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DOI
10.1016/j.gaitpost.2020.01.010

Publication date
2020

Document Version
Final published version

Published in
Gait and Posture

Gait & Posture 77 (2020) 14–19

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

The effect of mono- versus multi-segment musculoskeletal models of the foot on simulated triceps surae lengths in pathological and healthy gait

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ARTICLE INFO

Keywords:
Cerebral palsy
OpenSim
Biomechanics
Foot model
Gastrocnemius muscle

ABSTRACT

Background: Estimating muscle-tendon complex (MTC) lengths is important for planning of soft tissue surgery and evaluating outcomes, e.g. in children with cerebral palsy (CP). Conventional musculoskeletal models often represent the foot as one rigid segment, called a mono-segment foot model (mono-SFM). However, a multi-segment foot model (multi-SFM) might provide better estimates of triceps surae MTC lengths, especially in patients with foot deformities.
Research question: What is the effect of a mono- versus a multi-SFM on simulated ankle angles and triceps surae MTC lengths during gait in typically developing subjects and in children with CP with equinus, cavovarus or planovalgus foot deformities?
Methods: 50 subjects were included, 10 non-affected adults, 10 typically developing children, and 30 children with spastic CP and foot deformities. During walking trials, marker trajectories were collected for two marker models, including a mono- and multi-segment foot; respectively Newington gait model and Oxford foot model. Two musculoskeletal lower body models were constructed in OpenSim with either a mono- or multi-SFM based on the corresponding marker models. Normalized triceps surae MTC lengths (soleus, gastrocnemius medialis and lateralis) and ankle angles were calculated and compared between models using statistical parametric mapping RM-ANOVAs. Root mean square error values between simulated MTC lengths were compared using Wilcoxon signed-rank and rank-sum tests.
Results: Mono-SFM simulated significantly more ankle dorsiflexion (7.5 ± 1.2°) and longer triceps surae lengths (difference; soleus:2.6 ± 0.29 %, gastrocnemius medialis:1.7 ± 0.2 %, gastrocnemius lateralis:1.8 ± 0.2%) than a multi-SFM. Differences between models were larger in children with CP compared to typically developing children and larger in the stance compared to the swing phase of gait. Largest differences were found in children with CP presenting with planovalgus (4.8 %) or cavovarus (3.8 %) foot deformities.
Significance: It is advisable to use a multi-SFM in musculoskeletal models when simulating triceps surae MTC lengths, especially in individuals with planovalgus or cavovarus foot deformities.

1. Introduction

Children with spastic cerebral palsy (CP) experience, among other things, impaired motor control, spasticity and soft-tissue contractures [1]. Additionally, children with CP are very likely (93 %) to develop foot deformities [2]. Both functionally short muscle-tendon complexes (MTCs) and foot deformities contribute to gait difficulties in children with spastic CP. A commonly used procedure to facilitate gait in

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https://doi.org/10.1016/j.gaitpost.2020.01.010
Received 31 August 2019; Received in revised form 8 December 2019; Accepted 7 January 2020

children with CP is MTC lengthening surgery [3]. It is known that treatment satisfaction following lengthening surgery for the hamstrings depends on the pre-operative MTC length [4]. Therefore, appreciation of dynamic pre-surgery MTC lengths is important to ensure a satisfactory outcome of MTC lengthening surgery. Musculoskeletal (MS) modelling can be used to estimate MTC lengths [5]. However, when MS modelling is used to guide treatment selection, it is critical that the model is appropriate for the patient.

Accurate modelling of the foot may be of particular importance when estimating lower leg MTC lengths. While in 3D gait analysis, multi-segment marker models of the foot are increasingly used [6,7], in MS modelling it is still common to use mono-segment foot models (mono-SFM). Large joint angle differences have been found between the outcomes of common mono- and multi-segment marker models of the foot [8]. For example, the dorsiflexion angle is overestimated in a mono-SFM compared to a multi-SFM and this difference is even more prominent in pathological feet [8]. To our knowledge, only one pilot study has been performed that compared MTC lengths based on mono- and multi-segment foot models [9]. This study showed that soleus (SOL) MTC lengths were significantly shorter when using a mono-SFM compared to a multi-SFM [9]. Surprisingly, this finding is not in line with previous results which showed that a mono-SFM overestimates the ankle dorsiflexion angle [8], which means that a longer MTC length is expected for a mono-SFM. Due to the aforementioned contradictory findings between joint angles and MTC lengths of mono- and multi-SFM's, it is not clear what the effect of a mono- versus a multi-SFM is on simulated SOL MTC lengths. In previous studies, no distinctions were made between the stance and swing phase of gait [8,9]. This may be of interest because more intrinsic foot motions (i.e. larger range of motion (ROM)) in the stance phase due to foot deformation [10] could increase the discrepancy between models. Additionally, the effect of a mono- versus multi-SFM on the more complex bi-articular gastrocnemius medialis (GM) and lateralis (GL), which are commonly affected in CP, is not yet known. Furthermore, it is unknown how the magnitude of discrepancy between models may differ between a variety of subject groups and foot deformities.

Hence, the aim of this study was to determine the effect of a mono- versus a multi-segment MS foot model on simulated ankle angles and triceps surae MTC lengths in gait of typically developing subjects and of children with CP with equinus, cavovarus or planovalgus foot deformities. Additionally, the differing effects between the stance phase and swing phase of gait were assessed.

It was hypothesised that a mono-SFM would simulate longer triceps surae MTC lengths and more ankle dorsiflexion than a multi-SFM. This effect was expected to be largest in children with CP. Furthermore, larger differences were expected in the stance phase compared to the swing phase of gait.

2. Methods

2.1. Subjects

A total of 50 subjects were included in this study (Table 1). Ten non-affected adults and ten typically developing children without any neurological or physical limitations were included. Thirty children with CP were retrospectively included from the Oxford gait lab database when they had a gross motor function classification system level I or II [11], presence of spasticity as indicated by a "catch" during fast passive ankle dorsiflexion and presence of one of the three most common foot deformities in CP, i.e. equinus, planovalgus or cavovarus [12], as assessed by both a clinical exam and video gait analysis. Children were excluded if they had prior surgery on the foot, ankle or triceps surae, or a botox treatment to the triceps surae within six months prior to gait analysis. An informed consent was signed for all subjects, either by the subjects themselves and/or by their parents. Ethical approval for the different measurements was provided by the local ethics and medical ethics committees.

2.2. Data collection

Reflective markers according to the Newington marker model [13], also known as Plug-in Gait (PIG), were placed on both sides of the lower body for all subjects. To be able to track the in/eversion of the foot with respect to the tibia, and endo/exorotation of the tibia with respect to the thigh, additional markers on the head of the fifth metatarsal and the tuberositas tibia were placed, see Appendix A. For non-affected adults and typically developing children, markers according to the Oxford Foot model (OFM) were placed on the right lower leg [14]. For children with CP the OFM markers were placed on both lower legs. Subjects were instructed to walk barefoot at a self-selected speed over a 10-meter walkway. 3D marker trajectories of the lower body were measured with a 12 or 16 camera VICON system (Vicon Motion Systems Ltd., Oxford, UK) at a sample rate of 100 Hz. Measurements of non-affected adults and typically developing children took place at the gait laboratory of Amsterdam UMC, location VUmc. Data of children with CP had previously been collected at the Oxford gait laboratory as part of clinical practice.

2.3. Foot and ankle modelling

Two lower body MS models were created with either a mono- or multi-SFM (Fig. 1). To construct these models, adaptations were made to a combination of the lower body of the standard OpenSim model with 23 degrees of freedom (DOF) and 92 muscle-tendon actuators (i.e. gait 2392 model) [5] and the KU Leuven foot model [15] in OpenSim (version 3.3) [5]. The gait 2392 model was used to create the pelvis, femur and tibia, including the axes of rotation. The KU Leuven foot model was used to create the segments distal to the tibia. Axes of rotation for the joints distal to the tibia for both the MS mono- and multi-SFM were based on axes of rotation of the PIG and OFM marker model, respectively. The mono-SFM consisted of one segment with three rotational DOF between the foot and the tibia. The multi-SFM consisted of two segments; a combination of the hindfoot and midfoot (further called hindfoot) and a forefoot [14]. This multi-SFM had six rotational DOF; three between hindfoot and tibia and three between forefoot and hindfoot. A more detailed description of the models can be found in Appendix B.

2.4. Data analysis

Four representative strides were randomly included for each subject. Marker trajectories were filtered in Vicon Nexus (version 2.4) using a Woltring filter [16]. Strides of only the right leg of non-affected adults and typically developing children and the most affected leg of the children with CP were analyzed and normalized to percentage of gait cycle, starting with the initial contact of that side. Initial contact and toe-off values were determined by the algorithm of Zeni and colleagues [17]. To acquire simulated ankle angles and triceps surae MTC lengths, the scaling, inverse kinematics and muscle analysis tools of OpenSim were used. To obtain normalized MTC lengths, simulated MTC lengths were divided by their anatomical reference length (i.e. MTC length when all joint angles are set to zero) for both the scaled mono- and multi-SFM [5]. The magnitude of the difference between the mono- and multi-SFM was calculated as the root mean square error (RMSE) value over the gait cycle for each subject and trial. Additionally, mean RMSE values over both the stance and swing phase were calculated separately.

2.5. Statistical analysis

To test the effect of foot models on ankle angles in the sagittal plane, a statistical parametric mapping (SPM) paired *t*-test was performed. To

Table 1
Characteristics of the various subject groups. GMFCS = gross motor function classification system. TD = typically developing.

	Number of subjects	Sex (male/female)	Age (year) (mean ± SD)	Height (cm) (mean ± SD)	Mass (kg) (mean ± SD)	Included leg	GMFCS level	Uni/bi-lateral
Non-affected / TD	20	8/12	17.9 ± 8.7	160.3 ± 21.0	53.0 ± 17.8	R: 20	–	–
- Adults	10	4/6	26.8 ± 2.6	176.4 ± 8.1	67.2 ± 8.5	R: 10	–	–
- Children	10	4/6	10.2 ± 2.3	144.1 ± 16.6	39.0 ± 12.3	R: 10	–	–
Cerebral palsy	30	22/8	10.1 ± 2.1	138.6 ± 14.9	34.8 ± 14.1	R: 18 L: 12	I: 9 II:21	Uni: 7 Bi: 23
- Equinus	10	7/3	10.3 ± 2.3	139.9 ± 16.9	37.8 ± 18.3	R: 5 L: 5	I: 4 II: 6	Uni: 3 Bi: 7
- Planovalgus	10	9/1	9.3 ± 0.7	140.0 ± 11.5	33.2 ± 4.5	R: 5 L: 5	I: 2 II: 8	Uni: 1 Bi: 9
- Cavovarus	10	6/4	10.8 ± 1.4	136.0 ± 16.2	32.6 ± 14.6	R: 8 L: 2	I: 3 II: 7	Uni: 3 Bi: 7

test for within- and between-group differences of the foot models on MTC lengths, an SPM 2-factor repeated measures ANOVA was performed for each of the three MTCs [18]. The factors consisted of the five subject groups and two foot models. To test the effect of foot model for each group separately, post-hoc SPM paired t-tests were performed within all subject groups, with Bonferroni correction.

Normality of RMSE values was tested with a Kolmogorov-Smirnov test and Levene's test. To test for between-group differences in the magnitude of MTC length differences between the mono- and multi-SFM (i.e. RMSE values), an ANOVA (or Kruskal-Wallis test, if normality was not shown) was performed for each MTC. Post-hoc unpaired t-tests (or Wilcoxon rank sum tests) were performed between subject groups. Additionally, mean RMSE values over the stance and swing phase of gait for all subjects were compared with paired t-tests (or Wilcoxon signed rank tests) for each of the three MTCs. Bonferroni corrections were applied for each test in which multiple comparisons were made. Results were significant when p-value was smaller than 0.05 divided by the number of comparisons performed. All statistical analyses were performed in Matlab (R2016a, MathWorks, USA).

3. Results

The mono-SFM simulated significantly larger ankle dorsiflexion angles compared to multi-SFM during the complete gait cycle (mean difference ± SD: 7.5 ± 1.2°) (Fig. 2). Normalized mono-SFM MTC lengths were significantly longer than multi-SFM MTC lengths over the entire gait cycle, as indicated by a significant main effect of foot model on the MTC lengths of SOL, GM and GL during the gait cycle ($p < 0.001$) (Fig. 3). Additionally, a significant main effect of subject group and an interaction effect of subject group and foot model were found for all MTCs during the entire gait cycle ($p < 0.001$). Post-hoc SPM paired t-tests showed that mono-SFM MTC lengths were significantly longer than multi-SFM MTC lengths during the entire gait cycle for all subject groups except for non-affected adults (Fig. 4).

A significant main effect for subject group was found for the MTC length difference between a mono- and multi-SFM of all normalized MTCs, as quantified by RMSE values ($p < 0.001$) (Fig. 5). This difference was larger in typically developing children than in non-affected adults, as demonstrated by a higher RMSE value ($p < 0.001$), and larger in children with CP than in typically developing children (median(interquartile range); (SOL: 3.8(2.4–4.8) vs 2.0(0.9–2.9), GM: 2.6(1.5–3.0) vs 1.3(0.6–1.8), GL: 2.5(1.7–3.2) vs 1.4(0.7–2.0)) ($p < 0.001$). Within

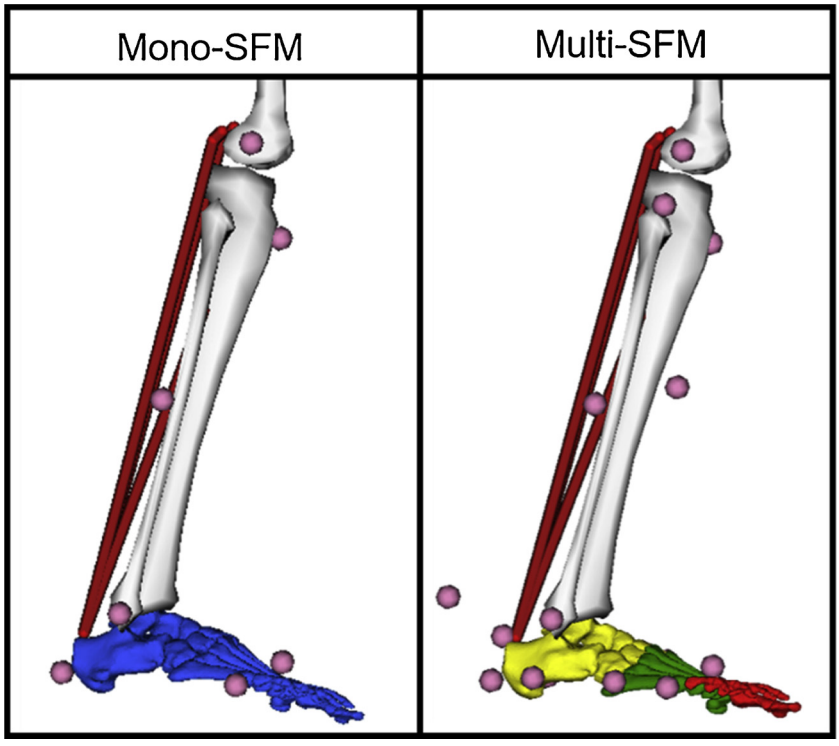

Fig. 1. The right lower leg of the constructed musculoskeletal mono- and multi-segment foot models (SFM). The blue area in the left figure represents the foot segment of the mono-SFM. The yellow and green areas on the right figure represent the hindfoot and forefoot segment, respectively. The red area represents the toes but these are not modelled, these are only added for visualization purposes. Red cables represent the triceps surae. Pink dots represent the markers from the corresponding marker models (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

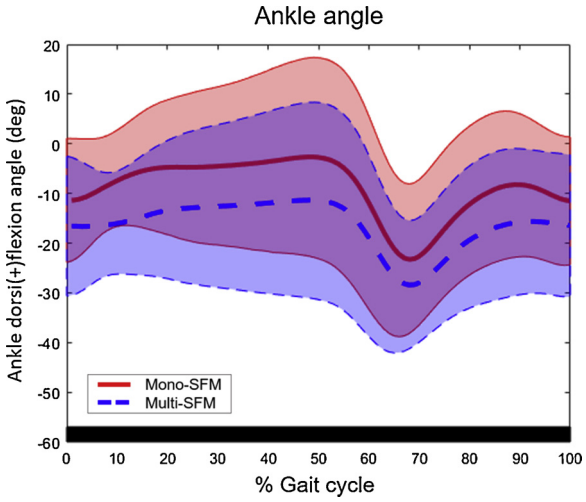

Fig. 2. Simulated ankle dorsiflexion angles during gait for all subjects together for both the mono-SFM (solid line) and multi-SFM (dashed line). Shaded areas show the standard deviation around the group mean. The black bar below the graph indicates when mono-SFM ankle dorsiflexion angles were significantly larger than multi-SFM angles ($p < 0.001$).

the group of children with CP, the RMSE value between a mono- and multi-SFM was largest for children with planovalgus foot deformities, followed by cavovarus and equinus deformities ($p < 0.001$). RMSE values of children presenting with an equinus foot deformity did not significantly differ from typically developing children ($p > 0.02$). Finally, RMSE differences between the models were significantly larger in the stance compared to the swing phase of gait (median(interquartile range); SOL: 4.4(1.7–6.9) vs 3.5(1.1–5.8). GM: 2.8(1.1–4.3) vs 2.2(0.7–3.5), GL: 2.9(1.3–4.5) vs 2.3(0.8–3.8)) ($p < 0.02$).

4. Discussion

This study compared simulated ankle angles and MTC lengths of SOL, GM and GL between a mono- and multi-SFM in various subject groups. The main finding was that the mono-SFM overestimated the ankle dorsiflexion angle during the complete gait cycle compared to the multi-SFM with an amount larger than one third of the actual range of motion. Consequently, the mono-SFM simulated longer triceps surae MTC lengths than the multi-SFM for a large part of the gait cycle in all subject groups. Differences in MTC lengths between a mono- and multi-SFM were larger in children with CP compared to typically developing children, and largest in children with CP presenting with a planovalgus or cavovarus foot deformity. Additionally, differences between models were larger in typically developing children compared to non-affected adults, and larger in the stance compared to the swing phase of gait.

The longer triceps surae MTC lengths for a mono-SFM compared to a multi-SFM are likely caused by erroneously attributing mid-foot motion to ankle motion in the mono-SFM. The main determinant for triceps surae MTC lengths is the orientation of the calcaneus relative to the tibia, since the triceps surae inserts into the posterior surface of the calcaneus. In a mono-SFM, all motions within the foot are attributed to rotations around the ankle joint, while a multi-SFM contains a separate hindfoot segment and therefore represents pure ankle motion, rather than the combination of ankle and midfoot motion. In this study, the ankle dorsiflexion angle was found to be overestimated in a mono-SFM compared to a multi-SFM, which is in line with previous research [8]. Triceps surae MTC lengths were found to be longer in a mono-SFM compared to a multi-SFM, which confirms our hypothesis. However, these results contradict the findings of Stewart et al. [9]. An explanation for these differences could be that we included multiple homogeneous subject groups and scaled the MS models to the size of the subjects. It can be assumed that the multi-SFM provides a more accurate estimate of the triceps surae MTC lengths because it allocates the midfoot motions more appropriately. Differences in joint axes between the mono- and multi-SFM might also affect triceps surae MTC lengths. The same motion might be measured in different planes (i.e. crosstalk), which can result in offsets in the ankle joint angles. However, no differences in MTC lengths were found when data were reprocessed using the same joint axes for both the mono- and multi-SFM, indicating that this is unlikely to be the cause for the observed differences.

In line with our hypothesis, the difference in MTC length between a mono- and multi-SFM was larger in children with CP presenting with foot deformities compared to typically developing children, as shown by higher RMSE values. Differences between the mono- and multi-SFM were largest for foot deformities affecting the medial longitudinal arch (e.g. cavus/planus) and the orientation of the calcaneus in the frontal plane (i.e. varus/valgus). Since a multi-SFM already tends to produce smaller ankle dorsiflexion angles, an additional plantarflexion (i.e. planus) or dorsiflexion (i.e. cavus) of the hindfoot enhances the magnitude of this discrepancy. Hence, this explains the difference in RMSE values between children with CP presenting with a cavovarus or planovalgus deformity. For children with CP presenting with an equinus deformity, the difference in MTC length between a mono- and multi-SFM was smaller than for the other foot deformities and did not significantly differ from typically developing children. Only children with a very distinct equinus deformity (i.e. walking without heel contact) were included, since they were selected based on a clinical exam and video analysis of their gait pattern. These children were prone to rigid contractures within the foot, which limits ROM of the forefoot relative to the hindfoot. Due to this reduction in midfoot ROM, the difference in

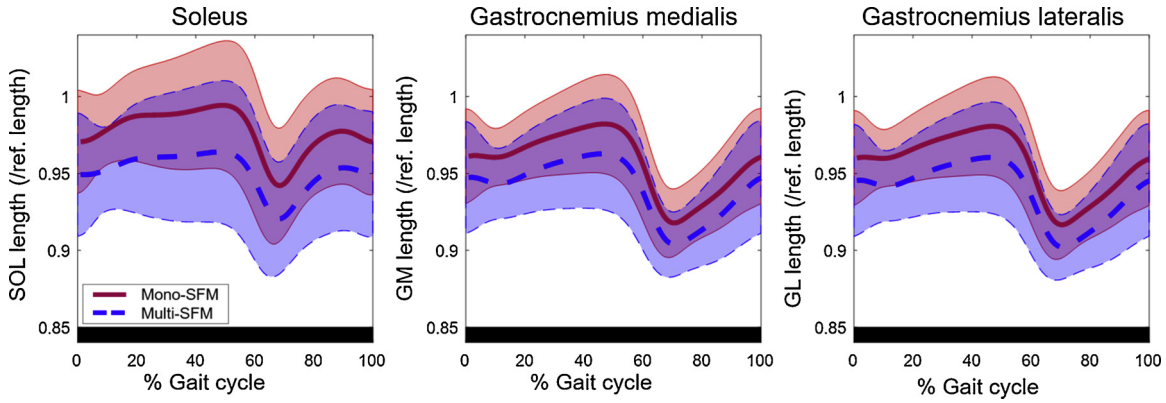

Fig. 3. Mean normalized MTC lengths during gait of all subjects together for both the mono-SFM (solid line) and multi-SFM (dashed line). Shaded areas show the standard deviation around the group mean. Black bars below the graphs indicate when mono-SFM MTC lengths were significantly longer than multi-SFM MTC lengths ($p < 0.001$).

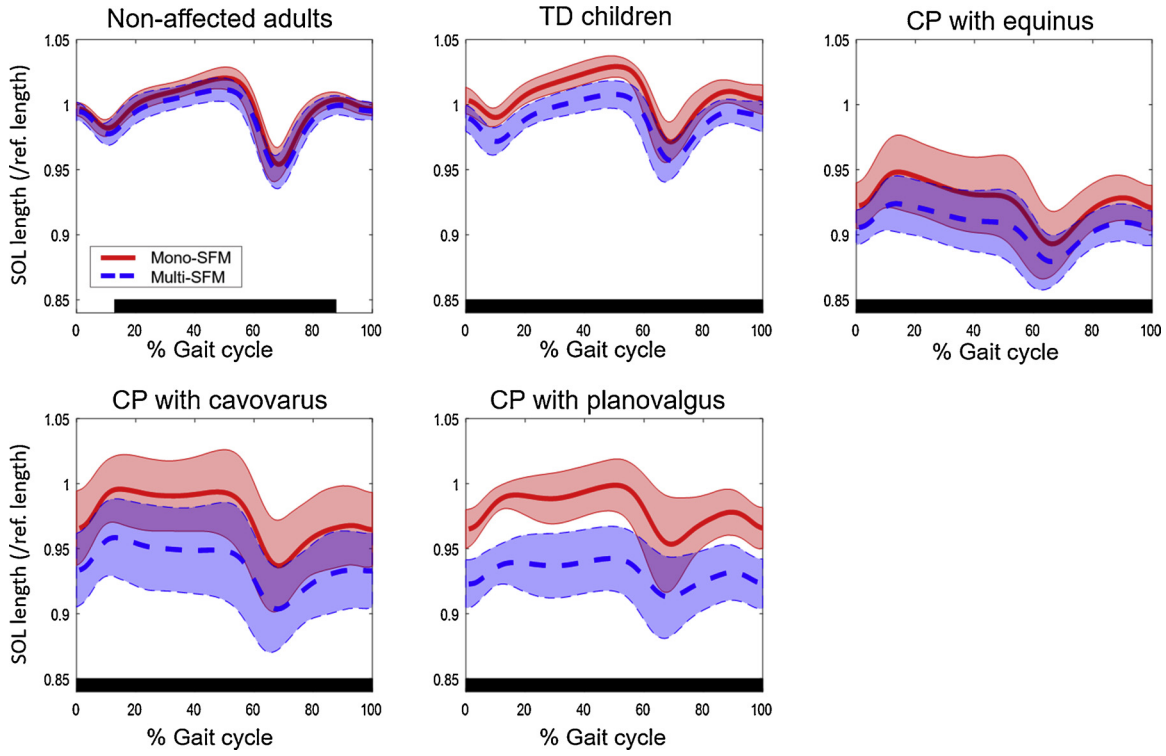

Fig. 4. Mean normalized SOL MTC lengths during gait for both the mono-SFM (solid line) and multi-SFM (dashed line) for the various subject groups. Shaded areas show the standard deviation around the group mean. Black bars below the graphs indicate when multi-SFM lengths were significantly shorter than mono-SFM MTC lengths ($p < 0.001$). TD = typically developing.

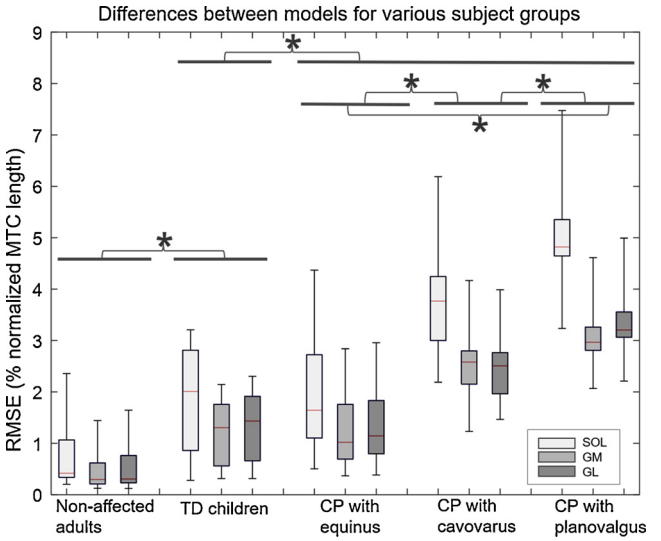

Fig. 5. Boxplots showing the RMSE values between mono- and multi-SFM MTC lengths for the various subject groups. Asterisks represent the main significant differences between subject groups. TD = typically developing.

MTC lengths between a mono- and multi-SFM is not larger in children with CP and an equinus deformity compared to typically developing children.

The larger effect of a multi-SFM in the stance compared to swing phase may be due to higher midfoot ROM (foot deformation) in stance due to loading on the foot [10]. Even though differences in MTC lengths between a mono- and multi-SFM were larger in the stance phase, some differences were also found in the swing phase. These are probably caused by a static offset in plantar/dorsiflexion angle of the ankle between the mono- and multi-SFM due to a different marker model definition. A reduction in ROM within the foot and ankle during the stance phase of gait with advancing age [10] explains the larger MTC length differences for typically developing children compared to non-affected adults. To conclude, larger RMSE values in the stance phase and in typically developing children compared to non-affected adults are assumed to be caused by different degrees of foot deformation and more internal foot ROM in the stance phase.

In this study, markers on the skin were used to calculate MTC lengths. Skin-mounted markers are prone to soft tissue artefacts (i.e. movement of the marker relative to the bone) [20]. Since the markers used in the mono-SFM were also present in the multi-SFM, soft tissue artefact would predominantly result in a systematic error, which might influence the accuracy of the estimation of MTC lengths, but not the differences between mono- and multi-segment foot models and therewith the conclusions of this study. Although significant and considerable differences in MTC lengths between a mono- and multi-SFM were found in this study, it is not clear whether this would really influence the current clinical decision making based on MS modelling. However, these results are of importance for the further development of MS models, especially in children with CP that present a foot deformity, and therewith for future clinical decision making and treatment evaluation. MTC lengths in this study were estimated by MS modelling. A more direct measure like ultrasound [19] might be a method for future studies to evaluate the outcomes of this study. Furthermore, MS modelling involves certain assumptions. It was for instance assumed that muscle paths and bone shapes did not deviate from the generic model. However, it is known that children with CP often have torsions in long bones [1]. To acquire a more patient-specific MS lower limb model, such bony torsions should be included, but this would probably have limited effect on the differences between the models, since both would be influenced by the same error.

This study has shown that simulated triceps surae MTC lengths depend on the type of foot model that is used. Since a multi-SFM is able to represent midfoot motion, it can be assumed that this model is more representative for a wide variety of feet. Therefore, a multi-SFM should

be preferred for MS modelling of triceps surae MTC lengths, especially in patients with foot deformities.

Funding

This work was supported by both the Gerrit-Jan van Ingen-Schenau promising young scientist 2018 award and the Amsterdam Movement Sciences Innovation Student call 2018.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

Acknowledgements

The authors would like to thank the subjects for their time and willingness to participate in this research. This work was supported by both the Gerrit-Jan van Ingen-Schenau promising young scientist 2018 award and the Amsterdam Movement Sciences Innovation Student call 2018.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2020.01.010.

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