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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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Abstract

Introduction: 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.

Methods: 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 (biarticular muscle) and soleus (monoarticular muscle), corresponding at 0°, 10°, 20°, and 30° ankle plantarflexion contracture (knee-flexed and knee-extended). Range of motion was limited by ropes attached for soleus on heel and below the knee and for gastrocnemius on heel and above the knee. 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.

Results: Gastrocnemius and soleus contractures influence gait kinematics, with an increase of the Gait Profile Score. 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 contractures. Gastrocnemius contractures cause greater knee flexion (during the stance phase) and hip flexion (during all the gait cycle) than the same level of soleus contractures.

Conclusion: 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

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 [1]. Contracture is involved in many neurological conditions (e.g., cerebral palsy, multiple sclerosis, spinal cord injury, stroke) and can impair walking [2-4]. Among contractures, ankle plantarflexion contracture (APC) is one of the most common causes of gait deviations in many conditions (cerebral palsy [5], neuropathy [6] and muscular dystrophy [7]) and can lead to other complications (e.g., metatarsalgia, neuropathic ulceration, plantar fasciitis and Charcot midfoot breakdown) [8]. Gait with APC is characterized by an absence of a first rocker (which enables a heel-toe pattern at initial contact [9]) and a limitation of dorsiflexion during swing [10], causing an inadequate foot clearance [11]. 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) [12, 13].

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) [14]. 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 [15]. These approaches include a comparison of APC in patients and matched healthy subjects (pathological contracture versus healthy controls) [16, 17], comparison of patient’s gait before and after treating APC (pre- and post-kinematics after surgical muscle lengthening) [18, 19], and emulation of contracture(s) with an exoskeleton or an orthosis (simulated contracture versus healthy controls) [10, 13, 20-22].

The systematic review by Attias et al. [15] showed that it is difficult to isolate a contracture because it is always associated with other impairments, such as spasticity or muscle weakness [11, 23]. A mixed of several impairments makes it difficult to establish a clear relationship between the impairments and the gait deviations. The isolation of a specific impairment (contracture) would permit to better establish this relationship. Two previous studies have compared the effects of gastrocnemius and soleus contractures on gait [13, 24] by emulating these contractures unilaterally with an exoskeleton. They found that on the ipsilateral side, soleus contracture mainly influenced the ankle angle increasing ankle plantarflexion during gait, whereas gastrocnemius contractures influenced the ankle and knee angles (increase of ankle plantarflexion but less than soleus associated with increase knee flexion during gait). However, no studies have investigated the effect of gastrocnemius and soleus contractures bilaterally whereas equinus is commonly a bilateral gait impairment [25]. In cerebral palsy patient, equinus is the 4th gait impairment for diplegic patient [26].

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 isolated bilateral gastrocnemius (biarticular muscle) and soleus (monoarticular muscle)

2) to compare the kinematic adaptations between isolated bilateral gastrocnemius (biarticular muscle) and soleus (monoarticular muscle) at the same degree of emulated contracture.

Method

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.

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 [27]. All participants were requested to walk along a 10-meter walkway at a spontaneous, self-selected speed and were equipped with the MIkE exoskeleton (Figure 1a), which the characteristics and reliability were reported in a previous study [22]. The main components of the exoskeleton are listed below in order to allow the understanding of this article. The exoskeleton was built to bilaterally embrace the pelvis, thighs, and shanks with plastic cuffs, with modified shoes that include attachment points. Contractures were induced by ropes attached to rings (see Figure 1b). 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. 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 [22]. In addition, 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 [22]. 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 [28]. This exoskeleton was used in the current study to emulate gastrocnemius and soleus contractures bilaterally. 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 on both muscles (soleus and gastrocnemius), based on the study by Drefus et al. [29] that simulated ankle equinus but with an ankle foot orthosis not allowing the differentiation of 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 [30] and controlled it with a goniometer (Figure 1b). For soleus (monoarticular muscle), the knee was flexed at 90° (with the aim to set the contracture following the clinical examination procedure [30]), and the plantarflexion of the ankle was adjusted according to the desired degree of contracture. The adjustment of the soleus contracture with the exoskeleton did not affect the knee because the attachment points for soleus emulation were on heel and below the knee respecting muscle insertions (Figure 1b). For gastrocnemius (biarticular muscles), the knee was extended at 0° and the same procedure was used. The knee was considered for the adjustment of the gastrocnemius contracture because the attachment points for gastrocnemius emulation were on heel and above the knee respecting muscle insertions (Figure 1b).

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) [31] 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 [32] and SPSS Version 23 (IBM, Armonk, NY, USA) were used for data analysis, statistics and figure creation.

Results

The comparisons between CC and different degrees of emulated contracture are shown in Table 1 for walking speed, GPS and kinematic parameters. Figure 2 depicts differences between each degree of contracture and CC for respectively gastrocnemius and soleus concerning the walking speed and GPS.

Comparison with CC:

Concerning the walking speed and GPS (Table 1 and Figure 2), 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.

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), $p<0.01$).

Comparison between soleus and gastrocnemius contractures:

There were significant different effects of soleus and gastrocnemius were observed in the ankle, knee and hip kinematics (Table 1 and Figure 3). 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.

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. 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 [12]. Therefore, contractures of gastrocnemius or soleus limit the maximum ankle dorsiflexion during the gait, as reported by other authors [10, 11, 24, 33]; 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 contracture studies (with an emulation system applied only on the ankle level without direct link with knee) concerning maximum dorsiflexion in stance: Goodman et al. [34] (mean APC at -24°: -7° (±7.8), Houx et al. [10] (APC at -20°: -6.08° (±3.82), our study (30° of soleus (-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° [35], 2) the force applied by the evaluator at the ankle is inferior to the force applied during walking [36]; 3) patients/participants are not fully relaxed during clinical examination [37]; 4) the measurement of ankle kinematics considering one foot segment overestimates ankle dorsiflexion [38]. Moreover, these differences could explain a part of the poor relationships between clinical examinations and CGA results [39-41].

Concerning the effect of induced soleus contracture on the knee, literature results (based on unilateral induced contractures) are contradictory. Leung et al. [11] found a knee recurvatum during stance whereas Goodman et al. [34] found a permanent knee flexion. Houx et al. [42] and Matjacic et al. [13] 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. [42] and Matjacic et al. [13]. Moreover, Svehlik et al. [17] 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. [43] 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 [44].

Hence, we suspect that knee hyperextension during gait observed by Svehlik et al. [17], Galli et al. [43] on cerebral palsy patients and by Leung et al. [11] on healthy participants with induced contractures could be due to soleus contracture associated with the plantarflexion-knee extension moment [44]. However, Leung et al. [11] 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 [45].

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 [10, 11, 13, 29, 34, 42].

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.

Conclusion

Soleus contractures act mainly on ankle kinematics with no effect on the knee 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.

Conflicts of interest

There are no conflicts of interest associated with this research.

Acknowledgments

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Table 1: Walking speed, Gait Profile Score (GPS) and kinematic parameters (median, 1^{st} and 3^{rd} 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							20° plantarflexion							30° plantarflexion						
	No contracture			**Gastrocnemius**			**Soleus**				**Gastrocnemius**			**Soleus**				**Gastrocnemius**			**Soleus**				**Gastrocnemius**			**Soleus**			
	Med	*1st / 3rd quartile*		**Med**	*1st / 3rd quartile*		**Med**	*1st / 3rd quartile*		p-value	**Med**	*1st / 3rd quartile*		**Med**	*1st / 3rd quartile*		p-value	**Med**	*1st / 3rd quartile*		**Med**	*1st / 3rd quartile*		p-value	**Med**	*1st / 3rd quartile*		**Med**	*1st / 3rd quartile*		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	**1.0**	*0.9*	*1.0*	**1.0**	*0.9*	*1.1*	0.631	**0.9**	*0.9*	*1.1*	**1.0**	*0.9*	*1.1*	0.631
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	**7.5**	*6.9*	*7.9*	**6.5**	*4.9*	*7.1*	0.015	**8.2**	*7.0*	*9.5*	**7.0**	*5.6*	*8.3*	0.165
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	**5.4**	*-3.8*	*9.8*	**6.1**	*-2.5*	*6.6*	0.912	**5.4**	*-4.6*	*10.4*	**6.0**	*-1.2*	*9.9*	0.971
Ankle (sagittal)																															
Dors-IC (°)	**4.4**	*3.4*	*6.7*	**-2.8**	*-10.6*	*1.9*	**0.1**	*-1.8*	*1.2*	0.912	**-10.8**	*-13.4*	*-7.6*	**-12.5**	*-14.4*	*-9.5*	0.247	**-14.1**	*-23.6*	*-6.1*	**-14.6**	*-17.7*	*-10.9*	0.529	**-10.1**	*-21.3*	*-6.7*	**-17.7**	*-23.1*	*-16.5*	0.19
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*	**3.4**	*-0.8*	*7.0*	0.089	**4.7**	*-7.9*	*9.1*	**1.2**	*-1.8*	*2.3*	0.063	**4.5**	*-9.3*	*7.1*	**-3.9**	*-7.6*	*-2.5*	0.043
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	**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 (°)	**2.6**	*0.2*	*4.2*	**16.2**	*11.1*	*19.7*	**4.7**	*-0.6*	*8.1*	<0.001*	**23.4**	*17.1*	*27.8*	**10.6**	*7.7*	*14.3*	<0.001*	**28.5**	*20.5*	*30.0*	**13.1**	*7.9*	*15.5*	<0.001*	**29.8**	*22.8*	*35.0*	**12.4**	*6.9*	*20.3*	<0.001*
Min-Flex-ST (°)	**-0.1**	*-2.5*	*1.5*	**13.6**	*8.8*	*16.4*	**2.1**	*-1.7*	*4.7*	0.089	**19.7**	*17.3*	*25.5*	**3.7**	*1.2*	*6.8*	0.001*	**24.3**	*19.3*	*28.1*	**4.9**	*0.3*	*9.1*	0.007*	**26.7**	*19.8*	*32.9*	**5.5**	*1.9*	*14.7*	0.001*
ROM (°)	**67.2**	*65.1*	*69.4*	**48.7**	*42.2*	*54.2*	**62.9**	*61.4*	*65.5*	0.001*	**38.2**	*33.5*	*41.0*	**50.9**	*42.9*	*57.4*	0.002*	**36.4**	*30.1*	*38.6*	**45.9**	*39.6*	*51.5*	0.002*	**32.7**	*29.0*	*35.5*	**37.7**	*33.9*	*50.0*	0.011
Hip (sagittal)																															
ROM (°)	**40.3**	*36.7*	*43.6*	**31.1**	*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	**32.5**	*31.2*	*34.1*	**34.9**	*33.4*	*41.1*	0.393	**30.6**	*26.0*	*36.4*	**32.4**	*28.6*	*37.8*	0.436
Min-Flex-ST (°)	**-9.4**	*-13.4*	*-5.4*	**3.1**	*0.5*	*6.6*	**-7.4**	*-8.1*	*-5.4*	0.001*	**4.2**	*-0.4*	*7.1*	**-8.1**	*-9.2*	*0.4*	0.004*	**7.3**	*3.5*	*11.3*	**-5.1**	*-9.4*	*-0.1*	<0.001*	**10.2**	*7.4*	*18.5*	**-2.0**	*-5.9*	*0.3*	0.002*
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	**15.4**	*12.1*	*17.9*	**13.5**	*12.4*	*15.6*	0.912	**16.8**	*12.4*	*21.0*	**14.2**	*12.7*	*15.8*	0.315
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	**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

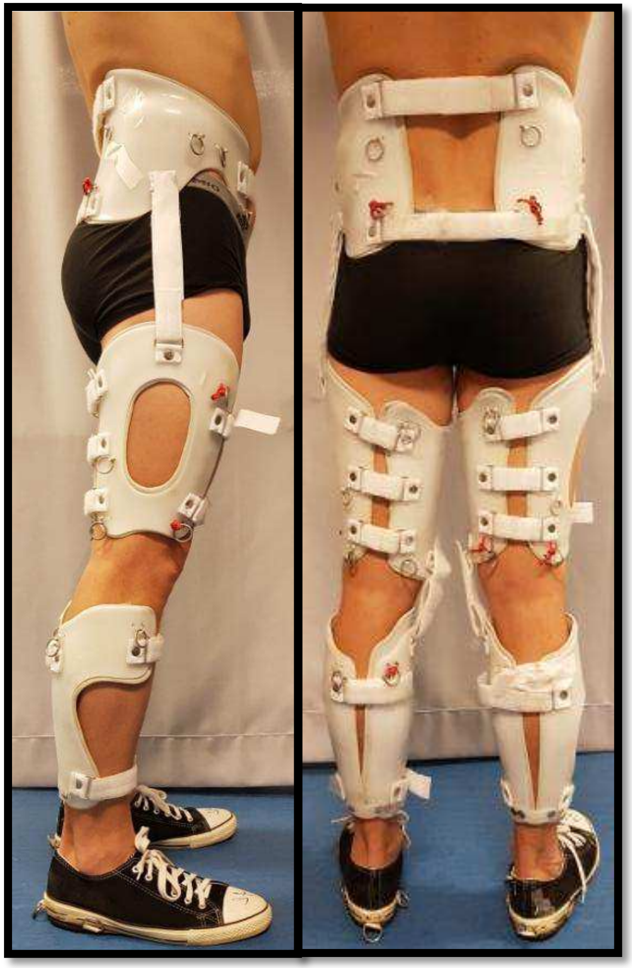
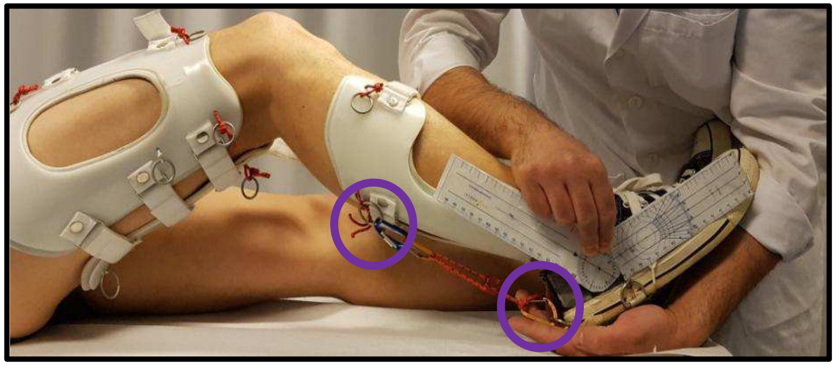


Figure 1a: The exoskeleton, “ MIkE” Muscle contracture Induced by an Exoskeleton (Attias et al. 2016)

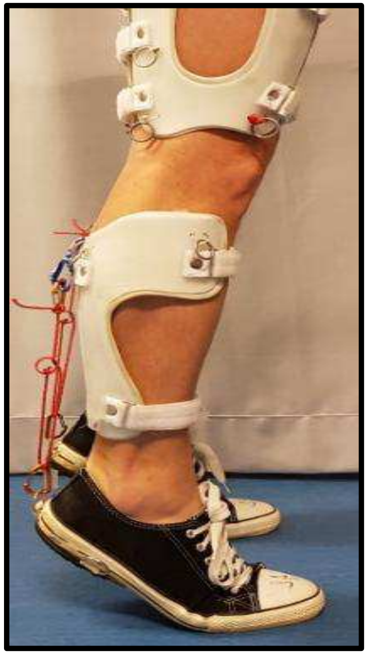
Soleus (monoarticular muscle)



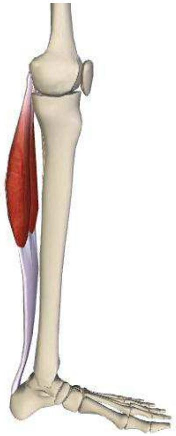
Adjustment of ankle plantarflexion angles with desired limitation of movement with a goniometer. (Example with 30° ankle plantarflexion)

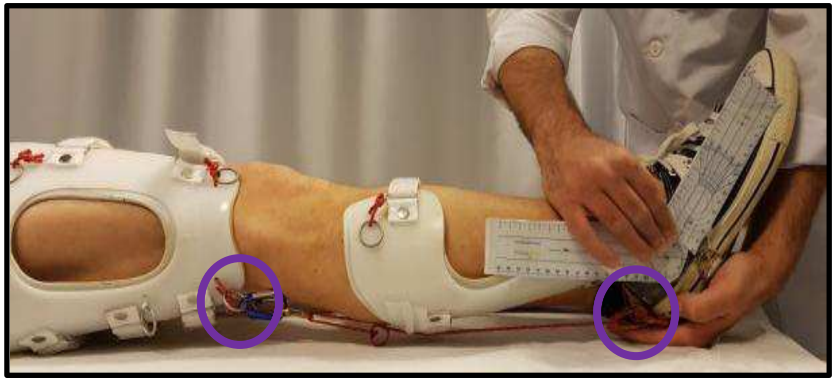
→

Emulation of soleus contractures during walking



Gastrocnemius (biarticular muscles)





Adjustment of ankle plantarflexion angles with desired limitation of movement with a goniometer. (Example with 30° ankle plantarflexion)

→

Emulation of gastrocnemius contractures during walking

Figure 1b: Setting up the exoskeleton « MIkE » (Muscle contracture Induced by an Exoskeleton) to emulate different degrees of contracture at the gastrocnemius (biarticular muscles) and soleus (monoarticular muscle) during walking. As example, a 30° degree of plantarflexion contractures have been illustrated with specific attachment points highlighted in purple on the pictures.

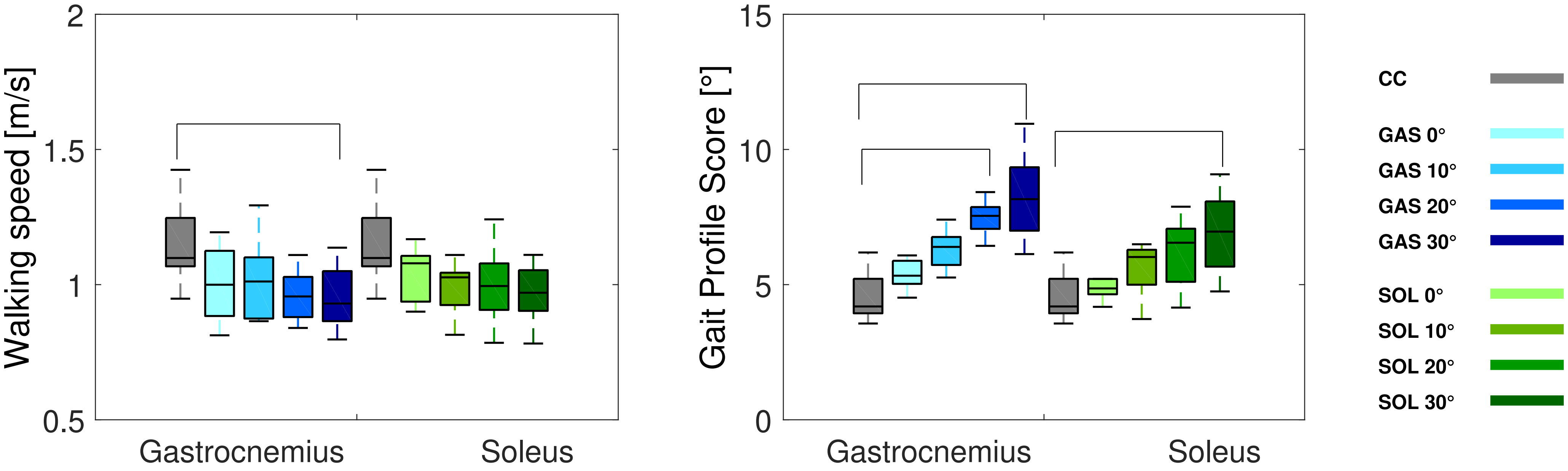


Figure 2: Boxplot for walking speed and Gait Profile Score (GPS) at different degrees of emulated contractures for the gastrocnemius and soleus muscles (control condition (CC), 0°, 10°, 20° and 30° plantarflexion contractures). Lines represent significant differences between two conditions.

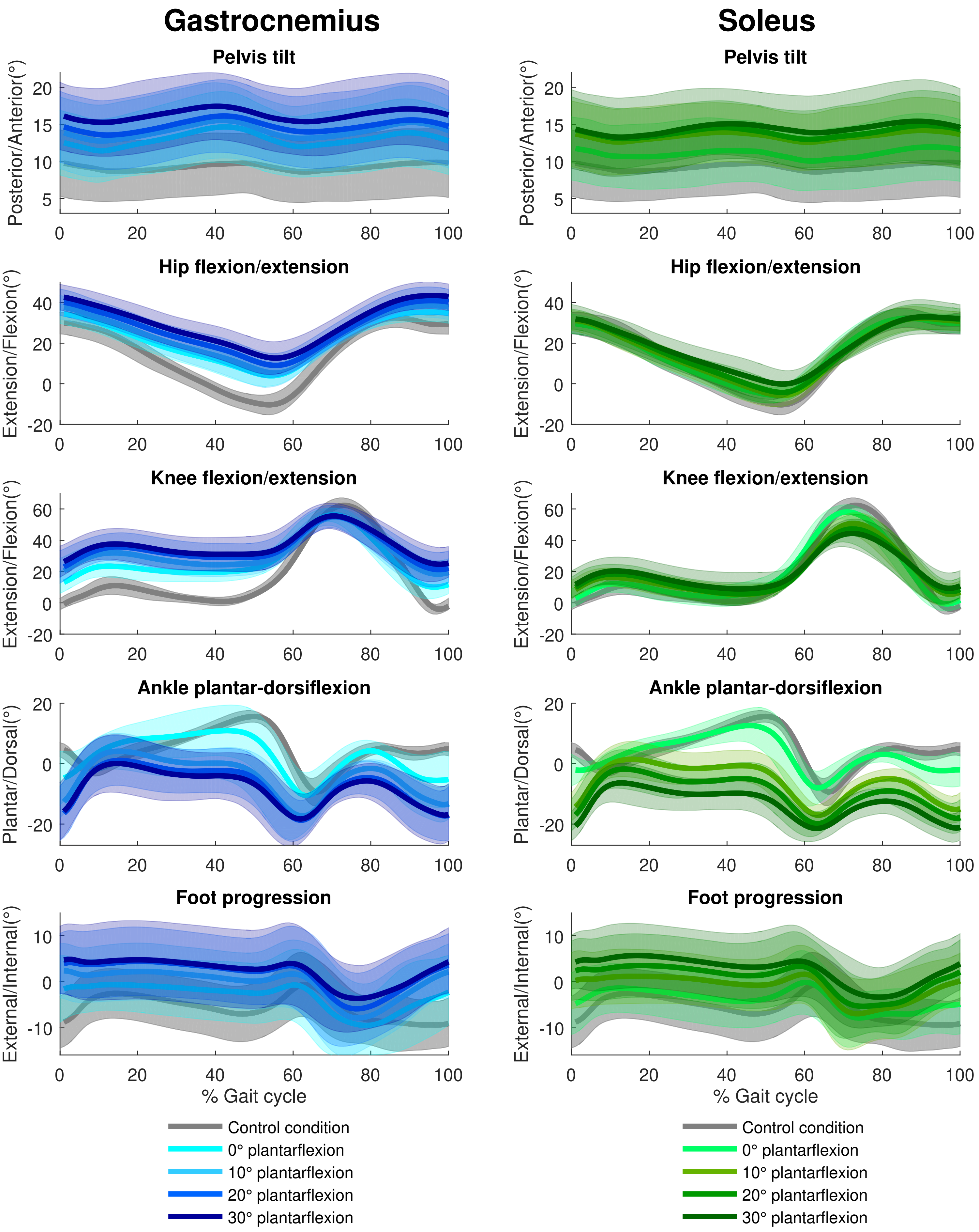


Figure 3: Mean (and standard deviation) kinematics for the pelvis, hip, knee, and ankle in the sagittal plane and foot progression at different degrees of emulated contracture for the gastrocnemius and soleus muscles.