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Toe-walking and its impact on first and second rocker in gait patterns with different degrees of artificially emulated soleus and gastrocnemius contracture

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ABSTRACT

Background: 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) of the foot during walking.
The aim of this study is to evaluate the effect of emulated artificially 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. Ten healthy participants were recruited to walk under the following conditions: without emulated contractures or with bilateral emulated contractures at 0°,10°, 20° and 30° of plantarflexion of the soleus or gastrocnemius in order to create an artificial restriction of dorsiflexion ankle movement. A linear regression from the ankle plantar-dorsiflexion angle pattern was performed on 0–5 % of the gait cycle (first rocker) and on 12–31 % of the gait cycle (second rocker) to compute the slope of the curve. The proportion of participants with the presence of the first and second rocker was then computed. A Statistical Parametric Mapping (SPM) analysis assessed the kinematic variations among different degrees of emulated contractures.
Findings: The first and second rockers are completely absent from 10° of plantarflexion emulated contracture. The data indicate there was a non-linear shift of the gait pattern of the ankle kinematics and an important shift toward plantarflexion values with the loss of the rockers.
Interpretation: This study suggests that toe-walking in the experimental simulation situation is not necessarily due to a high emulated contracture level and can occur with a small emulated contracture by an adaptation choice. This study may improve interpretation of clinical gait analysis and shows that the link between the level of gastrocnemius/soleus emulated contracture and progression of toe-walking (increased plantarflexion during gait) is not linear.

1. Introduction

Contracture of the triceps surae is very common in the following diseases / physical alteration: cerebral palsy, muscular dystrophy, neuropathy, bony deformities, and fractures [1,2]. The contracture is generally caused by the weakness of the tibialis anterior muscle and/or spasticity of the gastrocnemius and/or soleus [3]. Soft tissue contracture is defined as the inability to perform the full range of motion of a joint and an excessive resistance during passive mobilisation of this joint [4]. The structures involved in soft-tissue contractures are mainly aponeurosis, tendons and muscles, but also ligaments and capsules, for which the extensibility may have been limited and the stiffness increased [5].

Skeletal muscle contractures occur due to permanent shortening of muscle-tendon units, resulting in joint deformation and loss of elasticity. They can be caused by neuromuscular disorders and often require surgery. Abnormal stretching of sarcomeres and changes in collagen amount and arrangement contribute to high passive forces. Perimysial cables may cause increased stiffness [6].

The floor-foot contact and the progression of the body are provided

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by a pivot system during the process of normal walking, which is associated with three or four gait rockers (heel, ankle, forefoot, and toes) [7–9]. The first rocker (heel rocker) corresponds to the progression of the limb using the heel as a pivotal area. This rocker occurs at initial contact (0–2 % of the gait cycle) of the gait cycle, and extends through the loading response (2–12 % of the gait cycle). The second rocker (ankle rocker) corresponds to the progression of the tibia segment in the sagittal plane using the ankle as a pivot. This rocker occurs during the mid-stance (single support), and from approximately 12 % to 31 % of the gait cycle. The movement of the tibia causes the ankle to move from a position of plantar flexion to dorsiflexion as the tibia advances over the flat foot [7]. The heel and forefoot contact during walking is critical for maintaining stability and propelling the body forward. However, when contractures limit ankle dorsiflexion, the ability to achieve a flat foot during walking may be compromised, which can result in altered joint mechanics and increased energy expenditure [8,10–12].

Contracture of the triceps surae can lead to a toe-walking gait pattern that compromises the first and second rocker [7]. There have been several kinematic gait patterns identified in toe-walkers. The relationships between maximal dorsiflexion measured during clinical examination and clinical gait analysis (CGA) are poor and difficult to highlight using statistical approaches [13,14]. One explanation is linked to the one segment foot model used with the conventional gait model, which can lead to an overestimation of dorsiflexion [15]. A second possible explanation is that patients prefer to walk naturally with a toe-walking pattern [16]. A third possible reason is a non-linear relationship between clinical and CGA data. Thus, the relationship between limitation of dorsiflexion and gait patterns has not been clearly established in the scientific literature. A first step analyzed the influence of different degrees of bilaterally emulated contractures of the triceps surae on gait kinematics, distinguishing between the effects of the gastrocnemius and soleus [10].

The aim of this study from now on is to evaluate the effect of a limited range of motion of ankle dorsiflexion on the first and second rocker during walking with different degrees of soleus and gastrocnemius contractures artificially induced (emulated contracture). We used an experimental approach to emulate the muscle contracture with an exoskeleton. While it is unable to fully replicate the complexity of true contracture, it does capture kinematic aspects and has the potential to serve as a simple experimental paradigm for testing hypotheses and clinical assumptions. We hypothesised that the toe-walking pattern occurs with a mild limited range of motion (due to emulated contracture) and the impact of severity of gastrocnemius/soleus emulated contracture on the toe walking pattern progression (increased plantarflexion during gait) is not linear.

2. Method

2.1. Participants

This study involved 10 healthy participants (6 females, 4 males) with the following characteristics: age 27.9 ± 3.2 years; height: 171.4 ± 9.7 cm; mass 64.0 ± 10.3 kg, and no known neurologic or orthopaedic problems. The ethical approval and participant informed consent were obtained prior to beginning data collection.

2.2. Gait evaluation

All participants were equipped with the *exoskeleton MIkE*, which is able to emulate gastrocnemius and soleus contractures bilaterally. The characteristics and reliability of which were previously reported in a study [17] and the data have previously been utilized to investigate the impact of varying degrees of bilaterally emulated triceps surae contractures on gait kinematics in a preliminary study, which distinguished between the effects of the gastrocnemius and soleus [10]. In order to allow the understanding of this article, only the main characteristics of the exoskeleton are listed below. The MIkE exoskeleton was built to bilaterally embrace the pelvis, thigh, and 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. The fairly rigid cords, attached to the orthotics on the rings (see Fig. 1), allowed for a certain flexibility and to avoid sudden stops and mimic a progressive increase in stiffness at the limit of the range of motion, similar to what is observed in muscle contractures. Since muscle insertion points are typically deep and numerous, only the primary muscle lines of action were utilized to define the ropes attached to the rings [17].

The conventional gait model [18,19] was used to analyse gait using a motion analysis system (Opus 7+, 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. 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 [20]. The computation of angles was performed with Visual 3D (C-Motion, Germantown, USA).

To emulate contractures, for soleus, the knee was flexed at about 90° and the minimum ankle plantarflexion (limitation toward dorsiflexion) was adjusted according to the desired degree of contracture. For gastrocnemius, the knee was extended at 0° and the same procedure was used. We selected four degrees of contracture, 0°, 10°, 20°, and 30° of

Fig. 1. the exoskeleton " MIkE " (Muscle contracture Induced by an Exoskeleton) with example of emulate contracture at the gastrocnemius and soleus muscles with visualization during standing before walking.

plantarflexion, based on the study of Drefus et al. [21] 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 and literature [21–23]. To set the contractures, the examiner adjusted the rope length of the exoskeleton in the position used for standard physical examination [24] and controlled it with a goniometer (Fig. 1).

The participants walked along a 10-meter walkway at a spontaneous self-selected speed. Soleus was emulated at first and after a rest period, the gastrocnemius was emulated to avoid a possible fatigue effect. Before data capture, the participants walked around 2 min for each experimental condition. The capture started when the participants felt accustomed to the walking condition.

2.3. *Data analysis and statistics*

The frames for 0–5 % of the gait cycle of the ankle plantar-dorsiflexion angle were used in a linear regression to compute the slope of the curve. The decision to use 0–5 % of the gait cycle and not 0–12 % of the gait cycle, as defined in normal walking, was to consider that the first rocker can be shorter in walking conditions with contractures. 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.

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.

In addition, to assess the kinematic variations among different degrees of emulated contractures (0°, 10°, 20°, 30°) in the plantarflexion of the gastrocnemius and soleus, compared to the control condition (CC), Statistical Parametric Mapping (SPM1d) was employed [25]. A one-way repeated-measures ANOVA and post hoc analyses with Bonferroni correction were conducted to evaluate significant differences ($p < 0.0125$) [26]. All data analysis, statistics, and figures were performed with MATLAB R2012b (MathWorks, Natick, Massachusetts, USA), the open-source Biomechanical ToolKit package for MATLAB [27], open-source SPM1d code (vM.0.4.10; www.spm1D.org) in Matlab and IBM SPSS Statistics Version 23 (IBM, Armonk, NY, USA).

3. Results

The results showed the presence of first and second rockers for all participants in the control condition (Fig. 2).

The percentages of participants with a first rocker were the following: 20 % for gastrocnemius and 60 % for soleus in condition 0° of plantarflexion contracture and then 0 % for gastrocnemius and 0 % for

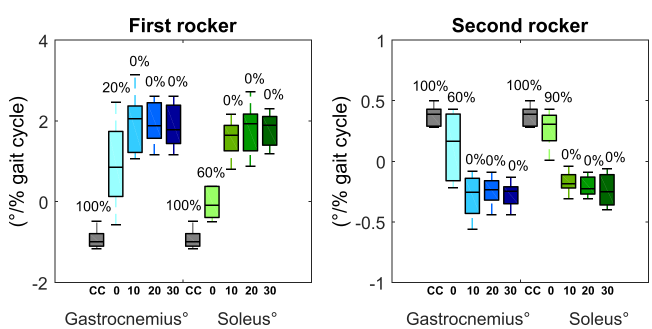

Fig. 2. Boxplot of the slopes (degrees/ % gait cycle) of the first and second rocker of Gastrocnemius (GAS) and Soleus (SOL) with different levels of contractures (0°; 10°; 20°; 30° of plantarflexion contractures and CC (control condition)).

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 Wilcoxon test showed no significant difference between the slope of the curve for gastrocnemius and soleus conditions on the first rocker and second rocker (Table 1). The ankle kinematic patterns in the sagittal plane are depicted in Fig. 3. The bars below the kinematic figure indicate the significant gait phases where the SPM1D statistic surpassed the critical threshold. Differences compared to the control condition are shown at the level of the first rocker starting from 10 degrees of emulated plantarflexion in the gastrocnemius and soleus. For the second rocker, a consistent increase is observed starting from 10 degrees of soleus plantarflexion, while no significant difference is observed for the gastrocnemius.

4. Discussion

In this study, we evaluated the effect of a limited range of motion of ankle dorsiflexion on the first and second rocker during walking with different degrees of soleus and gastrocnemius contractures artificially emulated. The first and second rockers are completely absent (Fig. 2) with more than 10° of plantarflexion contracture. Additionally, we observed a clear "breakdown" in the ankle pattern change (showing a non-linear transition) and an important shift toward plantarflexion values with loss of the rockers (Fig. 3). 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 than for contractures above 10. This result suggests there is greater variability of the ankle kinematic pattern that was confirmed by the boxplot (Fig. 2) showing 20 % (gastrocnemius) and 60 % (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 gait patterns around this 0° of plantarflexion contracture. The choice of one of these patterns is certainly based on the best strategy to support forward progression [28] and to minimise the energy cost [12], while maintaining balance and stability [29]. SPM analysis showed the impact of contracture on the soleus muscle appears to be more pronounced/determinant than on the gastrocnemius muscles. Additionally, starting from 10 degrees of soleus plantarflexion, the increase appears to be consistent, while no significant difference is observed for the gastrocnemius. This can be attributed in part to the bi-articular nature of the gastrocnemius muscles, which partially absorbs the emulated contracture and likely leads to greater variability [10,30,31].

According to the study of Harkness-Armstrong et al. [32] showed that children with idiopathic toe-walking exhibit a more plantarflexed ankle position and longer muscle fascicle lengths than typically developing children during gait. However, these ranges utilized during gait correspond to optimal strength for children with idiopathic toe-walking. According to Veerkamp et al. [33], commented on the article, the simulation experiment provides evidence that modeling can be a valuable tool to complement in vivo experiments and aid in data interpretation, as it allows for the simulation of experimental variables that are hard to measure in vivo. While the findings of this study [32] may suggest that the gastrocnemius muscle functions optimally at longer lengths, the simulation results suggest otherwise.

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 patients who exhibit a toe-walking pattern with a slight limited dorsiflexion.

According to Houx et al. [3], the minimal plantarflexion contracture to influence kinematics and kinetics is 10° of plantarflexion. These findings are consistent with our results if we consider all the participants but influence can occur for a smaller limitation (0°) for some participants. The onset of changes occurred near 0° of plantarflexion.

Table 1
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) and control condition (CC) 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
Control condition	**-0.99**	*-1.11*	*-0.78*	**-0.99**	*-1.11*	*-0.78*	-	**0.39**	*0.29*	*0.43*	**0.39**	*0.29*	*0.43*	-
0° plantarflexion	**0.85**	*-0.01*	*1.81*	**-0.09**	*-0.42*	*0.67*	0.059	**0.16**	*-0.16*	*0.39*	**0.31**	*0.13*	*0.39*	0.114
10° plantarflexion	**2.06**	*1.21*	*2.40*	**1.65**	*1.26*	*1.96*	0.241	**-0.25**	*-0.44*	*-0.13*	**-0.18**	*-0.024*	*-0.09*	0.074
20° plantarflexion	**1.88**	*1.55*	*2.47*	**1.93**	*1.25*	*2.21*	0.386	**-0.24**	*-0.35*	*-0.16*	**-0.22**	*-0.28*	*-0.12*	0.333
30° plantarflexion	**1.79**	*1.38*	*2.44*	**1.90**	*1.38*	*2.16*	0.799	**-0.25**	*-0.36*	*-0.20*	**-0.23**	*-0.36*	*-0.11*	0.445

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

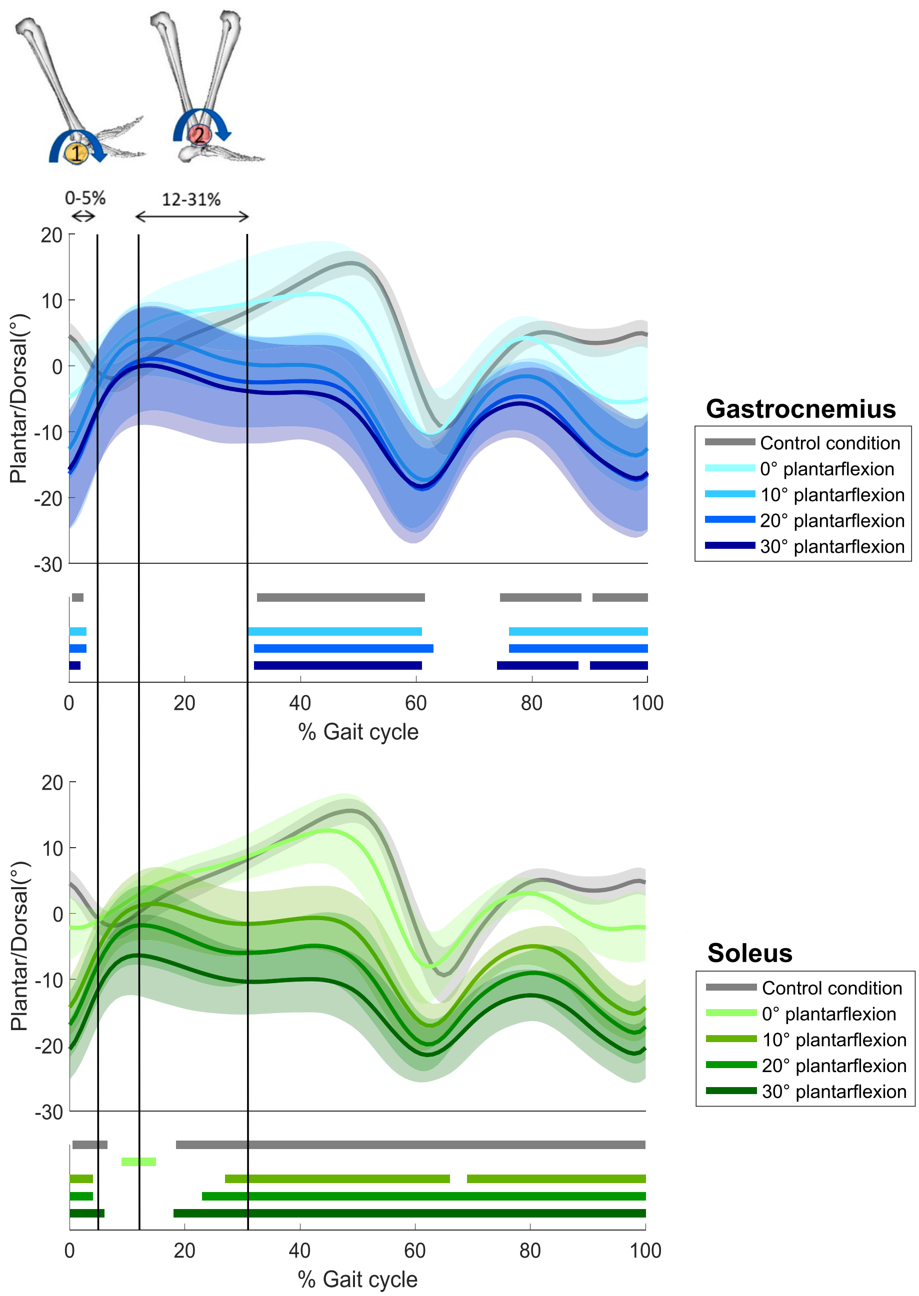

Fig. 3. Top graph shows kinematics in the sagittal plane (mean and standard deviation) of the first rocker (0–5 % of gait cycle) and second rocker (12–31 % of gait cycle) for the soleus and gastrocnemius conditions with different levels of contractures (0°; 10°; 20°; 30° of plantarflexion contractures and CC (control condition)). Bars indicate significant gait phases during which the SPM1D statistic exceeded the critical threshold based on one-way repeated-measures ANOVA and post hoc analyses with Bonferroni correction ($p < 0.0125$).

These experimental findings suggest that the relationship between clinical parameters and ankle kinematics are not easy to establish because the kinematic gait pattern - reflects both clinical impairments and compensation mechanisms [13]. Moreover, a linear modification of clinical impairments does not necessarily lead to a linear modification of the gait patterns but shifts (non-linear progressive transition) between several gait patterns can occur as it is highlighted by our results. This may partly explain the low correlation observed between clinical impairments and gait deviations [14] and may require further investigation for other gait deviations (e.g. knee recurvatum) that may have a similar behaviour with a non-linear transition.

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. Several possible gait adaptations 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 (several possible gait patterns) with a low contracture level [10]. We observed the same trends with the second rocker. However, there was no significant difference observed. The other main limitation is that this experience is a "simulation" of a contracture on healthy subjects (in order to isolate this phenomenon), and that the transposition to pathological subjects (who must adapt gradually over long periods of time) is not obvious. Another limitation is the lack of simulated contracture. It would have been interesting to have data up to 10° of dorsiflexion emulated contracture to identify more clearly the nonlinearity transition of gait patterns. The walking speed influences gait and particularly its kinematics [34,35] and can be considered as a limitation in this simulation experiment as only the spontaneous walking speed was considered. Comparing one or more similar speeds between conditions (imposed by the experimenter) would have allowed controlling this confounding factor in the analysis. However, it was chosen not to impose a specific walking speed for three reasons. First, a patient presenting for a gait analysis usually walks at a spontaneous speed. In order to follow our methodology of faithfully reproducing contracture emulations in clinical practice, only spontaneous walking speed was analyzed. Second, some contractures imposed significant constraints where it would have been difficult for participants to follow an imposed walking speed. Third, to limit bias due to fatigue, we chose to prioritize the number of contracture conditions rather than the number of different walking speeds.

5. Conclusion

This study evaluated the effect of gastrocnemius and soleus emulated contractures on the first and second rocker during walking. We found that a non-linear progressive transition between two main gait patterns arises around 0° of plantarflexion emulated contracture. It appears that the kinematics impact of emulated contracture on the soleus muscle on the second rocker is more pronounced than on the gastrocnemius muscles.

Toe-walking is not necessarily a result of a high level of emulated contracture, and it can occur even with a small emulated contracture due to an "adaptation choice." This adaptation choice is observed more frequently in the gastrocnemius muscles and may be influenced by their bi-articular nature, which allows for greater variability in gait patterns. Our approach helps to understand a principle and a hypothesis that could aid in the interpretation of clinical gait analysis. Specifically, our study shows that the link between a clinical impairment, such as the level of gastrocnemius/soleus contracture, and a gait deviation, (altered ankle kinematics) is not continuous. It is important to note that this hypothesis is based on an experimental simulation situation. The identification of transitions in gait patterns may allow better targeting of treatment strategies.

Declaration of Competing Interest

We confirm that there was no conflict of interest during this study for each author.

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