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Mechanical and material properties of the plantarflexor muscles and Achilles tendon in children with spastic cerebral palsy and typically developing children

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ABSTRACT

Background: Children with spastic cerebral palsy (CP) experience secondary musculoskeletal adaptations, affecting the mechanical and material properties of muscles and tendons.

CP-related changes in the spastic muscle are well documented whilst less is known about the tendon. From a clinical perspective, it is important to understand alterations in tendon properties in order to tailor interventions or interpret clinical tests more appropriately. The main purpose of this study was to compare the mechanical and material properties of the Achilles tendon in children with cerebral palsy to those of typically developing children.

Methods: Using a combination of ultrasonography and motion analysis, we determined tendon mechanical properties in ten children with spastic cerebral palsy and ten aged-matched typically developing children. Specifically, we quantified muscle and tendon stiffness, tendon slack length, tendon strain, cross-sectional area, Young's Modulus and the strain rate dependence of tendon stiffness.

Findings: Children with CP had a greater muscle to tendon stiffness ratio compared to typically developing children. Despite a smaller tendon cross-sectional area and greater tendon slack length, no group differences were observed in tendon stiffness or Young's Modulus. The slope describing the stiffness strain-rate response was steeper in children with cerebral palsy.

Interpretation: These results provide us with a more differentiated understanding of the muscle and tendon mechanical properties, which would be relevant for future research and paediatric clinicians.

1. Introduction

Spastic cerebral palsy (CP) results from damage to the developing brain before, during or shortly after birth (Reddihough and Collins, 2003). During maturation, secondary musculoskeletal adaptations occur, which can affect the mechanical and material properties of muscles and tendons. Previous research has primarily focused on the atypical development of the muscle in children with spastic CP compared to their typically developing (TD) peers. There is consistent evidence of a shorter gastrocnemius muscle belly length (Malaiya et al., 2007; Wren et al., 2010) reduced muscle volume (Malaiya et al., 2007), increased connective tissue (Booth et al., 2001), and increased muscle and fascicle stiffness (Barber et al., 2011; Fridén and Lieber, 2003; Smith et al., 2011). The adaptations of the tendon in children with spastic CP are less well established. However, the tendon also plays an integral role in movement, alongside the muscle. The mechanical properties of the tendon govern the transfer of muscular forces to the bone, and the storage and return of elastic energy during functional activities (Lichtwark and Wilson, 2008). It is possible that the aforementioned CP-related changes in the mechanical properties of the muscle, result in secondary mechanical adaptations of the tendon, which could have implications for functional movement. Thus, the overall goal of this study was to characterise the mechanical properties of the tendon in children with spastic CP, and compare them to TD children.

As the muscle and tendon are closely integrated in the production of movement, the mechanical properties of both structures in children with spastic CP should not be considered independent to one another. Importantly, the length and compliance of the Achilles tendon can affect the force-generating capacity of the muscles (Lichtwark et al., 2007; Lichtwark and Wilson, 2008). For example, certain tendon compliance may allow muscle fibres to operate close to an optimal length and at relatively low shortening velocities, thereby aiding force

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production (Lichtwark et al., 2007; Lichtwark and Wilson, 2006). Understanding CP-related differences in the tendon's mechanical properties alongside mechanical properties in the muscle would provide useful insights into the mechanisms underlying CP-specific characteristics of functional movement. Therefore, the first specific aim of this study was to compare plantarflexor muscle and Achilles tendon stiffness in children with spastic CP and TD children.

Tendon stiffness is determined by both its dimensions and material properties. Regarding the former, a long tendon with a small cross-sectional area will be more compliant than a short tendon with a large cross-sectional area (Matson et al., 2012; Alexander, 2003). Regarding the latter, the tendon's material properties are independent of its dimensions and depend primarily on collagen fibre type, size and organisation (Silver et al., 2003). One way to differentiate between the dimensional and material properties of the tendon is to calculate Young's modulus, which can be thought of as tendon stiffness normalised by its dimensions. It has previously been demonstrated that in TD children, tendon stiffness increases with maturation (Waugh et al., 2012), due to changes in both dimensions and material properties. The adaptations of the tendon occur in response to chronic mechanical loading, predominantly due to an increase in muscle size and force (Kubo et al., 2001; Wu et al., 2011). Within the context of CP, a lack of mechanical loading from the spastic muscle due to atrophy and weakness (Malaiya et al., 2007) may cause atypical growth of the tendon. The lack of mechanical loading and inability to fully weight bear in more severely affected CP children (GMFCS IV and V) could exacerbate this weakness and atypical tendon growth. The Achilles tendon has been shown to be longer than in TD children, and cross-sectional area has been reported to be smaller (Gao et al., 2011), presumably as an adaptation to the atypical shortening of the muscle belly (Barber et al., 2012; Wren et al., 2010). One might expect these dimensional changes to cause the tendon to be more compliant in children with spastic CP. However, Barber et al. (2012) did not find any differences in tendon stiffness between children with CP and TD children, which could indicate concomitant alterations in tendon cross-sectional area and/or maturation of the tendon's material properties, independent of dimensions. Understanding the CP-related changes in the dimensional and material contributions to tendon stiffness is an important prerequisite to better understand movement efficiency and control in children with spastic CP. Therefore, the second specific aim was to compare dimensions and material properties of the Achilles tendon between children with spastic CP and TD children.

Another mechanical property of the tendon is its viscoelasticity. Tendons recoil elastically after stretch, but they also become stiffer at higher loading rates (Knudson, 2007, pp. 73; Pearson et al., 2007; Theis et al., 2012a). Previously, we have shown that the slope of the strain-rate-stiffness relationship is lower in TD children than in adults (Theis et al., 2012b). This phenomenon may partly explain previously observed differences in movement efficiency between adults and children (Ebbeling et al., 1992). From a clinical perspective, it is important to understand the strain-rate-tendon stiffness relationship in children with CP, as it could lead to more differentiated (and therefore more meaningful) assessments of spasticity. Thus, the third specific aim of the study was to determine the strain-rate response of the Achilles tendon in children with spastic CP and TD children.

2. Methodology

2.1. Participants

Ten children with clinically diagnosed diplegic or quadriplegic spastic CP participated in this study. The CP group had knee deformities of less than 10° and ankle deformities of less than 15° (5 males, 5 female; age 11.4 ± 3.0 y; 6 children were GMFCS III, 4 children GMFCS IV). Participants that were GMFCS level III were able to fully weight bear and walk with an assistive frame. Those participants at GMFCS level IV were predominantly wheelchair users but could weight bear with assistance and walk short distances with an assistive frame. All participants wore foot orthotics. In addition, none of the CP participants received botulinum toxin type A (Botox) injections or serial casting in the 6 months prior to testing or had orthopaedic surgery of the lower extremities in the 12 months prior to testing. The physical therapy routines of the CP groups were variable in the level of activity and duration. Normal routines consisted of approximately 3–4 h per week of dynamic movement activities and use of a standing frame, however, adherence to this was variable across participants.

Ten age-matched TD children (5 males, 5 female; age 12.0 ± 2.9 y) also participated in this study. Children and their guardians provided informed assent and consent, respectively. The study was approved by the institutional and relevant NHS Ethics Committees.

2.2. Protocol and instrumentation

To measure ankle torque, participants were seated on the dynamometer chair. The right knee was straightened to full extension for the TD group, and for the CP group the knee was straightened as much as possible, which was on average 7.0 ± 2.0° from full extension across CP participants. The relative hip angle was set to 85° for both groups. The lateral malleolus of the right ankle was aligned with the rotational axis of the dynamometer arm. The dynamometer footplate was positioned perpendicularly to the tibia, and this was considered to be 0°. Stabilisation straps were applied tightly over the foot, thigh and chest to minimise movement of the upper body or leg.

The participants' available range of motion (ROM) was determined by dorsi- and plantarflexing the foot, until any discomfort was reported. This occurred between 6.3 ± 0.7° dorsiflexion and 20.3 ± 4.0° of plantarflexion for the CP group, and 19.0 ± 8.3° dorsiflexion and 23.1 ± 3.6° of plantarflexion for the TD group. The dynamometer system was then set to apply passive angular rotations to the right ankle joint at constant angular velocities of 1, 10 and 30° s^{-1} within the available ROM. Participants were instructed to relax the muscles of the lower limb. Three rotations were recorded at each angular velocity; the order of angular velocities was randomised. Electrical activity of the medial gastrocnemius (EMG) was monitored throughout the rotations (Trigno wireless system, Delsys Inc., Ltd., Boston, USA). Both torque and EMG signals were sampled at 1000 Hz. Torque data were filtered using a low-pass, fourth-order, zero-lag Butterworth filter with a cut-off frequency of 14 Hz.

Muscle and tendon elongation were measured as the displacement of the medial gastrocnemius muscle–tendon junction. The muscle–tendon junction was visualised using B-mode ultrasonography and collected at 25 Hz (Megas GPX, Esaote, Italy; 45 mm Linear array probe, 10 MHz transducer scanning). The 2D coordinates of the MTJ were then manually digitised (Peak Performance, Cambridge, UK). Muscle–tendon junction position data were then filtered using a low-pass fourth-order zero-lag Butterworth filter with a 3.25 Hz cut-off frequency.

2.3. Derivation of dependent variables

Motion analysis markers were placed on the calcaneus, medial and lateral femoral epicondyles, and the handle of the ultrasound probe. These were tracked using 3D motion analysis. The coordinates of two markers from the handle of the ultrasound probe, combined with the coordinates of the muscle–tendon junction in the ultrasound image, allowed the global position of the muscle–tendon junction to be calculated in the sagittal plane. Tendon length was defined as the linear distance from its insertion on the calcaneus to the medial gastrocnemius muscle–tendon junction. Medial gastrocnemius muscle length was defined as the distance between the medial femoral epicondyle and the global coordinates of the muscle–tendon junction. Thus, both medial gastrocnemius and Achilles tendon were modelled as straight lines. The slack length of the Achilles tendon was calculated as the length at which there was a sustained increase in ankle torque above zero (Barber et al., 2012), and thus, where tendon slack had been taken up. Tendon slack length was expressed in absolute terms at this point and normalised by resting muscle–tendon unit length.

Tendon stiffness was calculated as the change in muscle–tendon force divided by the corresponding change in Achilles tendon length. Muscle–tendon force was calculated over the range, neutral (0°) to maximum dorsiflexion, by dividing ankle torque by the Achilles tendon moment arm. Moment arm was calculated using the tendon excursion method as the mathematical derivative of Achilles tendon excursion with respect to the angular displacement of the ankle joint. According to recommendations of Fath et al. (2010), a third-order polynomial was fitted to approximate the relationship between tendon elongation and angular displacement from 5° dorsiflexion to 5° plantarflexion, and differentiated at the neutral ankle position to obtain the moment arm. An estimate of "total" plantarflexor muscle stiffness was derived using a similar method to that described by Morse et al. (2008). For this purpose, the change in force was divided by changes in medial gastrocnemius muscle length.

Muscle and tendon stiffness for both groups was determined during dorsiflexion in the 10° s^{-1} trial. Stiffness was calculated relative to each participant's