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published in
Journal of Biomechanics
2020

DOI (link to publisher)
10.1016/j.jbiomech.2019.109532

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Download date: 28. Oct. 2023
Foot flexibility confounds the assessment of triceps surae extensibility in children with spastic paresis during typical physical examinations

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Article info
Article history:
Accepted 18 November 2019

Keywords:
Joint range of motion
Typical development
Foot deformation
Cerebral palsy

Abstract
Accurate assessment of the talo-crural (ankle) joint angle at physical examination is important for assessing extensibility of m. triceps surae (TS) in children with spastic cerebral paresis (SCP). The main aim of this study was to quantify foot flexibility during standardized measurements of TS muscle-tendon complex extensibility (i.e. based on foot-sole rotation) in SCP children, and typical developed (TD) ones. Additionally, we aim to define a method that minimizes the confounding effects of foot flexibility on estimates of talo-crural joint angles and TS extensibility.

Children, aged 6–13 years, with SCP (GMFCS I-III, n = 13) and TD children (n = 14) participated in this study. Externally applied 0 Nm, 1 Nm and 4 Nm dorsal flexion foot plate moments were imposed. Resulting TS origin-insertion lengths, foot sole rotations (\(\varphi_{\text{FoSo}}\)) and changes in talo-crural joint angle (\(\varphi_{\text{TaCr}}\)) were measured. Foot flexibility was quantified as \(\Delta(\varphi_{\text{TaCr}} - \varphi_{\text{FoSo}})\) between the 0 Nm and 4 Nm dorsal flexion conditions.

In both groups, \(\varphi_{\text{FoSo}}\) rotations of approximately 20° were observed between 0 Nm and 4 Nm dorsal flexion, of which about 6° (\(\approx 30\%\)) was related to foot flexibility. Foot flexibility correlated to \(\varphi_{\text{FoSo}}\) (\(r = 0.69\)) but not to \(\varphi_{\text{TaCr}}\) (\(r = 0.11\)). For \(\varphi_{\text{FoSo}}\) no significant differences were found between groups at 4 Nm. However, for SCP children the mean estimate of \(\varphi_{\text{TaCr}}\) was 4.3° more towards plantar flexion compared to the TD group (\(p < 0.05\)). Normalized TS lengths show a higher coefficient of correlation with \(\varphi_{\text{TaCr}}\) (\(r^2 = 0.82\)) than with \(\varphi_{\text{FoSo}}\) (\(r^2 = 0.60\)), indicating that TS lengths are better estimated by talo-crural joint angles.

In both SCP and TD children aged 6–13 year, estimates of TS length and extensibility based on foot sole assessments are confounded by foot flexibility. Assessments of TS extensibility at physical examination will be more accurate when based on measurements of talo-crural joint angles.

1. Introduction

Children with spastic cerebral paresis (SCP) often develop a limited ankle dorsiflexion range of motion, that impedes walking performance. This impairment may be caused by (1) hyper excitation and/or by (2) increased stiffness of TS or parts thereof and/or (3) relative shortening of the muscle-tendon complexes because of soft tissue adaptations (van den Noort et al., 2017; de Bruin et al., 2014), and/or (4) by interaction of TS with other muscles and tissues (Huijing and Baan, 2001).

Because of the anatomical specifics of the talo-crural joint, it is not easy to measure the talo-crural joint angle precisely during physical examination. In clinical practice, but also in sports sciences and in general in biomechanics (Honert and Zelik, 2016; Bobbert et al., 1986; Vinti et al., 2018), assessment on TS extensibility is commonly inferred from foot sole range of motion being interpreted as ankle joint range of motion. Typically, at physical examination, the examiner applies force on the forefoot driving the foot manually into dorsal flexion to test, either by observation (estimation) or by measurement (handheld goniometry or inclinometry), how much change in orientation of the foot sole is affected (Gracies et al., 2010; Tardieu, 1954). This is referred to as dorsal ankle range of motion and commonly interpreted as being related directly to TS extensibility (e.g. Weide et al., 2015). Note that such a proportional relation between TS extensibility and foot sole rotation, mostly implicitly, assumes a rigid foot (e.g. Tardieu et al., 1976).
Over the last 40 years several studies have shown that this assumption is violated because, the foot deforms internally upon application of external forces (Iwanuma et al., 2011; Tardieu et al., 1976; Wrbaškic and Dowling, 2007; Tardieu et al., 1977a; Carlson et al., 2000; Huijing et al., 2013; Bruening et al., 2012). Moreover, in SCP children, such foot flexibility was found to be more prominent when compared to that in developing (TD) children (Huijing et al., 2013; Tardieu et al., 1977a).

In view of the above, to allow accurate assessment of TS extensibility during physical examination, net effects of foot flexibility need to be accounted for. A method is needed to discriminate between foot sole rotation due to deformation within the foot and due to actual angular talo-crural joint changes. Such an approach has been proposed as early as 1977 by Tardieu et al. (1977a). They estimated talo-crural joint angular changes by correcting the foot sole angle with an estimate of foot flexibility.

Inspired by the approach by C. Tardieu, the aim of this study was to quantify foot deformations during standardized TS extensibility assessments in children with spastic cerebral paresis and compare results to those of typically developing children. Additionally, we aim to define a method that minimizes the confounding effects of foot flexibility on estimates of talo-crural joint angles.

2. Methods

2.1. Subjects

Thirteen children aged 6–13 years with uni- or bilateral Spastic Cerebral Paresis (SCP) (GMFCS I-III) (Palisano et al., 1997) were selected from a population visiting the Amsterdam University Medical Centre. Selected children for the SCP group had not undergone any surgical intervention of the muscles of the lower limb, nor chemical denervation (Botulinum toxin-A) 6 months prior to the measurements. A sample of typically developing children (TD) within the identical age range participated as the control group. In addition, for both groups, the presence of any other disability assessments in children with spastic cerebral paresis and compare results to those of typically developing children. Additionally, we aim to define a method that minimizes the confounding effects of foot flexibility on estimates of talo-crural joint angles.

2.2. Anthropometry

Body mass, body height, and foot length were measured. Lower leg length of the target leg was approximated as the mean of distances, measured medially and laterally, from the most prominent point of each femur epicondyle to the most prominent point of the corresponding malleolus. Mean malleoli height was defined as the mean of the distances measured medially and laterally from the most prominent point on the malleolus perpendicular towards the foot sole. These measurements were done using a 3D pointing stylus, tracked by a motion capture system (NDI Optotak 3020).

2.3. Electromyography

In order to assess muscle excitation during inclino-dynamometry, as well as during foot sole and 3D stylus measurements, surface electromyography (EMG) of gastrocnemius lateralis and tibialis anterior muscles were collected (MOBI, TMS-International, The Netherlands). Preparation of the skin and placements of the EMG electrodes were performed according to SENIAM instructions (Hermens et al., 1999). Using a multichannel system EMG signals were A/D converted at 1024 Hz and recorded synchronously on a PC. Prior to the measurements, participants were asked to perform a 5 s isometric maximal voluntary contraction (MVC, against resistance supplied by the assessor) towards dorsal and plantar flexion.

2.4. Inclino-dynamometer: Externally applied ankle moments induced foot plate angles

Subjects were lying prone on the examination table with both feet hanging over the edge (allowing free movements of the feet). The orientation of the selected foot was imposed using a custom designed apparatus (Bénard et al., 2010), comprising an adjustable foot plates and a torque wrench equipped with an inclinometer for angular measurements (this system will be referred to below as inclino-dynamometer) (Bénard et al., 2010; Huijing et al., 2013). The inclino-dynamometer was connected to the adjustable foot plate (Fig. 1A). Similar to the stabilization of the foot performed during physical examination, as well as during fitting of an ankle-foot orthoses, this foot plate allows adjustments targeted to stabilize the subtalar joint as much as possible during foot sole rotations (Huijing et al., 2013). In short: (1) Positioning of the calcaneus in a neutral position under the tibia. (2) Adduction of the foot until the midline of the calcaneus points between 2nd and 3rd ray of the forefoot. (3) Applying additional fore and midfoot supination until no movement within the subtalar joint can be detected by palpation (Huijing et al., 2013). To ensure that we moved the foot sole into dorsal flexion within the sagittal plane we carefully moved the arm of the hand-held inclino-dynamometer within the longitudinal orientation of the tibia.

Fig. 1. Schematic representation of assessment of the foot and triceps surae length. A. Schematic representation of experimental setup: in grey inclino-dynamometer attached to the foot plate. White star indicates the points of application of moments exerted. Red line: used in assessments of foot sole angle (\(\Omega_{\text{FoSo}}\)). Green line: origin to insertion length (\(\Omega_{\text{OI}}\)) of the triceps surae (TS). Blue line: estimated talo-crural joint angle (\(\Omega_{\text{TaCr}}\)). Green filled circles represent the anatomical landmarks from a sagittal perspective (i.e. medial and lateral femur epicondyles, medial and lateral malleoli and TS insertion on the calcaneus). The resultant angle colored in yellow between \(\Omega_{\text{TaCr}}\) and \(\Omega_{\text{OI}}\) represents the relative orientation of the line between the insertion and center of the bis-malleolar line with respect to the foot plate (\(\Omega_{\text{TaCr}} - \Omega_{\text{OI}}\)). B. Schematic representation of foot flexibility for a hypothetical situation in which foot flexibility \(\Delta\) (\(\Omega_{\text{TaCr}}\) - \(\Omega_{\text{OI}}\)) fully explains foot sole dorsal flexion (\(\Omega_{\text{FoSo}}\)) without any changes in talo-crural joint angle (\(\Omega_{\text{TaCr}}\)) and without changes in triceps surae length \(\Delta\) (\(\Omega_{\text{OI}}\) - stem) in response to 0–4 Nm externally applied moments. (For interpretation of the references to the colors in this figure legend, the reader is referred to the web version of this article.)
2.5. Foot sole angle and 3D stylus measurements

Foot sole angles were measured corresponding to externally applied dorsal flexion moments (i.e. −1 Nm, 0 Nm, 1 Nm and 4 Nm exerted to the foot plate). The angle of the foot sole was measured as the angle between the lateral rim of the foot sole (defined as the line between the most distal point at the lateral heel and the most distal point of the fifth metatarsophalangeal joint) and the lower leg (i.e. the line connecting the center of the bi-malleolar line and the center of the line connecting the femoral epicondyles) (Fig. 1). At each foot sole angle, 3D coordinates of bony-landmarks (i.e. medial and lateral femur epicondyles, medial and lateral malleolus and triceps surae muscle insertion on the calcaneus) were recorded using the 3D stylus measurements.

2.6. Data analysis

For each externally applied moment condition, foot sole angle, muscle-tendon complex length and estimates of talo-crural joint were calculated based on 3D pointer measurements. Angles of the foot sole and talar-calcaneal joint were presented with a 90° offset, e.g. a foot sole angle of 0° corresponds to foot sole orientated perpendicular with respect to the lower leg. The distance related to the muscle-tendon complex length, was defined as the distance between the estimated muscle origin to the point of insertion (being referred to as origin-insertion distance (OI)), i.e. from the center of the line between the femur epicondyles to the location of insertion on the calcaneus). Note that this line does not necessarily have to pass through the muscle belly and tendon.

As a function of \( \varphi_{\text{FOSO}} \), a third-order polynomial fit of muscle–tendon complex lengths, normalized for lower leg length, was made to allow comparison at identical \( \varphi_{\text{FOSO}} \) between subjects. Talar-calcaneal joint rotation (\( \varphi_{\text{TaCr}} \)) was estimated as the difference in angle between the line connecting the Achilles tendon insertion to the center of the inter-malleolar line and the lower leg (Fig. 1A). Both values of \( \varphi_{\text{TaCr}} \) and \( \varphi_{\text{FOSO}} \) are presented as a deviation from their perpendicular orientation (i.e. an offset) with respect to the lower leg. Angle, angular changes and external moments in the dorsal direction are indicated as positive values.

We used a simple planimetric approach to compare \( \varphi_{\text{TaCr}} \) and \( \varphi_{\text{FOSO}} \) in the rotational plane (i.e. sagittal plane) (see Fig. 1). Our estimate of foot deformation is expressed as the difference between \( \varphi_{\text{TaCr}} \) and \( \varphi_{\text{FOSO}} \) measured at 0 Nm externally applied footplate moment: \( \varphi_{\text{TaCr},\varphi_{\text{FOSO}},0\text{Nm}} \). Net foot flexibility was defined as the change in \( \varphi_{\text{TaCr},\varphi_{\text{FOSO}},0\text{Nm}} \) between 0 Nm and 4 Nm externally applied moments \( \Delta(\varphi_{\text{TaCr},\varphi_{\text{FOSO}},0\text{Nm}}) \) (Fig. 1B).

EMG signals were high-pass filtered at 20 Hz, to eliminate movement artefacts; then rectified and subsequently low-pass filtered at 5 Hz, to get the linear envelope. MVC normalized EMG values were used to assess the amount of muscle excitation during the measurements. MVC normalized experimental results were discarded if low pass filtered MVC normalized EMG values from inclino-dynamometer and pointer measurements exceeded 10% of MVC. However, actual values measured during the experiments were considerably lower.

2.7. Statistics

For age, body mass, body height, lower leg length, foot length and malleoli height, a student t-test was used to test for significant differences between SCP and TD children. Two-Way mixed ANOVA with between subject factor (experimental group) and within subject factor (conditions: externally applied moment) was performed to test for interaction effects (group × condition) and main effects of group. Note that two participants could not be included in this analysis because of missing data points (in 1 SCP participant the −1 Nm plantar flexion condition is missing and in 1 TD participant the 4 Nm dorsal flexion condition is missing).

Pearson’s correlation regression analyses were used to determine correlation and direction of the linear relationship of foot deformation (i.e. \( \varphi_{\text{TaCr}} \) or \( \varphi_{\text{FOSO}} \)) and angles of the foot (i.e. \( \varphi_{\text{TaCr}} \) and \( \varphi_{\text{FOSO}} \)).

In order to evaluate the agreement between the TS extensibility measured directly (\( \ell_{\text{OI}} \)) versus the estimated TS extensibility via the \( \varphi_{\text{TaCr}} \) or \( \varphi_{\text{FOSO}} \) assessments, we converted the data from all conditions to Z-scores (Z-score = (individual values-mean value of group)/SD). Agreements between TS extensibility (determined as normalized difference in \( \ell_{\text{OI}} \) between 0 Nm and 4 Nm) and the estimated TS extensibilities (i.e. Z-scores based on \( \varphi_{\text{TaCr}} \) and \( \varphi_{\text{FOSO}} \)) were assessed using Bland-Altman analysis (Bland and Altman, 1999). For all statistics we used SPSS (version 21.0, SPSS Inc., 2008). The level of significance was set at \( p < 0.05 \).

3. Results

3.1. Subject characteristics

Characteristics for SCP (GMFCS (Palisano et al., 1997) characterization I-III) and TD children are presented in Table 1. No significant mean differences between these groups were found. In addition, a distribution of SCP specific patient characteristics (GMFCS, uni/bi-lateral, foot) are presented in Table 1 for the SCP group.

3.2. Degree of muscle excitation

During measurements, normalized EMG activity was low (mean = 2.2% MVC) and not different between groups. In addition, all measurements were well below the criterion a priori set at 10% MVC. Therefore, we conclude that the results are not affected by muscle excitations.

3.3. Normalized TS origin-insertion length as a function of foot sole angles

Fig. 2 shows TS origin-insertion length normalized for lower leg length, as a function of foot sole angle. Note that mean values for \( \ell_{\text{OI}}/\ell_{\text{lowerleg}} \) as a function of \( \varphi_{\text{FOSO}} \) for the SCP children are within the 95% confidence interval of the TD children (shaded area), and vice versa.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Descriptive and anthropometric variables of SCP and TD children and a distribution of patient characteristics.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCP (n = 13)</td>
<td>TD (n = 14)</td>
</tr>
<tr>
<td><strong>Age (years)</strong></td>
<td>9.7 ± 0.6</td>
</tr>
<tr>
<td><strong>Body mass (kg)</strong></td>
<td>33.2 ± 2.7</td>
</tr>
<tr>
<td><strong>Body Height (cm)</strong></td>
<td>136.8 ± 3.5</td>
</tr>
<tr>
<td><strong>Lower leg length (cm)</strong></td>
<td>31.2 ± 1.1</td>
</tr>
<tr>
<td><strong>Foot length (cm)</strong></td>
<td>20.7 ± 0.7</td>
</tr>
<tr>
<td><strong>Malleoli height (cm)</strong></td>
<td>7.9 ± 0.2</td>
</tr>
<tr>
<td><strong>Patient characteristics</strong></td>
<td></td>
</tr>
<tr>
<td><strong>GMFCS (I/II/III)</strong></td>
<td>(3/9/1)</td>
</tr>
<tr>
<td><strong>Foot (pes planovalgus/pes planus/normal)</strong></td>
<td>(5/5/3)</td>
</tr>
<tr>
<td><strong>Affected</strong> (unilateral/bilateral/unknown)</td>
<td>(2/10/1)</td>
</tr>
</tbody>
</table>
3.4. Normalized TS origin-insertion length as a function of externally applied moments

Also, for changes in normalized TS origin-insertion length ($\Delta l_{OI}/l_{lower\ leg}$) ANOVA showed a significant main effect for externally applied moments exclusively (F(3,69) = 86.43, p < 0.01). Note that, as there was no main effect of group (F(1,23) = 2.56, p = 0.12), nor a significant interaction effect (F(3,69) = 2.1, p = 0.14). This indicates that no distinction in normalized TS $l_{OI}$ between these groups can be made over the particular range of externally applied moments studied.

3.5. Foot sole and talo-crural joint changes

Fig. 3A shows values of $\varphi_{FoSo}$ and $\varphi_{TaCr}$ as a function of externally applied moments. For $\varphi_{FoSo}$, two-way mixed ANOVA showed neither a significant main effect of groups (F(1,23) = 1.53, p = 0.23), nor interaction (F(3,69) = 0.14, p = 0.78). Exclusively, a significant main effect of externally applied moments on $\varphi_{FoSo}$ was found (F(3,69) = 197.72, p < 0.01). These findings show that the present two groups cannot be distinguished statistically based on $\varphi_{FoSo}$ changes in response to externally applied moments.

For $\varphi_{TaCr}$, ANOVA showed no interaction effects (F(3,69) = 0.20, p = 0.71) between main factors, however it did show a main effect of group: the $\varphi_{TaCr}$ curve having shifted 4.3° more towards plantar flexion for the SCP group compared to the TD group (F(1,23) = 5.54, p = 0.03). In addition, ANOVA showed main effects of externally applied moments for $\varphi_{TaCr}$ (F(3,69) = 133.45, p < 0.01).

In summary, at similar externally applied moments, the corresponding values for $\varphi_{TaCr}$ were more towards plantar flexion in the SCP group, however $\Delta(\varphi_{TaCr})_{0-4Nm}$ over the range of externally applied moments was not different between groups. In conclusion, between groups, no differences in changes of $\varphi_{FoSo}$ and $\varphi_{TaCr}$ over the range of externally applied moments were found.

3.6. Foot deformation

Fig. 3A + B shows that between 0 and 4 Nm externally applied dorsal flexion moments $\varphi_{FoSo}$ increased more compared to $\varphi_{TaCr}$. Note that for both groups, lines corresponding to $\varphi_{FoSo}$ and $\varphi_{TaCr}$ diverge with respect to each other, particularly at higher moments (at >0 Nm) (Fig. 3A). Upon dorsal flexion of the foot by increasing externally applied moments from 0 Nm to 4 Nm, dorsal flexion range, $\Delta(\varphi_{FoSo})_{0-4Nm}$ exceeded $\Delta(\varphi_{TaCr})_{0-4Nm}$. This indicates that with higher applied moments, deformations within the foot increased. In both groups, $\varphi_{FoSo}$ rotations of approximately 20° were observed between 0 Nm and 4 Nm dorsal flexion, of which about 6° (±30%) was related to foot flexibility. Since the value of foot sole rotation exceeds the value of talo-crural joint rotation in both groups, it is concluded that foot flexibility $\Delta(\varphi_{TaCr} - \varphi_{FoSo})$ occurs in both groups. In addition, since values of $\varphi_{TaCr} - \varphi_{FoSo}$ over the range of externally applied moments are not different between groups, we cannot conclude foot flexibility to be more prominent in the SCP group compared to the TD group.

3.7. Individual variation in foot sole rotation is largely explained by individual variation in foot deformation

Although no difference in $\varphi_{TaCr} - \varphi_{FoSo}$ could be shown between groups, regression analysis shows that individual values of $\varphi_{TaCr} - \varphi_{FoSo}$ at 0 Nm, were correlated to $\varphi_{FoSo}$ at 0 Nm (r = -0.67, Fig. 4A). This is a surprising effect, indicating that at 0 Nm external moment, individuals who have flatter foot (i.e. smaller values of $\varphi_{TaCr} - \varphi_{FoSo}$ at 0 Nm) attain a more dorsal flexed foot sole at 0 Nm external moment exerted ($\varphi_{FoSo}$) 0Nm. In addition, regression analysis showed that higher negative values of $\Delta(\varphi_{TaCr} - \varphi_{FoSo})_{0-4Nm}$ (i.e. more flexible foot) corresponded to a larger range of foot sole motion (r = -0.69) (i.e. higher values of $\Delta(\varphi_{FoSo})_{0-4Nm}$, Fig. 4B). These results indicate that individuals exhibiting more dorsal flexion of the foot sole also show more foot flexibility over the moment range studied. In other words, subjects with both a high value of $\varphi_{FoSo}$ at 0 Nm, as well as high value of $\Delta(\varphi_{FoSo})_{0-4Nm}$, were most likely the subjects with flatter and more flexible feet. Note that for $\varphi_{TaCr}$ in contrast to $\varphi_{FoSo}$, no such effects for flexibility were found (Fig. 4CD).

3.8. Estimates for origin-insertion length changes

Fig. 5 shows for Z-scores of normalized origin-insertion length a higher coefficient of correlation with Z-scores of $\varphi_{TaCr}$ (r² = 0.82) than with Z-scores of $\varphi_{FoSo}$ (r² = 0.60). This indicates that changes in origin-insertion lengths are better estimated by changes in...
B. Bland-Altman plot of Z-score differences between foot angle (of angle and TS length. Blue and red dotted lines represent the 95% confidence interval between normalized origin-insertion lengths data and moreover, Bland-Altman analysis (Fig. 5) shows a better agreement talo-crural joint angles compared to changes in foot sole angles. }

Fig. 4. Individual values of foot deformation plotted as functions of several angular variables of foot and ankle. Left hand panels (i.e. A and C): Foot deformation values at exertion of 0 Nm externally applied moment as a function of angular variables of foot (A) and ankle (C). A. Foot deformation \((\varphi_{\text{foSo}} - \varphi_{\text{foSo}})\) plotted as a function of foot sole angle \((\varphi_{\text{foSo}})\). C. Foot deformation \((\varphi_{\text{TaCr}} - \varphi_{\text{foSo}})\) plotted as a function of talo-crural ankle joint angle \((\varphi_{\text{TaCr}})\). Right hand panels (i.e. B and D): Foot flexibility in response to 0–4 Nm \((\Delta (\varphi_{\text{foSo}} - \varphi_{\text{foSo}})_{0-4N\text{m}})\) as a function of angular variables of foot (B) and ankle (D). B. Foot flexibility as a function of changes in foot sole angle \(\Delta (\varphi_{\text{foSo}})_{0-4N\text{m}}\). D. Foot flexibility as a function of changes in talo-crural ankle joint angle \(\Delta (\varphi_{\text{TaCr}})_{0-4N\text{m}}\). Note that panel B shows that subjects with larger dorsal flexion foot sole ranges between 0 and 4 Nm display increased foot flexibility. In addition, panel D shows that increases in talo-crural ankle joint range of motions, between 0 Nm and 4 Nm, were not related to increases in foot flexibility, whatever.

Fig. 5. Foot angular predictors of triceps surae (TS) lengths. A. Z-scores of normalized TS origin-insertion length (tou/lowerleg) as a function of Z-scores of foot angles, i.e. foot sole angles \((\varphi_{\text{foSo}})\) and talo-crural joint angles \((\varphi_{\text{TaCr}})\). The grey dotted line indicates the line of identity. B. Bland-Altman plot of Z-score differences between foot angle \((\varphi_{\text{foSo}})\) and \((\varphi_{\text{TaCr}})\), red squares, \((\varphi_{\text{foSo}})\) blue circles and TS length as a function of the mean Z-score between foot angle and TS length. Blue and red dotted lines represent the 95% confidence interval of \(\varphi_{\text{foSo}}\) and \(\varphi_{\text{TaCr}}\), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

talo-crural joint angles compared to changes in foot sole angles. Moreover, Bland-Altman analysis (Fig. 5) shows a better agreement between normalized origin-insertion lengths data and \(\varphi_{\text{TaCr}}\) than between normalized muscle-tendon complex lengths and \(\varphi_{\text{foSo}}\). Therefore, it is concluded that assessment of the talocrural joint angle improves estimation of triceps surae muscle origin-insertion lengths.

4. Discussion

In clinical and scientific work, assessments of TS extensibility is difficult because the talo-crural joint angle is not easily measured. A practical approach used to assess TS extensibility has been to assume a direct relation of foot sole rotation with TS extensibility. However, deformation of the foot (i.e. the forefoot rotating relative to the hindfoot) confounds TS extensibility assessments by allowing enhanced foot sole dorsal flexion at the midfoot.

Using a straightforward geometrical approach, we found that for both the SCP and TD groups, up to 30% of foot sole rotations was obtained by dorsal flexion within the foot, rather than at the talo-crural joint \((\varphi_{\text{TaCr}})\). Taking into account foot geometry and its changes provide insight in effects of foot flexibility on TS extensibility. This suggests that TS extensibility, if to be inferred from foot manipulations and likely also gait kinematics, should be based on measurements or estimates of talo-crural angular changes \(\Delta (\varphi_{\text{TaCr}})\) and not on foot sole angular changes \(\Delta (\varphi_{\text{foSo}})\). To obtain estimates of moment arm at the talo-crural joints based on angular changes and muscle-tendon complex length changes, the use of \(\Delta (\varphi_{\text{TaCr}})\) is advised.

4.1. Foot deformation in SCP and TD children

With regard to foot deformation in relation to TS length and extensibility, two elements can be distinguished: (1) differences in foot geometry present when no external moment is applied (i.e. static, described as static foot deformation) and (2) added deformation within the foot in response to higher externally applied moments (i.e. deformation, described here as foot flexibility). Previously, using ultrasound imaging methods, it was shown that muscle-tendon lengths even if normalized for lower leg length, at equal footplate angles were smaller in SCP children compared to that of TD children (Huijing et al., 2013). In addition, based on X-rays, that study also found that in a child with SCP deformation of the foot was twice that of a TD subject (Huijing et al., 2013). Excellent studies by the group of Tabary and Tardieu in the 1970’s did indicate that foot flexibility needs to be considered to obtain adequate estimates of the triceps surae extensibility in children with SCP (e.g. Tardieu et al., 1977b). We showed that in SCP children dorsal flexion within the mid foot occurs. However, contrary to our expectation, ANOVA did not show differences between SCP and TD groups, neither for static foot deformation nor foot flexibility. This may be related to our limited group size in the presence of high individual variation, but also to the fact that SCP children in this study were only mildly affected, i.e. less than in previous work. We were anticipating a more compliant subtalar joint in children with SCP, so our targeted stabilization of the subtalar part of the hind foot (see method) may also have been successful to decrease foot flexibility in children with SCP to equal extents compared to TD children. Further research is needed to quantify how effects of stabilization or repositioning bones constituting the foot affects foot deformities in SCP children. Altogether, we found 30% differences between \(\Delta (\varphi_{\text{foSo}})\) and \(\Delta (\varphi_{\text{TaCr}})\) rotations, indicating that foot flexibility in both SCP and TD children was apparent.

4.2. Typical assessments of TS extensibility and flexibility of the foot

In a common clinical setting, although attempts are made to stabilize the foot, TS extensibility assessments based on foot sole
rotation are biased by foot flexibility. The relation between angular change of the foot sole and TS extensibility has been shown in cadaveric tendon excursion studies (Grieve et al., 1978). Note that because the Achilles tendon was cut in that study, driving the foot into dorsal flexion can be done at low force (i.e. without the need to stretch the TS) so it evokes limited or no foot flexibility in fixed preparations compared to in-vivo or in-situ experiments. Maybe because of this, numerous studies aiming to assess TS length or its extensibility ignored effects of foot flexibility and confused foot sole angle with ankle angle (Weide et al., 2015; Kawakami et al., 2008; Muraoka et al., 2005).

Moreover, in the intact ankle-foot complex, forces that are applied on the foot in cadaveric experiments lead to sizeable (spring like) flexion or extension within the foot (Ker et al., 1987). So far only a few studies have addressed foot flexibility during low activity dynamic TS extensibility assessments in-vivo (Iwanuma et al., 2011; Tardieu et al., 1977a; Huijing et al., 2013). Variations in flexibility of the foot are likely related to variations in both length, and stiffness of muscles and ligamentous structures connecting the 28 bones within the foot (Mosca, 2010). In addition, internal foot mechanics have a substantial effect on foot sole angles and malleoli, to estimate TS extensibility in response to dorsal flexion moments is related primarily to rotation within the sagittal plane at the talo-crusal joint axis that lengthens TS. We defined changes in the talo-crusal joint as the changes in orientation of the line connecting the Achilles tendon insertion and the center of the inter-malleolar line, with respect to the lower leg. Since angular changes will also be affected by movement of the calcaneus relative to the talus or translation of the malleoli with respect to the talus, our estimate is not strictly an estimator of the talo-crusal joint movement. The suggested estimate of talo-crusal joint rotation provides an intuitive approach to estimate talo-crusal ankle joint angles without the use of X-ray or fluoroscopy allowing to measure more subjects. However, not all individual TS lengths could be explained by estimated talo-crusal joint angles, which besides measurement noise, could be related to variations in moment arm lengths and as the talo-crusal joint axis is likely to translate due to specific articulating bone surfaces it could also be related to inaccurate assessments of the joint axis (Lundberg et al., 1989). Incorrect placements of the line connecting the insertion and malleoli, to estimate \( \theta_{TAC} \) will introduce inaccuracies. Nevertheless, our estimate of TS extensibility based on talo-crusal joint rotation is an improvement over foot sole based measurements.

5. Conclusion

It is concluded that for the foot dorsal flexion range studied, internal foot mechanics have a substantial effect on foot sole angles attained particularly at higher externally applied dorsal flexion moments. Therefore, estimates of triceps surae muscle length changes based on interpretation of foot sole angles are not accurate, and should be based on the talo-crusal joint angles or assessment of TS length instead. Further investigations are warranted to study underlying mechanisms of foot deformation and flexibility, particularly in children with spastic cerebral paresis. In addition, further research before implementation is required to design concrete guidelines for assessment of talo-crusal joint rotations during clinical examinations.

Declaration of Competing Interest

The authors declares that there are no conflicts of interest.

Acknowledgements

We thank Lynn Bar-On, Lizeth Sloat and Erik Elings for their help during the measurements. The authors would also like to acknowledge and thank the participants and their families for their willingness to take part in this study.

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