axis of the proximal segment, adduction/abduction (transversal plane) about the vertical axis of the distal segment and inversion/eversion (frontal plane) about an axis orthogonal to the first two axes.[23,44]

Joint forces (F) and moments (M) were computed in the Inertial Coordinate System by a bottom-up inverse dynamic method using a Newton-Euler recursive algorithm based on a homogeneous matrix formalism during the stance phase of gait.[24] Kinematic and force data were filtered using a low-pass zero-lag, 4th order, Butterworth filter, with a cut-off frequency of 10 Hz. Inertia and weight parameters of each foot segment were discounted as the inertia effects were negligible during gait compared to the external forces. The force plate data were distributed over each foot segment using the proportionality scheme described by Morlock & Nigg (1991) and validated by Saraswat et al. (2014) based on the distribution of the vertical ground reaction forces as measured by each sensor of the plantar pressure platform (i.e. if 15% of the total vertical force acted on the forefoot, it was assumed that 15% of the total horizontal force also acted on the forefoot).[30,39] The estimation of the subarea of each foot segment was achieved for each time frame by projecting the position of the retro-reflective markers vertically on the sensor matrix of the plantar pressure platform. The resulting center of pressure (CoP) of each estimated subarea was then used as the CoP for each foot segment in then inverse dynamics calculations. The joint moments were expressed in the proximal segment coordinate system.

For the computation of foot kinematics and kinetics, a virtual cuboid marker was created and defined as being at 2/3 of the distal distance between the peroneal tubercle and the base of the fifth metatarsal (Figure 4.1). Inter-segment center definitions of the four segment foot model were based on Deschamps et al. (2017). For both kinematic and kinetic foot models, the ankle joint center was defined as the midpoint between the malleoli markers. Ankle joint motion was described between the foot and the shank for the one-segment foot model (hereafter referred as Ankle), and between the calcaneus and the shank for the multi-segment foot model (hereafter referred as Shank-Calcaneus) (Figure 4.1). Calcaneus-Midfoot center (hereafter referred as Chopart joint) was determined as being the midpoint between the cuboid and the navicular bone. Midfoot-Metatarsus center (hereafter referred as Lisfranc joint) was determined as being on the base of the second metatarsal. First Metatarso-Phalangeal joint center was the projection of first metatarsal head marker vertically at mid distance to the ground.[10]

In supplement to the joint power, the 3D angle $\alpha_{M\omega}$ between the joint moment (**M**) and the joint angular velocity (**ω**) vectors was calculated as described by Dumas and Chèze (2008). When the 3D vectors **M** and **ω** are mainly aligned ($\alpha_{M\omega}$ <60° or > 120°), the moment either results in propulsion (**P**) or resistance (**R**). When the 3D vectors **M** and **ω** are almost orthogonal ($\alpha_{M\omega}$ >60° and <120°), the moment stabilizes the joint (**S**).[12] Inter-segment kinematic and kinetic computations were performed using an in-house constructed Matlab program. Joint moments and powers were normalized by subject-mass and all variables were time-normalized for the stance phase.

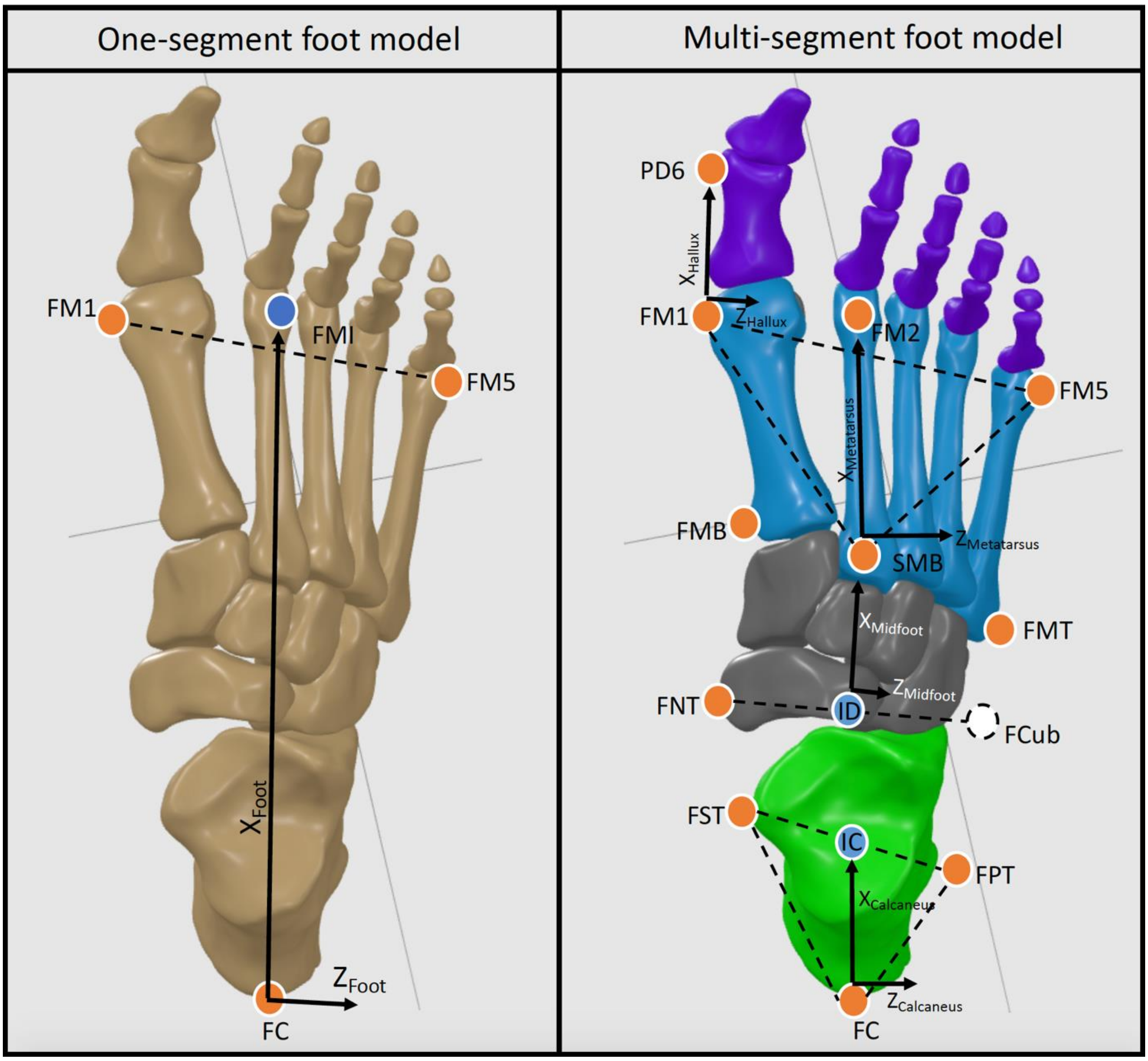

Figure 4.1 : Inter-segment center definitions were defined according to an adapted version of Rizzoli foot model (Leardini et al. 2007) developed by Deschamps et al. (2017) (IOR-4Segment-model 1). Markers name : upper ridge of the posterior surface of the calcaneus (FC); peroneal tubercle (FPT); sustentaculum tali (FST); virtual cuboid marker (FCub), tuberosity of the navicular bone (FNT); first, second and fifth metatarsal base (FMB, SMB, FMT); first, second and fifth metatarsal head (FM1,FM2, FM5); PD6 : distal dorso-medial aspect of the head of the proximal phalanx of the hallux; First Metatarso-phalangeal joint center (FM1; Midfoot-Metatarsus center (SMB); Calcaneus-Midfoot center (ID)

The 3D angle $\alpha_{M\omega}$ curves show that the four joints are never fully propelling, resisting or stabilized, but adopt a stabilized-resistive configuration during most of the stance phase, except at pre-swing with all joints in a propulsive configuration (Figure 4.5). At loading response, all major joints quickly show a peak resistance (Ankle, Shank-Calcaneus, Lisfranc) or a stabilization configuration (Chopart) followed by a short period of stabilization occurring first at ankle, Shank-Calcaneus and then for Lisfranc joints. The First Metatarso-Phalangeal joint demonstrates a propulsive configuration during loading response. During midstance, the Ankle and Shank-Calcaneus predominantly show a resistive configuration, whereas the Chopart adapts a stabilized-resistive configuration. In contrast, Lisfranc and First Metatarso-Phalangeal joints show a stabilized configuration. The propulsive configuration appears for Lisfranc joint first at terminal stance, then for other foot joints at pre-swing in the following order : shank-calcaneus, Ankle, Chopart and First Metatarso-Phalangeal joint.

Ankle versus Shank-Calcaneus joints

The Ankle and shank-Calcaneus joint powers remained low during the stance phase, except at loading response, when a peak of negative power occurred corresponding to a resistive configuration (both joints ~161°), and during pre-swing when a peak of positive power occurred corresponding to a propulsive configuration (Shank-Calcaneus ~50° versus Ankle ~26°) (Figure 5). The 3D angle $\alpha_{M\omega}$ of both joints demonstrated a high variability during loading response and at the end of midstance (Figure 4.5).

At loading response, the moments and angles (Figure 4.2-4.4) of both joints showed a predominantly dorsiflexion inter-segmental action, and a combination of plantarflexion and eversion movements. At midstance, the joint moments and angles of both joints showed a plantarflexion inter-segmental action and a dorsiflexion movement. At terminal stance and pre-swing, the joint moments and angles of both joints showed a predominantly plantarflexion inter-segmental action combined with a plantarflexion movement. Both peak power generation and absorption were lower in the Shank-Calcaneus joint than in the Ankle joint.

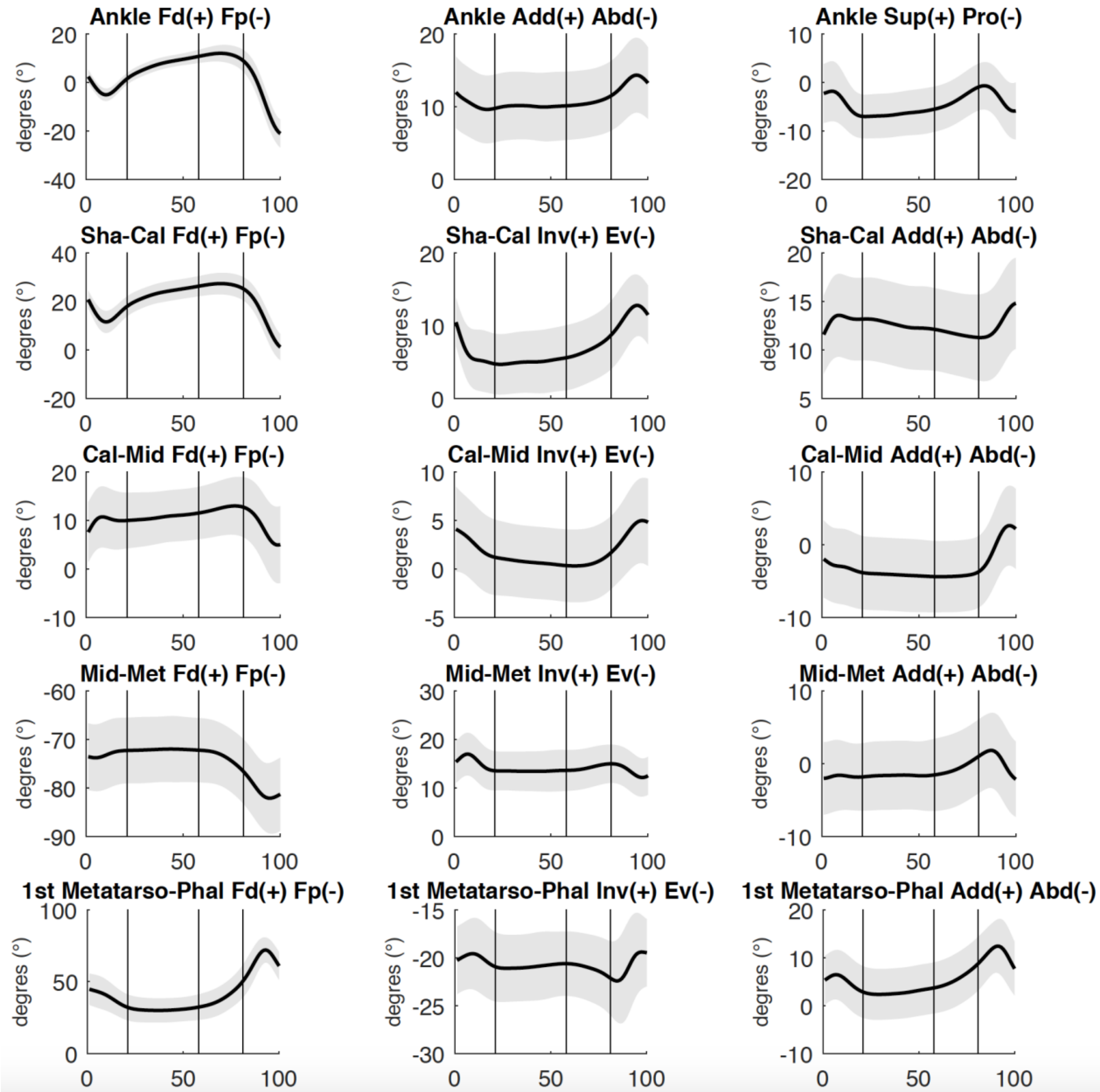

Figure 4.2 : Mean 3D kinematics (degrees) for the Ankle, Shank-Calcaneus (Sha-Cal), Chopart joint (Cal-Mid), Lisfranc joint (Mid-Met), First Metatarso-Phalangeal joint (1st Metatarso-Phal). Standard deviations are visualized as bands.

Calcaneus-Midfoot (Chopart)

The Calcaneus-Midfoot power remained low during the stance phase, except during terminal stance when a peak of negative power occurred corresponding to a resistive configuration (~143°), and during pre-swing when a peak of positive power occurred corresponding to a propulsive configuration (~36°). The 3D angle $\alpha_{M\omega}$ demonstrated a high variability during loading response and midstance (Figure 4.5).

At loading response, Calcaneus-Midfoot power was negligible and the moments and angles showed a predominantly plantarflexion inter-segmental action and a combination of dorsiflexion and eversion movements (Figure 4.2-4.4). Calcaneus-Midfoot power was also low during midstance and the 3D angle $\alpha_{M\omega}$ demonstrated a stabilised-resistive configuration. At terminal stance, the moments and angles showed a predominantly plantarflexion inter-segmental action combined with a dorsiflexion movement. At pre-swing, the moments and angles showed a predominantly plantarflexion inter-segmental action combined with a plantarflexion movement.

Midfoot-Metatarsus (Lisfranc)

The Midfoot-Metatarsus power remained low during the stance phase, except at the end of terminal stance and the beginning of pre-swing when a peak of positive power was seen to occur corresponding to a propulsive configuration (~33°). The 3D angle $\alpha_{M\omega}$ demonstrated a high variability during midstance and terminal stance (Figure 4.5).

At loading response, Midfoot-Metatarsus power was negligible and the moments and angles showed a predominantly plantarflexion inter-segmental action and a combination of dorsiflexion and inversion/eversion movements (Figure 4.2-4.4). Midfoot-Metatarsus power were also low during midstance and the 3D angle $\alpha_{M\omega}$ demonstrated a stabilised configuration (~90°). At terminal stance, the moments and angles showed a predominantly plantarflexion inter-segmental action combined with a plantarflexion movement. The moments and angles at the transition between terminal stance and pre-swing showed a predominantly plantarflexion inter-segmental action combined with a plantarflexion movement. In contrast to the ankle and Chopart joints, the Lisfranc joint demonstrated a stabilized configuration at the end of pre-swing. The moments and angles showed an eversion inter-segmental action combined with an eversion movement.

First metatarso-phalangeal

The First Metatarso-Phalangeal power remained low during the stance phase, except at pre-swing when a peak of negative power was seen to occur corresponding to a resistive configuration (peak at ~163°). The 3D angle $\alpha_{M\omega}$ demonstrated a high variability during the entire stance phase, except during pre-swing (Figure 4.5).

The First Metatarso-Phalangeal power was negligible from loading response to terminal stance. 3D angle $\alpha_{M\omega}$ showed a propulsive configuration at loading response and a stabilised configuration during midstance. At terminal stance and pre-swing, the moments and angles showed a predominantly plantarflexion inter-segmental action combined with a dorsiflexion movement (Figure 4.2-4.4).

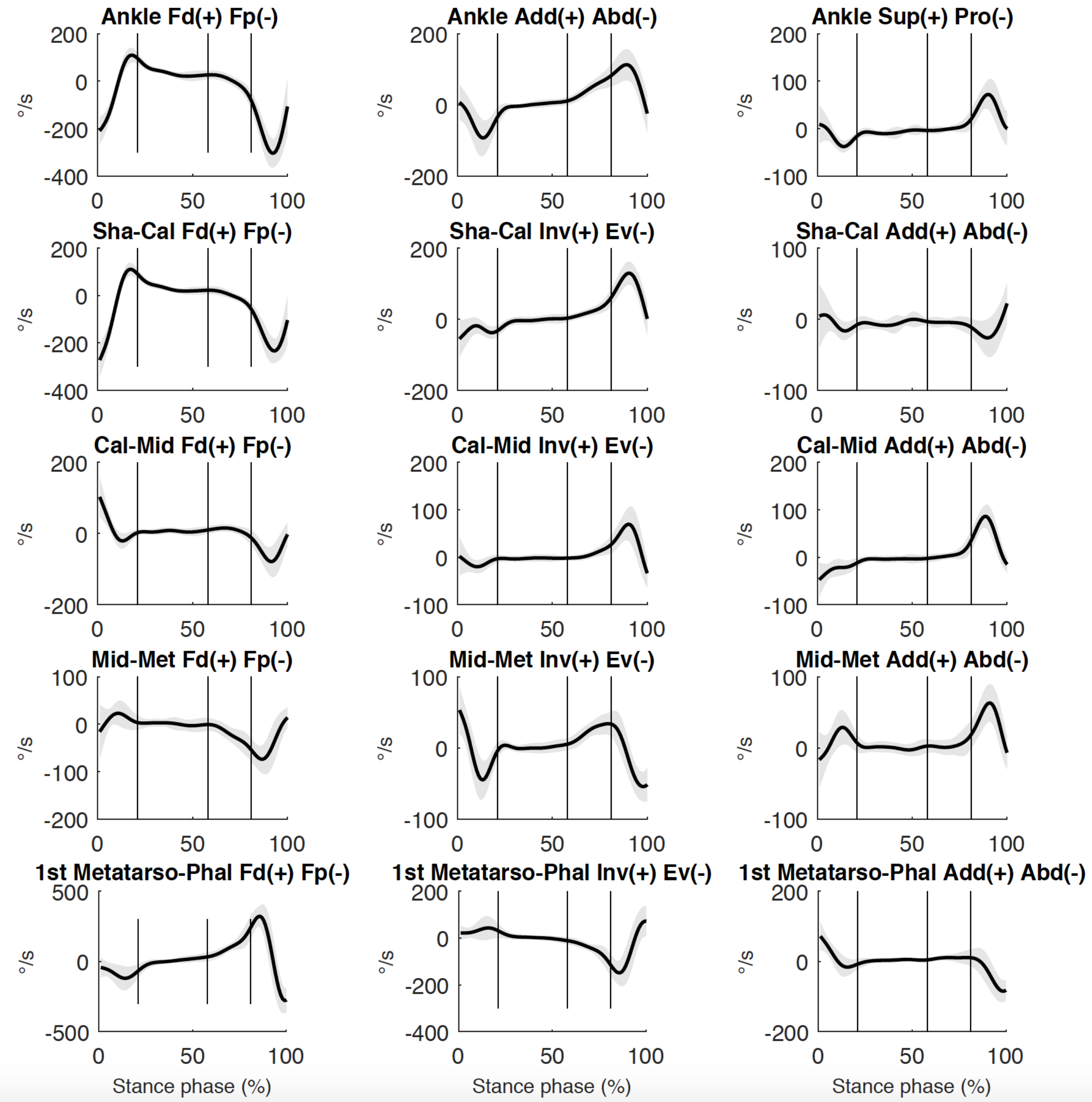

Figure 4.3 : Mean 3D angular velocities (degrees/second) for the Ankle, Shank-Calcaneus (Sha-Cal), Chopart joint (Cal-Mid), Lisfranc joint (Mid-Met), First Metatarso-Phalangeal joint (1st Metatarso-Phal). Standard deviations are visualized as bands.

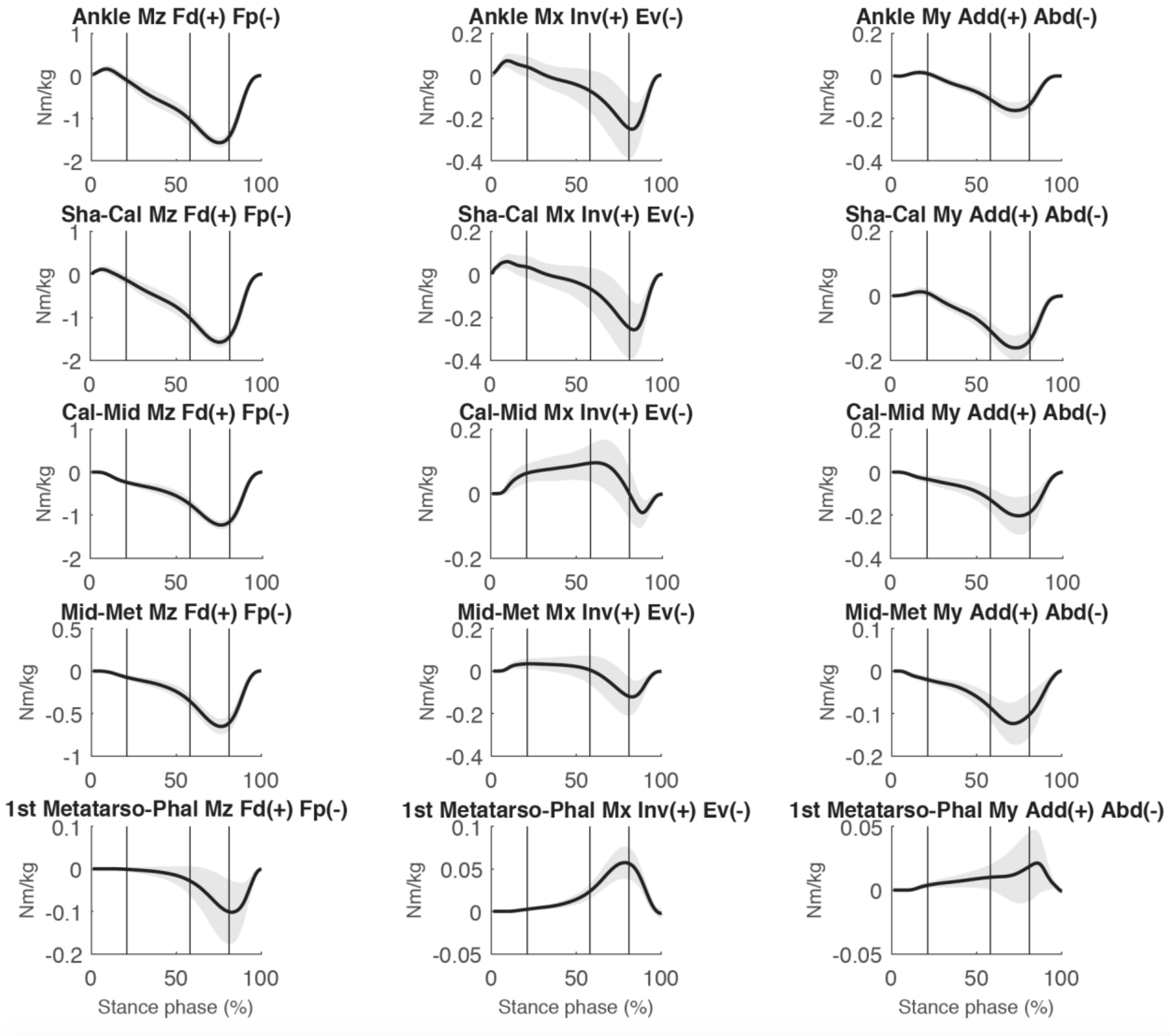

Figure 4.4 : Mean 3D joint moments (Nm/kg) for the Ankle, Shank-Calcaneus (Sha-Cal), Chopart joint (Cal-Mid), Lisfranc joint (Mid-Met), First Metatarso-Phalangeal joint (1st Metatarso-Phal). Standard deviations are visualized as bands.

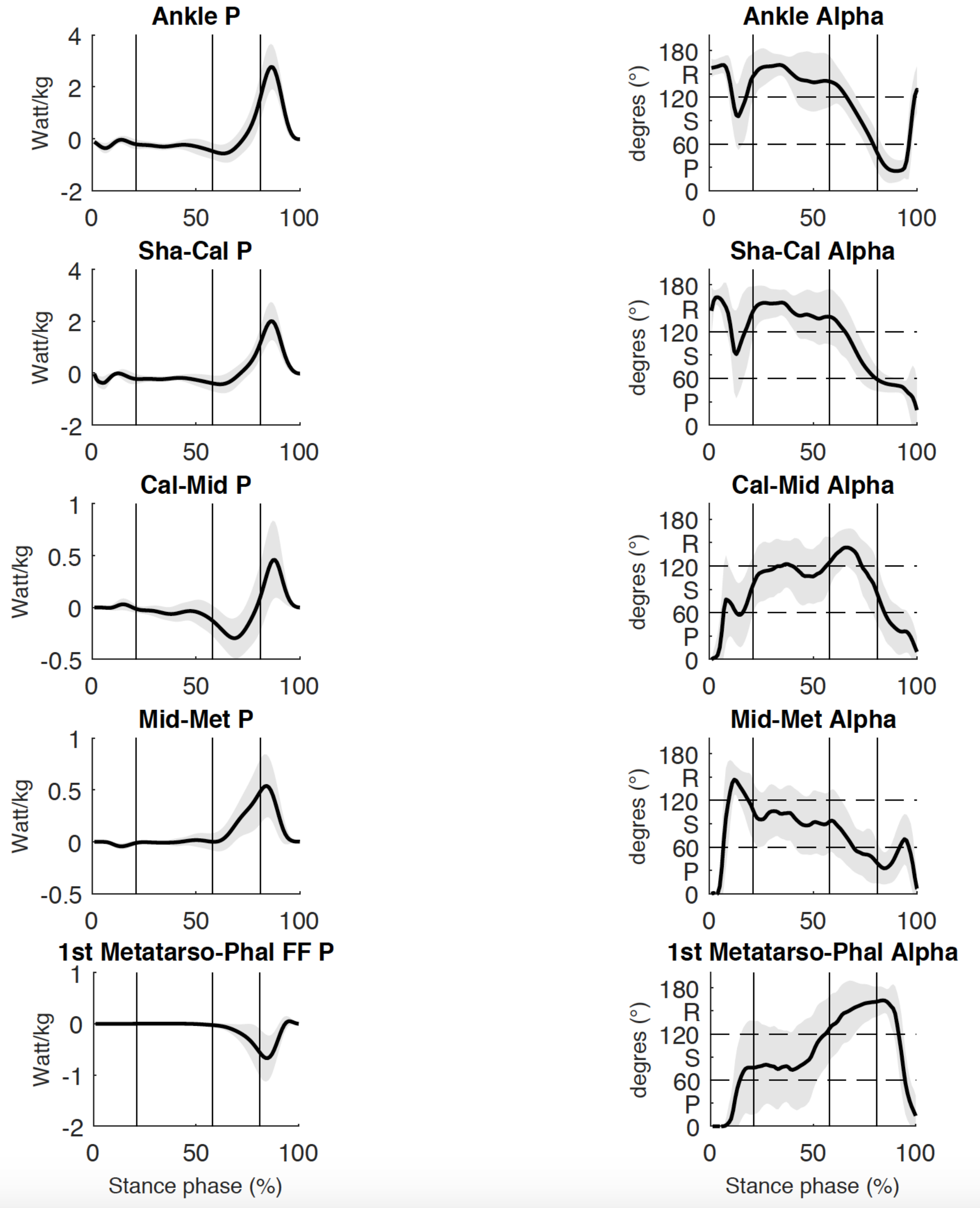

Figure 4.5 : Mean 3D joint power (Watt/kg) and mean 3D angle between joint moment and joint angular velocity vectors for the Ankle, Shank-Calcaneus (Sha-Cal), Chopart joint (Cal-Mid), Lisfranc joint (Mid-Met), First Metatarso-Phalangeal joint (1st Metatarso-Phal). Standard deviations are visualized as bands. Subphases of the gait cycle. Abbreviations : R : resistance configuration; P : propulsion configuration; S : stabilisation configuration.

DISCUSSION

The current study proposes the use of a 3D angle $\alpha_{M\omega}$, which encapsulates a 3D angular relationship between the joint moment (**M**) and the joint angular velocity (**ω**) vectors, in an attempt to provide a "simple" measure of the function of intrinsic foot joints during gait. Our hypothesis was confirmed by the results which showed that the intrinsic foot joints are never fully propelling, resisting or stabilized, but instead adopt a stabilized-resistive configuration during most of the stance phase, with the exception of during pre-swing when all joints adopt a propulsive configuration. This stabilized-resistive configuration keeps the foot from collapsing while bearing weight, allowing stabilization of the foot and thus accomplishing the stability requirements of locomotion.[40]

This study expanded the calculation of 3D angle $\alpha_{M\omega}$ from a lower limb model to a four-segment kinetic foot model. The 3D angle $\boldsymbol{\alpha_{M\omega}}$ pattern of the Ankle joint found in this study was generally similar to that proposed by Dumas and Chèze (2008).[12] The most notable difference between the results of the two studies was that during loading response Dumas and Chèze (2008) found a stabilized configuration as opposed to the resistive configuration found in this study. The decomposition of 3D angle $\boldsymbol{\alpha_{M}}$ revealed that this discordance in configuration is likely to arise from different kinematic patterns, as Dumas and Chèze (2008) found a predominant combination of abduction and external rotation movements, whereas this study showed a combination of plantarflexion and eversion movements. It may be concluded that the observed differences may therefore come from the variation in foot kinematics between participants, since both studies used the same joint center, anatomical landmarks and reference frame to model the ankle joint.

A point of interest which deserves discussion is the critical role of the method by which the ankle joint is modelled. The simplified representation of the foot as a single functional segment is still widely used to quantify ankle joint kinetics in clinical biomechanical studies. The results showed that both peak power generation and absorption to be lower in the Shank-Calcaneus joint than in the Ankle joint (Figure 4.5). This is in accordance with previous gait studies for asympatomatic[3,26,45] and symptomatic[14] subjects. However, in terms of 3D angle $\alpha_{M\omega}$ waveforms, the Shank-Calcaneus joint and the Ankle joint showed similar waveforms during the stance phase of gait.

Adding 3D angle $\alpha_{M\omega}$ waveforms to the computation of foot kinetics creating a four-segment foot model enabled the discovery of new insights into how the Chopart and Lisfranc joints are contributing to foot function from midstance to pre-swing. However, the interpretation of 3D angle $\alpha_{M\omega}$ of both joints during loading response should be undertaken with care, as the forefoot may not yet be in contact with the ground, and their respective joint moments were found to be close to zero. The computed 3D angle $\alpha_{M\omega}$ waveforms of both joints appear to correspond with their respective functional anatomy. The Lisfranc joint shows predominantly a stabilized configuration during midstance, possibly caused by the anatomical stiffness of the tarsometatarsal joints. The passive stability of the Lisfranc joint is largely provided by the plantar ligaments and the second metatarsal with its encased base between the cuneiforms. The peroneus longus tendon, inserted at the plantar aspect of the first metatarsal base, and the first cuneiform further contribute to the stabilization of the first ray in opposition to dorsiflexion moments that are commonly exerted by ground reaction forces acting plantar to the first metatarsal head.[36] In contrast to the Lisfranc joint, the Chopart joint has considerably more freedom of movement and requires a resistive-stabilized configuration to control the deformation of the longitudinal arch under load, and to avoid collapsing during midstance and propulsion. Recent evidence suggests that the stability of the longitudinal arch is not only provided by the passive structures (e.g. plantar ligaments and plantar fascia), but also by contraction of the plantar intrinsic foot muscles.[29] These muscles act as local stabilisers increasing the inter-segmental stability of the longitudinal arch. They have small cross-sectional areas and therefore produce small rotational moments.[29] Flexor hallucis longus and tibialis posterior provide further substantial dynamic support to the medial longitudinal arch. These muscles provide both resistive and propulsive capabilities during gait.[27,42]

The foot's rigidity in late stance is mainly attributed to the windlass and midtarsal locking mechanisms.[17,28] The stiffening of the foot is required to resist the ground reaction forces and allow efficient propulsion of the body in late stance. At heel off, 3D angle $\boldsymbol{\alpha_{M\omega}}$ waveforms of the ankle and Lisfranc joints are simultaneously adopting a propulsive configuration at terminal stance, which means that both joints are predominantly being driven by their respective plantarflexion moments, and thus contributing to power generation (Figure 4.4-4.5). Recent studies suggest that this power generation at the Lisfranc joint during terminal stance is the result of the Windlass mechanism.[3,10,13] The activation of this mechanism results in tension the plantar fascia by winding it around the metatarsal heads as the toes extend in terminal stance.[17] The power generated at the Lisfranc joint would then in turn result in the optimal repositioning of the bones around the Chopart joint.[16] The reorientation of the midfoot bones were mainly characterized in our results by a plantarflexion moment combined with a dorsiflexion and inversion movement of the Chopart joint resulting in a resistive configuration. This phenomenon is often referred in the literature as the midtarsal locking mechanism.[28,35] However, the term “locking” seems inappropriate as rotational movement at the Chopart joint was observed at terminal stance. It has also been suggested that the increased tension in the plantar fascia, and possibly other muscle-tendon structures, would result in a shortening and rise of the longitudinal arch through flexion and adduction of the metatarsals in combination with an inversion of the rearfoot.[7,17] The longitudinal arch raise would then induce a first ray plantarflexion, an inversion of the Chopart joint, an inversion of the rearfoot, and ankle dorsiflexion.[16] At 65% of the stance, the resistive configuration adopted by the Chopart joint is converted into a propulsive configuration where the moments and angles show predominantly a plantarflexion inter-segmental action combined with a plantarflexion movement (Figure 4.2-4.5). This configuration conversion allows the Chopart joint to contribute to power generation. Elastic recoil of the tibialis posterior as well as of the plantarflexors of the ankle and toes’ further add to power generation at the Chopart and ankle joints during terminal stance and pre-swing.[10]

A last point of interest is the functioning of the First Metatarso-phalangeal joint during propulsion, which tends to absorb relatively more power than the joints distal to the Ankle joint (Figure 4.5). The ankle and the First Metatarso-Phalangeal joints, among all joints of the foot, undergo the largest ranges of motion in the sagittal plane, while moving in opposite directions during the majority of the stance phase of gait. Both joints are crossed by the tendon of flexor hallucis longus, which acts as a plantarflexor of the ankle and a joint-stabilizer of the First Metatarso-Phalangeal joint. Further active stabilization of the hallux against the ground is provided by the flexor hallucis brevis, adductor and abductor hallux muscles which exert a plantar flexion moment. Evidence suggests that this power absorption observed at the First Metatarso-Phalangeal joint could be the result of the flexion-pressor pull of the intrinsic foot muscles and the flexor hallucis longus to stabilize the hallux against the ground and to counteract the dorsiflexion and eversion moments externally produced by the ground reaction forces.[20,38] Kelly et al. (2014) further suggested that the intrinsic foot muscles also served to decrease the stress on passive elements, such as the plantar ligaments, plantar fascia and plantar plate, crossing the First Metatarso-Phalangeal joint.[21] It may therefore be concluded that the resistive configuration adopted by the First Metatarso-Phalangeal joint at terminal stance and pre-swing is in accordance with earlier findings describing the mechanisms countering the ground reaction forces.

There are several limitations to this study. A first issue concerns the estimation of the center of pressure and resultant ground reaction forces for each foot segment, derived from combining force and pressure data. The use of a proportionality scheme was originally validated for the calculation of joint kinetics of a three segment foot model and not for a four segment foot model.[39] Validity of the proportionally scheme was assessed by comparing the predicted shear forces obtained from the same experimental setup as the present study with the measured shear forces obtained by asking the participants to adopt a 3 step controlled foot placement approach on two adjacent force plates during a walking trial. Mean differences of less than 3% between the shear force measured by 2 adjacent force plates and the shear force predicted by the proportionality scheme in the hindfoot and forefoot segments were found in a paediatric population. However, these results should be viewed with care as errors in the determination of the point of force application have been found towards force plate edges.[25] Therefore, the results of the current study should be considered as an estimation and further research is needed. A second limitation is the use of skin markers to estimate joint centers and segmental kinematics. Soft tissue artefacts have been reported to reach 3.29 mm on the surface of the foot[22], and the impact of this error on the estimation of the moments and powers is difficult to estimate. A third limitation concerns the recruitment of asymptomatic participants, which does not mean that all feet were entirely free of degenerative changes in foot structure (e.g. clinical osteoarthritic changes). Studies have shown that a sizeable percentage of asymptomatic individuals may present abnormal findings of soft tissues on magnetic resonance imaging [9,34]. Finally, since walking speed results in different foot kinetics, the effect of walking speed on 3D angle $\alpha_{M\omega}$ should be further investigated in future studies.[10]

CONCLUSION

This study reports a first attempt to gain additional insight into the kinetic behaviour of multiple foot joints through the use of a “simple” variable (3D angle $\alpha_{M\omega}$) during gait. Intrinsic foot joints adopt a stabilized-resistive configuration during the majority of the stance phase. Results of the current study should be considered with care as skin markers and a proportionality scheme were used to estimate foot joint kinematics and kinetics. The notion of stabilization, resistance and propulsion should be further investigated in subjects with foot and ankle disorders.

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Chapter 5 : Post-sprain versus post-fracture post-traumatic ankle osteoarthritis : impact on foot and ankle kinematics and kinetics

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ABSTRACT

Background: The most common etiologies for post-traumatic end-stage ankle osteoarthritis are ankle fractures and chronic ankle instability. As the nature of trauma is different for these two etiologies, it might be expected that the two subtypes of post-traumatic ankle osteoarthritis would display different foot mechanics during gait. The overall objective of this study was to compare the foot kinematics and kinetics of patients suffering from post-fracture ankle osteoarthritis with those of patients suffering from post-sprain ankle osteoarthritis.

Methods: Twenty-nine subjects with post-traumatic ankle osteoarthritis and fifteen asymptomatic control subjects participated in this study. A four-segment kinematic and kinetic foot model was used to calculate intrinsic foot joint kinematics and kinetics during gait. Anova and statistical parametric mapping were used to compare the data from the two groups.

Findings: No differences in the joint angles and moments were found between the two post-traumatic ankle osteoarthritis groups. Both osteoarthritis groups showed decreased spatio-temporal variables, and reduced ankle joint angles and moments compared to the control subjects. Post-fracture ankle osteoarthritis group were found to exhibit lower power generation at the Lisfranc joint complex, and lower power absorption at the first metatarso-phalangeal joint compared to the control group.

Interpretation: No differences were found in foot joint mechanics between the two post-traumatic ankle osteoarthritis groups. However, both pathological groups showed altered foot mechanics during gait compared to the control subjects. Alteration in foot mechanics was not limited to the painful ankle joint, but also affected the kinetics of the neighbouring foot joints.

Keywords: post-traumatic osteoarthritis; ankle osteoarthritis; foot kinetics; foot kinematics; gait

INTRODUCTION

Ankle osteoarthritis (OA) is a progressive and degenerative joint disease affecting approximately 1% of the world's adult population.[26] Recent publications have demonstrated that the degree of physical impairment from ankle osteoarthritis is at least as severe as that from congestive heart failure and hip osteoarthritis using the SF-36.[9,22] Numerous clinical and epidemiologic studies of patients suffering from ankle osteoarthritis have identified previous trauma as the most common aetiology.[21,26] Post-traumatic ankle osteoarthritis most frequently occurs secondary to ankle-related fractures (post-fracture) and to chronic ankle instability (post-sprain).[21] Evidence suggests that post-fracture ankle osteoarthritis results either from irreversible cartilage damage which occurs at the time of the fracture, or from chronic cartilage overloading which occurs as a result of post-fracture articular incongruity. The evidence also suggests that post-sprain ankle osteoarthritis results from pathological cartilage overloading due to chronic joint instability.[15]

Significant biomechanical alterations of the entire foot and lower limb have been reported in patients suffering from post-traumatic ankle osteoarthritis.[24,28] Their gait is asymmetrical and characterized by a decreased walking speed, decreased stride length and reduced mobility of the ankle joint complex.[29] They also seem to adopt an antalgic walking strategy to prevent shear loading through the painful joint.[29] Despite this knowledge, no study has so far compared the gait mechanics of patients suffering from post-fracture ankle osteoarthritis to those of patients suffering from post-sprain ankle osteoarthritis. Moreover, ankle joint kinetics reported in patients suffering from post-traumatic ankle osteoarthritis have in the past been calculated using a rigid foot modelling approach, which is known to overestimate the amount of ankle joint power, potentially leading to clinical misinterpretations.[6,30] The development of a more full understanding of the difference in the gait mechanics, including those of both the ankle joint and intrinsic joints of the foot, of these two subgroups of patients is therefore required. Currently, to the authors' knowledge, no research has been conducted using patients suffering from the two types of post-traumatic ankle osteoarthritis using a four-segment kinetic foot model. This approach may show kinetic patterns to occur that a rigid foot model would mask, and give additional information regarding forefoot function by assessing Chopart and Lisfranc joint complex kinetics.

The overall objective of this study was to compare the foot kinematics and kinetics of patients suffering from post-fracture ankle osteoarthritis with those of patients suffering from post-sprain ankle osteoarthritis. As the nature of the causative trauma is different, one might expect that the two types of post-traumatic ankle osteoarthritis would display different foot mechanics during gait. In addition, each pathological group was individually compared to an asymptomatic group of peer-matched control subjects.

METHODS

Participants

A convenience sample of twenty-nine subjects with post-traumatic ankle osteoarthritis and fifteen asymptomatic subjects (CTRL) participated in this study (Table 5.1). All patients suffered from post-traumatic ankle osteoarthritis secondary to ankle-related fracture (post-fracture (PF OA; n=15 subjects; 9 males and 6 females) or to chronic ankle instability (post-sprain (PS OA; n=14 subjects; 9 males and 5 females). Exclusion criteria for both post-traumatic groups were (1) being younger than 18 years, (2) systemic or neurological diseases, (3) any medical problem other than post-traumatic ankle osteoarthritis that could possibly affect gait. The inclusion criteria for the pathological groups were post-traumatic end-stage ankle osteoarthritis with an indication for either ankle fusion or total ankle replacement. The severity of ankle osteoarthritis was scored using the Canadian Orthopaedic Foot & Ankle Society (COFAS) classification system (Table 5.1).[12] Control subjects (10 males and 5 females) were peer-matched with both PF and PS OA groups according to their demographics. Exclusion criteria for the control subjects were any medical problems that could possibly affect normal gait. The local ethical committee approved the study (B200-2017-061) and all participants signed an informed consent form.

Data collection

Participants were first fitted with sixteen 8mm retro-reflective markers on the foot and shank in accordance with the multi-segment Rizzoli foot model.[13] The measurement protocol was started by asking participants to walk at a self-selected speed along a 10m walkway in which a pressure plate (Footscan®, dimensions 0.58 m x 0.42 m, 4096 sensors, 2.8 sensors per cm^2, RSscan International, Paal, Belgium) was mounted upon an AMTI force plate (Advanced Mechanical Technology, Inc., Watertown, MA, US). The force plate was custom-made to fit the surface dimensions of the plantar pressure plate. The advantage of this set-up was the continuous calibration of the pressure plate with the force plate using an RsScan® 3D interface box (RSscan International, Paal, Belgium). A passive optoelectronic motion analysis system

(Qualysis, Göteborg Sweden) comprised of 8 Miqus cameras tracked the kinematic data of the participants while walking over the instrumented walkway. The integration and synchronization of the three hardware devices was achieved by connecting them using a Miqus Sync unit interface (Qualysis, Göteborg Sweden). Data from the three hardware devices were measured at a sampling rate of 200Hz. Data was collected from five valid trials for each participant. A trial was considered valid when the foot under investigation made a clear contact with the pressure and force plate combination without visible gait adjustments. Walking speed was also required to remain relatively constant across all trials of a recording session. All marker trajectories were calculated using Qualysis Tracking Manager 2.16 (Qualysis, Göteborg Sweden).

Data analysis

Inter-segment center definitions of the four segment foot model were based on an adapted version of Instituto Orthopedico Rizzoli 3D multi-segment foot model developed by Deschamps et al. (2017) (IOR-4Segment-model 1) (Figure 5.1).[2] The ankle joint center was defined as the midpoint between the malleoli markers, and motion at this joint was considered to describe the motion between the foot and the shank. This was the only joint considered in the 1-segment foot model. In the 4-segment model, the same joint center was used to describe the motion between the calcaneus and the shank (hereafter referred as shank-calcaneus). To define the calcaneus-midfoot joint center, an additional virtual cuboid marker was created and defined as being at 2/3 of the distal distance between the peroneal tubercle and the base of the fifth metatarsal. The calcaneus-midfoot joint center was defined as the midpoint between the cuboid and the navicular bone (hereafter referred as Chopart joint). The midfoot-metatarsus center (hereafter referred as Lisfranc joint complex) was defined as being on the base of the second metatarsal. The first metatarso-phalangeal joint center was defined as being at intersection of the projection of the first metatarsal head marker vertically at mid distance and the floor.[2] Inter-segment 3D rotations were calculated according to IOR-4Segment-model 1 of Deschamps et al. (2017) following ISB recommendations.[2]

Joint forces (**F**) and moments (**M**) were calculated in the Inertial Coordinate System using a bottom-up inverse dynamic method utilising a Newton-Euler recursive algorithm based on a homogeneous matrix formalism during the stance phase of gait.[14] Kinematic and force data were filtered using a low-pass zero-lag, 4^{th} order, Butterworth filter, with a cut-off frequency of 10 Hz. Inertia and weight parameters of each foot segment were not accounted for considering that the inertia effects were negligible during stance in comparison to the external forces.[8,20] The force plate data were distributed over each foot segment using a validated proportionality scheme.[5,23] The estimation of the subarea of each foot segment was achieved for each time frame by projecting the markers' position vertically onto the sensor matrix of the pressure platform. The resulting center of pressure (CoP) of each estimated subarea was then used as the CoP for the corresponding foot segment in the inverse dynamics calculations. The joint moments were expressed in the proximal segment coordinate system. In addition to the joint power, the 3D angle $\alpha_{M\omega}$ between the joint moment (**M**) and the joint angular velocity (**ω**) vectors was calculated as described by Dumas and Chèze (2008).[3] When the 3D angle $\alpha_{M\omega}$ was smaller than 60° or greater than 120°, the moment was considered to result mainly in the joint being driven in propulsion (**P**) or resistance (**R**) respectively. If the 3D angle $\alpha_{M\omega}$ was between 60° and 120°, the moment was considered to result in the joint being mainly stabilized (**S**).[3] An in-house written Matlab© program (The Mathworks Inc., Natick, Massachusetts, US) was used for inter-segment kinematic and kinetic computations. Internal joint moments and powers were normalized by subject-mass, and all one-dimensional data were time-normalized to 100% of the stance phase.

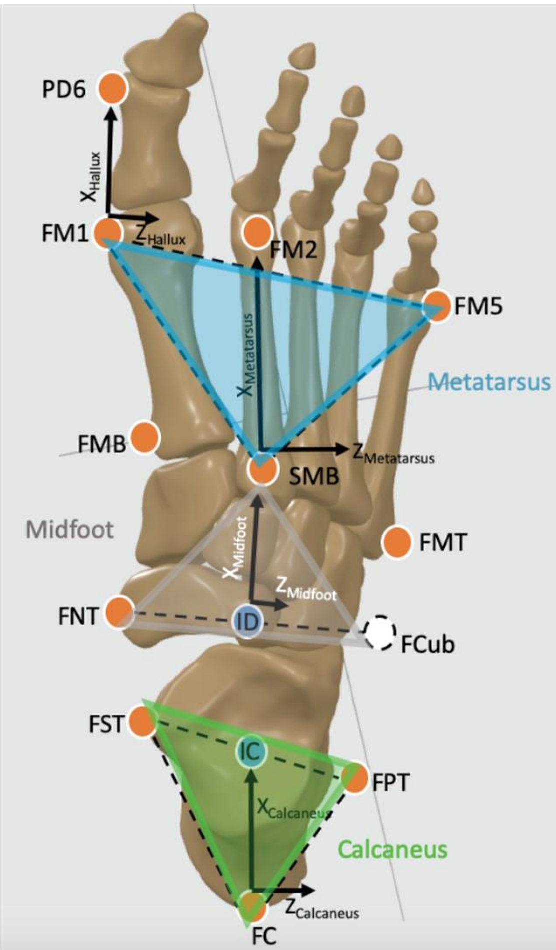

Figure 5.1 : Inter-segment center definitions were defined according to an adapted version of Rizzoli foot model (Leardini et al. 2007) developed by Deschamps et al. (2017) (IOR-4Segment-model 1). Markers name: upper ridge of the posterior surface of the calcaneus (FC); peroneal tubercle (FPT); sustentaculum tali (FST); virtual cuboid marker (FCub), tuberosity of the navicular bone (FNT); first, second and fifth metatarsal base (FMB, SMB, FMT); first, second and fifth metatarsal head (FM1,FM2, FM5); PD6: distal dorso-medial aspect of the head of the proximal phalanx of the hallux; First Metatarso-phalangeal joint center (FM1; Midfoot-Metatarsus center (SMB); Calcaneus-Midfoot center (ID)

Statistical analysis

First, a Shapiro-Wilk test was used to check for data normality. A one-way ANOVA test and Kruskal-Wallis test were used to identify statistically significant differences between groups for demographic and spatio-temporal data. In cases where significant differences were observed, a Post hoc Tukey honest significant difference test was used to indicate which groups were different. An adjusted *P*-value (0.05/3=0.017) was used to control the type 1 error rate when performing multiple comparisons. All statistical tests were conducted using SPSS (version 25, IBM Corp, Chicago, USA).

One-dimensional statistical parametric mapping (SPM) was used to compare foot kinematics and kinetics between groups using an open-source code (v.M.0.4.5; www.spm1d.org) in Matlab© (The Mathworks Inc., Natick, Massachusetts, US).[7,17] The main advantages of this methodological approach are that SPM regards the whole time-series as the unit of observation, and that time dependence is incorporated directly in the statistical testing. The scalar output one-way between subjects ANOVA (SPM{F}) was calculated separately for each time interval. To test the null hypothesis, the critical threshold at which only α = 5% of smooth random curves would be expected to cross was calculated. This threshold was based on estimates of trajectory smoothness gained from temporal gradients[19] and Random Field Theory.[17] This approach was validated for 1D data.[18] Individual probability values were then calculated for each supra-threshold cluster that could have resulted from an equally smooth random process. If statistical significance was reached in the SPM{F}, then post-hoc two-sample t-test (SPM{t})(post-hoc *p*-value 0.05/3 = 0.017) was performed to determine the between-group differences (using the same processes as described above to establish the significance of the SPM{F}).

RESULTS

Demographic and spatio-temporal data

No significant differences between the groups were found for age, weight, height or BMI (Table 5.1). No significant differences were found between PF OA and PS OA groups for walking speed or stride length (Table 5.1). However, both post-traumatic ankle OA groups showed significantly shorter stride lengths (P<0.001) and slower walking speeds than the control group (P<0.001).

Table 5-1 : Demographic and spatio-temporal data between 1) post-sprain post-traumatic ankle osteoarthritis (PS OA); 2) post-traumatic post-fracture ankle osteoarthritis (PF OA) and 3) asymptomatic control subjects (CTRL). Abbreviations: COFAS: Canadian Orthopaedic Foot & Ankle Society classification system for ankle osteoarthritis (Type 1 has isolated ankle osteoarthritis; Type 2 signifies ankle osteoarthritis associated with intra-articular ankle deformity or a tight heel cord or both, Type 3 patients have ankle osteoarthritis with deformity of the hind- or midfoot, tibia or forefoot; and Type 4 includes Type 1 to Type 3 plus subtalar or calcaneocuboid or talonavicular osteoarthritis); SD:standard deviation; BMI: body mass index; N.S.: not significant. *Post hoc Tukey honestly test (adjusted p-value 0.3/3=0.017).

	PS OA (n=15 ankles)			**PF OA (n=15 ankles)**			**CTRL (n= 15 ankles)**			**ANOVA (F)[a] / Kruskal-Wallis (H)[b]**		**CAI OA vs PF OA**	**CAI OA vs CTRL**	**PF OA vs CTRL**
	Mean	**SD**	**Min-Max**	**Mean**	**SD**	**Min-Max**	**Mean**	**SD**	**Min-Max**	**F / H**	***P-value***	***P-value***	***P-value***	***P-value***
Age (years)	63.86	5.96	51-70	58.47	9.79	38-74	59.67	7.96	43-70	3.216 (H)	0.196	N.S.	N.S.	N.S.
Height (m)	1.72	0.11	1.48-1.90	1.73	0.08	1.57-1.85	1.72	0.07	1.63-1.83	0.218 (H)	0.897	N.S.	N.S.	N.S.
Weight (kg)	82.64	12.50	59-100	84.13	15.09	64-111	77.36	15.85	53-111	0.888 (F)	0.419	N.S.	N.S.	N.S.
BMI	28.01	4.23	21.7-34.6	28.01	4.21	21.4-34.6	26	4.27	20.0-34.6	1.109 (F)	0.34	N.S.	N.S.	N.S.
Walking Speed (m/s)	0.91	0.17	0.61-1.27	0.97	0.19	0.65-1.27	1.25	0.15	0.96-1.46	16.498 (F)	< 0.001	0.592*	< 0.001*	< 0.001*
Stride Length (% Height)	0.64	0.05	0.56-0.75	0.65	0.09	0.44-0.75	0.78	0.06	0.66-0.88	19.835 (F)	< 0.001	0.940*	< 0.001*	< 0.001*
COFAS	Type 1	4		Type 1	7		N/A							
	Type 2	5		Type 2	0									
	Type 3	5		Type 3	6									
	Type 4	1		Type 4	2									

SPM analysis

The results showed significant SPM{F} main effects for all three groups for foot kinematics (ankle, shank-calcaneus, Chopart), and kinetics (ankle, shank-calcaneus, Chopart, Lisfranc, first metatarso-phalangeal joints). Post-hoc comparisons of the time-series data showed no differences between PF OA and PS OA groups for all foot kinematic and kinetic variables. In contrast, differences were shown in kinematics and kinetics between PF OA and CTRL groups and between PS OA and CTRL groups.

Foot joint angles

During loading response and midstance, the PF OA group showed a more abducted shank-calcaneus joint position (*P*=0.003; 0-60%) associated with a less abducted position of the Chopart joint (*P*=0.012; 4-26%) compared to the CTRL group. Further significant differences were found at pre-swing, where the ankle and shank-calcaneus joints of both pathological groups exhibited a less plantarflexed position (PS vs CTRL : ankle (*P*=0.006) & shank-calcaneus (*P*=0.017); PF vs CTRL : ankle (*P*=0.012) & shank-calcaneus (*P*=0.015)) as well as a less adducted shank-calcaneus position compared to CTRL (PS vs CTRL : shank-calcaneus (*P*=0.017); PF vs CTRL : shank-calcaneus (*P*=0.016)) (Figure 5.2).

Joint moments

Comparison of the joint moments of all intrinsic joints of the foot of the two pathological groups to those of the CTRL group, showed the largest differences to occur in the sagittal plane at between pathological 60% and 86% of the stance phase of gait (*P*<0.001)(Figure 5.3-5.5). The PS OA group also showed a decreased abduction moment at the ankle (*P*=0.007; 57-62%) and the shank-calcaneus joint (*P*<0.001; 54-66%) compared to the CTRL group. In contrast, the PF OA group showed only a decreased abduction moment at the shank-calcaneus joint (vs CTRL : *P*<0.001; 54-66%). With respect to the frontal plane, significant differences were only observed for the ankle joint (for both pathological groups) and for the first metatarso-phalangeal joint (PF OA) compared to CTRL.

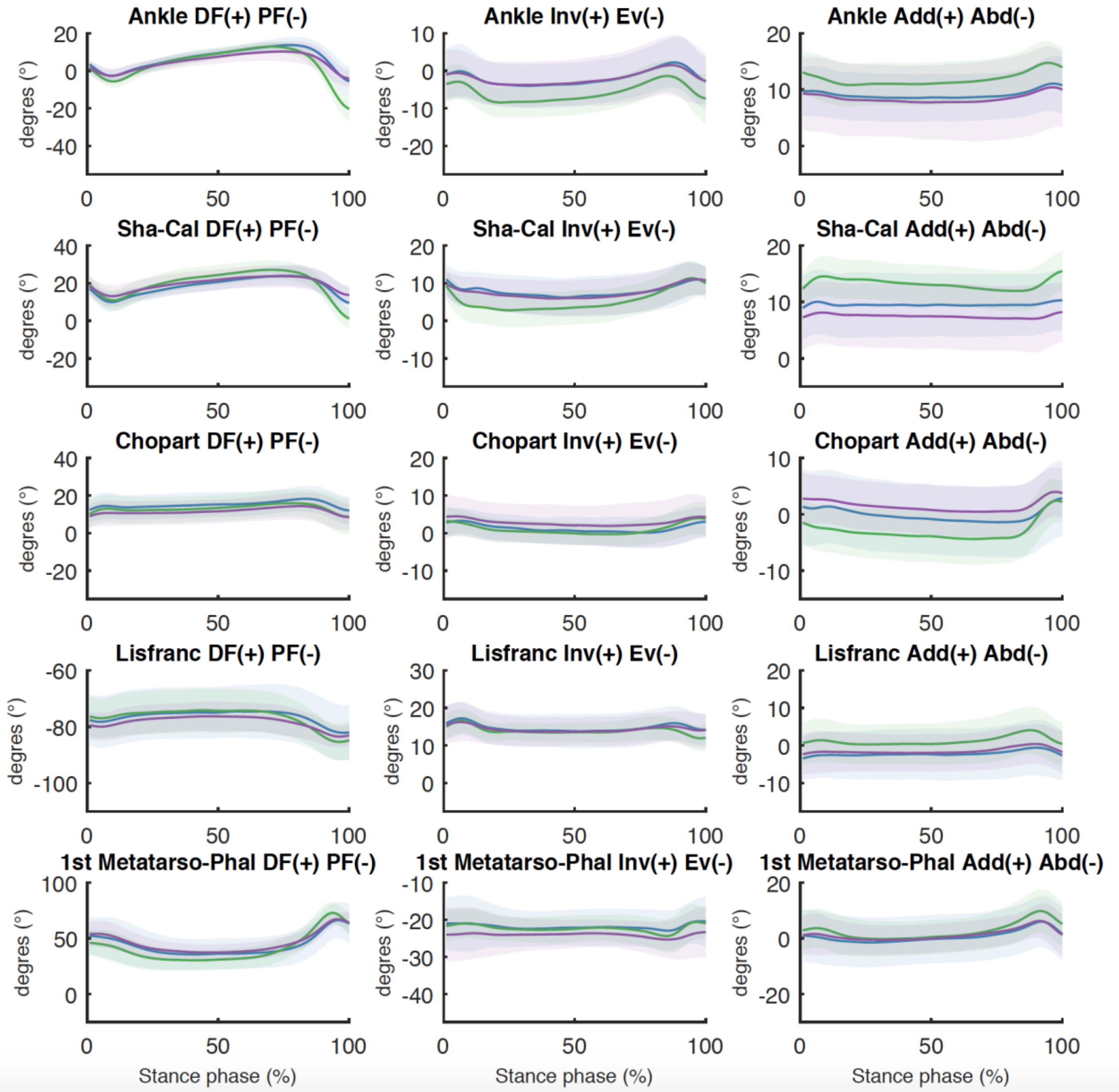

Figure 5.2 : Kinematic waveforms representation with +/- 1 standard deviation cloud for the intrinsic joints of the foot: Ankle (between the Foot and Shank); Sha-Cal: Shank-Calcaneus ; 1st Metatarso-Phal: 1st Metatarso-Phalangeal joint. PS OA group (blue), CTRL group (green) and PF OA (purple); DF: dorsiflexion ; PF: plantarflexion; Add: Adduction ; Abd :Abduction ; Inv: Inversion ; Ev: Eversion.

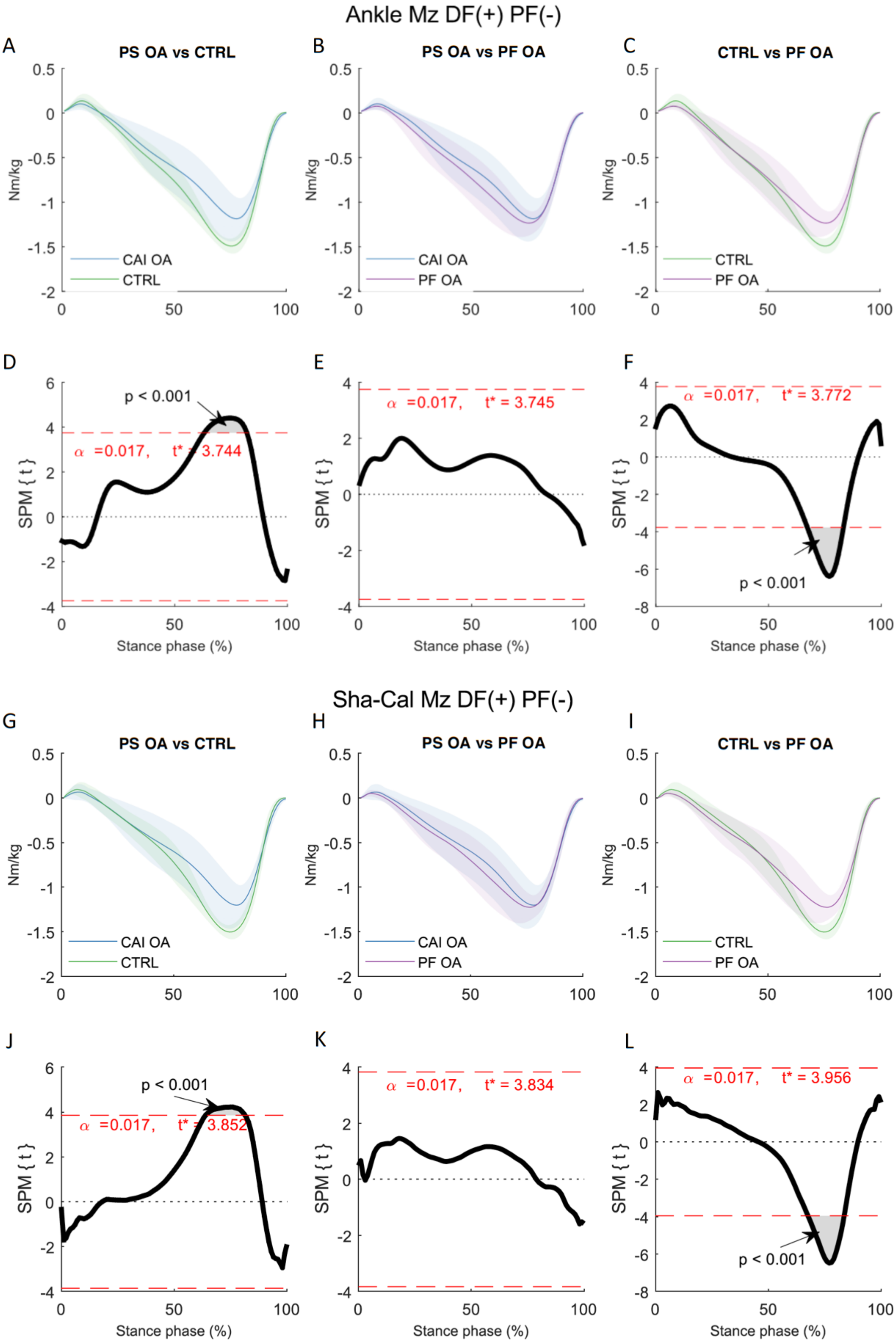

Figure 5.3 : Kinetic between-group comparison of inter-segmental Ankle and Shank-Calcaneus joint moment (Mz) during the stance phase of gait. PS OA group (blue), CTRL group (green) and PF OA (purple). Absorption. *A-C,G-I*:Mean kinetic trajectories with their respective standard deviation clouds. *D-F, J-L*: SPM results: SPM{t} is the trajectory of the post-hoc two-sample t-test. The dotted red lines indicate the random field theory threshold for significance and p-values indicate the likelihood that a random process of the same temporal smoothness would be expected to produce a suprathreshold cluster of the observed size.

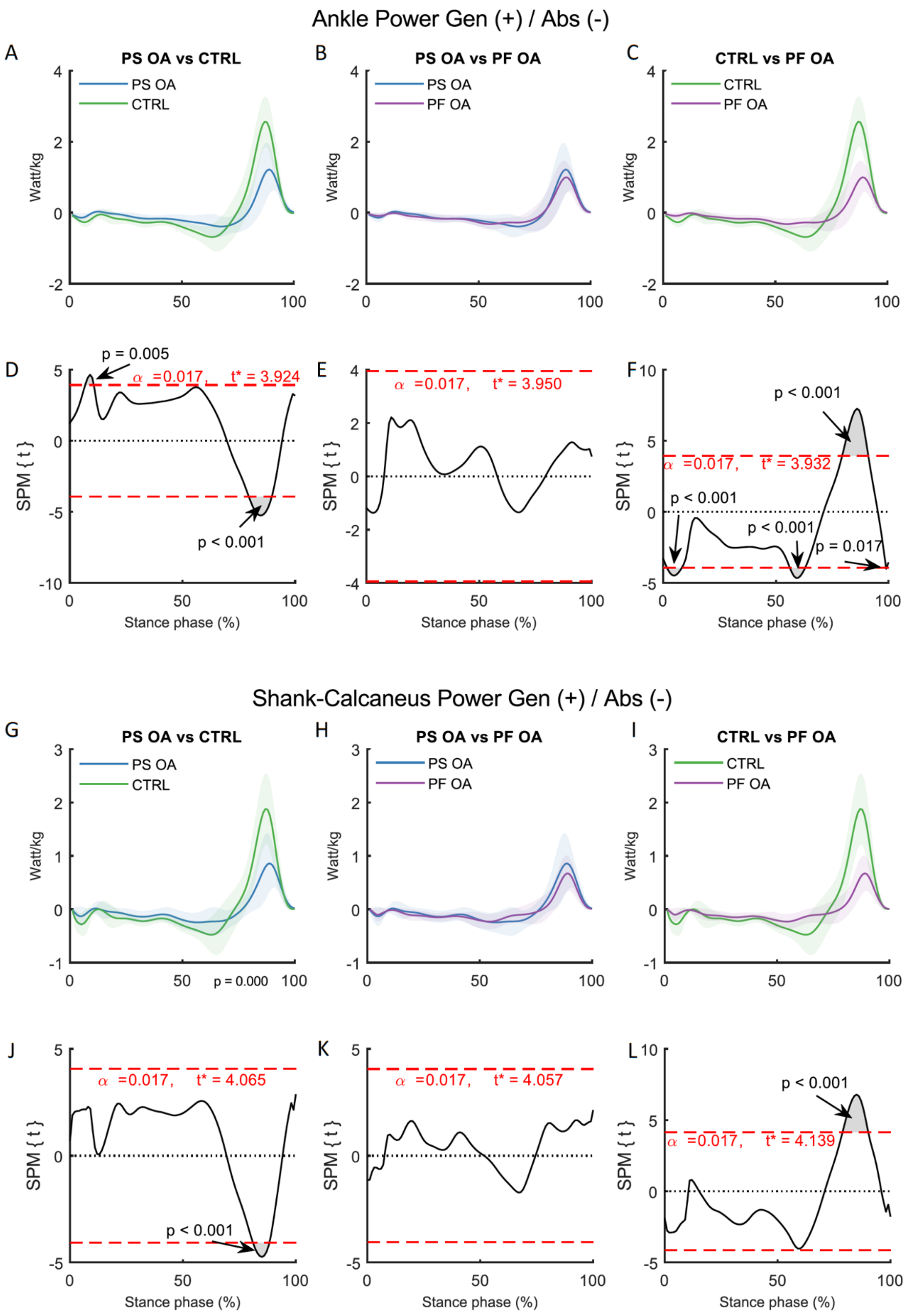

Figure 5.4 : Kinetic between-group comparison of inter-segmental Ankle and Shank-Calcaneus joint power during the stance phase of gait. PS OA group (blue), CTRL group (green) and PF OA (purple). Abbreviations: Gen (+): Generation ; Abs (-): Absorption. *A-C,G-I*: Mean kinetic trajectories with their respective standard deviation clouds. *D-F, J-L*: SPM results: SPM{t} is the trajectory of the post-hoc two-sample t-test. The dotted red lines indicate the random field theory threshold for significance and p-values indicate the likelihood that a random process of the same temporal smoothness would be expected to produce a suprathreshold cluster of the observed size.

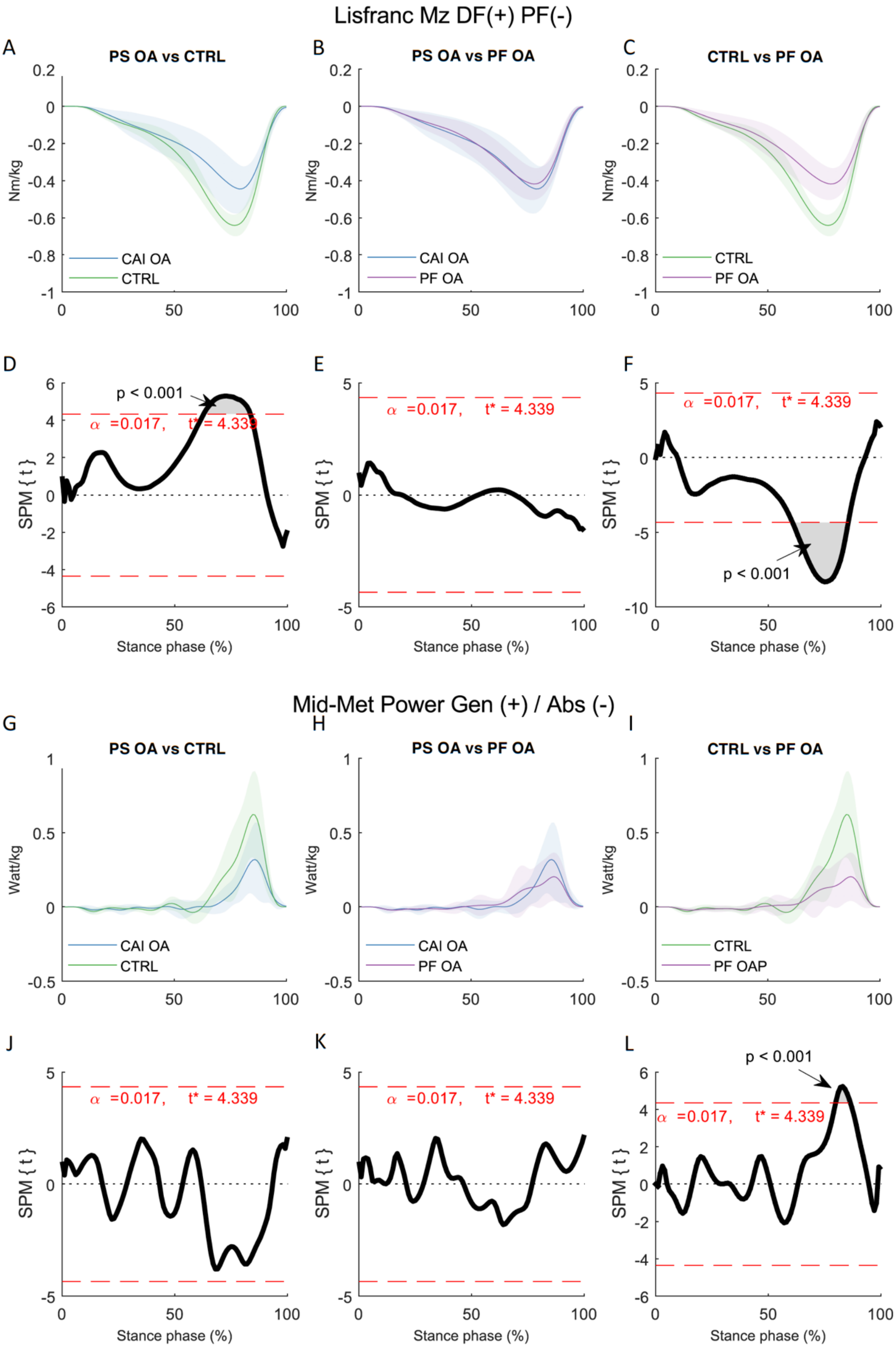

Figure 5.5 : Kinetic between-group comparison of inter-segmental Lisfranc joint moment (Mz) and power during the stance phase of gait. PS OA group (blue), CTRL group (green) and PF OA (purple). Abbreviations: Gen (+): Generation; Abs (-): Absorption. *A-C,G-I*: Mean kinetic trajectories with their respective standard deviation clouds. *D-F, J-L*: SPM results: SPM{t} is the trajectory of the post-hoc two-sample t-test. The dotted red lines indicate the random field theory threshold for significance and p-values indicate the likelihood that a random process of the same temporal smoothness would be expected to produce a suprathreshold cluster of the observed size.

Power and 3D angle $\alpha_{M\omega}$

During loading response, a significantly lower ankle power absorption was observed for both pathological groups (PS vs CTRL (*P*=0.004; 6-11%); PF vs CTRL (*P*=0.012; 3-8%)) (Figure 5.4). In addition, the PS OA group demonstrated a lack of resistance-configuration during loading response (*P*=0.015) compared to the CTRL group based on 3D angle $\alpha_{M\omega}$. At the end of midstance, the PF OA group showed a lower ankle power absorption compared to the CTRL group. At heel off, significantly lower ankle and shank-calcaneus power generation were observed for both pathological groups compared to the CTRL group (Figure 5.4). More noteworthy differences in power patterns were observed for the PF OA group highlighting lower Lisfranc joint complex power generation (*P*<0.001; 79-87%) as well as lower power absorption at the first metatarso-phalangeal joint (*P*<0.001; 75-85%) compared to CTRL (Figure 5.5).

DISCUSSION

To our knowledge, this was the first study to compare the foot kinematics and kinetics of patients suffering from post-fracture ankle osteoarthritis to those of patients suffering from post-sprain ankle osteoarthritis. We did not find any differences in joint angles and moments between the pathological groups. We believe that there may be two possible explanations for this lack of differences. Firstly, patients suffering from end-stage ankle osteoarthritis adopt an antalgic walking strategy to prevent shear loading through their painful ankle joint.[29] This may suggest that the results of this study could be attributed to the fact that both pathological groups had adopted a similar walking pattern to avoid pain in their arthritic ankle. Secondly, patients with ankle osteoarthritis often present concomitant foot and ankle deformities, which may affect the intrinsic foot joint mechanics during gait.[10,11] It is therefore plausible to suggest that both pathological groups may have had similar intra- and extra-articular foot and ankle deformities, the effects of which masked the more subtle differences resulting from the primary pathologies. Future biomechanical studies should therefore include the assessment of intra- and extra-articular foot and ankle deformities, the addition of which may provide further insight into the mechanical deficits associated with ankle osteoarthritis.

One of the objectives of this study was also to compare the foot mechanics of patients suffering from post-traumatic ankle osteoarthritis to those of a group of asymptomatic subjects. Overall, the gait alterations identified were comparable with corresponding results from previous studies. The gait of our post-traumatic patients was characterized by a decreased walking speed, decreased stride length and reduced ankle kinematics and kinetics in comparison with the CTRL group.[1,24,26] A reduction in sagittal plane range of motion (ROM) at the ankle and shank-calcaneus joints, particularly during pre-swing, as well as a reduced transverse plane ROM at the shank-calcaneus joint, were observed in both pathological osteoarthritis groups compared to the CTRL group. These findings are in accordance with those from previous studies.[1,24,29] In contrast to the results of Valderrabano et al. (2007), no significant reduction in ROM was observed in the frontal plane. However, both post-traumatic ankle osteoarthritis groups tended to have a more inverted ankle and shank-calcaneus joint position during loading response and early midstance compared to the CTRL group. Furthermore, the PF OA group exhibited a significantly more adducted position of the Chopart joint during the same period of gait. It is reasonable to assume that the inverted hindfoot position, in association with a more adducted position of the Chopart joint, may be explained by a co-contraction phenomenon between the tibialis anterior and gastrocnemius muscle, both foot and ankle adductor and invertor muscles, in an attempt to keep the ankle joint stable from heel strike to midstance.[25]

Multi-segment kinetic foot models have recently been shown to be sensitive enough to detect differences between the gait of healthy subjects and the gait of patients with ankle osteoarthritis.[6,20] This study has provided further insight into the kinetic behavior of the Chopart joint and Lisfranc joint complex by using a four-segment foot model. The results showed that both post-traumatic ankle osteoarthritis groups displayed significantly less plantarflexion moment for all intrinsic joints of the foot during propulsion compared to the control group. Valderrabano et al. (2007) suggested that the reduction of moments in post-traumatic ankle osteoarthritis may be a consequence of the associated atrophy and weakness of the lower leg muscles or a protective gait strategy to reduce loading in the painful joint.[29]

Direct comparison between the two ankle osteoarthritis groups revealed no differences in joint power. However, when the two groups were individually compared to the CTRL group, the results suggested that PS OA reduces power generation only at the ankle and shank-calcaneus joints, whereas PF OA results in reductions in joint power at the ankle and shank-calcaneus joints as well as at the Lisfranc and first metatarso-phalangeal joints. This could be explained by the nature of trauma in the PF OA group, as the soft-tissue envelope around the fractured ankle may have become scarred and inelastic due to fibrosis after osteosynthesis surgery, affecting the functioning of the extrinsic foot muscle tendons, and thus the function of the joints distal to the ankle joint. Previous studies have provided further evidence of lower leg muscle dysfunction in patients suffering from end-stage post-traumatic ankle osteoarthritis resulting from secondary arthritic muscle atrophy, arthrogenous muscle inhibition or a combination of the two.[16,25]

Since walking speed affects foot kinetics, caution should be exercised when interpreting the differences in joint moments and power between our pathological groups and the control group as their walking speed differed.[4] However, it is of interest to note that the 1D-analysis did not reveal any significant differences in the 3D angle $\alpha_{M\omega}$ variable between the groups. This could mean that subjects suffering from post-traumatic ankle osteoarthritis have adapted their gait to avoid loading the painful ankle without affecting how the joints of the foot are driven or stabilized by the moments. The findings therefore suggest that walking speed may not fully explain the differences observed in foot kinetics between the CTRL and the ankle osteoarthritis groups. Future studies investigating foot joint kinetics should address this limitation by comparing symptomatic subjects with speed-matched control subjects.

CONCLUSION

This paper provides the first quantification and comparison of multi-segment foot kinematics and kinetics between subjects suffering from post-fracture ankle osteoarthritis and post-sprain ankle osteoarthritis. No significant differences were found between the two pathological groups. However, it was found that the alteration in foot mechanics in the two pathological groups was not limited to the painful ankle joint, but also affected the kinetics of the adjacent and non-adjacent foot.

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Chapter 6 : The effect of ankle and hindfoot malalignment on foot mechanics in patients suffering from post-traumatic ankle osteoarthritis

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ABSTRACT

Background: Ankle and hindfoot malalignment is a common finding in patients suffering from post-traumatic ankle osteoarthritis. However, no studies have addressed the effect of concomitant foot deformities on intrinsic foot kinematics and kinetics. Therefore, the objective of this study was to investigate the effect of ankle and hindfoot malalignment on the kinematics and kinetics of multiple joints in the foot and ankle complex in patients suffering from post-traumatic ankle osteoarthritis.

Methods: Twenty-nine subjects with post-traumatic ankle osteoarthritis participated in this study. Standardized weight-bearing radiographs were obtained preoperatively to categorize patients as having cavus, planus or neutral ankle and hindfoot alignment, based on 4 X-ray measurements. All patients underwent standard gait assessment. A 4-segment foot model was used to estimate intrinsic foot joint kinematics and kinetics during gait. Statistical parametric mapping was used to compare foot kinematics and kinetics between groups.

Findings: There were 3 key findings regarding overall foot function in the 3 groups of post-traumatic ankle osteoarthritis: (i) altered frontal and transverse plane joint angles and moments of the hindfoot and Chopart joint in the cavus compared to the planus group; (ii) in cavus OA group, Lisfranc joint abduction sought to compensate the varus inclination of the ankle joint; (iii) there were no significant differences in joint angles and moments between the planus and neutral OA groups.

Interpretation: Future studies should integrate assessment of concomitant foot and ankle deformities in post-traumatic ankle osteoarthritis, to provide additional insight into associated mechanical deficits and compensation mechanisms during gait.

Keywords: ankle osteoarthritis, malalignment, foot kinetics, kinematics, gait

INTRODUCTION

End-stage ankle osteoarthritis rarely occurs in isolation, but more often presents concomitant ankle and hindfoot deformities.[18] As the ankle is a weight-bearing joint, the intra-articular load distribution is not only influenced by the alignment of the tibiotalar joint itself but is also highly dependent on extra-articular mechanical forces related to the 3D orientation of the subtalar joint, anatomic variants in the hindfoot joints, and alignment of the medial column of the foot.[16] Malalignment of the ankle and hindfoot joints in ankle osteoarthritis has been investigated intensively in the last decade, mainly on conventional radiography and weight-bearing computed tomographic scans.[16–18] However, there is a paucity of literature regarding the interrelationship between structural changes to underlying bony anatomy and alterations in foot mechanics during gait in patients suffering from post-traumatic ankle osteoarthritis.[10,12,15] Khazzam et al. (2006) used radiographic tibiotalar alignment measurements to correct the orientation and segment-embedded reference frames of their foot model.[15] Unfortunately, the effect of this angle on foot kinematics was not assessed. The interrelationship between radiographic tibiotalar alignment measure and plantar pressure distribution was investigated by Horisberger et al. (2009), who found that post-traumatic ankle osteoarthritis patients with a varus malalignment had a significantly greater pressure center excursion index than those with valgus malalignment.[12] In terms of kinematics and kinetics, Grier et al. (2016) investigated the effect of preoperative tibiotalar malalignment on postoperative lower-limb coronal plane mechanics during gait after total ankle replacement associated with realignment surgery. Patients with preoperative tibiotalar malalignment showed biomechanics similar to that of patients with neutral preoperative alignment.[10] However, the nature of the deformity was characterized only by a single radiographic value assessing the intra-articular ankle deformity, regardless of any concomitant foot deformities. The impact of concomitant foot deformities on intrinsic foot mechanics in post-traumatic ankle osteoarthritis has not been explored, as foot kinematics and kinetics were generally computed on a rigid foot modeling approach, without information on Lisfranc and Chopart joint function. The present study therefore aimed to investigate the effect of ankle and hindfoot malalignment on the gait kinematics and kinetics of multiple joints of the foot and ankle complex in patients suffering from post-traumatic ankle osteoarthritis.

METHODS

Participants

Twenty-nine subjects with post-traumatic ankle osteoarthritis scheduled for primary total ankle replacement or ankle fusion between January 2017 and June 2019 participated in this study (Table 6.1). This study was approved by the local review board (B200-2017-061) and all participants signed an informed consent form. Exclusion criteria were (1) age <18 years, (2) systemic or neurological disease, and (3) any medical problem other than post-traumatic ankle osteoarthritis liable to affect gait. Standardized weight-bearing radiographs of the foot and the ankle were obtained preoperatively to assess the concomitant foot and ankle deformities and categorize them in three deformity groups. Cavus type (hereafter referred as cavus OA) was defined as: varus position of the hindfoot and ankle joint complex, bony dorsum deformity of the midfoot characterized by dorsiflexion of the talus within the ankle, upward position of the metatarsals with respect to the ground, and high medial longitudinal arch (Figure 6.1 A,B,C). Planus type (hereafter referred as planus OA) was defined as: valgus position of the hindfoot and ankle joint complex, collapse deformity of the midfoot characterized by a plantar flexion of the talus within the ankle, downward position of the metatarsals with respect to the ground, and low medial longitudinal arch (Figure 6.1 D,E,F). Neutral type ((hereafter referred as neutral OA) had no midfoot, hindfoot or ankle malalignment. Osteoarthritis severity was scored on the Canadian Orthopaedic Foot & Ankle Society (COFAS) classification system (Table 6.1)[18]: Type 1, isolated ankle osteoarthritis; Type 2, ankle osteoarthritis associated with intra-articular ankle deformity or tight heel cord or both; Type 3, ankle osteoarthritis with deformity of the hindfoot, midfoot, tibia or forefoot; and Type 4, Type 1 to 3 with subtalar or calcaneocuboid or talonavicular osteoarthritis.[18]

Radiographic assessment

Radiographic assessment comprised: (1) standardized anteroposterior ankle Méary view to measure the hindfoot deformity (<90° = valgus; >90° = varus) and intra-articular ankle varus or valgus alignment (Tibia-Talus) (<90° = valgus; >90° = varus);[18,21] (2) standardized weight-bearing lateral foot (and ankle) view to measure the midfoot deformity as the talar/1st metatarsal angle (≥10°)[18](≤ 170° = bony dorsum deformity; ≥ 190° = collapse deformity) and the medial longitudinal arch deformity as Djian-Annonier angle (≥10°) (≤ 115° = high arch; ≥ 130° = low arch) (Table 6.1 & Figure 6.1).[5]

Table 6-1 : Demographic, spatio-temporal and radiographic data for the three patient groups: post-traumatic ankle osteoarthritis associated with planus foot deformity (Planus OA), with cavus foot deformity (Cavus OA), and without foot deformity (Neutral OA). Abbreviations: COFAS: Canadian Orthopaedic Foot & Ankle Society classification system for ankle osteoarthritis; MLA: medial longitudinal arch; SD: standard deviation; BMI: body mass index; N/A: not applicable; N.S.: not significant. Statistics: Depending on the distribution of the demographic and spatio-temporal data, 1-way ANOVA (normal distribution) or Kruskal-Wallis test (non-normal distribution) were used to assess statistical differences for each variable between the three groups. *Gabriel's post-hoc test (adjusted *P*-value 0.3/3=0.017); ** post-hoc Mann-Whitney U test (adjusted *P*-value 0.3/3=0.017).

	Planus OA (n=8 ankles)			**Cavus OA (n=10 ankles)**			**Neutral OA (n=12 ankles)**			**ANOVA (F)[a] / Kruskal-Wallis (H)[b]**		**Planus OA vs Cavus OA**	**Planus OA vs Neutral OA**	**Cavus OA vs Neutral OA**
	Mean	**SD**	**Min-Max**	**Mean**	**SD**	**Min-Max**	**Mean**	**SD**	**Min-Max**	**F / H**	***P-value***	***P-value***	***P-value***	***P-value***
Age (years)	63.50	11.32	38-74	61.44	7.4	51-73	59.17	7.3	46-68	2.848 (H)	0.241	N.S.	N.S.	N.S.
Height (m)	1.71	0.12	1.48-1.87	1.73	0.08	1.65-1.90	1.73	0.1	1.57-1.90	0.171 (F)	0.844	N.S.	N.S.	N.S.
Weight (kg)	84.6	11.00	69-99	79.6	12.3	65-100	85.5	16.4	59-111	0.511 (F)	0.606	N.S.	N.S.	N.S.
BMI	29.1	3.79	24.3-33.8	26.5	4.21	22.0-34.6	28.4	4.32	21.4-34.6	0.940 (F)	0.403	N.S.	N.S.	N.S.
Walking Speed (m/s)	0.88	0.21	0.61-1.27	0.98	0.17	0.73-1.22	0.95	0.17	0.65-1.27	0.693 (F)	0.509	N.S.	N.S.	N.S.
Stride Length (% Height)	0.63	0.07	0.56-0.75	0.65	0.06	0.58-0.74	0.66	0.08	0.45-0.75	0.424 (F)	0.659	N.S.	N.S.	N.S.
Meary (degrees)	79.6	2.86	75-84	91.4	4.03	85-99	85.5	2.84	81-90	28.513 (F)	< 0.001	< 0.001*	0.002*	0.001*
MLA (degrees)	126.4	10.41	108-141	110.6	4.62	104-115	118.9	4.66	111-126	14.967 (H)	0.001	0.002**	0.044 (N.S.)**	0.002**
TALOM1 (degrees)	187.5	11.07	174-202	170.4	6.54	162-185	178.4	5.07	170-186	11.513 (F)	< 0.001	<0.001*	0.038 (N.S.)*	0.055*
TibiaTalus (degrees)	83.6	7.07	72-93	97.2	7.5	90-109	89.5	3.9	82-93	12.610 (H)	0.002	0.001**	0.052**	0.022 (N.S.)**
COFAS	Type 1	1		Type 1	2		Type 1	8						
	Type 2	2		Type 2	3		Type 2	0						
	Type 3	5		Type 3	4		Type 3	2						
	Type 4	0		Type 4	1		Type 4	2						

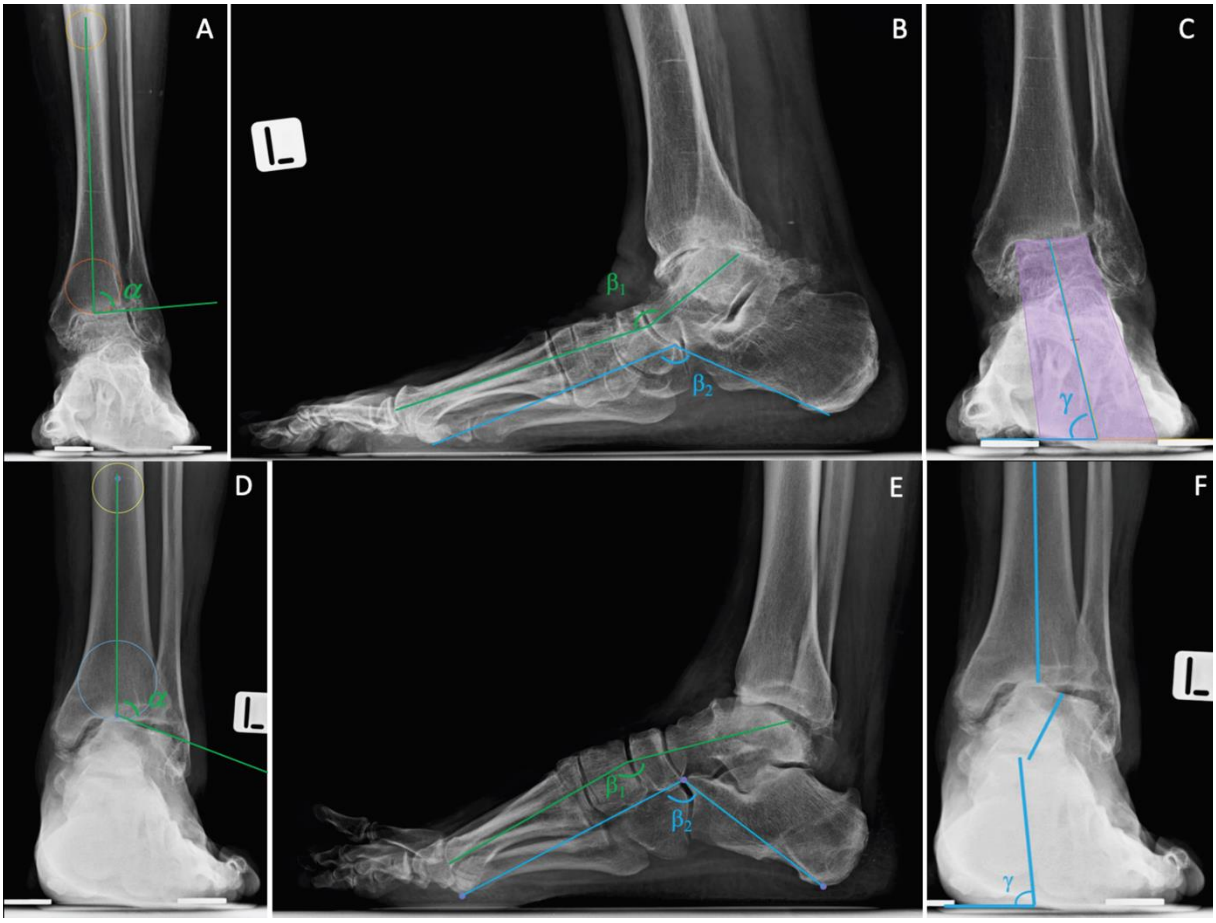

Figure 6.1 : (A,C,D,F) Standardized anteroposterior ankle Méary radiographic view to measure the hindfoot deformity. Hindfoot axis with respect to the ground (γ angle: valgus ≤ 80 degrees; varus ≥ 95 degrees) and the intra-articular ankle varus or valgus alignment (position of the talus with respect to the axis of the tibia: ≤80° valgus; ≥ 100° varus);[12,19] (B,E) Standardized weight-bearing lateral foot (and ankle) radiographic view to measure the midfoot deformity as the talar/1st metatarsal angle (β1 angle: ≤ 170° high arch (cavus); ≥ 190° low arch (planus)) and medial longitudinal arch deformation as the Djian-Annonier angle (β2 angle: ≤ 115° high arch (cavus); ≥ 130° low arch (planus)). Fig 1 A,B,C are foot and ankle deformities associated with the planus OA group; D,E,F, associated with the cavus OA group. Fig. F shows the "zig-zag" deformity, as the subtalar joint goes in the opposite direction (valgus) of the tibiotalar deformity (varus).

Data collection

In the measurement session, patients walked at self-selected speed over a 10m walkway in which an AMTI (Advanced Mechanical Technology, Inc., Watertown, MA, USA) with embedded force plate and Footscan® pressure plate (0.58 m x 0.42 m; 4,096 sensors, 2.8 sensors per cm^2; RSscan International, Paal, Belgium). The force plate was custom-made to fit the dimensions of the pressure plate. This set-up provided continuous calibration of the pressure plate with respect to the force plate, using an RsScan® 3D box. Sixteen 8mm retro-reflective markers were placed on the foot and shank of each participant, according to the multi-segment Rizzoli foot model.[19] To record kinematic data during walking over the walkway, a passive optoelectronic motion analysis system (Qualysis, Göteborg Sweden) consisting of 8 Miqus cameras was used, sampling at 200 Hz. All marker trajectories were computed by Qualysis Tracking Manager 2.16 (Qualysis, Göteborg Sweden). Integration and synchronization of the 3 hardware devices used a Miqus Sync unit interface (Qualysis, Göteborg Sweden). Data from the force and pressure plates were measured at a sampling rate of 200 Hz. Five representative trials were collected per participant. A trial was considered representative when the foot of interest made clear contact with the pressure plate without visual adjustment in walking behavior. Walking speed was required to be similar across all trials in a given recording session.

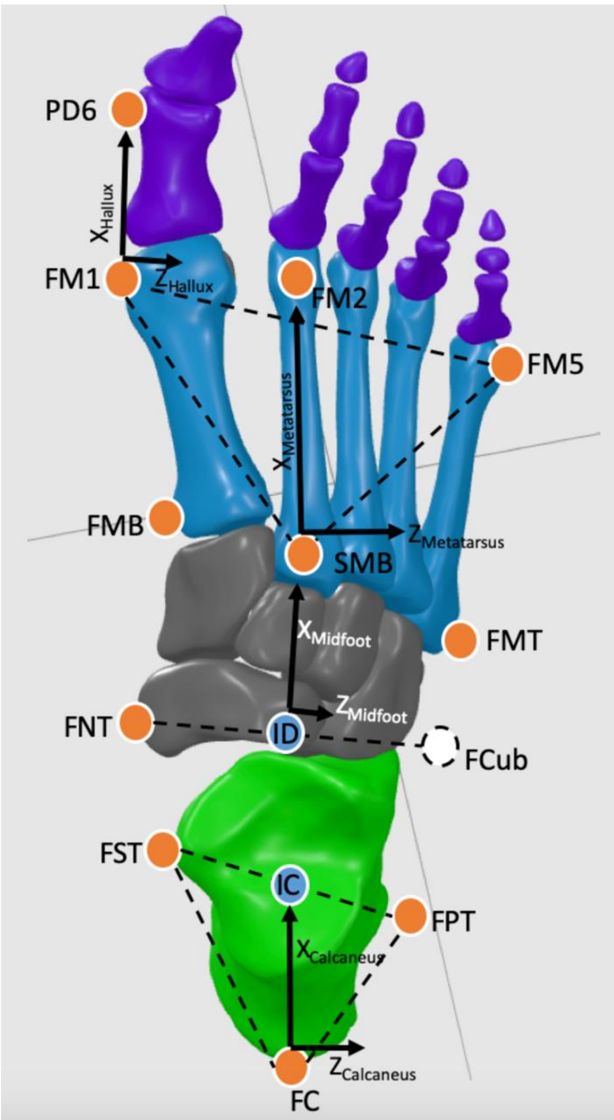

Figure 6.2 : Inter-segment centers were defined according to an adapted version of Rizzoli's foot model (Leardini et al. 2007) developed by Deschamps et al. (2017) (IOR-4Segment-model 1). Marker names: upper ridge of the posterior surface of the calcaneus (FC); peroneal tubercle (FPT); sustentaculum tali (FST); virtual cuboid marker (FCub), tuberosity of the navicular bone (FNT); 1st, 2nd and 5th metatarsal base (FMB, SMB, FMT); 1st, 2nd and 5th metatarsal head (FM1, FM2, FM5); PD6: distal dorso-medial aspect of the head of the proximal phalanx of the hallux; 1st metatarso-phalangeal joint center (FM1; midfoot-metatarsus center (SMB); calcaneus-midfoot center (ID)

Data analysis

Inter-segment center definitions of the 4-segment foot model were based on an adapted version of Rizzoli's 3D multi-segment foot model, developed by Deschamps et al. (2017) (IOR-4Segment-model 1) (Figure 6.2).[4] The main differences between IOR-4Segment-model 1[4] and Rizzoli's foot model[19] consists in the creation of a virtual cuboid marker at two-thirds of the distal distance between the peroneal tubercle and the base of the fifth metatarsal, and in the definition of the calcaneus-midfoot joint center. Inter-segment 3D rotations were computed according to Deschamps et al.'s IOR-4Segment-model 1 (2017), following ISB recommendations[4], and were defined as follows: shank-calcaneus joint (midpoint between the malleoli markers, describing the shank-calcaneus center), Chopart joint (midpoint between the cuboid and the navicular bone, describing the calcaneus-midfoot center), Lisfranc joint (at the second metatarsal base, describing the midfoot-metatarsus center), and 1st metatarso-phalangeal joint (projection of 1st metatarsal head marker vertically at mid distance to the ground, describing the metatarsus-hallux center).

Joint forces (**F**) and moments (**M**) were computed in the inertial coordinate system by a bottom-up inverse dynamic method using a Newton-Euler recursive algorithm based on a homogeneous matrix formalism during the stance phase of gait.[20] Kinematic and force data were filtered using a low-pass zero-lag 4th order Butterworth filter, with 10 Hz cut-off frequency. Inertia and weight parameters of each foot segment were neglected, considering that inertia effects during stance are negligible compared to external forces.[23] The force plate data were distributed over each foot segment using a validated proportionality scheme.[8,24] The subarea of each foot segment was estimated for each time frame by projecting the markers' position vertically on the sensor matrix of the pressure platform. The resulting center of pressure (CoP) of each estimated subarea was used as the CoP for the corresponding foot segment in inverse dynamics calculations. The joint moments were expressed in the proximal segment coordinate system. In supplement to the joint power, the 3D angle $\alpha_{M\omega}$ between the joint moment (**M**) and the joint angular velocity (**ω**) vectors was calculated as described by Dumas and Chèze (2008).[7] When the 3D angle $\alpha_{M\omega}$ is <60° or >120°, the moment mainly drives the joint, with, respectively, propulsion or resistance; when it is between 60° and 120°, the moment mainly stabilizes the joint.[7] Inter-segment kinematic and kinetic computations and extraction of discrete spatio-temporal variables (walking speed and stride length) were performed using an in-house Matlab© program (The Mathworks Inc., Natick, MA, USA). Internal joint moments and powers were normalized by subject-mass and all 1D data were time-normalized to 100% of the stance phase.

Statistical analysis

First, the Shapiro-Wilk test was used to check data normality. One-way ANOVA and Kruskal-Wallis test were used to identify significant differences between groups for demographic, spatio-temporal and radiographic variables. For significant differences, Gabriel's post-hoc test or the Mann-Whitney-U test (adjusted *P*-value (0.5/3=0.017) were used to indicate which groups were different. All statistical tests were conducted on SPSS software (version 25, IBM Corp, Chicago, USA). One-dimensional statistical parametric mapping (SPM) was used to compare foot kinematics and kinetics between groups, using an open-source code (v.M.0.4.5; www.spm1d.org) in Matlab© (The Mathworks Inc., Natick, MA, USA).[5,16] The main advantages of this methodological approach is that SPM regards the whole time-series as the unit of observation and that time-dependence is incorporated directly in statistical testing. 1D-SPM 1-way ANOVA over the normalized time series was used to confirm significant differences between groups. If statistical significance was reached, a post-hoc 1D-SPM 2-sample t-test (post-hoc *P*-value 0.05/3 = 0.017) was used to determine between which groups the significant differences occurred.

RESULTS

Demographic, spatiotemporal and radiographic data

No inter-group differences were found for the demographic and spatio-temporal variables (Table 6.1). Significant differences were found between the cavus and planus OA groups for all radiographic parameters. The cavus OA group also showed significantly greater medial longitudinal arch deformation than the neutral OA group. Méary angle was significantly different on all between-groups comparisons.

SPM analysis

There were significant SPM{F} main effects between the three groups for all the intrinsic foot joints.

Planus OA versus neutral OA

Post-hoc comparisons showed no differences between planus and neutral OA groups for any foot joint angles or moments. However, 1D-analysis revealed that the planus OA group exhibited a greater shank-calcaneus power pattern (*P*=0.016; 93-94%) at end of stance phase than the neutral OA group.

Cavus OA versus neutral OA

The cavus OA group showed a more inverted angle of the shank-calcaneus joint (*P*=0.017, 0-6% & *P*<0.001, 10-72%) associated with a more abducted angle of the Lisfranc joint (*P*<0.001; 0-100%) than the neutral OA group during almost the entire stance phase. The 1st metatarso-phalangeal joint showed greater dorsiflexion (*P*=0.013; 40-50%) in the cavus than in the neutral OA group during midstance. Post-hoc comparisons showed no differences in kinetics between these two groups.

Cavus OA versus planus OA

The main differences observed between the planus and cavus OA groups all concerned the frontal and transverse plane (Figure 6.3-6.4). The planus OA group showed a significantly more everted shank-calcaneus joint angle (*P*<0.001; 0-77%) associated with a more abducted Chopart joint angle (*P*<0.001; 0-94%) than the cavus OA group. The moment patterns revealed that the planus OA group exhibited larger shank-calcaneus inversion moment (*P*<0.001; 10-35%) than the cavus OA group (Figure 6.4). During propulsion, the cavus OA group showed larger shank-calcaneus abduction moment (*P*<0.001; 88-95%) than the planus OA group. However, no differences were observed for power or 3D $\alpha_{M\omega}$ angle patterns between the cavus and planus OA groups.

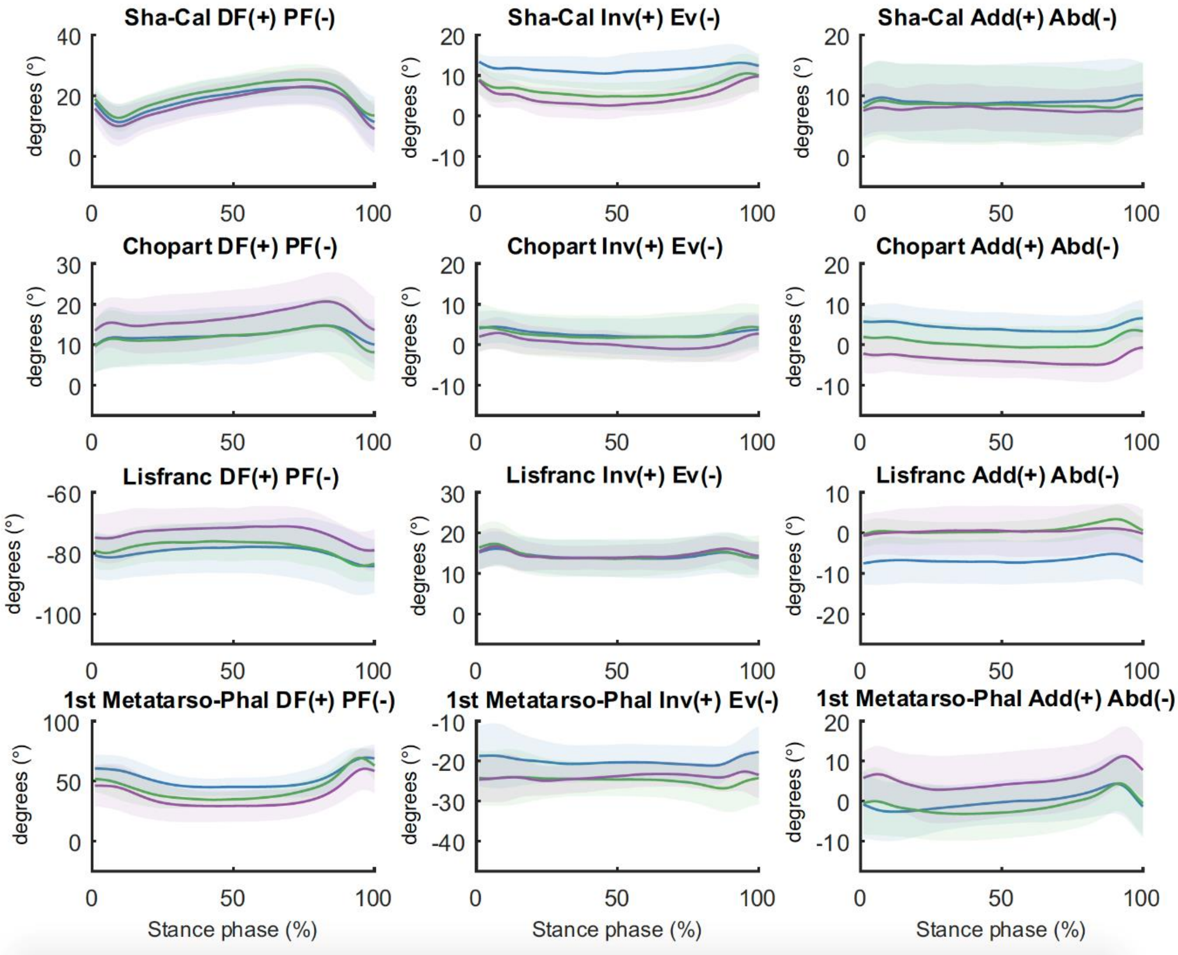

Figure 6.3 : Kinematic waveform representation with ±1 standard deviation cloud for the intrinsic foot joints: Sha-Cal: Shank-Calcaneus; 1st Metatarso-Phal: 1st Metatarso-Phalangeal joint. Cavus OA group (blue), Neutral OA group (green) and Planus OA (purple); DF: dorsiflexion; PF: plantar flexion; Add: Adduction; Abd: Abduction; Inv: Inversion; Ev: Eversion.

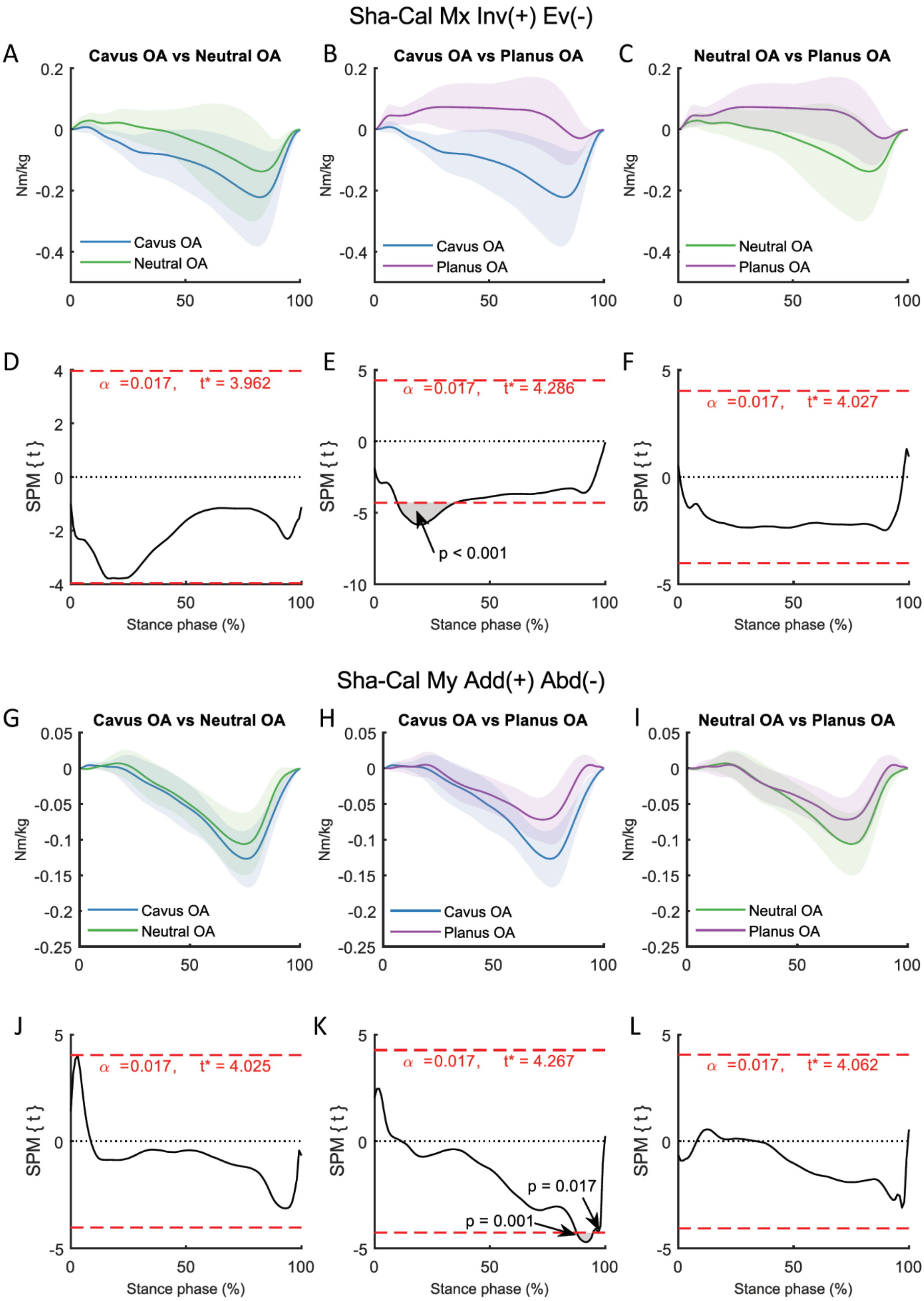

Figure 6.4 : Kinetic between-group comparison of inter-segmental Shank-Calcaneus joint moments (Mx & My) during the stance phase of gait. Cavus OA group (blue), Neutral OA group (green) and Planus OA group (purple); Sha-Cal: Shank-Calcaneus; *A-C,G-I*: Mean kinetic trajectories with their respective standard deviation clouds. *D-F, J-L*: SPM results: SPM{t} is the trajectory of the post-hoc 2-sample t-test. The dotted red lines indicate the random field theory threshold for significance, and p-values indicate the likelihood that a random process of the same temporal smoothness would be expected to produce a suprathreshold cluster of the observed size.

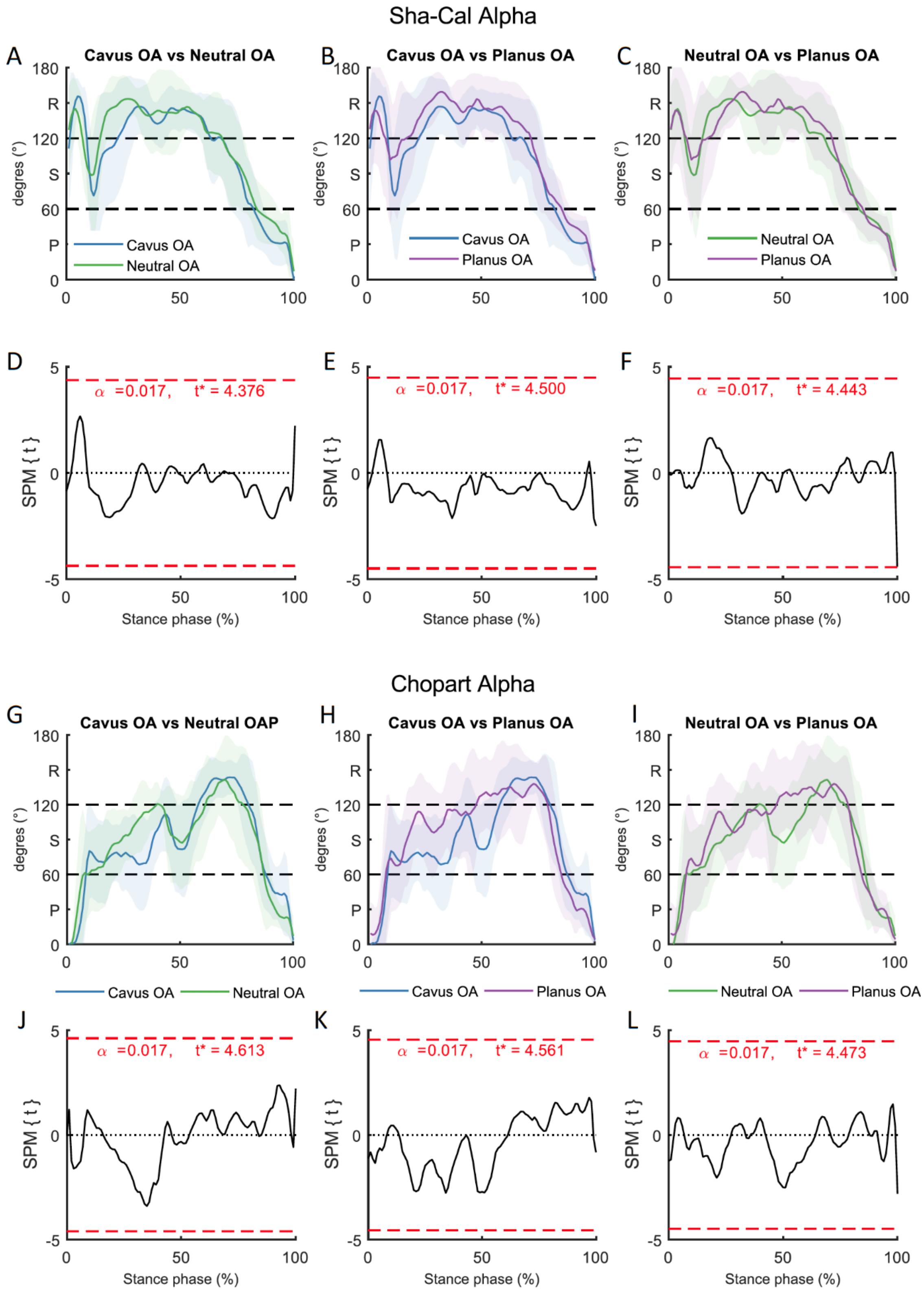

Figure 6.5 : Kinetic between-group comparison of 3D angle $\alpha_{M\omega}$ of the Shank-Calcaneus and Chopart joints during the stance phase. Cavus OA group (blue), Neutral OA group (green) and Planus OA group (purple); Sha-Cal: Shank-Calcaneus; When the 3D angle $\alpha_{M\omega}$ is <60° or >120°, the moment mainly drives the joint, with, respectively, propulsion (P) or resistance (R). When the 3D angle $\alpha_{M\omega}$ is between 60° and 120°, the moment mainly stabilizes the joint (S); *A-C,G-I*: Mean kinetic trajectories with their respective standard deviation clouds. *D-F, J-L*: SPM results: SPM{t} is the trajectory of the post-hoc 2-sample t-test. The dotted red lines indicate the random field theory threshold for significance, and p-values indicate the likelihood that a random process of the same temporal smoothness would be expected to produce a suprathreshold cluster of the observed size.

To our knowledge, this was the first study to investigate the effect of ankle and hindfoot malalignment on the intrinsic foot mechanics in patients suffering from post-traumatic ankle osteoarthritis. Results showed that the cavus OA group presented a distinctive pattern of joint angles and moments compared to the neutral and planus OA groups. These differences shed light on a number of radiographic concepts which are currently used regarding the compensatory mechanism of the neighboring joints of the ankle, and in particular in the surgical management of intra- and extra-articular deformities in ankle osteoarthritis.

Concerning 3D inter-segmental rotations and actions, the most important differences were observed between the cavus and planus OA groups in the shank-calcaneus and Chopart joints during almost the entire stance phase. Our data seem to provide further evidence of the interrelationship between foot structure and alterations in foot mechanics. The cavus OA group showed a significantly greater inverted shank-calcaneus joint angle and a more adducted Chopart joint angle than the planus OA group. It is further believed that the etiology of these differences is mainly guided by the multiplanar orientation of the talus, guided in turn by the geometry of the subtalar joint.[13] Radiographic and anatomical studies suggested that pes cavus feet have a high vertical subtalar joint axis associated with a talar head placed tightly within a subtalar joint geometry featuring a V-shaped groove, limiting subtalar joint motion.[6,13] In contrast, the subtalar joint in pes planus feet seems to be characterized by a lower vertical axis associated with larger and relatively flat articular facets, allowing greater range of motion in the subtalar joint.[1,13] This notion of talar head stability provided by the orientation of the axis and the subtalar joint geometry is further underpinned by the 3D $\alpha_{M\omega}$ angle of the shank-calcaneus and Chopart joints. Even though, with the numbers available, no significant difference could be demonstrated here, it could be observed from the 3D $\alpha_{M\omega}$ angle waveforms that both joints in the planus OA group adapted a more resistant configuration than in the cavus OA group (Figure 6.5). This could mean that the planus OA group has to counter higher external forces than the cavus OA group, to keep the foot from collapsing and to stabilize it during walking.

Another noteworthy finding in our study was the significant difference in joint angles between the cavus and the neutral OA groups. As expected, the cavus OA group showed a more inverted angle of the shank-calcaneus joint than the neutral OA group during a significant part of the stance phase. One may expect from the kinematic coupling between the foot segments that cavus OA would exhibit a more adducted angle of the Lisfranc joint in association with the inverted position of the shank-calcaneus joint compared to neutral OA; instead, a significantly more abducted position of the Lisfranc joint was found. This 'twist" in the osteo-articular geometry of foot may represent a compensatory mechanism to counter the varus inclination of the ankle joint and therefore to reduce the stress concentration located in the medial part of the joint. We further believe that this mechanism originates from an eversion of subtalar joint to compensate for the varus deformity of the ankle joint.[11,16] This osteo-articular configuration of the hindfoot and ankle joint complex has often been referred as the "zig-zag" deformity, as the subtalar joint goes in the opposite direction to the tibiotalar deformity (Figure 6.1.F).[11]

The positioning of the 1st metatarso-phalangeal joint was also found to be significantly different, as the cavus OA group showed less hallux plantar flexion with respect to the forefoot than the neutral OA group. This reduced plantar flexion of the 1st metatarso-phalangeal joint may reduce loading underneath the hallux during the stance phase. This finding is supported by comparable studies analyzing kinematic and plantar pressure measurements between normal, planus and cavus feet.[2,3]

The majority of the significant differences were found in the cavus group versus both the neutral and planus groups. In contrast, no significant differences in joint angles or moments were observed between the planus and neutral groups. This suggests that the present results may be attributed to these two pathologic groups adopting a similar walking pattern to avoid pain in their arthritic ankle. Inspection of between-group comparisons found that the cavus OA group had significantly greater radiographic deformities than the neutral and planus OA groups. Only one variable differed significantly between the planus and neutral OA groups. This could mean that the difference in malalignment of the ankle and hindfoot between these two groups was not sufficiently great to be detected dynamically during gait.

The findings of this study should be considered in the context of two limitations. First, our classification of multi-joint, multi-planar foot deformities was based on 2D plain weight-bearing radiographs. Assessment of submalleolar deformity is challenging, due to the limited imaging modalities. New-generation weight-bearing CT scans may be a valuable tool to better represent the 3D orientation of the hindfoot and ankle malalignment in ankle osteoarthritis. Moreover, partitioning of the total ground reaction forces acting on the calcaneus segment was based on an estimation method (proportionality scheme) which combined pressure and force plate data together with marker placement data. Even though this proportionality scheme was validated, the reported ankle joint moments and powers should be regarded as estimates. A second limitation was the use of skin markers to estimate joint centers and segment kinematics. Soft-tissue artefacts have been reported to be as much as 3-4 mm on the surface of the foot.[14] The impact of these errors on the estimation of the moments and powers is currently difficult to estimate.

CONCLUSION

Three key findings in overall foot function were observed between three groups of post-traumatic ankle osteoarthritis: (i) altered frontal and transverse plane joint angles and moments of the hindfoot and Chopart joints in the cavus OA group compared to the planus OA group; (ii) the cavus ankle group, Lisfranc joint abduction tried to reduce the varus inclination of the ankle joint; and (iii) there were no significant differences in joint angles or moments between the planus OA group and the neutral OA group. These findings indicate that malalignment of the hindfoot and the ankle as revealed by radiographic assessment does indeed influence foot mechanics during gait in patients suffering from post-traumatic ankle osteoarthritis.

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Chapter 7 : Quantifying the effect of total ankle replacement using a 1-segment versus a multi-segment foot modeling approach: a pilot study

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ABSTRACT

Background: Kinetic foot models showed that computing ankle joint moments and power with a rigid foot modeling approach overestimates ankle joint power. Nevertheless, studies continue to implement rigid foot models to assess the effect of total ankle replacement on gait. Therefore, our aim was to compare the effect of total ankle replacement on ankle joint angles, moments and power as assessed on a 1-segment versus a multi-segment kinematic and kinetic foot model. In addition to the comparison between pre- and postoperative conditions of the patients, postoperative condition were compared to a peer-matched control group.

Methods: A sample of 10 subjects with post-traumatic ankle osteoarthritis scheduled for total ankle replacement and 10 asymptomatic subjects was recruited. A 1-segment and a multi-segment kinematic and kinetic foot model were used to calculate intrinsic foot joint kinematics and kinetics during gait. A first linear mixed model was used to investigate the effect of total ankle replacement (preop versus postop) and the effect of the foot model on ankle joint kinematic and kinetic analysis. A second linear mixed model was used to compare ankle joint kinematics and kinetics between groups and the effect of the foot model. Statistical parametric mapping was used to statistically compare pre- to post-operative differences between the two modeling approaches.

Findings: Ankle and shank-calcaneus joint angles did not improve postoperatively except for an increase in range of motion during the loading response phase. Peak plantar flexion moment and peak power generation of both the ankle and the shank-calcaneus joints improved postoperatively, but remained reduced compared with asymptomatic control subjects. No difference in pre- to post-operative outcome was found between the two modelling approaches for the ankle joint.

Interpretation: The effect of total ankle replacement on ankle kinematics is limited. However, the ankle joint kinetics of the two modelling approaches improved postoperatively. Pre- to post-operative outcome difference in ankle joint kinematics and kinetics was not significantly overestimated when computed with 1-segment rigid foot model. Although no significant difference could be demonstrated, we strongly believe that neglecting the intrinsic foot joints can hinder our clinical understanding of how a therapeutic intervention benefits or degrades the patient's biomechanical performance.

INTRODUCTION

Currently, therapeutic success in total ankle replacement is primarily assessed on clinical, radiographic and questionnaire outcomes.[5,22] Recent publications have indicated that function is not systematically restored, even if clinical and radiographic parameters show ilmprovement.[22,31] Therefore, during the last decade, substantial efforts have gone into characterizing the impact of total ankle replacement on ankle joint angles and moments during gait.[15] These studies showed that, implantation of a total ankle replacement prosthesis improved ankle joint angles and moments compared to preoperative values, but that they remain impaired compared to asymptomatic subjects.[1,15]

Over the last decade, an increasing number of 3D multi-segment kinematic foot models have become available for clinical use and have clearly shown their clinical relevance in detecting intrinsic foot mobility impairments.[14] Recently, multi-segment kinetic foot models have received increasing attention in methodological and clinical studies, providing new insights into the individual power distributions of the intrinsic joints of the foot.[2,6,18,33] These kinetic foot models further highlighted the shortcomings of computing ankle joint moments and power with a rigid foot modeling approach, as it overestimates ankle joint power,[8,33] potentially leading to clinical misinterpretation of how a therapeutic intervention benefits or degrades biomechanical performance, as the estimated changes simply reflect methodological errors inherent to conventionally modeling the foot as a single rigid segment.[33] Nevertheless, gait analysis studies continue to implement a rigid foot modeling approach to assess the effect of total ankle replacement on ankle joint angles and moments.[29,30]

The purpose of this pilot study was to compare the effect of total ankle replacement on ankle joint angles, moments and power as assessed on 1-segment versus multi-segment kinematic and kinetic foot models, comparing pre- to post-operative difference between the two modeling approaches. We also assessed the effects of the foot model and of the surgical intervention. In supplement, the postoperative ankle kinematics and kinetics of the patients were compared to a peer-matched control group. It was hypothesized that ankle joint angles, moments and power improve after total ankle replacement but remain different from the control group, irrespective of the ankle joint modeling approach, and that the effect of total ankle replacement on ankle joint angles and moments is overestimated on a 1-segment compared to a multi-segment foot model.

METHODS

Participants

A sample of 10 asymptomatic and 10 symptomatic adult patients participated in the study (Table 7.1). All patients suffered from post-traumatic ankle osteoarthritis scheduled for primary total ankle replacement between January 2017 and June 2019. Severity of ankle osteoarthritis was scored using the Canadian Orthopaedic Foot & Ankle Society (COFAS) classification system (Table 7.1).[12] The inclusion criteria for the pathologic group were: post-traumatic end-stage ankle osteoarthritis with indication for total ankle replacement; exclusion criteria comprised: (1) age <18 years, (2) systemic or neurological disease, and (3) any medical problem other than post-traumatic ankle osteoarthritis liable to affect gait. All patients were scheduled for total ankle replacement within 2 weeks of their preoperative data collection, and were tested again 1 year after surgery. A two-component fixed-bearing Cadence® prosthesis (Integra Life Sciences, Plainsboro, NJ, USA) was implanted in all patients. Control subjects were peer-matched according to demographics; exclusion criteria comprised any medical problem possibly affecting normal gait. The local review board approved the study (B200-2017-061) and all participants signed an informed consent form.

Table 7-1 : Demographic data of patients and control subjects (Abbreviations: CTRL: control subjects; BMI: body mass index; SD: standard deviation; N/A: not applicable; preop: preoperative; postop: postoperative)

	Ankle osteoarthritis patients		CTRL subjects		P-values	
	Mean	SD	Mean	SD	Patients vs CTRL	Preop vs Postop
Age (years)	62.7	8.1	61.9	6.4	0.810	N/A
Height (m)	1.7	0.1	1.7	0.1	0.928	N/A
Weight (kg)	80.5	14.2	73.9	17.6	0.370	N/A
BMI (kg/m²)	27.6	4.3	25.2	4.4	0.237	N/A
Male:Female	4	6	6	4	N/A	N/A
Preop Walking speed (m/s)	0.93	0.17	1.18	0.13	0.001	0.009
Postop Walking speed (m/s)	1.08	0.17			0.134	
Preop Stride length (% Height)	0.66	0.06	0.76	0.06	0.001	0.002
Postop Stride length (% Height)	0.74	0.06			0.430	
COFAS						
Type 1	2					
Type 2	1					
Type 3	5					
Type 4	2					

Data collection

The measurement session consisted in asking participants to walk at a self-selected speed over a 10m walkway in which a Footscan® pressure plate (0.5m x 0.4m, 4,096 sensors, 2.8 sensors per cm^2; RSscan International, Paal, Belgium) was mounted on a AMTI-force plate (0.5 x 0.4m; Advanced Mechanical Technology, Inc., Watertown, MA, USA) custom-made to fit the surface dimensions of the pressure plate. This set-up provided continuous calibration of the pressure plate with respect to the force plate, using an RsScan® 3D box. Sixteen 8mm retro-reflective markers were placed on the foot and shank of each participant according to the multi-segment Rizzoli foot model.[13] A passive optoelectronic motion analysis system (Qualysis, Göteborg Sweden) composed of 8 Miqus cameras tracked kinematic data during walking over the instrumented walkway. The 3 different hardware devices were integrated and synchronized by connecting them all up to the Miqus Sync unit interface (Qualysis, Göteborg Sweden). Data from the 3 devices were measured at a sampling rate of 200Hz. Patients suffering from ankle osteoarthritis often experience pain during barefoot walking; to avoid maladaptive walking strategies, 3 representative trials were collected per participant, a trial being considered representative when the foot of interest made clear contact with the pressure plate without visual adjustments in walking behavior. Walking speed was required to remain similar across all trials in a given recording session.

Data analysis

Ankle joint angles and moments were calculated from the rigid Rizzoli foot model (hereafter referred as the ankle joint)[16] and the multi-segment IOR-4Segment-model 1 (hereafter referred as shank-calcaneus joint).[6] In this study, the term joint signifies the modeled biomechanical interaction between two body segments. In the rigid Rizzoli foot model, the ankle joint is defined as the interaction between a rigid-body shank (tibia + fibula) and a rigid-body 1-segment foot. In the 4-segment model, the shank-calcaneus joint refers to the interaction between a rigid-body shank (tibia + fibula) and a rigid-body calcaneus segment. The joint center of both joints was defined as the midpoint between the 2 malleoli markers. Inter-segment 3D rotations were calculated according to rigid Rizzoli foot model and the multi-segment IOR-4Segment-model 1, following ISB recommendations.[6,13,32]

Joint forces (**F**) and moments (**M**) were computed in the Inertial Coordinate System by a bottom-up inverse dynamic method using a Newton-Euler recursive algorithm based on a homogeneous matrix formalism during the stance phase of gait.[17] Kinematic and force data were filtered using a low-pass zero-lag 4^{th} order Butterworth filter, with cut-off frequency of

10 Hz. Inertia and weight parameters of each foot segment were discounted, as the inertia effects were negligible compared to external forces during stance.[10,27] The force plate data were distributed over each foot segment using a validated proportionality scheme.[7,28] Subarea per foot segment was estimated for each time frame by projecting the marker positions vertically on the sensor matrix of the pressure platform. The resulting center of pressure (CoP) of each estimated subarea was then used as the CoP for the corresponding foot segment in the inverse dynamics calculations. Joint moments were expressed in the proximal segment coordinate system. An in-house Matlab© program (The Mathworks Inc., Natick, MA, USA) was used for inter-segment kinematic and kinetic computations. Internal joint moments and powers were normalized by subject-mass and all 1-dimensional data were time-normalized to 100% of the stance phase.

The main characteristic for ankle osteoarthritis is the alteration of the sagittal plane ankle mechanics. Therefore, the following discrete zero-dimensional variables were extracted from the sagittal plane: range of motion of both joints for 5 gait sub-phases (stance phase, loading response, midstance, terminal stance and pre-swing), peak plantar flexion and dorsiflexion angles, peak plantar flexion moment and peak ankle power generation. Even though joint power is computed from 3D data, ankle joint power represents a variable of interest as it is essentially generated by the ankle plantarflexor muscles. In addition, walking speed and stride length were extracted as discrete zero-dimensional spatio-temporal variables.

Statistics

First, the Shapiro-Wilk test was used to check data normality. Independent t-tests (significance threshold, $p<0.05$) were conducted to compare demographic data between asymptomatic and symptomatic participants. A linear mixed model was used to model the relationship of dependent variables (RoM for each subphase of interest of the gait cycle; peak plantar flexion moment and peak ankle power generation) over time (pre- versus post-operative) in patients receiving total ankle replacement for post-traumatic ankle osteoarthritis.[19,26] All results were analyzed in 3 ways: according to time, to foot model, and to time plus foot model, each as the main effect. A second linear mixed model was used to model the relationship of dependent variables (RoM for each subphase of interest of the gait cycle; peak plantar flexion moment and peak ankle power generation) between groups (patients versus controls).[19,26] All results were analyzed in 3 ways: according to group, to foot model, and to group plus foot model, each as the main effect. All statistical tests used R software, version 3.4.3. (https://www.r-project.org/; The. R Foundation for Statistical Computing, Vienna, Austria). Considering that there were 7 statistical tests performed on the dorsi-/plantarflexion kinematic curve of each modelling approach of the ankle joint, the significance threshold was corrected to α = 0.007 (0.05/7) for the kinematic data to control the type 1 error rate when performing multiple comparisons. Significance threshold was set at α = 0.05 for joint moment and power variables.

One-dimensional statistical parametric mapping (SPM) was used to statistically compare pre- to post-operative difference values between the two ankle joint modeling approaches for the dorsiflexion and plantar flexion joint angles, joint angular velocity, dorsiflexion and plantar flexion joint moments, and joint power using an open-source code (v.M.0.4.5; www.spm1d.org) in Matlab© (The Mathworks Inc., Natick, MA, USA).[5,16] The main advantages of this methodological approach is that SPM regards the whole time-series as the unit of observation and that time-dependence is incorporated directly in statistical testing. 1D-SPM paired t-test over the normalized time series was used to assess significant differences between pre- and post-operative conditions.

RESULTS

Demographic and spatiotemporal data

No significant differences between the two groups were found for age, weight, height or BMI (Table 7.1). The spatiotemporal parameters showed a statistically significant improvement in walking and stride length after surgery, with the postoperative values comparable to controls (Table 7.1).

Pre- versus post-operative condition

Time as main effect. No significant 'time' effect was found for the kinematic variables except for the loading response. However, a nearly significant increase in range of motion was observed for midstance (P = 0.008). Significant increases in peak plantar flexion moment (P = 0.002) and in peak power generation (P = 0.007) were found after surgery.

Foot model as main effect. A significant 'foot model' effect was found, in which ankle osteoarthritis patients showed higher values both pre- and post-operatively for peak plantar flexion, peak power generation, loading response and pre-swing range of motion on the 1-segment (ankle) than on the multi-segment (shank-calcaneus) foot model (Table 7.2).

Time plus foot model as main effect. No significant 'time plus foot model' effect was found for any of the investigated variables (Table 7.2).

Table 7-2 : Kinematic and kinetic comparison of ankle joint outcome variables measured with a 1-segment and a multi-segment foot model between pre- and post-operative conditions. *P*-values for kinematic variables (α = 0.007) and for kinetic variables (α = 0.05) of between-times effect, between-models effect and time*foot model interaction effect are presented. Bold P-values indicate significant difference.

Variable	Preoperative (n=10) (Mean ± SD)		Postoperative (n=10) (Mean ± SD)		Effect (P-values)		
	One-segment	Multi-segment	One-segment	Multi-segment	Time	Foot Model	Time*Foot Model
Ankle kinematics (°)							
- RoM	17.1 ± 5.4	13.5 ± 5.3	21.2 ± 4.0	16.7 ± 2.9	0.067	0.014	0.720
- Peak DF	9.4 ± 3.7	7.5 ± 4.2	9.2 ± 3.2	7.8 ± 2.9	0.833	0.302	0.764
- Peak PF	9.6 ± 5.5	4.0 ± 6.4	13.4 ± 3.8	7.5 ± 4.7	0.081	**0.006**	0.910
- Loading response RoM	6.8 ± 2.9	6.5 ± 2.2	9.3 ± 2.6	7.5 ± 2.4	**<0.001**	**0.004**	0.072
- Midstance RoM	8.6 ± 3.0	6.3 ± 2.9	10.4 ± 2.4	8.7 ± 2.5	0.008	0.064	0.572
- Terminal stance RoM	0.7 ± 0.5	0.7 ± 0.7	1.2 ± 0.8	0.9 ± 0.8	0.344	0.189	0.305
- Pre-Swing RoM	16.3 ± 5.4	11.9 ± 5.2	20.5 ± 4.0	15.5 ± 3.3	0.036	**0.005**	0.777
Moment (N.m/kg)							
- Peak PF moment	1.2 ± 0.2	1.2 ± 0.2	1.3 ± 0.2	1.3 ± 0.2	**0.002**	0.764	0.726
Power (W/kg)							
- Peak Generation	1.2 ± 0.5	0.8 ± 0.3	1.8 ± 0.7	1.3 ± 0.7	**0.007**	**0.018**	0.858

Table 7-3 : Kinematic and kinetic comparison of ankle joint outcome variables measured with a 1-segment and a multi-segment foot model in control subjects and patients after total ankle replacement (TAR). *P*-values for kinematic variables (α = 0.007) and for kinetic variables (α = 0.05) of between-times effect, between-models effect and time*foot model interaction effect are presented. Bold P-values indicate significant difference.

Variable	Control (n=10) (Mean ± SD)		TAR Patients (n=10) (Mean ± SD)		Effect (P-values)		
	One-segment	Multi-segment	One-segment	Multi-segment	Group	Foot Model	Time*Foot Model
Ankle kinematics (°)							
- RoM	31.0 ± 7.0	26.9 ± 6.3	21.2 ± 4.0	16.7 ± 2.9	**<0.001**	**<0.001**	0.678
- Peak DF	11.0 ± 2.9	7.6 ± 3.2	9.2 ± 3.2	7.8 ± 2.9	0.192	0.010	0.240
- Peak PF	23.4 ± 6.1	15.9 ± 6.4	13.4 ± 3.8	7.5 ± 4.7	**0.003**	**<0.001**	0.347
- Loading response RoM	7.8 ± 2.5	7.1 ± 1.8	9.3 ± 2.6	7.5 ± 2.4	0.186	0.101	0.072
- Midstance RoM	11.6 ± 2.9	10.0 ± 3.3	10.4 ± 2.4	8.7 ± 2.5	0.308	**<0.001**	0.809
- Terminal stance RoM	2.0 ± 1.1	1.7 ± 0.8	1.2 ± 0.8	0.9 ± 0.8	0.081	0.0933	0.873
- Pre-Swing RoM	29.6 ± 6.4	25.5 ± 5.8	20.5 ± 4.0	15.5 ± 3.3	**<0.001**	**<0.001**	0.296
Moment (N.m/kg)							
- Peak PF moment	1.5 ± 0.1	1.5 ± 0.1	1.3 ± 0.2	1.3 ± 0.2	**0.021**	**0.001**	0.404
Power (W/kg)							
- Peak Generation	2.8 ± 0.8	2.2 ± 0.7	1.8 ± 0.7	1.3 ± 0.7	**0.016**	**<0.001**	0.378

Control subjects versus patients after total ankle replacement

Group as main effect. A significant 'group' effect was found for peak plantar flexion, and stance phase and pre-swing range of motion, with total ankle replacement patients showing lower peak and range of motion values than controls (Table 7.3). Significant differences in peak plantar flexion moment (P=0.021) and peak power generation (P = 0.016) were found, with control subjects showing higher peak values than patients.

Foot model as main effect. A significant 'foot model' effect was found, with total ankle replacement patients and control subjects all showing lower range of motion and peak values (peak plantar flexion, and stance, midstance and pre-swing range of motion) on the 1-segment (ankle) than on the multi-segment (shank-calcaneus) foot model (Table 7.3). A significant 'foot model' effect was also found for peak plantar flexion moment and peak joint power generation.

Group plus foot model as main effect. No significant 'group plus foot model' effect was found for any of the investigated variables (Table 7.3).

Outcome differences between ankle joint and shank-calcaneus joint

1D-analysis did not reveal any differences in pre- to post-operative change between the ankle joint and shank-calcaneus joint for any of the variables of interest (Figure 7.1).

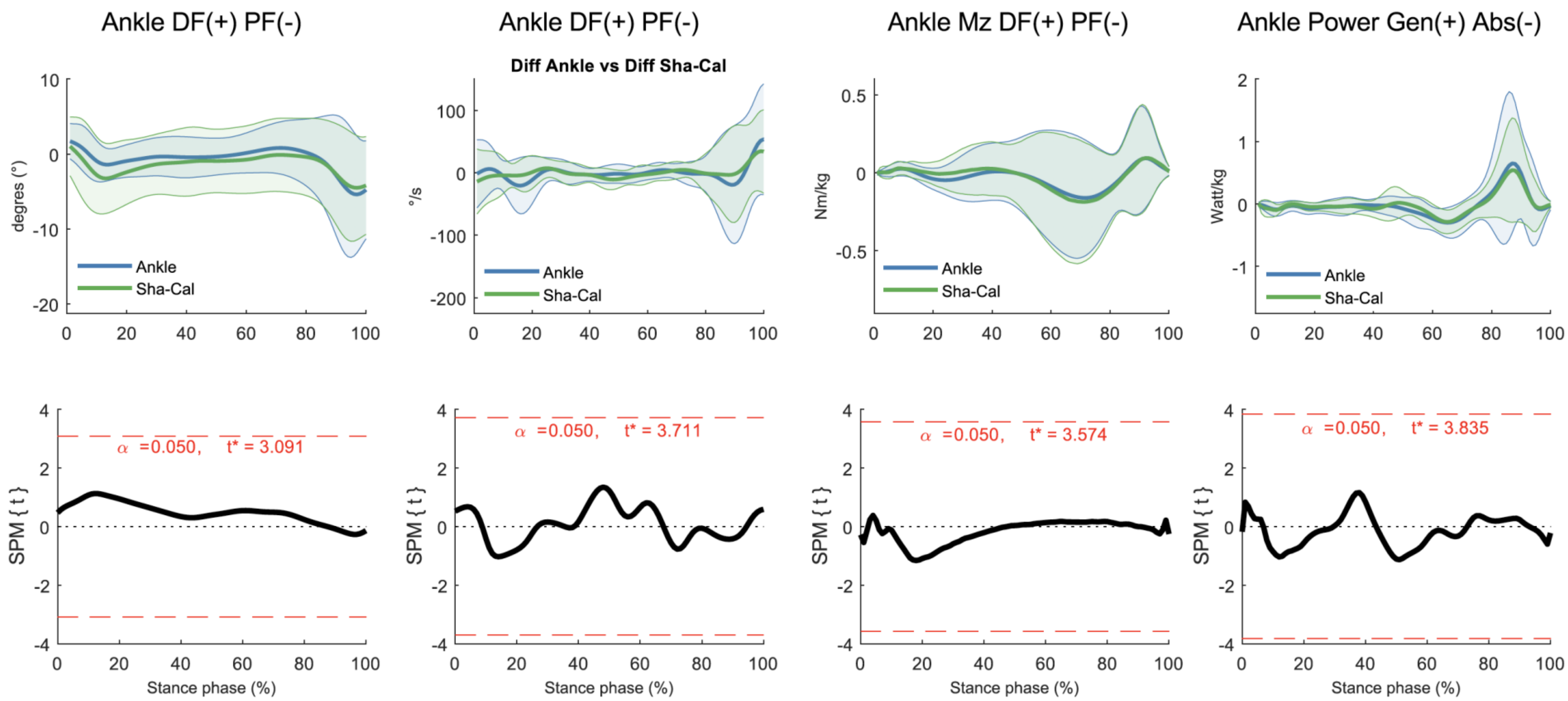

Figure 7.1 : *A-D*: Pre- to post-operative outcome differences between the two ankle joint modeling approaches (blue line: ankle joint; green line: shank-calcaneus joint) for the dorsiflexion-plantar flexion joint angle (A), joint angular velocity (B), dorsiflexion-plantar flexion joint moment (C) and joint power (D). *E,F,G,H:* SPM{t} is the trajectory of the post-hoc paired t-test. The dotted red lines indicate the random field theory threshold for significance and p-values indicate the likelihood that a random process of the same temporal smoothness would to produce a suprathreshold cluster of the observed size. Abbreviations: DF: dorsiflexion; PF: plantarflexion; Gen (+): Generation; Abs (-): Absorption.

DISCUSSION

The aim of this pilot study was to compare the effect of total ankle replacement on ankle joint angles, moments and power assessed with a 1-segment versus a multi-segment kinematic and kinetic foot model. The first hypothesis was only partially confirmed by the results, as the ankle and shank-calcaneus joint angles did not improve post-operatively, except for an increase in range of motion during the loading response phase. However, the peak plantar flexion moment and peak power generation of both ankle and shank-calcaneus joints improved postoperatively, mainly due to patients' ability to walk faster with less pain after surgery. Few studies analyzed fixed-bearing prostheses, and reported contrasting results in terms of increase and decrease in ankle joint angles and moments after surgery.[4,23–25,29] These contrasting results may arise from differences in fixed-bearing implant designs between and within studies. Another explanation may be the data extraction from biomechanical curves in a relatively small number of so-called "summary" metrics (e.g. range of motion values during sub-phases of the gait cycle): as each point on the biomechanical curve has a relationship with other points on the curve, such data reduction may inflate the 'false positives' observed with traditional null-hypothesis significance testing and even lead to opposing results.[20] However, there seems to be a general agreement in earlier studies as well as in the present results, that gait mechanics after total ankle replacement remains impaired compared with asymptomatic control subjects.

One of the objectives of the present study was to compare the effect of total ankle replacement on ankle joint kinematics and kinetics computed with a 1-segment (ankle) and multi-segment (shank-calcaneus) foot model. The outcome of the linear mixed model showed that the 'foot model' had a significant effect on range of motion, peak plantar flexion and peak power generation estimates. This is in accordance with earlier studies highlighting the overestimation of ankle joint angles and peak power generation by the 1-segment foot model compared to the multi-segment foot model.[3,8,33] However, no research yet confirmed this overestimation in patients treated surgically for post-traumatic ankle osteoarthritis. Furthermore, no previous research investigated the effect of the foot modeling approach on how a surgical intervention such as total ankle replacement is estimated to benefit or degrade biomechanical performance. The present study showed no difference in pre- to post-operative outcome between the two modelling approaches for the ankle joint (Table 7.2 and Figure 7.1). However, the danger of modeling the foot as a single rigid body is that motion occurring in the intrinsic foot joints may add an extra rotation of the foot segment relative to the shank. This could then overestimate ankle joint kinematics and angular velocity, resulting in overestimation of ankle joint power. Although no significant difference could be demonstrated on the present data, the pre- to post-operative outcome difference curves suggest that the peak values were greater on the 1-segment (ankle) foot model than on the multi-segment (shank-calcaneus) foot model. Therefore, we strongly believe that neglecting the intrinsic foot joints can hinder our clinical and scientific understanding of how a therapeutic intervention benefits or degrades the patient's biomechanical performance.

The findings of this pilot study should be considered in the context of three limitations. Firstly, sample size was limited to 10 symptomatic and 10 asymptomatic subjects. To detect a minimal clinical change between pre- and post-operative conditions for the variables of interest in the ankle joint (range of motion, peak dorsi- and plantar flexion, peak plantar flexion moment and peak power generation), 35 participants would be needed to detect a significant difference with 80% power and a p-value at 0.05. A second limitation was the partitioning of the total ground reaction forces acting on the calcaneus segment based on an estimation method (proportionality scheme) which combined pressure and force plate data together with marker placement data. Even though this proportionality scheme was validated, the reported ankle joint moments and power should be regarded as estimates. A third limitation was the use of skin markers to estimate joint centers and segment kinematics. Kessler et al. (2019) compared foot motion measured by biplanar videoradiography and optical motion capture,[11] and found soft-tissue artefacts of 3.29 mm on the surface of the foot.[11] However, they found also strong agreement between the two systems for foot motion in the sagittal plane which is the anatomical plane of interest of this pilot study. The impact of these soft tissue errors on the estimation of the foot joint moments and powers is difficult to determine. Therefore, the results of the current study should be considered as an estimation and further research is needed.

CONCLUSION

This paper provides a first estimation of the effect of total ankle replacement on ankle joint angles, moments and power assessed with a 1-segment and a multi-segment kinematic and kinetic foot model. The foot modeling approach may affect the clinical interpretation of how a surgical intervention such as total ankle replacement benefits or degrades the patient's biomechanical performance. Therefore, it is of clinical relevance to assess ankle joint kinematics and kinetics on a multi-segment foot modeling approach.

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Additional reflections and future directions

Methodological considerations

The implementation of an advanced clinical examination platform involved some additional methodological considerations, which were outside the scope of the gait studies presented in this doctoral project.

Firstly, marker placement is often impaired by the close anatomical proximity of foot segments, which may amplify the effect of marker placement errors on subsequent angular calculations. The inter- and intra-session reliability of the Rizzoli Foot Model used in this doctoral project was found to be good to excellent (CMC > 0.88) in both an asymptomatic and a symptomatic population.[6,7] Standardized pre- and post-operative weight-bearing foot and ankle radiographs were systematically taken for each patient, allowing the clinician to measure and estimate the orientation of the foot bones prior to gait analysis, and thus reduce the risk of marker placement error. Recently, efforts were made to develop a foot-related device to standardize marker placement at the calcaneus irrespective of anatomical landmarks.[5,24] The authors suggested that variations in marker placement between therapists were considerably reduced when their calcaneal marker device was used, rather than the palpation method.[5] Their efforts to develop such custom-made devices are to be applauded. However, to the author's knowledge, their use in clinical gait analysis departments or in clinical research is limited to the teams who developed the device. Therefore, the present doctoral project initiated the development of a heel device to standardize and facilitate marker placement on the calcaneus (Figure Heel device 1). Unlike in previously reported calcaneal devices, rulers were integrated in the device, enabling the inter-position between each segment of the device to be recorded and preoperative marker placement to be replicated for postoperative gait assessment. The added value of such a device remains to be evaluated.

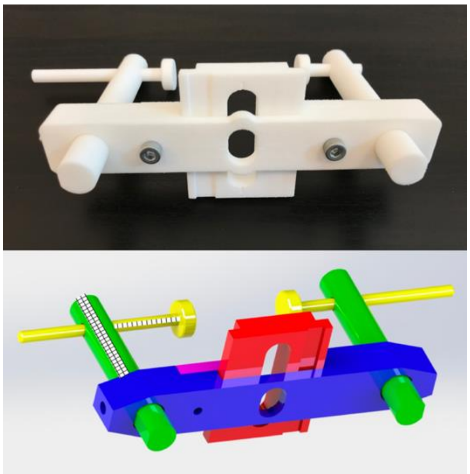

Figure Heel Device 1 : The "Heel Device" was designed to standardize marker placement on the sustentaculum tali and the lateral apex of the peroneal tubercle.

Secondly, soft-tissue artefacts must be considered in segmental foot analysis.[14,20,27] The assumption in the present doctoral project was that the movement of the overlying skin accurately represents the actual movement produced by the underlying bone, which is known as the rigid-body assumption. To assess the errors in experimental data due to violation of the rigid-body assumption, studies compared the use of bone-mounted markers with skin-mounted markers[20,27], and found no systematic error pattern in the degree of skin motion over the underlying foot bones and that the degree of error varied between subjects and between anatomical sites. Recently, Kessler et al. (2019) compared foot motion measured by biplanar videoradiography and optical motion capture.[14] They found good agreement between the two systems for foot motion in the sagittal plane, and reported soft-tissue artefacts of 3.29 mm on the surface of the foot.[14] The impact of these errors on the estimation of foot joint moments and powers is difficult to assess. Therefore, the results of the current study should be considered as an estimate, and further research is needed.

Thirdly, a more comprehensive, detailed and accurate view of foot mechanics was obtained by integrating plantar pressure measurements with a 3D motion analysis system. In the present doctoral project, integration means that both marker trajectories and plantar pressure measurements are measured simultaneously. Plantar pressure was measured by placing a standard Footscan® pressure plate (0.5m x 0.4m, 4,096 sensors, 2.8 sensors per cm^2; RSscan International, Paal, Belgium) on top of an AMTI-force plate (0.5 x 0.4m; Advanced Mechanical Technology, Inc., Watertown, MA, US). The force plate was custom-made to fit the surface dimensions of the plantar pressure plate. This set-up enabled continuous calibration of the pressure plate with respect to the force plate, using a Footscan® 3D interface box (RSscan International, Paal, Belgium), and also synchronized the motion analysis system and the pressure plate by measuring the optimal signal correlation between the force signals of both the pressure and force plates.[11] Furthermore, this 'fusion' approach allowed us to create a 4-segment kinetic foot model, providing new insights into the individual power distributions of the intrinsic joints of the foot. However, the scientific community has formulated doubts about the method used to partition the total ground reaction forces acting on each foot segment. In the present doctoral project, the force plate data were distributed over each foot segment using the proportionality scheme described by Morlock & Nigg (1991) and validated by Saraswat et al. (2014).[19,22] The validity of the proportionality scheme was assessed by comparing the predicted shear forces obtained from the same experimental setup as the present study with the measured shear forces obtained by asking the participants to adopt a 3-step controlled foot placement approach on two adjacent force plates during a walking trial. Mean differences between the shear force measured by 2 adjacent force plates and the shear force predicted by the proportionality scheme in the hindfoot and forefoot segments in a pediatric population were less than 3%. The clinical applicability of the proportionality scheme was further investigated in ankle and hindfoot osteoarthritis subjects, revealing insignificant over- and under-estimation errors in multi-segment foot kinetics by comparing estimated shear forces versus shear forces measured by the adjacent force-plate method.[9] However, these results should be viewed with caution, as errors in determining the point of force application have been found towards the edges of the force plate.[17] Although this proportionality scheme seems to be validated, the reported ankle joint moments and powers in the present doctoral project should be regarded as estimates. However, during the last decade, there seems to be an emerging interest in the development of plantar shear-stress measurement technologies. Integrating such devices in our current measurement set-up could provide further insight into partitioning errors and the clinical validity of the proportionality scheme.

Finally, gait analysis has progressed during recent decades and is now considered the gold standard for the functional assessment of lower-limb pathologies.[10] Moreover, in our opinion, functional evaluation of patients' capabilities should be investigated not only during gait, but also during other more demanding motor tasks. Activities of daily living are not limited to straight walking tasks, but require the ability to adapt in order to avoid obstacles, to support the entire body weight on different terrains, and to change speed and direction as needed to meet functional objectives.[18,23] Currently, no literature exists on the use of 3D multi-segment foot models and plantar pressure measurements in foot and ankle patients in demanding motor tasks that challenge the various foot segments during the complex functions frequently performed in daily life. Demanding motor tasks have proved to be valuable in discriminating subjects with knee disorders,[7] inducing ranges of motion in knee rotation out of the sagittal plane large enough to exceed experimental error and variability across repeated trials.[13] Consequently, the change in skeletal kinematics in pathologic patients was more detectable than during walking. Therefore, we strongly believe that future studies should incorporate demanding motor tasks to evaluate the functional capacity of patients, to provide further insight into their foot mechanics. Furthermore, assessment of these demanding motor tasks should not be restricted to artificial conditions created in the gait laboratory, but could also be evaluated in more natural environment through the use of wearable sensors.

Clinical considerations

In contrast to hip and knee osteoarthritis, the etiology of osteoarthritis and arthritis in the ankle joint is often secondary to a group of diseases (rheumatoid pathology, hemophilia, hemochromatosis, etc.) or injuries (fracture, ankle sprain, etc.). The loss of joint space and cartilage frequently results from a progressive pathomechanical process induced by joint and bone geometry as well as by soft-tissue imbalance. As a consequence of the individual pathomechanical processes associated with ankle osteoarthritis, 'ankle osteoarthritis' covers a large diversity of categories, subtypes and levels of involvement. It is therefore reasonable to assume that there is also a wide variety in gait biomechanics. The interpretation of results can only be valid if this large variability is taken into account.

In research, this is theoretically managed by strict implementation of inclusion and exclusion criteria, to recruit a homogenous study group. However, the systematic review and meta-analysis performed in the present doctoral project showed that the ankle osteoarthritis being investigated, in terms of subtype and associated osteo-articular deformities, was poorly described in 14 of the 17 included gait studies.

Evaluating concomitant joint deformities and intrinsic foot mobility plays an essential role in the surgical management of patients suffering from ankle osteoarthritis.[15,16] However, these key factors and the corresponding alterations in foot biomechanics have never been truly investigated (Cf. Chapters 5 & 6). Chapter 6 aimed at comparing the effect of ankle and hindfoot malalignment on the gait kinematics and kinetics of multiple joints of the foot and ankle complex in patients suffering from post-traumatic ankle osteoarthritis. Our data seem to provide further evidence of the interrelationship between foot structure and alterations in foot mechanics. Therefore, future studies should further investigate this interrelationship, by breaking down the three deformity groups of Chapter 5 into the subgroups presented in Figure Ankle OA Classification. Profiling groups of patients has proved to be a powerful approach in medicine, and is often the first step in treatment algorithms. In ankle osteoarthritis, classification may be used to understand and treat dysfunction, with three major objectives: understanding biomechanical factors related to etiology, predicting progression, and designing optimal treatment strategies. The major challenge associated with the profiling approach is to be able to recruit a sufficient number of patients to create homogeneous study groups for each ankle osteoarthritis profile. The low prevalence (1% of the adult population) of ankle osteoarthritis further complicates recruitment. The number of patients suffering from symptomatic hip and knee osteoarthritis is 9 to 10 times higher than those suffering from symptomatic ankle osteoarthritis.[3,4,13] Therefore, the present doctoral project initiated a multicenter study in two foot and ankle research centers (Lyon and Brussels), following the same research protocol. Recruitment of preoperative ankle osteoarthritis cases has recently started in Lyon (January 2019) and will provide adequate sample size for meaningful statistics. No such multicenter studies have previously been developed.

Critical appraisal of the literature further reveals that the effect of ankle arthrodesis and total ankle replacement is poorly understood from the point of view of foot biomechanics, as the foot is still implemented as a rigid functional segment in gait studies (Chapter 3). There is also a lack of knowledge concerning the correlation between ankle arthrodesis or total ankle arthroplasty positioning and the patient's foot mechanics. Although gait is improved after total ankle replacement or ankle arthrodesis compared to the preoperative situation, patients still experience impaired lower-limb function.[1,8,21,26] They have to make compensatory functional adaptations to remain capable of performing basic activities of daily living. These compensations are known as accessory offending motion hypermobility, which takes the path of least resistance of motion and is an underlying characteristic of degenerative joint disease.[10] Studies showed secondary postoperative arthritic changes in the ipsilateral adjacent joints, with most degeneration occurring in the subtalar joint, followed by the midtarsal joints.[2,25] This is the result of tissue trauma caused by repeated compensatory movements during activities of daily living. When these arthritic changes become symptomatic, additional surgical procedures will be required, exacerbating the functional deficiencies.[12] Unfortunately, these secondary functional limitations and compensatory adaptations and their impact on structures of neighboring joints during activities of daily living have been little studied. Therefore, we strongly believe that future studies should extend biomechanical assessment of the affected to the adjacent and non-adjacent foot joints in order to improve postoperative care.

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General conclusion

In conclusion, this doctoral project provided biomechanical insight into the (patho-)mechanics of ankle osteoarthritis by developing an advanced clinical examination platform. The integration of all the hardware devices composing the platform enabled the creation of a 4-segment kinematic and kinetic foot model, providing valuable information for future clinical reasoning and interpretation. We strongly believe that the combination of such an advanced clinical examination platform in association with clinical and radiographic information will help us to gain further insight into the complex of foot and ankle biomechanics. Before being able to determine an optimal approach, further research is needed. The present doctoral project suggests that profiling ankle osteoarthritis patients solely according to etiology would be a considerable limitation, whereas a biomechanical approach integrating clinical and radiographic information to develop a new classification system may be the state-of-the-art methodological approach for future studies on the mechanical component of ankle osteoarthritis, forming the basis for research on etiology, prediction and treatment of pathological conditions related to ankle osteoarthritis.

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Appendix

Appendix 1 : Chapter 3 : Supplementary material 1 : Results of modified Downs and Black scale

				Segal Cl Biomech 2018		Brodsky FAI 2017		Tenenbaum et al. FAS 2017		Queen CORR 2017		Brodsky BJJ 2016		Grier G&P 2016		Caravaggi Cl Biomech 2015		Queen FAI 2014		Queen JBJS 2014	
				R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
Number	Criteria	Scoring Criteria	Score	1		2		3		4		5		6		7		8		9	
1	Is the hypothesis/aim/objective of the study clearly described?	A point was given if the hypothesis aim or objective of the study was implicitly or explicitly indicated anywhere in the article.	0 = No; 1=Yes	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	Are the main outcomes to be measured clearly described in the "Introduction" or "Methods" section?	A point was given if the main outcomes to be measured were clearly described in the "Introduction" or "Methods" section. The present criteria should be rated with respect to the chosen biomechanical model.	0 = No 1 = Yes	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	Are the characteristics of the patients included in the study clearly described?	A point was given if the inclusion or exclusion criteria, or both, were indicated. Papers should clearly described as criteria : end-stage osteoarthritis; the type of surgery (ankle prosthesis or ankle fusion); if patients are affected on both sides; if patients had previous surgeries on the lower limb or any other disease which could affect gait except osteoarthritis of the ankle and rearfoot; able to walk without aid	0 = No 1 = Yes	1	1	1	1	0	0	1	1	1	1	1	1	1	0	1	0	1	1
4	Are the interventions of interest clearly described?	A point was given if the criteria for guideline adherence were described in detail (description of the prosthesis and ankle arthrodesis or reference to description of the surgery; if not : 0; mentionning the name of the prosthesis is not enough)	0 = No 1 = Yes	0	0	1	1	0	0	1	0	1	1	1	1	1	1	1	1	1	0
5	Are the distributions of principal confounders for each group of participants to be compared clearly described?	Two points were awarded if a study reported the following 5 confounders (Age, Sex ratios, BMI or weight and height and the type of ankle osteoarthritis, walking speed) that might account for differences between groups clearly in table format. One point was awarded if the study indicated that groups were matched for any such demographical variables or if potential confounders were mentioned in the text of the article but not clearly listed in table format OR 3 of the 5 confounders are described. No points were awarded if the study did not report less than 3 or any confounders.	0 = No 1 = Partially 2 = Yes	1	2	1	2	1	1	1	2	2	2	1	1	1	1	1	1	1	1

	Queen et al. Cl Biomech 2014		Choi FAI 2013		Flavin FAI 2013		Queen et al. FAI 2012		Hahn et al. FAI 2012		Brodsky et al. JBJS 2011		Ingrosso et al. G&P 2009		Valderrabano et al. Cl Biomech 2007	
	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
Number	10		11		12		13		14		15		16		17	
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	0	1	0	0	0	0	0	1	0	0	0	0	1	1	1	1
5	1	1	2	2	2	1	2	1	2	1	2	2	2	2	2	2

				Segal CI Biomech 2018		Brodsky FAI 2017		Tenenbaum et al. FAS 2017		Queen CORR 2017		Brodsky BJJ 2016		Grier G&P 2016		Caravaggi CI Biomech 2015		Queen FAI 2014		Queen JBJS 2014		Queen et al. CI Biomech 2014		Choi FAI 2013		Flavin FAI 2013		Queen et al. FAI 2012		Hahn et al. FAI 2012		Brodsky et al. JBJS 2011		Ingrosso et al. G&P 2009		Valderrabano et al. CI Biomech 2007	
				R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
Number	Criteria	Scoring Criteria	Score	1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17	
6	Are the main findings of the study clearly described?	A point was awarded if quantitative data were reported for all of the main outcome measures indicated in the "Introduction" or "Methods" section. Studies analyzing two intervention groups should at least report pre- and post-op results for each group individually or reporting global pre-and post-op results of both groups	0 = No 1 = Yes	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7	Does the study provide estimates of the random variability in the data for the main outcomes?	A point was awarded if the median and interquartile range (for non-normally distributed data), mean, standard error, standard deviation, or confidence intervals (for normally distributed data) were reported for all the main variables related to the biomechanical model.	0 = No 1 = Yes	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8	Have all of the important adverse events that may be a consequence of the intervention been reported?	A point was awarded if any adverse events, unwanted side effects, or lack thereof were explicitly indicated from either adherence or failure to adhere to recommended guidelines. A point was not awarded if the study made no mention of the presence or absence of adverse events.	0 = No 1 = Yes	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	1	0	1	0	0	1	1	0	0
9	Have the characteristics of patients lost to follow-up been describe?	The authors of this tool indicated that this question should be answered "yes" when clear reasons for loss to follow-up were described. For the purposes of this review, a point was awarded if a study explicitly reported the number and reason for patients lost to follow-up.	0 = No 1 = Yes	1	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1	1	0	0	0	0	0	0
10	Have actual probability values been reported (e.g. 0.035 rather than < 0.05) for the main outcomes except where the probability value is less than 0.001?	A point was awarded if the exact P value was provided for both statistically significant and non-significant results for at least the main outcome measures. A point was not awarded if a study simply indicated that the results for the main outcome measures were not significant without providing the exact P value.	0 = No 1 = Yes	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1

Number	Criteria	Scoring Criteria	Score	Segal Cl Biomech 2018		Brodsky FAI 2017		Tenenbaum et al. FAS 2017		Queen CORR 2017		Brodsky BJJ 2016		Grier G&P 2016		Caravaggi Cl Biomech 2015		Queen FAI 2014		Queen JBJS 2014	
				R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
				1		2		3		4		5		6		7		8		9	
11	Were the subjects asked to participate in the study representative of the entire population from which they were recruited?	A point was awarded if the study identified the source population for patients and described how the patients were selected. Patients were determined to be representative if they comprised the entire source population, an unselected sample of consecutive patients, or a random sample (only feasible where a list of all members of the relevant population exists). Where a study did not report the proportion of the source population from which the patients are derived, the question was answered as unable to determine.	1 = Yes 0 = No 0 = Unable to determine	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0
12	Were those subjects who were prepared to participate representative of the entire population from which they were recruited?	The proportion of patients included in the study were representative of the population. Those asked who agreed to participate or responded should be stated. Validation that the sample was representative would include demonstrating that the distribution of the main confounding factors was the same in the study sample and the source population. No point was awarded if the proportion of those asked who agreed to participate or responded was not stated.	1 = Yes 0 = No 0 = Unable to determine	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0
13	Were the staff, places and facilities where the patients were treated, representative of the treatment the majority of patients receive?	A point was awarded unless the study specifically stated that patients were treated by a therapist who received specialized training relative to guideline recommendations.	1 = Yes 0 = No 0 = Unable to determine	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
14	Was an attempt made to blind study subjects to the intervention they have received?	A point was awarded if the patients were not aware of, or would have no way of knowing (as in the case of retrospective studies), which intervention they received. The study was not awarded a point if it was prospective and failed to mention whether the patients had knowledge of whether they were assigned to the guideline adherence group.	1 = Yes 0 = No 0 = Unable to determine	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0
15	Was an attempt made to blind those measuring the main outcomes of the intervention?	A point was awarded if the study specifically stated that those assessing the outcome measures were unaware of (or would have no way of knowing) whether the patients were in the guideline adherence group.	1 = Yes 0 = No 0 = Unable to determine	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Number	Queen et al. Cl Biomech 2014		Choi FAI 2013		Flavin FAI 2013		Queen et al. FAI 2012		Hahn et al. FAI 2012		Brodsky et al. JBJS 2011		Ingrosso et al. G&P 2009		Valderrabano et al. Cl Biomech 2007	
	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
	10		11		12		13		14		15		16		17	
11	1	0	1	1	0	0	1	1	1	1	1	0	1	0	0	0
12	1	0	1	1	0	0	1	1	0	1	1	0	0	1	0	0
13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0

				Segal Cl Biomech 2018		Brodsky FAI 2017		Tenenbaum et al. FAS 2017		Queen CORR 2017		Brodsky BJJ 2016		Grier G&P 2016		Caravaggi Cl Biomech 2015		Queen FAI 2014		Queen JBJS 2014		Queen et al. Cl Biomech 2014		Choi FAI 2013		Flavin FAI 2013		Queen et al. FAI 2012		Hahn et al. FAI 2012		Brodsky et al. JBJS 2011		Ingrosso et al. G&P 2009		Valderrabano et al. Cl Biomech 2007	
				R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
Number	Criteria	Scoring Criteria	Score	1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17	
16	If any of the results of the study were based on "data dredging", was this made clear?	A point was awarded if no retrospective unplanned (at the outset of the study) subgroup analyses were reported.	1 = Yes 0 = No 0 = Unable to	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
17	In trials and cohort studies, do the analyses adjust for different lengths of follow-up of patients, or in case-control studies, is the time period between the intervention and outcome the same for cases and controls?	Where follow-up was the same for all study patients the answer should yes. If diVerent lengths of follow-up were adjusted for by, for example, survival analysis the answer should be yes. Studies where differences in follow-up are ignored should be answered no. The functional state of each subject should be measured at the same time pre-op and post-op. For example, before surgery and 12 months post-op	1 = Yes 0 = No 0 = Unable to determine	1	1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	0	0	1	1	1	1
18	Were the statistical tests used to assess the main outcomes appropriate?	If the distribution of the data (normal or not) was not described, it was assumed that the estimates used were appropriate, and a point was awarded. No point was awarded for studies that reported qualitative or quantitative data without any form of statistical comparisons or if the statistical tests reported were not appropriate.	1 = Yes 0 = No 0 = Unable to determine	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
19	Was compliance with the intervention/s reliable?	If the authors in prospective studies reported non-adherence to physical therapy intervention or adherence could not be determined, the study was not awarded a point. In retrospective studies, data were collected only for those patients who completed their episode of care (adherence to physical therapy assumed), and a point was awarded. For studies where the effect of any non-adherence was likely to bias any association to the null, the study was not awarded point.	1 = Yes 0 = No 0 = Unable to determine	QUESTION EXCLUDED																																			
20	Were the main outcomes measures used accurate (valid and reliable)?	A point was awarded if the primary outcome measures were thought to be valid and reliable (e.g., number of physical therapy visits per chart report), regardless of whether reliability or validity was reported. A point was not awarded if at least one of the primary outcome measures in the study was not valid or reliable or if this information was not reported or could not be determined (i.e., a questionnaire without reported validity or reliability).	1 = Yes 0 = No 0 = Unable to determine	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Number	Criteria	Scoring Criteria	Score
21	Were the patients in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited from the same population?	A point was awarded when participants from both adherence and non-adherence groups were recruited from the same population. Otherwise, a point was not awarded (e.g., a point was not awarded when all participants from the adherence group received care at clinic A and all participants in the non-adherence group received care at clinic B, because they could have represented 2 distinct populations).	1 = Yes 0 = No 0 = Unable to determine
22	Were study subjects in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited over the same period of time?	A point was awarded when the study provided a specific time line for patient recruitment (prospective studies) or when data were collected between reported dates of patient care (retrospective studies).	1 = Yes 0 = No 0 = Unable to determine
23	Were study subjects randomized to intervention groups?	A point for random allocation was awarded if random allocation of patients was stated in the "Method" section of the article. The precise method of randomization need not be specified. Quasi-randomization allocation procedures, such as allocation by bed availability, did not satisfy this criterion. For crossover study designs, a point was awarded when participants were randomly allocated in the order in which treatments were received.	1 = Yes 0 = No 0 = Unable to determine
24	Was the randomized intervention assignment concealed from both patients and healthcare staff until recruitment was complete and irrevocable?	The study did not receive a point unless the participants were randomly allocated and the methods for ensuring random allocation were specified. If assignment was concealed from patients but not from staff, it should be answered no.	1 = Yes 0 = No 0 = Unable to determine
25	Was there adequate adjustment for confounding in the analyses from which the main findings were drawn?	A point was awarded unless the effect of the main confounders was not investigated or confounding was demonstrated, but no adjustment was made in the final analyses.	1 = Yes 0 = No 0 = Unable to determine

Number	Segal Cl Biomech 2018		Brodsky FAI 2017		Tenenbaum et al. FAS 2017		Queen CORR 2017		Brodsky BJJ 2016		Grier G&P 2016		Caravaggi Cl Biomech 2015		Queen FAI 2014		Queen JBJS 2014		Queen et al. Cl Biomech 2014		Choi FAI 2013		Flavin FAI 2013		Queen et al. FAI 2012		Hahn et al. FAI 2012		Brodsky et al. JBJS 2011		Ingrosso et al. G&P 2009		Valderrabano et al. Cl Biomech 2007	
	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
	1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17	
21	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1
22	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	1	1	0	0	0	0	1	1	0	0
23	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	1	1	1	1	1	1	1	1	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1

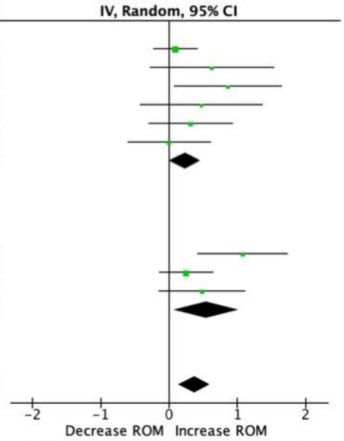
				Segal Cl Biomech 2018		Brodsky FAI 2017		Tenenbaum et al. FAS 2017		Queen CORR 2017		Brodsky BJJ 2016		Grier G&P 2016		Caravaggi Cl Biomech 2015		Queen FAI 2014		Queen JBJS 2014		Queen et al. Cl Biomech 2014		Choi FAI 2013		Flavin FAI 2013		Queen et al. FAI 2012		Hahn et al. FAI 2012		Brodsky et al. JBJS 2011		Ingrosso et al. G&P 2009		Valderrabano et al. Cl Biomech 2007	
				R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
Number	**Criteria**	**Scoring Criteria**	**Score**	**1**		**2**		**3**		**4**		**5**		**6**		**7**		**8**		**9**		**10**		**11**		**12**		**13**		**14**		**15**		**16**		**17**	
26	Were losses of patients to follow-up taken into account?	A point was awarded as long as the number of dropouts lost to follow-up accounted for less than 10% of the initial number of total participants or a maximum of 5% from each group. The question was answered with "unable to determine" if the number of patients lost to follow-up were not reported, could not be deduced from the outcome data (i.e., initial and final sample sizes not indicated) or the study methodology would not infer such information.	1 = Yes 0 = No 0 = Unable to determine	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0
27	Did the study have sufficient power to detect a clinically important effect where the probability value for a difference being due to chance is less than 5%?	Size of smaller intervention group A $<n_1$ 0 B n_1–n_2 1 C n_3–n_4 2 D n_5–n_6 3 E n_7–n_8 4 F n_8+ 5	0 to 5	QUESTION EXCLUDED																																	

Appendix 2 : Chapter 3 : Supplementary material 2 : The change in gait parameters (Ankle Dorsiflexion RoM, Ankle Plantarflexion RoM) following total ankle replacement (TAR global, Mobile-bearing prosthesis and Fixed-bearing prosthesis) compared to pre-operative status

TAR : Ankle Dorsiflexion ROM

Study or Subgroup	Postop Mean	Postop SD	Postop Total	Preop Mean	Preop SD	Preop Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.2.1 Mobile-bearing								
Brodsky FAI 2017 Mobile-bearing	8.9	3.6	76	8.5	4.9	76	23.2%	0.09 [-0.23, 0.41]
Caravaggi CI Biomech 2015 Mobile-bearing	7.9	5.54	10	4.75	3.99	10	5.4%	0.62 [-0.28, 1.53]
Flavin FAI 2013 Mobile-bearing	11.2	6	14	6.3	5	14	7.0%	0.86 [0.08, 1.64]
Ingrosso G&P 2009 Mobile-Bearing	6.31	4.81	10	3.03	8.07	10	5.5%	0.47 [-0.42, 1.36]
Tenenbaum 2017 Old Mobile-Bearing	10.7	3.3	21	9.3	5.2	21	10.4%	0.32 [-0.29, 0.92]
Tenenbaum 2017 Young Mobile-Bearing	6.8	4.7	21	6.8	4.4	21	10.5%	0.00 [-0.60, 0.60]
Subtotal (95% CI)			**152**			**152**	**62.0%**	**0.23 [0.01, 0.46]**
Heterogeneity: Tau² = 0.00; Chi² = 4.89, df = 5 (P = 0.43); I² = 0%								
Test for overall effect: Z = 2.02 (P = 0.04)								
1.2.2 Fixed-bearing								
Choi FAI 2013 Fixed-bearing	10.6	2.6	21	7.1	3.7	21	9.3%	1.07 [0.42, 1.73]
Queen FAI 2012 Fixed-bearing	8	3.5707	51	6.9	4.999	51	18.8%	0.25 [-0.14, 0.64]
Segal CI Biomech 2018 Fixed-bearing	15.7	5.2206	20	13.5	3.6373	20	9.9%	0.48 [-0.15, 1.11]
Subtotal (95% CI)			**92**			**92**	**38.0%**	**0.55 [0.07, 1.03]**
Heterogeneity: Tau² = 0.10; Chi² = 4.51, df = 2 (P = 0.10); I² = 56%								
Test for overall effect: Z = 2.27 (P = 0.02)								
Total (95% CI)			**244**			**244**	**100.0%**	**0.37 [0.14, 0.59]**
Heterogeneity: Tau² = 0.03; Chi² = 10.96, df = 8 (P = 0.20); I² = 27%								
Test for overall effect: Z = 3.22 (P = 0.001)								

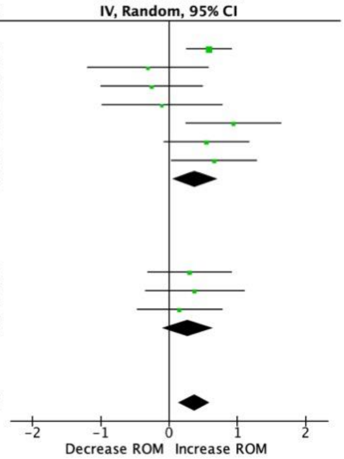
Std. Mean Difference IV, Random, 95% CI



TAR : Ankle Plantarflexion ROM

Study or Subgroup	Postop Mean	Postop SD	Postop Total	Preop Mean	Preop SD	Preop Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.3.1 Mobile-bearing								
Brodsky FAI 2017 Mobile-bearing	9.6	4.5	76	6.8	5	76	22.6%	0.59 [0.26, 0.91]
Caravaggi CI Biomech 2015 Mobile-bearing	2.05	5.52	10	5.11	12.09	10	5.8%	-0.31 [-1.19, 0.57]
Flavin FAI 2013 Mobile-bearing	8	4.3	14	9.3	5.4	14	7.7%	-0.26 [-1.00, 0.49]
Ingrosso G&P 2009 Mobile-Bearing	5.93	4.59	10	6.6	7.28	10	5.8%	-0.11 [-0.98, 0.77]
Queen CORR 2017 Mobile-Bearing	4.3	2.6408	18	1.2	3.7	18	8.6%	0.94 [0.25, 1.64]
Tenenbaum 2017 Old Mobile-Bearing	8	4.9	21	5.3	4.8	21	10.3%	0.55 [-0.07, 1.16]
Tenenbaum 2017 Young Mobile-Bearing	10.2	7.1	21	5.7	6.3	21	10.2%	0.66 [0.04, 1.28]
Subtotal (95% CI)			**170**			**170**	**71.1%**	**0.38 [0.06, 0.71]**
Heterogeneity: Tau² = 0.08; Chi² = 11.01, df = 6 (P = 0.09); I² = 46%								
Test for overall effect: Z = 2.30 (P = 0.02)								
1.3.2 Fixed-bearing								
Choi FAI 2013 Fixed-bearing	10	4.9	21	8.7	3.5	21	10.6%	0.30 [-0.31, 0.91]
Queen CORR 2017 Fixed-bearing	4.7	4.0216	15	3.2	3.8	15	8.1%	0.37 [-0.35, 1.10]
Segal CI Biomech 2018 Fixed-bearing	18.4	5.9055	20	17.5	5.7158	20	10.2%	0.15 [-0.47, 0.77]
Subtotal (95% CI)			**56**			**56**	**28.9%**	**0.27 [-0.11, 0.64]**
Heterogeneity: Tau² = 0.00; Chi² = 0.23, df = 2 (P = 0.89); I² = 0%								
Test for overall effect: Z = 1.40 (P = 0.16)								
Total (95% CI)			**226**			**226**	**100.0%**	**0.37 [0.14, 0.60]**
Heterogeneity: Tau² = 0.03; Chi² = 11.98, df = 9 (P = 0.21); I² = 25%								
Test for overall effect: Z = 3.18 (P = 0.001)								

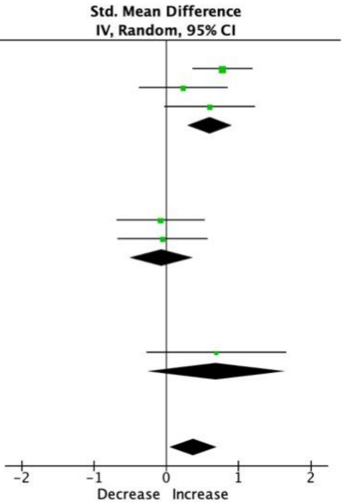
Std. Mean Difference IV, Random, 95% CI



Appendix 3 : Chapter 3 : Supplementary material 3 : The change in gait parameters (Knee and Hip RoM) following total ankle replacement (TAR global, Mobile-bearing prosthesis and Fixed-bearing prosthesis) compared to pre-operative status

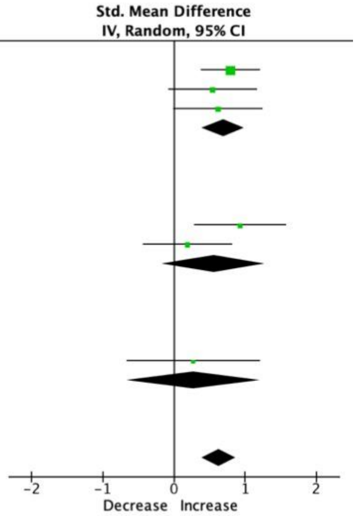
TAR: Knee ROM

Study or Subgroup	Postop Mean	Postop SD	Postop Total	Preop Mean	Preop SD	Preop Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.6.1 Mobile-bearing								
Brodsky JBJS 2011 Mobile-bearing	58	7.1	50	51.4	9.5	50	24.6%	0.78 [0.37, 1.19]
Tenenbaum 2017 Old Mobile-Bearing	54.1	7.3	21	52.5	6	21	16.8%	0.23 [−0.37, 0.84]
Tenenbaum 2017 Young Mobile-Bearing	59.6	10.2	21	53.1	11	21	16.4%	0.60 [−0.02, 1.22]
Subtotal (95% CI)			**92**			**92**	**57.7%**	**0.60 [0.29, 0.91]**
Heterogeneity: $Tau^2 = 0.01$; $Chi^2 = 2.14$, df = 2 (P = 0.34); $I^2 = 7\%$								
Test for overall effect: Z = 3.81 (P = 0.0001)								
1.6.2 Fixed-bearing								
Choi FAI 2013 Fixed-bearing	52.5	11.3	21	53.3	8.5	21	16.9%	−0.08 [−0.68, 0.53]
Segal Cl Biomech 2018 Fixed-bearing	53.4	4.3112	20	53.7	6.8505	20	16.4%	−0.05 [−0.67, 0.57]
Subtotal (95% CI)			**41**			**41**	**33.2%**	**−0.07 [−0.50, 0.37]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 0.00$, df = 1 (P = 0.95); $I^2 = 0\%$								
Test for overall effect: Z = 0.30 (P = 0.77)								
1.6.3 Not reported								
Hahn FAI 2012	35	5	9	31	6	9	9.0%	0.69 [−0.27, 1.65]
Subtotal (95% CI)			**9**			**9**	**9.0%**	**0.69 [−0.27, 1.65]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 1.41 (P = 0.16)								
Total (95% CI)			**142**			**142**	**100.0%**	**0.37 [0.04, 0.70]**
Heterogeneity: $Tau^2 = 0.07$; $Chi^2 = 8.83$, df = 5 (P = 0.12); $I^2 = 43\%$								
Test for overall effect: Z = 2.21 (P = 0.03)								



TAR: Hip ROM

Study or Subgroup	Postop Mean	Postop SD	Postop Total	Preop Mean	Preop SD	Preop Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.7.1 Mobile-bearing								
Brodsky JBJS 2011 Mobile-bearing	39.9	5.1	50	35.1	6.8	50	34.5%	0.79 [0.38, 1.20]
Tenenbaum 2017 Old Mobile-Bearing	40.6	4.7	21	37	8	21	15.1%	0.54 [−0.08, 1.16]
Tenenbaum 2017 Young Mobile-Bearing	41.9	6.1	21	36.8	9.7	21	14.9%	0.62 [−0.00, 1.24]
Subtotal (95% CI)			**92**			**92**	**64.5%**	**0.69 [0.39, 0.99]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 0.53$, df = 2 (P = 0.77); $I^2 = 0\%$								
Test for overall effect: Z = 4.55 (P < 0.00001)								
1.7.2 Fixed-bearing								
Choi FAI 2013 Fixed-bearing	43.7	4.4	21	37.6	8	21	14.0%	0.93 [0.29, 1.57]
Segal Cl Biomech 2018 Fixed-bearing	40.4	7.1849	20	39.4	1.3	20	14.9%	0.19 [−0.43, 0.81]
Subtotal (95% CI)			**41**			**41**	**28.9%**	**0.55 [−0.17, 1.28]**
Heterogeneity: $Tau^2 = 0.17$; $Chi^2 = 2.63$, df = 1 (P = 0.11); $I^2 = 62\%$								
Test for overall effect: Z = 1.50 (P = 0.13)								
1.7.3 Not reported								
Hahn FAI 2012	39	6	9	37	8	9	6.6%	0.27 [−0.66, 1.20]
Subtotal (95% CI)			**9**			**9**	**6.6%**	**0.27 [−0.66, 1.20]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 0.57 (P = 0.57)								
Total (95% CI)			**142**			**142**	**100.0%**	**0.62 [0.38, 0.86]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 4.03$, df = 5 (P = 0.55); $I^2 = 0\%$								
Test for overall effect: Z = 5.10 (P < 0.00001)								

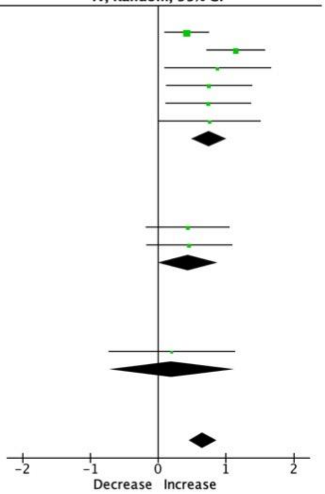


Appendix 4 : Chapter 3 : Supplementary material 4 : The change in spatio-temporal parameters (Cadence, Stance Duration, Step Length) following total ankle replacement (TAR global, Mobile-bearing prosthesis and Fixed-bearing prosthesis) compared to pre-operative status

TAR: Cadence

Study or Subgroup	Postop Mean	Postop SD	Postop Total	Preop Mean	Preop SD	Preop Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.9.1 Mobile-bearing								
Brodsky FAI 2017 Mobile-bearing	110.4	12.3	76	104.3	16.1	76	26.4%	0.42 [0.10, 0.75]
Brodsky JBJS 2011 Mobile-bearing	113.7	8.9	50	100.8	13.1	50	17.9%	1.14 [0.72, 1.57]
Flavin FAI 2013 Mobile-bearing	108.96	5.06	14	97.81	16.66	14	6.3%	0.88 [0.10, 1.66]
Tenenbaum 2017 Old Mobile-Bearing	111.8	8.7	21	104.4	10.5	21	9.4%	0.75 [0.12, 1.38]
Tenenbaum 2017 Young Mobile-Bearing	111.6	10.7	21	101.4	15.8	21	9.4%	0.74 [0.11, 1.37]
Valderrabano Cl Biomech 2007 Mobile-bearing	109.9	5.4222	15	104.3	8.5206	15	6.9%	0.76 [0.02, 1.51]
Subtotal (95% CI)			**197**			**197**	**76.2%**	**0.75 [0.49, 1.02]**
Heterogeneity: Tau² = 0.03; Chi² = 7.27, df = 5 (P = 0.20); I² = 31%								
Test for overall effect: Z = 5.57 (P < 0.00001)								
1.9.2 Fixed-bearing								
Choi FAI 2013 Fixed-bearing	109.8	11.3	21	104.4	12.9	21	9.8%	0.44 [-0.18, 1.05]
Segal Cl Biomech 2018 Fixed-bearing	115	14.3816	20	108	15.5885	20	9.4%	0.46 [-0.17, 1.09]
Subtotal (95% CI)			**41**			**41**	**19.1%**	**0.45 [0.01, 0.89]**
Heterogeneity: Tau² = 0.00; Chi² = 0.00, df = 1 (P = 0.96); I² = 0%								
Test for overall effect: Z = 2.00 (P = 0.05)								
1.9.3 Not reported								
Hahn FAI 2012	112	12	9	109	16	9	4.6%	0.20 [-0.72, 1.13]
Subtotal (95% CI)			**9**			**9**	**4.6%**	**0.20 [-0.72, 1.13]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 0.43 (P = 0.67)								
Total (95% CI)			**247**			**247**	**100.0%**	**0.66 [0.45, 0.87]**
Heterogeneity: Tau² = 0.01; Chi² = 9.42, df = 8 (P = 0.31); I² = 15%								
Test for overall effect: Z = 6.28 (P < 0.00001)								

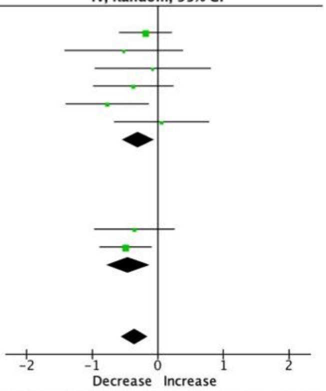
Std. Mean Difference IV, Random, 95% CI



TAR: Stance Duration

Study or Subgroup	Postop Mean	Postop SD	Postop Total	Preop Mean	Preop SD	Preop Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.10.1 Mobile-bearing								
Brodsky JBJS 2011 Mobile-bearing	0.627	0.031	50	0.634	0.042	50	25.6%	-0.19 [-0.58, 0.20]
Caravaggi Cl Biomech 2015 Mobile-bearing	0.5917	0.0172	10	0.6056	0.0318	10	4.9%	-0.52 [-1.42, 0.37]
Ingrosso G&P 2009 Mobile-Bearing	0.6148	0.0205	10	0.617	0.0315	10	5.1%	-0.08 [-0.96, 0.80]
Tenenbaum 2017 Old Mobile-Bearing	0.623	0.027	21	0.633	0.025	21	10.6%	-0.38 [-0.99, 0.23]
Tenenbaum 2017 Young Mobile-Bearing	0.612	0.016	21	0.637	0.042	21	10.0%	-0.77 [-1.40, -0.14]
Valderrabano Cl Biomech 2007 Mobile-bearing	0.603	0.0155	15	0.602	0.0194	15	7.7%	0.06 [-0.66, 0.77]
Subtotal (95% CI)			**127**			**127**	**64.0%**	**-0.30 [-0.55, -0.05]**
Heterogeneity: Tau² = 0.00; Chi² = 3.96, df = 5 (P = 0.56); I² = 0%								
Test for overall effect: Z = 2.35 (P = 0.02)								
1.10.2 Fixed-bearing								
Choi FAI 2013 Fixed-bearing	0.619	0.024	21	0.628	0.025	21	10.6%	-0.36 [-0.97, 0.25]
Queen FAI 2012 Fixed-bearing	0.599	0.0286	51	0.617	0.0428	51	25.4%	-0.49 [-0.88, -0.10]
Subtotal (95% CI)			**72**			**72**	**36.0%**	**-0.45 [-0.78, -0.12]**
Heterogeneity: Tau² = 0.00; Chi² = 0.12, df = 1 (P = 0.72); I² = 0%								
Test for overall effect: Z = 2.68 (P = 0.007)								
Total (95% CI)			**199**			**199**	**100.0%**	**-0.35 [-0.55, -0.15]**
Heterogeneity: Tau² = 0.00; Chi² = 4.61, df = 7 (P = 0.71); I² = 0%								
Test for overall effect: Z = 3.49 (P = 0.0005)								

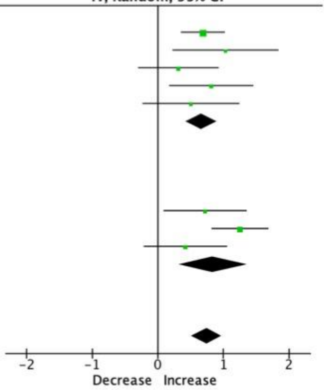
Std. Mean Difference IV, Random, 95% CI



TAR: Step Length

Study or Subgroup	Postop Mean	Postop SD	Postop Total	Preop Mean	Preop SD	Preop Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.11.1 Mobile-bearing								
Brodsky FAI 2017 Mobile-bearing	0.586	0.082	76	0.518	0.112	76	24.4%	0.69 [0.36, 1.02]
Flavin FAI 2013 Mobile-bearing	0.5601	0.07	14	0.4469	0.1335	14	7.1%	1.03 [0.24, 1.83]
Tenenbaum 2017 Old Mobile-Bearing	0.561	0.082	21	0.531	0.105	21	11.0%	0.31 [-0.30, 0.92]
Tenenbaum 2017 Young Mobile-Bearing	0.585	0.081	21	0.502	0.116	21	10.3%	0.81 [0.18, 1.45]
Valderrabano Cl Biomech 2007 Mobile-bearing	0.66	0.0387	15	0.64	0.0387	15	8.2%	0.50 [-0.23, 1.23]
Subtotal (95% CI)			**147**			**147**	**60.9%**	**0.66 [0.42, 0.90]**
Heterogeneity: Tau² = 0.00; Chi² = 2.52, df = 4 (P = 0.64); I² = 0%								
Test for overall effect: Z = 5.49 (P < 0.00001)								
1.11.2 Fixed-bearing								
Choi FAI 2013 Fixed-bearing	0.562	0.052	21	0.508	0.09	21	10.5%	0.72 [0.09, 1.35]
Queen FAI 2012 Fixed-bearing	35.9	4.2849	51	29	6.4273	51	18.1%	1.25 [0.83, 1.68]
Segal Cl Biomech 2018 Fixed-bearing	0.57	0.0823	20	0.53	0.1039	20	10.5%	0.42 [-0.21, 1.05]
Subtotal (95% CI)			**92**			**92**	**39.1%**	**0.84 [0.32, 1.36]**
Heterogeneity: Tau² = 0.13; Chi² = 5.20, df = 2 (P = 0.07); I² = 62%								
Test for overall effect: Z = 3.19 (P = 0.001)								
Total (95% CI)			**239**			**239**	**100.0%**	**0.75 [0.52, 0.98]**
Heterogeneity: Tau² = 0.03; Chi² = 9.52, df = 7 (P = 0.22); I² = 26%								
Test for overall effect: Z = 6.39 (P < 0.00001)								

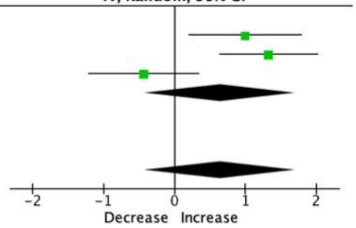
Std. Mean Difference IV, Random, 95% CI



Appendix 5 : Chapter 3 : Supplementary material 5 : The change in all gait parameters (Ankle Dorsiflexion RoM, Ankle Plantarflexion RoM, Knee and Hip RoM) following ankle arthrodesis compared to pre-operative status.

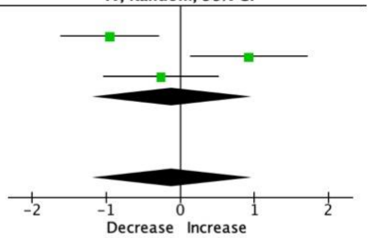
Fusion : Ankle Dorsiflexion ROM

Study or Subgroup	Postop Mean	Postop SD	Postop Total	Preop Mean	Preop SD	Preop Total	Weight	Std. Mean Difference IV, Random, 95% CI	Year
2.2.3 Fusion									
Flavin FAI 2013 Fusion	8.3	7.9	14	1.9	3.9	14	32.8%	1.00 [0.20, 1.79]	2013
Brodsky BJJ 2016 Fusion	11.91	4.9533	20	5.2	4.9533	20	34.3%	1.33 [0.64, 2.02]	2016
Segal Cl Biomech 2018 Fusion	14.1	5.2522	13	16.2	4.0249	13	33.0%	−0.43 [−1.21, 0.34]	2018
Subtotal (95% CI)			**47**			**47**	**100.0%**	**0.64 [−0.42, 1.70]**	
Heterogeneity: Tau² = 0.73; Chi² = 11.84, df = 2 (P = 0.003); I² = 83%									
Test for overall effect: Z = 1.18 (P = 0.24)									
Total (95% CI)			**47**			**47**	**100.0%**	**0.64 [−0.42, 1.70]**	
Heterogeneity: Tau² = 0.73; Chi² = 11.84, df = 2 (P = 0.003); I² = 83%									
Test for overall effect: Z = 1.18 (P = 0.24)									



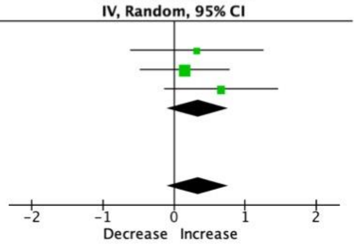
Fusion : Ankle Plantarflexion ROM

Study or Subgroup	Postop Mean	Postop SD	Postop Total	Preop Mean	Preop SD	Preop Total	Weight	Std. Mean Difference IV, Random, 95% CI
2.3.3 Fusion								
Brodsky BJJ 2016 Fusion	0.95	6.002	20	6.8	6.002	20	34.5%	−0.96 [−1.61, −0.30]
Flavin FAI 2013 Fusion	13.1	3.8	14	6.9	8.4	14	32.7%	0.92 [0.14, 1.71]
Segal Cl Biomech 2018 Fusion	17.3	6.1217	13	18.9	5.8138	13	32.9%	−0.26 [−1.03, 0.51]
Subtotal (95% CI)			**47**			**47**	**100.0%**	**−0.11 [−1.20, 0.97]**
Heterogeneity: Tau² = 0.77; Chi² = 12.95, df = 2 (P = 0.002); I² = 85%								
Test for overall effect: Z = 0.20 (P = 0.84)								
Total (95% CI)			**47**			**47**	**100.0%**	**−0.11 [−1.20, 0.97]**
Heterogeneity: Tau² = 0.77; Chi² = 12.95, df = 2 (P = 0.002); I² = 85%								
Test for overall effect: Z = 0.20 (P = 0.84)								



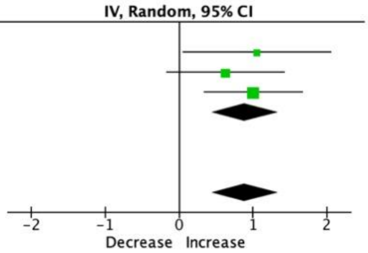
Fusion : Knee ROM

Study or Subgroup	Postop Mean	Postop SD	Postop Total	Preop Mean	Preop SD	Preop Total	Weight	Std. Mean Difference IV, Random, 95% CI	Year
2.6.3 Fair quality									
Hahn FAI 2012 Fusion	30	3	9	29	3	9	21.6%	0.32 [−0.61, 1.25]	2012
Brodsky BJJ 2016 Fusion	55.8	5.1953	20	55	5.1953	20	48.6%	0.15 [−0.47, 0.77]	2016
Segal Cl Biomech 2018 Fusion	54.5	5.4691	13	49.7	8.2928	13	29.8%	0.66 [−0.13, 1.45]	2018
Subtotal (95% CI)			**42**			**42**	**100.0%**	**0.34 [−0.09, 0.77]**	
Heterogeneity: Tau² = 0.00; Chi² = 0.99, df = 2 (P = 0.61); I² = 0%									
Test for overall effect: Z = 1.54 (P = 0.12)									
Total (95% CI)			**42**			**42**	**100.0%**	**0.34 [−0.09, 0.77]**	
Heterogeneity: Tau² = 0.00; Chi² = 0.99, df = 2 (P = 0.61); I² = 0%									
Test for overall effect: Z = 1.54 (P = 0.12)									



Fusion : Hip ROM

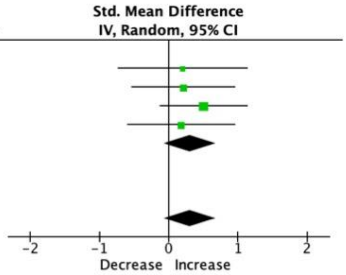
Study or Subgroup	Postop Mean	Postop SD	Postop Total	Preop Mean	Preop SD	Preop Total	Weight	Std. Mean Difference IV, Random, 95% CI
2.7.3 Fusion								
Hahn FAI 2012 Fusion	43	4	9	38	5	9	20.4%	1.05 [0.05, 2.05]
Segal Cl Biomech 2018 Fusion	42	3.948	13	38.8	5.7689	13	32.8%	0.63 [−0.16, 1.42]
Brodsky BJJ 2016 Fusion	40.06	5.9213	20	34	5.9213	20	46.8%	1.00 [0.34, 1.66]
Subtotal (95% CI)			**42**			**42**	**100.0%**	**0.89 [0.44, 1.34]**
Heterogeneity: Tau² = 0.00; Chi² = 0.64, df = 2 (P = 0.73); I² = 0%								
Test for overall effect: Z = 3.85 (P = 0.0001)								
Total (95% CI)			**42**			**42**	**100.0%**	**0.89 [0.44, 1.34]**
Heterogeneity: Tau² = 0.00; Chi² = 0.64, df = 2 (P = 0.73); I² = 0%								
Test for overall effect: Z = 3.85 (P = 0.0001)								



Appendix 6 : Chapter 3 : Supplementary material 6 : The change in spatio-temporal parameters (Cadence, Stance Duration, Step Length)) following ankle arthrodesis compared to pre-operative status

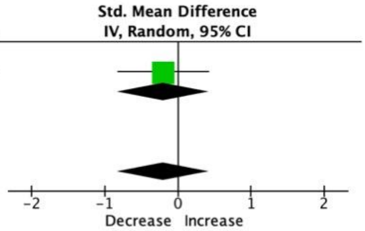
Fusion: Cadence

Study or Subgroup	Postop Mean	Postop SD	Postop Total	Preop Mean	Preop SD	Preop Total	Weight	Std. Mean Difference IV, Random, 95% CI	Year
2.9.3 Fusion									
Hahn FAI 2012 Fusion	112	12	9	109	16	9	16.2%	0.20 [−0.72, 1.13]	2012
Flavin FAI 2013 Fusion	108.05	9.15	14	106	9.72	14	25.2%	0.21 [−0.53, 0.95]	2013
Brodsky BJJ 2016 Fusion	110.4	6.6151	20	107	6.6151	20	35.1%	0.50 [−0.13, 1.13]	2016
Segal Cl Biomech 2018 Fusion	110	14.1646	13	107	17.8885	13	23.5%	0.18 [−0.59, 0.95]	2018
Subtotal (95% CI)			**56**			**56**	**100.0%**	**0.30 [−0.07, 0.68]**	
Heterogeneity: Tau² = 0.00; Chi² = 0.59, df = 3 (P = 0.90); I² = 0%									
Test for overall effect: Z = 1.60 (P = 0.11)									
Total (95% CI)			**56**			**56**	**100.0%**	**0.30 [−0.07, 0.68]**	
Heterogeneity: Tau² = 0.00; Chi² = 0.59, df = 3 (P = 0.90); I² = 0%									
Test for overall effect: Z = 1.60 (P = 0.11)									



Fusion: Stance Duration

Study or Subgroup	Postop Mean	Postop SD	Postop Total	Preop Mean	Preop SD	Preop Total	Weight	Std. Mean Difference IV, Random, 95% CI	Year
2.10.3 Fusion									
Brodsky BJJ 2016 Fusion	0.617	0.0144	20	0.62	0.0144	20	100.0%	−0.20 [−0.83, 0.42]	2016
Subtotal (95% CI)			**20**			**20**	**100.0%**	**−0.20 [−0.83, 0.42]**	
Heterogeneity: Not applicable									
Test for overall effect: Z = 0.64 (P = 0.52)									
Total (95% CI)			**20**			**20**	**100.0%**	**−0.20 [−0.83, 0.42]**	
Heterogeneity: Not applicable									
Test for overall effect: Z = 0.64 (P = 0.52)									



Fusion: Step Length

Study or Subgroup	Postop Mean	Postop SD	Postop Total	Preop Mean	Preop SD	Preop Total	Weight	Std. Mean Difference IV, Random, 95% CI	Year
2.11.3 Fusion									
Flavin FAI 2013 Fusion	0.5512	0.0961	14	0.5046	0.1211	14	32.2%	0.41 [−0.34, 1.16]	2013
Brodsky BJJ 2016 Fusion	0.6453	0.0307	20	0.67	0.0307	20	33.9%	−0.79 [−1.43, −0.14]	2016
Segal Cl Biomech 2018 Fusion	0.62	0.0867	20	0.53	0.1342	20	33.9%	0.78 [0.14, 1.43]	2018
Subtotal (95% CI)			**54**			**54**	**100.0%**	**0.13 [−0.84, 1.10]**	
Heterogeneity: Tau² = 0.61; Chi² = 12.21, df = 2 (P = 0.002); I² = 84%									
Test for overall effect: Z = 0.26 (P = 0.79)									
Total (95% CI)			**54**			**54**	**100.0%**	**0.13 [−0.84, 1.10]**	
Heterogeneity: Tau² = 0.61; Chi² = 12.21, df = 2 (P = 0.002); I² = 84%									
Test for overall effect: Z = 0.26 (P = 0.79)