# Étude de l'effet des rétractions musculaires sur la marche humaine

Michael Attias

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**Michael ATTIAS**

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**DETREMBLEUR, Christine** — **Rapporteure**
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**MARIN, Fréderic** — **Rapporteur**
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**DECOULON, Geraldo** — **Examinateur**
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Je dédie ce mémoire à mon épouse
Léa et ma fille Maayane

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## Résumé de la thèse


Etre capable de marcher sans ressentir de douleur, fatigue ou autres altérations est considéré comme une priorité pour les activités quotidiennes et est étroitement lié à la qualité de vie de chacun. De nombreuses atteintes du système neuro-musculo-squelettique peuvent engendrer des altérations de la marche. Une compréhension précise de ces altérations est nécessaire pour optimiser les stratégies thérapeutiques. Parmi ces atteintes, la rétraction musculaire est l'une des plus fréquentes. Elle correspond à un raccourcissement permanent du complexe musculo-tendineux limitant ainsi la mobilité des articulations. Elle est impliquée dans de nombreuses pathologies (paralysie cérébrale, hémiplégie, pieds bots, brûlures, etc.)

L'objectif global de ce travail de thèse était d'étudier les effets des rétractions sur la marche humaine. Pour cela, un dispositif permettant d'émuler des rétractions a été mis en place et évalué. Ce dispositif est composé d'un exosquelette et de cordes permettant de limiter les amplitudes articulaires, simulant ainsi la rétraction des principaux muscles des membres inférieurs atteints par cette pathologie. Grâce à ce dispositif, l'effet des rétractions des muscles a été analysé. Des rétractions isolées ont été émulées sur 35 participants unilatéralement et bilatéralement et une analyse quantifiée de la marche a été réalisée. Les patterns cinématiques obtenus sur chaque articulation ont été ensuite utilisés pour analyser les liens entre altérations de marche et rétractions musculaires.

Il a été montré que la rétraction des gastrocnemius peut provoquer un pattern de marche genoux fléchis, alors qu'une rétraction du soleus montre peu de modifications de la cinématique du genou. De plus, le lien entre la sévérité de la rétraction des gastrocnemius / soleus et la progression de la marche digitigrade (augmentation de la flexion plantaire pendant la marche) n'est pas linéaire. La marche «genoux fléchis» peut être causée par les rétractions des ilio-psoas, ischio-jambiers et gastrocnemius. Des patterns cinématiques particuliers ont été identifiées en lien avec les muscles responsables de la marche «genoux fléchis». Il a été également montré que les rétractions des muscles du membre inférieur ont des effets importants spécifiques sur la position moyenne du tronc et du bassin dans le plan sagittal.

Derrière son objectif scientifique, les résultats obtenus dans ce projet ont le potentiel d'améliorer le choix des stratégies de traitement et donc d'avoir un impact sur la qualité de vie des patients.

## Abstract of thesis

Preserving or restoring the ability to walk without pain, fatigue or any gait alterations is considered a priority for activities of daily living and is closely related to quality of life. Numerous alterations of the neuro-musculo-skeletal system lead to gait deviations. To treat these alterations, a precise understanding of gait deviations is required. For patients with gait disorders, instrumented gait analysis can be performed to measure precisely the gait deviations. Among the varied causes of gait alterations, one of the most frequent is contractures that affect numerous pathologies. It corresponds to a permanent shortening of a musculo-tendinous complex limiting the mobility of the joints. It is involved in many pathologies (cerebral palsy, stroke, clubfoot, burns, etc.)

The global objective of this thesis was to study the effects of contractures on human walking. For this purpose, a device for emulating contractures has been built and evaluated. This device consists of an exoskeleton and ropes to limit joint range of motion of the major lower limb muscles affected by contractures. With this device, the effect of contractures of the musculo-tendinous complex was analysed. Isolated contractures were emulated on 36 participants unilaterally and bilaterally and an instrumented gait analysis was performed. The kinematic patterns obtained for each joint were then used to link kinematic gait alterations with muscle contractures.

It has been shown that contracture of gastrocnemius can cause a knee flexion pattern, while a contracture of the soleus shows moderate changes in knee kinematics. Moreover, the relationship between the level of contracture of gastrocnemius / soleus and the progression of the equinus gait (increase in plantar flexion during walking) is not linear. «Knee flexion» gait pattern may be caused by the contractures of the iliopsoas, hamstrings and gastrocnemius. Particular kinematic patterns have been identified in relation to the muscles responsible to the «knee flexion» gait pattern. It has also been shown that retractions of the muscles of the lower limb have important specific effects on the mean position of the trunk and pelvis in the sagittal plane.

Behind the scientific objective, the results of this project have the potential to improve the choice of treatment strategies and therefore to have an impact on patient’s quality of life.

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# Préambule

Etre capable de marcher sans ressentir de douleur, fatigue ou autres altérations est considéré comme une priorité pour les activités quotidiennes et est étroitement lié à la qualité de vie de chacun (Hoang et al., 2014; Prabhu et al., 2013). De nombreuses atteintes au niveau neurologique, musculaire et/ou squelettique peuvent engendrer des altérations de la marche. Une compréhension précise de ces altérations est nécessaire pour optimiser les stratégies thérapeutiques. Cependant, cette compréhension n'est pas évidente car le système neuro-musculo-squelettique humain est complexe et la marche est un phénomène dynamique. Ainsi, ce travail de thèse se place dans un contexte général d'amélioration de la compréhension des altérations de marche en s'appuyant sur des expérimentations biomécaniques.

J'aimerais préciser que l'idée de cette thèse est partie d'une étude sur les mouvements du tronc chez les enfants atteints de paralysie cérébrale (PC). Cette dernière nous a montré les limites des études sur les patients et nous a guidés vers une nouvelle approche. Le résumé de cette étude est présenté ci-dessous et vous trouverez l'article complet en Annexe I.

### Étude des mouvements du tronc chez les enfants atteints de paralysie cérébrale (résumé)

*L'objectif était de décrire les caractéristiques des mouvements du tronc chez les enfants atteints de paralysie cérébrale (PC) selon leur type d'atteinte (diplégique / hémiplégique) et le niveau de sévérité de leur atteinte selon le score GMFCS[1] I, II et III. Les données de 92 enfants atteints de PC ont été rétrospectivement sélectionnées. Les paramètres cinématiques du tronc ont été extraits à partir des angles calculés dans le plan sagittal, frontal et transversal du thorax et du thorax par rapport au bassin. La position moyenne et l'amplitude des mouvements durant le cycle de marche complet ont été analysées. Les différences entre les enfants diplégiques, hémiplégiques, le groupe contrôle et les niveaux de sévérité GMFCS I, II, III ont été analysées par un test de Kruskal–Wallis. Les résultats ont montré que plus le niveau de sévérité était élevé chez les enfants (PC), plus les amplitudes de mouvement du tronc durant la marche étaient augmentées. Ainsi le tronc joue un rôle important durant la marche, en particulier dans la compensation de certains déficits.*

Des altérations de marche ont donc été identifiées dans cette étude. Cependant le lien entre les données cliniques et ces altérations de marche n'a pas pu être réalisé. L'atteinte multiple des patients n'a permis que de présenter une description des troubles de mouvement du tronc sans

[1] GMFCS : Gross Motor Function Classification System

en donner les causes. Parmi les causes responsables des altérations de marche, l'une des plus fréquentes est la rétraction des tissus mous qui affecte les patients dans de nombreuses pathologies.

Pour répondre à ce besoin d'amélioration de la compréhension des rétractions des tissus mous durant la marche, l'organisation générale de ce mémoire de thèse se décline en quatre grands chapitres : une introduction générale, la méthodologie générale, les résultats expérimentaux et une discussion générale. Les articles scientifiques (publiés ou soumis) associés à ce travail sont intégrés respectivement dans ces chapitres.

**Le premier chapitre** « introduction générale », présente les notions générales sur la marche humaine et pathologique ainsi que les éléments permettant de comprendre l'analyse de la marche. Il décrit aussi le contexte littéraire et scientifique de la thèse sous forme d'une revue systématique de la littérature sur l'influence des rétractions sur la marche humaine (article 1).

**Le deuxième chapitre** « méthodologie générale » décrit les outils développés et les méthodes mises en œuvre, incluant la conception, la construction et l'évaluation de la fiabilité de l'outil utilisé pour la partie expérimentale (article 2).

**Le troisième chapitre** « résultats expérimentaux » présente les études conduites et les résultats scientifiques obtenus dans l'objectif d'améliorer la compréhension des altérations de marche. Ce chapitre est composé de quatre articles scientifiques publiés ou soumis dans des journaux indexés. Ils décrivent les comportements cinématiques des articulations de la cheville, du genou, de la hanche et des segments bassin et thorax lors de l'émulation de rétractions musculo-tendineuses des membres inférieurs.

**Le quatrième chapitre** « discussion générale » expose le bilan de l'ensemble de ce travail avec les limites, les améliorations possibles et les perspectives.

# 1 Chapitre 1 : Introduction générale

## 1.1 La marche humaine

### 1.1.1 Définition de la marche

La marche peut être définie comme une répétition de séquences de mouvements des segments du corps permettant la propulsion et l'avancement du corps tout en maintenant l'équilibre (Perry and Burnfield, 2010).

### 1.1.2 Le cycle de marche

Le cycle de marche correspond à la période entre deux contacts successifs du même pied (Diopa et al., 2004). Il est souvent représenté en pourcentage, tel que le contact du talon (ou du pied en cas de marche pathologique) correspond à 0% du cycle de marche, le prochain contact du même talon (pied) correspondra à 100% du cycle de marche (Armand et al., 2015; Carcreff et al., 2016). Ce cycle est par la suite décomposé en deux phases. La phase d'appui (60% pour la marche normale) et la phase oscillante (40%) qui peuvent être décomposées elles-mêmes en sous-phases. On parle d'appui bipodal (ou double appui) lorsque les deux jambes sont en contact avec le sol et on parle d'appui unipodal (ou simple appui) lorsqu'une seule jambe est en contact avec le sol. Le cycle de marche est représenté sur la Figure 1.

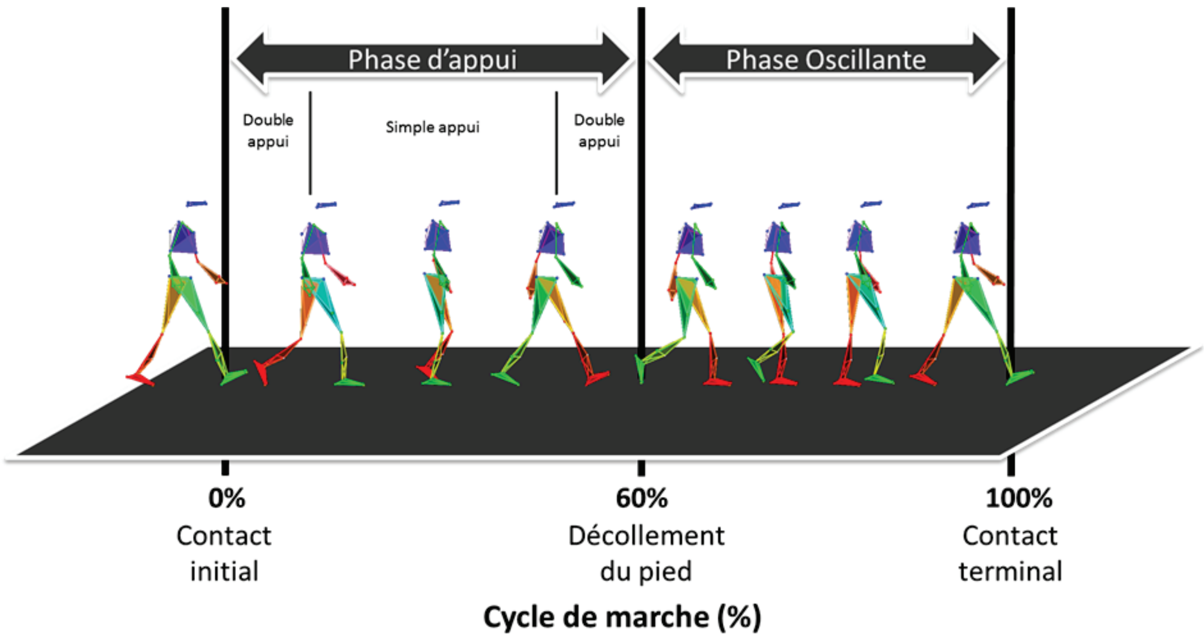


Figure 1 : Représentation du cycle de marche de la jambe droite (en vert)

### 1.1.3 Les pivots de la marche

Le contact du pied au sol et la progression du corps pour avancer sont décrits par un système de pivots (Figure 2). Lors de la marche « normale », des rotations successives autour de 3 ou 4 pivots sont nécessaires (talon « heel », cheville « ankle », avant pied « forefoot » et orteils « toe ») (Bober et al., 2008; Perry and Burnfield, 2010). Le premier pivot correspond à la progression de la jambe de l'attaque du pas jusqu'au contact de l'avant pied au sol, où le point de pivotement est le talon. Le second pivot correspond à la progression de la jambe vers l'avant, où le point de pivotement est la cheville. Le troisième pivot débute lorsque la ligne de gravité (verticale issue du centre de gravité du corps) atteint les têtes métatarsiennes et correspond au lever du talon, avec la base des métatarses comme point de pivotement (avant-pied). Le dernier et quatrième pivot se produit pendant la deuxième phase de double appui, avec les orteils comme point de pivotement. Les 3ème et 4ème pivots sont souvent regroupés.

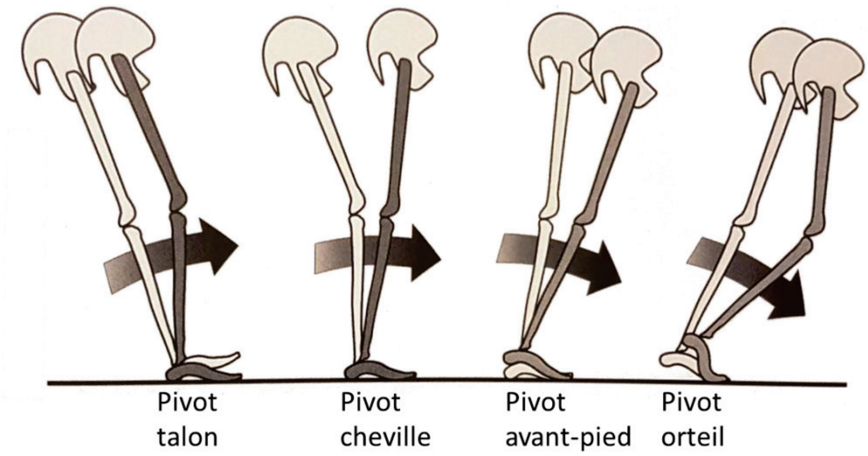


**Figure 2 : Représentation des pivots de la marche tirée du livre de Perry and Burnfield (2010).**

### 1.1.4 Les commandes de la marche : du système nerveux central (SNC) aux mouvements

Le mouvement est un phénomène complexe mettant en jeu de multiples systèmes. Les systèmes proprioceptif, visuel, vestibulaire apportent au SNC et au système nerveux périphérique les informations nécessaires (analyse des conditions extérieures, des contraintes éventuelles, de l'équilibre du corps ainsi que du ressenti de la position des différents segments du corps,…) permettant d'envoyer les influx nerveux vers les muscles. L'activité musculaire autour d'une articulation va ensuite permettre de créer le mouvement (Figure 3) (Armand et al., 2014).

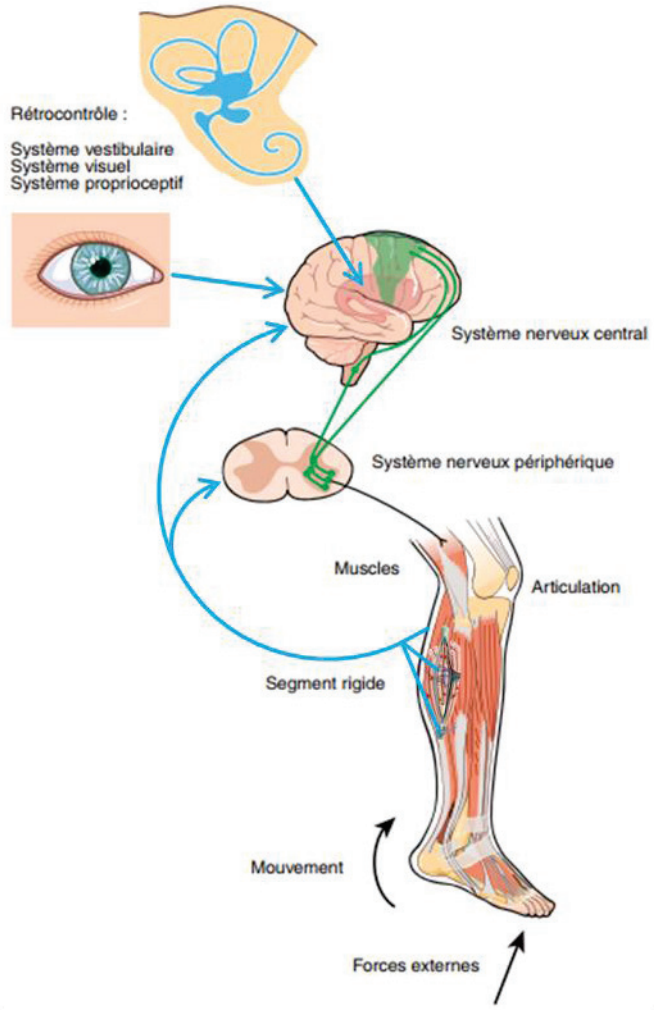


Figure 3 : Systèmes impliqués dans la réalisation d'un mouvement d'après Armand et al. 2014 (figure modifiée avec rajout de l'image du fuseau neuromusculaire et de l'organe tendineux de Golgi tiré du Kamina Tome 5).

La marche nécessite l'intégrité du système neuro-musculo-squelettique. Si l'un des éléments impliqué dans la chaine du mouvement est altéré, le mouvement sera généralement perturbé. Des difficultés à se mouvoir ou des douleurs peuvent survenir et c'est ainsi que l'on commencera à parler de marche « pathologique ».

## 1.2 La marche pathologique

De nombreuses pathologies peuvent avoir des conséquences sur la marche, notamment dans un contexte de lésion du SNC où les principales altérations motrices sont la parésie, l'hyperactivité musculaire et les rétractions des tissus mous (Gracies, 2005a, b) (Figure 4).

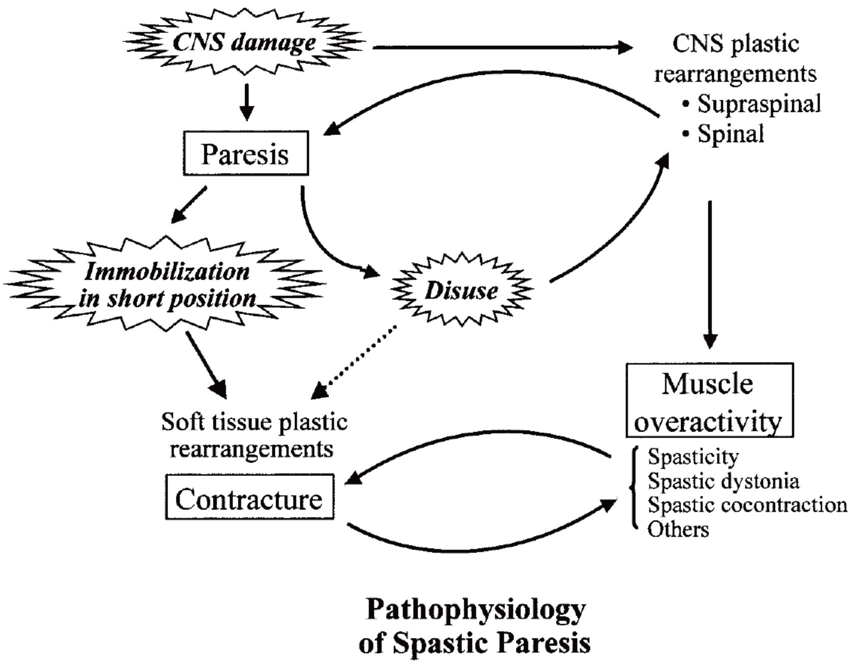


Figure 4 : Les troubles moteurs primaires dus à une lésion du système nerveux central tiré de Gracies (2005b). CNS: système nerveux central.

**La parésie** est définie comme une conséquence directe d'une lésion du SNC provoquant une incapacité ou des difficultés de recrutement volontaire des unités motrices générant le mouvement (Gracies, 2005a). La principale conséquence se présente sous forme de faiblesse musculaire.

**L'hyperactivité musculaire** est définie comme une augmentation involontaire du recrutement des unités motrices provoquant des mouvements non désirés que ce soit au repos ou lors de certaines tâches demandant l'implication d'autres muscles (Gracies, 2005b). L'une des formes la plus connue est la spasticité. Traditionnellement, elle est définie par un désordre moteur caractérisé par une exagération du réflexe myotatique involontaire (augmentation de la résistance musculaire à l'étirement de celui-ci) et l'augmentation de cette résistance serait influencée par la vitesse d'étirement du muscle (vitesse-dépendant) (Lance, 1980).

**La rétraction des tissus mous** (contracture en anglais) est définie comme une incapacité à effectuer une amplitude complète de mouvement autour d'une articulation et engendre une résistance passive excessive à la mobilisation sur cette articulation (Gracies, 2005a). Les structures impliquées sont principalement l'aponévrose, les tendons, les muscles, les ligaments, et la capsule articulaire. Ces structures sont limitées dans leur extensibilité et/ou présentent une raideur trop importante (Prabhu et al., 2013). Les rétractions peuvent être une conséquence indirecte d'une lésion du SNC (Figure 4). Chez les patients atteints de paralysie cérébrale (CP), il a été montré que le développement des rétractions musculaires a un lien avec l'augmentation de la raideur passive des faisceaux des fibres musculaires et avec l'augmentation de la longueur des sarcomères *in vivo (Smith et al., 2011)*. La rétraction ne provient donc pas d'un raidissement au niveau cellulaire mais plutôt extracellulaire conduisant à des contraintes passives plus élevées (Dayanidhi and Lieber, 2014). Les muscles spastiques des patients CP ont une croissance longitudinale et transversale réduite pendant la période postnatale. Un dérèglement dans le rapport de la croissance entre les os et les muscles (en défaveur des muscles) peut conduire à des rétractions musculo-tendineuses (Dayanidhi and Lieber, 2014). Ce processus est représenté sur la Figure 5.

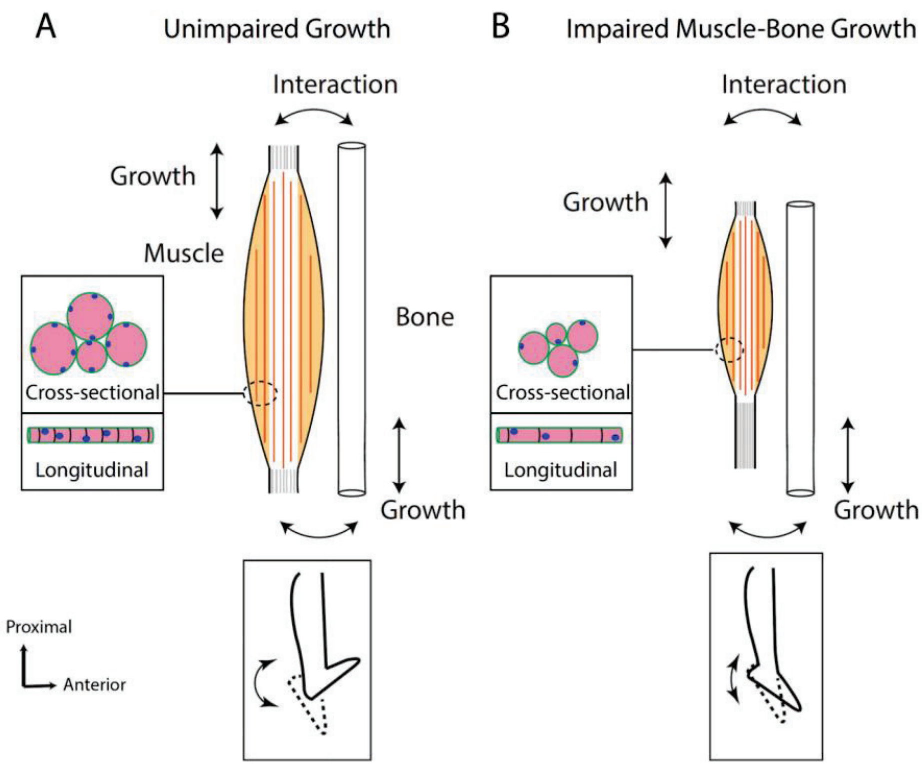


**Figure 5 : Représentation schématique de la croissance musculaire selon Dayanidhi and Lieber (2014). A) croissance musculaire intacte suivant la croissance osseuse. L'augmentation de la longueur des fibres musculaires est associée à celle des sarcomères, du noyau, de la circonférence due à l'augmentation des myofibrilles (croissance de l'aire de section transversale et longitudinale). Ceci permet une amplitude de mouvement normale (en bas à gauche). B) Dans les troubles du développement tels que la paralysie cérébrale (CP), la croissance longitudinale du sarcomère peut être altérée, ce qui entraine des sarcomères surdimensionnés amenant à une croissance réduite de l'aire de section transversale des fibres musculaires. Dans ce cas, pour des enfants atteints de CP, cela peut entraîner un développement de rétractions musculaires (en bas à droite).**

D'un point de vue mécanique, l'altération peut être représentée comme une perturbation relative à la longueur et/ou à la raideur (par exemple : au-dessus d'un certain seuil de longueur du complexe musculo-tendineux, le mouvement devient plus difficile voire impossible). Durant la marche, les rétractions induisent souvent des compensations cinématiques dépendantes de leur localisation et de leur niveau de sévérité (Attias et al., 2016d).

Ces déficits peuvent se combiner entre eux et créer des altérations de la marche complexes. Afin d'identifier, de comprendre et de choisir un traitement approprié à ces altérations de marche, une investigation de celles-ci peut être réalisée : l'Analyse Quantifiée de la Marche (AQM) (Whittle, 1996).

## 1.3 L'Analyse Quantifiée de la Marche (AQM)

### 1.3.1 Principe et déroulement d'un examen

L'AQM est un examen standardisé permettant d'analyser et de comprendre la complexité des mouvements de la marche et plus spécifiquement de la marche pathologique. Cet examen est intégré dans les prises de décision clinique des traitements neuro-orthopédiques visant à améliorer la capacité ou performance de marche (Davids et al., 2004; Gage, 1994; Gough et al., 2008; Wren et al., 2011).

L'AQM est réalisée dans un laboratoire d'analyse du mouvement en deux étapes généralement. La première étape consiste à effectuer un examen clinique où sont principalement évaluées les faiblesses musculaires, déterminées par l'examen de la force musculaire (échelles de testing musculaire (Florence et al., 1992)) ; le contrôle moteur sélectif (échelle de sélectivité (Fowler et al., 2009)), la spasticité réalisée par l'examen du tonus musculaire (évaluation par les échelles d'Ashworth (Bohannon and Smith, 1987) et de Tardieu (Gracies et al., 2010)) et les rétractions des tissus mous évaluées par la mesure passive des amplitudes articulaires à l'aide d'un goniomètre manuel (Viehweger et al., 2007). Les paramètres anthropométriques (taille, poids, longueur de jambes, etc.) sont eux aussi mesurés lors de cet examen clinique.

La seconde étape consiste à évaluer la marche d'un patient pieds nus, si possible sans aide, sur une distance de 10 mètres en passant sur une ou plusieurs plateforme(s) de force intégrée(s) dans le sol et à enregistrer de manière synchronisée : les vidéos, les trajectoires de marqueurs réfléchissants avec un système optoélectronique, les forces de réaction au sol à l'aide de plateformes de force, l'activité musculaire avec l'électromyographie de surface. Ces enregistrements permettent le calcul des paramètres spatio-temporels, cinématiques, cinétiques et électromyographique (Armand et al., 2015; Carcreff et al., 2016; Narayanan, 2007). Le matériel généralement utilisé pour réaliser une AQM est représenté dans la Figure 6.

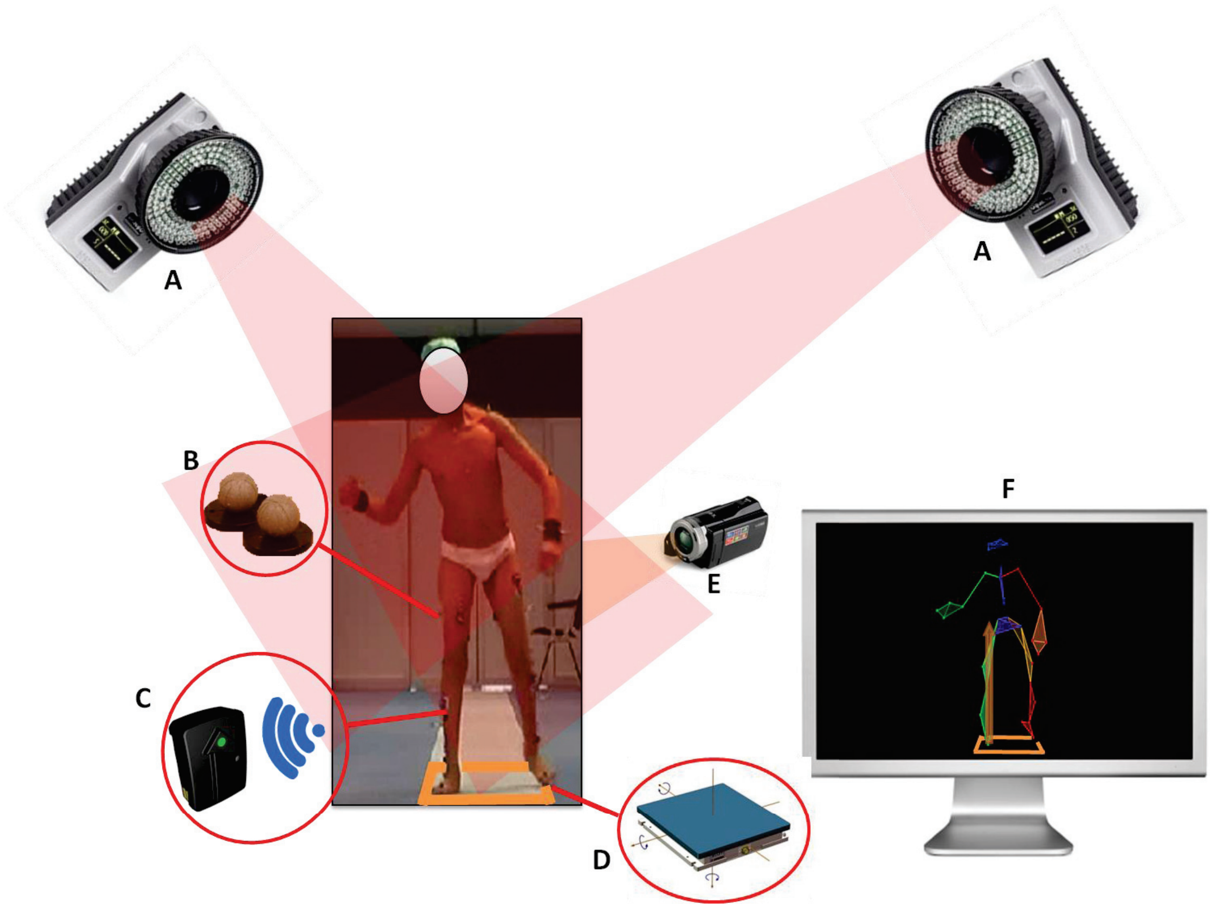


Figure 6 : Matériels généralement utilisés pour la réalisation d'une analyse quantifiée de la marche. A. Système optoélectronique avec cameras; B. Marqueurs réfléchissants ; C. Electromyographie de surface ; D. Plateforme(s) de force incorporée(s) dans le sol ; E. caméra numérique vidéo ; F. Matériels informatiques pour l'acquisition et le traitement des données.

### 1.3.2 Les paramètres de l'AQM

**Les paramètres spatio-temporels** sont basés sur la durée (absolue ou relative) et la longueur de paramètres en lien avec le cycle de marche. Ils incluent principalement la vitesse de marche (m/s), la cadence de marche (nombre de pas par minute), la longueur du pas (m) et la durée des phases du cycle de marche (en secondes ou pourcentage). Ces paramètres donnent une idée globale des caractéristiques de la marche d'un patient.

**Les paramètres cinématiques** (la cinématique étant l'étude du mouvement des corps, en faisant abstraction des causes du mouvement) correspondent aux angles articulaires exprimés en degrés.

Pour calculer les angles articulaires, un système optoélectronique permettant de déterminer les coordonnées tridimensionnelles (3D) des marqueurs réfléchissants collés sur le corps du patient est généralement utilisé. La lumière infrarouge issue de diodes électroluminescentes entourant l'objectif des caméras est réfléchie passivement par les marqueurs puis captée par des caméras sensibles à la lumière infrarouge. Le système étant au préalable calibré, la détection d'un même marqueur par au moins deux caméras permet le calcul de sa position dans l'espace 3D. A partir de modèles biomécaniques, ces points dans l'espace permettront de calculer les angles articulaires entre les segments du corps dans chaque plan de mouvement (sagittal, frontal et transversal) (Figure 7). En général, les angles d'Euler (ou séquence de rotation autour d'axes mobiles) sont utilisés pour calculer les angles entre deux segments selon l' «International Society of Biomechanics» (Wu et al., 2005). Les centres articulaires nécessaires à ce calcul (c'est à dire : la définition des axes des repères segmentaires) sont estimés par des équations de régression (Bell et al., 1990; Davis et al., 1991).

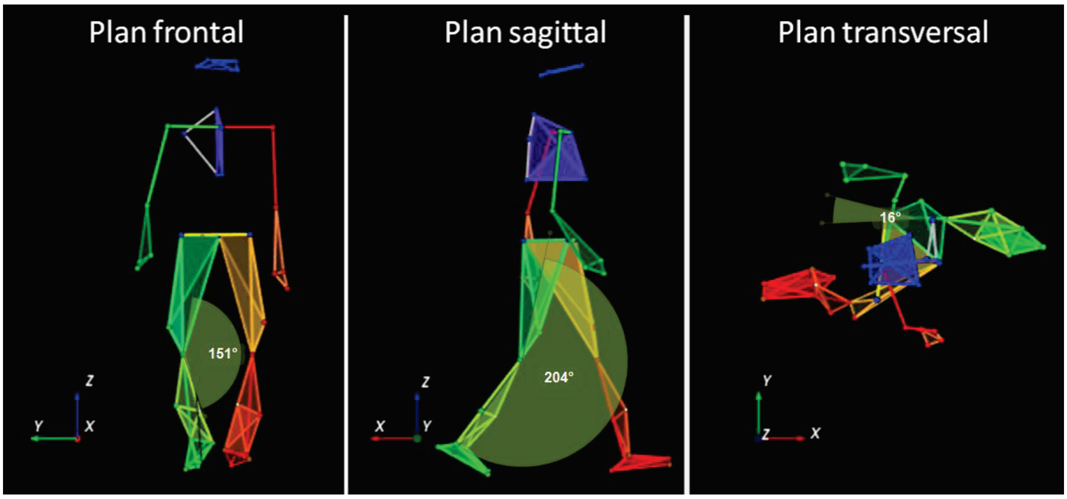


Figure 7 : Représentation des 3 plans de mouvement (frontal, sagittal et transversal) avec comme exemple de gauche à droite, l'angle du genou en valgus/varus, flexion/extension et rotation interne/externe

La cinématique est ensuite représentée par des courbes représentant l'évolution des angles articulaires (ou segmentaires) sur des graphiques généralement normalisés par rapport à un cycle de marche. La représentation de tous les cycles de marche permet de vérifier la reproductibilité de la marche. Par la suite, les cycles représentatifs peuvent être sélectionnés afin de servir de base pour l'interprétation. Plusieurs méthodes de sélection de ces cycles peuvent être proposées, soit en prenant en compte la courbe la plus représentative, soit, et c'est ce qui est le plus souvent utilisé dans les laboratoires, en prenant la moyenne des courbes obtenues qui est ensuite comparée aux courbes de marche normale (moyenne ±1 écart type)

(Figure 8) (Sangeux and Polak, 2015). Les données obtenues par l'analyse permettent de définir les déviations par rapport à une marche normale.

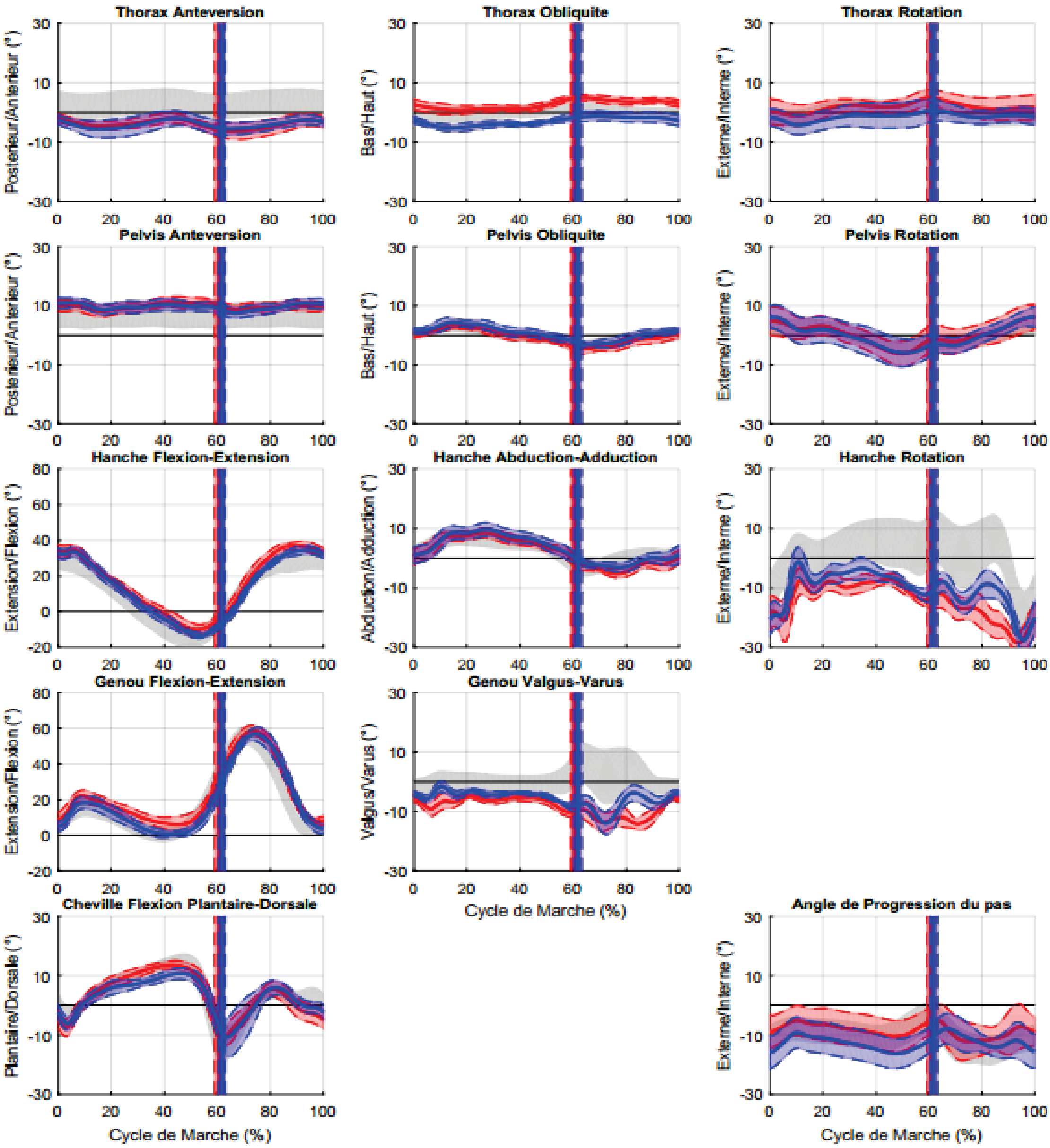


**Figure 8 : Représentation des moyennes cinématiques de la marche d'un patient, côté gauche en rouge et droit en bleu (moyenne ±1 écart type), avec la comparaison à la norme en gris (moyenne ±1 écart type), résultant d'une Analyse Quantifiée de la Marche.**

**Les paramètres cinétiques** (Figure 9) permettant de déterminer la cause du mouvement utilisent la mesure du torseur des forces d'appui du pied au sol. Ces forces de réaction au sol sont enregistrées par des plateformes de forces. Les moments de forces ainsi que les puissances articulaires peuvent être calculés à partir de cette mesure par dynamique inverse.

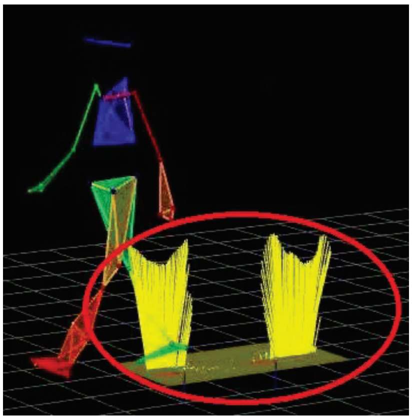

**Figure 9 : Représentation graphique de la force de réaction au sol.**

**Les paramètres électromyographiques** renseignent principalement sur le « timing » de l'activation de certains muscles ou groupes musculaires d'intérêt lors de la marche (Figure 10). Un système électromyographique enregistre l'activité électrique des muscles, correspondant à la différence de potentiel électrique au niveau des fibres musculaires. Pour l'AQM, des électrodes de surface placées sur la peau au niveau du corps musculaire sont généralement utilisées et mesurent une activité musculaire globale. Les recommandations de la SENIAM (Hermens et al., 2000) sur la préparation de la peau, le placement des électrodes et le traitement des données sont le plus souvent suivies.

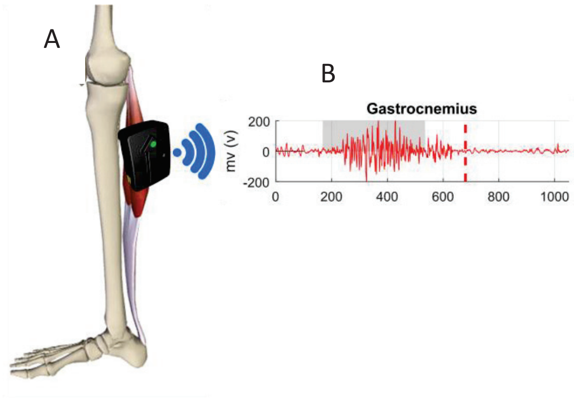


**Figure 10 : A) Représentation schématique d'un capteur électromyographique de surface ; B) visualisation de l'activité électrique d'un muscle sur un cycle de marche.**

Une fois l'examen réalisé, tous les paramètres (données) sont traités, vérifiés et représentés graphiquement dans un rapport. Celui-ci servira à l'interprétation des déficits de la marche (Armand et al., 2015).

### 1.3.3 Interprétation des altérations de la marche

En combinant les résultats de l'AQM, de l'examen clinique, de l'évaluation visuelle de la marche et en les comparant aux données de sujets asymptomatiques, il est possible d'identifier les altérations de la marche. Ces éléments, assemblés dans un rapport, vont permettre de fournir des hypothèses sur les causes des troubles de la marche et ainsi aider au choix des stratégies de traitement (Armand et al., 2015; Carcreff et al., 2016; Narayanan, 2007). Les différents éléments généralement présents dans un rapport d'AQM sont présentés dans la Figure 11.

L'interprétation de l'AQM est pluridisciplinaire. Elle demande une équipe composée d'au minimum un médecin spécialisé dans le domaine et de la personne ayant réalisé l'AQM (biomécanicien/kinésithérapeute/expert en science du mouvement) (Carcreff et al., 2016). Tous les éléments du rapport sont passés en revue incluant les vidéos de la marche du patient, les paramètres quantifiés de la marche, l'examen clinique. Les vidéos permettent d'analyser les séquences de mouvement a posteriori, de les montrer à l'équipe pluridisciplinaire, de travailler avec les ralentis ou les arrêts sur image et d'avoir un suivi sur le long terme des patients. Les paramètres spatio-temporels apportent une idée générale de la marche du patient. Les données cinématiques identifient les défauts de marche du patient pour chaque articulation dans chaque plan. Les données cinétiques renseignent sur les causes des mouvements obtenus. Les données électromyographiques permettent d'identifier les périodes anormales d'activité musculaire. Enfin l'examen clinique apporte des informations sur les déficits cliniques passifs. D'autres éléments qui n'ont pas été cités ici peuvent aussi être analysés et interprétés tels que les pressions plantaires, la consommation d'oxygène ou encore les scores de marche (Armand et al., 2015).

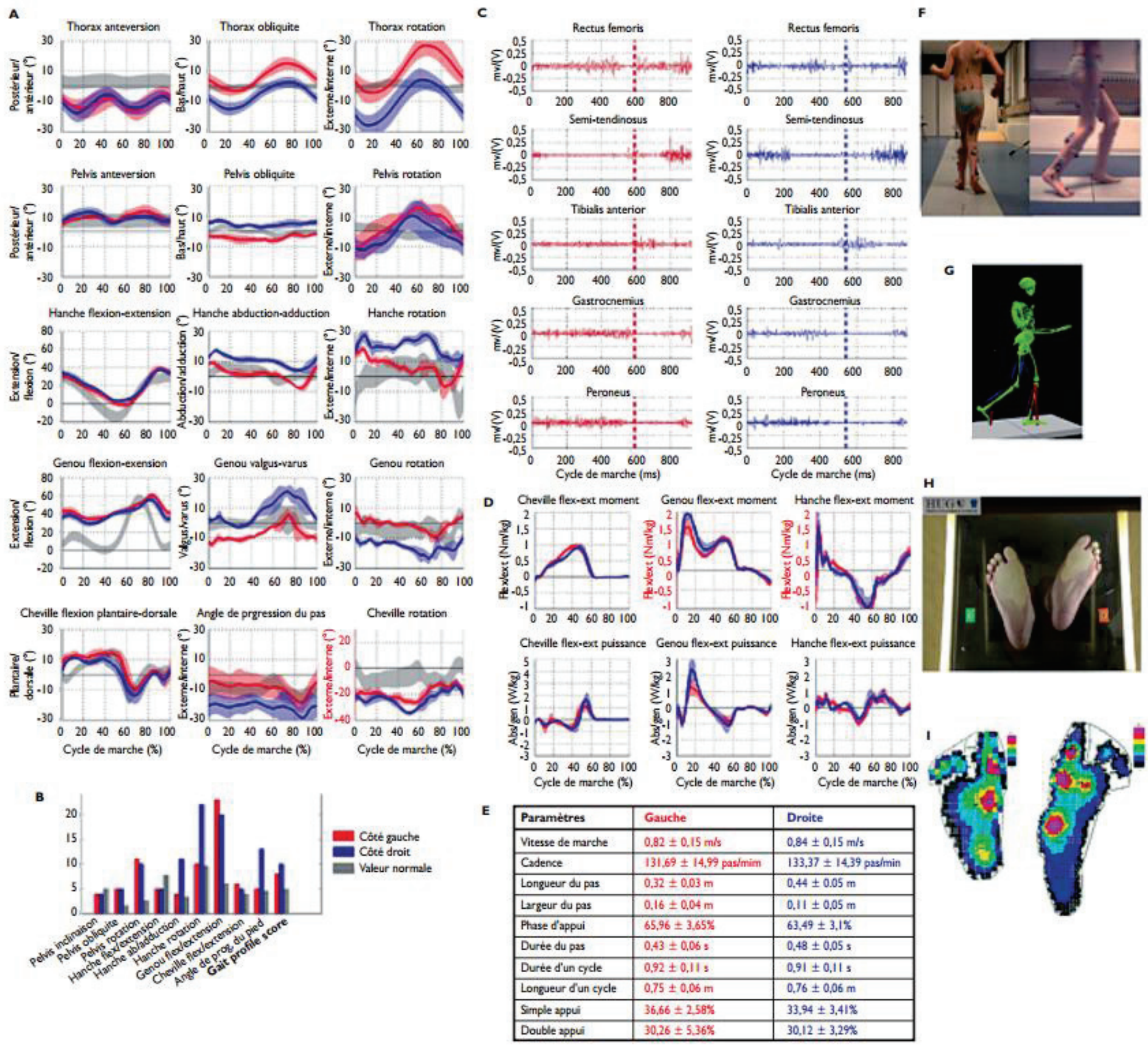


**Figure 11 : Image tirée de (Armand et al., 2015) sur les différents éléments généralement présents dans un rapport d'analyse quantifiée de la marche. A. Cinématique ; B. Score définissant le degré d'atteinte global et à chaque articulation ; C. Electromyographie ; D. Cinétique ; E Paramètres spatio-temporels ; F. Vidéos de face et de profil ; G. Reconstitution 3D ; H. Podoscope statique ; I. Pressions plantaires pendant la marche. Gen : génération ; Abs : absorbtion ; Ext : extenseur ; Prog. : progression ; Flex : fléchisseur.**

L'interprétation de l'AQM donne lieu à l'identification des défauts de marche et permet de générer des hypothèses sur leurs causes qui peuvent être confirmées ou infirmées dans certains cas par les données cliniques. Elle permet notamment de distinguer les altérations primaires (cause directe due à la pathologie) des compensations (stratégie mise en place pour compenser les altérations primaires) (Romkes et al., 2007). Cette distinction est fondamentale mais elle est aussi la principale difficulté de cette interprétation. Elle a un impact important sur le choix de traitement étant donné que l'objectif principal est de cibler l'altération primaire. Les mécanismes de compensation devraient disparaitre après le traitement des altérations primaires (Schmid et al., 2013).

### 1.3.4 Limites de l'AQM

Les limites de l'AQM doivent être repérées et reconnues afin de réduire les biais dans l'interprétation. Les plus importantes sont exposées ci-dessous:

#### *1.3.4.1 Liées à la mesure*

Le matériel utilisé tel que le nombre et la résolution des caméras, leur placement en fonction du volume disponible dans le laboratoire, la taille des marqueurs réfléchissants peuvent influencer la précision de la mesure notamment dans la reconstitution des positions des marqueurs dans l'espace de capture.

Les modèles biomécaniques et les algorithmes permettant les calculs des paramètres ne représentent pas complètement la réalité, du fait de la complexité anatomique du corps humain. Les modèles considèrent des segments rigides et indéformables et le calcul des repères segmentaires et des centres articulaires est basé sur des marqueurs positionnés sur la peau du patient. Le calcul des centres articulaires est basé sur des estimations (Carcreff et al., 2016). Il apparaît également des erreurs dues au placement des marqueurs (DellaCroce and Sullivan, 2005) et aux artefacts des mouvements des tissus mous aux alentours des marqueurs (Leardini et al., 2005) intervenant sur les résultats. Une revue systématique sur la variabilité de l'AQM a montré des différences jusqu'à 5° pour la cinématique excepté pour la rotation de hanche et du genou qui ont une variabilité plus élevée (McGinley et al., 2009). En somme, il est important de prendre en compte une certaine variabilité extrinsèque (due à l'erreur de mesure) des paramètres dans l'interprétation (Chia and Sangeux, 2017).

#### *1.3.4.2 Liées aux traitements des données*

Les analyses de l'AQM étant la plupart du temps normalisées par rapport à un cycle de marche, il est nécessaire de définir le contact initial et le décollement du pied soit manuellement, soit de manière automatique. Une erreur sur l'estimation de ces instants clefs peut engendrer un décalage de quelques images.

#### *1.3.4.3 Liées à l'interprétation*

De nombreuses données sont disponibles lors d'une AQM et l'interprétation clinique n'en est que plus compliquée. De plus, une grande partie de l'interprétation se base sur la mise en relation des données cliniques et de celles de la marche (cinématique). Cependant, le lien entre les données cliniques et la cinématique n'est pas encore clairement établi. Les corrélations entre les paramètres de marche et les données cliniques sont relativement basses avec des coefficients de corrélation (r) allant de faible (0.21–0.40) à modéré (0.41–0.60) avec la corrélation la plus élevée de 0.50 entre les mesures cliniques des amplitudes articulaires et les paramètres cinématiques (Desloovere et al., 2006; Domagalska et al., 2013). Les données cliniques ne fournissent pas suffisamment d'informations pour retrouver la cinématique de marche d'un patient par une approche linéaire (Bonnefoy-Mazure et al., 2016). La principale hypothèse concernant ce manque de corrélation est qu'une altération primaire peut engendrer des mécanismes de compensation à la marche (Desloovere et al., 2006).

Actuellement, il ne semble donc pas possible de prédire la marche d'un patient en utilisant uniquement les données issues de son examen clinique.

### 1.3.5 Proposition pour mieux comprendre les altérations de marche: isoler l'effet d'un déficit clinique sur la marche

Pour faciliter l'interprétation de l'AQM et la compréhension des déficits cliniques, en différentiant essentiellement les réelles altérations des mécanismes de compensation à la marche (Romkes and Brunner, 2007), isoler un déficit semble être une approche appropriée et pertinente pour investiguer son influence sur la marche (Attias et al., 2016d).

Parmi les déficits cliniques pouvant être isolés, l'un des plus fréquents se trouve être la **rétraction des tissus mous** qui affecte les patients dans de nombreuses pathologies. Plusieurs approches permettent d'étudier l'influence de ces rétractions sur la marche. Une revue systématique de la littérature (article 1) a notamment été effectuée afin de les répertorier et de caractériser l'influence des rétractions sur la marche.

## 1.4 Article 1 – Effects of contracture on gait kinematics: a systematic review

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Review

Effects of contracture on gait kinematics: A systematic review

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Michael Attias [a,b,d,*], Odile Chevalley [c], Alice Bonnefoy-Mazure [a], Geraldo De Coulon [e], Laurence Cheze [d], Stéphane Armand [a]

[a] Willy Taillard Laboratory of Kinesiology, Geneva University Hospitals and Geneva University, Switzerland
[b] HES-SO University of Applied Sciences and Arts Western Switzerland, School of Health Sciences, Geneva, Switzerland
[c] Bern University of Applied Sciences Bern, Switzerland
[d] Université Claude Bernard Lyon 1, Villeurbanne, France
[e] Pediatric Orthopaedic Service, Department of Child and Adolescent, Geneva University Hospitals and Geneva University, Geneva, Switzerland

Cette étape a consisté à réaliser une revue systématique de littérature qui a permis de mettre en évidence qu'isoler un déficit de marche permet de mieux l'étudier.

Les résultats ont été publiés et ont été présentés dans :

Publication "peer review"

Attias M, Chevalley O, Bonnefoy-Mazure A, De Coulon G, Cheze L, Armand S. Effects of contracture on gait kinematics: A systematic review. Clin Biomech (Bristol, Avon). 2016;33:103-10.

### 1.4.1 Résumé français


Contexte: Les rétractions des tissus mous autour des principales articulations des membres inférieurs peuvent altérer la marche humaine ainsi que d'autres activités de la vie quotidienne. Une rétraction est définie comme l'incapacité d'une articulation à effectuer toute son amplitude de mouvement et une résistance excessive pendant la mobilisation passive de l'articulation. Peu d'études ont rapporté des résultats décrivant les répercussions des rétractions sur la marche. Faire une synthèse de ces études semble essentiel pour améliorer la prise en charge des patients. Par conséquent, nous avons mené une revue systématique sur ce sujet afin de mettre en avant l'influence des rétractions sur la cinématique de la marche.

Méthodes: Une recherche électronique de la littérature a été effectuée. Les études ont été évaluées par titre et résumé et les textes complets ont été évalués secondairement pour une inclusion définitive. La qualité des études incluses a été évaluée indépendamment par les deux premiers auteurs avec la grille d'évaluation de qualité modifiée « Modified Quality Assessment Checklist ». Les études incluses ont été divisées en trois catégories: rétractions pathologiques versus sujets contrôles sains (descriptif), rétractions simulées/émulées sur sujets contrôles sains (expérimentale) et analyse pré- et post-traitement après allongement musculaire chirurgical (chirurgie).

Résultats: sur un total de 4402 références, 112 articles originaux ont été sélectionnés et 28 études ont été incluses dans cette revue systématique. Aucune différence significative n'a été observée entre les évaluateurs sur le score total de la grille d'évaluation de qualité modifiée « Modified Quality Assessment Checklist ».

Interprétation: Les rétractions influencent la marche en fonction de l'emplacement (muscle) et du niveau de sévérité (longueur muscle-tendon). Après avoir donné une définition de la rétraction, cette revue a identifié certaines altérations, telles que les rétractions provoquant une flexion plantaire, une flexion de genou et une flexion de hanche, avec une description cinématique et une présentation des différentes compensations possibles.



Mots-clés: Revue systématique, Rétraction, Cinématique, Longueur muscles-tendons, Raccourcissement musculaire, Marche

### 1.4.2 Abstract

Background: Contractures of a major joint in the lower limbs may impair human walking in addition to other daily living activities. A contracture is defined as the inability of a joint to perform the full range of motion and excessive resistance during passive mobilization of the joint. Few studies have reported methods describing how to evaluate contractures. Understanding the association among all of these studies seems essential to improve patient management. Therefore, we conducted a systematic review on this topic to elucidate the influence of contractures on gait kinematics.

Methods: An electronic search in the literature will be conducted. Studies were screened by title and abstract and full texts were evaluated secondarily for definitive inclusion. The quality of the included studies was assessed independently by the two review authors with the Modified Quality Assessment Checklist. The included studies were separated into three categories: pathological contracture versus healthy controls (descriptive), simulated contracture versus healthy controls (experimental), and pre- and post-kinematics after surgical muscle lengthening (surgery).

Findings: From a total of 4402 references, 112 original articles were selected, and 28 studies were identified in this systematic review. No significant difference between raters was observed on the total score of the Modified Quality Assessment Checklist.

Interpretation: Contractures influence walking depending on the location (muscle) and the contracture level (muscle-tendon length). After giving a definition of contracture, this review identified some contracture alterations, such as plantarflexion, knee flexion and hip flexion contractures, with a kinematic description and presented possible different compensations.

Keywords: Systematic review, Contracture, Kinematics, Muscle-tendon length, Muscle shortening, Gait

### 1.4.3 Introduction

A contracture is defined as the inability of a joint to perform the full range of motion and excessive resistance during passive mobilization of the joint (Gaudreault et al., 2009). The structures involved in contractures include ligaments, capsule, tendons and muscles for which the extensibility is limited and the stiffness is increased (Prabhu et al., 2013). Moreover, Perry and Burnfield (2010) differentiate between elastic and rigid contractures. An elastic contracture yields to the forceful stretch of an examiner or body weight, whereas a rigid contracture resists considerable force (stiffness) and is able to support body weight. **Causes of contracture** can be a result of different factors. Generally, a contracture is a common complication of many neurological and musculoskeletal conditions (Prabhu et al., 2013).

Contractures of a major joint in the lower limbs may impair human walking in addition to other daily living activities (Hoang et al., 2014; Prabhu et al., 2013).

Contractures have a high incidence in neurological and orthopedic conditions (Farmer and James, 2001), including ligament and joint capsule shortening, intra-articular adhesions, fibro-fatty tissue proliferation into the joint and muscular shortening (Fox et al., 2000), muscle retraction, tendinous adherence, skin or subcutaneous tissue loss, joint capsule thickening or a combination of these factors (Roberson and Giurintano, 1995). The primary factors that cause suffering from contractures are burns, spinal cord injuries, cerebral palsy, strokes, and advanced age (Hoang et al., 2014). The association among contracture, muscle weakness and spasticity is generally accepted, although it has not been demonstrated scientifically (Hoang et al., 2014).

**The main effect of contractures** is a limitation of joint range of motion resulting from soft tissue stiffness (Hoang et al., 2014), but contractures can also cause pain, sleep disturbances, pressure ulcers, and deformities (Fox et al., 2000; Prabhu et al., 2013). A limited range of motion affects mobility and daily life activities. Among these activities, walking is a **primordial activity of daily living**. Patients and therapists ranked “moving around indoors” as the most important activity to preserve/restore in patients (Chiou and Burnett, 1985). Contractures induce gait deviations and limit a person’s ability to walk (Hoang et al., 2014). In children with Duchenne muscular dystrophy, joint contracture represents the second most often occurring major clinical impairment that results in gait deviations (Gaudreault et al., 2009). In cerebral palsy, the commonest orthopedic deformity is equinus deformity caused by the contracture of the triceps surae (Galli et al., 2005). To choose the best therapeutic strategy in relation to gait deviations, it is mandatory to understand the gait deviations and to distinguish the primary deviation (directly resulting from the pathology) and the secondary deviation (compensatory mechanisms) (Schmid et al., 2013). Therefore, understanding the effects of contractures on gait deviations is important to support the therapeutic choice. In the literature, different approaches have been used to elucidate the effect of contractures on gait.

The first approach is to compare the gait patterns between persons with contractures and matched healthy persons (Gaudreault et al., 2009; Svehlik et al., 2010). The second approach is to replicate the gait patterns of a patient with contractures by having healthy participants imitate the gait patterns. To this end, the investigators ask the participants to replicate the gait pattern by imitating patients with contractures, e.g., to walk on their tiptoes to imitate a triceps contracture (Romkes and Brunner, 2007). The third approach is to replicate the gait patterns of a patient with contractures in healthy participants by induced constraints. In this case, the healthy participants are constrained in certain joint degrees of freedom with an exoskeleton (Matjacic and Olensek, 2007; Matjacic et al., 2006) or an orthosis (Houx et al., 2012; Houx et al., 2013). The fourth approach is to use a computer simulation to evaluate the effects of constraints induced by contractures on gait (Goldberg and Neptune, 2007; Hicks et al., 2008; Neptune et al., 2007). Finally, the fifth approach is based on the comparison of a patient's gait before and after treating the contracture (Baddar et al., 2002; Chimera et al., 2012; Galli et al., 2005, 2009; Hemo et al., 2006; Kadhim and Miller, 2014; Lofterod and Terjesen, 2008; Park et al., 2006; Tylkowski et al., 2009). These studies have demonstrated the importance of studying this subject. Associating these studies seems essential to improve patient management. Therefore, we conducted a systematic review on this topic to elucidate the influence of contractures on gait kinematics.

### 1.4.4 Methods

#### *1.4.4.1 Search strategy*

To provide a comprehensive overview of the literature, an electronic search will be conducted within the following databases: MEDLINE/PubMed, from January 1948 to July 2014; CINHAL (EBSCO), from January 1981 to July 2014; and EMBASE, from January 1980 to July 2014. In addition, the references of included studies will be searched to identify further studies. The search strategy will encompass the following search terms: contracture, muscle shortening, muscle length, range of motion, joint flexibility, kinematics, biomechanics, walking, gait, and locomotion. The search strategy for the databank MEDLINE will look as follows: #1 (#contracture OR # contracture* OR # muscle shortening OR # muscle length* OR # range of motion OR # joint flexibility); #2 (#kinematics OR # biomechanics); #3 (#walking OR # gait OR # locomotion); and #4 (#1 AND #2 AND #3).

##### 1.4.4.1.1 Inclusion and exclusion criteria

Studies were screened by title and abstract following the rules of inclusion and exclusion criteria (Table 1). Full texts were evaluated secondarily for definitive inclusion. Two categories were selected to keep a maximum of articles, embracing concerned fields. The inclusion criteria contained articles about patient and healthy controls, as well as the simulation of contracture by different means. This review also included studies about muscle lengthening surgical intervention; these studies observed the pre- and post-outcome on gait kinematics. Two review authors independently screened the titles and abstracts. Disagreements were resolved by discussion until consensus, and when necessary, a third author arbitrated. Next, reviewers subsequently independently assessed the full-length reports for eligibility of the studies based on the inclusion and exclusion criteria. Disagreements were also discussed and arbitrated by a third author if necessary.

**Table 1 : Inclusion and exclusion criteria**

| | Inclusion | Exclusion |
|---|---|---|
| Population | Contractures or simulated contractures and healthy controls.<br>Pre-intervention (muscle lengthening) versus post-intervention | Acute contracture, sportsmen, animal<br>Splint as treatment, or splint with pathology |
| Intervention | Observation, evaluation, interpretation, Clinical Gait Analysis | Cast, splint, stretching, botulinum toxin, multi- surgery |
| Outcome | Kinematics, gait deviations, compensations | No kinematics |
| Type of study | Original research, published in peer-reviewed scientific journals, case-study research (observational) | Conference abstracts, non peer-reviewed publications, single case, systematic review. |

##### 1.4.4.1.2 Data extraction and quality assessment

The two review authors independently extracted data from the included studies with a customized form. The following data were extracted: study design or aim, study population characteristics (diagnosis, age, sample size), parameters evaluated (kinematics, kinetics, EMG, etc.), major joints assessed and/or device, and main results (especially kinematics).

The quality of the included studies was assessed independently by the two review authors with the Modified Quality Assessment Checklist (Schmid et al., 2013). The checklist was first described by (Downs and Black, 1998). The authors developed this tool to assess the quality of randomized and non-randomized trials. It has a high internal consistency, good test-retest and inter-rater reliability, and good face and criterion validity. The checklist was modified to assess the quality of non-randomized observational studies (Schmid et al., 2013). The included studies are evaluated with 17 items with a total maximum score of 20 points. These 17 items were then classified in 5 categories and evaluated as follow: reporting quality (8 items, maximum 10 points), external validity (3 items, maximum 3 points), internal validity – bias (3 items, maximum 3 points), internal validity – confounding (2 items, maximum 2 points), and statistical power (1 item, maximum 2 points).

#### *1.4.4.2 Data Analysis*

The extracted data were analyzed in a qualitative manner. The included studies were separated into three categories: pathological contracture versus healthy controls (descriptive), simulated contracture versus healthy controls (experimental), and pre- and post-kinematics after surgical muscle lengthening (surgery). Given that it is difficult to assess the contribution of a single surgery during a multi-level surgery (Lofterod and Terjesen, 2008), we investigated only single surgeries.

An intraclass correlation coefficient (ICC) with (+/- confidence interval) and the p-value (t-test) were calculated to evaluate the inter-rater reliability on the total score of the modified quality assessment. ICC was described according to Shrout and Fleiss (1979) (> 0.75 excellent reliability, 0.4-0.75 fair to good reliability and <0.4 poor reliability). Statistical analyses were performed using MATLAB R2012b (MathWorks, USA).

**Table 2 : Extracted data from the included studies**

| First author | Study design or aim | Number of subjects / (gender M / F) / Participants type | Mean age in years (SD) or (range) | Parameters evaluated (other than spatiotemporal) | Major joints assessed and/or device | Main results (especially kinematics) |
|---|---|---|---|---|---|---|
| **Experimentation** | | | | | | |
| Balzer 2013 | Explore if an artificially induced bilateral knee flexion contracture (specially designed hip-knee-belt, to produce a symmetric artificial knee flexion contracture of 40°) causes compensatory mechanisms in foot motion during gait in healthy children. | 30 healthy children | 10.6 (+/- 1.8) | Kinematics<br>Kinetics | knee flexion contracture | Increase in maximal dorsiflexion, eversion and external rotation of the hindfoot. |
| Cerny 1994 | Adaptation in the stance phase of gait to knee flexion contractures simulated by a knee-ankle-foot orthosis. | 20 healthy women | 25(+/- 3.6 ) | Kinematics<br>Kinetics,<br>EMG | Knee flexion contracture | Knee flexion contracture resulted in decreased stride length and velocity: Increase forefoot weight bearing and flexion posture in stance. |
| Davids 1999 | Evaluate primary from secondary compensatory with normal children, walking normally and voluntarily toe-walking in comparison to real toe walking gait pattern. | 32 normal children;<br>15 toe walker | 9.3 (5.4-13.6); 8.2 (5.4-13.6) | Kinematics<br>Kinetics<br>EMG | Imitation of plantarflexion (toe-walking) | Loss of heel strike at initial contact, disruption of the first ankle rocker, inversion of the second rocker, ankle plantarflexion (instead of dorsiflexion) occuring at midstance, disruption of the third rocker in terminal stance |
| Goodman 2004 | Determine what compensatory gait deviations may occur as a result of an imposed, unilateral equinus constraint. | 12 normal adult subjects | 23.7 (SD) | Kinematics<br>Kinetics | Imposed ankle equinus by tape | Stance phase limitations in both hip and knee extension of persons with hemiplegia are not necessarily caused by limited length of the involved side hamstrings and/or hip flexors, but rather as the result of an ankle plantarflexor contracture alone. |

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| Harato 2008a | Investigate static and dynamic changes in trunk kinematics with simulated knee flexion contracture during walking. | 10 healthy females | 62 (60-64) | Kinematics Kinetics | Simulated knee flexion contracture | 30° contracture significantly changed the kinematics in each of the following planes. The trunk tilted to the contracture side in standing and walking. Posterior inclination of the pelvis in standing significantly increased. Anterior inclination of the trunk and pelvis significantly increased. Trunk rotation to the unaffected side significantly decreased. |
| Harato 2008b | Investigate the effect of knee flexion contracture on the knee mechanics both in affected and contralateral limbs during gait. | 10 healthy females | 62 (60-64) | Kinematics Kinetics | Simulated knee flexion contracture | knee flexion contracture greater than 15° led to mechanical overloads in both limbs. |
| Houx 2012 | Understand consequences of equinus foot on gait. Development of orthosis to induce equinus. | 10 healthy children | 9.7 (+/-1.25) | Kinematics Kinetics | Induced an adjustable degree of unilateral equinus | Significant kinematic and kinetic changes occurred at -10°, -20° and maximum plantarflexion. |
| Houx 2013 | Define threshold angle of equinus beyond which significant changes in 3D lower limb kinematics and kinetics occur in typically developing children | 10 healthy children | 9.7 (8-12) | Kinematics Kinetics | Induced an adjustable degree of unilateral equinus | Most of the kinematic and kinetic changes were significantly altered from the 10° condition: increased hip flexion at initial contact and increased anterior pelvic tilt, increased knee varus, reduced hip adduction and more internal foot progression. |
| Leung 2014 | Describe the effect of simulated plantarflexion contractures on knee biomechanics during the stance phase and on the spatiotemporal characteristics of gait by an ankle-foot-orthosis | 13 able-bodied adults | 30 (+/-7) | Kinematics Kinetics | Simulated ankle plantarflexion contractures | Ankle plantarflexion contractures are associated with an increase in knee extension during stance phase. Some people with simulated ankle contractures may walk with an increase in knee flexion instead. |

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|---|---|---|---|---|---|---|
| Matjacic 2006 | Characterize biomechanically three different toe-walking gait patterns, artificially induced, by a mechanical exoskeleton with elastic ropes, in six neurologically intact subjects and to compare them to selected cases of pathological toe-walking. | 6 neurologically intact subjects males | 22.5 (+/-1.9) | Kinematics Kinetics | Emulated contractures of soleus and gastrocnemius muscles | In ipsilateral side, soleus contracture mainly influenced the ankle angle trajectory, while gastrocnemius and soleus/gastrocnemius contractures influenced the ankle and knee angle trajectories. In the knee joint soleus contracture diminished, gastrocnemius contracture increased while soleus/gastrocnemius contracture approximately halved knee extensor moment during midstance as compared to normal walking. |
| Matjacic 2007 | To characterize biomechanically three different crouch walking patterns, artificially induced in eight neurologically intact subjects and to compare them to selected cases of pathological crouch walking. | 8 neurologically intact subjects males | 25.2 (+/-3.5) | Kinematics Kinetics | Emulated contractures of iliopsoas and hamstrings muscles by an exoskeleton with artificial muscles | Hamstring contracture (HAM) and iliopsoas/hamstring contracture (IPSHAM) shifted ankle-angle rotation profiles into dorsiflexion during midstance compared to iliopsoas contracture (IPS) and normal walking (NW) where ankle-angle trajectories were similar. HAM, IPS and IPSHAM shifted the knee angle of rotation profiles into flexion during stance, compared to NW. IPS and IPSHAM shifted hip angle of rotation profiles toward pronounced flexion while HAM shifted hip angle of rotation profiles toward extension, compared to NW. |

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|---|---|---|---|---|---|---|
| Olensek 2005 | Evaluate and compare gait variability as recorded in normal gait and when being constrained by a mechanical exoskeleton with elastic ropes. | 6 neurologically intact subjects males | 22.5 (+/-1.9) | Kinematics Kinetics | Emulated contractures of soleus and gastrocnemius muscles | The most constrained SOL-GAS condition showed comparable gait variability. |
| Ota 2014 | Investigate the acute influence of varied levels of restricted ankle dorsiflexion on knee joint sagittal and frontal plane kinematics and kinetics during gait using a dial lock joint and allowing unrestricted plantar flexion | 30 (15 / 15) healthy volunteers | 21.7 (+/-2.2) | Kinematics Kinetics | Restricted ankle dorsiflexion | Reduced ankle dorsiflexion during terminal stance of gait. Restriction in ankle dorsiflexion range of approximately 8°. |
| Romkes 2007 | Understand the differences between obligatory toe-walking as observed in hemiplegic CP gait and voluntary toe-walking. | 12 (8 / 4 ) hemiplegic children cerebral palsy(CP); 10 healthy adult (5 / 5) | 12.3 (+/-4.1); 29.5 (+/-3.3) | Kinematics Kinetics EMG | Healthy subjects mimicking toe-walking compared to hemiplegic CP. | The EMG pattern of the toe-walking leg was modified in gastrocnemius and tibialis anterior as compared with normal gait. This showed strong similarities to that of the patients and therefore can be regarded, at least in part, as activity required for toe-walking. |
| Whitehead 2006 | Determine the effect of simulated hamstring shortening on gait in normal subjects by an adjustable brace. | 6 normal female volunteers | 26.2 (21-42) | Kinematics Kinetics, Physiological cost index | Simulated hamstring shortening | Significant effects observed when the popliteal angle exceeded 85° and included increased effort of walking, decreased speed, stride and step length; decreased hip flexion and increased knee flexion in stance, increased posterior pelvic tilt, decreased pelvic obliquity and rotation and premature ankle dorsi- and plantar-flexion in stance. |

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| **Descriptive** | | | | | | |
| Choi 2011 | Investigate the clinical relevance of hip kinematic and kinetic parameters, and 3D modelled psoas length in terms of discriminant validity, convergent validity, and responsiveness | 24 cerebral palsy children ; 28 normal children | 6.9 (+/-1.6) ; 7.6 (+/-2.4) | Kinematics Kinetics | Hip flexor (psoas) contracture | Maximum pelvic tilt, maximum psoas length, hip flexor index, and maximum hip extension in stance were found to be clinically relevant parameters in evaluating hip flexor contracture. |
| Delp 1996 | Estimate the lengths of the hamstrings and psoas during normal and crouch gait on the basis of a computer model of the lower limb. Compare the lenghts of subjects'hamstrings and psoas muscle during walking with their lengths during static muscles tests. | 14 subjects with crouch gait ; 10 subjects without movement disorders | 10.5 ; 12.6 | Kinematics | Hamstrings and psoas lengths | 80% of the subjects with crouch gait had hamstring of normal length or longer, despite persistent knee flexion during stance. This occurred because the excessive knee flexion was typically accompanied by excessive hip flexion throughout the gait cycle. All subjects with crouch gait had a psoas shorter than normal during walking. |
| Gaudreault 2009 | Quantify the passive moments of force produced by ankle plantar flexor contractures and determine their mechanical contribution to the net ankle moment calculated during the gait of children with Duchenne muscular dystrophy (DMD). | 11 children with DMD; 14 healthy control children | 9.2 (+/-2.6) ; 9.7 (+/-1.9) | Kinematics Kinetics | Plantar flexion contractures | Contracture passive moments can compensate for the presence of progressive muscle weakness in the children with DMD. |
| Gordon 2013 | Describe the quantitative gait findings of the adolescent subject with a unilateral stiff hip and Determine whether these findings are similar to those of subjects presenting after arthrodesis. | 6 children with stiff hip | 13-17 | Kinematics Kinetics | Stiff hip | Increased arc of trunk and pelvic motion (sagittal, coronal); involved side: decreased arc of hip and knee motion (sagittal), decreased peak hip abduction in swing; contralateral side : increased arc of hip and knee motion (sagittal); and increased peak hip abduction in swing. |

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| Svehlik 2010a | Detect outcome measures that could help differentiate between dynamic equinus and fixed equinus deformities. Describe the function of the gastrocnemius and soleus muscles when either dynamic triceps surae tightness or fixed equinus contracture was present. | 23 CP children ; 12 C | none | Kinematics | Dynamic triceps surae tightness and fixed equinus contracture | Characteristic pattern changes for the ankle joint kinematics and abnormal kinetic patterns were identified for both types of equinus. Muscle-tendon lengthening velocity is an interesting parameter to distinguish between fixed equinus and dynamic equinus gait in CP children. |
| Svehlik 2010b | Confirm the hypothesis of the influence of the dynamic and fixed equinus deformity on the timing of knee recurvation (hyperextension). | 35 (21 /14) CP children<br><br>2 groups: early recurvatum (E-REC)<br><br>late recurvatum (L-REC)<br><br>12 developing healthy children | E-REC 8.01 (+/-2.7)<br><br>L-REC 7.62 (+/-2.36)<br><br>Healthy Children 10.32 (+/-2.96) | Kinematics<br>Kinetics<br><br>EMG | Dynamic and fixed equinus deformity on the timing of knee recurvation (hyperextension) | Both recurvatum groups had forefoot landing and neither achieved normal ankle dorsiflexion. Electromyographic examination revealed an abnormally high soleus activity in a single stance. Finding might simplify the decision as to which treatment to select for equinus deformity, present in patients with genu recurvatum. |
| **Surgery** | | | | | | |
| Baddar 2002 | Evaluate equinus gait relative to normal gait. Specifically, the length and excursion of the gastrocnemius-soleus muscle-tendon unit in relation to knee and ankle kinematics. | 34 (17 / 17) CP children<br><br>78 normal children | 7.2 (+/-3.4) ; 6.9 (+/-2.8) | Kinematics<br>Kinetics<br><br>EMG | Equinus gait and knee extension | Patients with an equinus gait pattern had a positive correlation (r = 0.7) between ankle and knee motion during single-limb stance. Ankle plantar flexion occurred while the knee moved into extension during single-limb stance. |

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| Chimera 2012 | Compare the sagittal plane ankle and knee mechanics during the stance phase of gait in patients with non-spastic isolated gastrocnemius contracture (IGC) associated with overuse foot pathology to those of healthy controls. Determine if sagittal plane ankle and knee mechanics would be altered with gastrocnemius recession. Compare post-surgical ankle and knee sagittal plane mechanics in these patients to those of healthy control participants. | 6 (1 /5) adult patients clinically diagnosed with non-spastic IGC ; 33 (15 / 18) healthy control participants | 53.2 (+/-5) ; 48.9 (+/-8) | Kinematics Kinetics | Isolated gastrocnemius contracture with full knee extension | Select post-surgical gait mechanics were unaltered; however, gait mechanics were not similar between non-spastic isolated gastrocnemius contracture patients and healthy control participants. Surgical intervention for patients with isolated gastrocnemius contracture does not appear to create any negative gait adaptations; however, patients may benefit from gait retraining post-recession as maladaptive gait patterns persist post operatively. |
| Galli 2005 | Analyze kinematic and kinetic effects of gastrocnemius fascia lengthening on gait pattern in CP children and the evaluation of push-off ability before and after treatment. | 20 CP children with equinus<br><br>10 healthy children | 8 (+/-2.7) ; 9 +/-3.1 | Kinematics Kinetics | Gastrocnemius fascia lengthening and the effects at the knee joint | After gastrocnemius fascia lengthening, a significant increase in ankle dorsiflexion (reduction in equinus foot) at initial contact and an increased in knee extension at initial contact. |
| Galli 2009 | Analyze kinematic and kinetic effects of gastrocnemius fascia lengthening over time using gait analysis in cerebral palsy (CP) | 12 CP children with equinus<br><br>20 healthy children | 9.3 (+/-2.7) ; 9 (+/-3.1) | Kinematics Kinetics | Gastrocnemius fascia lengthening and the effects at the knee joint | Improvements in ankle and knee kinematics and in ankle kinetics over time. The results showed that isolated gastrocnemius fascia lengthening improved lower extremity function without producing functional muscle weakness over time |
| Hemo 2006 | Determine whether children maintain adequate power generation at the ankle joint and how the kinematic parameters change after Achilles tendon lengthening for treatment of idiopathic toe walking (ITW) | 15 ITW children | 9 (4.2-13.1) | Kinematics Kinetics | Achilles tendon lengthening for treatment of idiopathic toe walking | Passive dorsiflexion improved from a mean plantarflexion contracture of 8 degrees to dorsiflexion of 12 degrees after surgery. Ankle kinematics normalized, with mean ankle dorsiflexion in stance improving from -8 to 12 degrees and maximum swing phase dorsiflexion improving from -20 to 2 degrees. |

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|---|---|---|---|---|---|---|
| Lofterod 2008 | Assess the local and distant effects of isolated calf muscle lengthening in ambulant CP children. | 15 (8 /7) CP children | 8.8 (6-14) | Kinematics Kinetics | Equinus gait with isolated calf muscle lengthening | The improvement in ankle kinematics and kinetics supported the experience of other studies. The distant effects, which have previously not been evaluated in three planes, showed improvement in several kinematic parameters indicating that additional surgery in selected patients could be abandoned or delayed. |
| Tylkowski 2009 | Evaluated the outcomes of operative intervention for isolated equinus contractures in individuals with CP using instrumented gait analysis. | 27 CP children | 11.4 (+/- 3.2) | Kinematics Kinetics | Gastrocnemius-soleus complex lengthenings on isolated equinus contracture | The passive range of motion at the ankle was improved and normalized postoperatively. Ankle kinematics normalized without compensatory changes occurring at the knee or hip kinematics. Ankle moments and powers become more normal but did not completely normalize. Kinematics and kinetics of the hip and knee were not adversely affected |

### 1.4.5 Results

#### *1.4.5.1 Selection of studies*

A total of 4402 references were found after the electronic database research. After screening the titles and abstracts and removing duplicates, 112 original articles were selected. Following the request for inclusion and exclusion criteria, 28 studies were identified in this systematic review. The major part of the excluded articles was due: 1) multilevel surgeries (35), 2) absence or inaccurate explanation about contractures (33), 3) absence or incomplete kinematic data (8), 4) letter to editor or commentary (5), 5) abstract (2) and 6) literature review (1). These 28 included studies were then classified in three groups: experimental (15), descriptive (6) and surgery (7). In the experimental group, 9 articles focused on plantarflexion contracture, 5 on knee flexion contracture, and 1 on hip and knee flexion contracture. Ten studies focused on adults and 5 on children. Twelve used an exoskeleton or an orthosis to impose contractures, 1 used tapes and 2 imitated gait pattern of patients with contractures. In the descriptive group, 3 articles focused on plantarflexion contracture, 1 on stiff hip, 1 on hip flexion contracture and 1 on hip and knee flexion contracture. These 6 articles focused on children. In the surgery group, 7 articles focused on plantarflexion contracture (gastrocnemius, soleus or achille tendon lengthening) with 6 on children and 1 on adults. The extracted data from the included studies are reported in Table 2 : study design or aim, number of subjects (gender and participants type), mean age in years, parameters evaluated, major joints assessed and/or device and main results.

#### *1.4.5.2 Quality assessment*

The Modified Quality Assessment Checklist with the evaluation for reporting quality, external validity, internal validity – bias, internal validity – confounding, and statistical power are described in

Table 3. The ICC (+/- confidence interval) 0.87 (0.94/0.73) on the total score of the modified quality assessment showed excellent reliability (Shrout and Fleiss, 1979) and a p-value of 0.783 between raters; no significant difference was observed. In the 28 studies, the total mean score and standard deviation (SD) of the modified quality assessment was computed and was 12.8 (2.0) on 20 points. The mean score (SD) for reporting was 8.4 (1.3) on 10 points; for external validity, 1.3 (0.6) on 3 points; for internal validity (Bias), 2.0 (0.8) on 3 points; for internal validity (confounding), 1 (0.6) on 2 points, and for power, 0.1 (0.4) on 2 points.

### 1.4.6 Discussion

This systematic review aims to characterize the influence of contractures on gait kinematics. Twenty-eight articles were selected and evaluated by 2 reviewers with excellent inter-rater reliability. These articles were divided in three groups according to the study method of the contractures (experimental, descriptive and surgery studies). Even if the definition of contracture is not consistent in all the studies, they agree that a contracture induces a restricted passive range of motion of one or several joints. It also frequently returned that contractures appear as a result of pathologic conditions (such as burns, spinal cord injury, cerebral palsy, stroke, elderly age (Hoang et al., 2014), and impaired walking).

The primary reported contractures that have an effect on gait are ankle plantarflexion (gastrocnemius or soleus contracture), knee flexion (hamstrings contracture) and hip flexion (psoas contracture).

A **plantar flexion contracture** can be the result of gastrocnemius muscle retraction or soleus muscle retraction if it is not a neurological problem. Several authors have studied walking in plantarflexion without separating the effect of gastrocnemius and soleus contractures. These studies mainly showed a loss of heel strike at initial contact (loss of first ankle rocker), ankle plantarflexion (instead of dorsiflexion) occurring at midstance, and disruption of the third rocker in a terminal stance (Davids et al., 1999). **Compensations** showed a limitation in both hip and knee extension (stance phase) without a short hamstring or hip flexor (van Trijffel et al., 2010), but another study showed an increase in knee extension during midstance and specify that some subjects walk in knee flexion (Leung et al., 2014). Therefore, the different compensations occur at the knee level with a plantarflexion contracture: knee flexion or knee extension during mid-stance. An increase of pelvic tilt, an increase of knee varus, reduction of hip adduction, and more internal foot progression were also reported (Houx et al., 2013). The minimal plantarflexion contracture to significantly change kinematics and kinetics is 10° of plantarflexion (Houx et al., 2012).

**Knee flexion contracture** has an effect on excessive knee flexion during walking commonly observed in a crouch gait (Balzer et al., 2013). Compensations that have been observed include a decreased stride length and velocity, increased forefoot weight bearing and flexion posture in stance (Cerny et al., 1994). Matjacic and Olensek (2007) described knee flexion contracture by hamstring contracture. The minimal popliteal angle (hamstring contracture) to have an effect on gait was found to be 85° and included increased walking effort, decreased speed, decreased stride and step length and increased knee flexion in stance (Whitehead et al., 2007).

**Compensations** of a knee flexion contracture include increased maximal dorsiflexion, eversion and external rotation of the hindfoot (Balzer et al., 2013), decreased hip flexion in stance, increased posterior pelvic tilt, decreased pelvic obliquity and rotation and premature ankle dorsi and plantarflexion in stance (Whitehead et al., 2007). It seems that we need a minimum of 30° of knee flexion contracture to change trunk kinematics in all planes. In the coronal plane, the trunk is tilted to the contracture side in standing and walking. In the sagittal plane, anterior inclination of the trunk increased during walking. In the axial plane, trunk rotation to the unaffected side decreased during walking (Harato et al., 2008a, b). Knee flexion contracture by hamstring contracture, when it is associated with iliopsoas contracture, leads to a tendency to dorsiflex the ankle angle during midstance while the hamstring only shifted the hip angle toward extension (Matjacic and Olensek, 2007). When we analyze knee flexion during walking, we need to be careful not to systematically associate this flexion with a contracture because 80% of subjects with a crouch gait for example, had a hamstring with a normal length or longer despite persistent knee flexion during stance; it seems that this was a problem with hip flexion with a psoas contracture (Delp et al., 1996).

Regarding a **hip flexion contracture** (psoas contracture), Matjacic and Olensek (2007) described a hip flexion because of a psoas contracture linked with knee flexion during stance. An ankle dorsiflexion during midstance was observed in association with a hamstring contracture, as was described above. All subjects with a crouch gait had a psoas during walking that was shorter than normal by more than 1 standard deviation (Delp et al., 1996).

Numerous studies have examined a multilevel contracture because it is difficult to have subjects with only one contracture. Moreover, a contracture is often associated with other alterations, such as muscle weakness. The physiopathology of contractures and how they develop remains unknown.

Table 3 : Modified Quality Assessment evaluated by MA and OC.

| Study ID | Reporting | | External validity | | Internal validity (Bias) | | Internal validity (Confounding) | | Power | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MA | OC | MA | OC | MA | OC | MA | OC | MA | OC | MA | OC |
| **Experimentation** | | | | | | | | | | | | |
| Balzer 2013 | 10 | 10 | 1 | 1 | 3 | 3 | 0 | 1 | 0 | 0 | 14 | 15 |
| Cerny 1994 | 9 | 8 | 1 | 1 | 2 | 2 | 1 | 2 | 0 | 0 | 13 | 13 |
| Davids 1999 | 9 | 8 | 2 | 1 | 3 | 3 | 1 | 2 | 0 | 0 | 15 | 14 |
| Goodman 2004 | 8 | 6 | 1 | 0 | 1 | 1 | 1 | 2 | 0 | 0 | 11 | 9 |
| Harato 2008a | 7 | 9 | 1 | 1 | 3 | 2 | 0 | 1 | 0 | 0 | 11 | 13 |
| Harato 2008b | 9 | 9 | 1 | 1 | 3 | 2 | 1 | 2 | 0 | 0 | 14 | 14 |
| Houx 2012 | 9 | 9 | 1 | 1 | 3 | 3 | 1 | 2 | 0 | 0 | 14 | 15 |
| Houx 2013 | 9 | 9 | 1 | 1 | 3 | 3 | 1 | 2 | 0 | 0 | 14 | 15 |
| Leung 2014 | 9 | 8 | 1 | 1 | 3 | 2 | 1 | 2 | 0 | 0 | 14 | 13 |
| Matjacic 2006 | 11 | 9 | 1 | 1 | 1 | 1 | 1 | 2 | 0 | 0 | 14 | 13 |
| Matjacic 2007 | 11 | 9 | 1 | 1 | 1 | 1 | 1 | 2 | 0 | 0 | 14 | 13 |
| Olensek 2005 | 10 | 9 | 1 | 1 | 1 | 1 | 1 | 2 | 0 | 0 | 13 | 13 |
| Ota 2014 | 9 | 9 | 1 | 2 | 3 | 2 | 1 | 2 | 0 | 0 | 14 | 15 |
| Romkes 2007 | 8 | 8 | 2 | 1 | 2 | 2 | 0 | 1 | 0 | 0 | 12 | 12 |
| Whitehead 2006 | 7 | 9 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 9 | 11 |
| **Description** | | | | | | | | | | | | |
| Choi 2011 | 9 | 9 | 2 | 2 | 2 | 3 | 0 | 1 | 2 | 2 | 15 | 17 |
| Delp 1996 | 7 | 7 | 2 | 2 | 1 | 2 | 1 | 2 | 0 | 0 | 11 | 13 |
| Gaudreault 2009 | 9 | 8 | 2 | 2 | 3 | 3 | 1 | 1 | 0 | 0 | 15 | 14 |
| Gordon 2013 | 5 | 4 | 2 | 3 | 1 | 0 | 0 | 1 | 0 | 0 | 8 | 8 |
| Svehlik 2010a | 9 | 8 | 2 | 1 | 2 | 1 | 0 | 2 | 0 | 0 | 13 | 12 |
| Svehlik 2010b | 9 | 9 | 2 | 1 | 2 | 2 | 1 | 1 | 0 | 0 | 14 | 13 |
| **Surgery** | | | | | | | | | | | | |
| Baddar 2002 | 9 | 6 | 2 | 2 | 2 | 2 | 0 | 1 | 0 | 0 | 13 | 11 |
| Chimera 2012 | 10 | 10 | 2 | 1 | 2 | 3 | 1 | 2 | 0 | 0 | 15 | 16 |
| Galli 2005 | 8 | 8 | 1 | 0 | 2 | 2 | 0 | 0 | 0 | 0 | 11 | 10 |
| Galli 2009 | 8 | 8 | 1 | 0 | 2 | 2 | 0 | 0 | 0 | 0 | 11 | 10 |
| Hemo 2006 | 8 | 6 | 2 | 2 | 2 | 1 | 1 | 2 | 0 | 0 | 13 | 11 |
| Lofterod 2008 | 8 | 7 | 2 | 1 | 2 | 1 | 0 | 1 | 0 | 0 | 12 | 10 |
| Tylkowski 2009 | 9 | 8 | 2 | 3 | 2 | 3 | 0 | 1 | 0 | 0 | 13 | 15 |

### 1.4.7 Conclusions

Contractures influence walking depending on the location (muscle) and the contracture level (muscle-tendon length). Different types of research studied contractures in experimental, descriptive and surgery studies. After establishing a definition for contracture, this review identified several contracture alterations, such as plantarflexion, knee flexion and hip flexion contractures, with a kinematic description and presented possible different compensations. By continuing to study and to differentiate gait alterations from compensations, treatment can be better targeted (e.g., surgery and physiotherapy).

## 1.5 Conclusion de l’introduction

Il a été montré dans cette revue systématique qu’une procédure expérimentale émulant des rétractions chez des sujets sains était une approche appropriée et pertinente pour étudier l’influence des rétractions musculo-tendineuses sur la marche. Cette approche permet notamment de différentier les réelles altérations des mécanismes de compensation.

## 1.6 Objectif général de la thèse

Le but de ce travail de thèse était donc d'identifier les effets de rétractions isolées des principaux muscles des membres inférieurs sur la marche humaine afin d'améliorer les connaissances sur la marche pathologique et d'aider à l'interprétation de l'AQM.

L'atteinte de cet objectif a nécessité plusieurs étapes :

1) concevoir et évaluer la faisabilité et fiabilité d'un dispositif capable d'émuler[2] de multiples rétractions unilatérales et bilatérales des muscles les plus affectés par les rétractions au niveau du membre inférieur.

2) comparer les adaptations cinématiques à différents degrés de rétraction et entre les rétractions émulées de manière isolée et bilatérale des muscles gastrocnemius et du muscle soleus.

3) évaluer l'effet des rétractions des gastrocnemius et soleus sur les premier et second pivots pendant la marche.

4) comparer les effets des rétractions de différents muscles pouvant causer une marche «genoux fléchis» sur la cinématique.

5) classifier et caractériser les mouvements du tronc pendant la marche causés par les rétractions principales des membres inférieurs.

[2] Dans cette thèse, ce terme doit être considéré comme une simulation par des moyens matériels. Le même terme est utilisé pour l'anglais « to emulate ».

# 2 Chapitre 2 : Méthodologie générale

La présentation générale du protocole est illustrée sur la Figure 12.

## 2.1 Protocole général

Le protocole impliquait trois étapes (A ; B ; C) : L'étape A comportait 9 participants qui ont été évalués à 2 reprises à une semaine d'intervalle afin d'évaluer la faisabilité et la fiabilité de la simulation de rétractions musculo-tendineuses par l'exosquelette. Tous les muscles répertoriés ont été analysés avec un seul niveau de sévérité de rétraction et émulés chacun séparément. Ces muscles ou groupes musculaires identifiés dans la littérature sont: peroneus, tibialis posterior, soleus, gastrocnemius, rectus femoris, adducteurs de hanche, ischio-jambiers[3] et ilio-psoas (Graham and Harvey, 2007; Molenaers et al., 2006; Molenaers et al., 2010; Van Campenhout and Molenaers, 2011). Cette étape est présentée dans l'article 2, située à la fin de ce chapitre. L'étape B comportait 10 participants qui ont été évalués sur quatre niveaux de sévérité de rétraction sur les gastrocnemius et soleus séparément. L'influence des rétractions de ces deux muscles est décrite dans le chapitre « résultats », articles 3 et 4. L'étape C comportait 10 participants évalués sur trois niveaux de sévérité de rétractions sur les ischio-jambiers, les ilio-psoas et les rectus femoris séparément. Cette étape a permis d'étudier la marche en flexion excessive de genoux causée par ces rétractions musculo-tendineuses présentée dans le chapitre « résultats », article 5. L'article 6, quant à lui, a utilisé toutes les rétractions émulées dans les étapes A, B et C afin d'identifier les altérations des mouvements du tronc causées par des rétractions.

Ainsi, au total, 35 participants ont pris part au protocole expérimental (en comptant l'étape D qui sera expliquée dans les perspectives). Quarante-six sessions d'analyse de marche représentant près de 113 conditions, 858 passages et environ 4700 cycles de marche ont été réalisées.

## 2.2 Participants

Les sujets sains qui ont participé à cette étude ne devaient présenter aucun problème neurologique ou orthopédique. Ils devaient être âgés de 18 à 35 ans et être volontaires.

---

[3] Les adducteurs de hanche et les ischio-jambiers sont des groupes musculaires et ne portent pas de nom latin

### 2.2.1 Commission d'éthique

La Commission d'éthique de la recherche sur l'être humain a accepté le projet de recherche sous le numéro de référence CER : 13-164 et tous les participants ont donné leur consentement.

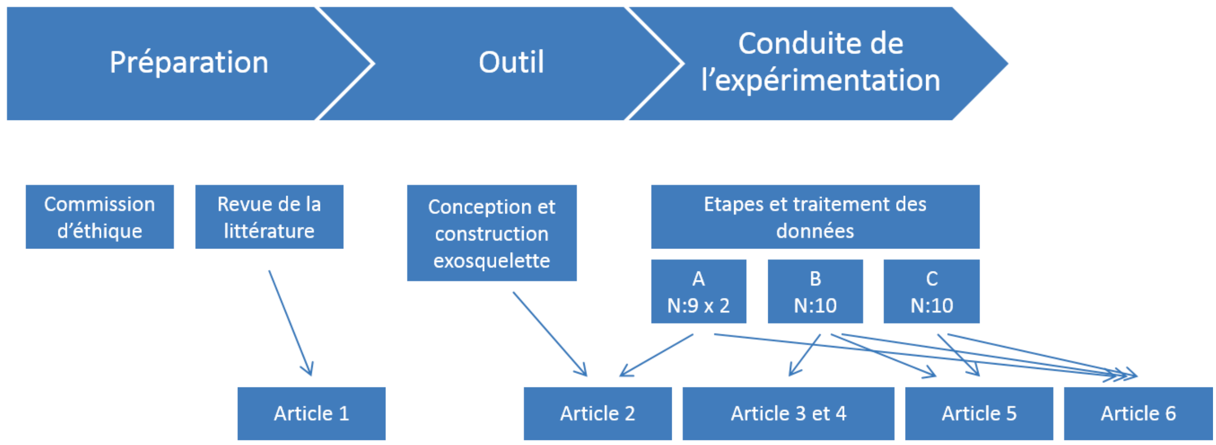


**Figure 12 : Représentation du protocole général de la thèse. N = nombre de participants pour chaque étape**

## 2.3 Création d'un dispositif pour répliquer des rétractions

Afin de pouvoir répondre à notre objectif, un exosquelette capable d'émuler de multiples rétractions musculaires unilatéralement et bilatéralement a été conçu. L'exosquelette a été construit sur la base de celui de Matjacic and Olensek (2007) en respectant les règles suivantes :

- L'exosquelette peut s'ajuster sur différentes morphologies.
- Pendant le mouvement, les coiffes en plastique sont solidaires du segment sur lequel elles sont attachées.
- Il permet la pose de marqueurs réfléchissants directement sur la peau.
- Il n'influence pas la marche normale si aucune rétraction n'est émulée.
- Il respecte les principales lignes d'action musculaire.
- Il peut émuler des rétractions sur les principaux muscles des membres inférieurs affectés par des rétractions.

La fabrication de l'exosquelette a été réalisée par la société Giglio Partners Orthopedie. L'exosquelette a été nommé « MIkE » : **M**uscle contracture **I**nduced by an **E**xos**k**eleton (Attias et al., 2016a). Il a été construit avec des coiffes en plastique englobant le bassin, les cuisses, les mollets et des chaussures modifiées avec des points d'attache. De plus, deux tailles d'exosquelette (petite et grande) ont été construites pour permettre un plus grand choix de morphologie chez les participants. Une découpe particulière des coiffes en plastique a permis de poser directement les marqueurs réfléchissants sur la peau des participants. Cette conception permet l'analyse de la marche des participants avec et sans l'exosquelette sans que les marqueurs ne soient déplacés lors du retrait de l'exosquelette. Il est présenté sur la

Figure 13.

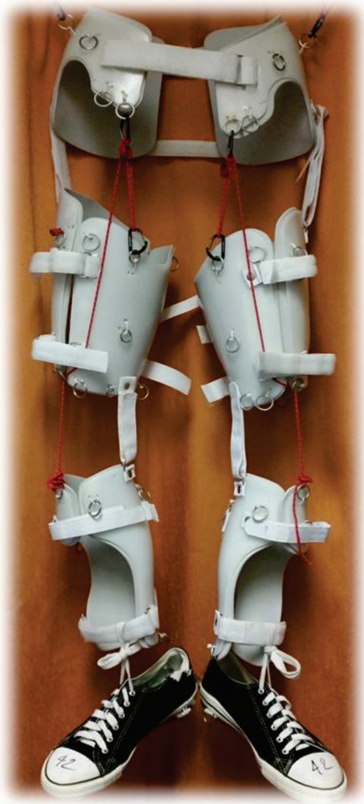

**Figure 13 : Exosquelette « MIkE » Muscle contracture Induced by an Exoskeleton (Attias et al, 2016a)**

L'exosquelette doit permettre d'émuler des rétractions unilatérales et bilatérales sur les principaux muscles ou groupes musculaires des membres inférieurs impliqués dans la marche pathologique. La rétraction a été induite par des cordes positionnées sur l'exosquelette (Figure 14). Les propriétés des cordes limitant les amplitudes articulaires ont été choisies de telle sorte qu'elles miment les propriétés passives du complexe musculo-tendineux selon deux conditions : les cordes ne doivent pas bloquer instantanément le mouvement, le blocage doit être progressif avec une force de freinage augmentée à la fin de la rétraction. La courbe d'hysteresis (force/longueur) caractérisant les propriétés élastiques du système d'ajustement des rétractions (corde, mousqueton et nœuds) est représentée sur la Figure 15. Les points d'insertion étant souvent trop profonds et multiples, pour les muscles sélectionnés, seule la ligne d'action musculaire principale a été utilisée pour définir les points d'attache des cordes sur l'exosquelette en lien avec l'anatomie sous-jacente du sujet.

Figure 14 : Système de corde réglable permettant d'émuler les rétractions musculo-tendineuses

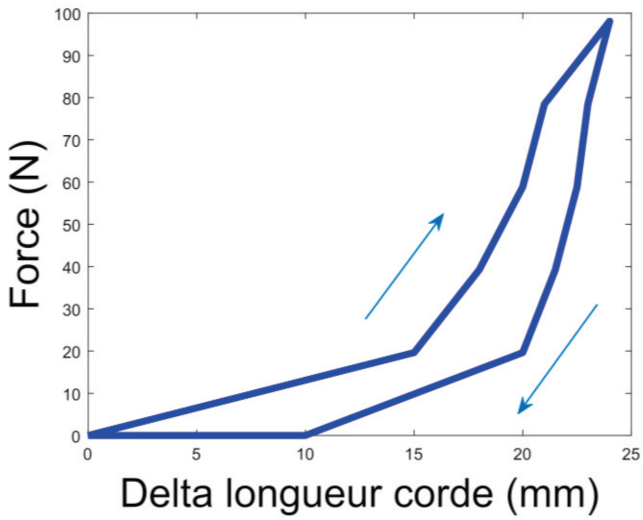


Figure 15 : Représentation de la courbe force (N) / longueur (mm) de la corde servant à émuler les rétractions (longueur initiale de 300 mm).

## 2.4 Evaluation de l'effet des rétractions à la marche

### 2.4.1 Emulation des rétractions

Les limitations des amplitudes articulaires (Figure 16) ont été réalisées par des cordes permettant de simuler la traction induite dans la direction du complexe musculo-tendineux, le réglage de la rétraction voulue étant contrôlé à l'aide d'un goniomètre. L'idée était de reproduire la mesure clinique des amplitudes articulaires passives sur table d'examen utilisée pour évaluer les rétractions articulaires des patients.

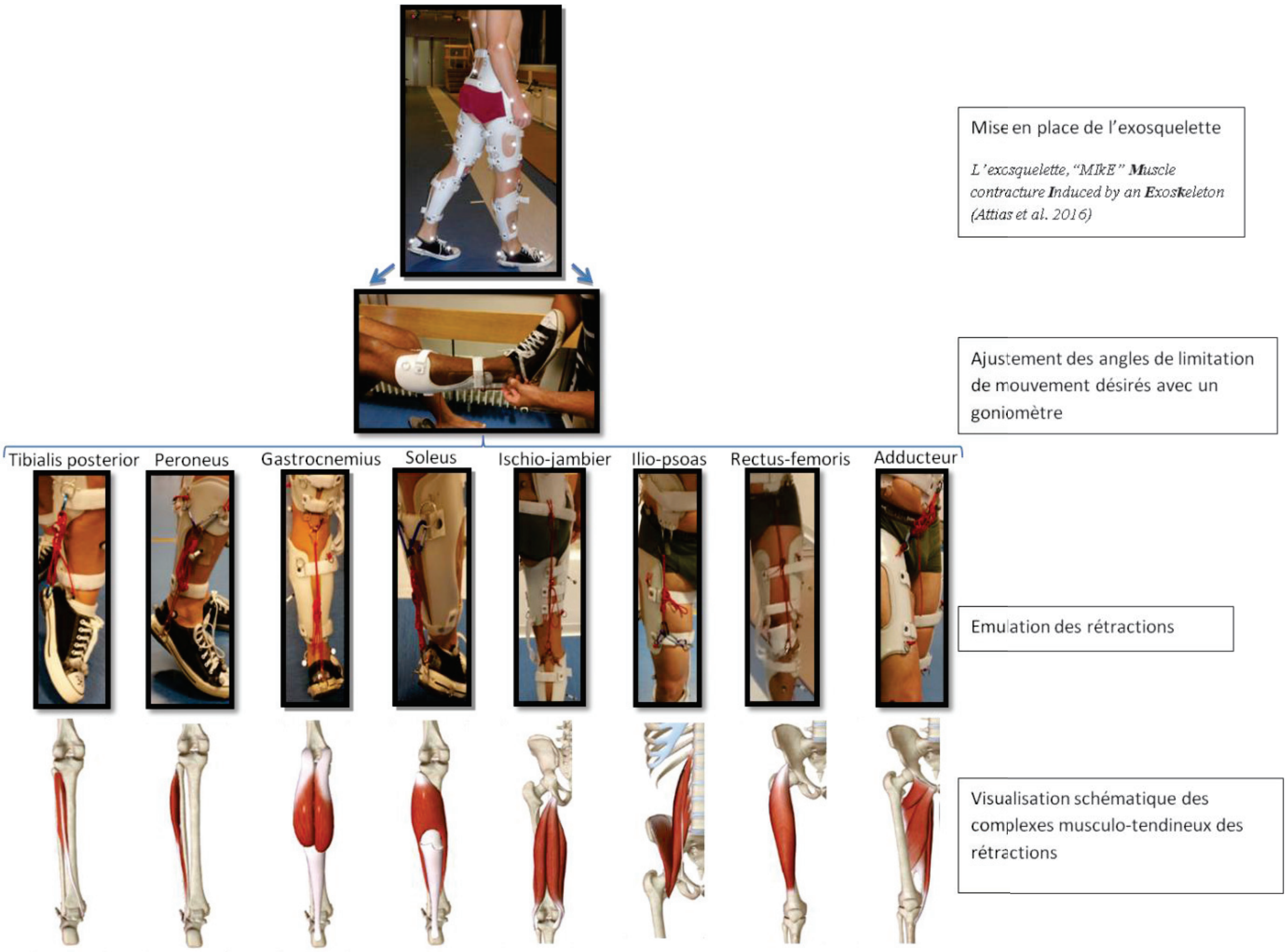


**Figure 16 : Réglage des limitations des amplitudes articulaires**

### 2.4.2 Evaluation de la marche :

Tous les participants ont été soumis à une analyse quantifiée de la marche (AQM) incluant un enregistrement de la cinématique avec un système d'analyse du mouvement de douze cameras Vicon Peak Mx3+, Oxford, UK pour l'étape A et Qualisys, Oqus 7+, Göteborg, Suède pour les étapes B et C. Il a été demandé aux participants de marcher le long d'un chemin de 10 mètres à vitesse spontanée. Un minimum de trois essais par condition a été réalisé pour l'étape A et 5 essais pour les étapes B et C. Les cycles de marche de ces essais ont été moyennés pour l'analyse. Certains auteurs préfèrent utiliser l'essai le plus représentatif plutôt que la moyenne (Brunner and Romkes, 2008; Carson et al., 2001; Duhamel et al., 2004; Schwartz et al., 2008). Néanmoins, il est difficile de prouver que l'essai le plus représentatif est suffisamment objectif (Schweizer et al., 2012) et la moyenne des essais est largement utilisée (Ballaz et al., 2010; Gaudreault et al., 2009; Houx et al., 2013; Leung et al., 2014; Matjacic and Olensek, 2007). Chaque participant était équipé de 34 marqueurs réfléchissants positionnés au niveau de la tête, du thorax, du bassin et bilatéralement des bras, des cuisses, des mollets et des pieds selon le modèle «Plug-in-Gait » (Davis et al., 1991). Le modèle de Gutierrez et al. (2003a) a été utilisé pour calculer la cinématique du tronc. La plupart des paramètres utilisés dans cette thèse sont représentés dans la Figure 17. Les segments bassin et thorax sont mesurés dans le système de référence du laboratoire et les angles articulaires de la hanche, genou et cheville sont calculés entre le segment proximal et le segment distal à l'articulation.

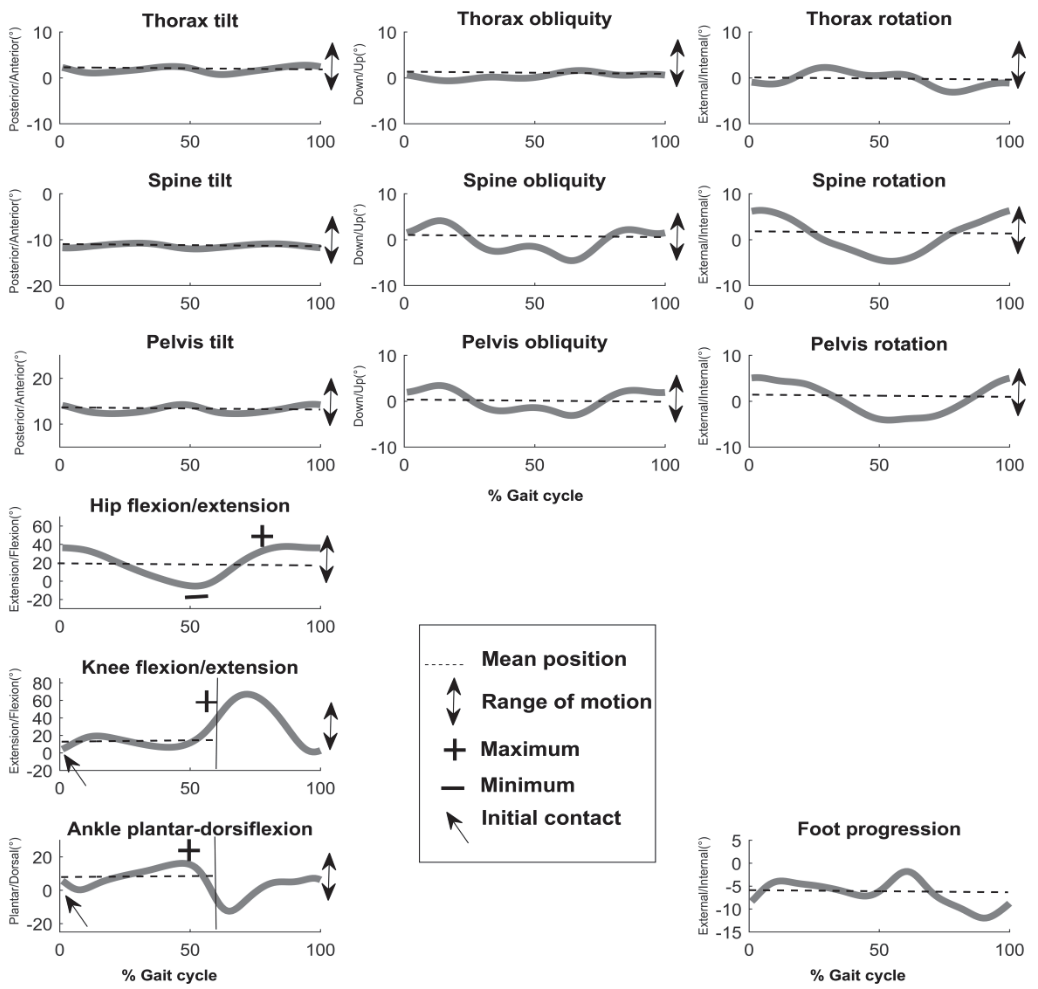


Figure 17 : Représentation graphique de la plupart des paramètres discrets utilisés dans cette thèse.

## 2.5 Article 2 – Feasibility and reliability of using an exoskeleton to emulate muscle contractures during walking

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Full length article

### Feasibility and reliability of using an exoskeleton to emulate muscle contractures during walking

M. Attias, MSc[a,b,c,*], A. Bonnefoy-Mazure, PhD[a], G. De Coulon, MD[d], L. Cheze, PhD[c], S. Armand, PhD[a]

[a] Willy Taillard Laboratory of Kinesiology, Geneva University Hospitals and Geneva University, Switzerland
[b] HES-SO University of Applied Sciences and Arts Western Switzerland, School of Health Sciences, Geneva, Switzerland
[c] Univ Lyon, Université Lyon 1, IFSTTAR, LBMC UMR_T9406, F69622, Lyon, France
[d] Pediatric Orthopaedic Service, Department of Child and Adolescent, Geneva University Hospitals and Geneva University, Geneva, Switzerland

Cette étape a consisté à concevoir et évaluer la faisabilité et fiabilité d'un dispositif expérimental capable d'émuler de multiples rétractions unilatérales et bilatérales des muscles les plus affectés par les rétractions au niveau du membre inférieur.

Les résultats ont été publiés et ont été présentés dans :

Publications "peer review"

Attias M, Bonnefoy-Mazure A, De Coulon G, Cheze L, Armand S. Feasibility and reliability of using an exoskeleton to emulate muscle contractures during walking. Gait Posture. 2016;50:239-245.

Attias M, Bonnefoy-Mazure A, Tabard A, Carcreff L, Hoffmeyer P, De Coulon G, Armand S. Faisabilité et reproductibilité d'un exosquelette capable de répliquer des contractures musculaires à la marche: application sur les gastrocnémiens et soléaires Mov Sport Sci/Sci Mot. 2016;93, 77-85.

Publications "abstract"

Attias M, Bonnefoy-Mazure A, Cheze L, De Coulon G, Armand S. Feasibility and reproducibility of using an exoskeleton able to emulate muscle contractures during walking. Gait Posture. 2015;42, S1, S82-S83.

Présentations publiques

Attias M, Bonnefoy-Mazure A, Cheze L, De Coulon G, Armand S, Feasibility and reproducibility of using an exoskeleton able to emulate muscle contractures during walking. ESMAC (European Society of Movement Analysis for Adults and Children); 2015 7-12 September 2015; Heidelberg (Germany).

Attias M, Bonnefoy-Mazure A, Tabard A, Carcreff L, Hoffmeyer P, De Coulon G, Armand S., Faisabilité et reproductibilité d'un exosquelette capable de répliquer des contractures musculaires à la marche: application sur les gastrocnémiens et soléaires. SOFAMEA (Société Francophone d'Analyse du Mouvement chez l'Enfant et d'Adulte); 04-06 February 2015; Geneva (Switzerland).

Conférencier invité

Attias M, Dans la peau du patient avec des problèmes moteurs ou fonctionnels ; SOFAMEA (Société Francophone d'Analyse du Mouvement chez l'Enfant et d'Adulte); 04 February 2015; Geneva (Switzerland).

### 2.5.1 Résumé français

La rétraction est un raccourcissement permanent du complexe musculo-ligamententaire-tendineux qui limite la mobilité articulaire. La rétraction est impliquée dans de nombreuses pathologies (paralysie cérébrale, accident vasculaire cérébral, etc.) et peut altérer la marche ainsi que d'autres activités de la vie quotidienne. Le but de cette étude était donc de quantifier la fiabilité d'un exosquelette conçu pour émuler les rétractions de muscles du membre inférieur unilatéralement et bilatéralement pendant la marche.

Un exosquelette a été construit selon les critères de conception suivants: ajustable à différentes morphologies; respect des lignes d'actions musculaires principales; placement de marqueurs réfléchissants sur des repères anatomiques; et possibilité de reproduire unilatéralement et bilatéralement les rétractions de huit muscles du membre inférieur (peroneus, tibialis posterior, soleus, gastrocnemius, rectus femoris, adducteurs de hanche, ischio-jambiers et ilio-psoas). Seize rétractions isolées ont été émulées sur les muscles unilatéraux et bilatéraux de neuf participants asymptomatiques. Deux séances d'analyse de la marche ont été effectuées avec un intervalle de temps d'une semaine pour évaluer la fiabilité des effets des rétractions émulées sur la cinématique de la marche.

Les résultats ont montré que l'exosquelette n'affecte pas la marche normale lorsqu'aucune rétraction n'est émulée. La fiabilité cinématique variait de faible à excellente selon le muscle ciblé. La fiabilité était bonne pour la rétraction du gastrocnemius, du soleus et du tibialis posterior (en bilatéral et unilatéral), ainsi que pour les groupes musculaires ischio-jambiers en bilatéral et les adducteurs de la hanche en unilatéral. L'exosquelette peut donc être utilisé pour simuler des rétractions chez les participants asymptomatiques. L'exosquelette nous permettra ainsi de différencier les effets primaires et les compensations des rétractions musculo-tendineuses sur la cinématique de la marche.

Mots-clés: rétraction, marche, exosquelette, simulation, émulation, cinématique

### 2.5.2 Abstract

Contracture is a permanent shortening of the muscle–tendon–ligament complex that limits joint mobility. Contracture is involved in many diseases (cerebral palsy, stroke, etc.) and can impair walking and other activities of daily living. The purpose of this study was to quantify the reliability of an exoskeleton designed to emulate lower limb muscle contractures unilaterally and bilaterally during walking.

An exoskeleton was built according to the following design criteria: adjustable to different morphologies; respect of the principal lines of muscular actions; placement of reflective markers on anatomical landmarks; and the ability to replicate the contractures of eight muscles of the lower limb unilaterally and bilaterally (psoas, rectus femoris, hamstring, hip adductors, gastrocnemius, soleus, tibialis posterior, and peroneus). Sixteen combinations of contractures were emulated on the unilateral and bilateral muscles of nine healthy participants. Two sessions of gait analysis were performed at weekly intervals to assess the reliability of the emulated contractures. Discrete variables were extracted from the kinematics to analyse the reliability.

The exoskeleton did not affect normal walking when contractures were not emulated. Kinematic reliability varied from poor to excellent depending on the targeted muscle. Reliability was good for the bilateral and unilateral gastrocnemius, soleus, and tibialis posterior as well as the bilateral hamstring and unilateral hip adductors. The exoskeleton can be used to replicate contracture on healthy participants. The exoskeleton will allow us to differentiate primary and compensatory effects of muscle contractures on gait kinematics.

Keywords: contracture, gait, exoskeleton, simulation, emulation, kinematics

### 2.5.3 Introduction

To be able to walk without feeling pain, fatigue, or another alteration is considered a priority in daily life and is linked to the quality of life (Hoang et al., 2014; Prabhu et al., 2013). Numerous impairments in the neurological and/or musculoskeletal systems generate walking alterations. A precise understanding of these alterations is required to optimise therapeutic strategies. Among impairments, contractures in the lower limbs occur frequently and alter human walking (Hoang et al., 2014; Prabhu et al., 2013). Contracture induces a restricted passive range of motion (ROM) (Katalinic et al., 2011; Prabhu et al., 2013) as a result of limited extensibility or increased stiffness of the soft tissues around the joints such as ligaments, capsule, tendons and muscles (Prabhu et al., 2013). Contractures have been reported in numerous pathologies such as cerebral palsy (Ballaz et al., 2010), multiple sclerosis, spinal cord injury and stroke (Hoang et al., 2014). Different mechanisms can be implicated in contractures, such as muscular shortening, shortening of ligaments, joint capsule alterations, intra-articular adhesions and proliferation of fibro-fatty tissues into the joint (Fox et al., 2000). The main causes of contractures are immobilisation (Akeson et al., 1980), muscle weakness (Farmer and James, 2001) and spasticity (Botte et al., 1988). The consequences of contractures on activities of daily life include walking deviations (Leung et al., 2014), loss of balance with risk of fall (Hoang et al., 2014) and bone deformities affecting posture (Nicodemo et al., 2014).

Experimental approaches have been used to induce the ROM limitations of joints using mechanical methods (rope, elastic, orthotics, and so on). Matjacic and Olensek (Matjacic and Olensek, 2007) investigated biomechanical characterisation and the clinical implication of artificially induced crouch walking, and this approach allowed them to determine the extent to which the iliopsoas and hamstring are implicated in crouch walking. Goodman et al. (Goodman et al., 2004) and Houx et al. (Houx et al., 2013) evaluated the compensation mechanisms of toe-walking unilaterally. They explained that in patients with hemiplegia, hip ROM limitations and knee extension in gait were not caused by hamstring and/or hip flexor contractures but were linked to ankle plantarflexor contractures only. Harato et al. (Harato et al., 2008a) studied the influence of knee contractures on trunk kinematics and determined the minimum degree of contracture required to obtain a significant difference in trunk movements in gait. Whitehead et al. (Whitehead et al., 2007) emulated hamstring contracture with an exoskeleton at the hip and knee level. They determined that to have an effect on knee kinematics, the popliteal angle would need to exceed 85°. These different results provide an important understanding on pathologic gait and support the links between clinical examination and gait deviations. However, these studies were focused on one or two muscles. To our knowledge, no study has used an external system that is able to emulate a combination of contractures on the main muscular groups of the lower limb. Therefore, the purpose of this study was to quantify the reliability of an exoskeleton designed to emulate lower limb muscle contractures unilaterally and bilaterally during walking.

### 2.5.4 Method

#### *2.5.4.1 Design exoskeleton:*

An exoskeleton was built based on the method of Matjacic and Olensek (Matjacic and Olensek, 2007) with the addition of certain criteria with:

Design criteria:

- Respects the main lines of action of the muscles.

- Is adjustable according to the anthropometry of participants.

- Avoids relative displacement between the plastic cuffs and the supporting body segment.

- Has the possibility to perform motion capture with reflective markers placed directly on the skin.

Assessed criteria:

- No modification of gait with the exoskeleton if no contractures were emulated.

- Can replicate contractures of the main lower limb muscles affected by contractures with a good level of reliability.

The exoskeleton was designed and built in collaboration with the Giglio Partners Orthopedie group based in Geneva, Switzerland. The exoskeleton, named “MIkE” for **M**uscle contracture **I**nduced by an **E**xos**k**eleton, is presented in Figure 18. It was built to bilaterally embrace the pelvis, the thigh and the shank with plastic cuffs and with modified shoes that included attachment points. A particular cut was made on the plastic cuffs to enable reflective markers to be placed directly on the skin as requested for clinical gait analysis (CGA). Moreover, this design enabled each participant to walk with and without the exoskeleton without removing any reflective marker.

The exoskeleton was built to induce unilateral and bilateral contractures in relation to the following main muscles or muscle groups affected by contractures in the lower body and identified in the literature: hamstring, iliopsoas, hip adductor, rectus femoris, gastrocnemius, soleus, tibialis posterior and peroneus (Graham and Harvey, 2007; Molenaers et al., 2006; Molenaers et al., 2010; Van Campenhout and Molenaers, 2011). Contractures were induced by ropes attached to rings. The characteristics of the ropes were chosen to avoid a sudden stop and to mimic a progressive increase of stiffness at the limit of the ROM as reported for muscle contractures (Prabhu et al., 2013). Because muscle insertion points are usually deep and multiple, only the main muscle lines of action were used to define the ropes attached to the rings. To respect the anthropometry of the participants, two different sizes of exoskeleton were built.

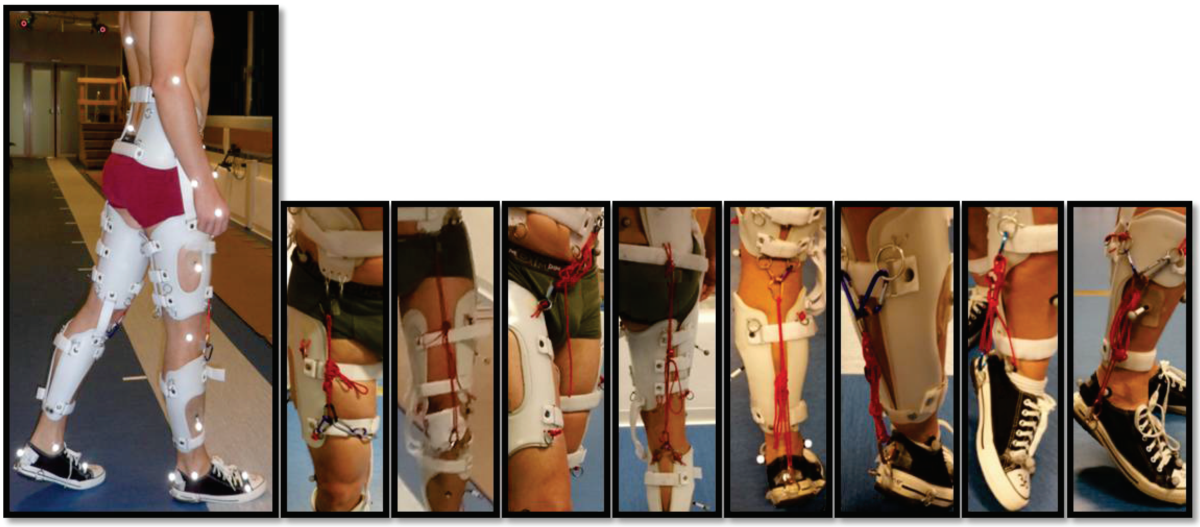

Figure 18: Pictures of the exoskeleton « MIkE » (Muscle contracture Induced by an Exoskeleton) From left to right: complete exoskeleton without contracture; psoas contracture; rectus femoris contracture; adductor contracture; hamstring contracture; gastrocnemius contracture; soleus contracture; tibialis posterior contracture; peroneus contracture

#### *2.5.4.2 Protocol:*

##### 2.5.4.2.1 Participants:

Nine healthy participants (6 females, 3 males) ages 18 to 35 years old (age: 27 ± 5.7 years; height: 1.70 m ± 0.09; weight 66.3 kg ± 7.8), with no known neurologic or orthopaedic problems, participated in this study. Ethical approval and participant consent were obtained before the data collection began.

##### 2.5.4.2.2 Gait evaluation:

The participants were equipped with 34 reflective markers that were aligned to anatomical landmarks on the head, trunk and pelvis, and bilaterally on the arms, thighs, shanks and feet according to the full-body Plug-in-Gait model (Davis et al., 1991). All participants were requested to walk along a 10-meter walkway at a spontaneous, self-selected speed. Kinematic recordings were performed with a 12-camera motion analysis system (Vicon Mx3, Vicon Peak, Oxford, UK). For the CGA, a minimum of three trials (corresponding to a minimum of three gait cycles) were averaged to produce a single angular displacement of the thorax, pelvis segments, and hip, knee, and ankle joints.

To emulate contractures in relation to patient contractures, the ROM from clinical examinations performed in patients who benefited of a CGA in our laboratory was analysed. The database including 985 patients with various pathologies (e.g., cerebral palsy [55%], idiopathic toe-walker [12%], clubfoot [7%], poliomyelitis [3%], neuropathy [3%], congenital flat foot [1%], spina bifida [1%] and various pathologies [18%]) affecting gait was analysed. The passive ROM, measured during clinical examination (maximum movement possible), was extracted for the following muscles: gastrocnemius, soleus, hamstring, rectus femoris and psoas. The percentiles of these ROM were computed and used to define the emulated contractures. The procedure to adjust the contracture was similar to the standard physical examination; with the patient lying on the examination table, we adjusted the ropes lengths for the desired limitation of movement with a goniometer (Viehweger et al., 2007). For the contractures of the tibialis posterior and peroneus muscles, the ROM limitation was assessed in the clinical examination with three categories: normal, limited, and blocked. Contracture of the adductors could not be emulated at a set angle. Instead, maximum abduction was set to the angle reached by the participants when their legs were against each other (approximately 5° adduction). Sixteen combinations of contractures were emulated on nine healthy participants on unilateral and bilateral muscles (Table 4). Before data capture, the participants practised walking for 2–5 minutes for each experimental condition. Once the participant was thought to have found a reliable gait in relation with the experimental condition, we assessed his/her gait (2 trials of 10 meters each). After each experimental condition, a resting period of 2 minutes was proposed to the participant to avoid the effect of fatigue. After the end of all of the experimental conditions, the exoskeleton was removed (but not the markers) to assess the gait without the exoskeleton. The order to emulate the contractures was always the same for each participant and for the two sessions (in unilateral and bilateral: gastrocnemius, hamstring, rectus femoris, soleus, psoas, hip adductor, tibialis posterior and peroneus). For unilateral conditions, the left and right legs were alternatively changed for each condition. The duration for each session was approximately 4 hours with 18 gait conditions and one iteration for each emulated contracture. Two sessions of CGA were performed at weekly intervals to assess the reliability of the emulated contractures.

**Table 4 : Amount of emulated contractures for each muscle and associated movement/position to adjust the emulated contractures.**

| Muscles | Amount of emulated contracture | Movements |
|---|---|---|
| Peroneus | Maximum | Foot eversion |
| Tibialis | Maximum | Foot inversion |
| Soleus | -10°* | Dorsiflexion (knee in flexion) |
| Gastrocnemius | -20°* | Dorsiflexion (knee in extension) |
| Hamstring | 95°* | Unilateral popliteal angle (hip and knee in flexion, contralateral lower limb in extension) |
| Rectus femoris | -40°* | Hip extension (knee in flexion) |
| Hip adductor | 5°* | Hip abduction (hip in extension, knee in flexion) |
| Psoas | -30°* | Hip extension (knee in extension) |

*** Based on the 1st percentile of ROM performed during clinical examination (database of 985 patients who performed a CGA in Geneva University Hospitals).**

#### 2.5.4.2.3 Data analysis and statistics:

First, to evaluate if the first assessed criterion was respected (no modification of gait with the exoskeleton if no contractures were emulated), a Wilcoxon test was performed on the gait profile score (GPS) (Baker et al., 2009) and walking speed between the condition of walking without the exoskeleton and the condition of walking with the exoskeleton without emulated contracture (right and left sides merged together). In addition, the root mean square error (RMSE) was computed between these two conditions for the following angles: pelvis and hip (sagittal, frontal, and transverse planes), knee and ankle (sagittal plane) and foot progression.

Second, to verify the second assessed criterion (exoskeleton can replicate contractures of the main lower limb muscles affected with a good reliability), the reliability of the exoskeleton with emulated contractures was analysed. For each emulated contracture, discrete parameters were extracted on the lower limb kinematics depending of the joint (ankle, knee, and hip) involved in the contracture and described in Table 5.

Table 5 : discrete parameters extracted on the lower limb kinematics depending of the joint (ankle, knee and hip) involved in the contracture

| | Ankle | | Foot | Knee | | Hip | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Flex Ext IC | Flex Ext ROM | Progression MP | Flex Ext IC | Flex Ext ROM | Flex Ext MP | Flex Ext ROM | Abd Add MP | Abd Add ROM |
| Gastrocnemius | x | x | X | x | x | | | | |
| Soleus | x | x | X | | | | | | |
| Hamstring | | | | x | x | x | x | | |
| Rectus femoris | | | | x | x | x | x | | |
| Psoas | | | | | | x | x | x | x |
| Hip adductor | | | | | | x | x | x | x |
| Tibial posterior | x | x | X | | | | | | |
| Peroneus | x | x | X | | | | | | |

x=measured parameters
IC = angle at initial contact; ROM = range of motion; MP = mean position angle
Flex/Ext = flexion / extension; Abd/Add = abduction / adduction

For each gait condition and each parameter, the intraclass correlation coefficient (ICC), standard error of measurement (SEM) (Standard deviation(SD) $\times \sqrt{(1 - \text{ICC})}$) and smallest detectable change (SDC) ($1.96 \times \text{SEM} \times \sqrt{2}$) (Allet et al., 2008; Ota et al., 2014; Turcot et al., 2008) were computed between the two sessions to evaluate the reliability (Allet et al., 2008; Ota et al., 2014; Turcot et al., 2008). The ICC was evaluated according to the Shrout and Fleiss (1979) scale (ICC < 0.4: poor reliability; ICC 0.4-0.75: fair to good reliability; ICC > 0.75: excellent reliability). In addition, Bland and Altman graphs were designed as a graphical approach to explore the reliability of the bias existing between the different conditions at a 1-week interval and provided the mean difference with the limit of agreement ($\text{mean difference} \pm \text{SD [difference]} * 1.96$) (Vidal et al., 2013) to evaluate the precision within which 95% of the differences fall. To evaluate the difference between the two sessions, the RMSE for all conditions between the two sessions was computed and averaged for the following angles: pelvis and hip (sagittal, frontal, and transverse planes), knee and ankle (sagittal plane) and foot progression. When the emulated contracture was unilateral, one side was considered (ipsilateral contracture side). When emulated contractures were bilateral, both sides were considered.

The data analysis, statistics and figures were performed with MATLAB R2012b (MathWorks, Natick, Massachusetts, USA) and the open-source Biomechanical ToolKit package for

MATLAB (Barre and Armand, 2014). A $p < 0.05$ was considered to show a statistically significant difference.

### 2.5.5 Results

#### *2.5.5.1 Gait reliability without emulated contractures*

The GPS and walking speed showed no significant difference between the two conditions of gait with a p-value of 0.983 for GPS and a p-value of 0.071 for walking speed (Figure 19). The medians (first and third quartiles) are presented for the condition without the exoskeleton: GPS 4.5° (4-5.4°), walking speed 1.4 m/s (1.2-1.5 m/s); and with the exoskeleton: GPS 4.5° (3.9-5.0°), walking speed 1.3 m/s (1.2-1.4 m/s). A mean RMSE for all of the considered angles (pelvis, hip, knee, and ankle) of 3.1° (± 0.9) was computed between these two conditions.

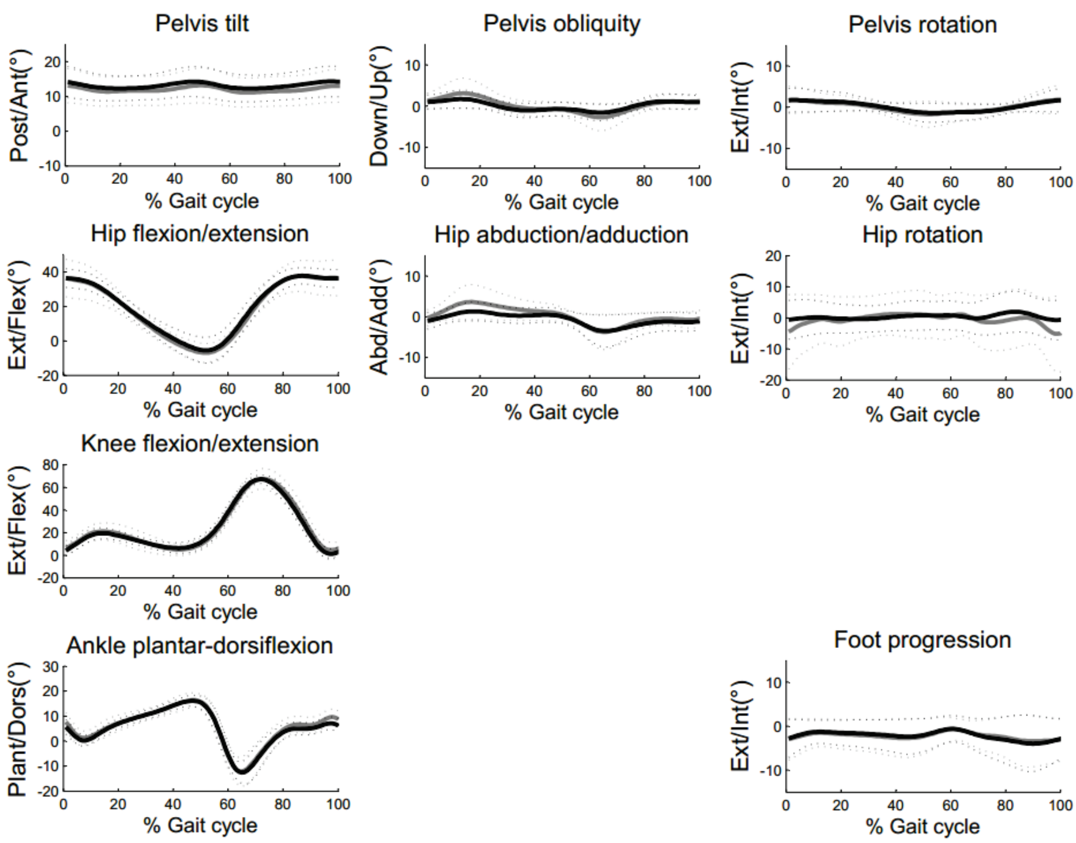


**Figure 19: Mean kinematics without and with the exoskeleton without emulated contractures in the three planes for pelvis and hip, in the sagittal plane for knee and ankle and foot progression. Black curve and dashed: mean kinematics with the exoskeleton and standard deviation. Grey curve and dashed: mean kinematics without the exoskeleton and standard deviation. Post/Ant: posterior/anterior; Ext/Flex: extension/flexion; Plant/Dors: plantar/dorsal; Abd/Add: abduction/adduction; Ext/Int: external/internal**

#### 2.5.5.2 Gait reliability with emulated contractures

The results showed (Table 6) from fair to good (ICC: 0.4-0.75) to excellent (ICC: >0.75) reliability for gastrocnemius, soleus and tibialis posterior unilaterally and bilaterally, as well as hamstring bilaterally and hip adductor unilaterally. Rectus femoris, psoas and peroneus were less reliable with some parameters showing poor reliability (ICC < 0.4) and three were non-interpretable (negative value can appear when the within-group variance exceeds the between-group variance) highlighted in grey in Table 6. The SEM and SDC showed the lowest reliability for the rectus femoris bilateral in knee ROM (flex/ext), showing more than 9° of SEM. Bland and Altman graphs showed the differences between conditions at a 1-week interval. Most of the differences were within the limits of agreement, with a few displacements of the mean difference around zero (<8° for the adductor bilaterally and <5° for the other conditions), which indicates a good reliability at a 1-week interval between conditions. The RMSE (Table 6) showed that most results were between 3° and 6°. Only adductors showed results higher, with 6.9° for adductor unilateral and 7.9° for adductor bilateral.

**Table 6 : Gait kinematics reliability for different emulated contractures between two sessions at weekly interval. ICC, SEM and SDC were computed for each contracture with involved joint (ankle, knee and hip). RMSE was computed based on the average of following angles: pelvis and hip (sagittal, frontal and transverse planes), knee and ankle (sagittal plane) and foot progression.**

| | | Ankle | | Foot | Knee | | Hip | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | RMSE (°) | Flex Ext IC | Flex Ext ROM | Progession MP | Flex Ext IC | Flex Ext ROM | Flex Ext MP | Flex Ext ROM | Abd Add MP | Abd Add ROM |
| Gastrocnemius bilateral | 4.32 | | | | | | | | | |
| ICC | | 0.74 | 0.78 | 0.83 | 0.65 | 0.67 | - | - | - | - |
| SEM(°) | | 3.12 | 2.09 | 2.38 | 4.95 | 5.02 | - | - | - | - |
| SDC(°) | | 8.64 | 5.78 | 6.59 | 13.72 | 13.93 | - | - | - | - |
| Gastrocnemius unilateral | 4.52 | | | | | | | | | |
| ICC | | 0.66 | 0.91 | 0.90 | 0.73 | 0.65 | - | - | - | - |
| SEM(°) | | 4.93 | 1.70 | 1.80 | 4.50 | 6.16 | - | - | - | - |
| SDC(°) | | 13.68 | 4.70 | 4.98 | 12.46 | 17.09 | - | - | - | - |
| Soleus bilateral | 4.06 | | | | | | | | | |
| ICC | | 0.95 | 0.77 | 0.90 | - | - | - | - | - | - |
| SEM(°) | | 1.45 | 1.80 | 2.50 | - | - | - | - | - | - |
| SDC(°) | | 4.03 | 4.98 | 6.94 | - | - | - | - | - | - |
| Soleus unilateral | 5.02 | | | | | | | | | |
| ICC | | 0.81 | 0.78 | 0.94 | - | - | - | - | - | - |
| SEM(°) | | 1.65 | 2.84 | 1.02 | - | - | - | - | - | - |
| SDC(°) | | 4.56 | 7.88 | 2.82 | - | - | - | - | - | - |
| Hamstring bilateral | 4.58 | | | | | | | | | |
| ICC | | - | - | - | 0.89 | 0.77 | 0.95 | 0.83 | - | - |
| SEM(°) | | - | - | - | 3.83 | 4.68 | 2.08 | 3.48 | - | - |
| SDC(°) | | - | - | - | 10.62 | 12.97 | 5.77 | 9.65 | - | - |
| Hamstring unilateral | 4.44 | | | | | | | | | |
| ICC | | - | - | - | 0.27 | 0.80 | 0.91 | 0.88 | - | - |
| SEM(°) | | - | - | - | 6.03 | 4.65 | 2.40 | 2.42 | - | - |
| SDC(°) | | - | - | - | 16.73 | 12.88 | 6.66 | 6.71 | - | - |
| Rectus femoris bilateral | 5.52 | | | | | | | | | |
| ICC | | - | - | - | 0.69 | 0.56 | 0.91 | 0.58 | - | - |
| SEM(°) | | - | - | - | 2.35 | 9.75 | 3.84 | 5.08 | - | - |
| SDC(°) | | - | - | - | 6.51 | 27.01 | 10.66 | 14.09 | - | - |
| Rectus femoris unilateral | 6.07 | | | | | | | | | |
| ICC | | - | - | - | 0.54 | NI | 0.86 | 0.47 | - | - |
| SEM(°) | | - | - | - | 3.93 | NI | 4.65 | 5.54 | - | - |
| SDC(°) | | - | - | - | 10.89 | NI | 12.88 | 15.35 | - | - |
| Psoas bilateral | 5.32 | | | | | | | | | |
| ICC | | - | - | - | - | - | 0.28 | 0.77 | 0.40 | 0.63 |
| SEM(°) | | - | - | - | - | - | 5.93 | 2.89 | 1.96 | 1.70 |
| SDC(°) | | - | - | - | - | - | 16.45 | 8.01 | 5.42 | 4.70 |
| Psoas unilateral | 4.55 | | | | | | | | | |
| ICC | | - | - | - | - | - | 0.25 | 0.51 | 0.70 | 0.62 |
| SEM(°) | | - | - | - | - | - | 6.11 | 4.26 | 1.42 | 1.71 |
| SDC(°) | | - | - | - | - | - | 16.92 | 11.80 | 3.95 | 4.74 |
| Adductor bilateral | 7.93 | | | | | | | | | |
| ICC | | - | - | - | - | - | 0.76 | 0.86 | NI | 0.57 |
| SEM(°) | | - | - | - | - | - | 5.38 | 2.84 | NI | 1.00 |
| SDC(°) | | - | - | - | - | - | 14.92 | 7.86 | NI | 2.77 |
| Adductor unilateral | 6.92 | | | | | | | | | |
| ICC | | - | - | - | - | - | 0.72 | 0.81 | 0.61 | 0.82 |
| SEM(°) | | - | - | - | - | - | 5.09 | 3.47 | 2.79 | 0.91 |
| SDC(°) | | - | - | - | - | - | 14.10 | 9.63 | 7.74 | 2.53 |
| Tibial posterior bilateral | 5.38 | | | | | | | | | |
| ICC | | 0.91 | 0.76 | 0.78 | - | - | - | - | - | - |
| SEM(°) | | 2.52 | 2.42 | 2.98 | - | - | - | - | - | - |
| SDC(°) | | 6.97 | 6.72 | 8.26 | - | - | - | - | - | - |
| Tibial posterior unilateral | 4.71 | | | | | | | | | |
| ICC | | 0.88 | NI | 0.84 | - | - | - | - | - | - |
| SEM(°) | | 2.99 | NI | 3.34 | - | - | - | - | - | - |
| SDC(°) | | 8.28 | NI | 9.26 | - | - | - | - | - | - |
| Peroneus bilateral | 5.54 | | | | | | | | | |
| ICC | | 0.16 | 0.78 | 0.81 | - | - | - | - | - | - |
| SEM(°) | | 5.23 | 3.21 | 4.99 | - | - | - | - | - | - |
| SDC(°) | | 14.49 | 8.91 | 13.83 | - | - | - | - | - | - |
| Peroneus unilateral | 4.91 | | | | | | | | | |
| ICC | | 0.26 | 0.90 | 0.88 | - | - | - | - | - | - |
| SEM(°) | | 2.93 | 1.75 | 3.76 | - | - | - | - | - | - |
| SDC(°) | | 8.12 | 4.84 | 10.42 | - | - | - | - | - | - |

**ICC interpretation: excellent reliability = (> 0.75); fair to good reliability = (0.4-0.75); poor reliability = (< 0.4);**
**ICC = Intra-class correlation coefficient; SEM = Standard error of measurement; SDC = Smallest detectable change; IC= initial contact; ROM = range of motion; MP = mean position angle; NI = non-interpretable; RMSE = Root mean square error; Flex/Ext = flexion / extension; Abd/Add = abduction / adduction**
**The poor ICC and NI were highlighted in light gray and the SEM >6.2° was highlighted in dark gray**

### 2.5.6 Discussion

The aim of this study was to design an exoskeleton that is able to emulate gait contractures on healthy participants and to analyse the reliability of this tool. Our experimental approach offers the opportunity to isolate each contracture to understand its specific impact on gait. First, an exoskeleton was built according to selected design criteria, and we demonstrated that normal walking was not influenced when the exoskeleton was worn without any emulated contractures. Second, contractures were emulated with good repeatability on healthy participants using this exoskeleton for some muscles (gastrocnemius, soleus and tibialis posterior unilaterally and bilaterally, as well as hamstring bilaterally and hip adductor unilaterally). Schwartz et al. (Schwartz et al., 2004) showed that variability can be caused by different biases, such as inter-trial, inter-session and inter-therapist errors, and that natural variability exists in the gait of healthy persons but should not be confused with experimental error. In our study, the main causes of variability were anatomical landmark misplacement (DellaCroce and Sullivan, 2005), soft tissue artefacts (Leardini et al., 2005) and the exoskeleton installation and configuration.

In the gait analysis, experimental error can reach an SEM of approximately 5-6° for hip rotations and ≤4° for other angles (Fernandes et al., 2016). In our study, one parameter exceeded an SEM of 6.2°, corresponding to the gait with bilateral emulation of contractures on the rectus femoris. Indeed, this can be explained by the fact that the rope can slide on the patella with the effect of changing the line of action and the level of contracture. In addition, the main line of action was difficult to respect for the muscles that have a small joint ROM such as the tibialis posterior, peroneus, and hip adductor. We observed that the emulation of these contractures can interact with other movements. For example, we observed that the emulations of hip adductors have a tendency to limit hip extension. These difficulties can explain the lower reliability for the adductor bilateral muscle (RMSE: 7.93), but they do not seem to have a high impact on the tibialis posterior and peroneus.

In the literature, other studies have used contracture emulation systems or imitations on healthy participants to better understand the effects of contracture on gait. Concerning the ankle joint, the triceps surae contracture has been evaluated in many studies (Davids et al., 1999; Goodman et al., 2004; Houx et al., 2012; Houx et al., 2013; Leung et al., 2014; Matjacic et al., 2006; Olensek et al., 2005; Ota et al., 2014; Romkes and Brunner, 2007). At the knee joint, the hamstring contracture has also been evaluated (Balzer et al., 2013; Cerny et al., 1994; Harato et al., 2008a, b; Matjacic and Olensek, 2007; Whitehead et al., 2007). Finally, at the hip joint, only one study has evaluated the effect of psoas contracture (Matjacic and Olensek, 2007). Most of the studies on the ankle have analysed only one side, and only two studies have evaluated bilateral knee flexion contracture (Balzer et al., 2013; Whitehead et al., 2007). Further, it will be interesting to use MIkE to develop these lacking aspects by studying bilateral contractures with a large range of combinations. None of these studies has evaluated the influence of their emulated contracture systems on gait kinematics (evaluating walking with and without their tools or contracture systems), nor have any of these studies analysed the reliability of their system, with the exception of the study by Ota et al. (Ota et al., 2014). With the support of a reliable emulated contracture system MIkE, future studies will provide new insights to understand the effects of contractures on gait. A further interesting approach using MIkE, might be to study the effect of artificially restricted movement on patients with neurologic disorders without contracture to observe how they could adapt this gait.

#### *2.5.6.1 Limitations*

The first limitation of this study concerns the inter-rater reliability, which was not evaluated. Actually, because of the complexity involved in adjusting the exoskeleton, only one rater has been trained in the use of the exoskeleton.

The second limitation concerns the exoskeleton. Indeed, despite the fact that this exoskeleton is adjustable according to the anthropometry of participants with two different sizes and Velcro attachments, we noticed a tendency of the exoskeleton to slide when it is used on subjects with a high body mass index, despite being designed with non-slip pads.

The third limitation concerns the choice of the ropes that mimic the passive properties of the muscle-tendon complex. The rope properties avoid a sudden blocking of the motion, but we have no measurement of these properties. The rope properties were also similar for all of the emulated contractures even if the muscle–tendon complex has different passive properties according to the muscles used (Zajac, 1989).

The fourth limitation specifically concerns the different adaptation strategies and the different types of walking chosen by the participants when contractures were emulated on biarticular muscles. For example, gastrocnemius contracture can act on plantarflexion, knee flexion/extension, or a combination of both (Matjacic et al., 2006). The rectus femoris and hamstring can influence hip flexion/extension, knee flexion/extension, or both (Matjacic and Olensek, 2007). These different gait strategies are very interesting to study and can increase the variability of the results. However, we did not designate the choice of adaptation, and we allowed participants to self-select their adaptation and their more comfortable gait. The choice of the adaptations could be driven by a mix between different strategies such as to minimise energy (Selinger et al., 2015), to optimise forward progression (Attias et al., 2015), to assure balance and stability (Romkes et al., 2007), and certainly other undiscovered strategies. In addition, adaptation to contractures in patients with neurologic impairments might be different, because they also have associated impairments such as weakness, spasticity, or selectivity deficit. Even if the results of emulated contracture do not represent the reality, they will permit us to better understand the links between contractures (assessed during clinical examination) and gait deviations. Finally, contracture adaptation time can play an important role in the choice of different gait strategies by participants, and our study analysed only immediate adaptations (<5 minutes of training).

#### *2.5.6.2 Conclusion*

An exoskeleton MIkE was built and evaluated to emulate contractures during walking. Good reliability was found for gastrocnemius, soleus, and the tibialis posterior unilaterally and bilaterally, as well as the hamstring bilaterally and hip adductor unilaterally. The rectus femoris, psoas and peroneus were less reliable. The results demonstrate that the replication of contractures on healthy participants using an exoskeleton permit us to better understand the effect of contractures on gait. However, one should be aware of the limits of this approach. The exoskeleton allows us to differentiate between the primary and compensatory effects of muscle contractures on gait kinematics.

## 2.6 Validation clinique de l'exosquelette pour émuler des rétractions:

En plus de la faisabilité et fiabilité de l’exosquelette, une comparaison des patterns cinématiques d’un patient (rétraction du soleus à -10° de flexion dorsale de cheville) de la base de données du Laboratoire de Cinésiologie Willy-Taillard et d’un sujet avec rétractions simulées (rétraction émulée du soleus à -10° de flexion dorsale de cheville) a été réalisée dans le but de vérifier si les modifications observées par rapport à une marche normale étaient cohérentes. A titre d’exemple, le graphique de la flexion dorsale et plantaire de cheville de ce patient et du sujet sain utilisant l'exosquelette (côté droit) est illustré sur la Figure 20. Par inspection visuelle, on remarque que la courbe de l’exosquelette suit le même pattern de marche que la courbe du patient avec une absence de premier pivot et un manque de flexion dorsale de cheville durant tout le cycle de marche. Il n'est pas possible d'effectuer de tests statistiques avec uniquement un patient, néanmoins, le pattern simulé semble se rapprocher d'une véritable condition pathologique.

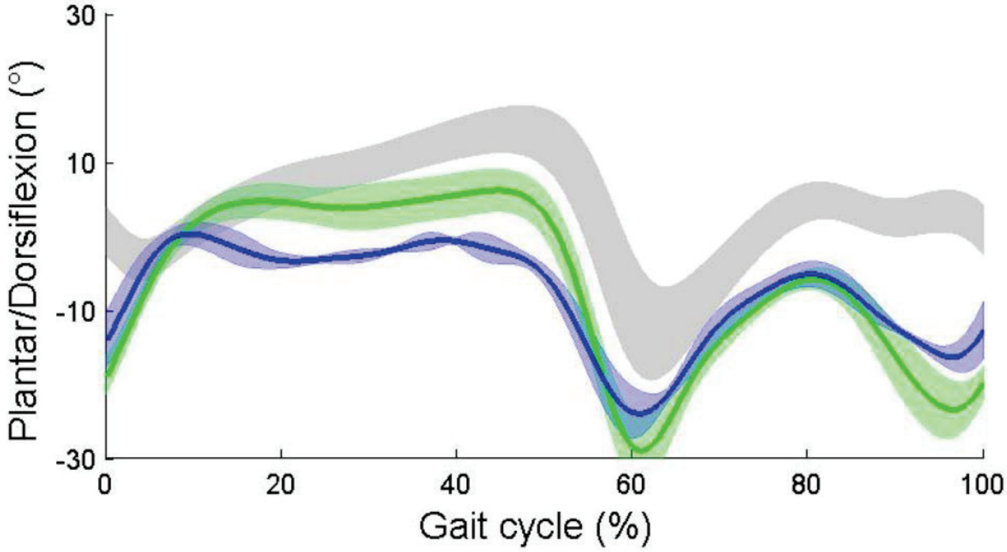


**Figure 20 : Exemple de comparaison d'un patient (rétraction soleus à -10° de flexion dorsale de cheville) et d'un participant sain utilisant l'exosquelette (rétraction émulée du soleus à -10° de flexion dorsale de cheville) sur la cinématique de la cheville au cours d'un cycle de marche dans le plan sagittal (côté droit). Courbe verte et aire: valeur moyenne pour le patient et écart-type. Courbe bleue et aire: Valeur moyenne pour l'exosquelette et écart-type. Zone grise: marche normale avec ± 1 écart-type.**

# 3 Chapitre 3 : Résultats expérimentaux

Une fois l'exosquelette construit et sa fiabilité vérifiée, plusieurs études expérimentales ont été menées pour répondre à notre objectif principal : identifier les effets de rétractions isolées des principaux muscles des membres inférieurs sur la marche humaine. Les articulations des chevilles, genoux, hanches, et les segments bassin et thorax ont été inclus dans ces études.

Résultats expérimentaux 1 : Article 3 – Comparaison des adaptations cinématiques à différents degrés de rétraction et entre les rétractions émulées de manière isolée et bilatérale des gastrocnemius et du soleus

Résultats expérimentaux 2 : Article 4 – Evaluation de l'effet des rétractions des gastrocnemius et soleus sur les premier et second pivots pendant la marche

Résultats expérimentaux 3 : Article 5 – Comparaison des effets des rétractions de différents muscles pouvant causer une marche « genoux fléchis » sur les paramètres cinématiques.

Résultats expérimentaux 4 : Article 6 – Classification et caractérisation des mouvements du tronc causés par les rétractions principales des membres inférieurs pendant la marche.

## 3.1 Article 3 – Influence of different degrees of bilateral emulated contractures at the triceps surae on gait kinematics: The difference between gastrocnemius and soleus

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O35 presented in OS06: Healthy walking

Influence of different degrees of bilateral emulated contractures at the triceps surae on gait kinematics: Difference between gastrocnemius and soleus

Michael Attias [1,2,3,*], Alice Bonnefoy-Mazure [1], Laurence Cheze [3], Geraldo Decoulon [1], Stéphane Armand [1]

[1] Willy Taillard Laboratory of Kinesiology, Geneva University Hospitals, Geneva, Switzerland
[2] HES-SO University of Applied Sciences and Arts Western Switzerland, School of Health Sciences, Geneva, Switzerland
[3] Université de Lyon, Université Claude Bernard Lyon 1, IFSTTAR, Lyon, France

Cette étape consistait à comparer les adaptations cinématiques à différents degrés de sévérité de rétractions émulées de manière isolée et bilatérale des gastrocnemius et du soleus.

Les résultats sont actuellement en soumission et ont été présentés en congrès :

<u>Publication "peer review"</u>
Attias M, Bonnefoy-Mazure A, De Coulon G, Cheze L, Armand S. Influence of different degrees of bilateral emulated contractures at the triceps surae on gait kinematics: Difference between gastrocnemius and soleus ; Gait Posture (**en révision**).

<u>Publication "abstract"</u>
Attias M, Bonnefoy-Mazure A, Cheze L, De Coulon G, Armand S. Influence of different degrees of bilateral emulated contractures at the triceps surae on gait kinematics: Difference between gastrocnemius and soleus ; Gait Posture. 2016;49, S2, 42

<u>Présentation publique</u>
Attias M, Bonnefoy-Mazure A, De Coulon G, Cheze L, Armand S. Influence de différents degrés de rétractions musculaires bilatérales du triceps sural sur la cinématique de la marche: différence entre gastrocnémiens et soléaire. – SOFAMEA (Société Francophone d'Analyse du Mouvement chez l'Enfant et d'Adulte); 2016; Brest, France

Attias M, Bonnefoy-Mazure A, De Coulon G, Cheze L, Armand S. Influence of different degrees of bilateral emulated contractures at the triceps surae on gait kinematics: difference between gastrocnemius and soleus ; - ESMAC (European Society of Movement Analysis for Adults and Children); 2016; Seville, Spain

### 3.1.1 Résumé français

La rétraction des fléchisseurs plantaires de cheville résulte d'un raccourcissement permanent du complexe musculo-tendineux de ses extenseurs (triceps sural incluant les muscles gastrocnemius et soleus). Il conduit souvent à des altérations de marche. L'objectif de cette étude était de comparer les adaptations cinématiques à différents degrés de sévérité de rétractions et entre les rétractions émulées de manière isolée et bilatérale des gastrocnemius et du soleus en utilisant un exosquelette.

Huit combinaisons de rétractions ont été émulées bilatéralement sur 10 participants asymptomatiques utilisant un exosquelette capable de reproduire différents niveaux de rétraction des muscles gastrocnemius et soleus, correspondant à 0 °, 10 °, 20 ° et 30 ° de flexion plantaire de cheville (mesurée respectivement genoux en extension et genoux fléchis). Une analyse de la marche a été réalisée pour évaluer l'effet de ces différentes rétractions émulées sur le score du profil de marche – Gait Profil Score (GPS), la vitesse de marche et la cinématique articulaire.

Les résultats ont révélé que les rétractions des gastrocnemius et du soleus influencent la cinématique de marche, entrainant une augmentation du GPS. Des différences significatives ont été observées sur l’évolution des angles des chevilles, des genoux et des hanches. La rétraction du soleus provoque une diminution plus importante de l’amplitude de mouvement à la cheville que pour le même niveau de rétraction des gastrocnemius. La rétraction des gastrocnemius induit une plus grande flexion de genou (pendant la phase d’appui) et de flexion de hanche (au cours du cycle de marche) que pour le même niveau de rétraction du soleus.

Ces résultats sont en accord avec l'anatomie et la littérature. Une rétraction des gastrocnemius peut provoquer un pattern de marche genoux fléchis, alors qu'une rétraction du soleus limite la dorsiflexion avec de faibles modifications de la cinématique du genou. Ces résultats peuvent étayer l'interprétation des Analyses Quantifiées de la Marche en fournissant une meilleure compréhension de l'effet de la rétraction isolée du soleus et des gastrocnemius sur la cinématique articulaire.

Mots-clés: rétraction, marche, exosquelette, simulation, gastrocnemius, soleus

### 3.1.2 Abstract

Ankle plantarflexion contracture results from a permanent shortening of the muscle-tendon complex. It often leads to gait alterations. The objective of this study was to compare the kinematic adaptations of different degrees of contractures and between isolated bilateral gastrocnemius and soleus emulated contractures using an exoskeleton.

Eight combinations of contractures were emulated bilaterally on 10 asymptomatic participants using an exoskeleton that was able to emulate different degrees of contracture of gastrocnemius and soleus muscles, corresponding at 0°, 10°, 20°, and 30° ankle plantarflexion contracture (knee-flexed and knee-extended). A gait analysis session was performed to evaluate the effect of these different emulated contractures on the Gait Profile Score, walking speed and gait kinematics.

The results revealed that gastrocnemius and soleus contractures influence gait kinematics, with an increase of the GPS. Significant differences were found in the kinematics of the ankles, knees and hips. Contractures of soleus cause a more important decrease in the range of motion at the ankle than the same degree of gastrocnemius contracture. Gastrocnemius contractures cause greater knee flexion (during the stance phase) and hip flexion (during the gait cycle) than the same level of soleus contracture.

These results are in agreement with anatomy and literature. A contracture of gastrocnemius can cause a knee-flexed gait pattern, whereas a contracture of soleus causes a limitation of dorsiflexion with low modifications of the knee kinematics. These results can support the interpretation of the Clinical Gait Analysis data by providing a better understanding of the effect of isolate contracture of soleus and gastrocnemius on gait kinematics.

**Keywords**: contracture, gait, exoskeleton, simulation, gastrocnemius, soleus

### 3.1.3 Introduction

Contracture is defined as the inability of a joint to move through its full range of motion and an excessive resistance during passive mobilization of this joint. The expression “soft tissue contracture” is often used to define contracture because the structures involved are mainly muscles, tendons, aponeurosis, and, but also ligaments and capsules, for which the extensibility may have been limited and the stiffness increased (Gracies, 2005a). Contracture is involved in many neurological conditions (e.g., cerebral palsy, multiple sclerosis, spinal cord injury, stroke) and can impair walking (Ballaz et al., 2010; Fergusson et al., 2007; Hoang et al., 2014). Among contractures, ankle plantarflexion contracture (APC) is one of the most common causes of gait deviations in many conditions (cerebral palsy (Tylkowski et al., 2009), neuropathy (Kwon et al., 2003) and muscular dystrophy (Armand et al., 2005)) and can lead to other complications (e.g., metatarsalgia, neuropathic ulceration, plantar fasciitis and Charcot midfoot breakdown) (Abdulmassih et al., 2013). Gait with APC is characterized by an absence of a first rocker (which enables a heel-toe pattern at initial contact (Perry and Burnfield, 2010)) and a limitation of dorsiflexion during swing (Houx et al., 2012), causing an inadequate foot clearance (Leung et al., 2014). APC is caused by a contracture of the triceps surae that is composed of two muscles: gastrocnemius (a biarticular muscle which passes through on the ankle and knee joints) and soleus (a monoarticular muscle which passes through only on the ankle joint (Matjacic et al., 2006; Wren et al., 2004).

To rectify gait deviations, it is necessary to understand gait deviations; and to distinguish between primary deviations (directly resulting from the pathology) and secondary deviations (compensatory mechanisms) (Schmid et al., 2013). Clinicians need to understand the influence of contracture of individual muscle to evaluate its biomechanical impact in terms of primary deviations and secondary deviations (compensations). Different approaches have been used to elucidate the effect of APC on gait and are described in a systematic review (Attias et al., 2016d). These approaches include a comparison of APC in patients and matched healthy subjects (Gaudreault et al., 2009; Svehlik et al., 2010), comparison of patient’s gait before and after treating APC (Chimera et al., 2012; Kadhim and Miller, 2014), and emulation of contracture(s) with an exoskeleton or an orthosis (Attias et al., 2016a; Attias et al., 2016c; Houx et al., 2012; Matjacic et al., 2006; Romkes and Brunner, 2007).

The systematic review by Attias et al. (Attias et al., 2016d) showed that it is difficult to isolate a contracture because it is always associated with other impairments, such as spasticity or muscle weakness (Herzenberg et al., 2007; Leung et al., 2014). Among these studies, two studies isolated gastrocnemius and soleus muscle contractures (Matjacic et al., 2006; Olensek et al., 2005) by emulating these muscles unilaterally with an exoskeleton. They found that on the ipsilateral side, soleus contracture mainly influenced the ankle angle, whereas gastrocnemius contractures influenced the ankle and knee angles. However, no studies have investigated the effect of gastrocnemius and soleus contracture bilaterally.

Hence, with the support of an exoskeleton to emulate contractures, the aim of this study was 1) to compare the kinematic adaptations of varying degrees of emulated contracture for the bilateral gastrocnemius and soleus 2) to compare the kinematic adaptations between isolated bilateral gastrocnemius and soleus at the same degree of emulated contracture.

### 3.1.4 Method

#### *3.1.4.1 Participants:*

Ten healthy participants (6 females, 4 males) aged 27.9 years ± 3.2, with a height of 1.71 m ± 0.09 and weight of 64.0 kg ± 10.3 and no known neurologic or orthopedic problems, participated in this study. Ethical approval and the participant's informed consent were obtained prior to data collection.

#### *3.1.4.2 Gait evaluation*

The participants were equipped with 34 reflective markers aligned to anatomical and technical landmarks on the head, trunk and pelvis and bilaterally on the arms, thighs, shanks and feet according to the full-body Plug-in-Gait model (Davis et al., 1991). All participants were requested to walk along a 10-meter walkway at a spontaneous, self-selected speed and were equipped with the MIkE exoskeleton, which is able to emulate gastrocnemius and soleus contractures bilaterally (Attias et al., 2016a). It was built to bilaterally embrace the pelvis, thighs, and shanks with plastic cuffs, with modified shoes that include attachment points. A cut was made in the plastic cuffs to enable reflective markers to be placed directly on the skin as required for Clinical Gait Analysis (CGA). CGA is a clinical examination enabling to get quantitative information on the patient's gait including generally video, spatio-temporal, kinematic, kinetic and EMG data (Carcreff et al., 2016). Each participant also walked without the exoskeleton for a control condition (CC). Kinematic recordings were performed with a twelve-camera motion analysis system (Oqus 7+, Qualisys, Göteborg, Sweden). A minimum of five gait cycles was averaged to produce a single angular displacement of the pelvis segments, hip, knee, and ankle joints.

To emulate contractures, we selected four degrees of contracture, 0°, 10°, 20°, and 30° of plantarflexion, based on the study by Ryall et al. (Drefus et al., 2016) on both muscles (soleus and gastrocnemius). The 0° level is considered to be a mild contracture and the 30° level is considered to be a severe contracture according to our experience. To set the contractures, the examiner adjusted the rope length of the exoskeleton in the position used for standard physical examination (Viehweger et al., 2007) and controlled it with a goniometer (Figure 21). For soleus, the knee was flexed at 90° and the plantarflexion of the ankle was adjusted according to the desired degree of contracture. For gastrocnemius, the knee was extended at 0° and the same procedure was used.

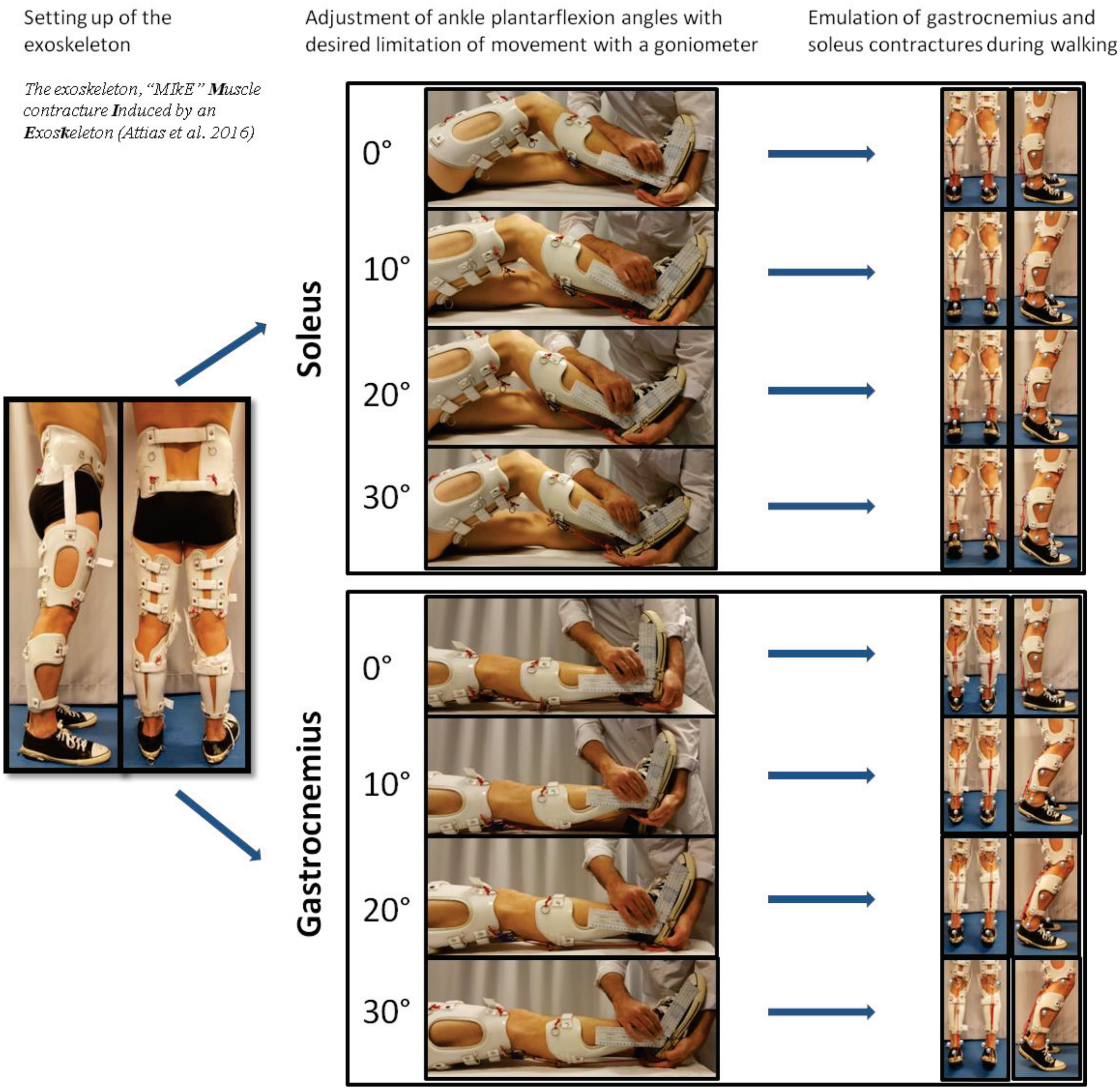


**Figure 21 : Setting up the exoskeleton « MIkE » (Muscle contracture Induced by an Exoskeleton) to emulate different degrees of contracture at the gastrocnemius and soleus muscles during walking.**

#### 3.1.4.3 Data analysis and statistics

As non parametric tests are used, median and 1st and 3rd quartile are reported: median (1st quartile; 3rd quartile)

First, to evaluate whether there were significant differences in the different degrees of contracture for each muscle (gastrocnemius and soleus from 0° to 30° plantarflexion), a Kruskal-Wallis test and post hoc with Bonferroni correction were performed on the Gait Profile Score (GPS) (Baker et al., 2009) and walking speed (right and left sides together). CC and different degrees of emulated contracture (0°, 10°, 20° and 30° plantarflexion contractures) were compared with Wilcoxon tests considering Bonferroni correction.

Second, to evaluate the kinematic differences between gastrocnemius and soleus contractures, a Wilcoxon test with Bonferroni correction was performed between the same degrees of contracture in walking speed, GPS and fourteen kinematic parameters per side in the sagittal plane: range of motion (ROM) and mean position for pelvis angle; ROM and minimum flexion for hip angle; flexion at initial contact (IC), minimum in stance and ROM during the gait cycle for knee angles; dorsiflexion at initial contact (IC), maximum in stance and ROM during the gait cycle for ankle angles; and mean foot progression angle. MATLAB R2012b (MathWorks, Natick, Massachusetts, USA), the open-source Biomechanical ToolKit package for MATLAB (Barre and Armand, 2014) and SPSS Version 23 (IBM, Armonk, NY, USA) were used for data analysis, statistics and figure creation.

### 3.1.5 Results

The comparisons between CC and different degrees of emulated contracture are shown in Table 7 for walking speed, GPS and kinematic parameters. Figure 22 depicts differences between each degree of contracture and CC for respectively gastrocnemius and soleus concerning the walking speed and GPS.

Table 7 : Walking speed, Gait Profile Score (GPS) and kinematic parameters (median, 1st and 3rd quartile) at different degrees of emulated contracture (control condition (CC), 0°, 10°, 20° and 30° plantarflexion contractures) for the gastrocnemius and soleus muscles with the significant difference (p-value) between the two muscles and compared to CC.

| | CC | | | 0° plantarflexion | | | | | | | 10° plantarflexion | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | No contracture | | | Gastrocnemius | | | Soleus | | | | Gastrocnemius | | | Soleus | | | |
| | Med | 1st / quartile | 3rd | Med | 1st / quartile | 3rd | Med | 1st / quartile | 3rd | p-value | Med | 1st / quartile | 3rd | Med | 1st / quartile | 3rd | p-value |
| **Walking speed (m/s)** | **1.1** | *1.1* | *1.3* | **1.0** | *0.9* | *1.1* | **1.1** | *0.9* | *1.1* | 0.381 | **1.0** | *0.9* | *1.1* | **1.0** | *0.9* | *1.1* | 0.684 |
| **GPS (°)** | **4.2** | *3.9* | *5.5* | **5.3** | *4.9* | *5.9* | **4.9** | *4.5* | *5.4* | 0.771 | **6.4** | *5.7* | *6.8* | **6.0** | *4.7* | *6.3* | 0.89 |
| **Foot progression** | | | | | | | | | | | | | | | | | |
| MP (°) | **-5.5** | *-11.2* | *-3.2* | **0.1** | *-8.5* | *3.8* | **-1.1** | *-5.5* | *-0.3* | 0.684 | **3.4** | *-3.3* | *5.5* | **1.5** | *-3.6* | *5.9* | 0.684 |
| **Ankle** (sagittal) | | | | | | | | | | | | | | | | | |
| Dors-IC (°) | **4.4** | *3.4* | *6.7* | **-2.8** | *-10.6* | *1.9* | **0.1** | *-1.8* | *1.2* | 0.912 | **<u>-10.8</u>** | *-13.4* | *-7.6* | **<u>-12.5</u>** | *-14.4* | *-9.5* | 0.247 |
| Max-Dors-ST (°) | **16.2** | *15.3* | *17.2* | **15.4** | *7.1* | *18.4* | **15.6** | *13.2* | *17.0* | 0.631 | **5.8** | *2.0* | *9.7* | **<u>3.4</u>** | *-0.8* | *7.0* | 0.089 |
| ROM (°) | **26.0** | *22.7* | *29.9* | **24.4** | *22.1* | *29.1* | **23.5** | *20.8* | *25.4* | 0.019 | **25.0** | *21.6* | *27.8* | **21.8** | *16.9* | *25.3* | 0.011 |
| **Knee** (sagittal) | | | | | | | | | | | | | | | | | |
| Flex/ext-IC (°) | **2.6** | *0.2* | *4.2* | **16.2** | *11.1* | *19.7* | **4.7** | *-0.6* | *8.1* | <0.001* | **<u>23.4</u>** | *17.1* | *27.8* | **10.6** | *7.7* | *14.3* | <0.001* |
| Min-Flex-ST (°) | **-0.1** | *-2.5* | *1.5* | **<u>13.6</u>** | *8.8* | *16.4* | **2.1** | *-1.7* | *4.7* | 0.089 | **<u>19.7</u>** | *17.3* | *25.5* | **3.7** | *1.2* | *6.8* | 0.001* |
| ROM (°) | **67.2** | *65.1* | *69.4* | **48.7** | *42.2* | *54.2* | **62.9** | *61.4* | *65.5* | 0.001* | **<u>38.2</u>** | *33.5* | *41.0* | **50.9** | *42.9* | *57.4* | 0.002* |
| **Hip** (sagittal) | | | | | | | | | | | | | | | | | |
| ROM (°) | **40.3** | *36.7* | *43.6* | **<u>31.1</u>** | *27.8* | *33.4* | **37.0** | *34.7* | *37.9* | 0.023 | **32.0** | *30.9* | *36.8* | **37.6** | *33.8* | *41.2* | 0.19 |
| Min-Flex-ST (°) | **-9.4** | *-13.4* | *-5.4* | **<u>3.1</u>** | *0.5* | *6.6* | **-7.4** | *-8.1* | *-5.4* | 0.001* | **<u>4.2</u>** | *-0.4* | *7.1* | **-8.1** | *-9.2* | *0.4* | 0.004* |
| **Pelvis** (sagittal) | | | | | | | | | | | | | | | | | |
| MP (°) | **9.3** | *5.9* | *12.9* | **13.0** | *12.3* | *16.0* | **12.8** | *8.7* | *14.3* | 0.315 | **15.3** | *11.4* | *16.5* | **13.0** | *11.8* | *15.1* | 0.579 |
| ROM (°) | **3.2** | *2.6* | *3.4* | **4.3** | *3.4* | *5.3* | **3.3** | *3.0* | *4.6* | 0.123 | **4.2** | *3.7* | *4.8* | **3.8** | *2.8* | *4.4* | 0.165 |

| | 20° plantarflexion | | | | | | | 30° plantarflexion | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Gastrocnemius | | | Soleus | | | | Gastrocnemius | | | Soleus | | | |
| | Med | 1st / quartile | 3rd | Med | 1st / quartile | 3rd | p-value | Med | 1st / quartile | 3rd | Med | 1st / quartile | 3rd | p-value |
| **Walking speed (m/s)** | **1.0** | *0.9* | *1.0* | **1.0** | *0.9* | *1.1* | 0.631 | **<u>0.9</u>** | *0.9* | *1.1* | **1.0** | *0.9* | *1.1* | 0.631 |
| **GPS (°)** | **<u>7.5</u>** | *6.9* | *7.9* | **6.5** | *4.9* | *7.1* | 0.015 | **<u>8.2</u>** | *7.0* | *9.5* | **<u>7.0</u>** | *5.6* | *8.3* | 0.165 |
| **Foot progression** | | | | | | | | | | | | | | |
| MP (°) | **5.4** | *-3.8* | *9.8* | **6.1** | *-2.5* | *6.6* | 0.912 | **5.4** | *-4.6* | *10.4* | **<u>6.0</u>** | *-1.2* | *9.9* | 0.971 |
| **Ankle** (sagittal) | | | | | | | | | | | | | | |
| Dors-IC (°) | **<u>-14.1</u>** | *-23.6* | *-6.1* | **<u>-14.6</u>** | *-17.7* | *-10.9* | 0.529 | **<u>-10.1</u>** | *-21.3* | *-6.7* | **<u>-17.7</u>** | *-23.1* | *-16.5* | 0.19 |
| Max-Dors-ST (°) | **<u>4.7</u>** | *-7.9* | *9.1* | **<u>1.2</u>** | *-1.8* | *2.3* | 0.063 | **<u>4.5</u>** | *-9.3* | *7.1* | **<u>-3.9</u>** | *-7.6* | *-2.5* | 0.043 |
| ROM (°) | **24.0** | *21.9* | *26.4* | **21.3** | *16.7* | *23.7* | 0.002* | **22.3** | *20.9* | *25.2* | **19.7** | *13.8* | *20.3* | 0.002* |
| **Knee** (sagittal) | | | | | | | | | | | | | | |
| Flex/ext-IC (°) | **<u>28.5</u>** | *20.5* | *30.0* | **13.1** | *7.9* | *15.5* | <0.001* | **<u>29.8</u>** | *22.8* | *35.0* | **12.4** | *6.9* | *20.3* | <0.001* |
| Min-Flex-ST (°) | **<u>24.3</u>** | *19.3* | *28.1* | **4.9** | *0.3* | *9.1* | 0.007* | **<u>26.7</u>** | *19.8* | *32.9* | **5.5** | *1.9* | *14.7* | 0.001* |
| ROM (°) | **<u>36.4</u>** | *30.1* | *38.6* | **45.9** | *39.6* | *51.5* | 0.002* | **<u>32.7</u>** | *29.0* | *35.5* | **<u>37.7</u>** | *33.9* | *50.0* | 0.011 |
| **Hip** (sagittal) | | | | | | | | | | | | | | |
| ROM (°) | **<u>32.5</u>** | *31.2* | *34.1* | **34.9** | *33.4* | *41.1* | 0.393 | **<u>30.6</u>** | *26.0* | *36.4* | **32.4** | *28.6* | *37.8* | 0.436 |
| Min-Flex-ST (°) | **<u>7.3</u>** | *3.5* | *11.3* | **-5.1** | *-9.4* | *-0.1* | <0.001* | **<u>10.2</u>** | *7.4* | *18.5* | **-2.0** | *-5.9* | *0.3* | 0.002* |
| **Pelvis** (sagittal) | | | | | | | | | | | | | | |
| MP (°) | **15.4** | *12.1* | *17.9* | **13.5** | *12.4* | *15.6* | 0.912 | **<u>16.8</u>** | *12.4* | *21.0* | **14.2** | *12.7* | *15.8* | 0.315 |
| ROM (°) | **3.7** | *3.4* | *4.7* | **4.0** | *2.9* | *4.6* | 0.912 | **3.8** | *3.3* | *4.4* | **3.8** | *3.1* | *4.7* | 0.912 |

* = P<0.01 (Bonnferroni's correction) significant differences between the two muscles ; underlined values = significant differences between CC and different degrees of emulated contractures (0°, 10°, 20° and 30° plantarflexion contractures)

GAS - Gastrocnemius ; SOL - Soleus ; ROM - range of motion ; MP - mean position ; Min - Minimum ; Max - Maximum ; Flex/ext - Flexion/extension; Dors - Dorsiflexion; ST - Stance phase; IC - Initial contact phase; Med – Median

Flex = positive value; Ext = negative value; Dorsiflexion = positive value; Plantarflexion = negative value; Internal foot progression = positive value; External foot progression = negative value; Pelvis MP anteversion = positive value; Pelvis MP retroversion = negative value

#### 3.1.5.1 Comparison with CC:

Concerning the walking speed and GPS (Table 7 and Figure 22), significant differences were found for each muscle (gastrocnemius and soleus from contractures 0° to 30°). For gastrocnemius, the walking speed was decreased for contracture 30° compared to CC. The GPS was increased for contractures 20° and 30° compared to CC. For soleus, the walking speed was not different between the different degrees of contracture and CC. The GPS was increased for contracture 30° compared to CC.

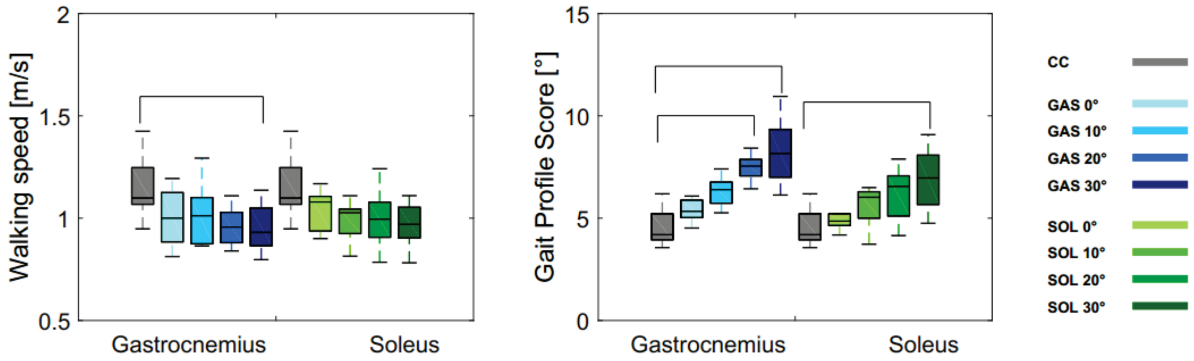


Figure 22 : Boxplot for walking speed and Gait Profile Score (GPS) at different degrees of emulated contractures for the gastrocnemius and soleus muscles (control condition (CC), 0°, 10°, 20° and 30° plantarflexion contractures). Lines represent significant differences between two conditions.

Concerning the foot angle progression, more internal rotation was observed for contracture 30° for soleus muscle compared to CC (mean foot angle progression for CC:-5.5° (-11.2;-3.2) vs. for soleus 30°: 6.0 (-1.2; 9.9), $p < 0.01$).

Concerning the ankle joint, reduced dorsiflexion were observed for the dorsiflexion at initial contact for contractures 10°, 20° and 30° of gastrocnemius and soleus. In addition, reduced dorsiflexion were observed for maximum of dorsiflexion during the stance phase for contractures 10°, 20° and 30° of soleus and for contractures 20° and 30° of the gastrocnemius.

Concerning the knee joint, a decrease of ROM was observed for contracture 30° for soleus (CC: 67.2 (65.1; 69.4) vs. soleus 30°: 37.7 (33.9; 50), $p < 0.01$). For the gastrocnemius, an increase of flexion was observed for the flexion-extension at initial contact and a decrease of ROM for contractures 10°, 20° and 30°. In addition, reduced knee extension was observed in minimum of flexion during stance for contracture 0°, 10°, 20°, 30° for gastrocnemius compared to CC.

Concerning the hip joint, no significant differences were observed for soleus muscle. However, a decrease of ROM were found for contractures of 0°, 20° and 30° and reduced hip extension was observed in minimum flexion during the stance phase for contractures 0°, 10°, 20° and 30° of the gastrocnemius. Concerning the pelvis, an increase anteversion was found for the mean position for a contracture 30° of gastrocnemius (CC: 9.3° (5.9; 12.9) vs. gastrocnemius 30°: 16.8° (12.4; 21), p<0.01).

#### *3.1.5.2 Comparison between soleus and gastrocnemius contractures:*

Significant differences between soleus and gastrocnemius were observed in the ankle, knee and hip kinematics (Table 7 and Figure 23). At the ankle, only the ROM plantarflexion was different for contractures 20° and 30° with less ROM for soleus compared to gastrocnemius. At the knee, minimum flexion in stance and knee flexion at initial contact were increased for gastrocnemius contractures at 0°, 10°, 20° and 30° compared to soleus contractures at the same degrees; ROM of knee flexion was decreased for gastrocnemius contractures at 0°, 10°, and 20° compared to soleus contractures. At the hip, the mean position was increased and minimum of flexion was decreased for gastrocnemius contractures at 0°, 10°, 20°, and 30° compared to soleus contracture. No differences were found for the pelvis angles and the foot progression angle between soleus and gastrocnemius contractures at the same degree.

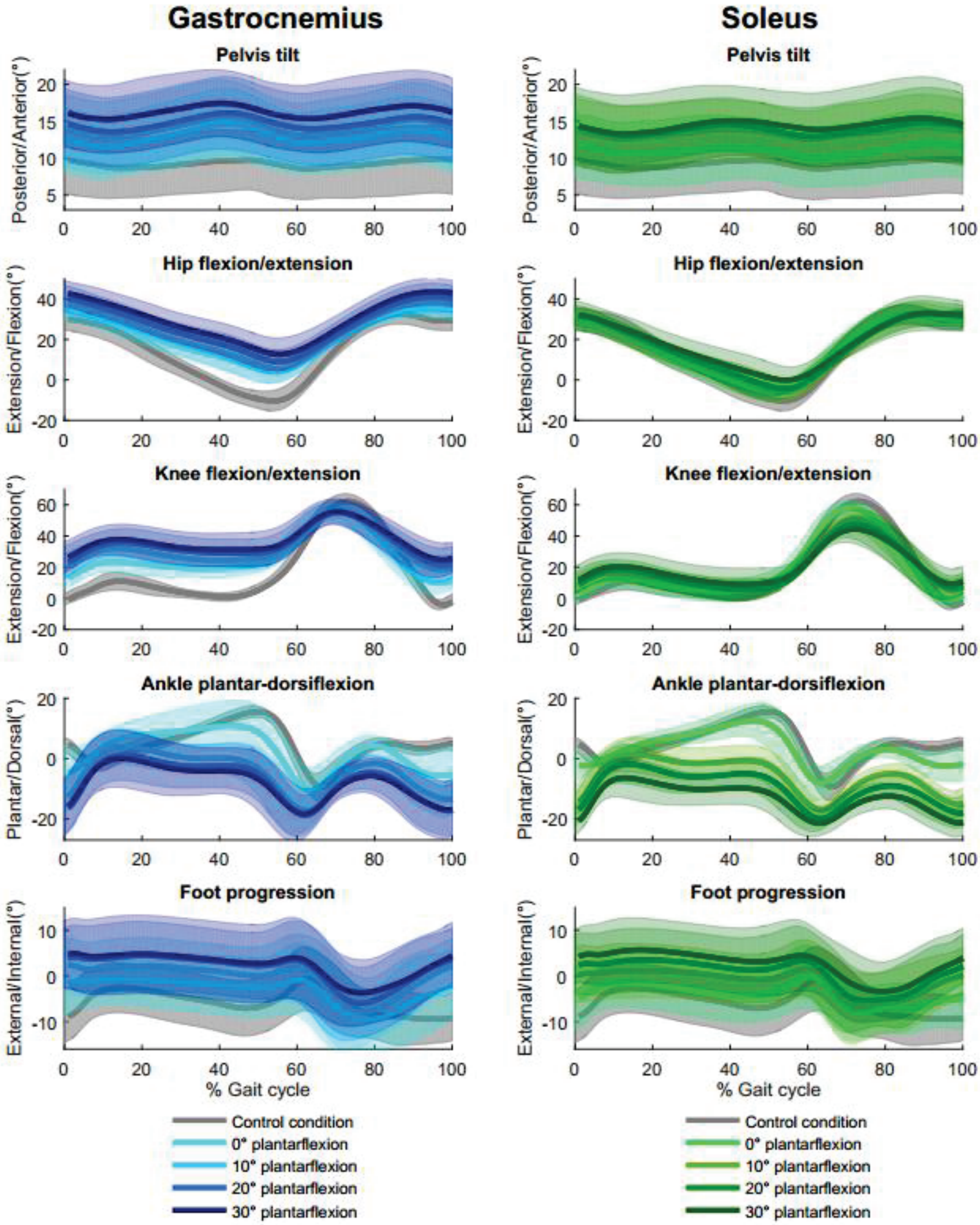


**Figure 23 : Mean (and standard deviation) kinematics for the pelvis, hip, knee, and ankle in the sagittal plane and foot progression at different degrees of emulated contracture for the gastrocnemius and soleus muscles.**

### 3.1.6 Discussion

This study aims to describe kinematic differences between different degrees of contracture and CC as well as between isolated bilateral gastrocnemius and soleus contractures. Compared to CC, we observed that soleus contractures have no impact on walking speed and a low impact on gait quality (GPS) in contrary to gastrocnemius contractures for which walking speed is reduced for contractures 30° and GPS increased for contractures 20 and 30°.

In addition, gastrocnemius and soleus contractures impact gait kinematics differently. Indeed, it appears from our results that soleus contractures cause a more pronounced limitation of dorsiflexion and decrease of ankle ROM than gastrocnemius contractures. On the other hand, gastrocnemius contractures cause a more important knee flexion (during stance phase) and hip flexion than soleus contractures.

Our results are in agreement with anatomy and the literature. Soleus is a monoarticular muscle and can mainly act on the ankle joint, whereas gastrocnemius is a biarticular muscle and can act simultaneously on the ankle and knee joints (Wren et al., 2004). Therefore, contractures of gastrocnemius or soleus limit the maximum ankle dorsiflexion during the gait, as reported by other authors (Houx et al., 2012; Leung et al., 2014; Olensek et al., 2005; Ota et al., 2014); contractures of gastrocnemius also cause a flexed knee in the stance phase of the gait despite the fact that the hamstrings is not short and there are no other impairments. Our results, obtained with bilateral contractures, are similar to unilaterally induced soleus contractures (with an emulation system applied only on the ankle level) studies concerning maximum dorsiflexion in stance: Goodman et al. (Goodman et al., 2004) (mean APC at -24°: -7° (±7.8) , Houx et al. (Houx et al., 2012) (APC at -20°: -6.08° (±3.82). our study (soleus at 30° (-3.9° (-7.6—2.5)). These results point out the differences between the degrees of contracture setting up in static with the emulation device and the maximal dorsiflexion during gait. In literature and our study, we can expect to have more agreement between these two measurements for soleus contractures. These differences, observed also in patients, can be attributed to several factors: 1) the reliability to measure dorsiflexion with a goniometer is moderate with a minimal detectable change ranged from 6° to 8° (Krause et al., 2011), 2) the force applied by the evaluator at the ankle is inferior to the force applied during walking (Maas et al., 2015); 3) patients/participants are not fully relaxed during clinical examination (van Trijffel et al., 2010); 4) the measurement of ankle kinematics considering one foot segment overestimates ankle dorsiflexion (Pothrat et al., 2015). Moreover, these differences could explain a part of the poor relationships between clinical examinations and CGA results (Aktas et al., 2000; Bonnefoy-Mazure et al., 2016; Desloovere et al., 2006).

Concerning the effect of induced soleus contracture on the knee, literature results (based on unilateral induced contractures) are contradictory. Leung et al. (Leung et al., 2014) found a knee recurvatum during stance whereas Goodman et al. (Goodman et al., 2004) found a permanent knee flexion. Houx et al. (Houx et al., 2013) and Matjacic et al. (Matjacic et al., 2006) found a small increase of knee flexion at IC but no effect at knee for maximal flexion in stance. Our results (based on bilateral induced contractures) are in agreement with those of Houx et al. (Houx et al., 2013) and Matjacic et al. (Matjacic et al., 2006). Moreover, Svehlik et al. (Svehlik et al., 2010) reported in cerebral palsy children that equinus position of the foot can lead to knee hyperextension. However, they did not specify whether soleus or gastrocnemius contracture were considered. Galli et al. (Galli et al., 2005) analyzed ankle and knee kinematics after gastrocnemius fascia lengthening; they reported increased ankle dorsiflexion and less knee flexion at initial contact. Our study also shows that gastrocnemius influences the ankle and knee angles (increase knee flexion with increase degree of gastrocnemius contracture), whereas soleus mainly influences the ankle angle. Nevertheless, the finding of our study does not rule out that soleus contracture can alter the knee biomechanics, in particular by the effect of plantarflexor-knee extension couple (Sangeux et al., 2015).

Hence, our hypothesis is that knee hyperextension during gait observed by Svehlik et al. (Svehlik et al., 2010), Galli et al. (Galli et al., 2005) on patients and by Leung et al. (Leung et al., 2014) on healthy participants with induced contractures could be due to soleus contracture associated with the plantarflexion-knee extension moment (Sangeux et al., 2015). However, Leung et al. (Leung et al., 2014) specified that a minority of their subjects walked with knee flexion. In our study most participants walked with a knee flexion pattern during gastrocnemius contractures and with quasi-normal knee flexion/extension or knee extension during soleus contracture (only one participant in the contractures 0°, 10°, 20° and 30° had a knee recurvatum pattern with emulated contractures on the soleus). The differences between studies concerning knee kinematics could be explained by different possible ways for the participants to walk with the same contracture. Future studies with a large sample size permitting to use classification methods are needed to better investigate adaptations chose by the participants and by the patients. It is possible that different gait adaptations are related to different optimization such as minimise energy expenditure or balance (Selinger et al., 2015).

Our study was the first study to investigate the influence of emulated bilateral contractures on the gastrocnemius and the soleus. As already mentioned, our results showed the same influence that unilateral emulated contractures on the ipsilateral side (Drefus et al., 2016; Goodman et al., 2004; Houx et al., 2012; Houx et al., 2013; Leung et al., 2014; Matjacic et al., 2006).

#### 3.1.6.1 Limitations

The first limitation concerns the small number of participants (10) in this study, which does not permit the use of parametric tests and reduces the power of inference tests. For example, we observed some tendencies between the different degrees of gastrocnemius and soleus contractures concerning the pelvis motions (the pelvis tends to be more tilted with increasing degrees of contracture) as well as in foot progression (the foot tends to be more in-toeing with increasing degrees of contracture). The second limitation concerns the short adaptation time to contracture emulations. Indeed, adaptation time can play an important role in the gait strategies of the participants. The third limitation is that no combinations of gastrocnemius and soleus contractures were evaluated. A future study could investigate the relative contribution of these muscle contractures to gait deviations through different combinations of contractures of these two muscles.

#### 3.1.6.2 Conclusion

Our results confirmed those in the literature and were in agreement with anatomy. Soleus contractures act mainly on ankle kinematics, whereas gastrocnemius contractures act on ankle and knee kinematics due to its biarticular role. A flexed-knee gait can be caused by a gastrocnemius contracture without other impairments. These findings can help for clinical interpretation and therefore support future treatment decisions.

## 3.2 Article 4 – Toe-walking due to different degrees of triceps surae contracture leads to a transition between gait patterns

**GASTROCNEMIUS / SOLEUS CONTRACTURE: INFLUENCE ON FIRST AND SECOND ROCKER DURING WALKING**

**Michael Attias (1-2-4), Alice Bonnefoy-Mazure (1), Geraldo Decoulon (3), Laurence Cheze (4), Stéphane Armand (1)**

*1. Willy Taillard Laboratory of Kinesiology, Geneva University Hospitals, Geneva University, Switzerland; 2. HES-SO University of Applied Sciences and Arts Western, School of Health Sciences, Geneva, Switzerland ; 3. Pediatric Orthopaedic Service, Department of Child and Adolescent, Geneva University Hospitals, Switzerland; 4. Université de Lyon, Université Claude Bernard Lyon 1, IFSTTAR, Lyon, France*

22nd Congress of the European Society of Biomechanics, July 10 - 13, 2016, Lyon, France

Cette étape consistait à évaluer l'effet des rétractions des gastrocnemius et soleus sur les premier et second pivots pendant la marche.

Les résultats sont actuellement en soumission et ont été présentés en congrès :

Publication "peer review"
Attias M, Bonnefoy-Mazure A, De Coulon G, Cheze L, Armand S. Toe-walking due to different degrees of triceps surae contracture leads to a transition between gait patterns. Journal of biomechanics. **(en révision)**

Présentation publique
Attias M, Bonnefoy-Mazure A, De Coulon G, Cheze L, Armand S. Gastrocnemius / soleus contracture : influence on first and second rocker during walking; - ESB (European Society of Biomechanics); 2016; Lyon, France

### 3.2.1 Résumé français


Introduction: La marche digitigrade est l'un des déficits les plus courants de la marche (due aux rétractions du muscle soleus et / ou des muscles gastrocnemius), compromettant le premier pivot (pivot de talon) et le deuxième pivot (pivot de cheville) pendant la marche[4].

Le but de cette étude est d'évaluer l'effet des rétractions des gastrocnemius et soleus sur le premier et le deuxième pivot pendant la marche.

Méthode : Un exosquelette a été construit pour émuler les rétractions des muscles gastrocnemius et soleus de manière bilatérale. Nous avons recruté 10 participants sains pour marcher à une vitesse spontanée dans les conditions suivantes : sans rétractions émulées et avec quatre rétractions émulées bilatérales à 0 °, 10 °, 20 ° et 30 ° de flexion plantaire du soleus (genoux fléchis) et gastrocnemius (genoux en extension) séparément. Une régression linéaire sur l'angle de flexion dorsale/plantaire de cheville a été effectuée sur 0-12% du cycle de la marche (premier pivot) et sur 12-31% du cycle de la marche (deuxième pivot) pour mesurer la pente de la courbe. Nous avons ensuite calculé la proportion de participants pour lesquels nous notions la présence du premier et du deuxième pivot.

Résultats : Le premier et le deuxième pivot sont complètement absents à partir de 10 ° de rétraction des fléchisseurs plantaires. Les données indiquent une nette altération de la cinématique de cheville et un décalage important vers la flexion plantaire avec la perte des pivots.

Conclusion : Les résultats de cette étude suggèrent que la marche digitigrade n'est pas nécessairement due à un niveau de rétraction élevé et peut se produire avec une légère rétraction par un choix d'adaptation.

Cette étude permettra d'améliorer l'interprétation de l'Analyse Clinique de la Marche et montre que le lien entre le niveau de rétraction des gastrocnemius / soleus et la progression de la marche digitigrade (augmentation de la flexion plantaire pendant la marche) n'est pas linéaire.



Mots-clés : rétraction, marche, exosquelette, simulation, marche digitigrade, pivots


[4] Voir section « Les pivots de marche » de la thèse, page 4).

### 3.2.2 Abstract

Introduction: Toe-walking is one of the most common gait deviations (due to soleus and/or gastrocnemius muscle contractures), compromising the first (heel rocker) and second (ankle rocker) rockers of the foot during walking.

The aim of this study is to evaluate the effect of gastrocnemius and soleus contractures on the first and second rocker during walking.

Method: An exoskeleton was built to emulate contractures of the bilateral gastrocnemius and soleus muscles. We recruited 10 healthy participants to walk at a self-selected speed under the following conditions: without emulated contractures or with four bilateral emulated contractures at 0°,10°, 20° and 30° of plantarflexion of the soleus (knee flexed) and gastrocnemius (knee in extension). A linear regression from the ankle plantar-dorsiflexion angle was performed on 0-12% of the gait cycle (first rocker) and on 12-31% of the gait cycle (second rocker) to compute the slope of the curve. We then computed the proportion of participants with the presence of the first and second rocker.

Results: The first and second rocker are completely absent from 10° of plantarflexion contracture. The data indicate there was a clear "breakdown" of the ankle kinematics and an important shift toward plantarflexion values with the loss of the rockers.

Conclusion: The results of this study suggest that toe-walking is not necessarily due to a high contracture level and can occur with a small contracture by an adaptation choice.

This study will improve interpretation of clinical gait analysis and show that the link between the level of gastrocnemius / soleus contracture and progression of toe-walking (increased plantarflexion during gait) is not linear.

Keywords: contracture, gait, exoskeleton, simulation, toe-walking, rockers

### 3.2.3 Introduction

A contracture of the triceps is very common in the following diseases: cerebral palsy, muscular dystrophy, neuropathy, bony deformities, and fractures (Armand et al., 2006; Williams et al., 2010). The contracture is generally caused by the weakness of the tibialis anterior muscle and/or spasticity of gastrocnemius and/or soleus (Houx et al., 2012).

The floor-foot contact and the progression of the body are provided by a pivot system during the process of normal walking, which is associated with three or four gait rockers (heel, ankle, forefoot, and toes) (Bober et al., 2008; Perry and Burnfield, 2010). The first rocker corresponds to the progression of the limb. The heel is the pivotal area of support from approximately zero to twelve percent of the gait cycle (heel rocker). The second rocker corresponds to the progression of the limb, and the ankle is the pivotal area of support from approximately 12-31% of the gait cycle (Perry and Burnfield, 2010).

The contracture of the triceps surae can lead to a toe-walking gait pattern that compromises the first and second rocker (Perry and Burnfield, 2010). There have been several kinematic gait patterns identified in toe-walkers. There are three distinct kinematic ankle patterns in the sagittal plane found in a variety of diseases (Armand et al., 2006). The first toe-walker gait pattern has a progressive dorsiflexion during the stance phase. The second pattern shows a short dorsiflexion with a progressive plantarflexion. The third pattern includes a double bump aspect during the stance phase (Armand et al., 2006). The clinical term used to describe these specific patterns is "idiopathic toe walking" (Armand et al., 2006). The relationships between maximal dorsiflexion measured during clinical examination and clinical gait analysis (CGA) are poor and difficult to highlight using mathematical approaches (Bonnefoy-Mazure et al., 2016). One explanation is linked to the marker placement during CGA, which can lead to an overestimation of dorsiflexion with a conventional gait model (Pothrat et al., 2015). A second possible explanation is that patients prefer to walk naturally with a toe-walking pattern (Kerrigan et al., 2000). A third possible reason is the lack of continuity in the relationship due to differences between clinical and CGA data. Thus, the relationship has not been established by the scientific community (or in the scientific literature). However, several authors have described a slightly limited range of motion during clinical examinations of idiopathic toe walkers (Crenna et al., 2005). This result suggests there is a lack of continuity in the relationship between clinical and CGA data. The aim of this study is to evaluate the effect of gastrocnemius and soleus contractures on the first and second rocker during walking. We used an experimental approach to emulate the muscle contracture with an exoskeleton. We hypothesise the toe-walking pattern occurs with a slightly limited range of motion (due to contracture) and the impact of severity of gastrocnemius / soleus contracture on the toe walking pattern progression (increased plantarflexion during gait) is not linear.

### 3.2.4 Method

#### *3.2.4.1 Participants:*

This study involved 10 healthy participants (6 females, 4 males) with the following characteristics: age 27.9 ± 3.2 years; height: 171.4 cm ± 9.7; weight 64 kg ± 10.3, and no known neurologic or orthopaedic problems. The ethical approval and participant informed consent were obtained prior to beginning data collection.

#### *3.2.4.2 Gait evaluation*

The full-body Plug-in-Gait model (Davis et al., 1991) was used to analyse gait with a motion analysis system (Qualisys, Göteborg, Sweden) that includes twelve cameras. The participants were equipped with 34 reflective markers that were aligned to anatomical landmarks bilaterally on the feet, shanks, thighs, arms, pelvis, trunk, and head. We then performed the kinematic recording. All participants were equipped with the exoskeleton MIkE, which is able to emulate gastrocnemius and soleus contractures bilaterally (Attias et al., 2016a). The participants walked along a 10-meter walkway at a spontaneous self-selected speed. The MIkE exoskeleton was built to bilaterally embrace the pelvis, thigh, and the shank with plastic cuffs and with modified shoes that included attachment points. A particular cut was made on the plastic cuffs to enable reflective markers to be placed directly on the skin as required for CGA. Each participant also walked without the exoskeleton as a control condition (CC). The markers were not moved between each gait condition. A minimum of five trials (corresponding to a minimum of five gait cycles) were averaged to produce a single angular displacement of the pelvis segment, hip, knee, and ankle joints for the gait analysis. The computation of angles was performed with Visual 3D (C-Motion, Germantown, USA).

#### *3.2.4.3 Data analysis*

The ankle plantar-dorsiflexion angle was used in the linear regression on the frame for 0-12% of the gait cycle to compute the slope of the curve. A negative slope indicated the first rocker was present. The same procedure was performed to characterise the second rocker from 12-31% of the gait cycle. A positive slope indicated a second rocker was present.

### *3.2.4.4 Statistical analysis*

The proportion of participants with both a first and second rocker was compared for each condition at 0°, 10°, 20°, and 30° of plantarflexion contracture. We used Wilcoxon tests with Bonferroni's correction to evaluate the differences between the curve slope for the gastrocnemius and soleus muscles with the same degrees of contracture. All data analysis, statistics, and figures were performed with MATLAB R2012b (MathWorks, Natick, Massachusetts, USA), the open-source Biomechanical ToolKit package for MATLAB (Barre and Armand, 2014), and IBM SPSS Statistics Version 23 (IBM, Armonk, NY, USA).

### 3.2.5 Results

The results showed the presence of first and second rockers for all participants in the control condition (Figure 24).

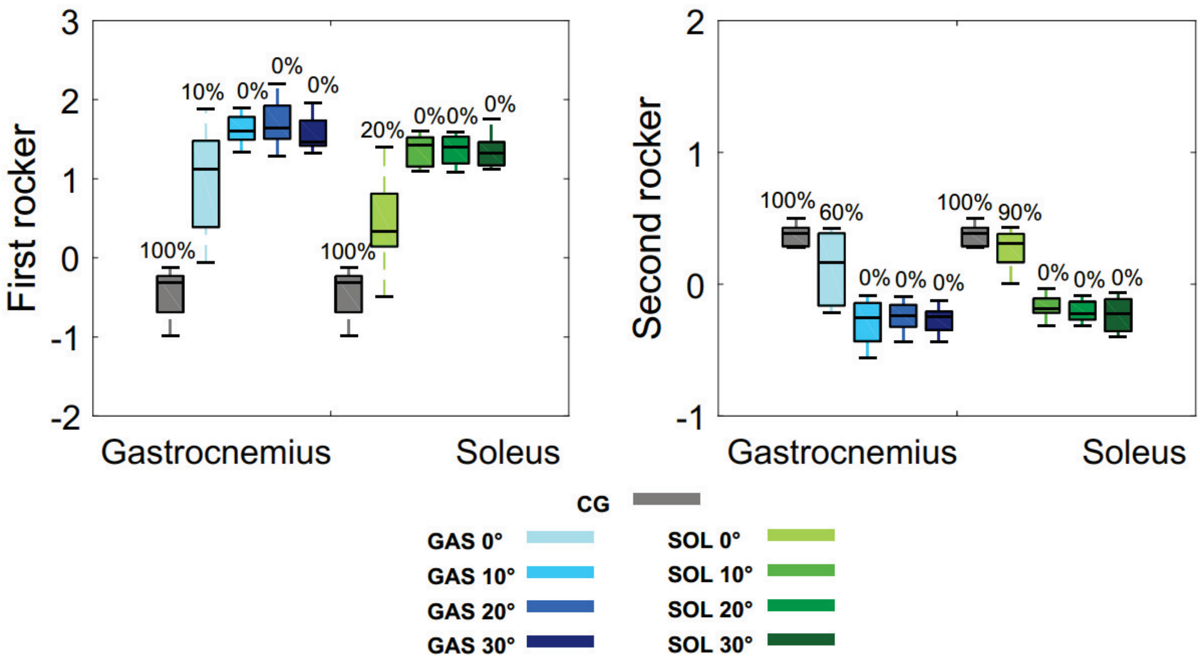


Figure 24 : Boxplot of the slopes (°/% gait cycle) of the first and second rocker of Gastrocnemius (GAS) and Soleus (SOL) with different levels of contractures (0°; 10°; 20°; 30° of plantarflexion contractures and CC (control condition)).

The percentages of participants with a first rocker were the following: 10% for gastrocnemius and 20% for soleus in condition 0° of plantarflexion contracture and then 0% for gastrocnemius and 0% for soleus in conditions 10°, 20°, and 30° of plantarflexion contractures. The presence of the second rocker was 60% for gastrocnemius and 90% for soleus at 0° of plantarflexion contracture. The results were 0% for gastrocnemius and 0% for soleus in conditions of 10°, 20°, and 30° of plantarflexion contractures. The kinematic angles for the ankle in the sagittal plane are shown in Figure 25.

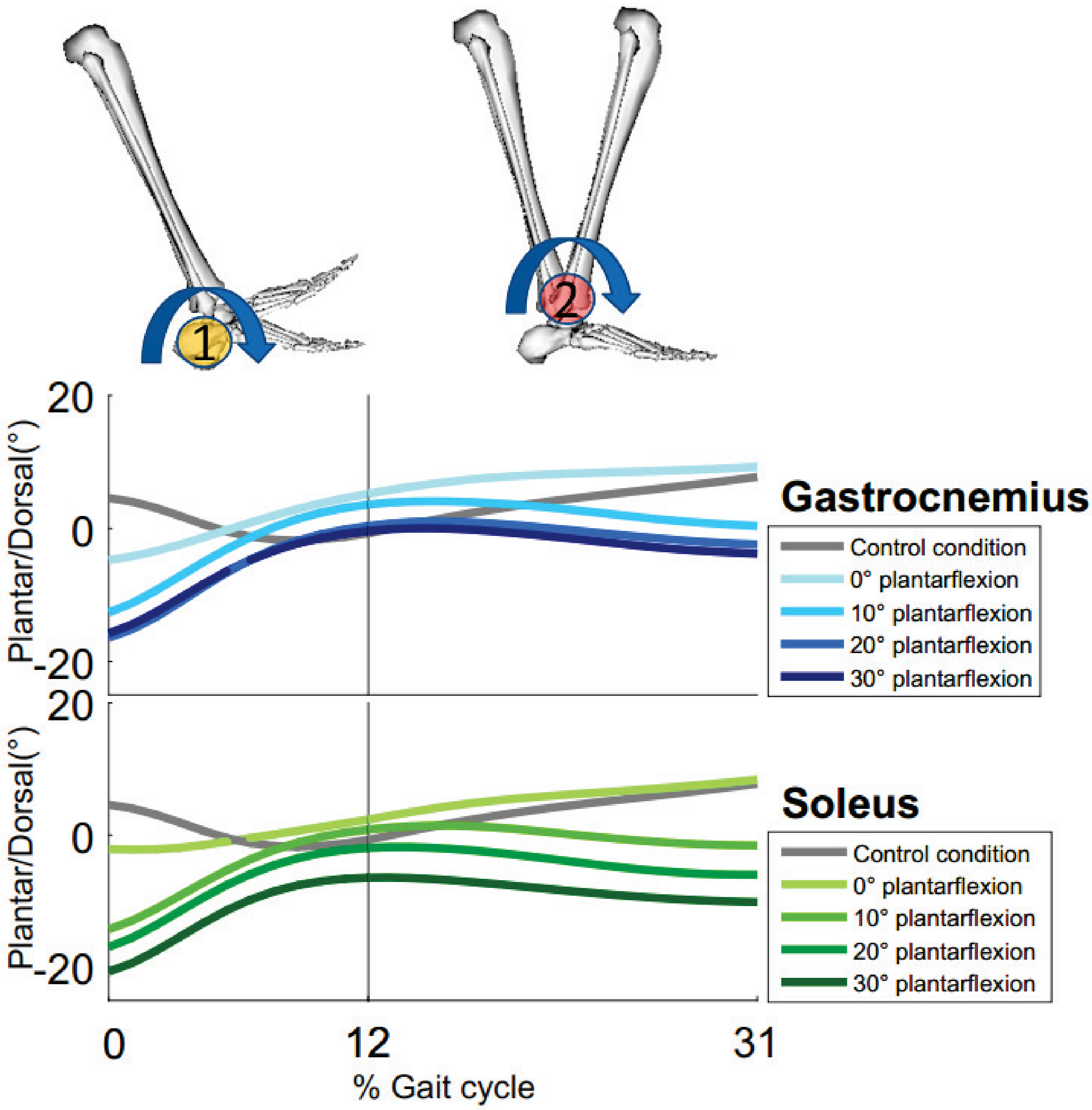


**Figure 25 : Kinematics in the sagittal plane of the first rocker (0-12% of gait cycle) and second rocker (12-31% of gait cycle) for the soleus and gastrocnemius conditions with different levels of contractures (0°; 10°; 20°; 30° of plantarflexion contractures and CC (control condition)).**

The Wilcoxon test showed only one significant difference between the slope of the curve due to the gastrocnemius and soleus conditions (first rocker) at 0° of plantarflexion (Table 8).

**Table 8 : Slope of the linear regression of the first and second rockers (median, 1st and 3rd quartile) at different degrees of emulated contractures (0°; 10°; 20°; 30° of plantarflexion contractures) for the gastrocnemius and soleus muscles and the significant difference (p-value) between these two muscles.**

| | First rocker | | | | | | | Second rocker | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Gastrocnemius | | | Soleus | | | | Gastrocnemius | | | Soleus | | | |
| | Med | *1st / 3rd quartile* | | Med | *1st / 3rd quartile* | | p-value | Med | *1st / 3rd quartile* | | Med | *1st / 3rd quartile* | | p-value |
| 0° plantarflexion | **1.12** | *0.30* | *1.51* | **0.34** | *0.07* | *0.96* | .005* | **.16** | *-.16* | *.39* | **.31** | *.13* | *.39* | .114 |
| 10° plantarflexion | **1.60** | *1.46* | *1.80* | **1.42** | *1.14* | *1.54* | .074 | **-.25** | *-.44* | *-.13* | **-.18** | *-.24* | *-.09* | .074 |
| 20° plantarflexion | **1.63** | *1.47* | *1.96* | **1.40** | *1.18* | *1.55* | .022 | **-.24** | *-.35* | *-.16* | **-.22** | *-.28* | *-.12* | .333 |
| 30° plantarflexion | **1.47** | *1.41* | *1.76* | **1.32** | *1.16* | *1.47* | .028 | **-.25** | *-.36* | *-.20* | **-.23** | *-.36* | *-.11* | .445 |

*= P<0.006 (Bonferroni's correction); Med = median

### 3.2.6 Discussion

In this study, we evaluated the effect of gastrocnemius and soleus contractures on the first and second rockers during walking. The first and second rockers are completely absent (Figure 24) with more than 10° of plantarflexion contracture. Additionally, we observed a clear "breakdown" in the ankle pattern change (showing the lack of continuity in the data) and an important shift toward plantarflexion values with loss of the rockers (Figure 25). We found that all ankle patterns are similar above this value of contracture. We found at 0° of plantarflexion contracture there was a less pronounced mean slope. This result suggests there is greater variability and was confirmed by the boxplot (Figure 24) showing 10% (gastrocnemius) and 20% (soleus) of participants have still the first rocker and 60% (gastrocnemius) and 90% (soleus) have still the second rocker. There is a transition between these two patterns during this plantarflexion contracture. The choice of one of these two patterns is certainly based on the best strategy to support forward progression (Attias et al., 2015) and to minimise the energy cost (Selinger et al., 2015), while maintaining balance and stability (Romkes et al., 2007).

Thus, toe-walking is not necessarily due to a high contracture level and can occur with a small contracture. Therefore, it is possible to have a patient with a slightly limited dorsiflexion who exhibits a toe-walking pattern.

According to Houx et al. (2012), the minimal plantarflexion contracture to influence kinematics and kinetics is 10° of plantarflexion. These findings are consistent with our results. We also found that the onset of changes occurred near 0° of plantarflexion.

These experimental findings suggest that the relationship between clinical parameters and ankle kinematics are not easy to establish because the gait pattern kinematics reflect both gait deviations and compensation mechanisms (Bonnefoy-Mazure et al., 2016).

The main limitation of this study concerns the contracture adaptation time, which can have an important role in the choice of different gait strategies. Our study analysed only immediate adaptations. There are several possible gait adaptations that can be used by the participants when contractures are emulated for the gastrocnemius, which is a bi-articular muscle that provides multiple possible strategy adaptations. The anatomical difference between the gastrocnemius and soleus may explain the significant difference at 0° of plantarflexion contracture during the first rocker. The gastrocnemius contractures provide more adaptation choices with a low contracture level (Attias et al., 2016b). We observed the same trends with the second rocker. However, there was no significant difference observed.

#### *3.2.6.1 Conclusion*

This study evaluated the effect of gastrocnemius and soleus contractures on the first and second rocker during walking. We found that there was a transition phase near 0° of plantarflexion contracture that permits a gait pattern choice. Thus, toe-walking is not necessarily due to the high contracture level and can occur with a small contracture by an "adaptation choice".

Our approach helps to improve interpretation of clinical gait analysis by showing that the link between the level of gastrocnemius / soleus contracture and the progression of toe-walking (increased plantarflexion during gait) is not continuous. We demonstrated that a shift between several patterns arises from 0 to 10° of plantarflexion contracture.

## 3.3 Article 5 – Kinematics can help to discriminate the implications of Iliopsoas, Hamstring and Gastrocnemius contractures to a knee flexion gait pattern

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La marche en « flexion de genoux » bilatérale causée par des rétractions musculaires : implication des muscles ilio-psoas, ischio-jambiers et gastrocnemius

Michael Attias[1, 2, 4], Alice Bonnefoy-Mazure[1], Geraldo Decoulon[3], Laurence Cheze[4], Stéphane Armand[1]

[1] Laboratoire de cinésiologie, université de Genève, hôpitaux universitaires de Genève, Suisse

[2] Haute École spécialisée de suisse occidentale (HES-SO), Haute École de santé de Genève, Suisse

[3] Service de pédiatrie orthopédique, hôpitaux universitaires de Genève, Suisse

[4] Université Lyon, université Claude-Bernard Lyon 1, IFSTTAR, LBMC UMR_T9406, 69622 Lyon, France

Cette étape consistait à comparer les effets des rétractions de différents muscles pouvant induire une marche « genoux fléchis » sur la cinématique.

Les résultats sont actuellement en soumission et ont été présentés en congrès :

<u>Publication “peer review”</u>
Attias M, Bonnefoy-Mazure A, De Coulon G, Cheze L, Armand S. Kinematics can help to discriminate the implication of iliopsoas, hamstring and gastrocnemius contractures to a knee flexion gait pattern. Clin Biomech. (**Soumis**).

<u>Publication “abstract”</u>
Attias M, Bonnefoy-Mazure A, Cheze L, De Coulon G, Armand S. La marche en « flexion de genoux » bilatérale causée par des rétractions musculaires : implication des muscles ilio-psoas, ischio-jambiers et gastrocnemius ; Neurophysiologie Clinique/Clinical Neurophysiology. 2016 ;46, I4-5, 242.

<u>Présentation publique</u>
Attias M, Bonnefoy-Mazure A, De Coulon G, Cheze L, Armand S. La marche en " flexion de genoux " bilatérale causée par des rétractions musculaires: implication des muscles ilio-psoas, ischio-jambiers et gastrocnemius; - PEM (Posture–Equilibre–Mouvement); 2016; Nancy, France

Attias M, Bonnefoy-Mazure A, De Coulon G, Cheze L, Armand S. Kinematics associated with a knee flexion gait pattern caused by isolated contracture of iliopsoas, hamstring and gastrocnemius; - ESMAC (European Society of Movement Analysis for Adults and Children); 2017; Trondheim, Norway (accepté oral)

### 3.3.1 Résumé français

Introduction : La marche en flexion excessive de genoux est un défaut fréquent chez les patients atteints de paralysie cérébrale. Les muscles dont les rétractions ont été identifiées comme pouvant être responsables d'une marche de type « genoux fléchis » sont les ilio-psoas, ischio-jambiers et gastrocnemius. Ainsi notre objectif était de comparer les effets des rétractions de différents muscles pouvant causer une marche « genoux fléchis » sur la cinématique.

Matériel et méthodes : Des rétractions (faibles, moyennes et fortes) ont été émulées bilatéralement à l'aide d'un exosquelette sur 10 participants « sains » pour les muscles ilio-psoas, ischio-jambiers et gastrocnemius. Une session d'analyse de la marche a été effectuée afin d'évaluer la cinématique articulaire pour les différentes rétractions émulées. Trente-et-une variables ont été choisies pour analyser la cinématique du thorax, du bassin, de la hanche, du genou et de la cheville. Une analyse en composante principale (ACP) a été utilisée pour déterminer les variables cinématiques influencées par la rétraction. L'effet sur la cinématique (basé sur les variables sélectionnées via l'ACP) des trois muscles rétractés a été comparé en fonction de trois valeurs moyennes de flexion de genou (20-30°, 30-40°, 40° et plus) (test de Kruskal-Wallis).

Résultats : En plus d'une flexion permanente de genou observée pour les 3 muscles rétractés, la rétraction des ilio-psoas induit un important flexum de hanche avec une antéversion du bassin prononcée; la rétraction des ischio-jambiers induit une dorsiflexion de cheville durant la phase d'appui avec une rétroversion du bassin; la rétraction des gastrocnemius induit une absence de premier et deuxième pivot du pied/cheville avec un léger flexum de hanche et une légère antéversion du bassin.

Discussion – conclusion : Sur la base de ces résultats, des tendances cinématiques ont été identifiées pour les muscles responsables d'un pattern particulier de marche «genoux fléchis». Une meilleure connaissance de ces patterns permet d'améliorer l'interprétation des analyses de marche en ciblant le muscle altéré de manière plus précise et plus rapide.

Mots-clés: Cinématique; Rétraction; Marche; Genoux fléchis; Exosquelette; Simulation

### 3.3.2 Abstract

Introduction: Excessive knee flexion gait pattern (KFGP) is a common gait deviation in many pathological conditions. The contractures of the muscles that have been identified as being responsible for a KFGP include iliopsoas (PSO), hamstring (HAM) and gastrocnemius (GAS). Our goal was to compare the associated kinematics to a KFGP between isolated PSO, HAM, and GAS contractures.

Methods: Several levels of contracture (mild, middle and severe) were emulated bilaterally using an exoskeleton on 10 healthy participants for the PSO, HAM, and GAS muscles. A gait analysis session was performed to evaluate the joint kinematics according to the different emulated contractures. Thirty-one parameters were chosen to analyse the kinematics of the thorax, pelvis, hip, knee, and ankle. A principal component analysis (PCA) was used to determine the kinematic parameters influenced by contractures. The effect on kinematics (based on parameters selected by PCA) of the 3 contracted muscles was compared according to 3 levels of the mean position of knee flexion during the stance phase (Kruskal-Wallis test).

Results: In addition to a permanent knee flexion observed for the 3 contracted muscles, the contracture of the PSO induces a large hip flexion with a pronounced anteversion of the pelvis; the contracture of the hamstrings induces an ankle dorsiflexion during the support phase with a retroversion of the pelvis; the contracture of the gastrocnemius induces an absence of the first and second rocker of the ankle with a slight flexion of the hip and a slight anteversion of the pelvis.

Conclusion: From these results, it is possible to identify the muscles responsible for a KFGP. A better knowledge of this type of kinematics will support the interpretation of the gait analysis by targeting the altered muscle more precisely and rapidly.

Keywords: kinematics; contractures; gait; knee flexion; exoskeleton; simulation

### 3.3.3 Introduction

A knee flexion gait pattern (KFGP) is a frequent gait deviation (Matjacic and Olensek, 2007; Wren et al., 2005) observed in many pathological conditions (such as cerebral palsy). It is defined by an excessive knee flexion during the stance phase greater than normally expected (Perry and Burnfield, 2010). During walking, knee functions are to assure smooth support in the stance phase and advancement in the swing phase while assuring foot clearance (Perry and Burnfield, 2010). In a normal condition, knee kinematics have 2 waves of flexion, the first that controls shock absorption during the first double support and the second during swing, which assists foot clearance (Perry and Burnfield, 2010).

A KFGP impairs gait performances by decreasing velocity, stride and step length and by increasing weight bearing and walking effort (Cerny et al., 1994; Whitehead et al., 2007). Physical consequence can be pain at the joint, degenerative arthritis, bony deformities and increased risk for falls due to inadequate foot clearance (Attias et al., 2016a). To reduce the consequences of a KFGP, treatment of the cause of this pattern is needed. To support the therapeutic choice, a clinical gait analysis (CGA) is generally performed to help identify and understand gait deviations. However, the interpretation of a CGA is complex because gait deviations can be caused by different clinical impairments such as contractures, spasticity, muscle weakness, problems with muscle selectivity, or pain (Gracies, 2005a, b).

Gait can be altered by the primary causes of gait deviations (impairments) or by secondary compensatory strategies (Houx et al., 2013; Romkes and Brunner, 2007). It is important to distinguish between these aspects because only impairments need to be treated (Davids, 2006). Secondary compensatory strategies should disappear once these primary impairments have been treated (Schmid et al., 2013). To help distinguish these aspects, a good way appears to isolate a particular impairment. This will help to establish the link between impairments and gait deviations (Attias et al., 2016d).

Among impairments that can lead to a KFGP, contractures of the PSO, HAM, and GAS muscles are possible causes (Attias et al., 2016d; Balzer et al., 2013; Matjacic and Olensek, 2007; Whitehead et al., 2007). The HAM and GAS pass through directly on the knee joint and are both biarticular muscles. The HAM also influences the hip joint and the GAS also influences the ankle joint (Perry and Burnfield, 2010). The PSO passes through the hip joint (Perry and Burnfield, 2010). Even if a KFGP can be caused by different impairments, we hypothesise that varying impairments will lead to different gait deviations at other joints/segments. Therefore, identifying associated gait deviations as possible causes of a KFGP will support the interpretation of a CGA when a KFGP occurs.

Hence, the aim of this study was to compare kinematics associated with a KFGP between isolated PSO, HAM and GAS contractures.

### 3.3.4 Methods

#### *3.3.4.1 Participants:*

Ten participants were included in this study with no known neurologic or orthopaedic problems. They had the following characteristics: 5 females/5 males; age: 25.7 years ± 3.6; height: 1.71 m ± 0.1; weight 64.4 kg ± 11.4.

Ethical approval and participant informed consent were obtained prior to the beginning of data collection.

#### *3.3.4.2 Gait evaluation*

To emulate PSO, HAM and GAS bilateral contractures, the participants wore the exoskeleton MIkE and walked along a 10-m walkway at a spontaneous self-selected speed (Attias et al., 2016a). The exoskeleton was designed to bilaterally embrace the pelvis, the thigh and the shank with plastic cuffs and with modified shoes that included attachment points. A particular cut was made on the plastic cuffs to enable reflective markers to be placed directly on the skin as requested for a CGA. Each participant walked with the exoskeleton without emulated contracture for the control condition (CC). The participants were equipped with 34 reflective markers aligned to anatomical and technical landmarks on the head, trunk and pelvis and bilaterally on the arms, thighs, shanks and feet according to the full-body Plug-in-Gait model (Davis et al., 1991). Kinematic recordings were performed with a 12-camera motion analysis system (Oqus 7+, Qualisys, Göteborg, Sweden). A minimum of 5 gait cycles was averaged to produce a single angular displacement of the pelvis segment and the hip, knee and ankle joints.

The level of contracture was selected as mild, middle and severe contracture according to our clinical experience and the literature (Attias et al., 2015; Attias et al., 2016d; Drefus et al., 2016). Hence, PSO was limited at 0°, -20° and -40° of the hip extension angle (knee in extension); HAM was limited at 40°, 70° and 100° of the unilateral popliteal angle; and GAS was limited at 10°, 20° and 30° of ankle plantarflexion. To set the contractures, the experimenter adjusted the rope length of the exoskeleton in the position used for a standard physical examination (Viehweger et al., 2007) and controlled it with a goniometer.

#### *3.3.4.3 Data analysis and statistics*

Two steps were performed to analyse the data.

First, to evaluate the kinematic parameters influenced by the contracture during walking, a PCA was performed on each condition (PSO, HAM and GAS). The PCA was used to identify the parameters influenced by the degree of contracture for each muscle condition. The parameters used were the range of motion (ROM) and the mean position in 3 planes for the thorax, pelvis and spine angle; ROM, maximum, minimum and mean position for the sagittal hip angle; flexion at initial contact (IC), maximum in stance, mean position in stance and ROM during the gait cycle for the sagittal knee and ankle angles; and the mean foot progression angle. These parameters were considered interesting for clinical interpretation experience and reliable according to the literature (Harato et al., 2008a; Houx et al., 2013; Lance, 1980; Matjacic and Olensek, 2007). A minimum of 4 parameters was selected based on the value of the squared cosines matrix of the PCA. If the values were higher than 0.85 for more than 4 parameters, all the parameters were selected. If the values were lower than 0.85, the 4 parameters with the highest values were selected. The closer the values were to 1, the more the parameters could explain the variability of gait due to the level of emulated contracture.

Second, considering all the conditions, 3 groups were created according to the mean knee position in stance: Group 1: 20-30°, Group 2: 30-40°, Group 3: 40° and more. The differences between the groups and the muscles (PSO, HAM and GAS) on the parameters selected by the PCA were analysed using the Kruskal-Wallis test with post hoc. Bonferroni's correction was used to limit the problem of multiple comparisons. Walking speed was also compared in the same analysis.

### 3.3.5 Results

First, the selection of kinematic parameters using the PCA is presented in Table 9. The first and second factors were chosen for all muscles (for PSO with a total inertia of 46%, for HAM with a total inertia of 43%, and for GAS with a total inertia of 46%).

Table 9: Kinematic parameters selected from a Principal Component Analysis (PCA) for each muscle and each segment/joint

| | Pelvis | Hip | Knee | Ankle/Foot |
|---|---|---|---|---|
| **Iliopsoas** | Obliquity ROM* | Flex MP* Flex Min* Flex Max* | Flex IC* Flex MP Stance* | |
| **Hamstring** | | Flex MP* Flex Min* | | Flex Max Stance** Flex MP Stance** |
| **Gastrocnemius** | Tilt MP* | | | Flex IC* Flex Max Stance* Flex MP Stance* |

**> 0.75; *> 0.85
ROM = range of motion; MP = mean position; IC = initial contact; Flex = flexion; Max = maximum; Min = minimum; Stance = stance phase of gait

Second, the selected parameters were compared between the 3 emulated muscle contractures (PSO, GAS, and HAM) for each group of KFGP. The results are presented in Table 10 and illustrated in Figure 26. **At the pelvis level**, the PSO and GAS contractures induced anteversion, whereas the HAM contracture induced a retroversion. The PSO induced a more important anteversion than the GAS. The PSO showed more pelvis ROM obliquity than other muscles. **At the hip level**, the PSO contracture induced a permanent flexion followed by the GAS with a mild but permanent flexion, whereas the hip flexion was close to that of the CC for the HAM contracture. **At the knee level**, the GAS and HAM contractures induced a more important flexion at the IC than the PSO that showed only a mild flexion at the IC. **At the ankle level**, the HAM contracture induced a permanent dorsiflexion during stance, the GAS contracture induced a plantarflexion along the complete gait cycle, and the PSO contracture showed kinematics close to the normal.

Table 10: Median angular value (°) or speed (m.s-1) [1st/3rd quarti1e (°/m.s-1)] for the different emulated contractures (gastrocnemius, hamstring and iliopsoas) according to group of knee flexion in stance (Group 1: 0-20°, Group 2: 20-40°, and Group 3: 40° and more) for the parameters determined by a PCA. Comparisons between conditions for each group were performed using the Kruskal-Wallis test and post hoc.

| | | | CC(°) | | | GAS (°) | | | | HAM (°) | | | | PSO (°) | | | | P Value (Post Hoc) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Parameters | Med | 1st/3rd quartile | | N | Med | 1st/3rd quartile | | N | Med | 1st/3rd quartile | | N | Med | 1st/3rd quartile | | GAS-HAM | GAS-PSO | HAM-PSO |
| Group 1: 20-30° MP Knee Stance | Pelvis | Tilt MP | 10.1 | 4.8 | 12.5 | 8 | 15.8 | 12.9 | 19.6 | 7 | 4.1 | 1.1 | 7.3 | 10 | 26.0 | 17.4 | 29.2 | 0.014* | 0.129 | < 0.001* |
| | | Obliquity ROM | 6.7 | 5.3 | 9.0 | | 8.7 | 6.4 | 11.3 | | 5.0 | 4.4 | 5.2 | | 11.7 | 9.6 | 14.7 | 0.017 | 0.171 | < 0.001* |
| | Hip | Flex MP | 8.6 | 5.8 | 13.0 | | 19.6 | 15.5 | 22.9 | | 6.9 | 5.2 | 8.9 | | 36.4 | 23.5 | 42.4 | 0.024 | 0.046 | < 0.001* |
| | | Flex Min | -9.1 | -12.9 | -7.0 | | 4.2 | 0.3 | 7.3 | | -7.8 | -11.0 | -6.0 | | 26.1 | 11.1 | 36.2 | 0.042 | 0.018 | < 0.001* |
| | | Flex Max | 35.1 | 30.7 | 37.1 | | 39.7 | 38.1 | 44.5 | | 28.9 | 27.0 | 31.0 | | 51.7 | 41.6 | 57.6 | 0.014* | 0.107 | < 0.001* |
| | Knee | Flex IC | 0.7 | -2.8 | 3.0 | | 20.9 | 12.8 | 25.5 | | 23.2 | 20.7 | 26.2 | | 7.3 | 5.1 | 10.1 | 0.445 | 0.003* | < 0.001* |
| | | Flex MP Stance | 11.3 | 7.7 | 15.4 | | 26.0 | 24.1 | 28.8 | | 25.0 | 21.1 | 25.5 | | 25.0 | 22.9 | 29.3 | | Grouping parameter | |
| | Ankle | Dors IC | 4.6 | 1.9 | 7.0 | | -12.1 | -20.4 | -9.8 | | 8.3 | 7.6 | 11.6 | | 5.0 | 1.7 | 6.2 | < 0.001* | 0.006* | 0.052 |
| | | Dors Max Stance | 16.8 | 14.3 | 18.4 | | 4.6 | -0.9 | 9.0 | | 17.8 | 16.4 | 22.6 | | 20.4 | 18.6 | 21.4 | 0.005* | < 0.001* | 0.422 |
| | | Dors MP Stance | 6.6 | 5.5 | 7.7 | | -4.5 | -9.6 | 0.4 | | 11.4 | 9.8 | 15.2 | | 10.0 | 8.9 | 10.8 | < 0.001* | 0.003* | 0.181 |
| | | Walking speed | 1.2 | 1.1 | 1.3 | | 1.1 | 1.0 | 1.1 | | 0.8 | 0.8 | 1.0 | | 0.9 | 0.7 | 1.1 | 0.011 | 0.019 | 0.676 |
| Group 2: 30-40° MP Knee Stance | Pelvis | Tilt MP | 10.1 | 4.8 | 12.5 | 14 | 13.0 | 11.5 | 17.6 | 9 | 5.7 | -1.3 | 8.1 | 9 | 23.7 | 20.9 | 29.9 | 0.017* | 0.004* | < 0.001* |
| | | Obliquity ROM | 6.7 | 5.3 | 9.0 | | 7.5 | 5.1 | 11.6 | | 6.0 | 3.8 | 6.8 | | 10.2 | 7.8 | 12.0 | 0.049 | 0.086 | 0.001* |
| | Hip | Flex MP | 8.6 | 5.8 | 13.0 | | 25.4 | 20.5 | 27.7 | | 15.2 | 7.6 | 17.8 | | 43.2 | 38.9 | 47.5 | 0.016 | 0.002 | < 0.001* |
| | | Flex Min | -9.1 | -12.9 | -7.0 | | 10.5 | 5.9 | 13.9 | | -0.4 | -5.3 | 2.7 | | 36.1 | 29.8 | 40.1 | 0.016 | 0.002 | < 0.001* |
| | | Flex Max | 35.1 | 30.7 | 37.1 | | 43.6 | 41.6 | 47.1 | | 30.6 | 23.5 | 40.1 | | 55.3 | 51.7 | 59.1 | 0.014* | 0.008* | < 0.001* |
| | Knee | Flex IC | 0.7 | -2.8 | 3.0 | | 28.6 | 24.2 | 29.2 | | 39.2 | 31.2 | 40.7 | | 11.5 | 8.9 | 16.9 | 0.017 | 0.003* | < 0.001* |
| | | Flex MP Stance | 11.3 | 7.7 | 15.4 | | 35.1 | 34.0 | 37.0 | | 35.5 | 34.5 | 36.8 | | 35.8 | 31.2 | 38.1 | | Grouping parameter | |
| | Ankle | Dors IC | 4.6 | 1.9 | 7.0 | | -11.6 | -24.2 | -8.7 | | 10.3 | 5.7 | 10.7 | | 7.6 | 1.7 | 9.3 | < 0.001* | < 0.001* | 0.466 |
| | | Dors Max Stance | 16.8 | 14.3 | 18.4 | | 5.8 | -6.7 | 9.4 | | 22.1 | 16.7 | 23.9 | | 19.5 | 17.2 | 21.9 | < 0.001* | < 0.001* | 0.763 |
| | | Dors MP Stance | 6.6 | 5.5 | 7.7 | | -0.3 | -13.0 | 1.6 | | 15.9 | 11.0 | 18.1 | | 10.0 | 8.1 | 11.7 | < 0.001* | 0.002* | 0.269 |
| | | Walking speed | 1.2 | 1.1 | 1.3 | | 0.9 | 0.9 | 1.0 | | 0.8 | 0.5 | 1.0 | | 0.9 | 0.8 | 1.1 | | No difference | |
| Group 3: 40° and more MP Knee Stance | Pelvis | Tilt MP | 10.1 | 4.8 | 12.5 | 4 | 18.8 | 9.6 | 21.2 | 12 | -1.8 | -8.1 | 1.2 | 7 | 33.4 | 31.9 | 35.7 | 0.041 | 0.196 | < 0.001* |
| | | Obliquity ROM | 6.7 | 5.3 | 9.0 | | 9.4 | 6.3 | 14.9 | | 5.4 | 4.6 | 6.2 | | 11.2 | 9.7 | 14.0 | 0.028 | 0.450 | < 0.001* |
| | Hip | Flex MP | 8.6 | 5.8 | 13.0 | | 31.8 | 22.5 | 36.6 | | 9.0 | 2.3 | 13.9 | | 55.9 | 53.5 | 60.0 | 0.050 | 0.176 | < 0.001* |
| | | Flex Min | -9.1 | -12.9 | -7.0 | | 16.9 | 9.7 | 25.5 | | -2.0 | -11.2 | 0.1 | | 49.2 | 45.5 | 53.4 | 0.050 | 0.176 | < 0.001* |
| | | Flex Max | 35.1 | 30.7 | 37.1 | | 50.2 | 37.4 | 52.8 | | 25.9 | 21.1 | 32.8 | | 68.4 | 65.2 | 72.5 | 0.050 | 0.176 | < 0.001* |
| | Knee | Flex IC | 0.7 | -2.8 | 3.0 | | 35.7 | 31.3 | 37.6 | | 50.1 | 45.1 | 54.4 | | 19.0 | 16.2 | 23.0 | 0.230 | 0.035 | < 0.001* |
| | | Flex MP Stance | 11.3 | 7.7 | 15.4 | | 42.7 | 40.5 | 47.9 | | 44.9 | 42.9 | 52.4 | | 45.9 | 41.3 | 50.5 | | Grouping parameter | |
| | Ankle | Dors IC | 4.6 | 1.9 | 7.0 | | -7.9 | -10.9 | -6.0 | | 11.3 | 4.6 | 17.4 | | 6.8 | 4.5 | 9.2 | 0.002* | 0.047 | 0.226 |
| | | Dors Max stance | 16.8 | 14.3 | 18.4 | | 8.4 | 3.6 | 11.0 | | 25.1 | 15.6 | 28.8 | | 21.6 | 19.6 | 23.0 | 0.003* | 0.034 | 0.445 |
| | | Dors MP Stance | 6.6 | 5.5 | 7.7 | | 0.5 | -2.8 | 1.7 | | 16.3 | 10.4 | 23.6 | | 10.4 | 9.1 | 12.9 | 0.002* | 0.068 | 0.163 |
| | | Walking speed | 1.2 | 1.1 | 1.3 | | 0.9 | 0.9 | 1.0 | | 0.6 | 0.6 | 0.7 | | 1.0 | 1.0 | 1.1 | 0.008* | 0.762 | < 0.001* |

*= P < 0.017 (Bonferroni's correction) significant differences

GAS = gastrocnemius; HAM = hamstring; PSO = iliopsoas; CC = control condition; Med = median; MP = mean position; Min = minimum; Max = maximum; IC = initial contact; PCA = principal component analysis; Flex = flexion; Ext = extension; Dors = dorsiflexion; Stance = stance phase; IC = initial contact phase; Med = median; N = number

Flex = positive value; Ext = negative value; Dorsiflexion = positive value; Plantarflexion = negative value; Pelvis MP anteversion = positive value

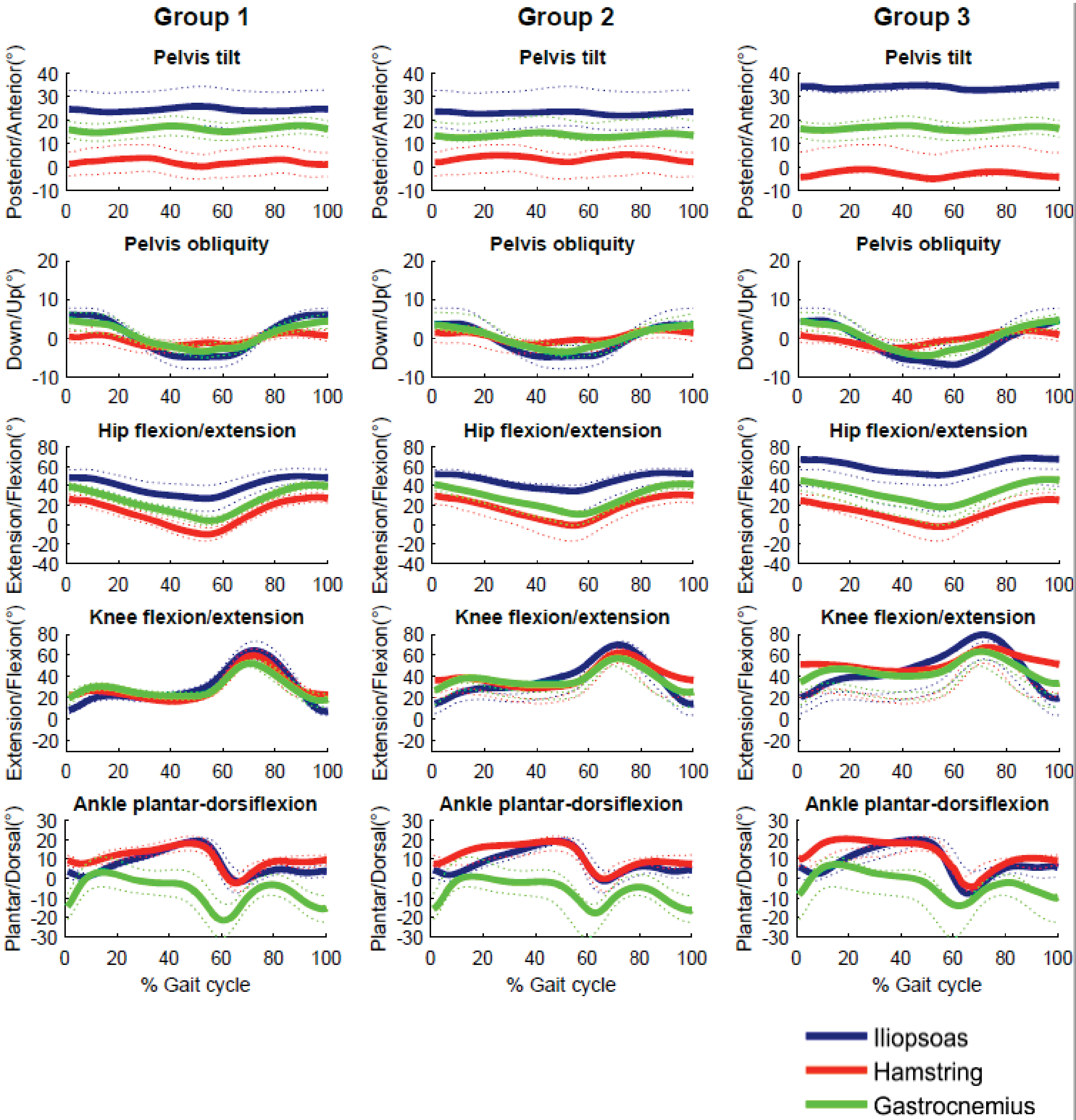


Figure 26: Mean kinematics for the pelvis, hip, knee, and ankle in the sagittal plane and foot progression according to the emulated contracture (PSO, HAM, and GAS) and to the group of knee mean positions in stance (Group 1: 20-30°, Group 2: 30-40°, and Group 3: 40° and more). Solid line: mean kinematics; dashed line: standard deviation; blue line: PSO; red line: HAM; green line: GAS.

### 3.3.6 Discussion

The objective of this study was to compare kinematics associated with a KFGP between isolated PSO, HAM, and GAS contractures. Results of this study support that a KFGP caused by contracture of different muscles induces different gait adaptations. The main kinematic associations for each of the 3 emulated muscle contractures were as follows: (1) PSO contracture induces an important hip flexion with a pronounced pelvis anteversion; (2) HAM contracture induces an ankle dorsiflexion during stance phase with a pelvis in retroversion; 3)

GAS contracture induces an ankle plantarflexion (with a mild hip flexion and a mild pelvis anteversion).

It is important to identify the primary impairment of a KFGP to choose the best treatment strategy. Lengthening of the HAM is often used to treat a KFGP if the popliteal angle is increased. This surgery is often performed in cerebral palsy patients with a crouch gait pattern to improve both the knee extension in stance and the ROM (MacWilliams et al., 2016). However, it has been demonstrated that a CGA did not agree with the initial plan of recommended HAM lengthening in 59% of cases (MacWilliams et al., 2016). The surgery should be indicated when the HAM is the cause of joint limitation and the clinician needs to verify and consider that other impairments may cause a KFGP. Goodman et al. highlighted that limitations in both the hip and knee extension of persons with hemiplegia are not necessarily caused by a limited length of the HAM and/or hip flexors (PSO), but rather as the result of an ankle plantarflexor contracture alone (Goodman et al., 2004). Rodda et al. showed an increased mean anterior pelvic tilt angle at 1 and 5 year's post-operative surgery and explained this deterioration by a high amount of intervention on the HAM rather than the PSO (Rodda et al., 2006).

The reliability and the limitations of the emulated contractures with the exoskeleton were shown in a previous study (Attias et al., 2016a). The first important limitation concerns the short adaptation time to contracture emulations. Indeed, the adaptation time can play an important role in gait strategies chosen by the participants. The second limitation concerns the walking speed that was not controlled between the different conditions of this study. We know that gait parameters vary due to walking speed (Schwartz et al., 2008) and can influence the results of this study. However, with patients, we encounter the same problems of different walking speed according to the impairments.

#### *3.3.6.1 Conclusion*

This study discriminates kinematic factors associated with a KFGP according to muscle contractures in the perspective to support the interpretation of a CGA. The results highlight that for the same level of KFGP, (1) PSO contracture induces an important hip flexion with a pronounced pelvis anteversion; (2) HAM contracture induces an ankle dorsiflexion during the stance phase with a pelvis in retroversion; and (3) GAS contracture induces ankle plantarflexion with a small hip flexion and a small pelvis anteversion. This knowledge associated with other clinical information (physical examination, imaging) will help identify the impairment(s) responsible for a KFGP. By improving the understanding of gait deviations, treatment decisions can be improved.

## 3.4 Article 6 – Classification of trunk movements during gait caused by lower limb contractures

### En préparation pour soumission


M. Attias, MSc[1, 2,3] ; A. Bonnefoy-Mazure, PhD[1]; A. Tabard[1] ; G. De Coulon, MD[4] ; P. Strasser[5] ; A. Kalousis[5] ; L. Cheze, PhD[3] ; S. Armand, PhD[1]

[1]Willy Taillard Laboratory of Kinesiology, Geneva University Hospitals and Geneva University, Switzerland.

[2]HES-SO University of Applied Sciences and Arts Western Switzerland, School of Health Sciences, Geneva, Switzerland

[3]Univ Lyon, Université Lyon 1, IFSTTAR, LBMC UMR_T9406, F69622, Lyon, France

[4]Pediatric Orthopaedic Service, Department of Child and Adolescent, Geneva University Hospitals and Geneva University, Geneva, Switzerland.

[5]HES-SO University of Applied Sciences Western Switzerland, Department of Business Informatics, Geneva, Switzerland

### 3.4.1 Résumé français

Introduction : Le tronc a une influence importante pendant la marche en contribuant au déplacement. Des stratégies compensatoires du mouvement du haut du corps peuvent se produire lorsque le mouvement des membres inférieurs est altéré. La répétition de ces stratégies compensatoires pendant de nombreuses années peut entraîner des déficits secondaires musculo-squelettiques. Parmi les déficits cliniques pouvant conduire à une altération du mouvement des membres inférieurs, l'un des plus fréquents est la rétraction des tissus mous. Ainsi, l'objectif de cette étude est de classifier et caractériser les mouvements du tronc liés aux principales rétractions du membre inférieur pendant la marche.

Méthode : Vingt-neuf participants sains (sans problèmes neurologiques ou orthopédiques connus) ont été recrutés. Des rétractions ont été émulées à différents degrés de sévérité sur les cinq muscles des membres inférieurs qui agissent principalement dans le plan sagittal et classiquement atteints: gastrocnemius, soleus, ilio-psoas, ischio-jambiers et rectus femoris. La cinématique du thorax et du bassin a été analysée dans les trois plans. Une classification hiérarchique a été effectuée sur toutes les conditions/participants pour identifier des groupes. La proportion de ces groupes a été comparée en fonction de chaque rétraction musculaire émulée et de chaque degré de sévérité de rétraction.

Résultats : Quatre groupes de mouvements du tronc ont été identifiés. Les différences les plus importantes entre les groupes ont été observées dans le plan sagittal pour l'inclinaison du bassin et du thorax. Le Groupe 1 est caractérisé par une légère antéversion du bassin et du thorax. Ce groupe avait une prévalence élevée de rétractions des gastrocnemius et soleus. Le Groupe 2 est caractérisé par une légère antéversion du thorax avec plus d'antéversion du bassin que le Groupe 1, en relation avec des rétractions légères de l'ilio-psoas ou du rectus femoris. Le Groupe 3 est caractérisé par la plus importante antéversion du thorax et du bassin en lien avec des rétractions sévères de l'ilio-psoas ou du rectus femoris. Le Groupe 4 est caractérisé par une rétroversion importante du bassin et une légère antéversion du thorax liées aux rétractions des ischio-jambiers.

Discussion : Les rétractions des muscles des membres inférieurs qui sont classiquement atteints ont des effets importants sur la position moyenne dans le plan sagittal du bassin et du thorax, et des effets plus faibles dans les plans frontal et transversal.

Mots-clés: Classification; Rétraction; Marche; Tronc; Exosquelette; Simulation

### 3.4.2 Abstract

*Introduction*: Trunk has an important influence during gait by contributing in displacement more as a 'locomotor' unit than a 'passenger' unit. Compensatory upper body movement strategies may occur when the movement of the lower limbs is impaired. The repetition of these compensatory strategies over many years can provide secondary musculoskeletal deficits. Among clinical conditions that can lead to lower limb impairments, one of the most frequent alterations is contracture. Hence the aim of this study is to classify and characterize the movements of the trunk during walking caused by main contractures of the lower limb.

*Method*: Twenty-nine healthy participants were selected with no known neurologic or orthopaedic problems. Contractures were emulated at different degrees of severity on the five most affected lower limb muscles that act mainly in the sagittal plane: gastrocnemius, soleus, iliopsoas, hamstring and rectus femoris. Kinematics of the thorax and pelvis was analyzed in the three planes. Clustering was performed with a hierarchical classification on all the gait cycles using a linkage method. Group proportion was compared relative to each emulated muscle contracture and each degree of contracture severities.

*Results*: Four groups of trunk movement were identified. The most important differences between groups were observed in the sagittal plane for pelvis and thorax tilt. Group 1 showed a mild pelvis and thorax anteversion. This group had a high prevalence of gastrocnemius and soleus contractures. Group 2 showed a mild thorax anteversion with more pelvis anteversion than Group 1, in relation with mild contracture of iliopsoas and rectus femoris. Group 3 showed most important thorax and pelvis anteversion in link with severe iliopsoas and rectus femoris contractures. Group 4 showed large pelvis retroversion and a mild thorax anteversion related to hamstring contractures.

*Discussion:* Contractures of the lower limb have important effects on the mean position of thorax and pelvis in the sagittal plane and low effects in frontal and transverse planes.

Keywords: Clustering; Contractures; Gait; Trunk; exoskeleton; simulation

### 3.4.3 Introduction

Walking is considered as one of the most important motor skills in daily life (Hoang et al., 2014; Prabhu et al., 2013), and can be altered by numerous impairments leading to gait deviations. Gait deviations are often difficult to understand due to the complexity of walking. Clinical gait analysis (CGA) is generally used to identify and understand the specific deficits of individual patients in order to improve therapeutic decisions (Moissenet and Armand, 2015).

Trunk has an important influence during gait by being one the most important contributor to forward movement (Gillet et al., 2003) and can be considered as 'locomotor' unit (Attias et al., 2015; Perry and Burnfield, 2010) rather than 'passenger' unit (Perry and Burnfield, 2010). Trunk movements during walking permit also to preserve head stability (Kavanagh et al., 2006) and hence protect vestibular and visual information needed in functions related to balance (Pozzo et al., 1991).

When the movement of the lower limbs is impaired, compensatory upper body movement strategies are needed to perform daily life activity such as walking (Leardini et al., 2011). The repetition over many years of compensatory upper body movement strategies can lead to secondary musculoskeletal deficits (e.g. pain) (Jahnsen et al., 2004).

Trunk movements during gait were studied in patients with lower-limb impairments in different pathological conditions. In cerebral palsy children (CP), larger movements of the trunk compared to typically developing children were reported (Attias et al., 2015; Heyrman et al., 2013; Romkes et al., 2007). In CP patients, low back pain was often described and often associated with compensatory upper body movement strategies (Andersson and Mattsson, 2001; Jahnsen et al., 2004; Opheim et al., 2009). In stroke patients, trunk performance is impaired related to balance, gait and functional ability (Verheyden et al., 2006). In lumbosacral myelomeningocele patients, trunk plays a role of stabilizer by a large lateral sway and large rotations in the transversal plane (Gutierrez et al., 2003b).

However, compensatory upper body movement strategies to lower-limb impairments were studied with a mixed of several impairments making it difficult to establish a clear relationship between each impairment and the gait deviations. The isolation of a specific clinical impairment would permit to better establish this relationship. A possible approach to establish this relationship is to isolate an impairment by miming it on healthy participants (Attias et al., 2016d), offering the advantage of being able to handle the severity of the impairment. Among types of impairment that can lead to gait deviations, one of the most frequent is contracture which induces a restricted passive range of motion of one or several joints (Attias et al., 2016d). Contractures are observed in many pathological conditions (e.g. cerebral palsy, multiple sclerosis, spinal cord injury and stroke (Hoang et al., 2014)) and can be emulated in healthy participants (Attias et al., 2016a).

Therefore, the aim of this study was to classify and characterize the movements of the trunk caused by induced contractures of the lower limb muscles during gait.

### 3.4.4 Methods

#### *3.4.4.1 Participants:*

Twenty-nine healthy participants were selected with no known neurologic or orthopaedic problems with the following characteristics: 17 females/12 males; age: 26.9 ± 4.2 years; height: 1.71 ± 9.1 m; weight 64.8 ± 9.7 kg.

Ethical approval and participant informed consent were obtained prior the beginning of data collection.

#### *3.4.4.2 Gait evaluation*

Muscles considered in this study were gastrocnemius (GAS), soleus (SOL), iliopsoas (PSO), hamstring (HAM) and rectus femoris (RF).

The emulation of GAS, SOL, PSO, HAM and RF contractures was performed using the exoskeleton MIkE (Attias et al., 2016a). The exoskeleton was designed to embrace the pelvis, and bilaterally the thigh and the shank with plastic cuffs and included modified shoes with attachment points. A particular cut was made on the plastic cuffs to enable reflective markers to be placed directly on the skin as requested for CGA. The participants were equipped with 34 reflective markers aligned to anatomical and technical landmarks on the head, trunk and pelvis and bilaterally on the arms, thighs, shanks and feet according to the full-body Plug-in-Gait model (Davis et al., 1991) and Gutierrez et al.'s model (Gutierrez et al., 2003a). Kinematic recordings were performed using a twelve-camera motion analysis system (Oqus 7+, Qualisys, Göteborg, Sweden).

The level of contracture was performed with 3 or 4 degrees of severity in order to cover a large range of clinical conditions (Attias et al., 2015; Attias et al., 2016d; Drefus et al., 2016). Hence, PSO and RF contractures limited to 0°, -20° and -40° the hip extension angle (knee in extension for PSO and knee in flexion for RF), HAM contractures limited to 40°, 70° and 100° the unilateral popliteal angle, GAS and SOL contractures limited to 0°, -10°, -20° and -30° the ankle dorsiflexion (knee in extension for GAS and knee in flexion for SOL). Bilateral and unilateral isolated contractures were emulated for each degree of severity. To set the contracture, the experimenter adjusted the corresponding rope length of the exoskeleton in the position used during standard physical examination (Viehweger et al., 2007) and controlled it with a manual goniometer. Participants wore the exoskeleton with the isolated contractures emulated at previous described levels. They walked along a 10-meter walkway at a spontaneous self-selected speed. A minimum of three gait cycles were averaged for each participant and contracture condition to produce a single angular displacement of the trunk and pelvis segments, and hip, knee and ankle joints by participant/condition.

#### 3.4.4.3 Data analysis and statistics

***Selection and extraction of gait data***

The kinematics of the thorax and pelvis were analyzed in the sagittal (tilt), coronal (obliquity) and transversal (rotation) planes with MATLAB R2015b (MathWorks, USA) and the open-source Biomechanical ToolKit package for MATLAB (Barre and Armand, 2014). To highlight only the modifications of emulated contracture on gait, the mean kinematics of a control condition (walking with the exoskeleton without any contracture emulated) for each participant was removed from the kinematics of the different contracture conditions to obtain an adjusted kinematics. This procedure permits to remove a possible bias related to different walking patterns between participants (e.g. different pelvis anteversion) and to keep only the modification induced on kinematics by the emulated contracture.

***Clustering and characterization of trunk movement patterns***

A clustering analysis was performed on the adjusted kinematics of the thorax and pelvis to determine homogeneous subgroups on the effect of lower-limb contracture on pelvis and thorax kinematics. The adjusted pelvis and thorax angle and its time-derivatives were considered in the clustering. Euclidean distance of the full gait cycle (101 points) was chosen as metric. Hierarchical clustering with the Ward linkage method was used. The number of clusters was determined by calculation of the agglomeration coefficient while increasing the number of clusters based on the decay curve of interclass distance as a function of the class number from 1 to 10 and adopting the ‘‘stopping rule’’ along with visually inspecting the dendrogram (Ferrarin et al., 2012; Kinsella and Moran, 2008).

For each identified cluster of thorax/pelvis movement, the proportion of participants/ conditions belonging to each emulated muscle contracture (GAS, SOL, PSO, HAM and RF) and each degree of contracture severity was compared with Khi2 and post hoc. Secondly, groups identified with the clustering method were compared by a Kruskal-Wallis test with Bonferroni correction and post hoc. The variables used for the comparison were mean position and range of motion (ROM) over the gait cycle of thorax and pelvis in the three planes.

### 3.4.5 Results

#### *3.4.5.1 Kinematics clustering*

##### 3.4.5.1.1 Kinematic description

Four groups of thorax/pelvis movement were identified (Figure 27). The most important differences between groups were observed in the sagittal plane for pelvis and thorax tilt. Group 1 showed a mild increased pelvis anteversion with a mild thorax anterversion. Group 2 showed an important increase of pelvis anteversion with a mild thorax anteversion. Group 3 showed an important increase of thorax and pelvis anteversion. Group 4 showed an increased pelvis retroversion with a mild thorax anteversion.

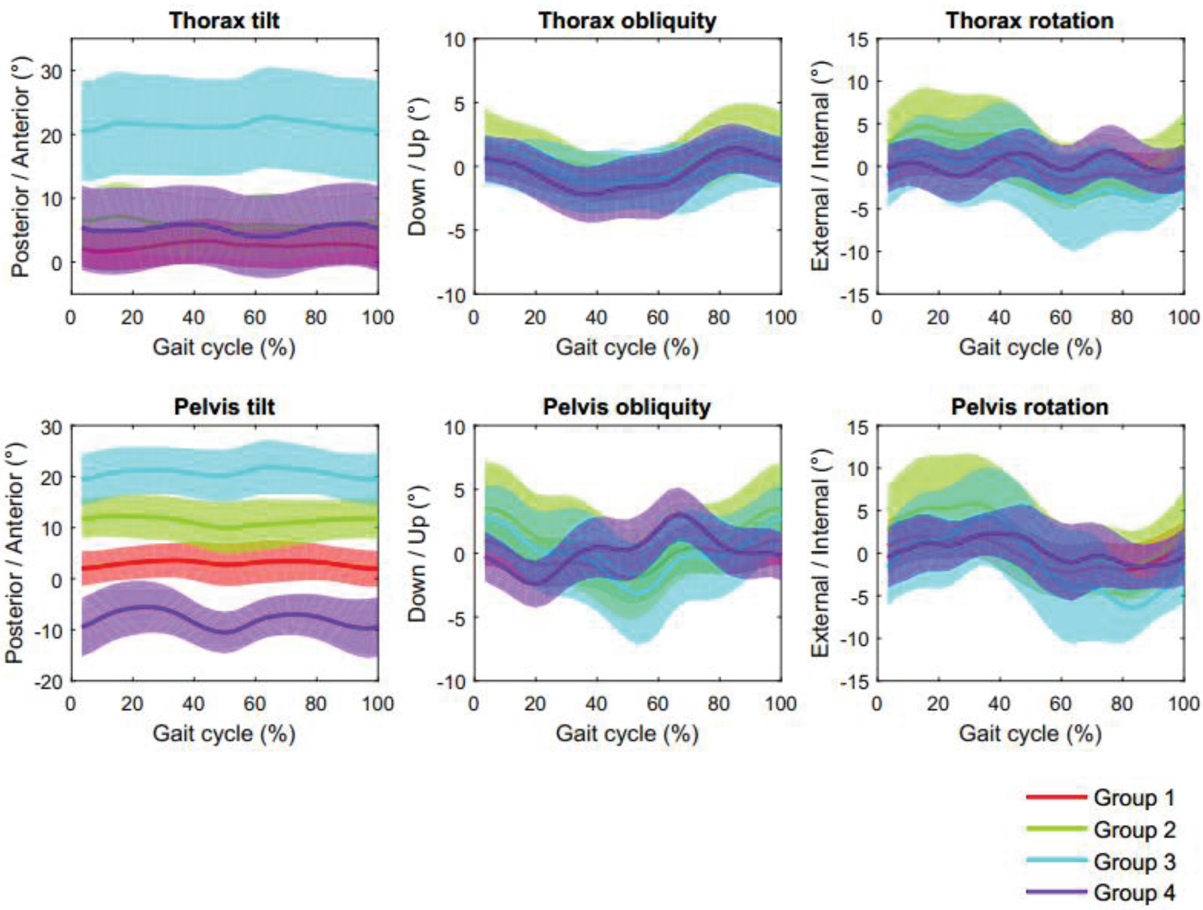


Figure 27 : Mean and standard deviation for the modified kinematics of pelvis and thorax in sagittal relative to control condition, coronal and transversal planes for the four groups identified with the clustering method.

### *3.4.5.2 Group characterization*

The Table 11 represents the difference in mean position and ROM for thorax and pelvis in the three planes per group with the significant differences between groups. The Table 12 shows the proportion of participants/conditions for each group according to emulated muscle contracture and severity of the contracture. As the distribution was not normal, statistical analysis to compare the groups was performed using Kruskal–Wallis tests and post hoc tests. As non-parametric tests were used, the median and inter-quartile ranges (IQR) were reported.

#### 3.4.5.2.1 Description per group

**Group 1** contained 62 % of all participants/conditions and contained mainly gastrocnemius and soleus emulated muscle contractures. In the sagittal plane, Group 1 showed a mild anteversion for mean position of thorax and pelvis but smaller than Group 2 and 3; a mild increased pelvis ROM was observed but smaller than Group 2 and 4. A mild increased thorax ROM was also observed but smaller than Group 2 and 3. In the coronal plane, mean position of thorax obliquity was reduced in Group 1 compared to other groups; ROM obliquity of thorax and pelvis was mildly decreased in Group 1 compared to other groups. In the transversal plane, Group 1 presented less thorax rotation than Group 2 for mean position, presented less pelvis rotation than Group 2 and 3 in mean position and presented less pelvis and thorax rotation than Group 2 and 3 in ROM.

**Group 2** was linked to an iliopsoas contracture and a rectus femoris contracture with a moderate severity. In the sagittal plane, Group 2 showed a thorax and pelvis anteversion in mean position less than Group 3 but more than Group 1 and 4. In the coronal plane, mean position of pelvis obliquity was increased in Group 2 compared to Group 1 and 4; Thorax and pelvis ROM obliquity was also increased compared to Group 1. In transversal plane, thorax and pelvis rotation in mean position was increased in Group 2 compared to Group 1 and 4; Thorax ROM rotation was increased compared to Group 1 and Pelvis ROM rotation was increased compared to Group 1 and 4.

**Group 3** contained also iliopsoas and rectus femoris contractures with a higher level of severity than Group 2. In the sagittal plane, Group 3 showed the most important anteversion in pelvis and thorax compared to other groups in mean position; Thorax ROM tilt was increased compared to Group 1 and pelvis ROM tilt was decreased compared to Group 4. In the coronal plane, thorax and pelvis obliquity was increased for mean position in Group 3 compared to Group 1; ROM obliquity was increased for thorax and pelvis compared to Group 1. In the transversal plane, pelvis rotation was increased for mean position in Group 3 compared to Group 1; ROM rotation was increased for thorax and pelvis compared to Group 1.

**Group 4** was entirely linked to hamstring contracture. In sagittal plane, it showed an increase in mean position of thorax anteversion compared to Group 1 and increased pelvis retroversion compared to other groups that are in anteversion; ROM tilt was increased for the pelvis compared to Group 1 and 3. In the coronal plane, thorax obliquity was increased for mean position compared to Group 1 and pelvis obliquity was decreased compared to Group 2; ROM obliquity was increased for thorax and pelvis compared to Group 1. In the transversal plane, thorax and pelvis obliquity were decreased for mean position compared to Group 2; ROM rotation was decreased for pelvis compared to Group 2.

**Table 11 : Median and interquartile of mean position for thorax and pelvis relative to control condition in the three planes per group with Post hoc comparisons of Kruskal-Wallis test between all the groups and control condition.**

| | G1 | | G2 | | G3 | | G4 | | Post hoc |
|---|---|---|---|---|---|---|---|---|---|
| | Med | *IQR* | Med | *IQR* | Med | *IQR* | Med | *IQR* | |
| *Mean position* | | | | | | | | | |
| Thorax tilt (°) | 2.1 | *3.3* | 5.5 | *6.8* | 18.8 | *10.7* | 4.7 | *6.7* | a;b;c;d;f |
| Thorax obliquity (°) | 0.6 | *0.9* | 0.9 | *1.4* | 1.1 | *1.5* | 1.2 | *1.3* | a;b;c |
| Thorax rotation (°) | 1.0 | *1.6* | 2.2 | *2.9* | 1.1 | *2.1* | 1.0 | *1.4* | a;e |
| Pelvis tilt (°) | 2.5 | *4.8* | 11.6 | *5.4* | 21.8 | *6.5* | -6.8 | *5.8* | a;b;c;d;e;f |
| Pelvis obliquity (°) | 0.7 | *1.3* | 1.6 | *2.8* | 1.7 | *2.5* | 0.7 | *1.3* | a;b;e |
| Pelvis rotation (°) | 1.0 | *1.5* | 2.1 | *3.4* | 1.6 | *1.5* | 1.3 | *1.6* | a;b;e |
| *ROM* | | | | | | | | | |
| Thorax tilt (°) | 3.1 | *2.1* | 4.3 | *3.8* | 4.1 | *3.4* | 3.8 | *2.5* | a;b |
| Thorax obliquity (°) | 3.2 | *2.1* | 4.7 | *2.5* | 4.5 | *2.8* | 4.4 | *2.5* | a;b;c |
| Thorax rotation (°) | 5.3 | *3.3* | 7.4 | *5.3* | 8.0 | *6.1* | 6.2 | *4.1* | a;b |
| Pelvis tilt (°) | 3.7 | *2.9* | 5.4 | *4.7* | 4.5 | *3.4* | 7.0 | *3.3* | a;c;f |
| Pelvis obliquity (°) | 4.2 | *2.5* | 6.7 | *3.6* | 7.2 | *4.6* | 5.9 | *2.3* | a;b;c |
| Pelvis rotation (°) | 6.9 | *4.3* | 10.6 | *6.9* | 11.4 | *8.8* | 7.8 | *5.4* | a;b;e |

**P < 0.005**
**a=G1-G2; b=G1-G3; c=G1-G4; d=G2-G3; e=G2-G4; f=G3-G4**
**G1=Group 1; G2=Group 2; G3=Group 3; G4=Group 4**
**Med= Median value; ROM=Range of motion; IQR= interquartile range**

**Table 12 : Proportion (%) of participants/conditions by group, by muscle emulated contracture and by degree of severity with a Khi2 test and pairwise comparison of proportions between groups (post hoc).**

| Contracture severity | G1 | G2 | G3 | G4 | Khi2 | G1/G2 | G1/G3 | G1/G4 | G2/G3 | G2/G4 | G3/G4 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Total (%)** | **62** | **18** | **10** | **10** | *p-value* | *p-value* | *p-value* | *p-value* | *p-value* | *p-value* | *p-value* |
| **Soleus (%)** | **84** | **14** | **2** | **0** | <0.001* | | | | | | |
| Mild (%) | *100* | *0* | *0* | *0* | | <0.001* | <0.001* | <0.001* | / | / | / |
| Moderate (%) | *79* | *18* | *4* | *0* | | <0.001* | <0.001* | <0.001* | 0.0646 | 0.0086* | 0.476 |
| Severe (%) | *90* | *10* | *0* | *0* | | <0.001* | <0.001* | <0.001* | 0.94 | 0.94 | / |
| Very severe (%) | *80* | *20* | *0* | *0* | | 0.002 | <0.001* | <0.001* | 0.228 | 0.228 | / |
| **Gastrocnemius (%)** | **94** | **5** | **1** | **0** | <0.001* | | | | | | |
| Mild (%) | *95* | *5* | *0* | *0* | | <0.001* | <0.001* | <0.001* | 1 | 1 | / |
| Moderate (%) | *95* | *5* | *0* | *0* | | <0.001* | <0.001* | <0.001* | 1 | 1 | / |
| Severe (%) | *95* | *5* | *0* | *0* | | <0.001* | <0.001* | <0.001* | 0.48 | 0.48 | / |
| Very severe (%) | *90* | *5* | *5* | *0* | | <0.001* | <0.001* | <0.001* | 1 | 1 | 1 |
| **Iliopsoas (%)** | **27** | **47** | **26** | **0** | <0.001* | | | | | | |
| Mild (%) | *45* | *55* | *0* | *0* | | 0.752 | 0.007* | 0.007* | 0.002* | 0.002* | / |
| Moderate (%) | *30* | *51* | *19* | *0* | | 0.096 | 0.259 | <0.001* | 0.004* | <0.001* | 0.008* |
| Severe (%) | *0* | *30* | *70* | *0* | | 0.08 | <0.001* | / | 0.008* | 0.008* | <0.001* |
| **Hamstring (%)** | **45** | **0** | **0** | **55** | <0.001* | | | | | | |
| Mild (%) | *70* | *0* | *0* | *30* | | <0.001* | <0.001* | 0.08 | / | 0.08 | 0.08 |
| Moderate (%) | *48* | *0* | *0* | *52* | | <0.001* | <0.001* | 0.085 | / | <0.001* | <0.001* |
| Severe (%) | *10* | *0* | *0* | *90* | | 0.94 | 0.94 | <0.001* | / | <0.001* | <0.001* |
| **Rectus femoris (%)** | **49** | **26** | **24** | **0** | <0.001* | | | | | | |
| Mild (%) | *95* | *5* | *0* | *0* | | <0.001* | <0.001* | <0.001* | 1 | 1 | / |
| Moderate (%) | *43* | *38* | *20* | *0* | | 0.7 | 0.043 | <0.001* | 0.12 | <0.001* | 0.006* |
| Severe (%) | *21* | *16* | *63* | *0* | | 1 | 0.086 | 0.338 | 0.039* | 0.458 | <0.001* |

***= p<0.01 (Bonferroni's correction) Significant differences**

### 3.4.6 Discussion

Compensatory upper body movement strategies related to lower limb contractures during gait were classified and characterized. Four clusters were identified based on thorax and pelvis movements. The main differences between the groups were observed in the sagittal plane for the mean position of the segments. Groups were related to emulated muscle contractures.

Group 1 showed a mild increase of pelvis anteversion and minimal impact on thorax motion. This group had a majority of triceps contracture (GAS and SOL). This result is in agreement confirmed by the study of Houx et al. (Houx et al., 2013) which showed a progressive increase of pelvis anteversion with the increase of equinus. Goodman et al. (Goodman et al., 2004) who imposed unilateral equinus constraint, found also an increased pelvis anteversion (17.2° (5.1) of pelvis anteversion angle).

Group 2 and 3 showed more important pelvis and thorax anteversion compared to Group 1 (more important for Group 3 than Group 2) and gathered a majority of contractures from the RF and PSO muscles but with different severities of contractures (Group 3 was related to more severe contractures than Group 2). In addition, these groups had the most increased pelvis range of motion for the rotation. Contractures of RF and PSO are frequent in CP patients (Rodda and Graham, 2001; Wren et al., 2005) and most CP patients walk with an increased pelvis anteversion (Attias et al., 2015; Heyrman et al., 2013; Romkes et al., 2007) compared to control participants. However, the results on CP patients are contradictory. Romkes et al. (Romkes et al., 2007) found an increased thorax anteversion(Romkes et al., 2007) whereas Heyrman et al. (Heyrman et al., 2013) reported an increased thorax retroversion. Our classification could explain the differences between these two studies, which may come from the different impairments. CP patients have heterogeneous gait patterns (Dobson et al., 2007) and many studies in CP are based on low sample size (<30) leading to gait analyses of patients with various characteristics (gross motor function classification system (GMFCS), age, clinical impairments). Therefore, in the outlook of our study, we can make the hypothesis that the thorax anteversion found by Romkes et al. (Romkes et al., 2007) could be linked to iliopsoas contracture (information not available in this study) whereas thorax retroversion found by Heyrman et al. (Heyrman et al., 2013) could be linked to hamstring contractures (information not available in this study). Concerning the increased pelvis range of motion for the rotation observed in Group 3, Romkes et al. and

Attias et al. (Attias et al., 2015; Romkes et al., 2007) have previously shown that CP patients use trunk ROM to help gait progression (Attias et al., 2015; Romkes et al., 2007). Heyrman et al. (Heyrman et al., 2013) suggested that this increased ROM of trunk during gait is an indicator of diminished dynamic stability. The increased trunk motion can enable to maintain feasible gait by contributing to forward movement (Gillet et al., 2003) and by diminishing the effect of lower limb impairments in order to preserve head stability (Kavanagh et al., 2006). Actually, this stability is needed to maintain the relevance of vestibular and visual information and to preserve balance (Pozzo et al., 1991).

Group 4 related to hamstring contractures showed the same trends (median (interquartile range) of increased pelvis retroversion: (-8.0° (4.7) of pelvis tilt mean position) as reported by Whitehead et al. (Whitehead et al., 2007). They showed that increased severity of hamstring contractures lead to an increased pelvis retroversion (mean (standard deviation)) -7°(6.52) of pelvis tilt mean position with a limitation of popliteal angle at 115°).

Studies on trunk deviations in pathological populations (CP, (Attias et al., 2015), Stroke (Van Criekinge et al., 2017)) combining a mixed of impairments (spasticity, muscle weakness, contractures) reported deviations in the frontal and transverse planes with an increase of trunk ROM compared to healthy subjects. In our study, thorax and pelvis ROM were increased in all groups with the most important increase for Group 2 and 3 especially for ROM of pelvis rotation. This could be related that the emulated contractures were mainly performed in the sagittal plane.

Several limitations can be pointed out in this study. Firstly, we have emulated contractures on healthy participants with an exoskeleton. This approach has limitations that were mentioned in a previous study (Attias et al., 2016a). Secondly, the clustering method is an objective and quantitative approach to determine gait clusters (Ferrarin et al., 2012; Rodda and Graham, 2001). However, several methods are available to compute the distance and to determine the number of clusters and can lead to different results. Thirdly, method used to remove the mean kinematics of a control condition to obtain an adjusted kinematics can be improved by recalculating the joint rotation matrices instead of subtracting the angles of the control condition. This ideal method was difficult to achieve through the full-body Plug-in-Gait model (Davis et al., 1991) and Gutierrez et al.'s model (Gutierrez et al., 2003a). However, we think the results will be similar.

#### 3.4.6.1 Conclusion

Clustering was used to identify groups according to pelvis and thorax movements associated with emulated muscle contractures during gait. Four clusters have been identified. The first Group is characterized by a quasi normal thorax motion and is associated mainly with soleus and gastrocnemius contractures. Second and third Groups showed an increased anteversion of the pelvis and the thorax as well as an increased pelvis ROM rotation. These groups are related to iliopsoas and rectus femoris contractures with different degrees of severities. Last group showed an increased pelvis retroversion related clearly to hamstring contracture. Our results support the fact that contracture can influence pelvis and thorax kinematics in different ways. Changes in thorax and pelvis kinematics depend on the location and the degree of contracture, and the relations pointed out between each other can help clinical interpretation of gait deviations.

# 4 Chapitre 4 : Discussion générale

L’objectif principal de ce travail était d’identifier les effets de rétractions isolées des principaux muscles des membres inférieurs sur la marche humaine. Pour répondre à cet objectif, nous avons réalisé une revue systématique de littérature qui a mis en évidence qu’isoler un déficit clinique permet de mieux étudier son impact sur la marche (Article 1). Suite à cette analyse, nous avons construit et évalué un exosquelette permettant d’émuler les principales rétractions musculo-tendineuses des membres inférieurs (Article 2). Puis à partir des résultats obtenus lors de nos campagnes expérimentales, nous avons identifié les comportements cinématiques des articulations de la cheville, du genou, de la hanche et des segments bassin et thorax lors de l’émulation de rétraction isolée. Ces résultats ont été présentés par article scientifique :

i) L’article 3, comparant les adaptations cinématiques à différents degrés de rétraction et entre les rétractions émulées de manière isolée et bilatérale des gastrocnemius et du soleus a montré que le déficit de ces muscles influencent la cinématique de marche et entrainent une augmentation du « Gait Profile Score » (GPS). La rétraction du soleus provoque une diminution plus importante de l’amplitude de mouvement à la cheville que le même niveau de rétraction des gastrocnemius. La rétraction des gastrocnemius induit une plus grande flexion de genou (pendant la phase d’appui) et de flexion de hanche (au cours du cycle de marche) que le même niveau de rétraction du soleus.

Ces résultats sont en accord avec l'anatomie (l’insertion proximale des muscles gastrocnemius se situe au-dessus de genou (muscle bi-articulaire) alors qu’elle est au-dessous du genou pour le muscle soleus (muscle mono-articulaire)). Une rétraction des gastrocnemius peut provoquer un pattern de marche genoux fléchis, alors qu'une rétraction du soleus limite la dorsiflexion avec de faibles modifications de la cinématique du genou. Ces résultats peuvent étayer l'interprétation des Analyses Quantifiées de la Marche en fournissant une meilleure compréhension de l'effet de la rétraction isolée du soleus et des gastrocnemius sur la cinématique articulaire.

ii) L’article 4 évaluant l'effet des rétractions des gastrocnemius et soleus sur les premier et second pivots pendant la marche a démontré que le premier et le second pivot sont complètement absents à partir de 10° de rétraction des fléchisseurs plantaires (soleus ou gastrocnemius). Une nette altération de la cinématique de cheville et un décalage important vers la flexion plantaire avec la perte des pivots ont été observés. Ces résultats suggèrent que la marche digitigrade n'est pas nécessairement due à un niveau de rétraction élevé et peut se produire avec une légère rétraction par un choix d'adaptation (à partir de 0° de limitation de flexion dorsale).

Ces résultats peuvent améliorer l'interprétation de l'Analyse Quantifiée de la Marche en montrant que le lien entre le niveau de rétraction des gastrocnemius / soleus et la progression de la marche digitigrade (augmentation de la flexion plantaire pendant la marche) n'est pas linéaire. Un changement de pattern peut apparaitre de manière brutale sans suivre de manière linéaire la progression du niveau de sévérité de la rétraction.

iii) L'article 5 comparant les effets des rétractions de différents muscles pouvant causer une marche « genoux fléchis » sur la cinématique a montré qu'en plus d'une flexion permanente de genou observée pour les 3 muscles rétractés (ilio-psoas, ischio-jambiers et gastrocnemius), la rétraction des ilio-psoas induit un important flexum de hanche avec une antéversion du bassin prononcée; la rétraction des ischio-jambiers induit une dorsiflexion de cheville durant la phase d'appui avec une rétroversion du bassin; la rétraction des gastrocnemius induit une absence de premier et deuxième pivot de la cheville avec un léger flexum de hanche et une légère antéversion du bassin. Sur la base de ces résultats, des tendances cinématiques ont été identifiées sur les muscles responsables d'un pattern particulier de marche «genoux fléchis». Une meilleure connaissance de ces patterns permet d'améliorer l'interprétation des analyses quantifiée de la marche en ciblant le muscle altéré par une rétraction et provoquant une marche genoux fléchis de manière plus précise et plus rapide.

iv) L'article 6 visant à classifier et caractériser les mouvements du tronc pendant la marche causée par les principales rétractions du membre inférieur a identifié quatre groupes de mouvements du tronc. Les différences les plus importantes entre les groupes ont été observées dans le plan sagittal pour l'inclinaison du bassin et du thorax. Le Groupe 1 présentait une légère antéversion du bassin et du thorax. Ce groupe avait une prévalence élevée de rétractions des gastrocnemius et soleus. Le Groupe 2 présentait une légère antéversion du thorax avec plus d'antéversion du bassin que le groupe 1, en relation avec des rétractions légères de l'ilio-psoas et du rectus femoris. Le Groupe 3 présentait la plus importante antéversion du thorax et du bassin en lien avec des rétractions importantes de l'ilio-psoas et du rectus femoris. Le Groupe 4 présentait une rétroversion importante du bassin avec une légère antéversion du thorax liée aux rétractions des ischio-jambiers.

Ces résultats montrent l'influence de différentes rétractions musculo-tendineuses sur les mouvements du tronc. En comparaison avec des patients atteints de paralysie cérébrale (PC) (Attias et al., 2015), il semble que les altérations des mouvements du tronc dues aux rétractations sont moins marquées que celles observées chez les patients PC. Aussi, pour mieux comprendre les mouvements altérés du tronc chez ces patients, il faudrait analyser également l'influence des faiblesses musculaires et de la spasticité ainsi que les combinaisons de tous ces déficits cliniques.

De manière générale, les 4 articles rédigés à partir de nos expérimentations mettent en évidence la complexité d'étudier la marche et ses altérations, essentiellement à cause des différentes compensations pouvant être mises en place par les patients. Néanmoins, les résultats obtenus permettent une meilleure compréhension des interactions primaires et secondaires (compensations) des rétractions musculo-tendineuses sur la cinématique de la marche.

## 4.1 Contribution clinique

Comprendre les mécanismes qui altèrent la marche ainsi qu'identifier les déficits moteurs sous-jacents est de première importance pour cibler, voire développer des stratégies de traitement efficaces. Cependant, le lien entre ces déficits moteurs évalués par un examen clinique et les altérations de la marche n'est pas évident et manque de preuves scientifiques (Aktas et al., 2000; Bonnefoy-Mazure et al., 2016; Desloovere et al., 2006; Domagalska et al., 2013). Le travail accompli pendant cette thèse a permis d'extraire des associations générales entre les rétractions musculo-tendineux et la cinématique de la marche, et a permis notamment d'identifier les répercussions directes et les compensations mises en place suite à une rétraction isolée.

Par ailleurs, ce travail met en évidence des pistes de réflexions pour expliquer le manque de corrélation entre ces déficits moteurs évalués par un examen clinique et les altérations de la marche :

i) les **modifications de la marche ne sont pas linéaires**. Le passage d'un pattern à un autre pattern peut apparaitre de manière brutale sans suivre forcément la progression linéaire du niveau de sévérité de la rétraction. L'article 4 démontre qu'une marche digitigrade n'est pas nécessairement due à une rétraction importante mais peut survenir même à de faibles rétractions par un choix d'adaptation.

ii) pour une même « configuration » de déficits moteurs, il existe **plusieurs possibilités de marche** dont le choix est propre aux participants/patients. Notamment, l'action des muscles multi-articulaires apporte une infinité d'adaptations possibles lors de la marche.

iii) En plus du choix d'adaptation, il existe une **variabilité intrinsèque de la mesure**. Cette variabilité est inhérente aux aptitudes neurologiques d'une personne, à sa santé métabolique et musculo-squelettique en lien avec les effets du vieillissement et les conditions pathologiques de chacun (Chau et al., 2005).

iv) Outre que les mécanismes internes à l'individu, la **variabilité des mesures** de la marche peut également découler de divers facteurs **externes** tels que l'environnement avec le type de surface de marche, le niveau d'éclairage ambiant. Ces facteurs ont une incidence sur la variabilité de la cadence, de la largeur des pas et de la réaction au sol (Chau et al., 2005). De plus, différentes chaussures (douces ou dures) peuvent affecter la variabilité des angles des articulations du genou et de la cheville, éventuellement en modifiant les entrées sensorielles périphériques (Chau et al., 2005; Kurz and Stergiou, 2003; Wolf et al., 2008). La variabilité peut également provenir de l'instrumentation utilisée pour les mesures de la marche ou de l'expérimentateur. Dans ces cas, la variabilité sera définie comme source d'erreur et est décrite dans la section « Limites de l'AQM » page 16 et dans l'article 2.

En ce qui concerne les interprétations des AQM, un livret synthétisant les courbes cinématiques obtenues pour chaque rétraction effectuée a été placé en Annexe II. Grâce à ce livret, les altérations cinématiques observées sur les courbes d'AQM d'un patient peuvent être liées aux muscles impliqués. Ceci apporte une aide précieuse à la compréhension des altérations de la marche et peut avoir une répercussion sur la prise de décision concernant le choix de traitements.

Les données obtenues dans le cadre de notre recherche permettent aussi à une autre équipe du laboratoire de travailler sur des techniques d'extraction de connaissances (machine learning) qui sont appliquées sur notre base de données pour extraire les caractéristiques de la marche pathologique liée à des rétractions musculaires. Ces connaissances seront ensuite utilisées pour créer un simulateur numérique permettant de visualiser les conséquences des rétractions sur la marche humaine. Une ébauche du projet du simulateur (Figure 28) peut être visualisée sur le lien suivant : [http://pgcs.unige.ch/](http://pgcs.unige.ch/)

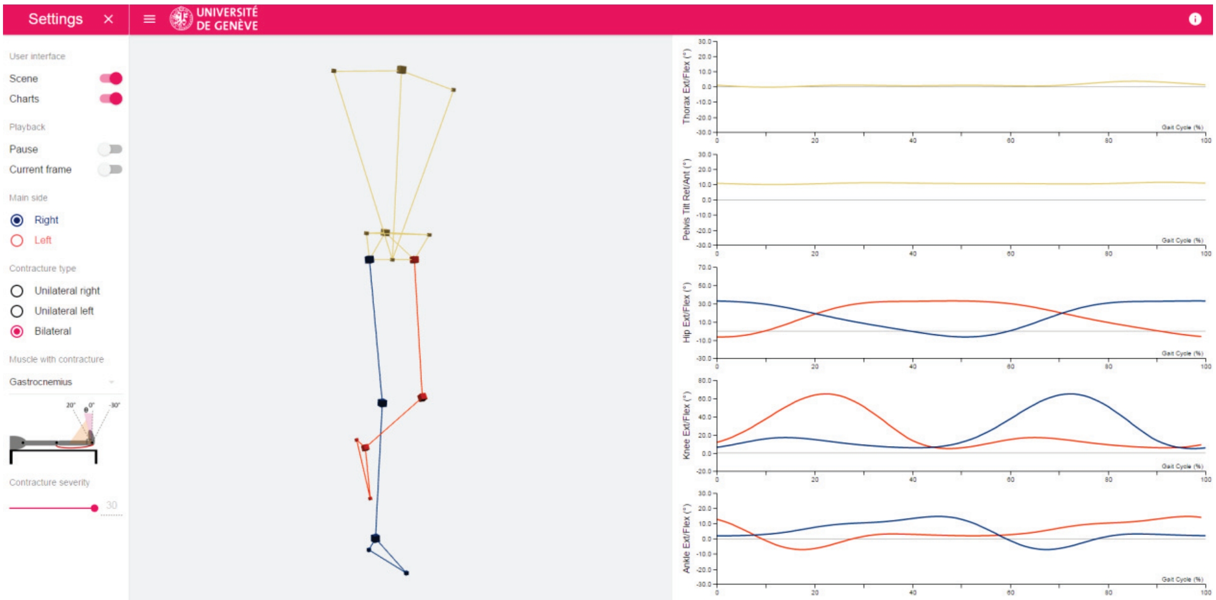


**Figure 28 : Simulateur de rétractions musculo-tendineuses durant la marche / Pathological Gait Contractures Simulator - (pgcs.unige.ch)**

## 4.2 Limitations de ce travail et compromis

Les limitations sont nombreuses et parfois des compromis ont dû être trouvés. Chaque article présenté dans cette thèse comporte ses propres limitations mais les principaux aspects sont repris ci-dessous.

i) **Isoler** un déficit ne représente que rarement la réalité. Les patients sont très souvent atteints de déficits associés aux rétractions musculaires tels que des faiblesses musculaires, de la spasticité, des défauts du contrôle moteur sélectif. C'est pourquoi il a été difficile de comparer la marche d'un patient atteint de rétraction musculo-tendineuse avec celle de la marche d'un participant équipé de l'exosquelette. Seule la rétraction du soleus pour laquelle il est possible de trouver quelques patients ayant uniquement cette atteinte a pu être évaluée dans la section « validation clinique de l'exosquelette pour émuler des rétractions » page 60.

ii) **Répliquer** une rétraction engendre une autre limite, celle de devoir prendre en considération uniquement la ligne d'action musculaire étant donné que les points d'attache musculaires peuvent être profonds et multiples (ex : l'ilio-psoas qui s'attache sur les 4 premières vertèbres lombaires).

Seules les caractéristiques mécaniques du système de corde permettant d'émuler les rétractions ont été analysées dans la partie « Création d'un dispositif pour répliquer des rétractions », page 41. Les caractéristiques passives du système en entier (exosquelette et cordes) n'ont pas pu être analysées. Cependant, les deux conditions à respecter pour cette émulation de rétraction était que les cordes ne devaient pas bloquer instantanément le mouvement et que le blocage devait être progressif avec une force de freinage augmentée à la fin de la rétraction. De multiples systèmes (différentes cordes, élastique, caoutchouc) ont été testés avant d'arriver au choix utilisé dans ce travail (Figure 29).

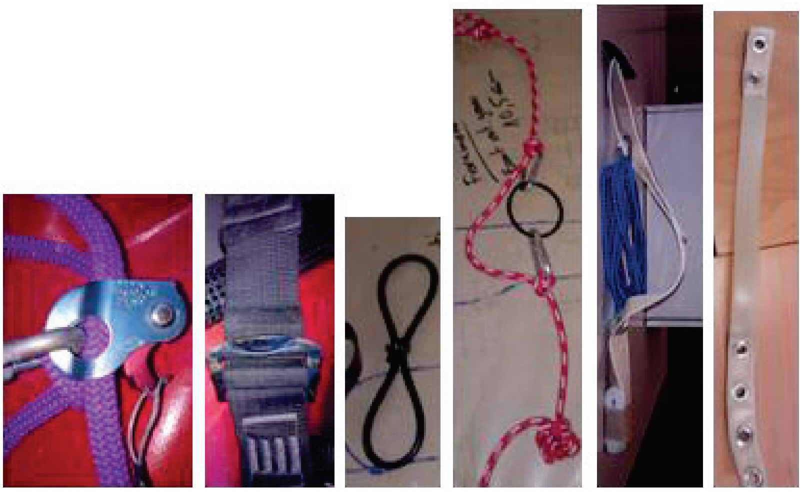

Figure 29 : Photos des différents systèmes (cordes, élastiques, caoutchouc), testés pour tenter d'émuler les rétractions.

iii) La **fiabilité de la mesure** par un goniomètre est relative comme discuté dans l'article 3 et montre des grandes variations selon l'articulation étudiée (Krause et al., 2011; Maas et al., 2015; van Trijffel et al., 2010). Cette fiabilité limitée de mesure peut être expliquée par la force relativement faible que produit l'évaluateur pour effectuer la mesure par rapport au moment de force exercé sur cette articulation lors de la marche (Maas et al., 2015).

De plus, les mesures des angles articulaires obtenues avec un appareil optoélectronique doivent être étudiées avec prudence car sources d'erreur peuvent altérer celles-ci. Ces sources sont décrites dans la discussion de l'article 2, page 58.

iv) **Le choix cinématique et le temps d'adaptation** peuvent jouer un rôle important dans les différentes stratégies de marche. Notre étude n'a analysé que des adaptations immédiates. Plusieurs adaptations de marche peuvent être utilisées par les participants lorsque des rétractions sont bi-articulaires. Par exemple, les gastrocnemius influencent aussi bien l'articulation de la cheville que celle du genou. Il existe une infinité de combinaisons possibles de stratégies d'adaptation. Avec une rétraction des gastrocnemius, un participant pourrait « choisir » de marcher avec uniquement une flexion plantaire de cheville sans adaptation au genou et un autre participant pourrait « choisir » de marcher avec uniquement une flexion de genou sans adaptation à la cheville. L'hypothèse émise à ce sujet est que les participants (probablement aussi valable pour les patients), tentent de trouver un compromis pour optimiser leur marche en préservant l'énergie (Selinger et al., 2015), l'équilibre (Romkes et al., 2007) et en améliorant l'efficience de la marche (Attias et al., 2015).

Les études réalisées au cours de cette thèse montrent différentes stratégies d'adaptation de marche pour des personnes « saines ». Il est évident que ces études prennent en compte uniquement l'aspect biomécanique et non les aspects neurologiques qui peuvent s'ajouter chez un patient. Ainsi l'émulation de pathologie sur des personnes « saines » se rapproche par l'expérimentation d'une condition pathologique sur l'humain mais néanmoins, de multiples biais sont encore présents.

v) **L'analyse de la cinétique et de l'EMG** aurait été intéressant car elle aurait permis de déterminer l'implication des forces musculaires en jeu le « timing » de l'activité musculaire. Cependant, elle n'a pas été réalisée dans cette étude. Lors d'un examen de marche, le calcul des données cinétiques nécessite que le participant/patient marche sur les plateformes de force et ne doit pas influencer sa marche en les visant. Etant donnée le nombre important de conditions de marche effectuées, attendre que le participant pose son pied correctement sur les plateformes, aurait demandé un temps trop important et induit une fatigue. L'exosquelette a été construit de telle manière qu'on puisse placer les marqueurs réfléchissants mais pas les capteurs EMG. Ainsi, seule l'analyse de la cinématique a été réalisée. En plus de ces paramètres, il aurait aussi été intéressant d'analyser la **dépense énergétique** des différentes conditions de rétraction.

vi) **La vitesse de marche** influence la marche et notamment la cinématique (Schwartz et al., 2008; Swinnen et al., 2013). En plus de la comparaison des différentes conditions à vitesse spontanée, une comparaison à une ou des vitesses similaires entre les conditions (imposées par l'expérimentateur) aurait permis de contrôler ce facteur confondant dans l'analyse. Cependant, il a été choisi de ne pas l'imposer et de garder une vitesse spontanée pour trois raisons. Premièrement, un patient se présentant à une AQM marche généralement à vitesse spontanée. Afin de suivre note méthodologie de réaliser les émulations de rétractions le plus fidèlement à la clinique, seule la vitesse spontanée a été analysée. Deuxièmement, certaines rétractions imposaient des contraintes importantes où il aurait été difficile pour les participants de suivre une vitesse de marche imposée. Troisièmement, afin de limiter les biais dû à la fatigue, nous avons choisi de privilégier le nombre de conditions de rétractions plutôt que celui de différentes vitesses de marche.

vii) Il aurait évidemment été souhaitable d'avoir un **plus grand nombre de participants**, et d'avoir testé **davantage de degrés de rétractions émulées**. L'une des principales limites à ces sujets concerne **la fatigue** due à aux réglages des rétractions (par exemple, le participant devrait se tenir sur une jambe et maintenir un équilibre précaire. De plus, à la marche avec exosquelette et rétractions émulées, certaines rétractions imposaient aux participants une marche genoux fléchis, ce qui entraine une forte contribution des quadriceps. Trop de fatigue musculaire due aux expérimentations avec de nombreuses conditions pourrait engendrer un changement de pattern de marche qui nuirait à la détection des modifications liées aux rétractions. A savoir que les expérimentations duraient entre 2,5 et 4 heures par participant. C'est pourquoi seule l'adaptation immédiate (2 minutes environ) a été prise en considération dans cette recherche. Il est vrai qu'une **adaptation longue** serait très intéressante à analyser pour être plus proche de la réalité. Le problème étant que porter l'exosquelette (tel qu'il a été construit) pendant une longue période serait très inconfortable.

## 4.3 Perspectives

i) La première perspective concerne la suite possible de ce travail en analysant **l'influence de rétractions d'autres muscles du membre inférieur** (peroneus, tibialis posterior, adducteurs de hanche et la combinaison de rétractions de plusieurs muscles du membre inférieur). Néanmoins, des limites supplémentaires se rajoutent pour l'étude de ces muscles car la ligne d'action musculaire est difficile à respecter. Le peroneus et le tibialis posterior ont un effet relativement faible sur l'amplitude de mouvement articulaire ce qui rend difficile la mise en place de la rétraction. Les adducteurs de hanche limitent aussi l'extension de hanche en plus de l'abduction de hanche ce qui complexifie l'interprétation et augmente la variabilité.

**L'analyse des combinaisons de rétractions** effectuées lors de la phase expérimentale (étape D), voire l'enrichissement de cette partie en émulant plus de combinaisons de rétractions pourra aussi être effectuée dans la suite de ce travail. L'étape D comportait 6 participants qui ont été évalués sur des combinaisons de rétractions. Celles-ci ont été réalisées par combinaisons de deux muscles parmi tous les muscles sélectionnés dans cette recherche. De plus, deux marches pathologiques déjà classifiées, la « jump knee » et la « crouch gait » (Rodda and Graham, 2001), ont aussi été induites à l'aide de l'exosquelette (Figure 30).

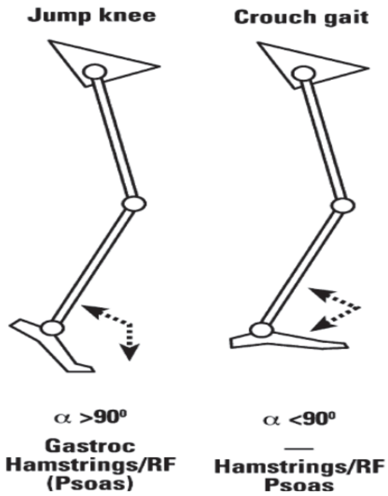


Figure 30 : Représentation des marches « jump knee » et « crouch gait » des patients diplégiques spastiques (Rodda and Graham, 2001).

Nous n'avons pas encore analysé en détails les résultats mais les courbes cinématiques obtenues pour ces deux marches pathologiques sont placées dans l'annexe II.

ii) La deuxième perspective, comme déjà stipulé, sera **l'utilisation des techniques d'extraction de connaissances** pour prédire les altérations de la marche à partir des déficits cliniques.

iii) La troisième perspective impliquerait **l'émulation d'autres déficits**, tels que la spasticité et la faiblesse musculaire. Ces études pourraient apporter une meilleure compréhension et améliorer notre connaissance sur la relation entre déficits cliniques et altérations de la marche. Grâce à une large base de données regroupant tous ces déficits, un simulateur de marche pathologique (déjà en création pour les rétractions musculaires) serait ainsi un outil très utile pour l'aide à la compréhension des troubles de la marche.

iv) La quatrième perspective serait de refaire des **expérimentations** avec **des données dynamiques** pour déterminer l'implication des forces musculaires en jeu, **avec l'EMG** afin d'avoir le « timing » de l'activité musculaire et avec un appareil permettant de mesurer les échanges gazeux dans le but d'évaluer la **dépense énergétique**. Ces éléments pourraient apporter des caractéristiques supplémentaires de ces marches pathologiques.

v) La cinquième perspective serait d'**utiliser l'exosquelette dans un but éducatif**. La mise en situation à la place du patient est utilisée pour faire ressentir aux professionnels de santé ce que vit et ressent le patient dans certaines conditions (Ryall et al., 2016). Elle permet de susciter la réflexion sur l'interaction soignant-patient, de mieux comprendre la pathologie avec pour conséquences d'être capable de mieux communiquer avec le patient et d'affiner le choix des traitements. De nombreuses mises en situation ont déjà été utilisées tel que le système « Age Man » (Nicole, 2015) pour émuler le processus de vieillissement. Il permet de prendre conscience des difficultés fonctionnelles et sensorielles que vivent des personnes âgées au quotidien. Un autre exemple d'étude utilise des lunettes modifiant la vision pour sensibiliser les étudiants en médecine à la difficulté de prise de médicaments causée par la déficience visuelle (Zagar and Baggarly, 2010). Une perspective de ce travail serait d'intégrer l'exosquelette MIkE dans le cursus de formation des métiers de la santé.

## 4.4 Conclusion générale

Cette approche développée pour étudier les altérations de marche en lien avec les rétractions musculo-tendineuses a permis d'obtenir des connaissances inédites dans le domaine. Cette évaluation de l'influence des **rétractions musculo-tendineuses** sur la marche humaine a été effectuée en 3 étapes: dans une première étape, une revue de la littérature décrivant les différentes approches permettant d'étudier les rétractions a montré que l'émulation de rétraction isolée pouvait être une approche intéressante pour comprendre l'influence des rétractions sur la marche ; la deuxième étape a consisté à concevoir et évaluer un exosquelette capable d'émuler de multiples rétractions unilatérales et bilatérales; la troisième et dernière étape était d'identifier les effets de rétractions isolées des principaux muscles des membres inférieurs sur la marche humaine.

Plusieurs altérations de la marche et stratégies de compensation liées aux rétractions de muscles du membre inférieur ont été observées grâce à l'utilisation d'un exosquelette. L'émulation des 8 principales rétractions musculaires des membres inférieurs (peroneus, tibialis posterior, soleus, gastrocnemius, rectus femoris, adducteurs de hanche, ischio-jambiers et ilio-psoas) a permis d'obtenir des preuves scientifiques sur les modifications de la cinématique 3D des articulations du corps humain utilisées durant la marche. Les principales connaissances acquises sur l'influence des rétractions durant la marche sont :

- La rétraction des gastrocnemius peut provoquer un pattern de marche genoux fléchis, alors qu'une rétraction du soleus montre peu de modifications de la cinématique du genou.
- Le lien entre la sévérité de rétraction des gastrocnemius / soleus et la progression de la marche digitigrade (augmentation de la flexion plantaire pendant la marche et perte des deux premiers pivots)) n'est pas linéaire.
- La marche «genoux fléchis» peut être causée par les rétractions des ilio-psoas, ischio-jambiers et gastrocnemius. Des patterns cinématiques particuliers ont été identifiées en lien avec les muscles responsables de la marche «genoux fléchis».
- Les rétractions du membre inférieur ont des effets importants spécifiques sur la position moyenne du tronc et du bassin dans le plan sagittal.

Par ce travail, nous espérons avoir contribué à améliorer la compréhension des altérations de la marche des patients atteints de rétractions musculo-tendineuses, ceci dans la perspective d’améliorer les choix thérapeutiques pour ces patients et ainsi leur qualité de vie.

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## 7.1 Annexe I

Contents lists available at ScienceDirect

Clinical Biomechanics

# Trunk movements during gait in cerebral palsy

Michael Attias [a,b], Alice Bonnefoy-Mazure [a,*], Mathieu Lempereur [d], Pierre Lascombes [c], Geraldo De Coulon [c], Stéphane Armand [a]

[a] Willy Taillard Laboratory of Kinesiology, Geneva University Hospitals, Geneva University, Switzerland
[b] School of Health, Geneva University of Applied Sciences Western Switzerland, Switzerland
[c] Pediatric Orthopaedic Service, Department of Child and Adolescent, Geneva University Hospitals, Geneva University, Geneva, Switzerland
[d] CHRU Brest, Hôpital Morvan, Service Médecine Physique et Réadaptation, Brest, France

a r t i c l e i n f o

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a b s t r a c t

*Background:* Lower limb deficits have been widely studied during gait in cerebral palsy, deficits in upper body have received little attention. The purpose of this research was to describe the characteristics of trunk movement of cerebral palsy children in terms of type of deficits (diplegia/hemiplegia) and gross motor function classification system (1, 2 or 3).

*Methods:* Data from 92 cerebral palsy children, which corresponds to 141 clinical gait analysis, were retrospectively selected. Kinematic parameters of trunk were extracted from thorax and spine angles in the sagittal, transverse and coronal planes. The range of motion and the mean positions over the gait cycle were analysed. Intra-group differences between the children with diplegia or hemiplegia, gross motor function classification systems 1 to 3 and typically developing participants were analysed with Kruskal–Wallis tests and post hoc tests. Pearson correlation coefficients between the gait profile score normalised walking speed and kinematic parameters of the thorax were assessed.

*Findings:* The results revealed: 1) the range of motion of the thorax and spine exhibited more significant differences between groups than the mean positions; 2) greater levels of impairment were associated with higher thorax range of motion, and 3) the children with diplegia and gross motor function classification system 3 exhibited a greater range of motion for all planes with the exception of spine rotation.

*Interpretation:* This study confirmed that greater levels of impairment in cerebral palsy are associated with greater thorax range of motion during gait. The thorax plays an important role during gait in cerebral palsy.


### 1. Introduction

Cerebral palsy (CP) is a non-progressive neurological disorder that results from brain damage caused before birth or during the first two or three years of life (Bax et al., 2005). CP is the most common cause of motor impairment in children in Europe with an incidence of two per 1000 births (Johnson, 2002; Sellier et al., 2010).

The motor disorders of individuals with CP are complex and are related to primary and secondary deficits (Aisen et al., 2011; Dabney et al., 1997; Davids et al., 1999; Goodman et al., 2004; Stebbins et al., 2010). The primary deficits include the following: muscle tone abnormalities (spasticity), and loss of selective motor control. Secondary deficits can include muscle weakness, muscle contractures and bony deformities. Based on this, each person with CP develops different motor skills related to their specific deficits (Beckung et al., 2008; Johnson et al., 1997; Molenaers et al., 2010; Narayanan, 2007).

* Corresponding author at: Willy Taillard Laboratory of Kinesiology, University Hospitals of Geneva, 4 Rue Gabrielle-Perret-Gentil, CH-1211 Geneva 14, Switzerland.
*E-mail address:* alice.bonnefoymazure@hcuge.ch (A. Bonnefoy-Mazure).

Walking is considered one of the most important motor skills in daily life. Due to the complexity of gait and, more specifically, pathological gait, clinical gait analysis (CGA) is generally used to understand the deficits specific to individual patients, this information is then used to inform and guide therapeutic decisions for that patient.

The literature surrounding gait deviations in CP is plentiful. However, most of these studies have focused on the lower extremities. Few studies have focused on the upper body during gait in CP (Heyrman et al., 2013; Heyrman et al., 2014; Romkes et al., 2007). During gait, the trunk, which is the heaviest segment of the body, provides the largest contribution to forward movement (Gillet et al., 2003) and is implicated in the control of locomotion (Cappozzo, 1983; Kavanagh et al., 2006). The trunk acts to decrease the effect of lower limb movements on the head and therefore serves to stabilise the head during walking (Kavanagh et al., 2006). This head stability is essential for the proper integration of vestibular and visual information needed in functions related to balance (Pozzo et al., 1991).

When the movement of the lower limbs is impaired, many activities of daily life can be performed using compensatory upper body movement strategies (Leardini et al., 2011). The repetition of these compensatory

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strategies over many years can lead to secondary musculoskeletal deficits (Jahnsen et al., 2004). Lower back pain is more common in adults with CP than in the general population and is often associated with gait disorders (Andersson and Mattsson, 2001; Jahnsen et al., 2004; Opheim et al., 2009). It seems evident that compensatory strategies and/or deficits that occur at the level of the trunk during pathological gait must be fully considered to understand gait alterations and to optimise treatment strategies (Goujon-Pillet et al., 2008; Romkes et al., 2007). The few studies that have examined trunk movements in CP children have reported larger movements of the trunk in CP compared to typically developing children (Heyrman et al., 2013; Heyrman et al., 2014; Romkes et al., 2007). However, these studies did not differentiate between types of CP (hemiplegia/diplegia) and were conducted using a small participant sample.

Therefore, to further understand the role of the trunk during gait in CP children, this study aimed to describe trunk movements in a large sample of CP children according to the type of CP (diplegia/hemiplegia) and the level of impairment (gross motor function classification system (GMFCS)).

## 2. Methods

### 2.1. Subjects

The database of the Willy Taillard Laboratory of Kinesiology was reviewed to retrospectively select CP children who had undergone CGA between 2005 and 2013. The inclusion criteria were as follows: (1) diplegia- or hemiplegia-type CP, (2) between five and 25 years of age, (3) able to walk 10 m without external aids (crutches, orthotics, walkers, etc.) and (4) had completed a full-body CGA. The exclusion criteria were as follows: (1) received surgery less than one year before the CGA and (2) received botulinum toxin injections less than six months before investigation.

### 2.2. Gait assessment

All children had undergone a complete CGA with a twelve-camera motion analysis system (Vicon Peak, Oxford, UK) along a 10-metre walkway. Some children had performed several CGAs and each CGA was considered independently. A minimum of three trials by CGA (corresponding to a minimum of five gait cycles) were averaged to produce a single angular displacement of the thorax, pelvis segments and hip, knee, and ankle joints. The children were equipped with 34 reflective markers that were aligned to anatomical landmarks on the head, trunk and pelvis and bilaterally on the arms, thighs, shanks and feet according to the full-body Plug-in-Gait model (Davis et al., 1991). The model of Gutierrez et al. (2003) was used to compute trunk kinematics.

### 2.3. Data analysis and statistics

#### 2.3.1. Selection and extraction of gait data

The kinematic parameters of the trunk were extracted from the thorax (trunk relative to the laboratory) and spine (trunk relative to the pelvis) angles in the sagittal (tilt), coronal (obliquity) and transverse (rotation) planes with MATLAB R2012b (MathWorks, Natick, Massachusetts, USA) and the open-source Biomechanical ToolKit package for MATLAB (Barre and Armand, 2014). The selected kinematic parameters for the thorax and the spine were the range of motions (RoMs) and mean positions over the gait cycle in the three planes. The absolute values of the mean positions were calculated for the transverse and coronal planes to account for differences in dependent sides. General gait characteristics were assessed in relation to normalised walking speed (based on the lengths of the legs of the children) (Bonnefoy-Mazure et al., 2013; Elsworth et al., 2006) and gait profile score (GPS) (Baker et al., 2009), which provided an indication of the kinematics data for the overall lower limb gait deviations as a single value. To analyse the data, several CP groups were defined according to the type of CP (diplegia/hemiplegia) and the level of impairment (GMFCS): diplegia with GMFCS 1 (D1), diplegia with GMFCS 2 (D2), diplegia with GMFCS 3 (D3), hemiplegia with GMFCS 1 (H1), and hemiplegia with GMFCS 2 (H2). In addition, these groups were compared with a group of children typically developed (TD). The data distribution was verified with a Shapiro–Wilk test. As the distribution was not normal, statistical analysis to compare the groups was performed using Kruskal–Wallis tests and post hoc tests. As non-parametric tests were used, the median and inter-quartile range (IQR) were reported. Pearson correlation coefficients were calculated between the GPS, normalised walking speed and kinematic parameters of the thorax to estimate the associations between the overall lower limb and upper body impairments during gait. Statistical analyses were performed using Statistica version 11 (StatSoft, Inc., USA). In order to control Type I error, the level of significance was set at 0.0045 (i.e., 0.05 divided by the number (11) of group's comparisons) according to the Bonferroni correction, however to reduce the risk of Type II error the results are presented with the corrected ($P = 0.0045$) and uncorrected ($P = 0.05$) significance levels.

## 3. Results

### 3.1. Population

The inclusion and exclusion criteria resulted in the inclusion of 92 CP children which corresponds to 141 CGA examinations in this study (CP children have performed between one and three CGA examinations). Each CGA examination was considered as an independent participant. This group was composed of 79 examinations of CP children with diplegia (median: 12.0 years (IQR 8.0)) and 62 examinations of CP children with hemiplegia (median: 10.0 years (IQR 5.8)). In terms of GMFCS, there were 101 examinations of CP children with a GMFCS 1, 32 with a GMFCS 2 and eight with a GMFCS 3. The age, height, weight and BMI of each subgroup are reported in Table 1, and no significant between-group differences were found in these parameters.

Twenty-two TD individuals (median: 11.0 years (IQR 3.0)) without problems or histories of neuro-musculo-skeletal disorders were recruited as a control group.

### 3.2. Overall gait parameters

Normalised walking speed (Table 2) was not significantly different between the hemiplegia and diplegia groups with the same impairment level (GMFCS) (e.g., D1/H1 and D2/H2). Some differences related to GMFCS were found. Lower GMFCS was associated with higher normalised walking speeds. The normalised walking speeds of the groups, listed from fastest to slowest, were as follows: H1 (1.6 m/s (IQR 0.4)); D1 (1.4 m/s (IQR 0.5)); D2 (1.3 m/s (IQR 0.4)); H2 (1.1 m/s (IQR 0.3)); and D3 (1.0 m/s (IQR 0.3)). TD (1.5 m/s (IQR 0.2)) was only significantly different (at the Bonferroni corrected significance level of $P$ b 0.0045) compared to D3 (1.0 m/s (IQR 0.3)).

Similar to the normalised walking speeds, the GPS (Table 2) was not significantly different between children with hemiplegia and diplegia with the same impairment levels (GMFCS). Some differences were found across the different GMFCS levels; higher GMFCS was associated with higher GPS. The GPSs for each group, listed from lowest to highest, were as follows: H1 (6.1° (IQR 2.3)); D1 (6.9° (IQR 1.7)); H2 (8.8° (IQR 1.4)); D2 (9.4° (IQR 3.7)); and D3 (9.8° (IQR 1.5)). TD (4.9° (IQR 1.3)) was significantly different between all groups.

### 3.3. Trunk movements

The thorax and spine kinematic data for the sagittal, coronal and transverse planes are described in Table 2. Most of the significant

Table 1
Median (inter quartile range) of each group describing population characteristics: diplegia with gross motor function classification system (GMFCS) 1 (D1); diplegia GMFCS 2 (D2); diplegia GMFCS 3 (D3); hemiplegia GMFCS 1 (H1); hemiplegia GMFCS 2 (H2) and of typically developing (TD). Body mass index (BMI).

| Population characteristics | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Diplegia developing | D1 (n = 46) | | D2 (n = 25) | | D3 (n = 8) | | Hemiplegia H1 (n = 55) | | H2 (n = 7) | | Typically TD (n = 22) | |
| Age (years) | 12.0 | (7.0) | 11.0 | (7.0) | 14.5 | (8.0) | 9.0 | (6.0) | 12.0 | (5.0) | 11.0 | (3.0) |
| Height (cm) | 153.5 | (31.0) | 145.0 | (31.0) | 151.0 | (24.0) | 139.0 | (29.3) | 153.5 | (46.0) | 146.3 | (23.6) |
| Weight (kg) | 39.0 | (29.0) | 33.0 | (26.0) | 44.0 | (19.8) | 34.0 | (28.0) | 56.0 | (46.0) | 38.4 | (15.7) |
| BMI (kg·m$^{-2}$) | 17.6 | (5.7) | 17.7 | (5.7) | 19.1 | (3.8) | 17.7 | (6.1) | 23.8 | (13.1) | 17.6 | (4.1) |

differences between groups were related to RoMs, and only one difference in mean position was found.

*3.3.1. Trunk movements of the children with diplegia*

The trunk movement of the children with diplegia was significantly different between groups at the Bonferroni corrected significance level (*P* b 0.0045): RoM of thorax obliquity was increased in D3 (25.4° (IQR 13.7)) and D2 (17° (IQR 7.9)) compared to D1 (7.7° (IQR 3.7)); and RoM of thorax rotation was higher in D3 (20.1° (IQR 10.5)) than in D1 (9.2° (IQR 4.1)). Most of the significant differences between children with diplegia and TD that involved the RoM of the thorax and spine included the following: thorax tilt and obliquity in D1, D2 and D3; thorax rotation in D2 and D3; spine tilt and obliquity in D1, D2 and D3, and mean position of spine tilt in D2.

Moreover, at *P* b 0.05 (without Bonferroni correction), RoM of thorax tilt was significantly higher in D2 (9.8° (IQR 4.9)) than in D1 (7.1° (IQR 2.7)). Spine obliquity exhibited a significantly greater RoM in D3 (31.1° (IQR 3.8)) than in D1 (15.7° (IQR 7.9)). The following differences were found in mean positions compared to TD: increased thorax tilt in D1 and increased rotation in D2; increased spine tilt in D1; and increased obliquity in D2 and D3.

*3.3.2. Trunk movements in the children with hemiplegia*

The trunk movement of children with hemiplegia compared to TD at the Bonferroni corrected significance level (*P* b 0.0045) showed: increased thorax tilt in H1; increased thorax rotation in H2; and increased spine tilt in H1 and H2.

Moreover, at *P* b 0.05 (without Bonferroni correction), RoM of thorax rotation was significantly higher in H2 (14.4° (IQR 2.3)) than in H1 (9.6° (IQR 3.5)). Significant differences between children with hemiplegia and the TD group appeared for RoM of the thorax and spine included the following: increased thorax tilt in H2; increased thorax obliquity in H1; and increased spine obliquity in H1.

Table 2
Median (inter quartile range) and *P*-value representation of trunk kinematic variables (range of motion (RoM) and mean position of thorax and spine) and overall gait parameters (gait profile score (GPS) and normalised walking speed (speed)) for six groups: diplegia with gross motor function classification system (GMFCS): diplegia GMFCS 1 (D1); diplegia GMFCS 2 (D2); diplegia GMFCS 3 (D3); hemiplegia GMFCS 1 (H1); hemiplegia GMFCS 2 (H2) and of typically developed (TD).

| Kruskal–Wallis test and post hoc | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Diplegia developed | | | | | | | Hemiplegia | | | | Typically | | *P*-values | |
| | D1 | | D2 | | D3 | | H1 | | H2 | | TD | | Post hoc comparison α = 0.05 | Post hoc comparison α = 0.0045 |
| *RoM* | | | | | | | | | | | | | | |
| Thorax | | | | | | | | | | | | | | |
| Tilt (°) | 7.1 | (2.7) | 9.8 | (4.9) | 11.2 | (5.3) | 7.8 | (3.2) | 7.6 | (2.4) | 4.8 | (1.7) | a; g; h; i; j; k | G; H; I; J |
| Obliquity (°) | 7.7 | (3.7) | 17.0 | (7.9) | 25.4 | (13.7) | 6.7 | (3.9) | 7.7 | (10.4) | 4.4 | (2.2) | a; b; g; h; i; j | A; B; G; H; I |
| Rotation (°) | 9.2 | (4.1) | 10.6 | (3.6) | 20.1 | (10.5) | 9.6 | (3.5) | 14.4 | (2.3) | 7.7 | (2.7) | b; f; h; i; k | B; H; I; K |
| Spine | | | | | | | | | | | | | | |
| Tilt (°) | 10.8 | (4.0) | 10.3 | (5.7) | 15.7 | (4.1) | 7.5 | (3.0) | 12.4 | (6.5) | 5.2 | (2.1) | c; g; h; i; j; k | C; G; H; I; J; K |
| Obliquity (°) | 15.6 | (5.2) | 21.0 | (7.2) | 31.1 | (3.8) | 16.1 | (5.4) | 13.0 | (8.7) | 12.0 | (3.4) | b; e; g; h; i; j | G; H; I |
| Rotation (°) | 15.7 | (7.9) | 12.9 | (5.3) | 16.7 | (5.9) | 14.4 | (7.7) | 17.2 | (10.2) | 12.5 | (4.9) | – | – |
| *Mean position* | | | | | | | | | | | | | | |
| Thorax | | | | | | | | | | | | | | |
| Tilt (°) | −1.9 | (5.4) | −1.9 | (7.9) | 4.1 | (9.3) | 0.4 | (6.9) | 6.8 | (9.0) | 3.0 | (6.1) | g | – |
| Obliquity – absolute value (°) | 2.1 | (1.6) | 1.9 | (1.7) | 3.0 | (1.6) | 1.8 | (1.6) | 3.7 | (2.5) | 1.5 | (2.1) | k | – |
| Rotation – absolute value (°) | 3.0 | (3.8) | 4.2 | (4.9) | 5.9 | (4.5) | 4.4 | (5.4) | 8.3 | (9.4) | 2.6 | (2.4) | h; j | – |
| Spine | | | | | | | | | | | | | | |
| Tilt (°) | −16.4 | (12.8) | −18.3 | (10.7) | −15.1 | (13.1) | −12.8 | (10.7) | −14.1 | (1.9) | −8.1 | (11.3) | g; h | H |
| Obliquity – absolute value (°) | 3.1 | (3.6) | 3.6 | (2.1) | 5.4 | (4.8) | 2.1 | (2.7) | 3.7 | (5.3) | 1.4 | (2.2) | h; i | – |
| Rotation – absolute value (°) | 2.8 | (2.5) | 2.7 | (3.9) | 2.5 | (3.7) | 2.5 | (3.0) | 3.1 | (3.3) | 2.1 | (2.5) | – | – |
| *Gait parameters* | | | | | | | | | | | | | | |
| Speed (m/s) | 1.4 | (0.5) | 1.3 | (0.4) | 1.0 | (0.3) | 1.6 | (0.4) | 1.1 | (0.3) | 1.5 | (0.2) | b; f; i | B; I |
| GPS (°) | 6.9 | (1.7) | 9.4 | (3.7) | 9.8 | (1.5) | 6.1 | (2.3) | 8.8 | (1.4) | 4.9 | (1.3) | a; b; f; g; h; i; j; k | C; G; H; I; J; K |

*P* b 0.05.
a = D1/D2; b = D1/D3; c = D1/H1; d = D2/D3; e = D2/H2; f = H1/H2; g = TD/D1; h = TD/D2; i = TD/D3; j = TD/H1; k = TD/H2.
*P* b 0.0045 (Bonferroni correction).
A = D1/D2; B = D1/D3; C = D1/H1; D = D2/D3; E = D2/H2; F = H1/H2; G = TD/D1; h = TD/D2; I = TD/D3; J = TD/H1; K = TD/H2.

### 3.3.3. Comparison of the trunk movements of the hemiplegia and diplegia groups

The comparisons between children with diplegia and hemiplegia with the same impairment levels (same GMFCS) revealed significant differences at the Bonferroni corrected significance level (*P* b 0.0045) in the RoM of spine tilt (H1 and D1, 7.5° (IQR 3.0) and 10.8° (IQR 4.0), respectively). Moreover, at *P* b 0.05 (without Bonferroni correction), the RoM of spine obliquity was lower in H2 (13.0° (IQR 8.7)) compared to D2 (21.0° (IQR 7.2)).

### 3.4. Correlations between overall gait parameters and thorax deviations

The Pearson correlations of the overall gait parameters and thorax deviations with normalised walking speed and GPS are shown in Table 3. The following variables were found to correlate with GPS (r N 0.40): the RoM of thorax tilt, obliquity and rotation. Significant moderate correlations were observed between GPS and mean positions (r between 0.21 and 0.30). Significant negative correlations were observed between normalised walking speed and the RoM of thorax obliquity and rotation (r: −0.32 and −0.22).

## 4. Discussion

The objective of this study was to determine the characteristics of thorax movements in a large sample of CP children in terms of the type of CP (i.e., diplegia or hemiplegia) and the level of impairment (i.e., GMFCSs 1, 2 and 3). At first, the results revealed that the patient group exhibited increased RoM of the thorax and spine compared with the TD controls. These results are in accordance with previous articles done in one smaller CP children (Heyrman et al., 2013; Romkes et al., 2007). In addition, results showed that these RoMs progressively increased with increasing impairment level (Heyrman et al., 2013) and a positive correlation (r N 0.40) was found between all of the RoMs and GPS. This increase in the RoMs of the thorax and spine can be a result of combination between the compensation of lower limb impairments and the presence of trunk control deficit. Indeed, Heyrman et al. (2014) provided first evidence that the presence of underlying trunk control deficit, measured in sitting position thank to their Trunk Control Measurement Scale, is due to altered trunk movement during gait in diplegia children. Moreover, different types of thorax compensations have been described in the literature. Perry and Burnfield (Perry and Burnfield, 2010) explained that "the phasic changes in thorax alignment recorded during walking represent postural adaptations to inadequate mobility or faulty muscle control at the hip, knee or ankle". Furthermore, Wagenaar and Beek (Wagenaar and Beek, 1992) described a decrease in counter-rotation between the thorax and pelvis in hemiplegic patients and a pelvic rotation that contributed to step lengthening. Hence, we hypothesise that the increased thorax and pelvis rotation is a mechanism to promote coordination of step length to support forward progression. Excessive thorax rotation could be caused by synergistic movement of pelvis and trunk (i.e., the trunk and pelvis move together rather than providing normal counterbalance by moving in opposite directions) (Perry and Burnfield, 2010).

Table 3
Correlation coefficient between gait profile score (GPS), normalised walking speed and thorax range of motion (RoM) and thorax mean position for the tilt, obliquity and rotation movements.

| Correlation with | GPS | Normalised walking speed |
|---|---|---|
| *RoM* | *r* | *r* |
| Thorax | | |
| Tilt | 0.47* | 0.05* |
| Obliquity | 0.55* | −0.32* |
| Rotation | 0.40* | −0.22* |
| *Mean position* | | |
| Thorax | | |
| Tilt | 0.11* | −0.11* |
| Obliquity − absolute value | 0.21* | −0.14* |
| Rotation − absolute value | 0.30* | −0.08* |

* Significant 'r'.

This counter-rotation is only necessary at a certain walking speed. It has previously been found in TD subjects that pelvis–trunk coordination evolves from in-phase coordination toward anti-phase coordination as walking velocity increases (Lamoth et al., 2002). Swinnen et al. (2013) reported decreases in the RoMs of the thorax and pelvis movements as walking speed decreases. Furthermore, children with hemiplegia exhibit significantly greater compensatory external rotation of the pelvis than children with diplegia (Saraph et al., 2002). Additionally, increased pelvis tilt range and pelvis retraction have been observed in children with hemiplegia (Salazar-Torres et al., 2011). The trunk compensates for lower limb alterations (Kavanagh et al., 2006; Perry and Burnfield, 2010) to maintain head stability (Heyrman et al., 2013; Kavanagh et al., 2006) needed to preserve the vestibular system (Pozzo et al., 1991). Heyrman et al.( 2013) found that children with diplegia exhibit an absence of counter rotation of the trunk and head in relation to the pelvis that results in a "bloc pattern" in these segments.

We observed the same tendency in the GMFCSs 1 and 2 children regarding the pelvis and trunk, but the results were not significant. A "bloc pattern" can be observed when the spine movement (trunk/pelvis) is lower than the thorax movement (trunk/laboratory). Heyrman et al. (2013) reported that children with diplegia exhibit an increased thorax lateral bending sway. We showed that children with diplegia exhibited increases in the RoM of thorax obliquity with increases in the level of impairment. This strategy could support forward progression. Children with hemiplegia use the RoM of the thorax rotation for forward progression, particularly as the impairment level increases.

Secondly, results showed several significant differences in the mean positions of the thorax and spine between the entire patient group and the TD controls and only one difference between the patient subgroups. The mean position of the thorax was moderately correlated with GPS and with normalised walking speed. The mean positions of the trunk were not discriminative between the levels of impairment or the type of CP. Only one significant difference in spine tilt mean position was found between the D2 and H1 groups. Given that there was no significant difference in the thorax, this difference may be attributable to the mean position of the pelvis in the sagittal plane. Similar results were reported by Heyrman et al. (2013).

Abnormal movements of the trunk and pelvis may result from spine deformations and cause back pain that affects balance and functional skills (Tsirikos, 2010). Furthermore, spine deformations are common in children and adolescents with CP. Some studies have reported occasional associations between some scoliosis deformations and hyperkyphosis (Tsirikos, 2010), and hyperlordosis is related to pelvic anteversion (Johnson et al., 2004). Increases in the RoM of the thorax likely result in the appearance of deformations and pain in the spine. In this study, children with hemiplegia (GMFCSs 1 and 2) exhibited less lumbar curvature (lumbar hyperlordosis) than did children with diplegia (GMFCSs 1, 2, 3) as estimated by spine angles; we suggest that these children are therefore at a reduced risk of hyperlordosis. Thorax and spine obliquity RoMs increased with impairment level (i.e., GMFCS increased mainly in the children with diplegia). A large RoM of pelvis obliquity can lead to the development of scoliosis (Comstock et al., 1998; Tsirikos, 2010). Hence, based on our results and those of previous studies, we hypothesise that children with diplegia are at a greater risk of developing back deformities, particularly when the level of impairment is high.

The first limitation of this study is that the trunk was considered to be a single rigid segment based on the markers placed in the clavicle, sternum, the C7 cervical vertebra and the T10 thoracic vertebra, however the trunk is comprised of several mobile parts. To simplify the analysis, the assumption that the trunk is a rigid segment is generally used for CGA (Armand et al., 2014). The second limitation concerned walking speed, which varied across subjects and that walking speed influences thorax movements (Bruijn et al., 2008; Swinnen et al., 2013). In normal walking, trunk movement increases and pelvis-trunk coordination evolves from in-phase coordination toward anti-phase coordination as walking velocity increases (Lamoth et al., 2002). Therefore the different walking speeds of the CP children can influence thorax kinematics and hide the differences between CP groups for the trunk movements. Our re- sults indicate that CP children have a trend to increase thorax rotation whilst walking speed decreases. However, it was difficult to ask to chil- dren with differing gait impairment severities to walk at several walking speeds that are comparable across the groups (Swinnen et al., 2013).

## 1. Conclusion

This study of a large database of CP children revealed that the RoM of the trunk increased compared to TD and increased with the level of impairment in children with diplegia. More specifically, the movement of the children with diplegia was better characterised by a higher RoM of trunk obliquity than the movement of the children with hemiplegia. Thus, the thorax plays an important role during gait in CP children, and clinicians should consider this role when making therapeutic deci- sions. Future studies are needed to identify the specific movements/ strategies for the lower limbs and upper body that lead to trunk alter- ations to optimise treatment strategies.

## 2. Conflict of interest

There are no conflicts of interest associated with this research.

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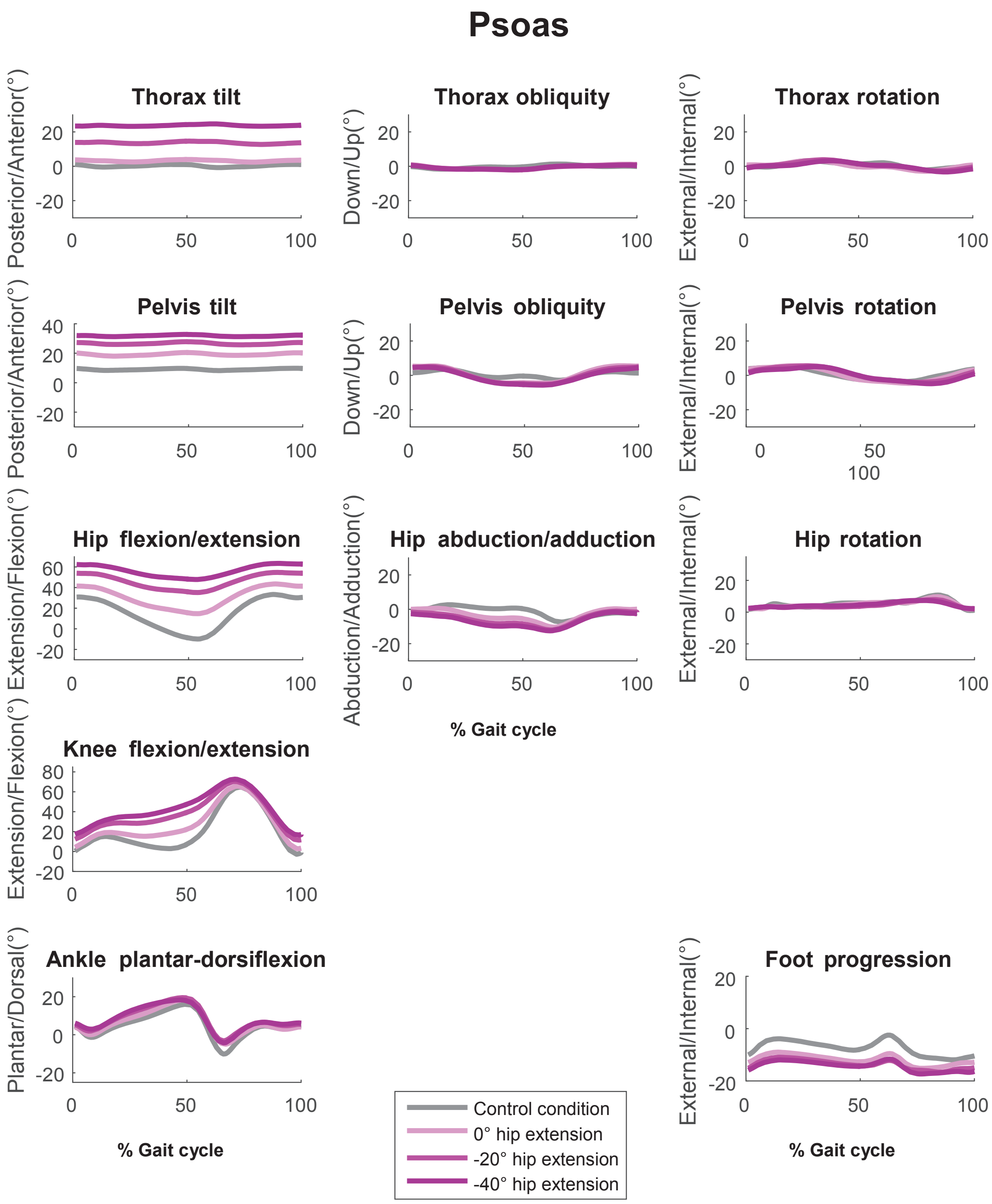
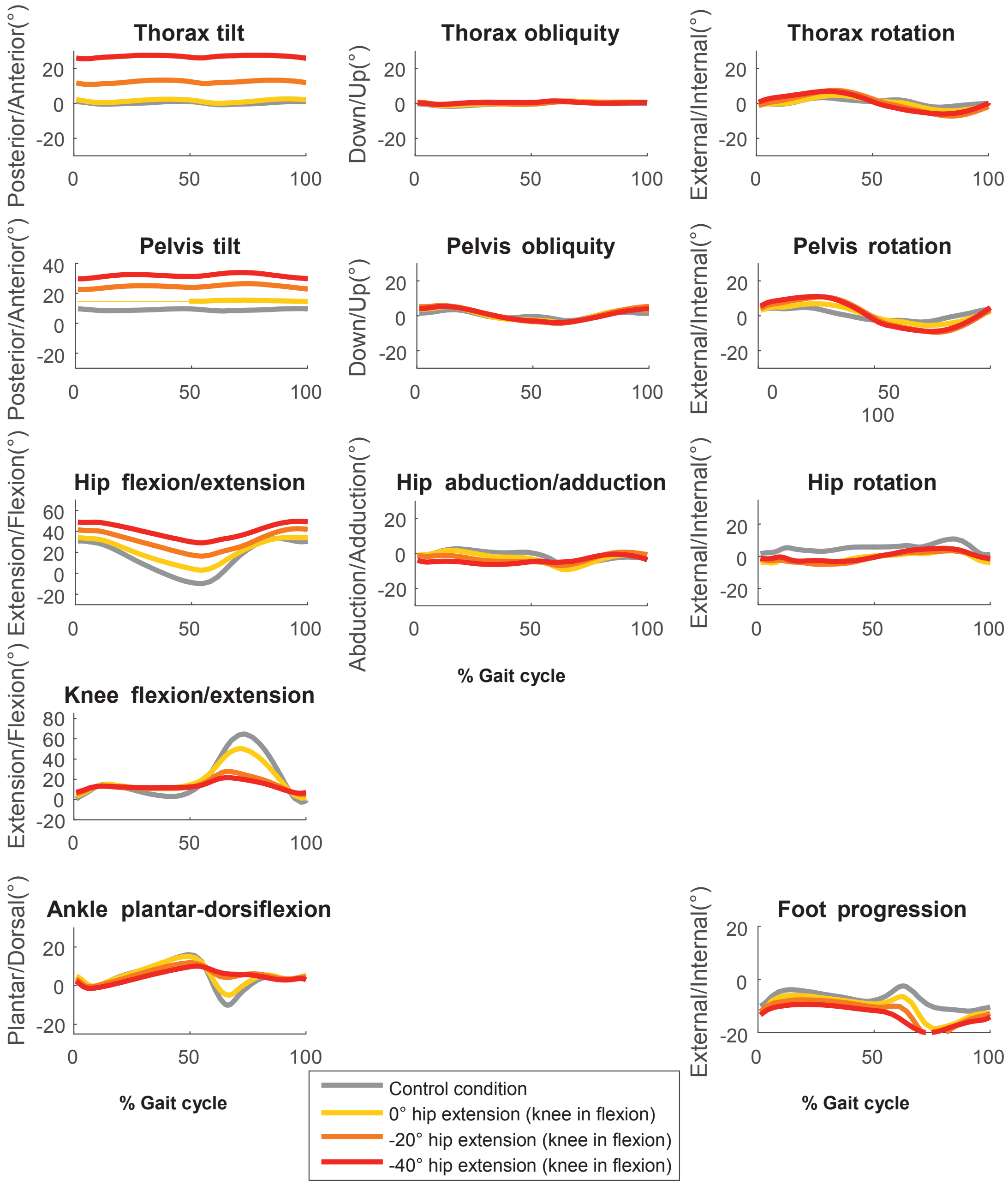
## 7.2 Annexe II

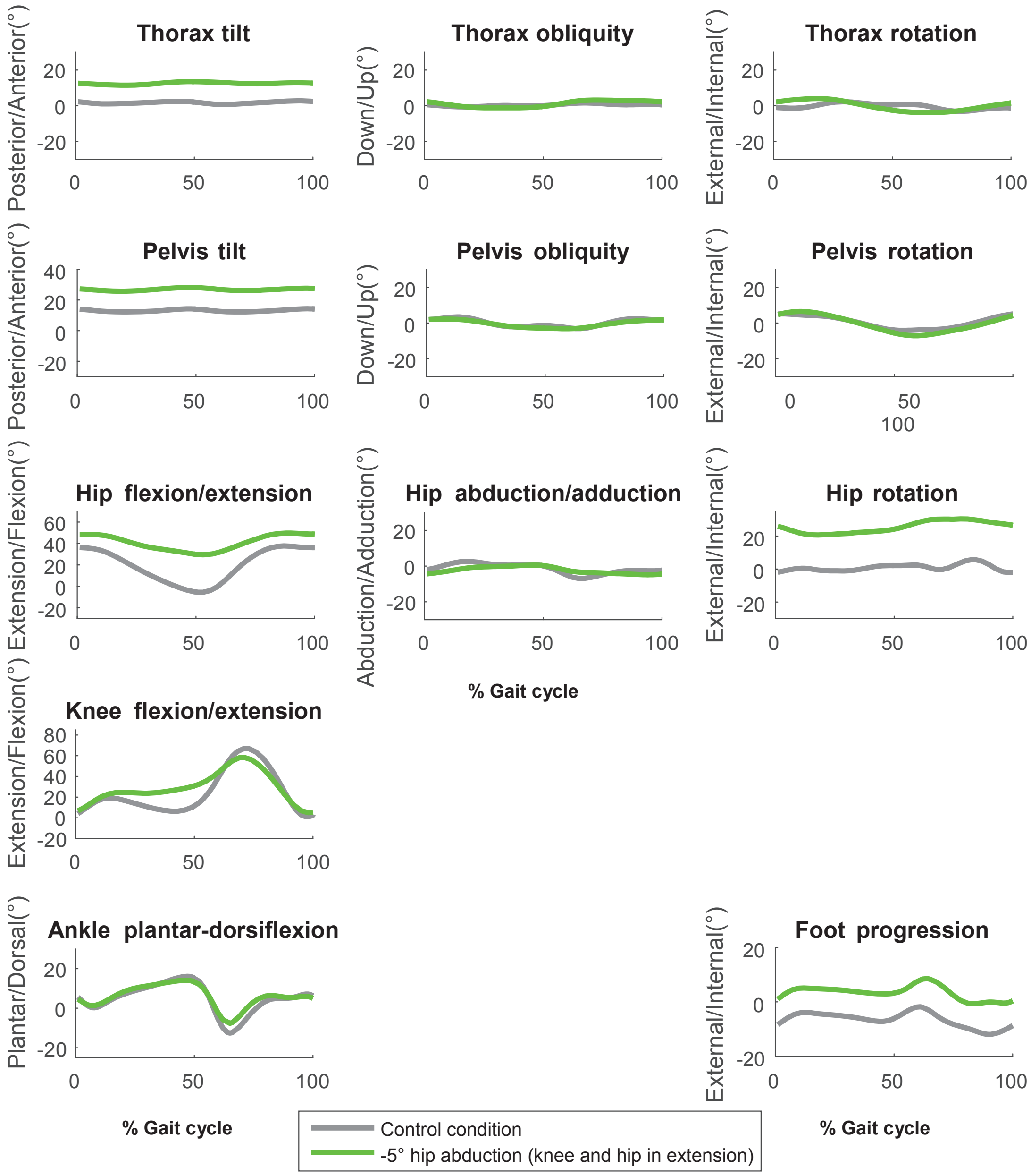


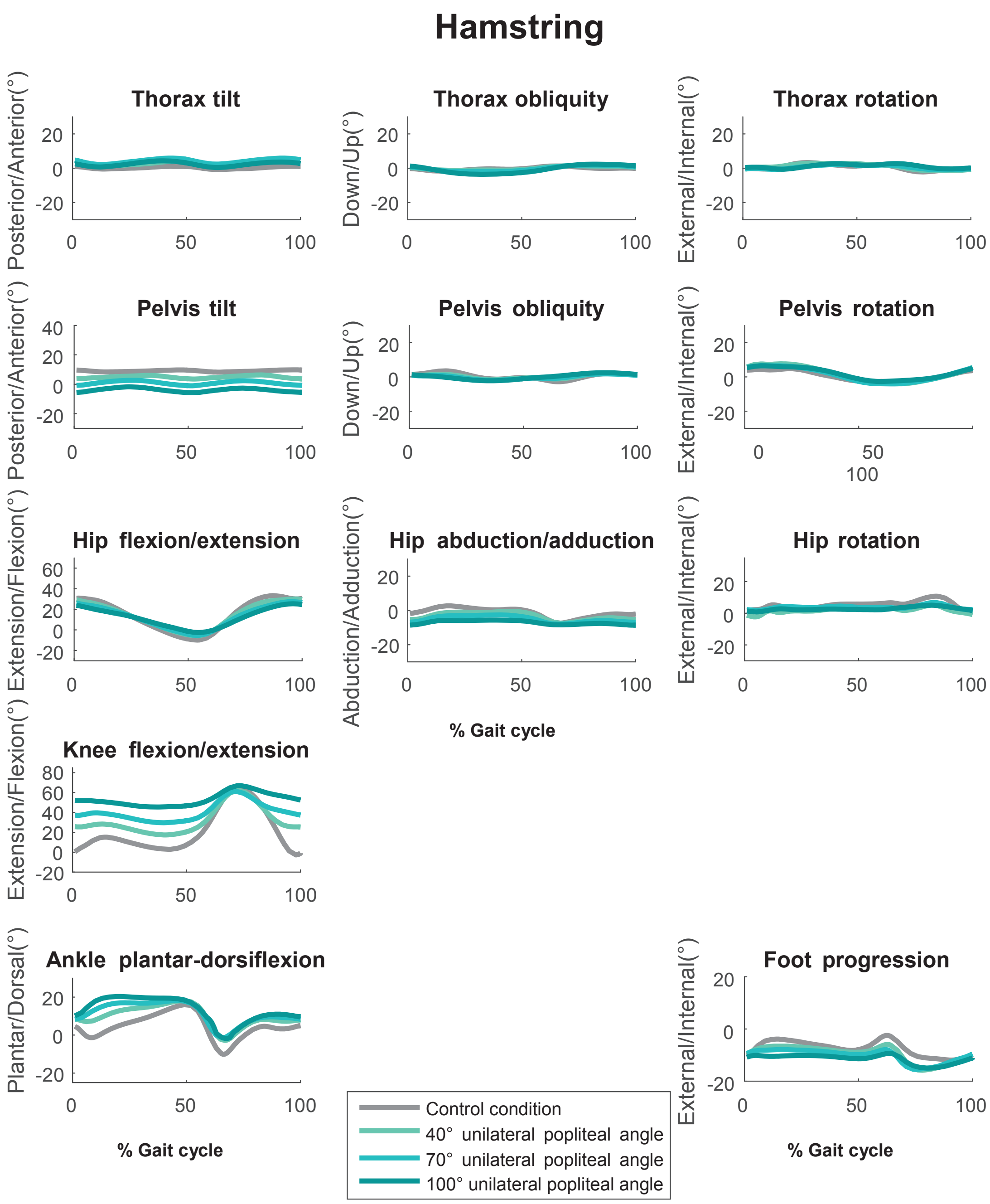
Psoas
Thorax tilt
Posterior/Anterior(°)
Thorax obliquity
Down/Up(°)
Thorax rotation
External/Internal(°)
Pelvis tilt
Posterior/Anterior(°)
Pelvis obliquity
Down/Up(°)
Pelvis rotation
External/Internal(°)
Hip flexion/extension
Extension/Flexion(°)
Hip abduction/adduction
Abduction/Adduction(°)
Hip rotation
External/Internal(°)
% Gait cycle
Knee flexion/extension
Extension/Flexion(°)
Ankle plantar-dorsiflexion
Plantar/Dorsal(°)
% Gait cycle
Control condition
0° hip extension
-20° hip extension
-40° hip extension
Foot progression
External/Internal(°)
% Gait cycle

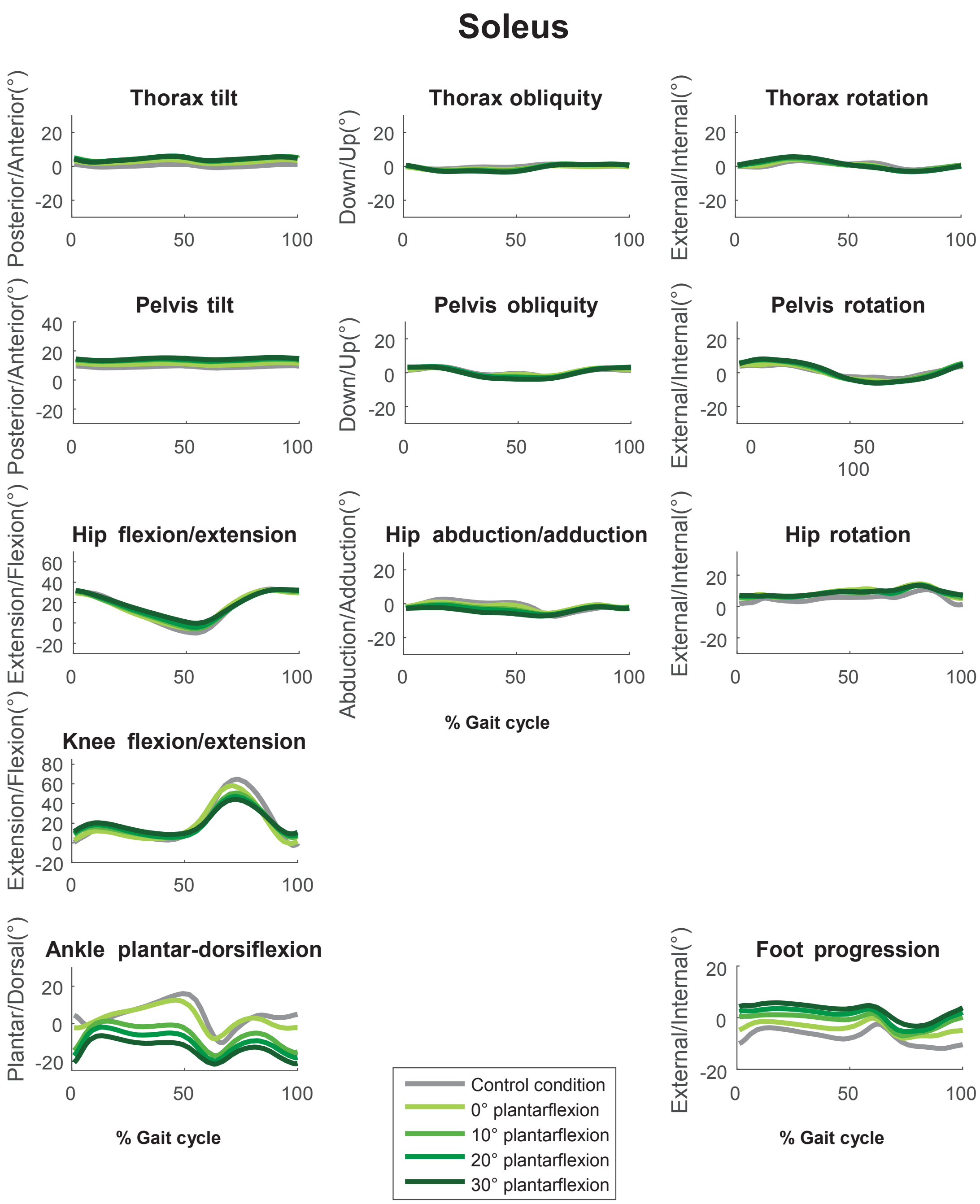
# Rectus Femoris

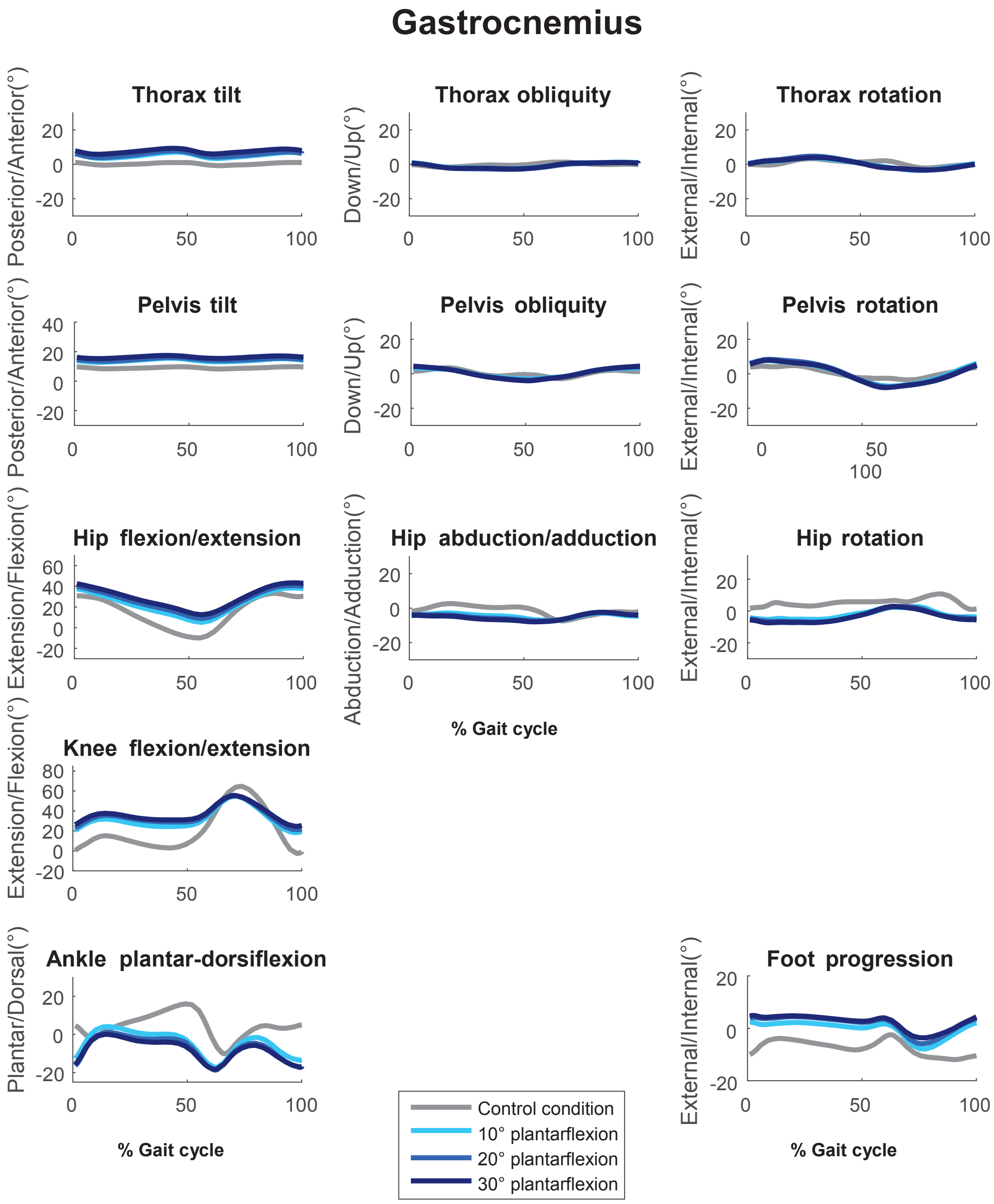


# Hip adductor

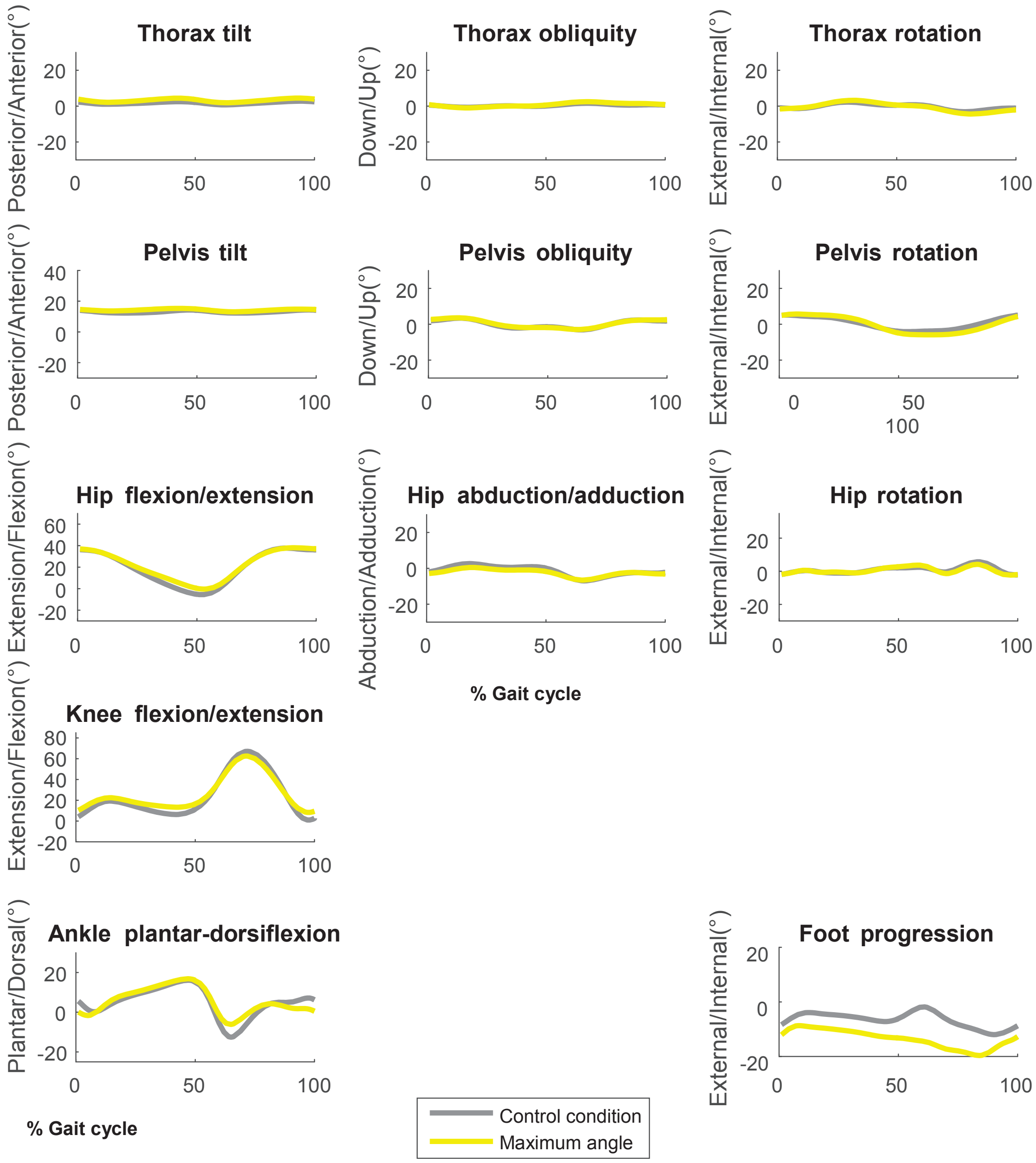



Hamstring
Thorax tilt
Posterior/Anterior(°)
Thorax obliquity
Down/Up(°)
Thorax rotation
External/Internal(°)
Pelvis tilt
Posterior/Anterior(°)
Pelvis obliquity
Down/Up(°)
Pelvis rotation
External/Internal(°)
Hip flexion/extension
Extension/Flexion(°)
Hip abduction/adduction
Abduction/Adduction(°)
Hip rotation
External/Internal(°)
% Gait cycle
Knee flexion/extension
Extension/Flexion(°)
Ankle plantar-dorsiflexion
Plantar/Dorsal(°)
% Gait cycle
Control condition
40° unilateral popliteal angle
70° unilateral popliteal angle
100° unilateral popliteal angle
Foot progression
External/Internal(°)
% Gait cycle

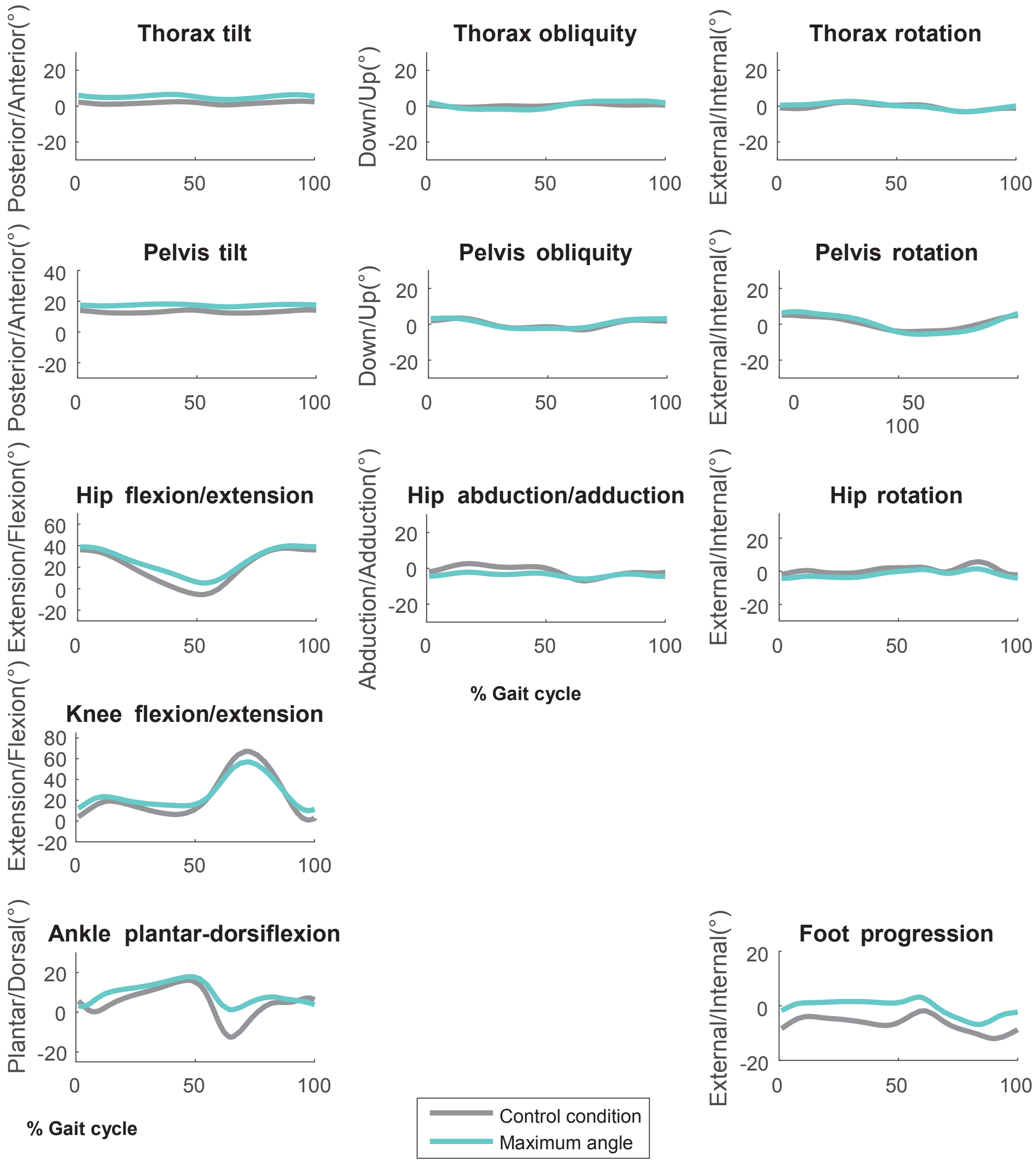

Soleus
Thorax tilt
Thorax obliquity
Thorax rotation
Pelvis tilt
Pelvis obliquity
Pelvis rotation
Hip flexion/extension
Hip abduction/adduction
Hip rotation
Knee flexion/extension
Ankle plantar-dorsiflexion
Foot progression
Posterior/Anterior(°)
Down/Up(°)
External/Internal(°)
Extension/Flexion(°)
Abduction/Adduction(°)
Plantar/Dorsal(°)
% Gait cycle
Control condition
0° plantarflexion
10° plantarflexion
20° plantarflexion
30° plantarflexion

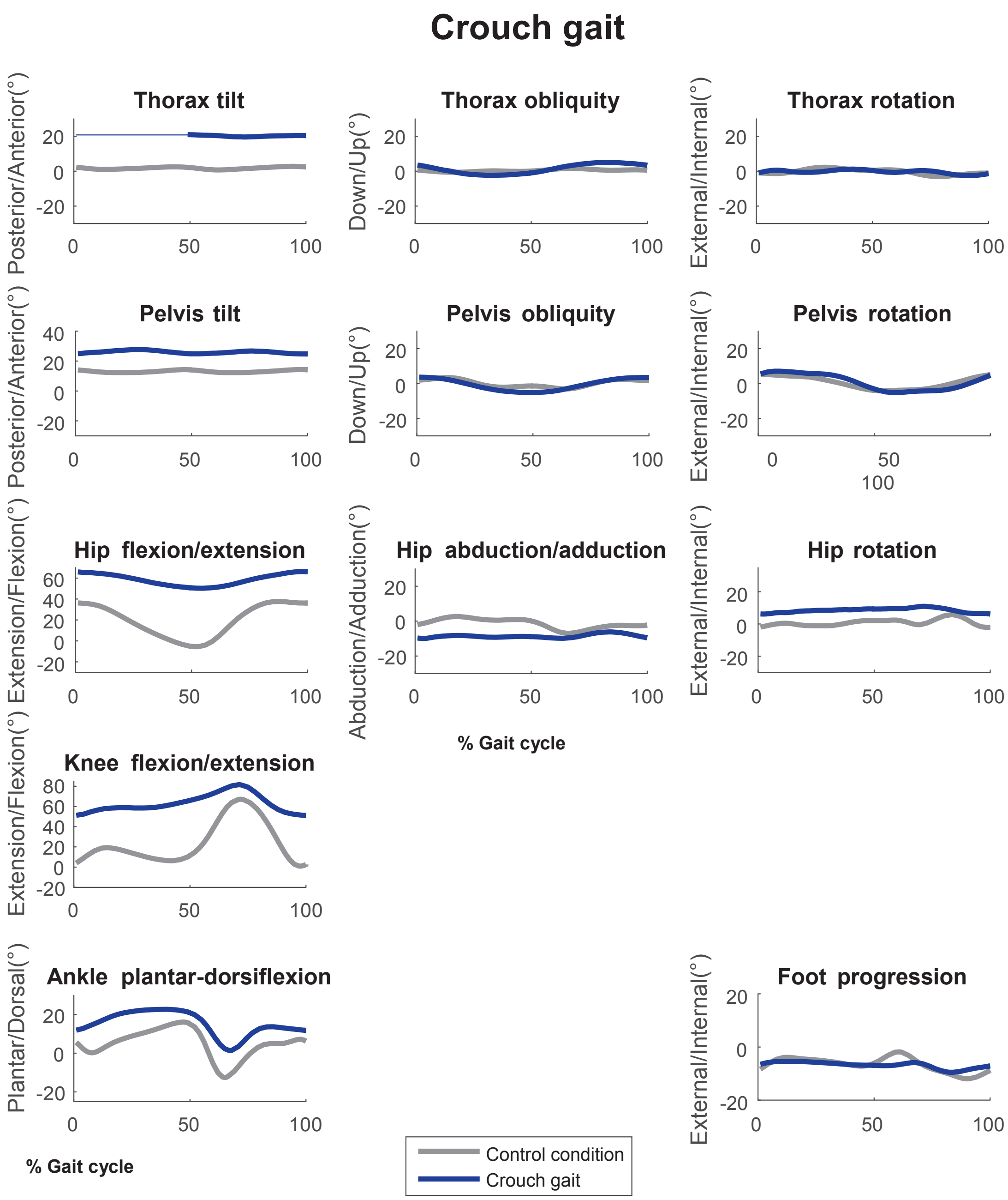

Gastrocnemius
Thorax tilt
Posterior/Anterior(°)
Thorax obliquity
Down/Up(°)
Thorax rotation
External/Internal(°)
Pelvis tilt
Pelvis obliquity
Pelvis rotation
Hip flexion/extension
Extension/Flexion(°)
Hip abduction/adduction
Abduction/Adduction(°)
Hip rotation
Knee flexion/extension
Ankle plantar-dorsiflexion
Plantar/Dorsal(°)
Foot progression
% Gait cycle
Control condition
10° plantarflexion
20° plantarflexion
30° plantarflexion

## Peroneus

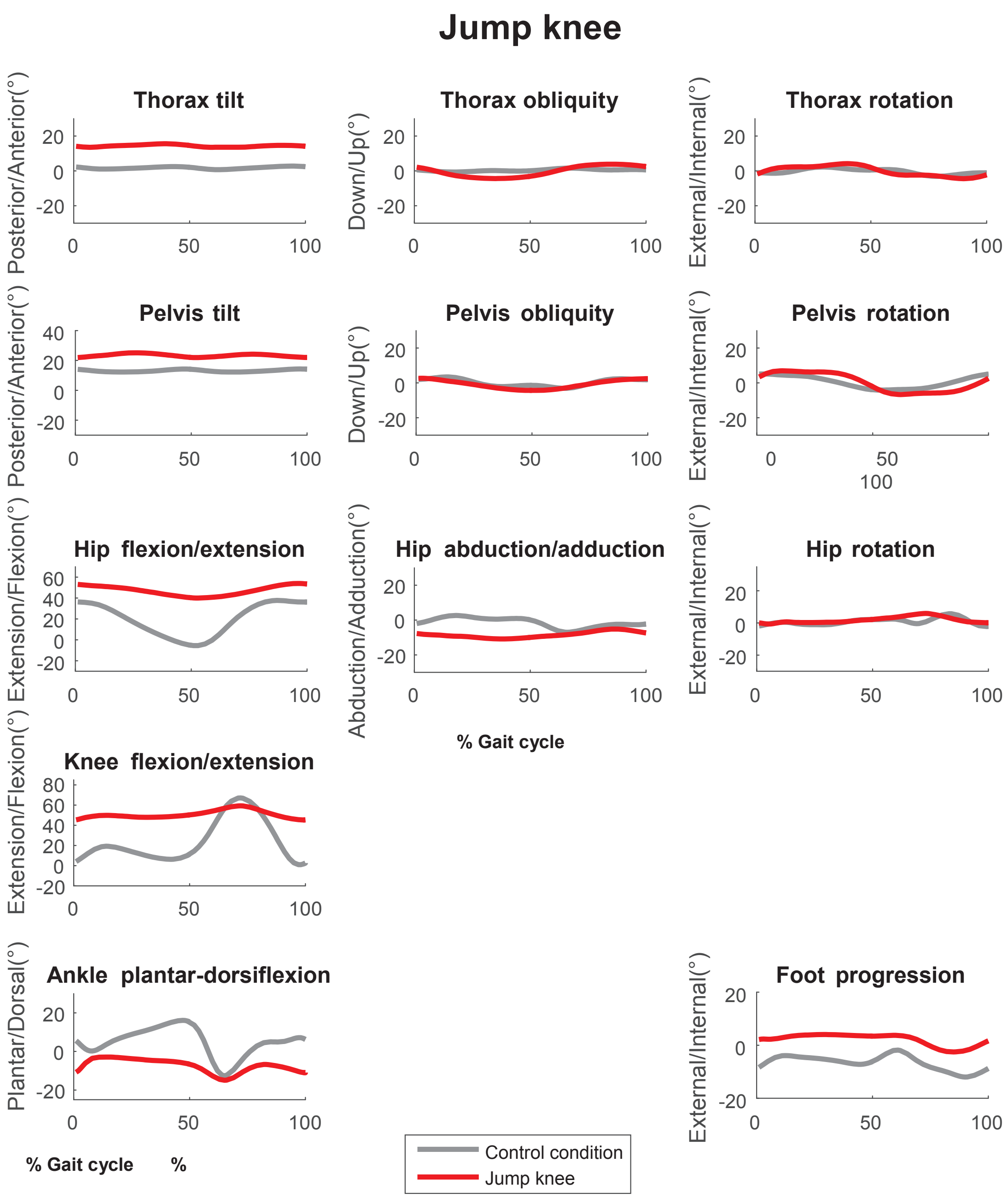

Thorax tilt
Posterior/Anterior(°)
Thorax obliquity
Down/Up(°)
Thorax rotation
External/Internal(°)
Pelvis tilt
Posterior/Anterior(°)
Pelvis obliquity
Down/Up(°)
Pelvis rotation
External/Internal(°)
Hip flexion/extension
Extension/Flexion(°)
Hip abduction/adduction
Abduction/Adduction(°)
Hip rotation
External/Internal(°)
% Gait cycle
Knee flexion/extension
Extension/Flexion(°)
Ankle plantar-dorsiflexion
Plantar/Dorsal(°)
% Gait cycle
Foot progression
External/Internal(°)
Control condition
Maximum angle

# Tibialis posterior





Crouch gait
Thorax tilt
Thorax obliquity
Thorax rotation
Pelvis tilt
Pelvis obliquity
Pelvis rotation
Hip flexion/extension
Hip abduction/adduction
Hip rotation
Knee flexion/extension
Ankle plantar-dorsiflexion
Foot progression
Posterior/Anterior(°)
Down/Up(°)
External/Internal(°)
Extension/Flexion(°)
Abduction/Adduction(°)
Plantar/Dorsal(°)
% Gait cycle
Control condition
Crouch gait


Jump knee
Thorax tilt
Posterior/Anterior(°)
Thorax obliquity
Down/Up(°)
Thorax rotation
External/Internal(°)
Pelvis tilt
Posterior/Anterior(°)
Pelvis obliquity
Down/Up(°)
Pelvis rotation
External/Internal(°)
Hip flexion/extension
Extension/Flexion(°)
Hip abduction/adduction
Abduction/Adduction(°)
Hip rotation
External/Internal(°)
% Gait cycle
Knee flexion/extension
Extension/Flexion(°)
Ankle plantar-dorsiflexion
Plantar/Dorsal(°)
% Gait cycle
%
Foot progression
External/Internal(°)
Control condition
Jump knee

## 7.3 Annexe III

### 7.3.1 Contributions scientifiques

#### *7.3.1.1 Présentations publiques (orale & poster)*

- Attias M, Bonnefoy-Mazure A, De Coulon G, Cheze L, Armand S. La marche en " flexion de genoux " bilatérale causée par des rétractions musculaires: implication des muscles ilio-psoas, ischio-jambiers et gastrocnemius; - PEM (Posture –Equilibre – Mouvement); présentation orale; 2016; Nancy

- Attias M, Bonnefoy-Mazure A, De Coulon G, Cheze L, Armand S. Influence of different degrees of bilateral emulated contractures at the triceps surae on gait kinematics: difference between gastrocnemius and soleus ; - ESMAC (European Society of Movement Analysis for Adults and Children); présentation orale; 2016; Seville

- Attias M, Bonnefoy-Mazure A, De Coulon G, Cheze L, Armand S. Gastrocnemius / soleus contracture : influence on first and second rocker during walking; - ESB (European Society of Biomechanics); poster & présentation; 2016; Lyon

- Attias M, Bonnefoy-Mazure A, De Coulon G, Cheze L, Armand S. Influence de différents degrés de rétractions musculaires bilatérales du triceps sural sur la cinématique de la marche: différence entre gastrocnémiens et soléaire. – SOFAMEA (Société Francophone d'Analyse du Mouvement chez l'Enfant et d'Adulte); présentation orale; 2016; Brest

- Attias M, Bonnefoy-Mazure A, De Coulon G, Cheze L, Armand S. Feasibility and reproducibility of using an exoskeleton able to emulate muscle contractures during walking. - ESMAC; poster & présentation; 2015; Heidelberg

- Attias M, Bonnefoy-Mazure A, Tabard A, Carcreff L, Hoffmeyer P, De Coulon G, Armand S. Faisabilité et reproductibilité d’un exosquelette capable de répliquer des contractures musculaires à la marche: application sur les gastrocnémiens et soléaires. - SOFAMEA; poster & présentation; 2015; Genève

#### 7.3.1.2 Conférencier invité

- Attias M, *Dans la peau du patient avec des problèmes moteurs ou fonctionnels* ; - SOFAMEA ; 2015 ; Genève

- Modérateur à la session « human movement » ; - ESB (European Society of Biomechanics); 2016, Lyon

#### 7.3.1.3 Articles publiés ou acceptés

- Attias M, Bonnefoy-Mazure A, Cheze L, De Coulon G, Armand S. Influence of different degrees of bilateral emulated contractures at the triceps surae on gait kinematics: Difference between gastrocnemius and soleus . Gait & posture. 2017;  58, 176-182.

- Attias M, Bonnefoy-Mazure A, De Coulon G, Cheze L, Armand S. Feasibility and reliability of using an exoskeleton to emulate muscle contractures during walking. Gait & posture. 2016; 50,239-245.

- Attias M, Chevalley O, Bonnefoy-Mazure A, De Coulon G, Cheze L, Armand S. Effects of contracture on gait kinematics: A systematic review. Clin Biomech (Bristol, Avon). 2016; 33,103-10.

- Attias M, Bonnefoy-Mazure A, Tabard A, Carcreff L, Hoffmeyer P, De Coulon G, Armand S. Faisabilité et reproductibilité d’un exosquelette capable de répliquer des contractures musculaires à la marche: application sur les gastrocnémiens et soléaires Mov Sport Sci/Sci Mot. 2016; 93, 77-85.

- Attias M, Bonnefoy-Mazure A, Lempereur M, Lascombes P, De Coulon G, Armand S. Trunk movements during gait in cerebral palsy. Clin Biomech (Bristol, Avon). 2015; 30,28-32.

#### 7.3.1.4 Résumés publiés

- Attias M, Bonnefoy-Mazure A, Cheze L, De Coulon G, Armand S. Kinematics associated witha knee flexion gait pattern caused by isolated contracture of iliopsoas, hamstring and gastrocnemius; Gait & posture. 2017;57, O38, 66-67

- Attias M, Bonnefoy-Mazure A, Cheze L, De Coulon G, Armand S. Influence of different degrees of bilateral emulated contractures at the triceps surae on gait kinematics: Difference between gastrocnemius and soleus ; Gait & posture. 2016;49, S2, 42

- Attias M, Bonnefoy-Mazure A, Cheze L, De Coulon G, Armand S. Feasibility and reproducibility of using an exoskeleton able to emulate muscle contractures during walking. Gait Posture. 2015;42, S1, S82-S83.

- Attias, M., Bonnefoy-Mazure, A., De Coulon, G., Cheze, L., Armand, S., 2016. La marche en « flexion de genoux » bilatérale causée par des rétractions musculaires : implication des muscles ilio-psoas, ischio-jambiers et gastrocnemius, PEM (Posture, Equilibre, Mouvement). Neurophysiologie Clinique/Clinical Neurophysiology, Nancy, p. 242.

#### 7.3.1.5 Articles soumis

- Attias M, Bonnefoy-Mazure A, De Coulon G, Cheze L, Armand S. Toe-walking due to different degrees of triceps surae contracture leads to a transition between gait patterns ; Journal of biomechanics

- Attias M, Bonnefoy-Mazure A, De Coulon G, Cheze L, Armand S. Kinematics can help to discriminate the implication of iliopsoas, hamstring and gastrocnemius contractures to a knee flexion gait pattern ; Clinical biomechanics