Kalkman, BM, Bar-On, L, Cenni, F, Maganaris, CN, Bass, A, Holmes, G, Desloovere, K, Barton, GJ and O'Brien, TD

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Muscle and tendon lengthening behaviour of the medial gastrocnemius during ankle joint rotation in children with cerebral palsy

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Running title: Muscle properties in children with cerebral palsy

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Abstract

Children with cerebral palsy (CP) commonly present with reduced ankle range of motion (ROM) partly due to changes in mechanical properties of the muscle-tendon-unit (MTU). Detailed information about how muscle and tendon interact to contribute to joint rotation is currently lacking, but may provide essential information to explain the limited effectiveness of stretching interventions in children with CP. The purpose of this study was to quantify which structures contribute to MTU lengthening and thus receive the stretch during passive ankle joint rotation. Fifteen children with CP (age:11.4±3y) and 16 typically developing (TD) children (age:10.2±3y) participated. Ultrasound was combined with motion tracking, joint torque and electromyography to record fascicle, muscle and tendon lengthening of the medial gastrocnemius during passive ankle joint rotations over the full and a common ROM. In children with CP, relative to MTU lengthening, muscle and fascicles lengthened less (CP: 50.4%, TD: 63% of MTU lengthening; $p<0.04$) and tendon lengthened more (CP: 49.6%, TD: 37% of MTU lengthening, $p<0.01$) regardless of the ROM studied. Differences between groups in the amount of lengthening of the underlying structures during a similar amount of joint rotation and MTU displacement indicate possible differences in tissue mechanical properties due to CP, which are not evident by assessment on a joint level. These factors should be considered when assessing and treating muscle function in children with CP, for example during stretching exercises as the muscle may not receive much of the applied lengthening stimulus.

New Findings:

What is the central question of this study?

Which structures of the medial gastrocnemius muscle tendon unit contribute to its lengthening during joint rotation and thus receive the stretching stimulus?

What is the main finding and its importance?

We show for the first time, that muscle and tendon lengthen differently between children with CP and TD children during a similar amount of muscle tendon unit lengthening or joint rotation. This indicates possible differences in mechanical muscle and tendon properties due to CP, which is not evident by assessment of muscle function on a joint level.

Introduction

Cerebral palsy (CP) is a non-progressive disorder caused by a brain lesion occurring in the early stages of development (Graham *et al.*, 2016). Children with spastic CP usually show increased ankle joint stiffness and reduced range of motion (ROM) compared to typically developing (TD) children (Alhusaini *et al.*, 2010). It has been reported that muscles of children with CP undergo significant changes in their mechanical properties, which contribute to the reduced ROM (Mathewson & Lieber, 2015). In the management of CP, treatment is often aimed at maintaining or increasing ankle ROM. Stretching therapies are commonly used, assuming they can increase muscle length and/or reduce its stiffness (Zhao *et al.*, 2011; Theis *et al.*, 2015). However, we have recently demonstrated that improvements in ROM acutely after stretching are not caused by changes in muscle properties, but might be due to an increase in stretch tolerance (Kalkman *et al.*, 2018). This is corroborated by others who show that the effectiveness of long term stretching interventions to improve fascicle length and/or passive muscle stiffness is uncertain (Wiart *et al.*, 2008; Theis *et al.*, 2015; Craig *et al.*, 2016). To understand the reason for the limited effectiveness of these stretching therapies it is essential to know if the muscle fascicles are actually lengthening and receiving the stretch stimulus when rotating the joint, or whether other structures of the MTU take up the stretch.

Previous studies of medial gastrocnemius (MG) muscle architecture in individuals with CP using ultrasound consistently report shorter muscle bellies compared to TD subjects (Fry *et al.*, 2004; Barrett & Lichtwark, 2010). In addition, longer Achilles tendon has been reported in children with CP (Wren *et al.*, 2010; Barber *et al.*, 2012), which could be a compensation for the shorter muscle belly length when MTU length is similar. Furthermore, some studies have reported smaller resting muscle fascicle lengths in children with CP than TD children (Mohagheghi *et al.*, 2008; Matthiasdottir *et al.*, 2014), but others have not detected differences (Shortland *et al.*, 2002; Mathewson *et al.*, 2014). Inconsistencies can be

attributed to different normalisation procedures, small sample sizes and the heterogeneity of symptoms associated with CP.

From investigations of muscle lengthening (defined as the displacement of the MG muscle-tendon-junction relative to the origin of the muscle), we know that when passively rotating the joint in children with CP, the MG muscle belly lengthens less compared to TD children (Matthiasdottir *et al.*, 2014). However, it is the passive stiffness of a muscle relative to its tendon that has implications for treating impaired joint function, because this determines how these two structures interact when lengthened by joint rotation. In TD adults it has been shown that when stretched, muscle fascicles undergo much smaller changes in length than the whole muscle-tendon unit (MTU) and both the tendon and intramuscular connective tissue contribute significantly to increased MTU length during joint rotation (Herbert & Moseley, 2002; Morse *et al.*, 2008). It is not known how muscle belly and tendon lengthen relative to each other during passive joint rotation in children with CP. Furthermore, due to the pennate nature of the medial gastrocnemius muscle, the lengthening of its muscle belly will depend on both the properties of the muscle fascicles and the connective tissue that ties them together. A relation that has not been studied before.

In children with CP, the amount of MG fascicle lengthening during passive joint rotation shows inconsistent results, with some studies indicating that there is no difference (Matthiasdottir *et al.*, 2014), while others found less fascicle lengthening (Barber *et al.*, 2011) in CP vs TD. This discrepancy could possibly be explained by differences in the ROM over which the results are compared between groups. A decreased ROM in children with CP could confound findings when comparisons are made over the full ROM. In fact, any comparison between CP and controls over absolute joint angles is inherently limited, because differences in the muscle's moment arm (Kalkman *et al.*, 2017) and passive joint torque (Alhusaini *et al.*, 2010) will influence the joint angle-tissue lengthening relationship.

Therefore, in contrast to previous investigations, we aim to explore muscle fascicle, muscle belly and tendon lengthening simultaneously during passive joint rotation in order to understand which tissue takes up the stretch. Furthermore, we innovatively compare the lengthening of these tissues over different ranges, accounting for the interaction between joint and underlying structures, and allowing for more robust conclusions.

Ultrasound has proved a valuable tool to improve understanding of *in vivo* behaviour of muscle and tendon during contraction and joint rotation. However, a calculation of the tissues' mechanical properties during passive joint rotation is more difficult as several assumptions are inferred. The passive torque measured at the ankle is a combination of different muscles and passive structures, and the contribution of each force-bearing structure to the net joint torque cannot be quantified *in vivo* nor can it be assumed to remain constant throughout the ROM. Nevertheless, the resulting passive elongations of muscle and tendon in response to stretch allow drawing conclusions about the relative contribution of the muscular and tendinous structures to ROM.

In order to explain the lack of change in muscle properties after stretching in children with CP (Kalkman *et al.*, 2018), the purpose of this study was to quantify which structures contribute to MTU lengthening and thus receive the stretch stimulus during passive ankle joint rotation. We hypothesized that the muscle belly and the fascicles would lengthen less in CP compared to TD children and that the tendon would lengthen more.

Method

Ethical approval

The study was approved by the National Health Service research ethics committee in the UK (project no 15/LO/0856) and the University Hospital's ethics committee in Leuven, Belgium (project no. S S57384). The study was conducted in accordance with the *Declaration of Helsinki*. This study was not registered in

a database. Written parental consent was obtained and written assent was given by children in accordance with local regulations.

Participants

Fifteen Children with CP and sixteen TD children aged 6-16 years were recruited for participation through the gait lab of Alder Hey Children's NHS Foundation Trust in Liverpool, UK and the University Hospital in Pellenberg, Belgium. Patient characteristics can be found in table 1. Five of the TD children were assessed with the same protocol for a second time after a two-hour break to determine reliability of the full measurement protocol. Children with CP were excluded if they had Botulinum Toxin-A injection to the lower limb muscles 6 months prior to testing, a baclofen pump, any lower limb neuro- or orthopaedic surgery or less than 20 degrees of ankle movement in the sagittal plane (to ensure sufficient stretch in the medial gastrocnemius muscle). Patients had previously received on average 2.3 Botulinum Toxin-A injections All TD children were free from neuromuscular or skeletal disorders.

Experimental protocol

Participants lay prone on a bed with the lower leg supported on an inclined cushion such that the knee was ~20° flexed, the leg was positioned in a custom-made orthosis, to control ankle movement in the sagittal plane (Figure 1A; Part of the experimental protocol has been published previously (Kalkman *et al.*, 2018). The axis of rotation of the orthosis was aligned with the lateral malleolus. The foot was secured to a rigid footplate with the help of an adjustable insole that ensured heel contact with the footplate during ankle rotation. The leg tested was the most affected, defined by clinical spasticity scores (Tardieu *et al.*, 1954; Bohannon & Smith, 1987), and the left in TD. Each participant underwent two trials involving three passive movements by manually rotating the foot from maximal plantarflexion to maximal dorsiflexion aiming for a maximum angular velocity of 15±5 °/sec , which is slow enough to not elicit a stretch reflex (Bar-On *et al.*, 2013) and at least 10 seconds rest in between individual

repetitions (Bar-On *et al.*, 2013). The reliability of data measured using the same equipment has been previously reported (Schless *et al.*, 2015). Forces and torques around the ankle were measured at 200Hz using a six degrees-of-freedom force sensor load-cell (ATI mini45: Industrial Automation) attached to the orthosis under the ball of the foot. The point of attachment of the load-cell to the orthosis could be adjusted according to foot length. 3D kinematics were collected with 3 cameras at 120Hz from 2 clusters of 3 markers placed on the foot-plate of the orthosis and on the shank and a single marker placed on the most superficial part of the posterior calcaneal tuberosity (Optitrack, US). Surface electromyography (sEMG), placed on the middle of the muscle belly as defined with ultrasound, collected signals at 1600Hz from the lateral gastrocnemius and soleus muscles during all trials and from the MG during the trials measuring muscle belly lengthening (Zerowire, Cometa, Milan, IT). Raw EMG signals were filtered with a sixth-order zero-phase Butterworth bandpass filter from 20 to 500 Hz. The root mean square envelope of the sEMG (RMS-EMG) was extracted by applying a low-pass 30 Hz sixth-order zero phase Butterworth filter on the squared signal. When, during joint rotation the RMS-EMG signal exceeded 10% of the maximum voluntary contraction value (collected prior to the stretch trials), the corresponding trial was discarded (Haberfehlner *et al.*, 2015).

Ultrasound

A B-mode ultrasound scanner (Telemed Echoblaster, Lithuania) with a 59mm linear transducer rigidly fitted with a cluster of 4 markers was used to identify the location of the medial femoral condyle in a local reference frame defined by the shank cluster.

To define myotendinous junction (MTJ) displacement, the probe with cluster was securely fixed over the MG MTJ using a custom-made holder. The long axis of the probe was aligned with the line of action of the muscle to minimize out of plane movement. The MTJ was tracked at 30Hz in the local reference frame on the shank during the first three passive movements.

Then, because MTJ and fascicles of the MG could not be visualized simultaneously, the US probe was fixed over the MG muscle belly to measure fascicle lengthening at 60Hz during the second three passive movements. Guidance regarding probe alignment was adhered to for minimising measurement errors (Bénard *et al.*, 2009).

Data analysis

Data analysis was carried out using custom-made software (Matlab R2015a, Python 2.7.11). Anatomical calibration of the shank and foot reference frames was applied to obtain ankle angle (Leardini *et al.*, 2007). During movement, displacement of the MTJ was manually tracked (Figure 1B) and muscle and tendon lengths were defined as the linear distances between the medial femoral condyle and the MTJ; and between the MTJ and the marker on the calcaneus, respectively. The MTU length was defined as the summation of muscle and tendon length. A modified semi-automated tracking software (Cronin *et al.*, 2011; Gillett *et al.*, 2013) was used to track fascicle length (l_{fas}). Both aponeuroses and a fascicle were manually defined in the first frame of the video. Thereafter, the software automatically tracked and calculated fascicle length by extrapolating the defined fascicle to the intersection point with the defined aponeuroses during the movement. Pennation angle (α) was measured as the angle between the fascicle and the deep aponeurosis. Next, fascicle length resolved along the axis of the MTU was calculated trigonometrically: $l_{fas\_resolved} = l_{fas}/\cos\alpha$. The net ankle joint torque was calculated from the exerted torques and forces on the load-cell, measured external moment arms, and the predicted torque caused by gravity on the foot and orthotic (Bar-On *et al.*, 2013). All kinematic and kinetic variables were filtered using a 2nd order Butterworth filter with a cut-off frequency of 6Hz. Starting length (length at maximal plantar flexion angle) was subtracted from absolute muscle, tendon and fascicle length to compare lengthening of these structures over the full ROM and over a common ROM that could be achieved by all participants (-5° to -25°, with negative angles reflecting plantarflexion). Furthermore, all lengthening parameters were assessed over a common joint torque from 0Nm (defined

as slack length) to 3Nm and over a common amount of MTU lengthening (20mm). Muscle belly, fascicle and tendon lengthening was additionally expressed as a percentage of MTU lengthening. The parameters described above were calculated for the individual data curves. For visualization purposes, average curves were obtained by normalizing the trajectories of all variables to the stretch cycle and subsequently averaged over trials. These average curves are shown in Figure 2.

Statistics

All parameters were checked to be normally distributed using the Shapiro-Wilk test and by inspection of the q-q plots. All data were found to be normally distributed. The between session reliability in the TD children of lengthening parameters was analysed using intra-correlation coefficients (ICC, 3,k) and the standard error of measurement (SEM), calculated from one-way ANOVA. A 2-sample independent t-test was used to compare lengthening parameters between CP and TD groups. Relations between muscle and tendon lengthening, ROM and age were made using Pearsons r^2-values. All statistical analyses were performed in Matlab (Mathworks, R2015). The α-level was set at 0.05. Effect sizes were expressed as Hedge's g, values of ≈0.1, ≈0.2 and ≥0.3 may be roughly considered small, medium and large effects (Hentschke & Stüttgen, 2011).

Results

Intra-correlation coefficients of the inter-session reliability ranged from 0.70-0.90. The full results of the reliability analysis are shown in table 2. At the starting position of the passive movement (individual maximal plantarflexion), joint angle was not different between TD and CP groups (mean (SD); CP: -38.3° (7.2), TD: -36.6° (9.4), p=0.59, CI [-7.85 4.53]). At this angle, torque (CP: -1.5 (0.9) Nm, TD: -1.8 (0.5) Nm, p=0.25, CI [-0.22 0.81]), absolute muscle (CP: 164.1 (28.8) mm, TD: 174.7 (30.9) mm, p=0.4, CI [-32.47 13.4]), tendon (CP: 166.9 (29.6) mm, TD: 159.6 (24.7) mm, p=0.54, CI [-13.74 25.85]) and fascicle lengths

(CP: 25.0 (6.6) mm, TD: 28.4 (4.1) mm, p=0.08, CI [-7.34 0.42]) were not significantly different between children with CP and TD children.

Movements were performed with an average maximal angular velocity of 12.7 (4.2) °/s. No movements were excluded due to inaccurate movement velocity. In the children with CP, eleven trials were excluded due to an elevated EMG signal. This equates to 10% of the total number of trials. A minimum of 2 trials per participant was available or analysis. The full ROM was 13° smaller towards dorsiflexion in the CP group. Absolute muscle and fascicle lengthening over full ROM were on average 9mm smaller in CP. Absolute tendon lengthening was similar between groups. Over the common ROM that could be achieved by all participants (-25° to -5°) absolute muscle and fascicle lengthening was on average 3mm smaller in CP and absolute tendon lengthening did not differ between groups. At -5°, being the most dorsiflexed position all participants could achieve, joint torques were significantly larger in children with CP (2.34 (1.77) Nm) than TD children (0.49 (0.94) Nm). Over a common joint torque (0 Nm to 3 Nm), absolute muscle and fascicle lengthening was on average 3.2 mm smaller in CP, and absolute tendon lengthening did not differ between groups. When analysed over a common range of MTU lengthening (20mm), absolute muscle and fascicle lengthening were on average 2.5mm smaller in CP and absolute tendon lengthening was on average 2.6 mm larger in CP. Finally, when expressed as a percentage of MTU lengthening, relative muscle lengthening was smaller and relative tendon lengthening larger in children with CP over all the studied ROMs (Table 3, Figure 2).

Pennation angle was not different between groups regardless the range over which it was studied ($p>0.05$). Fascicle lengthening resolved along the axis of the MTU was 8.2 (3.2) mm and 11.5 (2.0) mm respectively for CP and TD children over the common ROM ($p<0.01$). Over the full ROM this was 16.3 (6.3) mm and 26.5 (7.0) mm for CP and TD children ($p<0.01$).

Muscle lengthening increased significantly with age in TD children while in children with CP, tendon lengthening increased with age (Figure 3). Significant correlations were found between muscle and tendon lengthening with ROM in children with CP (Figure 4).

Discussion

Regardless of whether groups were compared according to common joint angle, joint torque, or relative to MTU lengthening, muscle and fascicle lengthening were always smaller in children with CP than TD children (Table 3). This confirms previous findings of smaller muscle and fascicle lengthening during passive ankle dorsiflexion in children with CP (Barber *et al.*, 2011; Matthiasdottir *et al.*, 2014). By simultaneously studying the relative contributions of the muscle and tendon to MTU lengthening, we also found that in TD children the muscle lengthens more than the tendon (63:37%) while in children with CP they lengthen equally (50:50%). This indicates greater stiffness of the muscle relative to tendon in children with CP than TD. Our data cannot distinguish whether this difference is caused by a stiffer MG muscle (Friden & Lieber, 2003), or by a longer tendon (Wren *et al.*, 2010; Barber *et al.*, 2012), making it more compliant in children with CP. However, the joint moments required to lengthen the muscle-tendon unit are greater in children with CP (Alhusaini *et al.*, 2010) and others have reported Achilles tendon stiffness not to be different between CP and TD (Theis *et al.*, 2016). Therefore, it is reasonable to conclude that an increased muscle stiffness contributes more to a difference in the relative lengthening between muscle and tendon as observed in this study. However, regardless of whether the explanation lies in the muscle, tendon or a combination, this reduced stretch at the muscle relative to the tendon might explain the lack of change in muscle properties both acutely (Kalkman *et al.*, 2018) and after long term (Theis *et al.*, 2015) stretching interventions.

Previous studies on muscle properties in children with CP analysed fascicle lengthening only over the full (Barber *et al.*, 2011) or a common ROM (Matthiasdottir *et al.*, 2014). However, due to differences in

Achilles tendon moment arm (Kalkman *et al.*, 2017) and joint stiffness (Alhusaini *et al.*, 2010) between TD and CP participants, comparison of lengthening parameters between groups only in terms of joint angles should be interpreted with caution. When data is analysed over a common ROM, it should additionally be noted that this common ROM could be at a different position relative to the full ROM in individual children and that children with CP develop torque earlier in their ROM. In this study the torque at the limit of the common dorsiflexion range (-5°) was higher in children with CP compared to TD children. To circumvent these issues, we compared our data in two additional ways. Firstly, over a common torque range to assure a similar stretching stimulus to the MTU. However, joint torque is also affected by differences in Achilles tendon moment arm, co-contraction and intrinsic joint stiffness. Therefore, lengthening values were additionally compared over a common MTU lengthening. Nevertheless, irrespective of the method used, we always found that relative to MTU lengthening, muscle lengthening is smaller and tendon lengthening larger in children with CP. This consistency confirms that the above changes in the mechanical behaviour of the MTU of children with CP are substantial and independent of the range used. However, when assessing the effect of an intervention or comparing different subgroups of children with CP, the differences may be less pronounced and the method of analysis will likely be important. This is a vital consideration when decomposing the causes of a reduced ROM in the clinical decision-making process.

This study, and others before us (Morse et al., 2008), observed a discrepancy between the amount of fascicle and muscle belly lengthening during a passive stretch. This decoupling of the elongation of the fascicles from that of the whole muscle can be explained by deformation of intra-muscular connective tissue (endomysium and perimysium), extra-muscular connective tissue (epimysium) and the aponeurosis (Lieber *et al.*, 2017). Additional analysis of the current data to explore fascicle:muscle lengthening showed that over a common ROM, muscle belly lengthening could be entirely explained by the resolved fascicle lengthening in both groups. This may imply that the increased resistance to stretch

of the muscle in children with CP results from similar changes in the lengthening characteristics of both the fascicles and passive connective tissue. When studied over the full ROM, average muscle belly lengthening in the CP group was 1.4mm larger than the resolved fascicle lengthening, while in the TD group muscle belly lengthening was equal to resolved fascicle lengthening. This could suggest that structures other than the fascicles, such as the perimysium and tissue between the fibres, deform to provide the additional lengthening required to achieve maximal dorsiflexion angles in children with CP, while in TD children this is not the case. Consistent with this interpretation, both intramuscular connective tissue (Malaiya *et al.*, 2007) and the expression of extracellular matrix production-related genes were found to be dramatically increased in spastic muscles and correlated with muscle mechanical properties, such as stiffness (Smith *et al.*, 2012).

It has been shown that muscle contractures already start developing at an early age in children with CP (Willerslev-Olsen *et al.*, 2013) and that growth is an important factor contributing to the development of contractures (Švehlík *et al.*, 2013). Therefore, it is important to capture the critical age at which treatment is most effective and consider the changes that occur in muscle-tendon properties with maturation. It has been reported that gastrocnemius muscle belly length increases with age in TD children (Bénard *et al.*, 2011; Weide *et al.*, 2015). However, muscle lengthening from 0 to 4Nm dorsiflexion torque, was not found to increase with age (Bénard *et al.*, 2011; Weide *et al.*, 2015). This is not supported by our data, since we found a tendency for muscle lengthening to increase with age in TD children (Figure 3). The inconsistency might be caused by differences in age range and methodology of applying the dorsiflexion torque. Interestingly, the increase in muscle lengthening with age was absent in children with CP, for whom tendon lengthening increased with age. This may indicate that muscle stiffness increases with age in children with CP, which is consistent with the progression of disease (Graham *et al.*, 2016). This is consistent with previous results showing impaired muscle growth and increased stiffness with age in children with CP (Willerslev-Olsen *et al.*, 2018) Additionally, it indicates a

possibility that the Achilles tendon acts as a compensation mechanism to partly preserve ROM, despite a shorter and stiffer muscle as children with CP grow.

The relative contribution of fascicle, muscle and tendon lengthening to ROM may be important in determining the best treatment. We show that both muscle and tendon lengthening are related to ROM in children with CP (Figure 4). A lack of this relationship in TD children shows that the MG does not play an essential role in determining their ROM. Stretching is often used to increase ROM in children with CP and is assumed to increase muscle length. However, the smaller muscle belly lengthening, caused by a change in the relative stiffness between muscle and tendon will lead to a smaller physiological stimulus, which may possibly explain the lack of effectiveness of stretching therapies (Wiart *et al.*, 2008). Altering the relative stiffness before starting stretching therapies, either by making the muscle less stiff, or by increasing the stiffness of the tendon might make stretching exercises more effective. The large variability amongst participants in the current study and those reported in literature suggests that patient- and muscle-specific information may be required to facilitate individualized treatment programs.

This study has some limitations. Currently, it is not possible to measure muscle and tendon stiffness during passive rotation in an intact joint, because there are no *in vivo* techniques to quantify forces in the muscle-tendon unit. However, the results of our study show less MG MTJ displacement in children with CP compared with TD children. Therefore, it is likely that in children with CP, the reduced contribution of the MG muscular component to MTU lengthening can, at least partly, be explained by an increased stiffness in the MG muscle. The SEM values of all parameters were lower than the average difference between groups, nonetheless, reliability of the calculated parameters was lower than expected based on Cenni *et al.*, 2018. Future studies could reduce possible sources of error by applying motorized instead of manual movements and automatic tracking algorithms for feature identification. In the current study, fascicle and tendon length were represented as straight lines, thus neglecting possible

effect of curvature. The influence of curvature has been reported to be small for passive fascicle length measurements in the MG (Muramatsu *et al.*, 2002). Neglecting tendon curvature leads to an overestimation of tendon lengthening in both groups especially at more plantarflexed ankle angles where the tendon is below slack length. Since we expect slack length to be at more plantarflexed angles in children with CP, an overestimation of tendon lengthening would be more likely in the TD children. Thus, controlling for tendon curvature would only amplify the between-group difference in tendon lengthening reported here. In addition, the methodology did not allow to visualise muscle belly and fascicle lengthening in the same trial. However, judged on the angle-time curves of the individual stretches, repetitions were considered repeatable between the two conditions. Also, in the TD children the leg tested was not randomized, but instead, always the left leg was assessed, which in most individuals would be the non-dominant leg. Since it is not known how limb dominance affects muscle lengthening, the lack of randomization for leg tested could have influenced our results. Furthermore, the effect of a single stretch on MTU properties has been shown to be negligible (Kalkman *et al.*, 2018). It is possible that previous treatments, i.e. Botulinum Toxin-A injections, received by the participants may have influenced the results of this study. Some studies show microstructural changes on the tissue level in animals (Pingel *et al.*, 2017) or observe an increase in muscle stiffness in *in silico* experiments (Wang *et al.*, 2018), while others report no changes in muscle stiffness (Alhusaini *et al.*, 2011) after Botulinum Toxin-A injections. Unfortunately, it is practically impossible to recruit a representative group of children with CP who have not had any interventions during their life. However, this does not confound the validity of the present results for the limited effect of the stretching intervention studied, as these interventions are applied regardless of Botulinum Toxin-A history. Finally, the exclusion of movements that showed muscle activation higher than a threshold helped minimize the effects of reflex-activity on the feature displacement. EMG activity during the analysed stretches was found to be

around 5% of RMS-MVC. However, small effects of background EMG activity below this threshold cannot be fully excluded.

In summary, this study demonstrates that when passively rotating the ankle joint to stretch the calf muscles, the tendon lengthens less than the muscle in TD children, while in children with CP, the muscle lengthens as much as the tendon. This suggests altered material properties of the muscle and tendon in children with CP. This should be considered when assessing and treating muscle function at joint level in children with CP, for example during stretching exercises.

Additional information

Competing interests

None declared.

Author contributions

Conception and design of the research: B.M.K., L.B., T.D.OB., C.N.M., K.D., G.H. and G.J.B. Data acquisition: B.M.K., L.B. and F.C. Data analysis: B.M.K. and L.B. Interpretation of the results: B.M.K., L.B., C.N.M., T.D.OB., A.B. and G.H. Drafting the manuscript: B.M.K. and L.B. Editing and revision of the manuscript: B.M.K., L.B., F.C., K.D., A.B., G.H., G.J.B., C.N.M. and T.D.OB. All authors have read and approved the final version of this manuscript and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All persons designated as authors qualify for authorship, and all those who qualify for authorship are listed.

Funding

This study was funded by a joint scholarship between Alder Hey Children's Hospital and Liverpool John Moores University and by grant 12R4215N from the Flemish Research Foundation (FWO), Belgium.

Acknowledgements

We thank Erwin Aertbeliën from the department of mechanical engineering, KU Leuven, for his help with the calculations of net joint torque.

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Figure Legends

Figure 1. A. Experimental design showing leg placement in a custom-made orthosis. A hand held force sensor load-cell was used to measure net joint torque at the foot plate during passive stretch. Two clusters of reflective markers on the shank and foot-plate were tracked with motion analysis and used to calculate the foot-plate angle in 3D. A single marker was placed on the most distal part of the calcaneus and additionally tracked in 3D using motion analysis. The ultrasound probe was placed above the medial gastrocnemius muscle-tendon junction (MTJ), or on the muscle belly, and the position and orientation of the image was tracked using motion analysis by means of a cluster of markers attached to the probe. **B.** Close-up of the foot attached with an insole to the foot plate of the orthotic. **C.** The MTJ was identified as the most distal insertion of the muscle into the tendon. **D.** Fascicle length was defined as the straight line distance between the upper and lower aponeurosis along the lines of collagenous tissue and pennation angle (α) was defined as the angle between the fascicle and the deep aponeurosis. With the exception of the ultrasound measurements, the same experimental setup was used in Kalkman et al. 2018.

Figure 2 Muscle/tendon length **(A)** and fascicle length **(B)** versus ankle angle with the common ROM indicated in shaded grey; Muscle/tendon length **(C)** and fascicle length **(D)** versus muscle-tendon-unit (MTU) length; muscle/tendon length **(E)** and fascicle length **(F)** versus ankle torque. 95% Confidence Intervals are shown at 4 representative time points.

Figure 3 Correlations between age and muscle **(A, B)**, tendon **(C, D)** and fascicle **(E, F)** lengthening across the range of motion (ROM) for children with cerebral palsy (CP) and typically developing (TD) children. A regression line is shown for significant relationships.

Figure 4 Correlations between muscle **(A, B)**, and tendon **(C, D)** lengthening and range of motion (ROM) in children with cerebral palsy (CP) and typically developing (TD) children. A regression line is shown for significant relationships.

Table 1. Participant characteristics

Participant characteristics	**CP (n=15)**	**TD (n=16)**
Age (years, months)	11y 5m (3y)	10y 4m (3y)
Male/female (n)	10/5	7/9
Height (cm)	142 (20.3)	138.1 (19.1)
Mass (kg)	36 (18)	35 (15)
Tibia length (mm)	339.7 (54.3)	329.4 (52.7)
GMFCS (I-IV) (n)	9 I, 6 II	n/a
Diagnosis (n)	8 Diplegia, 7 Hemiplegia	n/a
*Modified Ashworth Score(Bohannon and Smith, 1987) (n=7) and Average Modified Tardieu(Tardieu et al., 1954) (n=8)	MAS: 1.5 (n=6); 3 (n=1) Tardieu: 2 (n=5); 3 (n=3)	n/a
Botulinum toxin-A injections >6 months prior to the study date. Mean (range)	2.3 (0-11)	n/a

Data are mean (SD) unless otherwise stated. CP: cerebral palsy; TD: typically developing; GMFCS: gross motor functional classification system (Palisano et al., 1997); n/a: not applicable.

*Tardieu scores from children recruited at centre 2. MAS from children recruited at centre 1.

Table 2. Mean (SD) of lengthening values in a subgroup (n=5) of TD children for repeatability analysis.

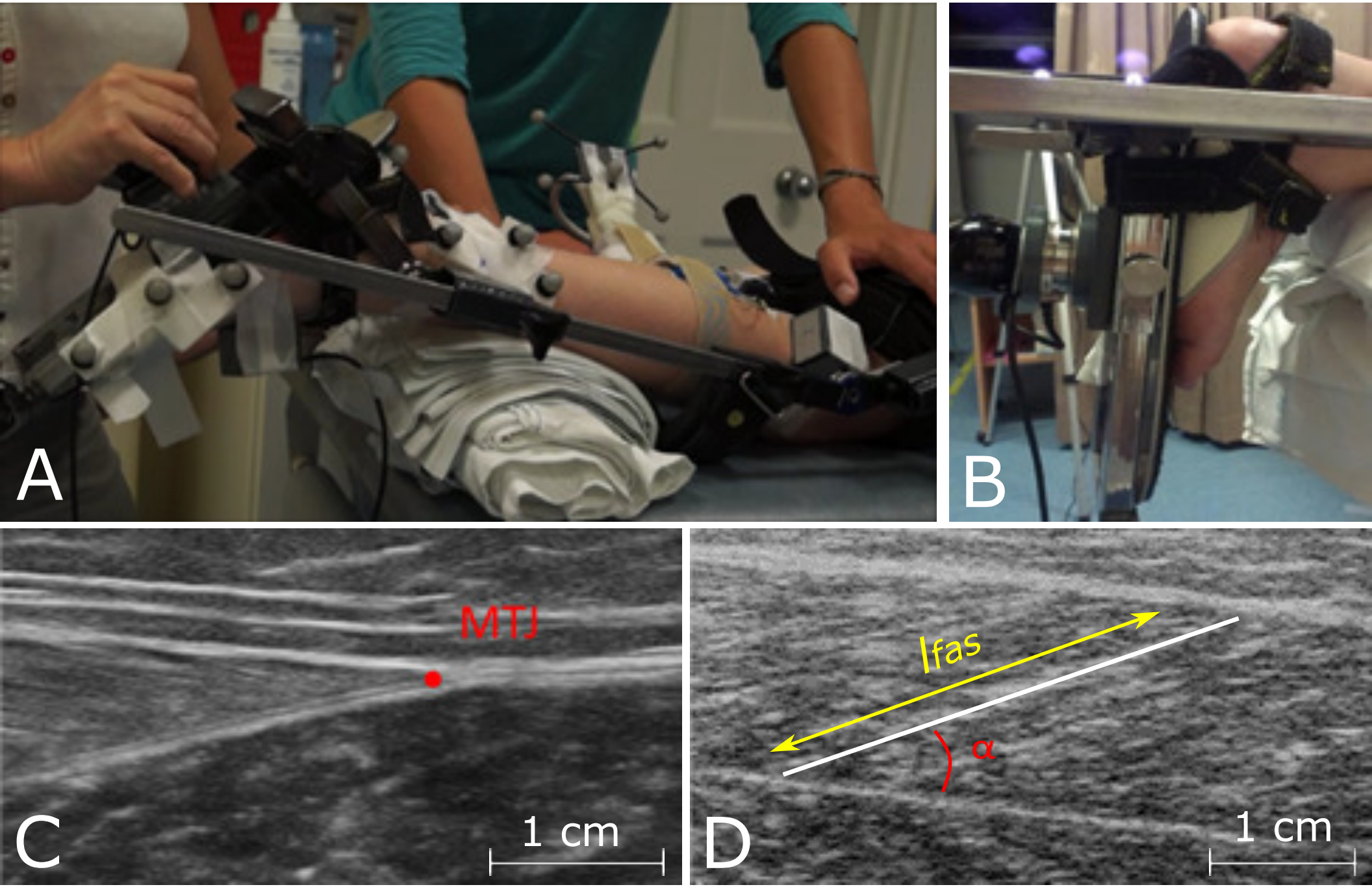
	Session 1	Session 2	ICC	SEM
Over common ROM (-25° to -5°)				
Fascicle	10.3 (1.9)	8.9 (1.4)	0.753	2.0
Muscle	10.4 (3.6)	9.2 (2.7)	0.822	1.7
Tendon	7.0 (2.6)	5.3 (3.3)	0.663	2.1
Over common MTU				
Fascicle	6.9 (2.5)	6.5 (4.1)	0.74	1.6
Muscle	10.9 (1.8)	10.1 (2.4)	0.739	2.3
Tendon	9.0 (1.8)	9.9 (2.4)	0.908	0.9
Over common torque				
Fascicle	20.9 (5.2)	19.9 (4.4)	0.926	1.8
Muscle	22.9 (2.8)	22.6 (3.5)	0.737	3.1
Tendon	15.8 (4.6)	14.5 (5.5)	0.799	2.8

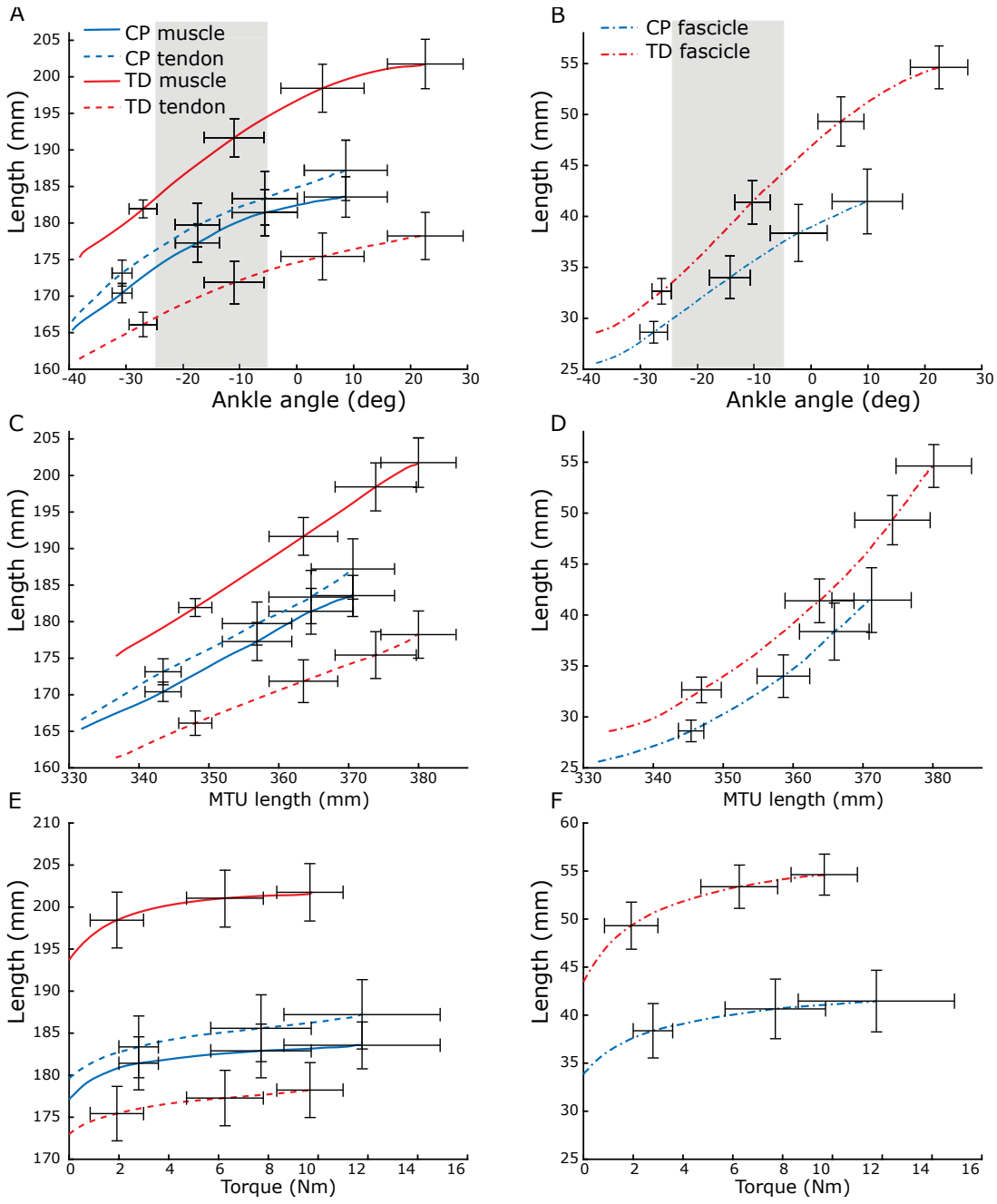
Table 3. Mean (SD) lengthening values in children with cerebral palsy (CP) and typically developing (TD) children during passive ankle rotation.

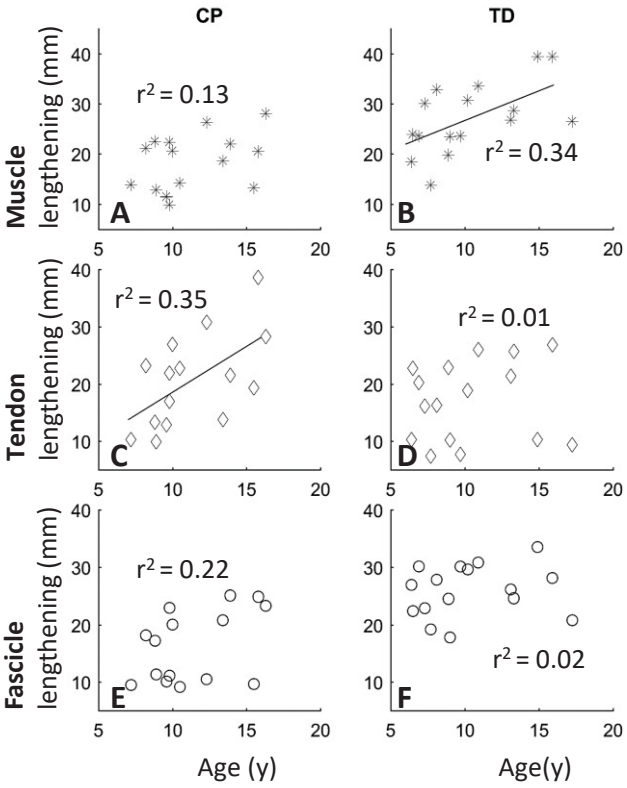
	Absolute lengthening (mm)			% of MTU lengthening	
	CP	TD	ES Hedge's g	CP	TD
Over the full ROM				Over the full ROM	
ROM (°)	48.0 (12.8)	60.6 (11.0) *	-1.03		
Fascicle	15.9 (6.2)	26.0 (4.3) **	-1.27	40.7 (10.7)	58.1 (14.3) **
Muscle	18.2 (5.4)	26.5 (7.0) **	-1.87	48.1 (9.2)	62.4 (9.2) **
Tendon	20.7 (8.1)	16.8 (6.7)	0.51	52.5 (8.8)	37.6 (9.2) **
Over common ROM (-25° to -5°)				Over common ROM (-25° to -5°)	
Fascicle	7.9 (3.2)	11.1 (2.1) **	-1.32	50.6 (20.4)	59.3 (14.6)
Muscle	8.5 (2.3)	11.4 (2.8) **	-1.20	53.9 (9.0)	64.9 (9.9) **
Tendon	7.6 (3.1)	6.45 (2.3)	0.32	46.1 (9.0)	35.1 (9.9) **
From maximum 0 to 3Nm				From maximum 0 to 3Nm	
ROM (°)	14.2 (3.2)	17.4 (5.6)	-0.81		
Fascicle	4.1 (1.6)	7.6 (3.2)**	-1.29	37.5 (9.6)	56.3 (14.9) **
Muscle	3.5 (1.9)	5.7 (2.5) *	-0.91	50.4 (9.3)	63.4 (8.5) **
Tendon	3.8 (2.9)	2.8 (1.3)	0.38	49.6 (9.3)	36.6 (8.5) **
Over a common MTU range (0-20mm)				Over a common MTU range (0-20mm)	
ROM (°)	17.7 (5.5)	18.7 (5.7)	-0.33		
Fascicle	5.7 (2.1)	7.6 (3.9) *	-0.52	25.4 (12.3)	39.1 (19.5) *
Muscle	9.9 (2.3)	12.1 (2.5) **	-1.08	49.3 (11.5)	61.4 (12.9) **
Tendon	10.1 (2.2)	7.9 (2.5) **	1.08	50.5 (11.2)	38.6 (12.8) **

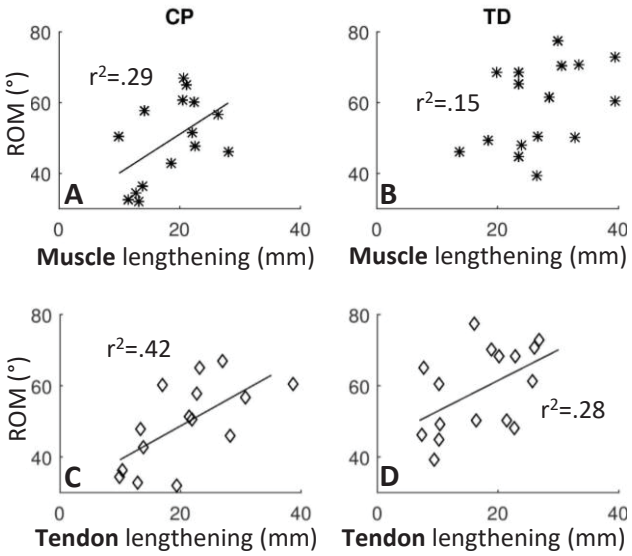
ROM: range of motion; PF: plantar flexion; MTU: muscle-tendon unit; CI: confidence interval; SEM: inter-session standard error of measurement in TD children; ES: effect size.

* Significant difference between CP and TD at $p < 0.05$ (** $p < 0.01$)


A
B
MTJ
1 cm
C
lfas
α
1 cm
D


A
CP muscle
CP tendon
TD muscle
TD tendon
Length (mm)
Ankle angle (deg)
B
CP fascicle
TD fascicle
Length (mm)
Ankle angle (deg)
C
Length (mm)
MTU length (mm)
D
Length (mm)
MTU length (mm)
E
Length (mm)
Torque (Nm)
F
Length (mm)
Torque (Nm)


CP
TD
Muscle
Tendon
Fascicle
lengthening (mm)
r² = 0.13
r² = 0.34
r² = 0.35
r² = 0.01
r² = 0.22
r² = 0.02
A
B
C
D
E
F
Age (y)
Age(y)


CP
TD
ROM (°)
r²=.29
r²=.15
r²=.42
r²=.28
A
B
C
D
80
60
40
0
20
40
Muscle lengthening (mm)
Muscle lengthening (mm)
Tendon lengthening (mm)
Tendon lengthening (mm)