MUSCULOSKELETAL MECHANISMS OF PAEDIATRIC IDIOPATHIC TOE-WALKING

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THESIS SUMMARY

Children who idiopathically toe-walk (ITW) walk in equinus with no known pathological, neurological, or orthopaedic cause. Therefore, they are a particularly challenging population for clinicians, as persistent, untreated equinus can lead to secondary problems, such as a worsening of symptoms, fixed deformity, and fixed contracture. Consequently, children who ITW are often prescribed with clinical interventions which target the plantarflexor muscles. However, at present, there is no knowledge about the musculoskeletal mechanisms which may contribute to the pathology of these children and thus, no knowledge as to the effect that such interventions may pose to muscle function.

Therefore, the main body of work presented within this thesis aims to improve our understanding of the musculoskeletal mechanisms of children who ITW, with a specific focus on (1) the architecture and passive lengthening properties of the gastrocnemius medialis muscle, (2) muscle strength and the *in vivo* operating lengths of the gastrocnemius medialis muscle during gait, and (3) the effective mechanical advantage of the plantarflexors.

Firstly, the gait kinematics and kinetics of children who ITW and typically developing (TD) children are presented in chapter 2. Between-group differences were observed in the sagittal plane at the ankle joint only. No between-group differences were found in the frontal or transverse planes at the ankle joint, or in any cardinal plane for the knee and hip joints.

Secondly, chapter 3 assesses the architecture and passive lengthening properties of the gastrocnemius medialis muscle and Achilles tendon. Children who ITW were shown to have longer muscle belly and fascicle lengths and a shorter Achilles tendon length than typically developing (TD) children, regardless of which common joint position that groups were compared.

Chapter 4 then assesses the gastrocnemius medialis muscle strength and functional properties relative to the demands of gait. Children who ITW were strongest at more plantarflexed angles and at longer fascicle lengths than TD children. Both alterations coincide with the ranges used during gait, suggesting that the alterations present in children who ITW are well adapted to the characteristic demands of equinus gait.

To calculate the effective mechanical advantage of the plantarflexors during gait in children who ITW, a new and novel method needed to be developed to calculate the Achilles tendon moment arm in extreme plantarflexed positions. Therefore, chapter 5 develops a new method that can account for tendon curvature in the calculation of the Achilles tendon moment arm length. This method was shown to not only be reliable in simulated toe-walking, but was also relatively simple to perform, which could facilitate the implementation of such measures into routine clinical practice.

Finally, in chapter 6, the new method was implemented to assess the effective mechanical advantage of the plantarflexors in children who ITW and TD children. Children who ITW were shown to have a greater plantarflexor effective mechanical advantage than TD children during propulsion, which consequently reduces the estimated muscle force requirements for children who ITW.

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PUBLICATIONS AND CONFERENCE PRESENTATIONS

Full Papers

- Harkness-Armstrong, C., Maganaris, C., Walton, R., Wright, D., Bass, A., Baltzopoulos V., and O'Brien, T. D. (2021). In vivo operating lengths of the gastrocnemius muscle during gait in children who idiopathically toe-walk. *Experimental Physiology, 106*, 1806-1813. https://doi.org/10.1113/EP089658

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- Harkness-Armstrong, C., Debelle, H. A., Maganaris, C., Walton, R., Wright, D., Bass, A., Baltzopoulos, V., and O'Brien, T. D. (2020). Effective mechanical advantage about the ankle joint and the effect of Achilles tendon curvature during toe-walking. *Frontiers in Physiology, 11*, 407. https://doi.org/10.3389/fphys.2020.00407

Abstracts in Scientific Conferences

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FREQUENTLY USED ABBREVIATIONS

CP	Cerebral palsy
EMA	Effective mechanical advantage
EMG	Electromyography
ES	Effect size
GRF	Ground reaction force
ITW	Idiopathically toe-walk
MTJ	Myotendinous junction
MTU	Muscle-tendon unit
MVC	Maximum voluntary contraction
ROM	Range of motion
TD	Typically developing

CHAPTER 1: GENERAL INTRODUCTION

Idiopathic Toe-Walking

When children first learn to walk, they do so by adopting a toe-to-toe gait pattern, whereby ambulation occurs with the absence of a heel contact with the floor. Whilst most children will outgrow this, some will not. This is considered abnormal if the toe-to-toe gait pattern, known as equinus, persists beyond the age of two, and therefore is normally investigated. Potential causes of equinus gait include cerebral palsy (CP) (Gage et al., 2009), Duchenne muscular dystrophy (DMD) (Bushby et al., 2010), autism spectrum disorder (ASD) (Ming et al., 2007), and other muscular, developmental, or neurological disorders (Stott et al., 2004). Many of these conditions can be either confirmed or excluded based on the child's history and/or their physical examination, which includes measures of muscle strength, selective motor control, muscle tone, joint range of motion (ROM), posture, and balance. However, if all possible causes are excluded, a diagnosis of idiopathic toe-walking is given.

The persistence of idiopathic toe-walking into adolescence is rather rare. Despite a reported prevalence of ~2% at age five (Engström & Tedroff, 2012), on average between 9-19 children who idiopathically toe-walk (ITW) present at major children's centres around the world each year (Baber et al., 2016; Davies et al., 2018; Engstrom et al., 2013; Fox et al., 2006). Specifically in the UK, Fox et al. (2006) reported that 44 children who ITW above the age of 2 years presented at their clinic between 1999 and 2003, suggesting an average of ~11 children who ITW per year. Therefore, the population of children who ITW that can be recruited for research are few in number, and thus the mechanistic underpinning of the condition remains unclear. Consequently, children who ITW are a particularly challenging population for clinicians to treat. Nonetheless, treatment is required because persistent equinus can lead to secondary symptoms, such as equinus contracture, fixed deformity and/or a worsening of symptoms. To prevent these, clinical treatments are prescribed to lengthen the plantarflexor muscle-tendon unit (MTU) and restore a typical heel-to-toe gait pattern. However, these interventions often do not normalise gait, and have an unpredictable medium to long term outcome with high rates of recurrence (Dietz & Khunsree, 2012; Pomarino et al., 2016; van Kuijk et al., 2014). Therefore, it is essential to understand the underlying mechanisms that contribute to idiopathic toe-walking, so that we can better inform current clinical practice for these children.

Management of Idiopathic Toe-Walking

As mentioned previously, clinical treatments which are prescribed to children who ITW are targeted at the plantarflexor MTU. However, different interventions can be implemented to target the different structures within the MTU (muscle or tendon), and it is currently not known what the optimal procedure should be. Therefore, it is essential to understand whether it is indeed the muscle or the tendon that should be targeted through intervention, to ensure that children who ITW can receive the most appropriate treatment.

Initially, the treatments prescribed to children who ITW are conservative, with the aim of maintaining or increasing ROM, to prevent an equinus contracture from developing. These interventions include observation and monitoring, stretching, botulinum toxin-A injections and/or serial casting (Gormley et al., 1997; Brouwer et al., 2000; Brunt et al., 2004; Fox et al., 2006; Hemo et al., 2006; McMulkin et al., 2006; Jahn et al., 2009; Engström et al., 2013; Satila et al., 2016). Botulinum toxin-A injections can be prescribed to reduce muscle stiffness, despite no neurological involvement, while all remaining treatments provide a mechanical stimulus to lengthen the MTU. Nonetheless, all conservative treatments in the management of idiopathic toe-walking target the muscle, under the assumption that they will increase muscle length and/or reduce muscle stiffness. However, if equinus persists and/or if conservative treatments are ineffective in preventing equinus contracture, then surgical interventions are prescribed.

There are three anatomical zones that can be targeted through surgical intervention (Figure 1.1). Zone 1 is located between the gastrocnemius origin and its myotendinous junction (MTJ) with the Achilles tendon. Procedures performed here, including the Baumann and Strayer techniques (Baumann & Koch, 1989; Strayer, 1950), target the gastrocnemius muscle through intramuscular lengthening. Zone 2 is located between the MTJ of the gastrocnemius and Achilles tendon, and the distal end of the soleus muscle. Procedures performed here, including the Vulpius and Baker techniques (Baker, 1954; Vulpius & Strofel, 1911), target the conjoined gastrocnemius aponeurosis and soleus fascia. Finally, zone 3 is the free Achilles tendon. Therefore, procedures performed here, known as tendo-Achilles lengthening procedures (Hoke, 1921; White, 1943), target the Achilles tendon in isolation.

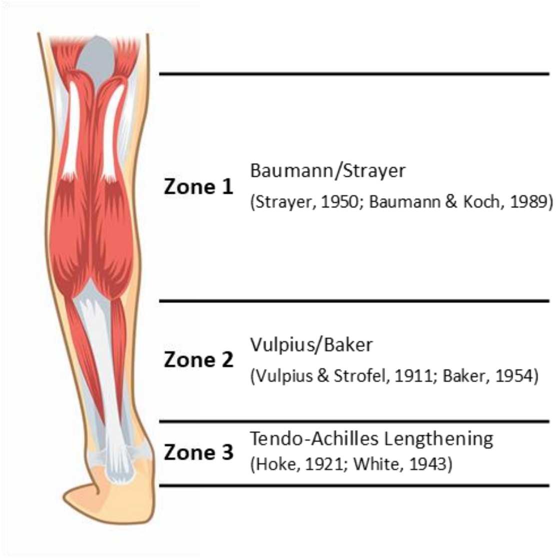

Figure 1.1. Anatomical zones of the plantarflexor muscle-tendon unit, with corresponding surgical procedures.

These different clinical interventions have been shown to result in variable outcomes. Conservative treatments, such as botulinum toxin-A injections and serial casting, have been shown to have beneficial effects in improving dorsiflexion ROM (Brouwer et al., 2000; Fox et al., 2006; Engström et al., 2010) and gait kinematics (Stott et al., 2004; Engström et al., 2010). However, these beneficial outcomes are only sustained in the short-term, with medium to long term outcomes being poor and resulting in high rates of recurrence (Hirsch & Wagner, 2004; Dietz & Khunsree, 2012; van Kuijk et al., 2014). Consequently, surgical interventions, of which the optimal procedure is not clear, have shown the most effectiveness in treating idiopathic toe-walking (Hemo et al., 2006; McMulkin et al., 2006; McMulkin et al., 2016; Jahn et al., 2009). However, as stated previously, surgical treatments are only prescribed as a last resort, if conservative treatments have failed and/or if an equinus contracture is already present. Therefore, the opportunity to increase dorsiflexion ROM is far more substantial in children who undergo surgery, as opposed to conservative treatments. Thus, this may contribute to the favourable outcomes.

Nonetheless, although improvements in ROM and gait kinematics can be achieved through intervention, often gait “normalisation” does not occur. Therefore, it is essential to gain an understanding as to the reasons why these treatments are often ineffective in treating idiopathic toe-walking. Thus, to do this, we must first identify the underlying musculoskeletal adaptations of these children.

Possible Causes of Idiopathic Toe-Walking

As idiopathic toe-walking is a diagnosis of exclusion, the reasons why some children continue to walk in equinus are not well understood. Previous work has suggested that idiopathic toe-walking may be hereditary (Fox et al., 2006; Sobel et al., 1997), be a learned behaviour that is never outgrown (Caselli et al., 1988), be caused by a shortening of the gastrocnemius MTU (Jahn et al., 2009), or due to a neural and/or sensory processing dysfunction (Williams et al., 2014). Nonetheless, whilst the primary cause of idiopathic toe-walking remains unclear, it is common for secondary symptoms to present. These symptoms, including equinus contracture, fixed deformity and/or a worsening of gait, directly affect the gait mechanics of children who ITW. Moreover, it is these mechanical factors that are directly targeted through clinical intervention. Thus, it is essential to better understand the musculoskeletal mechanisms that may contribute to and are directly affected by the equinus gait pattern of children who ITW.

The hypotheses for the mechanical reasons why children who ITW may walk in equinus are (1) they cannot achieve the necessary ankle joint ROM due to altered muscle and tendon structures, or that equinus gait is a compensation strategy to meet the mechanical demands of gait due to (2) muscle weakness, or (3) inadequate effective mechanical advantage (EMA). Therefore, to better understand the mechanisms that may contribute to equinus gait, we can assess the musculoskeletal alterations of children who ITW. The underlying structural and functional alterations associated with each of these possible causes are explored further in the following sections. These will establish mechanistic hypotheses to test in this thesis.

Restricted Range of Motion

Muscle Architecture

Equinus gait causes the MTU to operate at habitually shorter lengths than typical. Therefore, as muscles are a highly plastic tissue, they will likely remodel in length according to its utilised ROM (Matano et al., 1994; Williams & Goldspink, 1973). Thus, it is possible that the MTU of children who ITW will have remodelled due to the habitually altered gait pattern. This could have implications for muscle function and will be discussed later. However, as the gastrocnemius muscle architecture of children who ITW has never been measured, clinicians are often reliant on knowledge of the muscle alterations in other clinical populations who present with equinus to inform clinical decision making.

Children who ITW are often compared to children with cerebral palsy (CP), as they both present with a similar locomotor dysfunction. Moreover, significant equinus contractures, a fixed tightening of a structure that prevents normal ROM, can present in both groups if equinus gait is not corrected. This restricted ROM can be caused by either a shorter muscle, a shorter tendon, or a combination of the two. In children with CP, these contractures are often caused by a shorter and stiffer gastrocnemius muscle than typical (Barrett & Lichtwark, 2010; Fry et al., 2004; Willerslev-Olsen et al., 2018). Therefore, it is often clinically assumed that a shortening of the gastrocnemius muscle would also be the cause of contracture in children who ITW. Thus, children who ITW and children with CP are often prescribed with similar clinical interventions to lengthen and reduce the stiffness of the muscle, to prevent a contracture from developing. However, these interventions are often ineffective for medium to long term management of idiopathic toe-walking (Hirsch & Wagner, 2004; Dietz & Khunsree, 2012; van Kuijk et al., 2014). Moreover, it is only when these initial treatments fail, i.e., do not prevent contracture or if equinus persists, that surgical treatments to target the tendon are prescribed. These interventions have been shown to be more effective in the long-term treatment of idiopathic toe-walking, however normalisation of gait still does not occur (Hemo et al., 2006; McMulkin et al., 2006; McMulkin et al., 2016; Jahn et al., 2009). Therefore, it is essential that we gain an understanding of the underlying muscle architecture of children who ITW to better inform our understanding of the pathology and thus, better inform current clinical practice for these children.

Muscle architecture describes the anatomical shape, size, and structure of a muscle, as well as its fibre arrangement. These are important because they will directly influence the functional properties of a muscle (Wickiewicz et al., 1984). The parameters that are commonly assessed include the muscle, tendon, MTU and fascicle lengths, fascicle pennation angle to the deep aponeurosis, and muscle thickness (Figure 1.2). These structures can be studied *in vivo* using medical imaging techniques, such as ultrasonography.

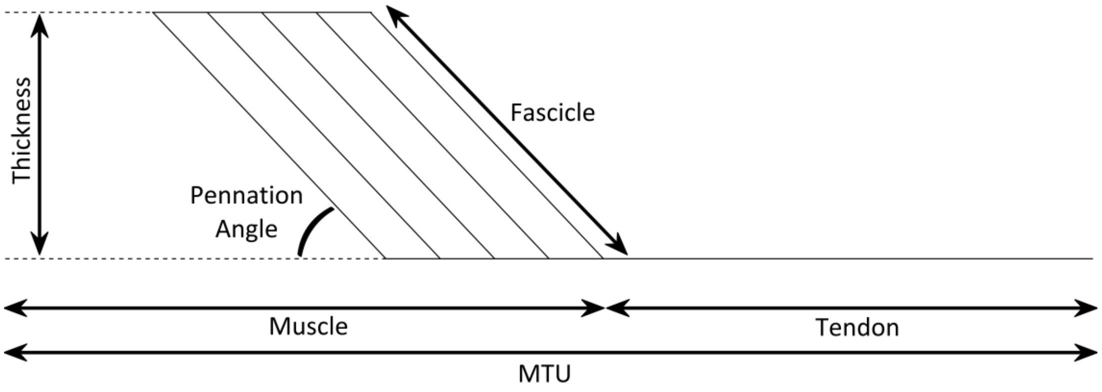

Figure 1.2. Schematic representation of a muscle-tendon unit and the common architectural structures that are commonly assessed.

The two main plantarflexor muscles important for gait are the gastrocnemius and soleus muscles. The main function of the gastrocnemius, a pennate biarticular muscle, is to plantarflex the ankle joint and flex the knee joint. The main function of the soleus, a bipennate uniarticular muscle, is to plantarflex the ankle joint and stabilise the tibia to limit forward sway. When compared, the soleus has a greater muscle volume and physiological cross-sectional area (PCSA) than the gastrocnemius (Fukunaga et al., 1992), therefore the gastrocnemius muscle contributes less than the soleus muscle during isometric voluntary plantarflexion contractions (Ratkevičius et al., 1998). However, whilst both the soleus and gastrocnemius muscles are important for general gait function (i.e., vertical support and anterior progression of the centre of pressure), and both can be affected by clinical interventions for children who ITW, it is the gastrocnemius which plays the functionally more important role for forward propulsion (Gottschall & Kram, 2003; Francis et al., 2013). Indeed, Francis et al. (2013) demonstrated that stimulation of the gastrocnemius muscle induced forward propulsion, whereas stimulation of the soleus muscle induced a breaking of forward velocity. Therefore, as propulsion is the primary gait phase of interest within this thesis, the gastrocnemius is studied as opposed to the soleus.

Moreover, it is also important to consider the potential role of the gastrocnemius muscle in the pathology of idiopathic toe-walking. As previously mentioned, it is well documented that a short and stiff gastrocnemius muscle causes equinus contracture in children with CP (Barrett & Lichtwark, 2010; Fry et al., 2004; Willerslev-Olsen et al., 2018). Therefore, as children who ITW experience similar chronic atypical loading of the ankle joint as children with CP, it is often clinically assumed that the gastrocnemius muscle would also be the primary cause of contracture in children who ITW. However, the gastrocnemius muscle architecture of children who ITW has never been studied. Therefore, it is essential to study the gastrocnemius muscle to confirm or reject this notion. Additionally, as measurements will be made using ultrasonography both at rest and during gait, the gastrocnemius muscle offers greater accuracy and reliability for ultrasound scanning, due to its superficial anatomical location.

The MTU of the gastrocnemius medialis consists of the muscle itself and the in-series Achilles tendon (Figure 1.2). Here, muscle length is described as the distance between the proximal origin of the muscle on the medial femoral condyle, and its MTJ with the Achilles tendon. Tendon length is described as the distance between the MTJ, and the distal insertion of the Achilles tendon onto the calcaneus. MTU length is therefore the total path from muscle origin to tendon insertion.

Passive Lengthening Properties of Muscle and Tendon

To achieve dorsiflexion ROM, the MTU must lengthen (Figure 1.2). There are three ways in which this can happen; either (1) the tendon will lengthen, (2) the muscle will lengthen, either caused by a lengthening and rotation of the muscle fascicles or a lengthening of the intramuscular connective tissue, or (3) both the muscle and tendon will lengthen. The structure that will lengthen to achieve the increase in MTU length will depend on the relative stiffness of the tissues. The more compliant tissue will be the one to lengthen and/or contribute more to joint rotation. Only if the relative stiffness' of the muscle and tendon are equal, will both tissues contribute equally to MTU lengthening.

In typically developed adults, it is a combination of both the tendon and the intramuscular connective tissue that contribute to the increased MTU length (Herbert et al., 2002; Morse et al., 2008). However, in TD children, the muscle has been shown to lengthen more than the tendon (63:37%) to achieve joint rotation (Kalkman et al., 2018). This suggests that in children, the muscle is relatively more compliant than the tendon. If, as discussed earlier, children who ITW present with a shorter and stiffer muscle than TD children, this may suggest that the muscle contribution to MTU lengthening would be less. Indeed, this was found to be the case in children with CP, who are known to have short and stiff muscles (Kalkman et al., 2018). However, as the passive lengthening properties of the gastrocnemius medialis muscle and Achilles tendon have not be studied before in children who ITW, we cannot be certain as to which structure contributes to MTU lengthening.

Knowledge of these passive lengthening properties would have implications for treating the impaired joint function, as knowing which structure (muscle or tendon) contributes to equinus contracture in children who ITW would indicate which structure should be targeted through clinical intervention. To quantify the passive lengthening properties of the muscle and tendon within this thesis, and therefore to approximate tissue stiffness, an established method will be adopted (Gao et al., 2009; Kalkman et al., 2018; Matthiasdottir et al., 2014). However, as this method quantifies changes in individual tissue length behaviours in response to increased load at the whole joint level, the term “pseudo-stiffness” is preferred.

Muscle Weakness

Locomotion relies on the production of joint moments to propel the body forwards, and so adequate contractile muscle force must be produced around all three lower limb joints. Previously, muscle weakness around these joints, but specifically at the ankle, have been suggested to contribute to equinus gait in populations such as CP and DMD (Hampton et al., 2003; Kennedy et al., 2020; Morozova et al., 2017; Wiley & Damiano, 1998). This is because anatomical changes in the muscle (Figure 1.2), such as those commonly associated with contracture, can cause muscle weakness (Moreau et al., 2010), and the altered gait kinematics can cause a reduction in the magnitude of muscle force required for gait (Neptune et al., 2007; Perry et al., 2003).

To the author’s knowledge, muscle strength around the knee or the hip has never been studied in children who ITW, whereas small (insignificant) effects of plantarflexor weakness have been reported in one fixed joint position (De Oliveira et al., 2021). Although useful to quantify the plantarflexor strength of children who ITW in one joint position, it does not allow for the strength requirements of gait to be quantified, as these children will likely operate at functionally different joint angles and muscle lengths during gait. Therefore, it is essential to assess muscle strength across the full ROM, so that these functionally relevant questions can be answered.

Functional Operating Ranges of Muscle During Gait

An alternative explanation for the reduced muscle force observed in equinus gait could be the functional operating lengths of the muscle. The length of the muscle and its velocity during contraction will dictate the maximum contractile force that can be produced (Gordon et al., 1966). The plantarflexors are a vital source of the required mechanical power for gait (Winter, 1983), and have been shown to operate close to the region of optimal sarcomere length in typically developed adults (Fukunaga et al., 2001). Therefore, this allows the plantarflexors to produce force economically during gait. However, this relies on gait kinematics that match the underlying muscle-tendon architecture and functional properties.

Children who ITW present with an altered gait pattern. Therefore, by operating at more plantarflexed positions, and thus at shorter MTU lengths, it is likely that children who ITW operate at functionally shorter muscle lengths than typical during gait. If so, this may cause children who ITW to operate at sub-optimal muscle lengths on the force-length relationship compared to TD children (Figure 1.3). However, as previously mentioned, muscle is a highly plastic tissue, therefore it is possible that the muscles of children who ITW could have remodelled to match the habitually altered gait pattern. Thus, it is essential to establish whether strength capacity, determined by the *in vivo* force-length and moment-angle relationships, may be contributing to equinus gait.

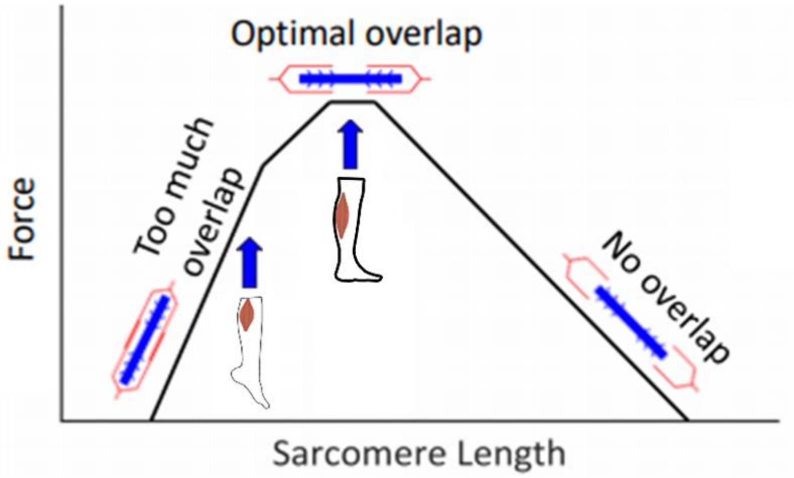

Figure 1.3. Visual representation of where typically developed adults are known to operate on the force-length relationship during gait, and the clinical assumption of equinus gait.

Effective Mechanical Advantage

The EMA of a joint is the ratio between the internal and external moment arm lengths. For the plantarflexors, this ratio therefore determines the required plantarflexor muscle force to overcome the external ground reaction force (GRF) (Lee & Piazza, 2009). Both moment arms can be altered by anatomical variations and/or kinematic changes, which in turn can greatly influence the required muscle force to generate adequate joint moments.

Equinus causes the GRF vector to act closer to the ankle joint centre (Hampton et al., 2003; Kerrigan et al., 2000), thus shortening the GRF moment arm length (Figure 1.4). Consequently, this would improve the EMA of the plantarflexors and reduce the plantarflexor muscle force required for gait. Therefore, equinus has previously been suggested to be, in part, a compensatory mechanism for plantarflexor weakness.

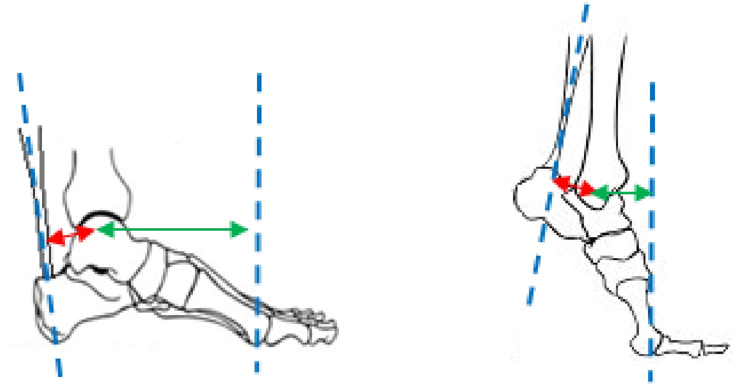

Figure 1.4. Alterations in effective mechanical advantage with equinus.

However, reducing the GRF moment arm length may alternatively be to compensate for anatomical changes in the Achilles tendon moment arm. In children and young adults with CP, the Achilles tendon moment arm has been found to be smaller than typical (Gallinger et al., 2019; Kalkman et al., 2017), which has been attributed to chronic atypical loading of the ankle joint. Children who ITW experience similar atypical loading at the ankle, therefore it is possible that these children may undergo similar skeletal alterations as children with CP. If so, then reducing the GRF moment arm length may restore EMA back to typical, rather than improve it. Thus, it is essential to understand whether an altered musculoskeletal leverage may be impacting the muscle force requirements and/or contributing to movement impairments in children who ITW, to ensure that appropriate clinical interventions can be provided.

Quantifying the plantarflexor EMA, specifically the Achilles tendon moment arm length, during functional tasks is extremely complex. This is further complicated when studying equinus because the Achilles tendon becomes curved in plantarflexed positions (Obst et al., 2014). Therefore, to assess the plantarflexor EMA of children who ITW, work must first be undertaken to establish a valid and reliable method to quantify the Achilles tendon moment arm length, whilst accounting for tendon curvature.

Summary

Children who ITW are a group of children who walk in equinus without a diagnosed pathological, neurological, or orthopaedic cause. Therefore, they are a particularly challenging population for clinicians. Persistent, untreated equinus can lead to secondary problems, such as a worsening of symptoms, equinus contracture, and fixed deformity. Consequently, children who ITW are often prescribed with clinical interventions which target the plantarflexor muscles. However, at present, the underlying mechanisms that may contribute to the pathology in these children have never been studied. Therefore, there is no knowledge about the musculoskeletal alterations of children who ITW, such as changes in the muscle architecture, functional properties, and/or leverage about the ankle joint. Thus, it is unclear as to what the optimal intervention for children who ITW should be (i.e., whether the muscle or tendon should be targeted), and no knowledge as to the effect that such interventions may pose on muscle and/or gait function.

Purpose and Outline of Thesis

The overall purpose of this thesis was to improve our understanding of the possible mechanisms that may contribute to idiopathic toe-walking. For this purpose, five main studies were performed to test our mechanical hypotheses.

The aim of chapter 2 was to describe the gait characteristics of children who ITW and TD children to confirm whether idiopathic toe-walking is purely a sagittal plane pathology, and to determine whether children who ITW adopt gait compensations to maintain dynamic stability. These data will also provide references for subsequent chapter.

The aim of chapter 3 was to assess whether children who ITW present with restricted ROM due to altered muscle and tendon structures. This was achieved by measuring the architecture and passive lengthening properties of the gastrocnemius medialis muscle and Achilles tendon of children who ITW and TD children.

The aim of chapter 4 was to assess whether children who ITW present with muscle weakness. To do this, muscle strength of the hip, knee, and ankle, and the *in-vivo* operating lengths of the gastrocnemius medialis muscle during typical and equinus gait were assessed.

The aim of chapter 5 was to develop a new and novel method to account for tendon curvature in the assessment of the Achilles tendon moment arm during gait. The method was developed, and its reliability assessed, using young adults who simulated toe-walking.

The aim of chapter 6 was to assess the plantarflexor EMA of children who ITW. To do this, the new method (chapter 5) was adopted to quantify the plantarflexor EMA of children who ITW and TD children during gait and estimate the muscle force requirements for propulsion.

Finally, in chapter 7, the findings of the experiments reported in this thesis are then synthesised in a general discussion to consider their clinical relevance and recommendations for future work.

CHAPTER 2: GAIT CHARACTERISTICS OF CHILDREN WHO IDIOPATHICALLY TOE-WALK AND TYPICALLY DEVELOPING CHILDREN

Abstract

Children who idiopathically toe-walk (ITW) ambulate without a heel contact with the ground, which can require clinical treatments to correct gait. Despite this, the gait characteristics of children who ITW are scarcely described within the literature. Moreover, the few known studies to document the gait of children who ITW only report the spatial-temporal parameters of gait, or joint data in the sagittal plane. Therefore, the aim of this study was to compare the gait characteristics and dynamic balance of children who ITW and typically developing (TD) children, to gain a further understanding of their locomotor dysfunction. Five children who ITW and 14 typically developing (TD) children completed a gait analysis on an instrumented split-belt treadmill. Children who ITW operated at a greater plantarflexion angle than TD children throughout most of the gait cycle (0-3%, p = 0.049; 27-100%, p < 0.001), and produced a significantly greater plantarflexor moment between 0-24% (p = 0.001), and a significantly smaller plantarflexion moment between 50-59% of the gait cycle (0 = 0.001) than TD children. No differences were found in the frontal or transverse planes at the ankle joint, or in any cardinal plane for the knee and hip joints between groups. Children who ITW had a significantly smaller margin of stability than TD children between 5-9% of stance (p = 0.014). However, no gait compensations were made to counteract this reduced stability. Consequently, the findings of this study support the common notion that idiopathic toe-walking is truly a sagittal plane ankle joint pathology. Therefore, clinical treatments should, as currently prescribed, target the ankle joint in isolation. Moreover, future work to better understand the musculoskeletal mechanisms that may contribute to idiopathic toe-walking should target the plantarflexors.

Introduction

Children who idiopathically toe-walk (ITW) ambulate with the absence of a heel contact with the floor. Persistent, untreated equinus can lead to secondary symptoms, such as contracture and/or fixed deformity, which often require clinical treatments. As there is no clear cause for idiopathic toe-walking (Pomarino et al., 2016), prescribing the correct clinical treatment can often be difficult. Common treatments for children who ITW target the ankle joint in isolation, with a primary aim to restore dorsiflexion range of motion and typical sagittal-plane gait characteristics, specifically to achieve a heel-to-toe gait pattern. However, despite this, the gait of children who ITW is scarcely described within the previous literature. Thus, it is essential that we systematically quantify the gait characteristics of children who ITW, to gain a better understanding of their locomotor dysfunction.

At the ankle, children who ITW are known to operate at greater plantarflexion angles throughout the gait cycle (Alvarez et al., 2006; Hemo et al., 2006; Hicks et al., 1988; Thielmann et al., 2019; Westberry et al., 2008), to produce greater plantarflexion moments during early stance, and to produce smaller plantarflexion moments during propulsion (Hemo et al., 2006; Westberry et al., 2008) than typically developing (TD) children. However, contradictory findings have been reported at the knee joint. Some children who ITW have been found to present with hyperextension during stance (Engstrom et al., 2013; Hemo et al., 2006), but others have typical knee kinematics and kinetics (Hemo et al., 2006; McMulkin et al., 2016). Furthermore, contradictory findings have also been reported when quantifying the spatial-temporal parameters of gait. Some studies have found no differences in gait spatial-temporal parameters between children who ITW and TD children (Fanchiang et al., 2016; Pendharkar et al., 2012), whilst Westberry et al. (2008) reported that children who ITW ambulated with a slower walking velocity, shorter step and stride length, and a reduced cadence compared to TD children.

Current clinical treatments for children who ITW target the ankle joint in isolation and have been shown to improve sagittal-plane gait kinematics and kinetics (Davies et al., 2018; Engström et al., 2013; Hemo et al., 2006; McMulkin et al., 2006; 2016). However, a full gait “normalisation” is usually not achieved, and the long-term (> 5yrs) outcomes for children who ITW following these treatments are often poor, with high rates of recurrence reported (Dietz & Khunsree, 2012; van Kuijk et al., 2014). Potentially, this might be explained by the assumption that the gait abnormalities only arise in the sagittal plane and at the ankle, because no known research has ever fully quantified the kinematics and kinetics of the ankle, knee, and hip joints of these children in all three cardinal planes.

In addition to kinematic normalisation, treatments also aim to improve the dynamic balance of children who ITW, which is compromised by the small base of support available during toe-walking (Kerrigan et al., 2000). However, little is known about the dynamic balance of children who ITW during gait and/or what compensations may be used to overcome poor balance. Thus, it is essential that we gain a full understanding of the gait characteristics of children who ITW, to ensure that appropriate clinical interventions can be prescribed.

Therefore, the aim of this study was to systematically quantify and compare the gait characteristics and dynamic balance of children who ITW and TD. The hypothesis was that children who ITW would only present with gait abnormalities at the ankle joint in the sagittal plane, and that children who ITW would be less stable than TD children throughout stance.

Method

Participants

Five children who bilaterally ITW (male n = 2; female n = 3; age 8 ± 2yrs; height 1.38 ± 0.15m; body mass 45.2 ± 26.7kg) and 14 TD children (male n = 5; female n = 9; age 10 ± 2yrs; height 1.39 ± 0.11m; body mass 37.8 ± 17.5kg) participated in this study. Detailed participant characteristics are shown in Table 2.1. Children who ITW were recruited from outpatient lists at a hospital gait laboratory and orthopaedic clinics. All children had a confirmed diagnosis of idiopathic toe-walking based on an exclusion of all other diagnoses. Children who ITW had not undergone any orthopaedic intervention (surgical or casting) within two years prior to the study and had not been given botulinum toxin A injections within six months prior to the study. Two children who ITW had received carbon fibre insoles and splints three years prior to participation. The remaining three children who ITW had significant fixed equinus contracture (Range: -12 to -30°) and had received no orthopaedic intervention. All TD children were free from neuromuscular and skeletal disorders and were free from lower limb injuries for six months prior to the study. This study was completed in accordance with the recommendations of both the institutional and National Health Service (UK) ethics committees (18/NW/0526). Written informed consent was obtained from parent/guardians and written assent given by children, in accordance with the declaration of Helsinki.

Table 2.1. Detailed participant characteristics of children who idiopathically toe-walk and typically developing children.

Group	ID	Age (yrs)	Height (m)	Mass (kg)	Contracture* (°)	Previous Treatment
ITW	1	8	1.29	32.0	-	Insoles
	2	9	1.32	46.9	-30	None
	3	6	1.29	23.9	-	Insoles and splints
	4	12	1.65	90.7	-12	None
	5	6	1.36	32.7	-25	None
TD	1	9	1.34	27.1	-	-
	2	12	1.45	42.8	-	-
	3	12	1.39	39.8	-	-
	4	7	1.20	26.7	-	-
	5	10	1.26	25.1	-	-
	6	11	1.43	36.7	-	-
	7	10	1.46	40.3	-	-
	8	6	1.26	23.3	-	-
	9	8	1.30	22.9	-	-
	10	13	1.39	46.3	-	-
	11	14	1.62	92.3	-	-
	12	9	1.40	39.5	-	-
	13	10	1.41	31.4	-	-
	14	11	1.48	34.6	-	-

*Abbreviations: ITW, children who idiopathically toe-walk; TD typically developing children. *Contracture measured with knee fully extended.*

Measurement Protocol

Children completed a gait analysis on an instrumented split-belt treadmill (Motek Medical, Amsterdam, The Netherlands). Prior to data collection, a 5-10-minute period of familiarisation was completed to ensure that the children could walk comfortably in their preferred gait pattern on the treadmill and to identify their self-selected walking speed. Following familiarisation, passive retro-reflective markers (n = 61) were positioned on the whole body in accordance with the 6-degrees-of-freedom marker set, to model the head (6 markers positioned using a headband), trunk (C7, T10, jugular notch, xiphoid process), upper limbs (acromion processes, lateral epicondyles of the humorous, ulna/radial styloid processes, 3rd metacarpal heads, with single tracking markers positioned on the upper arm and forearm segments), pelvis (sacrum, anterior superior iliac spines, posterior superior iliac spines) and lower limbs (medial/lateral femoral epicondyles, medial/lateral malleoli, calcanei, and 1st 2nd, and 5th metatarsal heads, with rigid clusters of four tracking markers positioned on the thigh and shank segments).

Participants walked barefoot in their preferred gait pattern and at their self-selected walking speed, whilst secured in an upper body fall-arrest harness for safety. Participants walked continuously until five consecutive successful gait cycles were collected on the same leg. Three-dimensional (3D) kinematics were collected using a 12-camera Vicon Vero system (Vicon, Oxford, UK) at a sample rate of 120 Hz. Kinetic data from the treadmill were also recorded in Vicon, at a sample rate of 1200 Hz.

Data Processing

Gait data were processed in Visual 3D software (C-Motion, Rockville, MD) using a custom-made pipeline. All data were low pass filtered with a cut-off frequency of 6Hz. A cut-off frequency of 6Hz was deemed appropriate for all data, confirmed using a Fast Fourier Transformation performed on the raw unfiltered kinematic and kinetic data (Appendix A). To identify individual gait cycles and stance phases, initial contact and toe-off events were defined using a force plate threshold of 10N. To compare the gait characteristics of children who ITW and TD children, joint angles and moments of the hip, knee, and ankle joints in all three cardinal planes were calculated. Angle conventions are presented in Table 2.2. Frontal plane data obtained from the left-hand side (n = 2) were negated to match the joint coordinate system of data obtained from the right-hand side (n = 17).

Table 2.2. Joint angle conventions of the ankle, knee, and hip joints. Frontal plane data obtained from the left-hand side (n = 2) was negated to match the joint coordinate system of data obtained from the right-hand side (n = 17).

Joint	Plane	+/-
Ankle	Sagittal	Dorsiflexion/Plantarflexion
	Frontal	Eversion/Inversion
	Transverse	In-toeing/Out-toeing
Knee	Sagittal	Flexion/Extension
	Frontal	Adduction/Abduction
	Transverse	Internal/External Rotation
Hip	Sagittal	Flexion/Extension
	Frontal	Adduction/Abduction
	Transverse	Internal/External Rotation

To assess dynamic balance the instantaneous margin of stability (MoS_{Inst}) was calculated. GRF angle, step width, step length and spatial-temporal characteristics of gait were quantified to explore compensatory characteristics to promote balance.

MoS_{Inst} was measured as the distance between the anterior boundary of the base of support (defined between the 2nd metatarsal head markers) and the extrapolated centre of mass (XCoM; Eq. 2.1) of the foot.

$$XCoM = P_{CoM} + \frac{V_{CoM} + V_{foot}}{\sqrt{\frac{g}{L}}} \qquad (2.1)$$

where P_{CoM} is the position of the centre of mass relative to the 2nd metatarsal head marker of the trailing foot, V_{CoM} is the velocity of the centre of mass, V_{foot} is the velocity of the 2nd metatarsal head marker of the measured side, g is gravitational acceleration, and L is the sagittal distance between the centre of mass and the ankle joint centre (defined as the mid-point of the transmalleolar axis).

Step width and length were defined as the respective sagittal and frontal plane distances between the left and right heel markers, at consecutive initial contact events.

Absolute and relative stance times (double *vs.* single-limb support) were computed as the absolute time in seconds between the appropriate initial contact and toe-off events. All gait data were averaged for five gait cycles per participant and exported to Matlab (MathWorks R2019a, UK) for subsequent analyses.

Statistical Analysis

All statistical analyses were completed in Matlab 2019a. All variables were checked for normal distribution using the Shapiro-Wilk test. Gait kinematics, kinetics and MoS_{Inst} were compared between groups using either Statistical Parametric Mapping (SPM) for normally distributed variables or Statistical Non-Parametric Mapping (SnPM) for non-normally distributed variables (Pataky et al., 2013). Spatial-temporal data were compared between groups using either a student's t-test for normally distributed variables or a Mann-Whitney U test for non-normally distributed variables. For all tests, statistical significance was set at $p < 0.05$. All results are presented as mean ± standard deviation (SD), unless stated otherwise.

Results

Children who ITW operated at significantly more plantarflexed angles than TD children between 0-3% ($p = 0.049$) and 27-100% ($p < 0.001$) of the gait cycle, and at peak plantarflexion moment during propulsion (-11° *vs.* 10°; $p = 0.002$) (Figure 2.1a). Children who ITW also produced a significantly greater plantarflexion moment between 0-24% of the gait cycle ($p = 0.001$), and a significantly smaller plantarflexion moment between 50-59% of the gait cycle ($p = 0.001$) than TD children (Figure 2.2a). At the ankle, there were no significant differences in the frontal or transverse plane joint angles (Figure 2.1b, 2.1c) or moments (Figure 2.2b, 2.2c) between groups. At the knee and hip joints, there were no significant differences in the joint angles (Figure 2.1d – 2.1i) or moments (Figure 2.2d – 2.2i) in any cardinal plane between groups.

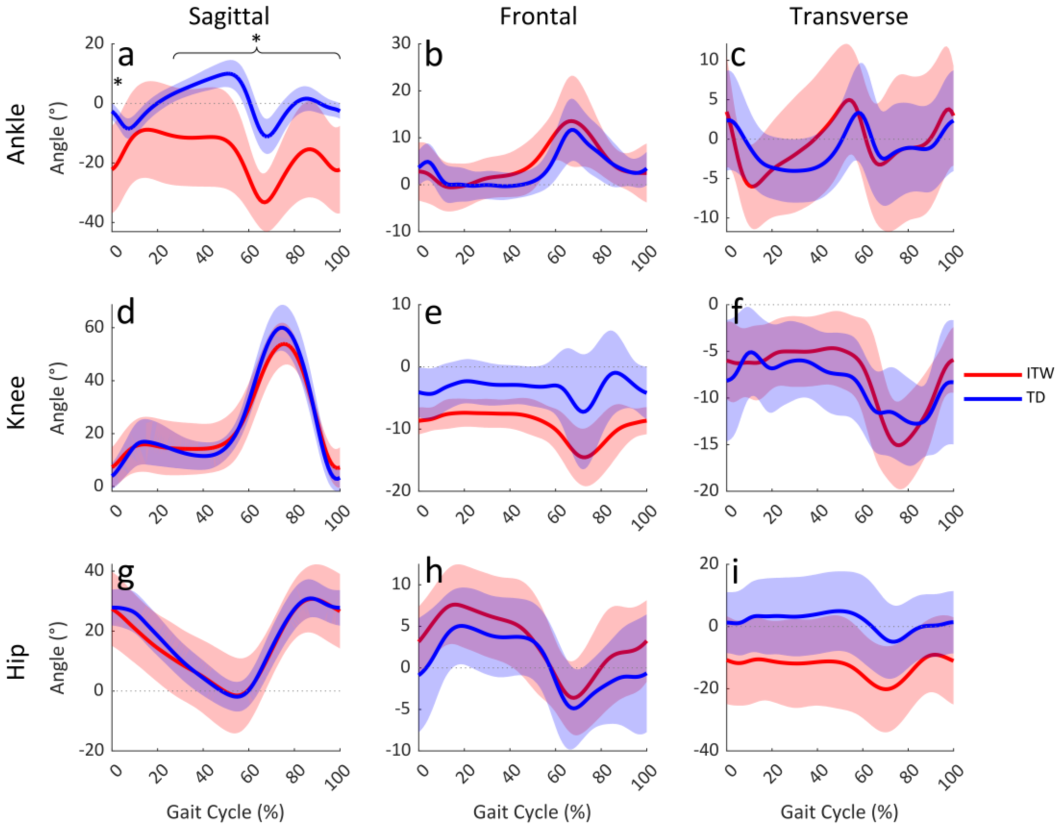

*Figure 2.1. Kinematics of the ankle (a-c), knee (d-f), and hip (g-i) joints throughout the gait cycle in all 3 cardinal planes of movement. Abbreviations: ITW, children who idiopathically toe-walk; TD, typically developing children. *Significant difference between groups (p < 0.05).*

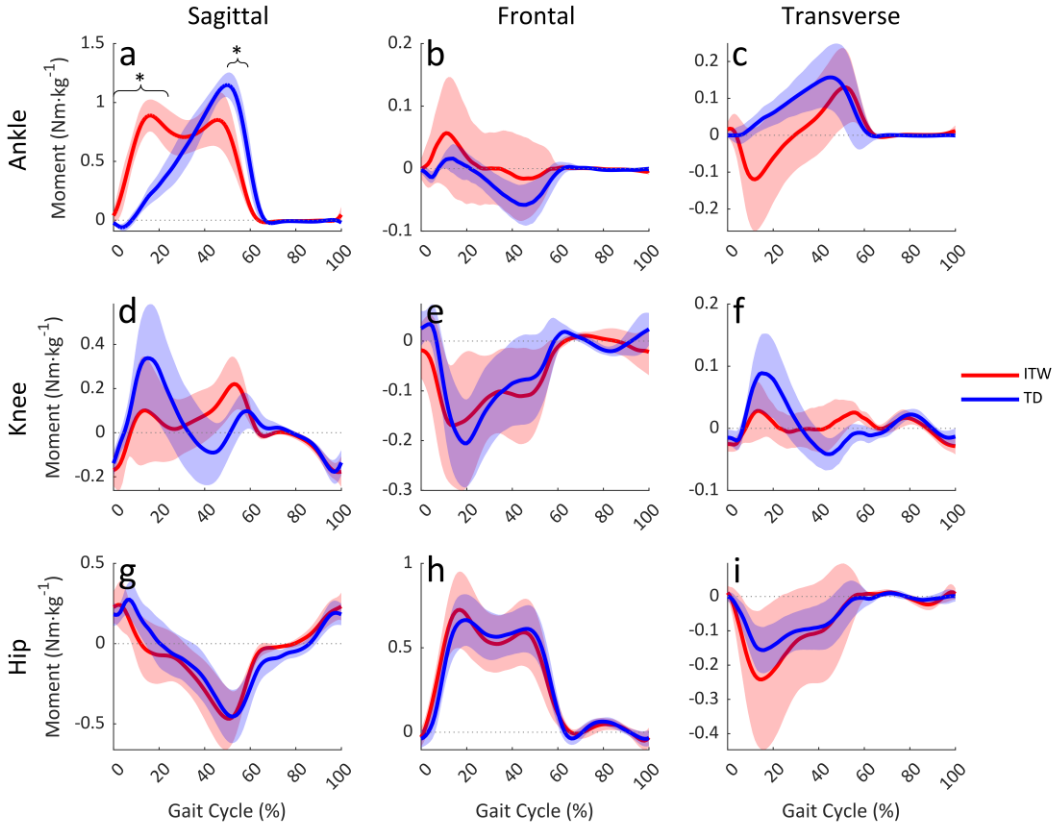

*Figure 2.2. Joint moments (normalised to body mass) of the ankle (a-c), knee (d-f), and hip (g-i) joints throughout the gait cycle in all 3 cardinal planes of movement. Abbreviations: ITW, children who idiopathically toe-walk; TD, typically developing children. *Significant difference between groups ($p < 0.05$).*

Further exploration of the individual sagittal plane ankle joint data of children who ITW is shown in Figure 2.3, as the within-group variability was notably greater than TD children (Figure 2.1; 2.2). Children who ITW were ranked according to the severity of equinus based on their ankle joint position throughout the gait cycle (Figure 2.3a). Kinetically, children who ITW with the highest severity of equinus appeared to produce the smallest plantarflexion moment during propulsion (Figure 2.3b).

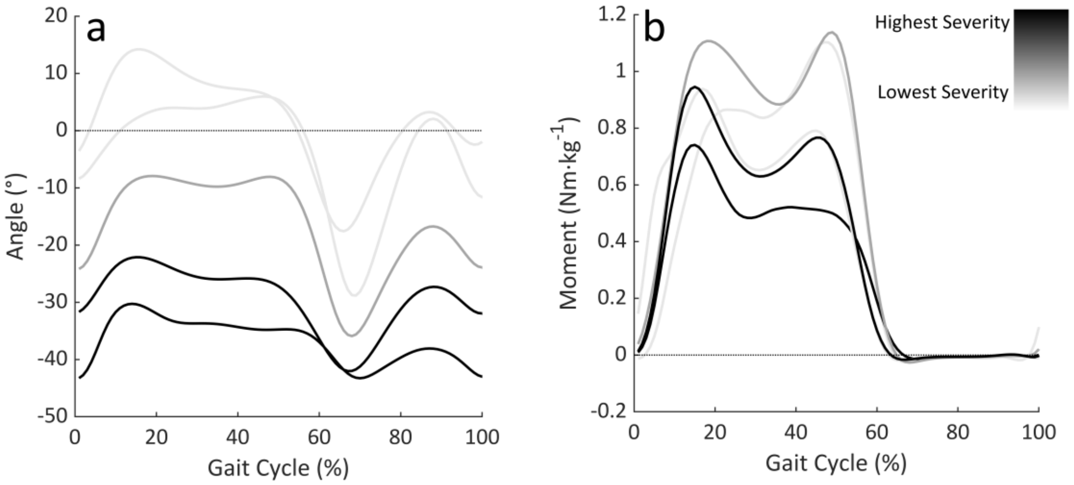

Figure 2.3. Individual sagittal-plane ankle joint (a) angles and (b) moments (normalised to body weight) throughout the gait cycle of children who idiopathically toe-walk.

The GRF vector of children who ITW was directed anteriorly earlier in stance than TD children (33 *vs.* 39%; p = 0.010; Figure 2.4b). The magnitude of the anterior GRF was significantly greater in children who ITW between 37-50% of the gait cycle (p < 0.001) than TD children (Figure 2.4b). There was no significant difference in the medio-lateral or vertical GRF between groups at any point throughout the gait cycle (Figure 2.4a, 2.4c).

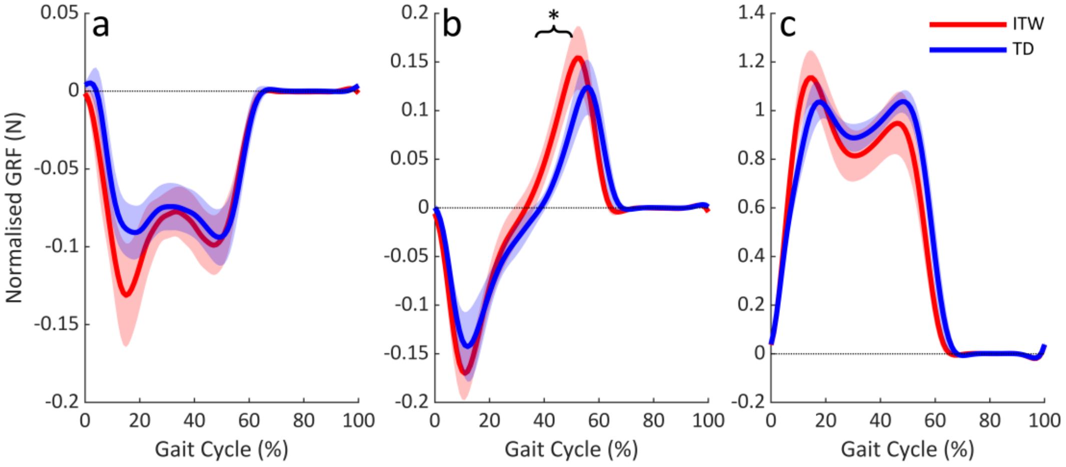

*Figure 2.4. Normalised (body weight) ground reaction forces in the (a) medio-lateral, (b) anterior-posterior, and (c) vertical directions. Abbreviations: ITW, children who idiopathically toe-walk; TD, typically developing children. *Significant difference between groups (p < 0.05).*

The $\mathrm{MoS}_{\mathrm{Inst}}$ of children who ITW and TD children was not different throughout most of stance (Figure 2.5). However, children who ITW had a significantly smaller $\mathrm{MoS}_{\mathrm{Inst}}$ than TD children between 5-9% of stance ($p = 0.014$; Figure 2.5).

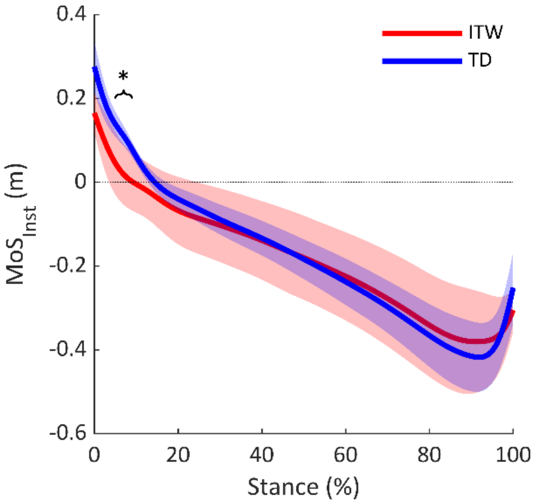

Figure 2.5. Instantaneous margin of stability throughout stance of children who idiopathically toe-walk and typically developing children. Abbreviations: ITW, children who idiopathically toe-walk; TD, typically developing children; $\mathrm{MoS}_{\mathrm{Inst}}$*, instantaneous margin of stability. *Significant difference between groups* ($p < 0.05$)*.*

Spatial-temporal data from the measured side are presented in Table 2.3. There was no significant difference in self-selected walking speed ($p = 0.186$), cadence ($p = 0.141$), step length ($p = 0.146$), or step width ($p = 0.628$) between groups. There was also no significant difference in absolute stride ($p = 0.676$) or stance time ($p = 0.071$) between groups, however children who ITW spent a significantly greater percentage of time in single support, and thus a significantly smaller percentage of time in double support, than TD children ($p = 0.045$).

Table 2.3. Mean ± SD spatial-temporal parameters of children who idiopathically toe-walk and typically developing children during gait.

	ITW	**TD**
Gait speed ($m \cdot s^{-1}$)	0.76 ± 0.15	0.86 ± 0.15
Cadence ($steps \cdot min^{-1}$)	76.9 ± 5.5	72.1 ± 6.0
Step length (m)	0.36 ± 0.09	0.42 ± 0.07
Step width (m)	0.20 ± 0.05	0.19 ± 0.03
Stride time (s)	1.00 ± 0.1	1.01 ± 0.1
Stance time (s)	0.64 ± 0.03	0.69 ± 0.07
Single support time (%)	57 ± 2	54 ± 3*
Double support time (%)	43 ± 2	46 ± 3*

*Abbreviations: ITW, children who idiopathically toe-walk; TD, typically developing children. *Significant difference between groups ($p < 0.05$).*

Discussion

The aim of this study was to systematically quantify and compare the gait characteristics and dynamic balance of children who ITW and TD children, to determine if the pathology of idiopathic toe-walking presents outside of the sagittal-plane ankle joint. Children who ITW only presented with gait abnormalities in the sagittal plane at the ankle joint. No between-group differences were found in the frontal or transverse planes at the ankle joint, in any plane at the knee or hip joint, or in dynamic balance throughout most of stance. Therefore, data from the present study supports the notion that idiopathic toe-walking is purely a sagittal plane, ankle joint pathology. Thus, clinical interventions, as are currently prescribed, should target the ankle joint in isolation.

Consistent with previous literature, children who ITW operated at greater plantarflexion angles throughout the gait cycle, produced a significantly smaller plantarflexion moment in early stance, and produced a significantly greater plantarflexion moment during propulsion than TD children (Alvarez et al., 2006; Hemo et al., 2006; Hicks et al., 1988; Kelly et al., 1997; Thielmann et al., 2019; Westberry et al., 2008). This is despite the large variation observed in the equinus severity of these children who ITW (Figure 2.3a). As the GRF magnitude was similar between groups, observed differences in the plantarflexion moments of children who ITW can likely be explained by alterations to the GRF moment arm length. This is supported by observed differences in the orientation of the GRF vector between groups (Figure 2.4), however future work is required to confirm this notion. No other between-group differences were found in the frontal or transverse planes at the ankle joint, or in any plane at the knee and hip joints. Therefore, these data suggest that idiopathic toe-walking is purely a sagittal plane ankle joint pathology. Future work to better understand the musculoskeletal mechanisms that may contribute to the equinus gait pattern of children who ITW, such as those presented in the subsequent chapters of this thesis (chapters 3-6), should also target the ankle joint in the sagittal plane.

Specific measures of dynamic balance (MoS_{Inst}) indicated that children who ITW were less stable than TD children between 5-9% of stance, during the double-limb support phase. However, consistent with previous work (Fanchiang et al., 2016; Pendharkar et al., 2012), children who ITW presented with similar spatial-temporal characteristics to TD children during gait. As these characteristics are good compensatory indicators of dynamic balance (An et al., 2017), this may suggest that children who ITW are not unstable as a consequence of the altered gait pattern. Children who ITW did not increase their double-limb support time to compensate for the reduced MoS_{Inst} in early stance and indeed, spent a smaller percentage of stance time in double-limb support than TD children. Therefore, the findings from this study may suggest that children who ITW are at the highest risk of becoming unstable in early stance from inaccurate foot placement or uneven surfaces, rather than a loss of balance during the single-limb support phase. However, further work is required to explicitly quantify gait stability in children who ITW under different challenging conditions.

The specific limitations for this experimental chapter should be acknowledged. Firstly, although care was taken in the placement of motion capture markers, it cannot be ruled out that small errors may have been introduced by marker misplacement and skin movement artefact (Peters et al., 2010). Secondly, children completed the gait analysis on an instrumented split-belt treadmill, rather than on level ground, and walked barefoot rather than in shoes. This may have had some small effects on the gait data when comparing to previous work presenting overground walking (Hollman et al., 2016; Oeffinger et al., 1999; van der Krogt et al., 2014). However, as both groups of children completed the gait analysis on the treadmill, it is not anticipated that the use of the treadmill has confounded our between-group comparisons (van der Krogt et al., 2015).

To conclude, data from the current study indicate that the pathology of children who ITW presents at the ankle joint, in the sagittal plane only. Therefore, clinical practice of targeting interventions at the ankle joint in isolation are supported. However, whilst this study has documented the gait abnormalities of children who ITW, the mechanistic reasons as to why these children walk in equinus remain unknown. Therefore, it is essential for future work to study the musculoskeletal mechanisms that may be contributing to the equinus gait pattern in children who ITW, to better our understanding of the pathology and thus, better inform clinical treatments for these children.

CHAPTER 3: MUSCLE ARCHITECTURE AND PASSIVE LENGTHENING PROPERTIES OF THE GASTROCNEMIUS MEDIALIS AND ACHILLES TENDON IN CHILDREN WHO IDIOPATHICALLY TOE-WALK

The information presented in this chapter has been reported in the paper:

Harkness-Armstrong, C., Maganaris, C. N., Walton, R., Wright, D. M., Bass, A., Baltzopoulos, V., and O'Brien, T. D. (2021). Muscle architecture and passive lengthening properties of the gastrocnemius medialis and Achilles tendon in children who idiopathically toe-walk. *Journal of Anatomy, 239*(4), 839-846.

Abstract

Children who idiopathically toe-walk habitually operate at greater plantarflexion angles and thus, at shorter muscle-tendon unit lengths than typically developing children. Therefore, it is often assumed that habitual use of the gastrocnemius muscle in this way will cause remodelling of the muscle-tendon architecture compared to typically developing children. However, the gastrocnemius muscle architecture of children who idiopathically toe-walk has never been measured. It is essential that we gain a better understanding of these muscle-tendon properties, to ensure that appropriate clinical interventions can be provided for these children. Five children who idiopathically toe-walk (age 8 ± 2 years) and 14 typically developing children (age 10 ± 2 years) participated in this study. Ultrasound was combined with isokinetic dynamometry and surface electromyography, to measure muscle architecture at common positions and passive lengthening properties of the gastrocnemius muscle and tendon across full range of motion. Regardless of which common condition groups were compared under, both the absolute and normalised to muscle-tendon unit muscle belly and fascicle lengths were always longer, and the Achilles tendon length always shorter in children who idiopathically toe-walk than typically developing children ($p < 0.05$; large effect sizes). The passive lengthening properties of the muscle and tendon were not different between groups ($p > 0.05$), however passive joint stiffness was greater in children who idiopathically toe-walk at maximum dorsiflexion ($p = 0.001$) and at a joint moment common to all participants ($p = 0.029$). Consequently, the findings of this study indicate a remodelling of the relative muscle-tendon unit that does not support the concept that children who idiopathically toe-walk commonly experience muscle shortening. Therefore, greater consideration of the muscle and tendon properties are required when prescribing clinical interventions which aim to lengthen the muscle-tendon unit, and treatments may be better targeted at the Achilles tendon in children who idiopathically toe-walk.

Introduction

Persistent, untreated toe-walking can lead to equinus contracture (Solan et al., 2010), therefore clinical treatments are often prescribed to lengthen the gastrocnemius muscle-tendon unit (MTU). However, the alterations in muscle and tendon properties that lead to this reduced range of motion (ROM) of children who idiopathically toe-walk (ITW) have never been measured. Understanding these muscle-tendon properties may improve our understanding of the pathology, and better target clinical interventions for these children.

In typically developed gait, the movement kinematics and muscle architecture combine so that the gastrocnemius medialis muscle operates close to optimal length, which favours the economical production of high contractile force (Fukunaga et al., 2001). This association between structure and function is common (Arnold & Delp, 2011) since muscles remodel in length according to the utilised ROM (Matano et al., 1994; Williams & Goldspink, 1973). Children who ITW ambulate with a greater plantarflexion angle compared to typically developing (TD) children, and therefore are likely operating at shorter gastrocnemius muscle and whole MTU lengths. Thus, it is expected that habitual use in this way will cause remodelling of the gastrocnemius medialis muscle architecture compared to TD children.

Equinus also presents in many children with cerebral palsy (CP). Although the pathway of cause-and-effect is more complex in CP (Gage & Novacheck, 2001), it is well documented that children with CP have shorter gastrocnemius MTU lengths (Kruse et al., 2018), which are, in turn, composed of shorter (Barrett & Lichtwark, 2010; Fry et al., 2004) and stiffer (Willerslev-Olsen et al., 2018) medial gastrocnemius muscle bellies, shorter fascicle lengths (Kalkman et al., 2018; Matthiasdottir et al., 2014; Mohagheghi et al., 2008), and longer Achilles tendon lengths (Barber et al., 2012; Kalkman et al., 2018; Wren et al., 2010) than TD children. The passive lengthening properties of the muscle and tendon are also altered in children with CP (Kalkman et al., 2018). Thus, to treat these muscle-tendon alterations, and to prevent permanent remodelling of the muscle to these shorter, sub-optimal lengths (contracture), clinical interventions (e.g., serial casting, botulinum toxin-A injections, surgery) are prescribed to restore dorsiflexion ROM and a typical heel-toe gait pattern, by lengthening the gastrocnemius MTU (Alhusaini et al., 2011; Brouwer et al., 2000; Jahn et al., 2009; Kay et al., 2004).

As children who ITW ambulate with a similar locomotor dysfunction to many children with CP, it is often assumed that they will have undergone similar muscle and tendon alterations within the gastrocnemius MTU complex. The expectation of shorter muscle belly and MTU lengths would explain why children who ITW are often prescribed with similar interventions as their CP counterparts (Williams et al., 2016). However, the muscle and tendon properties have never been measured in children who ITW. Therefore, it is not known if the MTU length, or indeed the relative lengths of muscle and tendon differ from typical. Nonetheless, children who ITW often undergo invasive clinical interventions to lengthen the MTU. However, it is not known what the optimal procedure should be (e.g., whether the muscle or tendon should be lengthened), or the implications that such interventions will pose. Consequently, if the assumptions of muscle length, and therefore function are in any way incorrect, this may explain why the current medium to long term effectiveness of interventions are often poor for children who ITW (Dietz & Khunsree, 2012; van Kuijk et al., 2014).

Therefore, it is essential that we gain a better understanding of the plantarflexor MTU architectural properties in these children. This will help to better understand the pathology, and better inform current clinical practice for these children. Thus, the aim of this study was to measure the architectural structure and passive lengthening properties of the gastrocnemius medialis muscle and Achilles tendon in children who ITW and TD children across the ROM. It was hypothesised that children who ITW would exhibit remodelled gastrocnemius MTU lengths, which would be composed of a shorter muscle belly and a longer Achilles tendon length than TD children.

Method

Participants

For this chapter, the participant characteristics, inclusion/exclusion criteria, recruitment process, and ethical approval number remain unchanged. They are described in the participants section of chapter 2.

Selection of Outcome Measures

The lengths of the medial gastrocnemius muscle belly, fascicles and tendon were compared between groups as absolute lengths and relative to total MTU length. To ensure that comparisons were not confounded by variations in relative ROM or passive tension amongst children, between-group comparisons were made at a joint angle (-15°; corresponded to the average 0 Nm joint moment of TD children and was close to the end ROM common to all participants) and MTU length (365mm) common to all participants, and at individual 0 Nm joint moment (assumed to approximate zero passive MTU force). Additionally, fascicle pennation angle and muscle thickness were compared at 0 Nm to ensure no tissue deformation (Dick & Wakeling, 2017).

However, the joint angles to achieve these specific joint positions differ between individual children and were not possible to predict a priori. Thus, physically measured data were obtained at five relative joint angles across ROM, including maximum dorsiflexion, maximum plantarflexion, and at 25% intervals between (full procedure described below). Data were then interpolated using a second-order polynomial (R^2 range: 0.90-0.99) to calculate and compare the specific parameters at the common joint angle, common MTU length and at individual 0 Nm joint moment.

Measurement Protocol

Data were collected in one testing session at a university laboratory. Measurements were obtained from the right leg of TD children, and the most affected leg of children who ITW, defined as the observed degree of plantarflexion angle during gait.

Participants lay prone on an isokinetic dynamometer (Humac Norm CSMI, MA, USA) bed with their hip in full extension and lower leg supported so that the knee was 20° flexed (Figure 3.1). The axis of rotation of the dynamometer arm was aligned with the lateral malleolus throughout passive rotation before the participant’s foot was securely fastened to the footplate. A custom-made arch support ensured that heel-contact was maintained with the footplate across full ROM. Ankle ROM in both directions was determined by manually rotating the footplate until either (1) no further joint rotation was achieved with the application of increased joint moment or (2) the participant indicated their stretch threshold. Ankle angle and moment were sampled from the dynamometer analogue output at 1600Hz in Acknowledge software (Biopac Systems, UK). Net plantarflexion moment was corrected for the moment caused by the weight of the footplate. The moment of the foot was considered negligible.

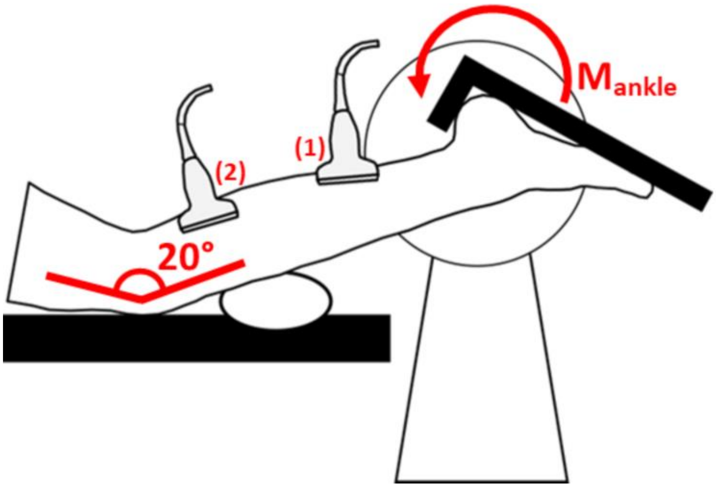

Figure 3.1. Experimental set-up to measure gastrocnemius muscle architecture and passive ankle moment throughout range of motion on an isokinetic dynamometer. Participants lay prone, with their hip extended fully and lower limb supported so that the knee was 20° flexed. In each joint position, an ultrasound probe was used to (1) identify the myotendinous junction of the medial gastrocnemius and Achilles tendon, and (2) to image the fascicle architecture from the mid-belly of the gastrocnemius medialis.

To ensure the muscle was at rest for all measurements, disposable surface electromyography (EMG) electrodes (BioNomadix, Biopac Systems, UK) were placed on the mid-portion of the tibialis anterior and the gastrocnemius lateralis. Muscle activity was recorded synchronously with angle and moment at 1600Hz in Acknowledge. EMG signals were inspected visually and any trials showing muscle activation were discarded.

To measure muscle, tendon, and muscle-tendon unit (MTU) length (Figure 3.2) an established ultrasound-based method was used (Barber et al., 2011). Specifically, the most superficial point on the posterior medial femoral condyle (assumed muscle origin) and the distal insertion of the Achilles tendon onto the calcaneus were identified using a linear B-mode ultrasound transducer (Phillips EPIQ7, The Netherlands) and marked on the skin with surgical marker. At each of the physically measured joint positions (maximum dorsiflexion, plantarflexion and the 25% intervals), the medial gastrocnemius myotendinous junction (MTJ) was identified with ultrasound in the sagittal plane and marked on the skin with surgical marker. Muscle and tendon lengths at each position were measured with a segmometer as the straight-line distance between the medial femoral condyle and the MTJ, and between the MTJ and calcaneal insertion, respectively. MTU length was calculated as the sum of the respective muscle and tendon lengths, to allow for a non-straight MTU path.

To measure fascicle length, muscle thickness and pennation angle at each joint position (Figure 3.2), the ultrasound transducer was moved from the MTJ to be positioned over the mid-belly of the gastrocnemius medialis muscle so that whole fascicle length between the superficial and deep aponeuroses of the muscle could be visualised within the scan's viewing window (Mohagheghi et al., 2007). Although measured across full ROM, pennation angle and muscle thickness (Figure 3.2) were only reported at 0 Nm, as any passive force in the MTU will cause these structures to deform (Dick & Wakeling, 2017) and thus, lose physiological meaning. All ultrasound data were analysed manually in ImageJ software (ImageJ 1.51j8, USA). All measurements of muscle architecture and tendon length were averaged between two measurements at each joint position.

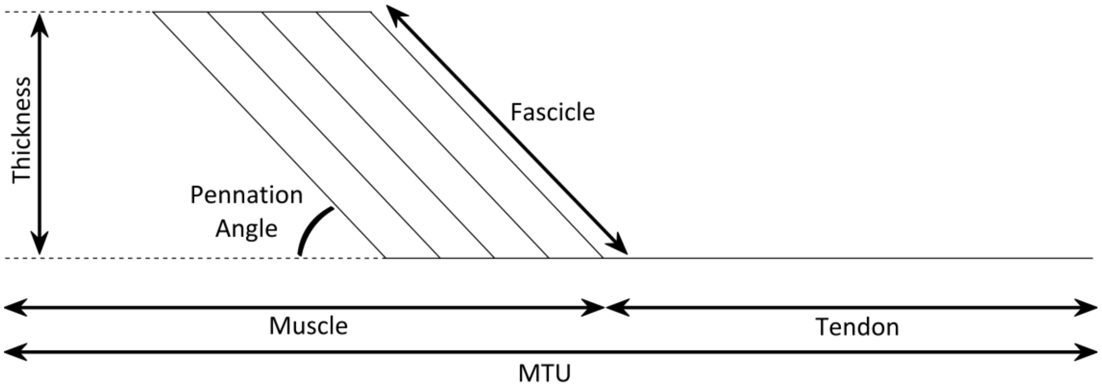

Figure 3.2. Schematic representation of the muscle-tendon unit architectural properties measured at maximum dorsiflexion, maximum plantarflexion, and at 25% intervals between. Muscle thickness and pennation angle were only reported at individual 0 Nm.

Passive joint stiffness was calculated for each participant by fitting a second-order polynomial (R^2 range: 0.96-0.99) to the measured joint moment-angle data. Similarly, fascicle pseudo-stiffness was calculated from a second-order polynomial (R^2 range: 0.86-0.99) fitted to the measured joint moment-fascicle length data. Whilst the underlying principles of this method have been used previously by others (Gao et al., 2009; Kalkman et al., 2018; Matthiasdottir et al., 2014), here the term "pseudo-stiffness" is preferred. This is to better reflect that the measurements obtained within the study can only approximate stiffness, by measuring changes in individual fascicle length behaviour in response to increased load at the ankle joint. For both measures of stiffness, the respective equations for each participant were then differentiated to calculate passive stiffness at maximum dorsiflexion, where passive moment is greatest, and at a passive joint moment common to all participants (0.02 $Nm\cdot kg^{-1}$), determined by the smallest maximum passive moment (Waugh et al., 2012).

Statistical Analysis

All statistical analyses were completed in RStudio (RStudio 1.3.959, Boston, USA). All variables were checked for normal distribution using the Shapiro-Wilk test and visual inspection of the q-q plots. Student's t-tests (normally distributed variables) and Mann-Whitney U tests (non-normally distributed variables) were used to compare absolute and relative to MTU length differences between groups at a common ankle angle, MTU length, and at 0 Nm joint moment, and the passive joint and fascicle stiffness' at maximum dorsiflexion and common passive moment. Lengthening data across the full and common ROM were compared between groups using Kruskal-Wallis tests with follow up post-hoc tests. Significance was set at $p < 0.05$. Effect sizes were calculated using Hedge's g, and considered small (>0.2), moderate (>0.5) or large (>0.8). Effect sizes were considered unclear if the 90% confidence internals included both substantial positive and negative values (≥±0.20) (Hopkins et al., 2009). Data are presented as means ± standard deviation (SD), unless stated otherwise.

Results

Across the full ROM, children who ITW had longer muscle and fascicle lengths, and a shorter tendon length than TD children (Figure 3.3). These differences were statistically significant when groups were compared at a common joint angle (-15 °) (large ESs: 1.03 to 2.00), common MTU length (365 mm) (large ESs: 1.41 to 3.23), and at individual 0 Nm (large ESs: 0.94 to 1.68) (Table 3.1), despite children who ITW being significantly more plantarflexed than TD children ($p = 0.016$).

When normalised to MTU length, the muscle remained significantly longer and the tendon significantly shorter in children who ITW at a common joint angle ($p = 0.032$; large ES: 2.13), MTU length ($p = 0.035$; large ES: 1.69), and at individual 0 Nm ($p = 0.049$; large ES: 1.98) than TD children. Fascicle length normalised to MTU length was also significantly longer in children who ITW than TD children in all considered joint positions ($p < 0.05$; large ESs: 2.16 to 3.27) (Table 3.1).

At 0 Nm, MTU length was not significantly different between groups, but children who ITW had a greater muscle thickness (17 ± 5 *vs.* 14 ± 3 mm; $p = 0.071$; moderate ES: 0.73) than TD children. There was no difference in pennation angle between groups (19 ± 2 *vs.* 20 ± 2 °; $p = 0.233$; unclear ES: -0.58).

Table 3.1. Mean ± SD of medial gastrocnemius medialis muscle-tendon architectural properties of children who ITW and TD children at a common joint angle (-15 °), common joint moment (0 Nm), and common MTU length (365 mm).

	Absolute lengths			Percentage of MTU (%)	
	ITW	TD	ES (Hedge's g)	ITW	TD
At common angle (-15 °)					
MTU (mm)	364 ± 42	373 ± 39	-0.20 ± 0.94	-	-
Muscle (mm)	229 ± 43	197 ± 25	1.03 ± 0.99	62 ± 6	53 ± 4*
Tendon (mm)	136 ± 14	176 ± 23*	-1.75 ± 1.06	37 ± 5	47 ± 4*
Fascicle (mm)	62 ± 17	42 ± 5*	2.00 ± 1.02	17 ± 3	11 ± 1*
At common moment (0 Nm)					
Ankle angle (°)	-22 ± 4	-16 ± 2*	-2.29 ± 1.06	-	-
MTU (mm)	353 ± 40	365 ± 39	-0.29 ± 0.95	-	-
Muscle (mm)	225 ± 40	197 ± 25	0.94 ± 0.98	62 ± 6	53 ± 4*
Tendon (mm)	137 ± 17	176 ± 24*	-1.64 ± 1.05	38 ± 5	47 ± 4*
Fascicle (mm)	59 ± 17	42 ± 5*	1.68 ± 0.98	17 ± 4	11 ± 1*
Thickness (mm)	17 ± 5	14 ± 3	0.73 ± 0.89	-	-
Pennation (°)	19 ± 2	20 ± 2	-0.58 ± 0.88	-	-
At common MTU length (365 mm)					
Ankle angle (°)	-8 ± 13	-32 ± 2*	3.38 ± 1.26	-	-
Muscle (mm)	231 ± 39	189 ± 24*	1.42 ± 1.02	63 ± 5	51 ± 5*
Tendon (mm)	140 ± 22	173 ± 22*	-1.41 ± 1.02	37 ± 7	48 ± 6*
Fascicle (mm)	63 ± 15	35 ± 5*	3.23 ± 1.23	18 ± 2	10 ± 4*

*Abbreviations: ITW, children who idiopathic toe-walk; TD, typically developing children; ES, effect size; MTU, muscle-tendon unit. *Significant difference between children who idiopathically toe-walk and typically developing children (p<0.05).*

Children who ITW had a significantly smaller ROM than TD children (53 ± 7 *vs*. 63 ± 4 °; p = 0.001). Excluding individual maximum plantarflexion (p = 0.065), children who ITW were significantly more plantarflexed at all remaining physically measured joint positions than TD children (p < 0.05). There was no difference in muscle or tendon lengthening between groups over full ROM or a ROM common to all participants (-42 to -13 °; p > 0.05; Figure 3.3a). However, muscle lengthening was significantly greater than tendon lengthening in both groups (p < 0.05; Figure 3.3a). Over the full ROM, fascicle lengthening was significantly less in children who ITW (p = 0.032), however there was no difference in fascicle lengthening between groups over a common ROM (Figure 3.3b).

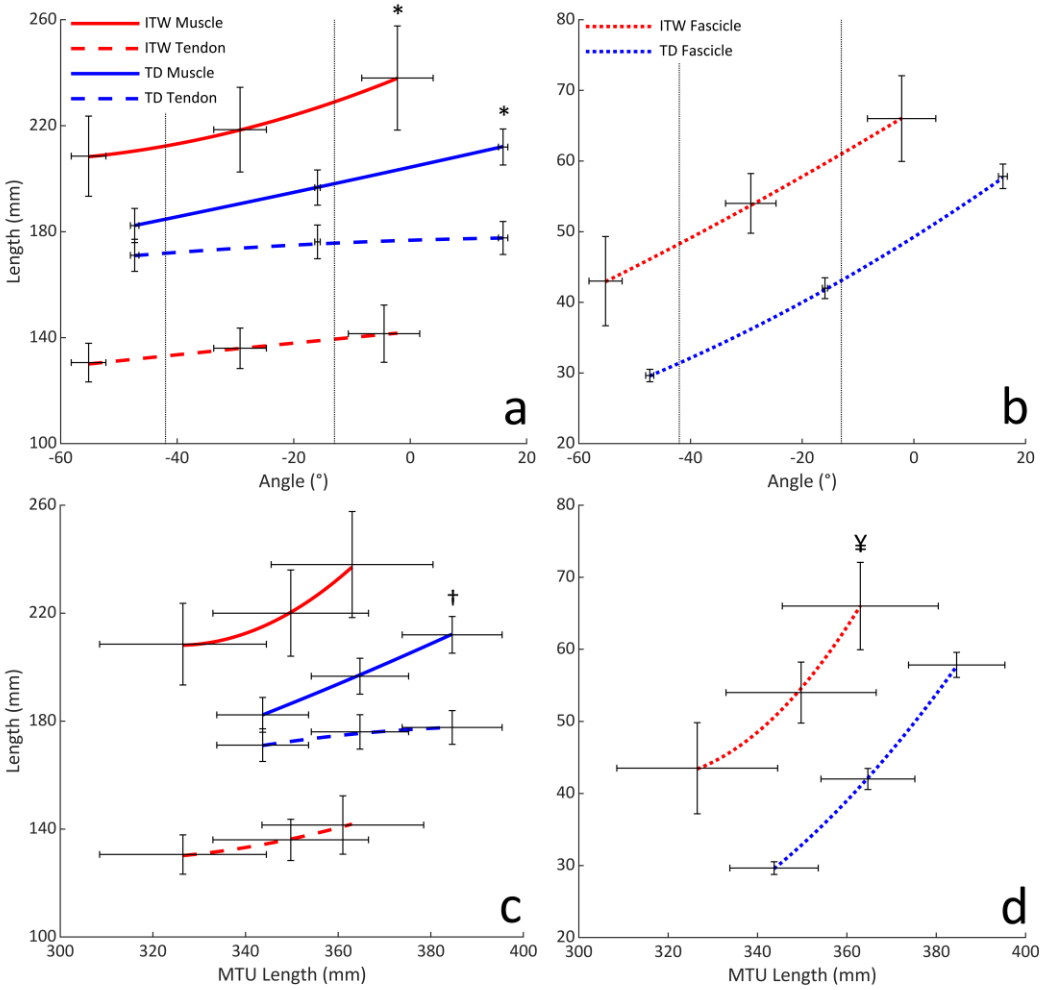

*Figure 3.3. a) Muscle/tendon length and b) fascicle length versus ankle angle over the full range of motion. Grey dashed lines indicate the common range of motion to all participants. c) Muscle/tendon length and d) fascicle length versus muscle-tendon unit length over the full range of motion. For clarity, standard error of the mean bars are shown at three joint positions only (maximum plantarflexion, 50% of range, maximum dorsiflexion). Abbreviations: ITW, children who idiopathically toe-walk; TD, typically developing children; MTU, muscle-tendon unit. *Significant difference between muscle and tendon lengthening throughout range of motion ($p < 0.05$). †Significant difference between groups in the ratio of muscle to tendon length when plotted against muscle-tendon unit length ($p < 0.05$). ¥Significant difference between groups in fascicle length when plotted against muscle-tendon unit ($p < 0.05$).*

Examination of individual fascicle length data are presented in Figure 3.4. In four out of five of the children who ITW, there is a general trend that children who ITW with the highest severity of equinus (consistently more plantarflexed throughout stance) have a greater resting fascicle length throughout full ROM than those with a lower severity of equinus. However, one child who ITW who was considered to have a moderate severity of equinus had the longest fascicle length through ROM. This can likely be explained by this participant being considerably taller than the remaining children who ITW (participant 4; Table 2.1).

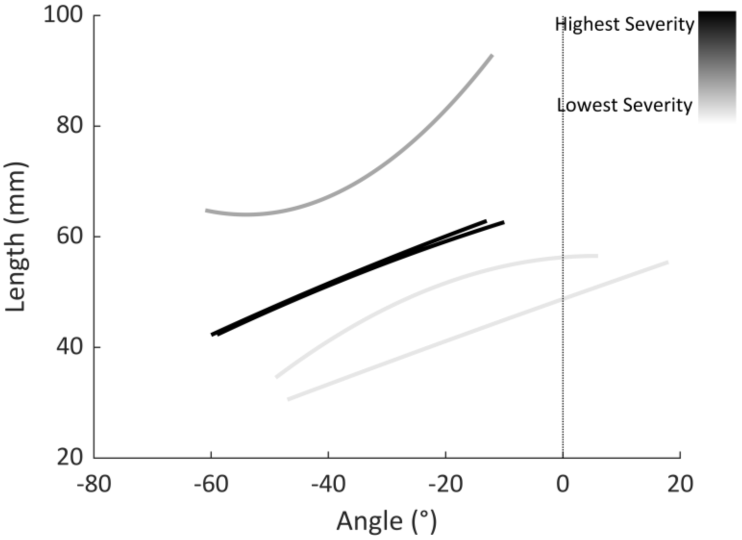

Figure 3.4. Individual fascicle lengths throughout full range of motion for children who idiopathically toe-walk.

At individual maximum dorsiflexion, children who ITW had a significantly greater passive joint stiffness than TD children (0.009 ± 0.003 *vs.* 0.005 ± 0.002 Nm·kg·deg^{-1}; p = 0.001; Figure 3.5a), however, there was no difference in the passive fascicle stiffness between groups (0.017 ± 0.011 *vs.* 0.010 ± 0.004 Nm·kg·mm^{-1}; p = 0.202; Figure 3.5b). At a common joint moment of 0.02 Nm·kg^{-1}, children who ITW also had a significantly greater passive joint stiffness than TD children (0.007 ± 0.002 *vs.* 0.003 ± 0.001 Nm·kg·deg^{-1}; p = 0.029; Figure 3.5a), however there was no difference in the passive fascicle stiffness between groups (0.013 ± 0.007 *vs.* 0.007 ± 0.002 Nm·kg·mm^{-1}; p = 0.112; Figure 3.5b).

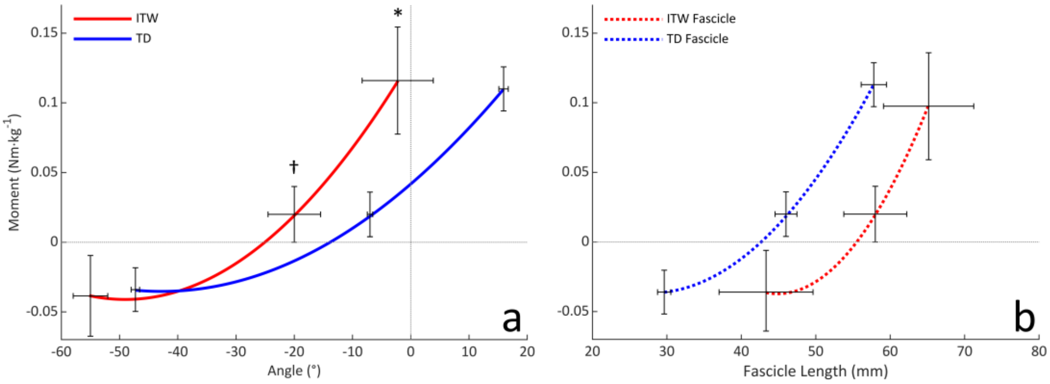

*Figure 3.5. Passive ankle moment versus a) ankle joint angle and b) resting fascicle length across full range of motion. For clarity, standard error of the mean bars are shown at three joint positions only (maximum plantarflexion, maximum dorsiflexion, and at the common joint moment that groups were compared). Abbreviations: ITW, children who idiopathically toe-walk; TD, typically developing children. *Significant difference between groups at maximum dorsiflexion ($p < 0.05$). †Significant difference between groups at common passive moment of 0.02 Nm·kg^{-1} ($p < 0.05$).*

Discussion

This study is the first to measure the muscle architecture and passive lengthening properties of the gastrocnemius medialis MTU in children who ITW. Contrary to the hypothesis, in all considered joint positions, children who ITW had longer absolute and normalised gastrocnemius medialis muscle belly and fascicle lengths, and a shorter Achilles tendon length than TD children, despite habitually operating at shorter MTU lengths. Consequently, these findings indicate a remodelling of relative MTU lengths that does not support the concept that these children commonly experience muscle shortening caused by a reduced ROM, as children with CP do. Therefore, clinical interventions may be better targeted at the Achilles tendon when aiming to restore MTU length and ROM in children who ITW.

To ensure that comparisons of the muscle architectural properties were not confounded by the differences in the relative ROM and passive stiffness of children, between-group comparisons were made at a common joint angle and MTU length, and at 0 Nm joint moment. Regardless of which common condition groups were compared under, both the absolute and normalised to MTU muscle belly and fascicle lengths were always longer, and the Achilles tendon length was always shorter in children who ITW than TD children (Table 1). This was particularly surprising at 0 Nm joint moment, because children who ITW were significantly more plantarflexed, but the muscle belly and fascicle lengths remained longer, and the tendon shorter, than TD children. At 0 Nm joint moment, the muscle thickness of children who ITW was greater than TD children (moderate ES: 0.73). This may suggest that children who ITW would be able to produce more plantarflexor force than TD children, despite the notion that plantarflexor weakness contributes to equinus gait (Hampton et al., 2003). Therefore, this should be explored in the future. Nonetheless, data from the present study led to the rejection of the hypothesis that children who ITW would have shorter absolute and normalised to MTU muscle and fascicle lengths, and a longer tendon length than TD children.

As the fascicle pseudo-stiffness was similar between groups, it appears that the reduction in ROM of children who ITW may be attributed to a shorter Achilles tendon length, which contributes to a greater ankle joint stiffness. Indeed, provided that it is made of the same material properties, shorter tendons are mechanically stiffer, meaning they lengthen less under the same forces. Therefore, whilst tendon stiffness was not explicitly measured within this study, a shorter, stiffer Achilles tendon would increase the stretching stimulus experienced by the in-series muscle and may therefore explain why the gastrocnemius muscle and fascicle lengths of children who ITW have remodelled to longer lengths than TD children (Herbert & Crosbie, 1997). The function of a shorter and stiffer tendon may allow children who ITW to better control the position of the ankle joint during gait (Alexander, 2002) and maintain plantarflexion during loading of stance without the requirement of greater muscle shortening. However, this hypothesis is also dependent on other musculoskeletal interactions and should be tested.

Treatments to increase MTU length are often based on the assumption that children who ITW will have developed similar gastrocnemius MTU alterations to those with CP (Alhusaini et al., 2011; Brouwer et al., 2000; Jahn et al., 2009; Kay et al., 2004; Williams et al., 2016). However, these data show that the MTU length of children who ITW is composed of a greater muscle to tendon ratio than typical. Therefore, the remodelling of muscle-tendon lengths of children who ITW are the exact opposite of that in children with CP, despite most of our patients exhibiting significant fixed equinus contracture. Consequently, although commonly associated, CP and idiopathic toe-walking appear to be two completely different conditions and therefore, may require different treatment approaches. Data from the current study suggest that clinical interventions for children who ITW should aim to lengthen the MTU, by lengthening the muscle aponeurosis (zone 2), or increasing the length and reducing the stiffness of the Achilles tendon (zone 3) rather than lengthening the gastrocnemius muscle (zone 1). Possible conservative treatments to lengthen the tendon in isolation without the need for surgery should also be explored.

In the present study, the muscle of children who ITW lengthened significantly more than the tendon to achieve full ROM, which suggests that there is a greater relative stiffness of tendon to muscle. Therefore, during conservative interventions which aim to stretch the MTU (stretching, serial casting etc.) the more compliant structure, in this case the muscle, will receive a higher physiological stimulus than the stiffer tendon (Kalkman et al., 2019). Consequently, it is more likely that the muscle will be the structure to “see” the stretch and increase in length. As the muscle is already longer than typical in children who ITW, it is possible that conservative clinical interventions could be lengthening an already long muscle. However, it is also possible that the between-group differences in muscle length may be due to general physiotherapy and stretching interventions provided to the children who ITW in the years since diagnosis. Nevertheless, further increasing the length of the gastrocnemius muscle would cause the discrepancy between the relative stiffness of the muscle and tendon to be even greater, which may have implications for physical function in these children. However, further work is required to assess the force producing capabilities at these altered lengths and thus, the functional operating lengths of the gastrocnemius muscle in children who ITW.

The specific limitations for this experimental chapter should be acknowledged. Firstly, the origin of the gastrocnemius medialis muscle was defined as the most superficial point on the posterior aspect of the medial femoral condyle. Therefore, differences in small portions of proximal tendon or muscle may have been neglected in our measurements of muscle and MTU length. However, this method is an established approach for these measurements (Barber et al., 2011), and the effect is considered negligible compared to the overall between-group differences. Achilles tendon lengths were measured as straight-line distances, thus neglecting the potential influence of curvature within structures in both groups. However, straight-line measures of Achilles tendon length have been shown to underestimate length only slightly by ~5 mm (Stosic & Finni, 2011). Therefore, as our significant between-group differences in tendon length are large (33-40 mm), it is unlikely that this has biased our conclusions. Finally, measurements were obtained from the gastrocnemius medialis MTU only, yet passive joint moments of the whole plantarflexor group were reported. Therefore, it is unclear as to the potential mechanical contributions of other plantarflexor muscles (e.g., the soleus) on the passive joint moments used to quantify fascicle pseudo-stiffness. Therefore, further work is required to establish the muscle-tendon architecture of other synergist muscles in the plantarflexor muscle group, and how these change throughout development and in response to treatment.

To conclude, contrary to the hypothesis, children who ITW had longer absolute and normalised muscle and fascicle lengths, and a shorter Achilles tendon length than TD children in all considered joint positions. Therefore, greater consideration of the muscle and tendon properties are required when prescribing current clinical interventions which aim to lengthen the MTU. However, further work is required to assess the implications of the greater muscle length on gait function and muscle force production capabilities in children who ITW. Future studies can also utilise the data from the current study to inform comprehensive musculoskeletal models of children who ITW.

CHAPTER 4: IN VIVO OPERATING LENGTHS OF THE GASTRONCEMIUS MUSCLE DURING GAIT IN CHILDREN WHO IDIOPATHICALLY TOE-WALK

The information presented in this chapter has been reported in the paper:

Harkness-Armstrong, C., Maganaris, C. N., Walton, R., Wright, D. M., Bass, A., Baltzopoulos, V., and O'Brien, T. D. (2021). In vivo operating lengths of the gastrocnemius muscle during gait in children who idiopathically toe-walk. *Experimental Physiology, 106*(8), 1806-1813.

Abstract

Children who idiopathically toe-walk (ITW) habitually operate at greater plantarflexion angles than typically developing (TD) children, which might result in shorter, sub-optimal gastrocnemius fascicle lengths. However, currently no experimental evidence exists to substantiate this notion. Five children who ITW and 14 TD children completed a gait analysis, whilst gastrocnemius fascicle behaviour was simultaneously quantified using ultrasound. The moment–angle (hip, knee, and ankle) and moment–length (gastrocnemius) relationships were determined from isometric maximum voluntary contractions (MVC) on an isokinetic dynamometer combined with ultrasound. During gait, children who ITW operated at more plantarflexed angles (Δ = 20°; P = 0.013) and longer muscle fascicle lengths (Δ = 12 mm; P = 0.008) than TD children. During MVC, no differences in the peak moment of any joint were found. However, peak plantarflexor moment occurred at significantly more plantarflexed angles (−16 vs. 1°; P = 0.010) and at longer muscle fascicle lengths (44 vs. 37 mm; P = 0.001) in children who ITW than TD children. Observed alterations in the moment–angle and moment–length relationships of children who ITW coincided with the ranges used during gait. Therefore, the gastrocnemius muscle in children who ITW operates close to the peak of the force–length relationship, similarly to TD children. Thus, this study indicates that idiopathic toe-walking is truly an ankle joint pathology, and children who ITW present with substantial alterations in the gastrocnemius muscle functional properties, which appear well adapted to the characteristic demands of equinus gait. These findings should be considered when prescribing clinical treatments to restore typical gait.

Introduction

Locomotion relies on joint moments to propel the body forwards, and so adequate contractile muscle force must be produced. The maximal contractile force is limited by the length and velocity of these muscles during contraction, according to the force-length-velocity relationship (Gordon et al., 1966). The plantarflexor muscles, a vital source of the required mechanical power for gait (Winter, 1983), have been shown to operate quasi-isometrically and close to the region of optimal sarcomere length during gait (Fukunaga et al., 2001), thereby maximising the potential muscle force and promoting the economical production of this force. However, this relies on gait kinematics that are matched to the underlying muscle-tendon architecture and functional properties.

Children who idiopathically toe-walk (ITW) present with an atypical gait pattern, despite no detected orthopaedic or neurological cause (Pomarino et al., 2016). Whilst the main pathology presents at the ankle joint (chapter 2), more proximal joints must also be considered. Whilst the gait kinematics and kinetics of the knee and hip are not altered (chapter 2), weakness of the hip and knee joint muscles have previous been suggested to contribute to equinus gait (Hampton et al., 2003; Kennedy et al., 2020; Morozova et al., 2017; Wiley & Damiano, 1998). For children who ITW, there has been an indication that there may be some small effects of ankle joint weakness (De Oliveira et al., 2021), however, to the author's knowledge, muscle strength around the hip or knee joint has never been objectively studied in children who ITW. Therefore, to improve our understanding of how the altered gait kinematics may affect the ability of children who ITW to produce force economically, it is important to establish whether muscle strength, determined by the *in vivo* force-length and moment-angle relationships, may be contributing to the toe-walking gait characteristic in these children.

Equinus gait also presents in many children with cerebral palsy (CP), which is associated with alterations in contractile muscle properties, such as a greater muscle stiffness (Barber et al., 2011), longer sarcomere lengths (Ponten et al., 2007; Lieber et al., 2017), muscle weakness around the hip, knee, and ankle joints (Eek & Beckung, 2008), and differences in the muscle lengthening characteristics (Kalkman et al., 2018) in the affected lower-limb muscles. However, although the gait kinematics in children with CP are similar to children who ITW, the pathway of cause-and-effect is far more complex in CP (Gage & Novacheck, 2001). Therefore, we should not assume that the muscle functional properties are similarly affected in children who ITW. Indeed, chapter 3 showed that children who ITW had longer resting absolute and normalised gastrocnemius medialis muscle belly and fascicle lengths than typically developing (TD) children. This is the exact opposite effect to that found in children with CP. Consequently, the more plantarflexed angles during gait and resulting shorter muscle fascicle lengths, may suggest that the sarcomeres of children who ITW operate at shorter lengths than optimal (Arnold & Delp, 2011). However, plantarflexor muscle fascicle lengths in children who ITW have never been measured during gait. Thus, it remains unknown how the altered muscle lengths relate to dynamic muscle function.

Current treatments for children who ITW primarily target the ankle joint because persistent, untreated, equinus gait can lead to muscle contracture, fixed deformity and/or worsening of symptoms (Dietz & Khunsree, 2012; Sobel et al., 1997; Solan et al., 2010). Therefore, interventions to lengthen the gastrocnemius muscle-tendon unit (MTU), such as casting with or without botulinum toxin-A injections and/or surgery (Engström et al., 2013; Fox et al., 2006; Jahn et al., 2009), are prescribed with the intention of restoring dorsiflexion range of motion (ROM) and a typical gait pattern. Therefore, there is a clinical assumption that achieving typical angles through intervention will restore optimal muscle length in children who ITW. However, as muscle function mirrors habitual use (Matano et al., 1994), it is possible that the MTU of children who ITW may have remodelled to match the altered gait kinematics. If true, then current treatments may negatively impact muscle function for these children, rather than improve it.

Therefore, it is vital to gain an understanding of the muscle strength and functional properties, relative to the demands of gait in these children. This will allow us to better understand the pathology and thus, better inform clinical interventions for these children, which often have poor medium-long term success rates (Dietz & Khunsree, 2012; van Kuijk et al., 2014). The aims of this study were to (1) measure the moment-angle relationship of the ankle, knee, and hip extensors of children who ITW and TD children relative to the demands of gait, and (2) to measure the moment-fascicle length relationship of the plantarflexors relative to the demands of gait. It was hypothesised that children who ITW would operate lower down on the ascending limb of the force-length relationship and thus, operate at joint angles that are further away from optimal than typical. It was also hypothesised that there would be no difference in the moment-angle relationships of the hip and knee extensors between groups.

Method

Participants

For this chapter, the participant characteristics, inclusion/exclusion criteria, recruitment process, and ethical approval number remain unchanged. They are described in the participants section of chapter 2.

Measurement Protocol

Data were collected over two testing sessions to first collect gait data and then collect muscle function data in the second session at a university laboratory, separated by no more than 14 days. Measurements were obtained from the right leg of TD children, and the most affected leg of children who ITW, defined by the observed degree of plantarflexion angle during gait.

Gait Measurements

Children completed a gait analysis on an instrumented split-belt treadmill (Motek Medical, Amsterdam, The Netherlands). Prior to data collection, there was a 5–10-minute period of familiarisation to identify the participants' self-selected walking speed and to ensure that they could walk comfortably in their preferred gait pattern. Following familiarisation, passive retro-reflective markers were positioned on the lower body in accordance with the 6-degrees-of-freedom marker set (37 total markers: ASIS, PSIS, sacrum, medial/lateral femoral epicondyles, medial/lateral malleoli, calcaneus, and 1st, 2nd, and 5th metatarsal heads, with rigid clusters of four tracking markers positioned on the thigh and shank segments). Participants walked barefoot in their preferred gait pattern and at their self-selected walking speed, whilst secured in an upper body fall-arrest harness for safety. Participants walked continuously until five consecutive successful gait cycles were collected on the measured side. Three-dimensional (3D) kinematics were collected using a 12-camera Vicon Vero system (Vicon, Oxford, UK) at a sample rate of 120 Hz. Kinetic data from the treadmill were also recorded in Vicon, at a sample rate of 1200 Hz.

To track fascicle lengthening during gait for the assessment of the moment-length relationship, a 60mm linear B-mode ultrasound transducer (LV8-5L60N-2; TELEMED Medical Systems, Milan, Italy) was securely fastened over the mid-belly of the gastrocnemius medialis muscle using a custom-made probe holder, following similar principles outlined by others (Fukunaga et al., 2001; Ishikawa et al., 2005; Lichtwark & Wilson, 2006). To minimise measurement error, guidance on probe alignment was followed (Bénard et al., 2009). Ultrasound data were recorded at 30 Hz, synchronised to motion data by a 5 V digital signal captured in Vicon.

Muscle Functional Properties and Strength Measurements

The active moment-angle relationship of the ankle, knee and hip extensors were determined on an isokinetic dynamometer (Humac Norm CSMI, MA, USA). Children performed two isometric maximum voluntary contractions (MVC) at five individualised joint positions (randomised order) across their full ROM. Joint positions included maximum hip and knee flexion and ankle dorsiflexion (0%), maximum hip and knee extension and ankle plantarflexion (100%), and at individual 25% intervals between (rounded to nearest degree). For the ankle, an additional measurement was obtained at 12.5% of ROM, to increase sensitivity to detect optimum joint angle, which is often towards extreme dorsiflexion (Gravel et al., 1990). Joint ROM was determined by manually rotating the joint until either (1) no further joint rotation was achieved with the application of increased joint moment or (2) the participant indicated their stretch threshold. Joint angle and moment were sampled from the dynamometer analogue output at 1600 Hz in AcqKnowledge software (Biopac Systems, UK). Net joint moment was corrected for the gravitational moment caused by the weight of both the dynamometer arm and the participant's limb.

Ankle Joint Set-Up

To measure the plantarflexor moment-angle relationship, participants lay prone on an isokinetic dynamometer bed with their hip in full extension and lower leg supported on a cushion so that the knee was 20° flexed. The axis of rotation of the dynamometer arm was aligned with the lateral malleolus throughout joint rotation before the participant's foot was securely fastened to the footplate. A custom-made arch support ensured that heel-contact was maintained with the footplate across full ROM.

To determine the moment-fascicle length relationship of the plantarflexors, a linear B-mode ultrasound transducer (Phillips EPIQ7, The Netherlands) was securely fastened in the same position as in the gait session, over the mid-portion of the gastrocnemius medialis muscle, using a custom-made probe holder and recorded at 15-30 Hz, depending on ultrasound settings. Pilot work was conducted to ensure that ultrasound measurements were not confounded by using a different system to the gait measurements (Appendix B). A 5V trigger switch recorded on the ultrasound video and in AcqKnowledge was used to synchronise data. To measure muscle activity, surface EMG electrodes (Biopac Systems Inc., USA) were placed on the mid-portion of the tibialis anterior and the gastrocnemius lateralis and recorded synchronously with angle and moment data at 1600Hz in AcqKnowledge.

Knee Joint Set-Up

To measure the moment-angle relationship of the knee extensors, participants were seated and securely strapped onto an isokinetic dynamometer chair so that their hip was 90° flexed. The axis of rotation of the dynamometer arm was aligned with the lateral femoral condyle during contraction before the distal end of the shank (proximal to malleolus) was securely fastened to the dynamometer arm.

Hip Joint Set-Up

To measure the moment-angle relationship of the hip extensors, participants lay supine and were securely strapped to the dynamometer bed. The axis of rotation of the dynamometer arm was aligned with the greater trochanter of the femur during contraction, before the participants distal end of the thigh (proximal to the knee joint) was securely fastened to the dynamometer arm.

Data Processing

Gait data were processed in Visual 3D software (C-Motion, Rockville, MD) using a custom-made pipeline. All data were low-pass filtered with a cut-off frequency of 6Hz. Initial contact and toe-off events were defined using a force plate threshold of 10N. All gait data were averaged for five gait cycles per participant and exported to Matlab (MathWorks R2019a, UK) for subsequent analyses to determine the moment-angle relationship of the hip, knee, and ankle joints during stance.

Dynamometer data were processed and analysed in Matlab, to determine the moment-angle relationship of the hip, knee, and ankle joints across the full ROM. EMG from the ankle joint muscles were also analysed in Matlab. At each joint angle, EMG at peak moment were extracted. Raw EMG signals were band-pass filtered from 20 to 400 Hz.

The root mean square envelope of the EMG was then extracted before EMG was averaged across the plateau of peak moment. All MVC data were averaged for two trials at each joint angle.

Ultrasound videos of the gastrocnemius medialis fascicles during gait, and at peak MVC at each joint angle on the dynamometer, were manually tracked in ImageJ software (ImageJ 1.51j8, USA) to determine the ankle moment-fascicle length relationship during stance, and across the full ROM, respectively. Each ultrasound video was analysed twice, and data averaged.

Statistical Analysis

All statistical analyses were completed in Matlab. All variables were checked for normal distribution using the Shapiro-Wilk test and visual inspection of the q-q plots. Gait data were compared between groups using either Statistical Parametric Mapping (SPM) for normally distributed variables or Statistical Non-Parametric Mapping (SnPM) for non-normally distributed variables. All MVC variables were normally distributed, therefore MVC data across ROM were compared between groups using a multi-variate analysis of variance (MANOVA). Follow up post-hoc tests were performed where appropriate. Statistical significance was set at $p < 0.05$. All results are presented as mean ± standard deviation (SD), unless stated otherwise.

Results

Moment-Angle Relationship

During gait, SPM analysis indicated that the ROM used by children who ITW was significantly more plantarflexed than TD children between 0-6% ($p = 0.049$) and 43-100% ($p = 0.013$) of stance and at peak plantarflexion moment during propulsion (-11° vs. 10°; $p = 0.002$) (Figure 4.1a; 4.1g). Additionally, children who ITW produced a significantly greater plantarflexion moment between 0-39% of stance ($p = 0.001$), and a significantly smaller plantarflexion moment between 80-93% of stance ($p = 0.011$) than TD children (Figure 4.1d). There were no significant differences in knee angle or moment, nor hip angle or moment at any point throughout stance between groups ($p > 0.05$) (Figure 4.1b, 4.1c, 4.1e, 4.1f).

The MVC moment-angle relationship of the ankle plantarflexors in children who ITW was displaced to more plantarflexed angles compared to TD children, with a significant difference in the angle of peak moment (-16° vs. 1°; $p = 0.010$) (Figure 4.1g). Children who ITW produced a significantly greater plantarflexion moment than TD children at individual maximum plantarflexion angle (0.58 vs. 0.32 $\mathrm{Nm \cdot kg^{-1}}$; $p = 0.005$) (Figure 4.1g), but there were no other differences in MVC between groups at any other relative joint position, or in the peak MVC moment ($p > 0.05$). There were no differences in the MVC moment-angle relationship of the knee or hip extensors between groups (Figure 4.1h, 4.1i). Therefore, when compared at similar relative joint positions across ROM, there was no difference in the knee or hip extensor MVC moment between groups ($p > 0.05$).

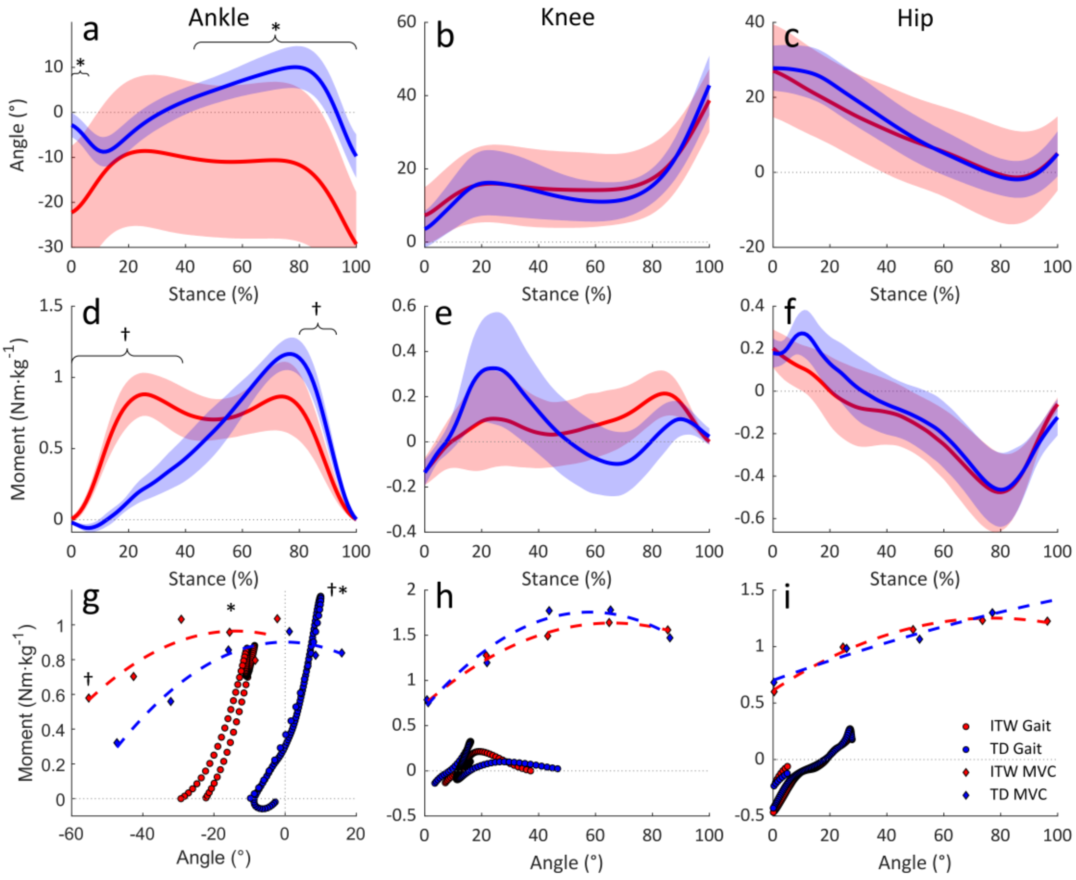

*Figure 4.1. (a-c) Joint angles and (d-f) joint moments (normalised to body mass) throughout stance. (g-i) Moment-angle relationship of the (g) ankle plantarflexors, (h) knee extensors, and (i) hip extensors measured during gait (circles) and during maximum voluntary isometric contractions across full range of motion (diamonds). Abbreviations: ITW, children who idiopathically toe-walk; TD, typically developing children; MVC, maximum voluntary contraction. *Significant difference in joint angle between groups (p < 0.05). †Significant difference in joint moment between groups (p < 0.05).*

Ankle Moment-Fascicle Length Relationship

During gait, medial gastrocnemius fascicle lengths were longer in children who ITW than TD children, between 9-70% of stance (p = 0.008) (Figure 4.2a, 4.2b). During plantarflexion MVC, the moment-fascicle length relationship was also at longer fascicle lengths in children who ITW, with peak moment occurring at a significantly longer optimal fascicle length (44mm vs. 37mm; p = 0.001) (Figure 4.2b) than TD children. When compared at similar relative joint positions, fascicle length at MVC was significantly longer in children who ITW at 25% (p = 0.007), 50% (p = 0.020), and 75% (p = 0.025) of individual ROM than TD children. In both groups, gastrocnemius lateralis muscle activity decreased (60%) in dorsiflexed positions compared to the peak EMG recorded at maximum plantarflexion (Figure 4.3).

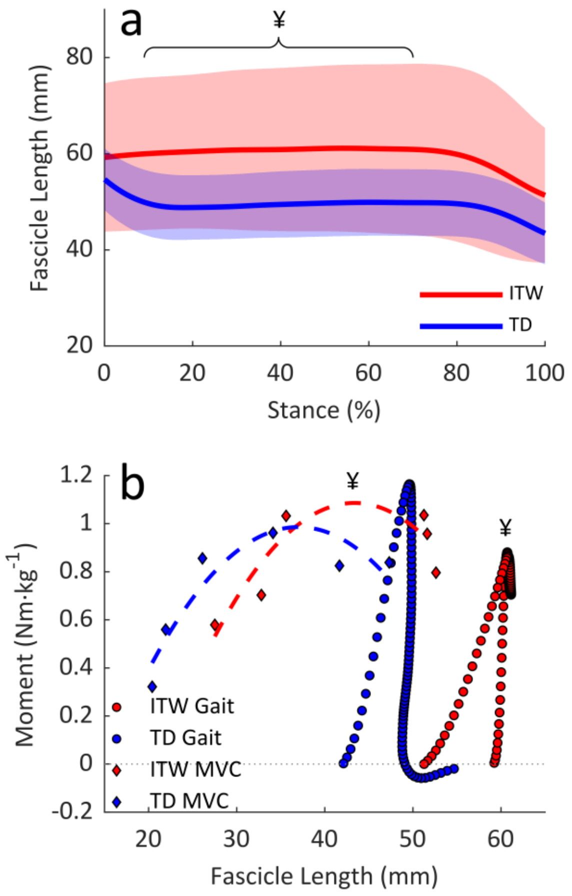

Figure 4.2. (a) Gastrocnemius medialis fascicle lengths throughout stance. (b) Moment-fascicle length relationship of the plantarflexors during gait (circles), and during maximum voluntary isometric contractions across full range of motion (diamonds). Abbreviations: ITW, children who idiopathically toe-walk; TD, typically developing children; MVC, maximum voluntary contraction. ¥Significant difference in fascicle length between groups ($p < 0.05$).

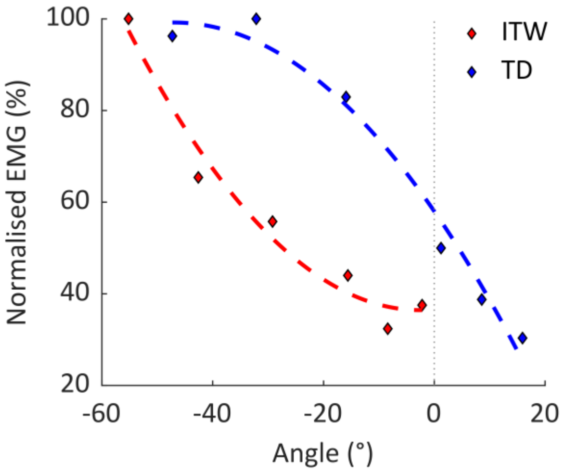

Figure 4.3. Normalised EMG at peak moment during maximum voluntary isometric contractions performed across full range of motion. Abbreviations: ITW, children who idiopathically toe-walk; TD, typically developing children.

Discussion

This study is the first to assess ankle, knee and hip extensor muscle strength, and the *in vivo* gastrocnemius medialis functional properties, relative to the demands of gait in children who ITW. During gait, children who ITW operated at more plantarflexed angles, but at longer fascicle lengths than TD children. This coincided with observed differences in the peak of the moment-angle and -length relationships, measured from MVCs, which showed that children who ITW had the greatest strength at more plantarflexed angles and an optimum fascicle length at longer lengths than TD children. Thus, data from the current study indicate that children who ITW present with substantial alterations in the gastrocnemius medialis functional properties, which appear well adapted to the characteristic demands of equinus gait. These should be considered when prescribing clinical treatments to restore typical gait.

Equinus gait has previously been linked with ankle, knee, and hip extensor weakness in other clinical populations (Hampton et al., 2003; Kennedy et al., 2020; Morozova et al., 2017; Wiley & Damiano, 1998). However, no differences were found in the peak moment of any joint during MVC between groups. Therefore, underlying weakness did not present in these children who ITW, and a lack of proximal joint weakness supports the notion that idiopathic toe-walking is truly an ankle joint pathology. Thus, clinical interventions should, as currently prescribed, target the ankle joint in isolation. During gait, there were no differences in the hip or knee joint moments between groups throughout stance, however children who ITW produced a significantly smaller plantarflexor moment during propulsion than TD children. As there were no differences in plantarflexor strength between groups, this suggests that the reduction of plantarflexor moment may be due to changes in moment arm length, however this should be studied.

A significant shift was observed in the moment-angle relationship of the plantarflexors in children who ITW, with peak moment occurring at a significantly more plantarflexed position than TD children (Figure 4.1g). Despite being more plantarflexed, the moment-fascicle length relationship shifted significantly towards longer fascicle lengths in children who ITW (Figure 4.2b). This is consistent with the longer resting muscle lengths reported in chapter 3 and corresponded with the ranges used during gait. Consequently, children who ITW and TD children both operated at similar joint angles and fascicle lengths relative to their respective measured optimum. Whilst both groups utilised their optimum joint angle, they both appear to operate at sub-optimal fascicle lengths, on the descending limb of the moment-fascicle length relationship. However, this apparent discrepancy may be explained by a deficit in muscle activation during the isometric contractions towards dorsiflexed positions (~60%; Figure 4.3), which would have shifted the measured peak moment to shorter fascicle lengths in both groups. Alternatively, between-group differences in Achilles tendon stiffness, moment arm length or role of the gastrocnemius medialis within the overall plantarflexor group may exist (Lichtwark & Wilson, 2008). Nonetheless, the data in this study demonstrate that children who ITW and TD children operate at similar portions of the moment-angle and -length profiles during gait. This suggests that for these children who ITW, equinus gait combined with the changes in functional muscle properties enables utilisation of their optimum joint angle, which may allow the economical production of high contractile force similarly to typically developing children, and as is the case in typically developed adults (Fukunaga et al., 2001). Future studies can utilise these data to inform comprehensive musculoskeletal models of children who ITW.

Current treatments for children who ITW aim to restore a typical heel-toe gait pattern by lengthening the gastrocnemius MTU (Engström et al., 2013; Fox et al., 2006; Jahn et al., 2009). However, these data have shown the presence of substantial alterations in the gastrocnemius medialis functional properties in children who ITW. Consequently, clinical interventions may compromise the force producing capabilities of the gastrocnemius medialis in the short-term, with unknown consequences. For example, if the primary aim is to restore a typical gait pattern, and thus to shift the functional moment-angle loop of children who ITW to overlay that of a TD child (Figure 4.1g), the gastrocnemius may no longer operate at optimum lengths post-intervention, until the contractile elements have remodelled to match the surgically altered MTU lengths and new gait pattern. If true, this may contribute to the low medium-long term success rates of these interventions for children who ITW (Dietz & Khunsree, 2012; van Kuijk et al., 2014). Thus, substantial changes in the muscle functional properties are required. However, a causal relationship between the muscle properties and altered gait kinematics currently cannot be distinguished. It is unclear whether an underlying neuro-structural alteration is present that causes the children to adapt functionally, or whether muscle remodelling has occurred in response to persistent equinus gait. Therefore, longitudinal studies of the development of muscle in children who ITW are needed. Additionally, whether these functional properties are also altered through clinical intervention is not known. Therefore, further work is also required to assess the gastrocnemius muscle functional properties pre and post intervention.

The specific limitations for this experimental chapter should be acknowledged. Firstly, co-contraction was not accounted for in our measurements of joint moments. This would cause an underestimation of moments produced by the agonist muscle groups on the dynamometer and during gait. For the hip and knee extensors, EMG was not recorded. For the plantarflexors, this was because of the difficulty for most children to perform the necessary dorsiflexion contractions, which would have introduced errors in itself (Billot et al., 2010). However, to our knowledge, there is no evidence to suggest that co-contraction differs between children who ITW and TD children. Secondly, to avoid excessive time demands on the children, fascicle behaviour was only measured from the gastrocnemius medialis, yet joint moments of the whole plantarflexor muscle group were reported. Therefore, it is unclear as to the potential mechanical contributions of other plantarflexor muscles (e.g., the soleus) to overall MVC and gait performance.

To conclude, data from the present study indicate that children who ITW have substantial alterations in the gastrocnemius medialis functional properties, which correspond to the functional operating ranges during gait. Therefore, by restoring a typical gait pattern, clinical interventions may, in the short-term, shift children who ITW away from their 'optimum' joint angle. However, further work is required to assess how these muscle functional properties are altered post intervention. Longitudinal studies of the development of muscle in children who ITW are also needed to determine the causal relationship of such alterations.

CHAPTER 5: EFFECTIVE MECHANICAL ADVANTAGE ABOUT THE ANKLE JOINT AND THE EFFECT OF ACHILLES TENDON CURVATURE DURING TOE-WALKING

The information presented in this chapter has been reported in the paper:

Harkness-Armstrong, C., Debelle, H. A., Maganaris, C. N., Walton, R., Wright, D. M., Bass, A., ... and O'Brien, T. D. (2020). Effective Mechanical Advantage About the Ankle Joint and the Effect of Achilles Tendon Curvature During Toe-Walking. *Frontiers in Physiology*, *11*, 407.

Abstract

Aim: To study the causes of locomotor dysfunction, estimate muscle forces, or understand the influence of altered sarcomere and muscle properties and behaviours on whole body function, it is necessary to examine the leverage with which contractile forces operate. At the ankle joint, current methods to quantify this leverage for the plantarflexors do not account for curvature of the Achilles tendon, and so may not be appropriate when studying equinus gait. Thus, novel methodologies need to be developed and implemented to quantify the Achilles tendon moment arm length during locomotion.

Methods: Plantarflexor internal moment arm length and effective mechanical advantage (EMA) of 11 typically developed young adults were calculated throughout stance, while heel-toe walking and voluntarily toe-walking on an instrumented treadmill. Achilles tendon moment arm was defined in two ways: (1) assuming a straight tendon, defined between the gastrocnemius medialis myotendinous junction and Achilles tendon insertion point, and (2) accounting for tendon curvature, by tracking the initial path of the Achilles tendon from the calcaneal insertion.

Results: When accounting for tendon curvature, Achilles tendon moment arm length and plantarflexor EMA did not differ between walking conditions ($p > 0.05$). In contrast, when assuming a straight tendon, Achilles tendon moment arm length ($p = 0.043$) and plantarflexor EMA ($p = 0.007$) were significantly greater when voluntary toe-walking than heel-toe walking in late stance.

Discussion: Assuming a straight Achilles tendon led to a greater Achilles tendon moment arm length and plantarflexor EMA during late stance, compared to accounting for tendon curvature. Consequently, plantarflexor muscle force would appear smaller when assuming a straight tendon. This could lead to erroneous interpretations of muscular function and fascicle force-length-velocity behaviour in vivo, and potentially inappropriate and ineffective clinical interventions for equinus gait.

Introduction

To study the causes of locomotor dysfunction, estimate muscle forces, or understand the influence of altered sarcomere and muscle properties and behaviours on whole body function, it is also necessary to examine the leverage with which the contractile forces operate. At the ankle, the ratio between the internal moment arm of the plantarflexors and the external moment arm of the GRF, also known as effective mechanical advantage (EMA), will determine the required muscle forces for gait. Alterations in either moment arm can greatly affect the required muscle forces. Therefore, understanding how this leverage may be impairing muscle function and/or contributing to movement impairments is vital in order to provide the appropriate interventions to improve mobility.

However, plantarflexor leverage is rarely ever quantified in research or even considered in clinical decision making for children who walk in equinus. This is despite the likelihood that clinical interventions would negatively affect this leverage. The lack of experimental evidence and clinical application may be because quantifying EMA, and specifically the Achilles tendon moment arm length, during functional tasks is complex. Only two known studies have implemented direct measurements of the Achilles tendon moment arm during gait (Rasske et al., 2017; Rasske & Franz, 2018). They combined motion capture with tracked ultrasound images of the proximal region of the Achilles tendon. The Achilles tendon line of action is extrapolated distally from a locally visible portion of the tendon within the ultrasound viewing window, to estimate moment arm length about the ankle joint axis. If the tendon distally to the scanned region remains straight over the same action line, then the moment arm length quantified by the linear extrapolation is an accurate representation of the force vector acting on the calcaneus during plantarflexor muscle contraction to generate ankle joint rotation. However, it is known that the Achilles tendon becomes curved in plantarflexed positions (Obst et al., 2014), due to its geometric architecture and configuration with surrounding tissues (Kinugasa et al., 2018). Such curvature would alter the orientation of the force acting on the calcaneus, bringing the vector closer to the ankle joint axis, thus reducing moment arm length (Csapo et al., 2013; Kinugasa et al., 2018). Therefore, defining the Achilles tendon line of force to act over a straight line, defined from any portion of the tendon more proximal than the curvature, grossly simplifies the anatomy and mechanics of the joint and may be subject to errors in estimating the moment arm length over the tendon’s distal region. This is particularly relevant when studying equinus gait patterns where large plantarflexion angles occur.

The only known study (Obst et al., 2017) to have accounted for tendon curvature when calculating Achilles tendon moment arm found that during passive joint rotations, assuming a straight path of the tendon overestimated moment arm length in plantarflexed positions, compared to accounting for curvature. However, this study used a 3D ultrasound sweep to define the curved action line of the Achilles tendon (Hashizume et al., 2012), which would not be possible in functional tasks such as gait, and it is unknown if the conclusion holds under dynamic loaded conditions. The alternative, of adapting the previous dynamic ultrasound method (Rasske et al., 2017; Rasske & Franz, 2018) to track the distal free tendon is not possible in equinus gait, as the ultrasound probe cannot maintain contact with the skin and becomes unstable.

Thus, to improve our understanding of coordinated bodily movement and estimate required contractile forces, novel methodologies need to be developed and implemented to quantify the Achilles tendon moment arm length during locomotion. Therefore, this study developed a practical method to quantify the Achilles tendon moment arm and account for curvature which is applicable to *in vivo* locomotor tasks, such as gait. The aim was to calculate the EMA of the plantarflexors during heel-toe walking and voluntary toe-walking gait and assess whether accounting for Achilles tendon curvature would alter EMA comparisons between walking conditions, when compared to a straight Achilles tendon. It was hypothesised that Achilles tendon moment arm length would be smaller when accounting for tendon curvature. Therefore, it was also hypothesised that the increase in EMA when voluntary toe-walking compared to heel-toe walking would be smaller when accounting for tendon curvature, compared to a straight Achilles tendon.

Method

Participants

Eleven typically developed young adults (male n = 4; female n = 7; age 24 ± 3 years; height 1.76 ± 0.05 m; body mass 73 ± 6 kg) were recruited for this study. To assess test-retest reliability, seven participants (male n = 1; female n = 6; age 25 ± 3 years; height 1.75 ± 0.06 m; body mass 74 ± 6 kg) returned later within the same day to repeat the protocol. All participants were free from lower-limb injuries within the six months prior to the study. Written informed consent was obtained and the study was conducted in accordance with the recommendations of the institutional ethics committee and the declaration of Helsinki.

Measurement Protocol

To identify the anatomical features of the Achilles tendon, static ultrasound images were obtained in the sagittal plane whilst participants stood under their own body weight (1) with feet-flat on the floor (Figure 5.1a), to locate Achilles tendon insertion (Figure 5.1c), and (2) on toes (Figure 5.1b), to identify the Achilles tendon bend point in plantarflexed positions (Figure 5.1d) (60mm linear B-mode transducer; Telemed Echoblaster, Vilnius, Lithuania). Achilles tendon bend-point was judged visually as the point of intersection between the initial path of the tendon from the calcaneal insertion, and the main portion of the tendon (Figure 5.1d). Both insertion and bend-point were marked on the skin with surgical marker.

Passive retro-reflective markers were placed on bony anatomical landmarks of the right foot and shank, including medial/lateral femoral epicondyles, medial/lateral malleoli, and 1st, 2nd, and 5th metatarsal heads. To track the Achilles tendon path into the calcaneal insertion, the calcaneal marker was placed directly on the tendon insertion skin marker. A second marker was placed distally to the Achilles tendon bend-point skin marker, to ensure that the marker remained below the defined bend-point. To track the myotendinous junction (MTJ) location, for the purpose of defining a straight Achilles tendon, the ultrasound scanner was securely fastened over the MTJ of the medial gastrocnemius and Achilles tendon using a custom-made probe holder, rigidly fitted with a cluster of three markers. To minimise out of plane movement, the long axis of the transducer was aligned with the line of action of the muscle.

Participants walked on an instrumented split-belt treadmill (Motek Medical, Amsterdam, The Netherlands) at 1.2m.s^{-1} in two walking conditions; (1) typical heel-toe gait, and (2) voluntary toe-walking, whilst secured in an upper body fall-arrest harness for safety. Before data were recorded, five minutes of familiarisation was provided. At completion of the familiarisation period, participants continued to walk for a further five gait cycles, during which three-dimensional kinematics were collected using a 12-camera Vicon Vero system (Vicon, Oxford, UK), at a sample rate of 120 Hz. Force data were also recorded within Vicon at a sample rate of 1200 Hz. Ultrasound data were recorded at 30 Hz, synchronised to motion data by a 5 V digital signal captured in Vicon. All data for both methods of defining Achilles tendon line of action were collected simultaneously. For test-retest measurements, all equipment was fully removed and relocated.

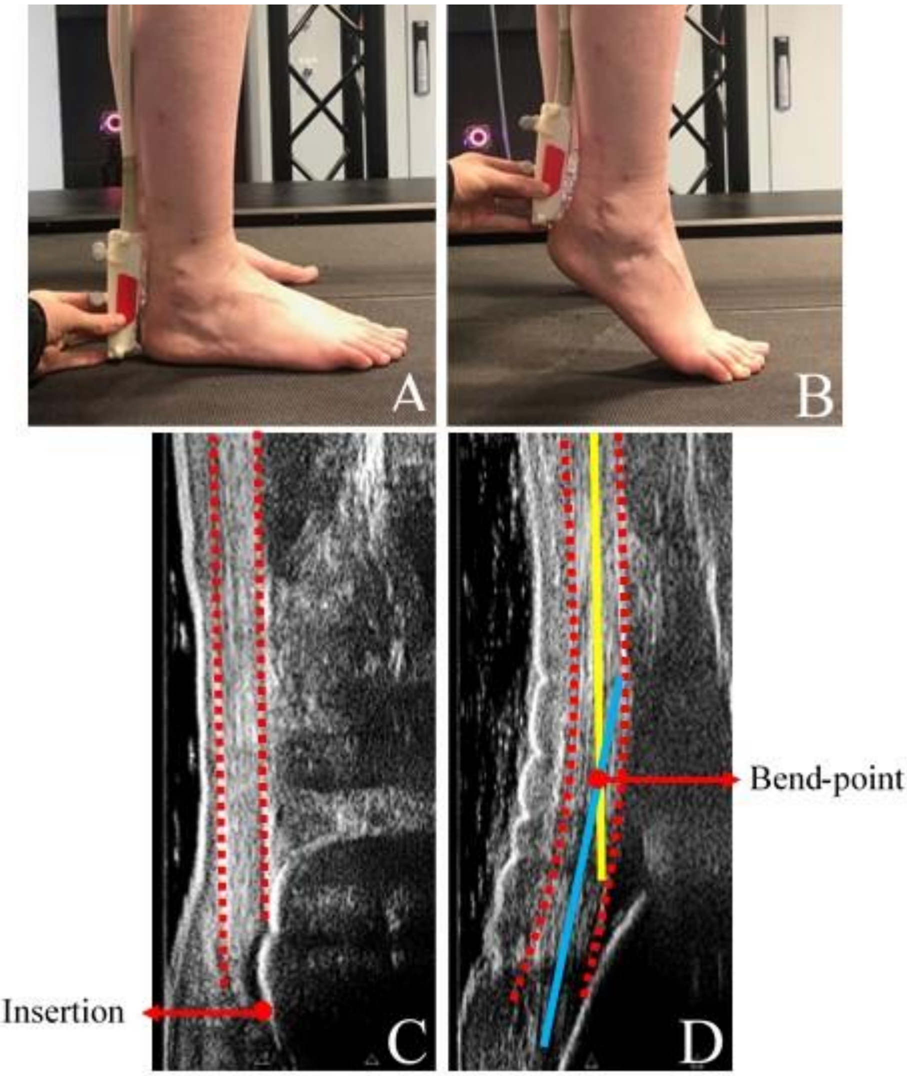

Figure 5.1. (A) Experimental set-up, showing ultrasonography positioned in the sagittal plane to identify Achilles tendon insertion and (B) Achilles tendon bend-point. (C) Identification of Achilles tendon insertion from ultrasound images taken during standing. (D) Identification of Achilles tendon bend-point from ultrasound images taken during loaded plantarflexion. Dashed red: Outline of Achilles tendon path, solid yellow: straight portion of Achilles tendon, solid blue: initial path of Achilles tendon. Bend-point was defined as the intersection of the yellow and blue lines. During data collection, the bend-point was judged visually.

Data Processing

Kinematic and kinetic data were processed in Visual 3D software (C-Motion, Rockville, MD, United States). All data were low-pass filtered with a cut-off frequency of 6Hz. Stance phase was defined between initial contact and toe-off of the right foot, identified using a force plate threshold of 50N. Data were then cropped between 20 and 90% of stance to only include positive external moment arm values in both conditions. Although a potentially large portion of the data has been omitted in early stance, importantly, there is nothing mechanically relevant to the research question, or that can be meaningfully compared prior to 20% of stance, because the joint positions and moments are so different in heel-toe walking compared to toe-walking (chapter 2).

Ultrasound images of calcaneus and Achilles tendon bend-point, and videos of MTJ displacement were analysed manually in ImageJ software (ImageJ 1.51j8, United States). All data were exported to Matlab (MathWorks R2019a, United Kingdom), where subsequent analysis was conducted using a custom-made script.

Effective mechanical advantage (EMA) was calculated between 20 and 90% of stance using Eq. (5.1):

$$EMA = \frac{InMA}{ExMA} \qquad (5.1)$$

where, InMA is the internal moment arm length and ExMA is the external moment arm length.

External moment arm length was calculated as the perpendicular distance between the trans-malleolar axis, defined as a straight line between medial and lateral malleoli markers, and the GRF vector (Figure 5.2).

Internal moment arm length was calculated as the perpendicular distance between the trans-malleolar axis and the line of action of the Achilles tendon force. To define the Achilles tendon action line, the calcaneal and bend-point markers were first corrected anteriorly along the foot plane (Figure 5.2) by the respective distances measured within the static ultrasound images (Figure 5.1C; 5.1D), to lie over the mid-point of the tendon. Achilles tendon line of action was then defined as a straight line between the Achilles tendon insertion and (1) the MTJ, to assume a straight tendon, and (2) the corrected Achilles tendon bend-point marker (Figure 5.2), to account for tendon curvature. Data were averaged for all five strides which were collected per participant.

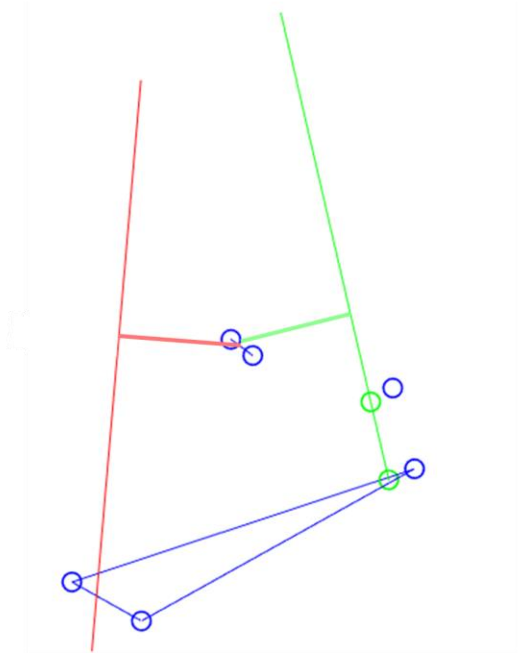

Figure 5.2. Visual representation of how the 3-dimensional moment arms were calculated during gait. Data is from a child who ITW at peak plantarflexion moment. Blue circles represent the physical motion capture marker locations. The blue triangle outlines the foot plane created between the calcaneus, MT1 and MT5 markers. The blue line represents the transmalleolar axis. Green circles represent the anterior-corrected motion capture markers along the foot plane. Green lines represent the line of action of Achilles tendon force and the resultant moment arm. Red lines represent the ground reaction force vector and the resultant moment arm.

Statistics

All parameters were normally distributed. To test whether the internal moment arm length and EMA differed between walking conditions or analysis methods, two one-way ANOVAs were performed using Statistical Parametric Mapping (SPM1D). Analyses were completed in Matlab 2019a, with additional post-hoc tests, and significance set at $p < 0.05$. An SPM1D paired t-test was used to determine whether the external moment arm length differed between walking conditions only, as differences between analysis methods were eliminated by collecting data simultaneously. The intra-rater reliability was assessed by calculating the average mean typical error throughout stance between test-retest sessions.

Results

When accounting for Achilles tendon curvature, internal moment arm length was constant throughout stance, with no significant difference between heel-toe walking and voluntary toe-walking conditions (mean 4.6 *vs* 4.7 cm, p > 0.05; Figure 5.3). When assuming a straight Achilles tendon, internal moment arm length was also constant throughout stance in the voluntary toe-walking condition (mean 5.2 cm) but decreased throughout stance in the heel-toe walking condition. This led to a significantly smaller internal moment arm length in the heel-toe walking condition than in voluntary toe-walking from 80% of stance onwards (~4.4 *vs* ~5.3 cm, p = 0.043; Figure 5.4).

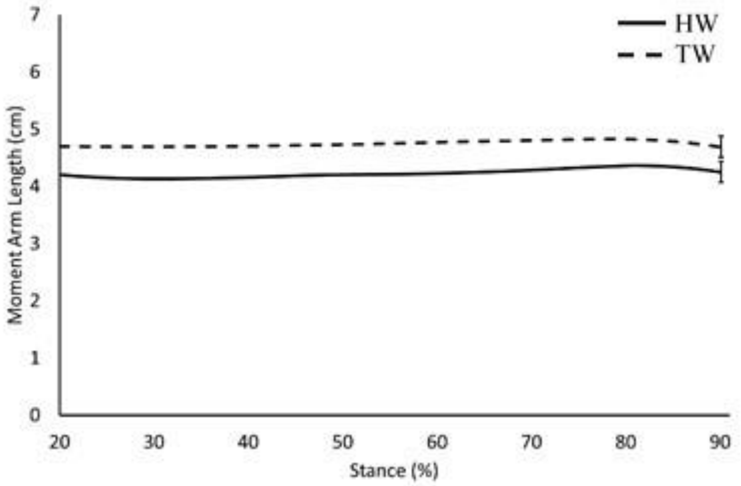

Figure 5.3. Internal moment arm length across 20-90% of stance when accounting for Achilles tendon curvature. Solid black: heel-toe walking, dashed black: voluntary toe-walking. For clarity, only average standard error of the mean bars are indicated.

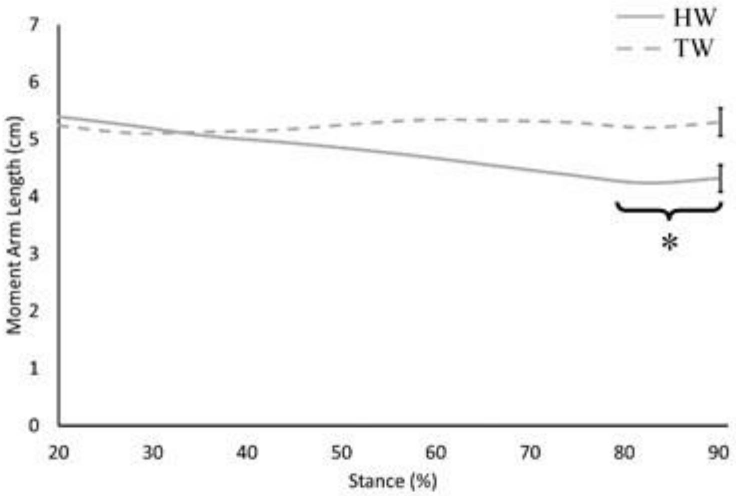

*Figure 5.4. Internal moment arm length across 20-90% of stance when assuming a straight Achilles tendon. Solid grey: heel-toe walking (HW), dashed grey: voluntary toe-walking (TW). *Significant difference between HW and TW from 80% of stance onwards (p = 0.043). For clarity, only average standard error of the mean bars are indicated.*

External moment arm length in the voluntary toe-walking condition remained relatively constant throughout stance (mean 11 cm), whereas for the heel-toe walking condition, external moment arm length increased throughout stance (Figure 5.5). External moment arm length was significantly smaller in the heel-toe walking condition between 20 and 40% of stance ($p < 0.001$; Figure 5.5), whereas there was no difference between conditions during late stance, where large plantarflexion moments are produced.

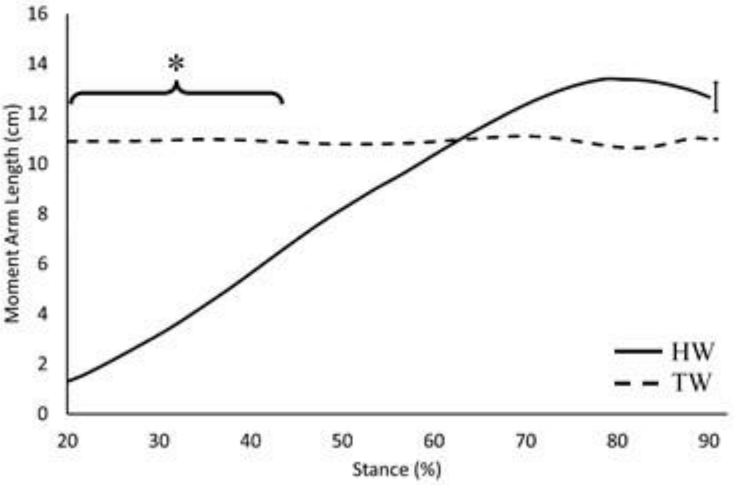

*Figure 5.5. External moment arm length across 20-90% of stance. Solid black: heel-toe walking, dashed black: voluntary toe-walking. *Significant difference between HW and TW between 20-40% of stance (p < 0.001). For clarity, only average standard error of the mean bars are indicated.*

When assuming a straight tendon, EMA was significantly smaller in the heel-toe walking condition compared to the voluntary toe-walking condition from 70% of stance onwards (average mean difference = 0.2, $p = 0.007$; Figure 5.6). Whereas there was no difference in the EMA between walking conditions when accounting for Achilles tendon curvature (average mean difference = 0.1, $p > 0.05$; Figure 5.7).

Both methods of defining Achilles tendon line of action showed good intra-rater test-retest reliability in both walking conditions, with an average mean typical error of EMA throughout stance of 0.05 (coefficient of variation = 4%).

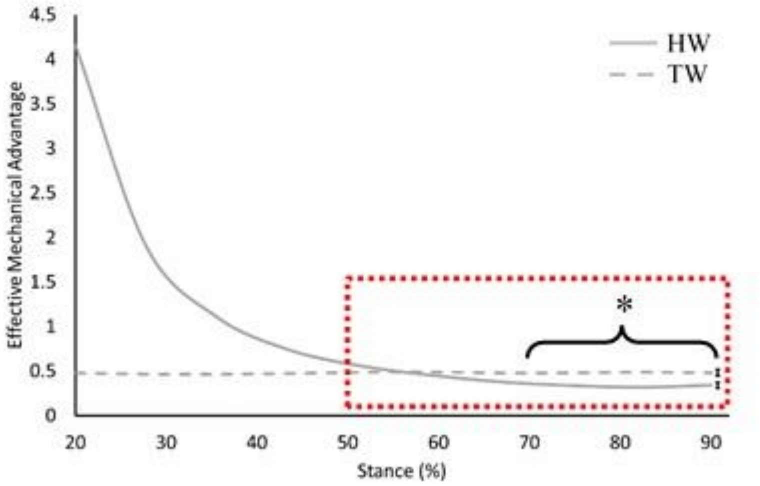

*Figure 5.6. Effective mechanical advantage of the ankle joint across 20-90% of stance when assuming a straight Achilles tendon. Solid grey: heel-toe walking (HW), dashed grey: voluntary toe-walking (TW), dashed red box: region of interest for statistical comparisons. *Significant difference between HW and TW from 70% of stance onwards (p = 0.007). For clarity, only average standard error of the mean bars for the region of interest are indicated.*

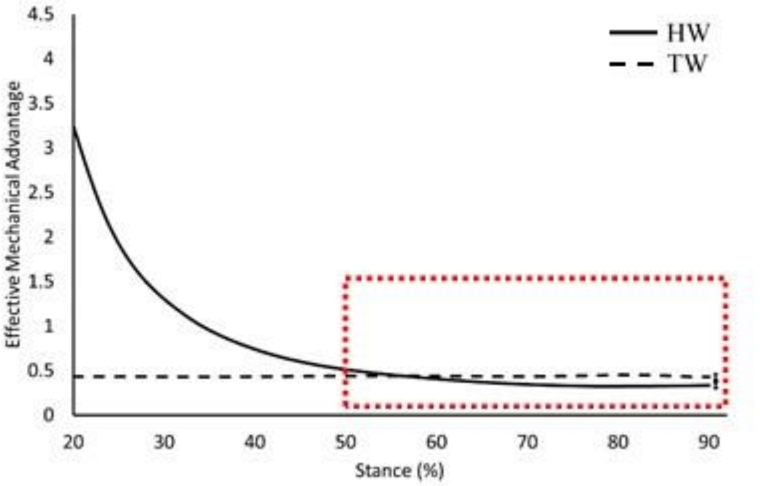

Figure 5.7. Effective mechanical advantage of the ankle joint across 20-90% of stance when accounting for Achilles tendon curvature. Solid black: heel-toe walking, dashed black: voluntary toe-walking, dashed red box: region of interest for statistical comparisons. For clarity, only average standard error of the mean bars for the region of interest are indicated.

Discussion

In this study, a reliable method was developed to account for Achilles tendon curvature in the assessment of internal moment arm length and EMA of the plantarflexors during locomotion. Using this method, significantly smaller estimates of the plantarflexors' mechanical advantage were found compared to methods assuming a straight Achilles tendon, particularly in plantarflexed positions. This will have implications for the estimation of the contractile forces required from the plantarflexors during gait to propel the body forwards.

Assuming a straight tendon led to a larger Achilles tendon moment arm length during locomotion compared to accounting for tendon curvature. This observation is consistent with previous measurements from passive ankle joint rotations (Obst et al., 2017). Regardless of walking condition, Achilles tendon moment arm length was greater throughout stance when assuming a straight Achilles tendon, with the greatest differences apparent in voluntary toe-walking, where plantarflexion angle and thus tendon curvature is greatest (Kinugasa et al., 2018). These findings are also reflected in the EMA comparisons, as differences in the external moment arm lengths were eliminated between analysis methods. Consequently, a larger Achilles tendon moment arm length, and therefore EMA, would result in smaller estimations of required plantarflexor force for locomotion. Thus, different conclusions could be reached depending on the method used to define the Achilles tendon line of action. The magnitude of this difference would be further increased if comparing between plantarflexed and more neutral joint angles, for example, between toe and heel-toe walking.

The decrease found in the Achilles tendon moment arm length throughout stance when assuming a straight Achilles tendon is in contrast with previous work. Rasske et al. (2017) reported slight increases in Achilles tendon moment arm length from 4 to 4.3 cm throughout stance when assuming a straight Achilles tendon. The observed differences in the direction of this change could be due to methodological differences in defining the ankle axis and Achilles tendon line of action, for the calculation of moment arm length. Rasske et al. (2017) considered the moment arm to be between the Achilles action line and the ankle joint centre. In contrast, the moment arm was calculated as the shortest distance to the vector along the trans-malleolar axis in this study. Furthermore, Rasske et al., (2017) tracked a section of the Achilles tendon more distal than the gastrocnemius medialis MTJ, but proximal to the curvature, while our 'straight' method defined the tendon between the

MTJ and calcaneal insertion, to reflect the overall path of the muscle-tendon unit between the mechanically important regions for proximal to distal force transmission, from muscle to tendon, and from tendon to bone. Nevertheless, similar Achilles tendon moment arm lengths were found in late stance (4.3 cm), where meaningful plantarflexion moments are produced.

The external GRF moment arm length increased throughout stance in the heel-toe walking condition (Figure 5.5), which is consistent with previous research (Giddings et al., 2000). This is due to the progression of the GRF vector along the foot and is the main reason why internal plantarflexion moments increase throughout stance. Since this magnitude of change is much greater than the changes in the internal moment arm length, the external moment arm plays the major role in determining the profile of EMA throughout stance. When voluntary toe-walking, there was no progression of the GRF vector along the foot, thus the external moment arm length remained relatively constant throughout stance (Range: 10.6 – 11.1 cm). This can therefore explain why the profile of the EMA also remains constant within this condition (Figure 5.6; Figure 5.7).

The EMA was compared between walking conditions in late stance, where meaningful plantarflexion moments are produced in heel-toe walking. Differences in the external moment arm length between analysis methods were eliminated, therefore comparisons of the EMA between walking conditions are explained by the differences found in the Achilles tendon moment arm length. When accounting for tendon curvature, there was no difference in the EMA between walking conditions (Figure 5.7), whereas assuming a straight Achilles tendon led to a greater EMA in voluntary toe-walking compared to heel-toe walking from 70% of stance onwards (Figure 5.6). Consequently, assuming a straight Achilles tendon would result in smaller estimates of the required plantarflexor muscle force for propulsion, compared to accounting for tendon curvature. For clinical context, the discrepancy in required muscle force at peak plantarflexion moment was less than 5% for heel-toe walking. Therefore, when assessing heel-toe walking only, a straight tendon path method may be acceptable, as the combination of a relatively small plantarflexion angle and large plantarflexor moment is unlikely to cause large curvature of the tendon. However, when assessing toe-walking, where large curvature of the tendon is expected, the discrepancy in required muscle force was ~10%. Therefore, adopting a straight tendon path method may not be appropriate for toe-walking, particularly when comparing pre and post clinical interventions whereby walking pattern, and potentially tendon curvature, will be altered.

Data from the present study indicate that equinus gait increases the EMA of the plantarflexors from 60% of stance onwards (Figure 5.6; Figure 5.7), the period when meaningful plantarflexor moments are produced to, in part, propel the body forwards. Therefore, the required muscle force would be reduced, supporting the notion that equinus gait could serve as a compensatory strategy to accommodate plantarflexor weakness (Hampton et al., 2003). Many clinical interventions for children who walk in equinus aim to improve walking pattern by altering the ankle joint range of motion or lengthening the external moment arm along the foot (Brouwer et al., 2000; Fox et al., 2006; Hemo et al., 2006; McMulkin et al., 2006; McMulkin et al., 2016; Jahn et al., 2009). Both would impact the EMA of the plantarflexors, yet little is known about the impact on muscle function. Surgical lengthening of the Achilles tendon, in particular, may also result in changes to the Achilles tendon curvature due to alterations in gross muscle-tendon architecture and the relationship with surrounding soft tissue structures. Nevertheless, different conclusions could be reached when comparing heel-toe walking to voluntary toe-walking, depending on how the Achilles tendon line of action was defined. Therefore, consideration of these erroneous EMA values in the decision-making process for management and treatment of equinus may lead to ineffective or inappropriate clinical interventions. For example, an overestimation of the EMA would suggest that a child has adequate plantarflexor strength to meet the demands of locomotion post-intervention, when muscle force was initially underestimated. Thus, the ability to measure the EMA correctly is essential if we are to start incorporating such measures into clinical practice. Musculoskeletal modelling offers an alternative to direct measurement but may not be appropriate, or routinely feasible due to the challenges of including individualised skeletal deformities for children with equinus gait (Rezgui et al., 2013). As a result, direct measurements are needed in order to start providing individualised conclusions and recommendations for these children.

This study has highlighted the need to account for tendon curvature when assessing equinus gait. However, further work is required to systematically study the proposed method, sources of error and anatomical validity in both typically developed and pathological populations. For example, the extent to which the tendon bend-point changes under altered joint angle and loading with respect to skin-mounted markers remains unclear. Moreover, the use of the transmalleolar axis in our calculation of EMA, as opposed to the true axis of rotation, which operates around the talo-crural joint and has a varying orientation across the ankle joint range of motion (Barnett & Napier, 1957; Lundberg et al., 1989), should be studied.

The specific limitations for this experimental chapter should be acknowledged. First, as the talo-crural joint is known to move further distally and anteriorly to the transmalleolar axis during loaded plantarflexion (Lundberg et al., 1989), there may be some discrepancies between the true moment arm lengths and those reported within this chapter. However, as both methods of calculating EMA were collected simultaneously, this would not have confounded the conclusions of this chapter. The use of functional joint calibrations may allow for closer estimates to true moment arm length (Wade et al., 2019). However, our method was developed for application in patients with gait pathologies and skeletal deformities, for whom functional joint calibrations may not be possible. A trans-malleolar axis would also account for bony deformities which are often present in conditions such as equinus gait. Moreover, as this new, proposed, method tracks the distal portion of the Achilles tendon, this ensures that alterations in foot posture would not confound the calculation of Achilles tendon moment arm, as the force vector acting on the calcaneus is always perpendicular to the plane in which the foot rotates to propel the body forwards. However, future work is required to confirm this notion.

Marker placement error and skin movement artefact may have introduced error in the tracking of the trans-malleolar axis and the Achilles tendon (Peters et al., 2010). Although care was taken in the acquisition of static ultrasound images, it is possible that alignment and pixelation errors (Goldstein, 2000) could have impacted the correction of motion capture markers. However, the method was shown to have good intra-rater reliability between test-retest sessions, with a mean typical error which is smaller than the magnitude of the differences between the measurements. Finally, the present study has simulated toe-walking in a group of typically developed young adults. Previous work has highlighted differences in the muscle behaviour of children who walk in equinus and children and adults who voluntarily toe-walk (Kalsi et al., 2016), therefore further work will be conducted to assess the applicability of this method in children with gait pathologies.

To conclude, it was shown that it is essential to account for Achilles tendon curvature in plantarflexed ankle positions, as assuming a straight Achilles tendon resulted in a larger Achilles tendon moment arm length and therefore EMA. Consequently, the required muscle force would be smaller when assuming a straight tendon, which could lead to erroneous interpretations of muscular function and sarcomere force-length-velocity behaviour *in vivo*, and potentially inappropriate and ineffective clinical interventions. It was shown that Achilles tendon curvature can be accounted for *in vivo* during functional tasks such as gait using a relatively simple method, which will allow for the calculation of Achilles tendon moment arm length in children who walk in equinus. This simple method could also facilitate the implementation of measurements of EMA into clinical practice. This would allow for future work to assess how clinical interventions alter the EMA, and the resultant impact on muscle function in children with equinus gait.

CHAPTER 6: CHILDREN WHO IDIOPATHICALLY TOE-WALK HAVE GREATER PLANTARFLEXOR EFFECTIVE MECHANICAL ADVANTAGE COMPARED TO TYPICALLY DEVELOPING CHILDREN

The information presented in this chapter is currently under review for publication.

Abstract

Purpose: The effective mechanical advantage (EMA) of the plantarflexor muscles is important for gait function and is likely different from typical in equinus gait. However, this has never been quantified for children who idiopathically toe-walk (ITW). It is essential to understand whether an altered musculoskeletal leverage may be impacting the muscle force requirements and/or contributing to movement impairments in children who ITW, to ensure that appropriate clinical interventions can be provided.

Methods: This study quantified the Achilles tendon and ground reaction force (GRF) moment arms, and the plantarflexor EMA of 5 children who ITW and 14 typically developing (TD) children, whilst walking on an instrumented treadmill.

Results: There was no difference in the Achilles tendon moment arm length throughout stance between groups ($p > 0.05$). Children who ITW had a significantly greater GRF moment arm length in early stance (20-24% $p = 0.001$), but a significantly smaller GRF moment arm length during propulsion (68-74% of stance; $p = 0.013$) than TD children. Therefore, children who ITW had a greater plantarflexor EMA than TD children when active plantarflexion moments were being generated (60-70% of stance; $p = 0.007$). Consequently, although muscle weakness does not present, it was estimated that children who ITW required 30% less plantarflexor muscle force for propulsion.

Conclusion: Clinical decision making should fully consider that interventions which aim to restore a typical heel-toe gait pattern risk compromising this advantageous leverage and thus, may increase the strength requirements for gait.

Introduction

Efficient locomotion requires the generation of adequate contractile muscle force to apply coordinated joint moments. The required magnitude of contractile force is partly determined by the leverage about which the muscle and ground reaction forces (GRF) act on the skeleton. For the plantarflexors, this leverage, known as effective mechanical advantage (EMA), is quantified as the ratio between moment arms of the internal Achilles tendon force and external GRF (Biewener et al., 2004). Both moment arms can be altered by anatomical variations and/or kinematic changes, which in turn greatly influence the muscle force required to generate adequate joint moments (Lee & Piazza, 2009).

Children who idiopathically toe-walk (ITW) walk in equinus despite no diagnosed orthopaedic or neurological disorder (Pomarino et al., 2016). This altered gait pattern likely affects the plantarflexor EMA. In simulated toe-walking (Kerrigan et al., 2000) and in simple 2-dimensional models of cerebral palsy (CP) (Hampton et al., 2003), equinus gait shortened the external GRF moment arm length, which consequently improved plantarflexor EMA and reduced the plantarflexor muscle force required. Therefore, equinus gait has been suggested to be, in part, a compensatory mechanism for plantarflexor weakness (Hampton et al., 2003). However, children who ITW do not present with plantarflexor weakness and indeed, were shown to operate close to optimal joint angle during gait (chapter 4).

Reducing the GRF moment arm length may therefore be a mechanism to compensate for anatomical changes in the Achilles tendon moment arm. In children (Kalkman et al., 2017) and young adults (Gallinger et al., 2019) with CP the Achilles tendon moment arm has been found to be smaller than typical, which has been attributed to chronic atypical loading of the ankle joint. Consequently, it has been suggested that for these individuals equinus gait may restore EMA back to typical, rather than improve it. Children who ITW experience this same chronic atypical loading of the ankle joint, therefore these children might undergo similar skeletal alterations as children with CP, resulting in similar alterations in plantarflexor leverage. However, this notion has never been confirmed experimentally. It is essential to understand whether an altered musculoskeletal leverage may be impacting the muscle force requirements and/or contributing to movement impairments in children who ITW, to ensure that appropriate clinical interventions can be provided.

Treatments for equinus gait in children who ITW aim to restore dorsiflexion range of motion and a typical heel-toe gait pattern, as if untreated, it can lead to muscle contracture (Solan et al., 2010), fixed deformity (Dietz & Khunsree, 2012) and worsening of symptoms (Sobel et al., 1997). Such interventions include serial casting (Brouwer et al., 2000; Fox et al., 2006), botulinum toxin-A injections (Brunt et al., 2004; Satila et al., 2016), a combination of the two (Engström et al., 2013; Gormley et al., 1997), or orthopaedic surgery if a contracture is already present (Hemo et al., 2006; Jahn et al., 2009; McMulkin et al., 2006). By restoring heel-toe walking these treatments will likely compromise the plantarflexor EMA, with unknown consequences.

In children with CP, similar clinical interventions can cause plantarflexor weakness (Gage et al., 2009; Orendurff et al., 2002). This may be because these treatments increase the GRF moment arm length, without full consideration of the impact on ankle moment requirements for locomotion. It is likely that these treatments negatively alter the plantarflexor EMA and thus, increase the plantarflexor muscle force required for gait. Moreover, it was recently shown that children who ITW present with substantial alterations in the gastrocnemius muscle functional properties, with the optimum joint angle in more plantarflexed positions than typical, but well aligned with the active range of motion during gait (chapter 4). Consequently, treatments may, in the short-term, shift children who ITW away from their optimum joint angle. This problem would then be compounded if EMA is reduced, with the effect being that the child would be weakened while they are simultaneously required to produce greater joint moments post-intervention. This may explain why current clinical interventions have poor medium to long-term outcomes for children who ITW, with high rates of recurrence (Dietz & Khunsree, 2012; van Kuijk et al., 2014). However, the effect of such interventions on plantarflexor EMA has not been measured.

Despite the evidence indicating that plantarflexor leverage is important for gait function and is likely altered through clinical intervention, it has never been quantified for children who ITW. It is important to understand whether the plantarflexor EMA of children who ITW differs from children who walk with a typical heel-toe gait pattern, and whether this altered leverage forms part of the pathology or is a compensation strategy. This knowledge is necessary to fully inform clinical decision-making. In chapter 5, a novel methodology was developed that can overcome the anatomical challenges of measuring plantarflexor EMA in equinus gait, including accounting for Achilles tendon curvature in extreme plantarflexed positions. Thus, the aim of this study was to use this method to determine the plantarflexor EMA during gait in TD children and children who ITW. It was hypothesised that children who ITW would present with a similar plantarflexor EMA as TD children, similarly to the proposed effect in children with CP, despite the altered gait pattern.

Method

Participants

Five children who bilaterally ITW (male n = 2; female n = 3; age 8 ± 2yrs; height 1.38 ± 0.15m; body mass 45.2 ± 26.7kg) and 14 TD children (male n = 5; female n = 9; age 10 ± 2yrs; height 1.39 ± 0.11m; body mass 37.8 ± 17.5kg) were recruited for this study. Children who ITW were recruited from outpatient lists at a hospital gait laboratory and orthopaedic clinics. All children had a confirmed diagnosis of idiopathic toe-walking based on an exclusion of all other diagnoses. Children who ITW had not undergone any orthopaedic intervention (surgical or casting) two years prior to the study and had not received botulinum toxin-A injections in the six months prior to the study. Two children who ITW had received carbon fibre insoles and splints. The remaining three children who ITW had significant fixed equinus contracture (Range: 12 to 30° of plantarflexion with knee fully extended) and had received no orthopaedic intervention. All TD children were free from neuromuscular and skeletal disorders and were free from lower limb injuries for six months prior to the study. This study was completed in accordance with both institutional and National Health Service (UK) ethical committee approval (18/NW/0526). Written informed consent was obtained from parent/guardians and written assent given by children, in accordance with the declaration of Helsinki.

Measurement Protocol

Data were collected in one testing session at a university laboratory. Prior to data collection, a 5-10-minute familiarisation period was given on an instrumented split-belt treadmill (Motek Medical, Amsterdam, The Netherlands) to ensure that (1) children could walk comfortably in their preferred gait pattern and (2) to identify self-selected walking speed.

Following familiarisation, anatomical features of the Achilles tendon, including the calcaneal insertion and Achilles tendon bend-point were identified through sagittal plane ultrasound images (Telemed Echoblaster, Vilnius, Lithuania) and marked on the skin, using a method previously reported (chapter 5). Passive retro-reflective markers were positioned in accordance with a modified 6-degrees-of-freedom marker set. Modifications were that the calcaneal marker was placed directly onto the Achilles tendon insertion skin marker and an additional marker was placed distally to the Achilles tendon bend-point skin marker, to track the tendon path into the calcaneal insertion and to account for tendon curvature in the assessment of moment arm length. Measurements were obtained from the right leg of TD children, and the most affected leg in children who ITW, defined as the observed degree of plantarflexion during gait.

Participants walked barefoot in their preferred gait pattern, at a self-selected walking speed on the instrumented split-belt treadmill, whilst secured in an upper body fall-arrest harness for safety. Participants walked continuously until a minimum of 25 gait cycles were collected from the measured side. Three-dimensional (3D) kinetics and kinematics were collected using a 12-camera Vicon Vero system (Vicon, Oxford, UK) at sample rates of 1200Hz and 120Hz, respectively.

Data Processing

Static ultrasound images of the Achilles tendon insertion and bend-point were analysed manually in ImageJ software (ImageJ 1.51j8, USA), where the distance between the skin and mid-portion of the tendon was measured. All kinematic and kinetic data were processed in Visual 3D software (C-Motion, Rockville, MD) using a custom-made pipeline. All data were low pass filtered with a cut-off frequency of 6Hz. Stance phase was defined using a force plate threshold of 10N. Data were then cropped to only include 20-90% of stance to (1) eliminate potential inaccuracies in centre of pressure calculations at low force outputs and (2) to only include positive (anterior) GRF moment arm values for TD children. All data were exported to Matlab (MathWorks R2019a, UK) for subsequent analysis, performed using a custom-made script.

Achilles tendon and GRF moment arm lengths were calculated using a method previously reported (chapter 5), which accounts for Achilles tendon curvature in extreme plantarflexed positions. In brief, the Achilles tendon path into the calcaneal insertion was tracked between the calcaneal and bend-point markers. Both markers were corrected anteriorly along the foot-plane by the respective distances measured from the static ultrasound images, to lie over the mid-portion of the tendon. Subsequent Achilles tendon and GRF moment arm lengths were normalised to height (normalised$_{\text{height}}$) to control for between-participant variability in stature of children of different age and maturation stage.

Height has been shown previously to be a predictor of Achilles tendon moment arm length in children (Kalkman et al., 2017) and young adults (Gallinger et al., 2019). All data were averaged for a minimum of 20 strides per participant.

Plantarflexor EMA was calculated throughout stance using Equation (6.1):

$$EMA = \frac{AT_{MA}}{GRF_{MA}} \quad (6.1)$$

where, AT_{MA} is the Achilles tendon moment arm length, and GRF_{MA} is the GRF moment arm length.

To estimate the effect of EMA differences on the required muscle forces between groups, the plantarflexor muscle force requirements at peak plantarflexor moment were approximated using Equation (6.2):

$$F_{AT} = \frac{GRF_v}{EMA} \quad (6.2)$$

where, F_{AT} is the Achilles tendon force, and GRF_v is the vertical GRF normalised to body weight.

Statistical Analysis

All statistical analyses were completed in Matlab 2019a. All variables were checked for normal distribution. Achilles tendon moment arm length was the only variable to be normally distributed, therefore between-group comparisons were made using a Statistical Parametric Mapping (SPM1D) (Pataky et al., 2013) independent sample t-test. Between-group comparisons of GRF moment arm length and plantarflexor EMA were therefore made using a Statistical Non-Parametric Mapping (SnPM1D) independent sample t-test. Comparisons of plantarflexor EMA were made between 50-90% of stance only, as this is where meaningful plantarflexor moments are generated in both groups of children (≥0.5 $Nm \cdot kg^{-1}$). Significance was set at $p < 0.05$. Data are presented as means ± standard deviation (SD).

Results

Self-selected walking speed did not differ between groups (0.76 ± 0.15 *vs* 0.86 ± 0.15m·s^{-1}; p = 0.186). Normalised$_{\text{height}}$ Achilles tendon moment arm length remained relatively constant throughout stance in both groups (Figure 6.1a) and did not significantly differ between children who ITW and TD children (mean across stance: 2.7 *vs* 2.5cm·m^{-1}; p > 0.05; Figure 6.1b).

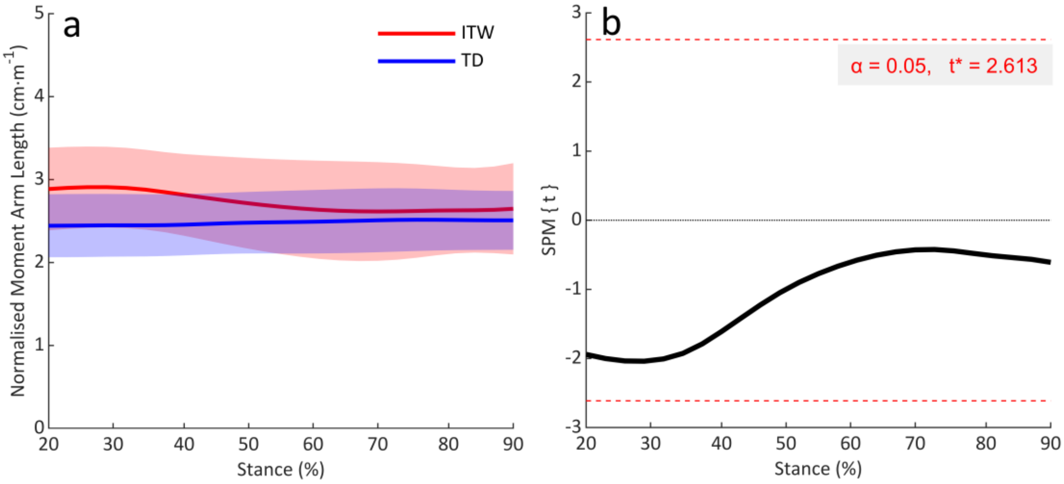

Figure 6.1. (a) Achilles tendon moment arm length normalised to height throughout 20-90% of stance. (b) SPM1D output for comparisons of normalised Achilles tendon moment arm length between groups. ITW: children who idiopathically toe-walk; TD: typically developing children.

Normalised$_{\text{height}}$ GRF moment arm length increased until late stance for both groups. For TD children, this was from 2.6 to a peak of 7.7cm·m^{-1} at 68% of stance. For children who ITW, this was from 5.2 to a peak 6.1cm·m^{-1} at 58% of stance (Figure 6.2a). This led to children who ITW having a significantly greater GRF moment arm length between 20-24% of stance (mean 5.3 *vs* 2.8cm·m^{-1}; %Δ = 89%; p = 0.001), and a significantly smaller GRF moment arm length between 68-74% of stance (mean 5.0 *vs* 7.5cm·m^{-1}; %Δ = 33%; p = 0.013) compared to TD children (Figure 6.2b).

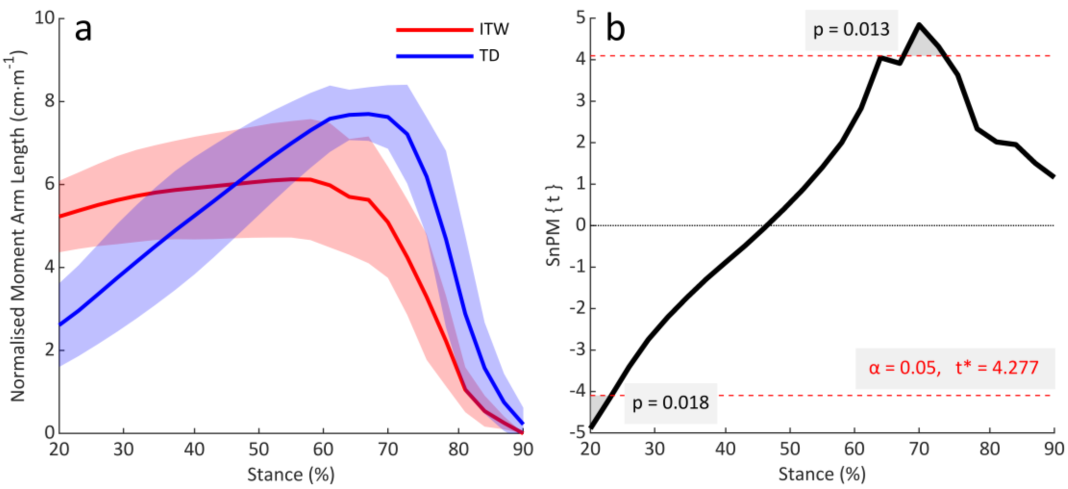

Figure 6.2. (a) GRF moment arm length normalised to height throughout 20-90% of stance. (b) SnPM1D output for comparisons of normalised GRF moment arm length between groups. ITW: children who idiopathically toe-walk; TD: typically developing children.

In the period when meaningful plantarflexor moments were generated in both groups (50-90% of stance), plantarflexor EMA was significantly greater in children who ITW than TD children (60-70% of stance; 0.5 *vs* 0.3; %Δ = 67%; p = 0.007; Figure 6.3b). Consequently, the estimated required plantarflexor muscle force (normalised to body weight) at peak plantarflexion moment was 30% smaller in children who ITW (2.58 N) than TD children (3.67 N). Throughout stance, plantarflexor EMA of TD children decreased from 1.5 to 0.3 at peak plantarflexor moment (74% of stance). Whereas for children who ITW, there was only a slight decrease from 0.6 to 0.5 at peak plantarflexion moment (69% of stance) (Figure 6.3a).

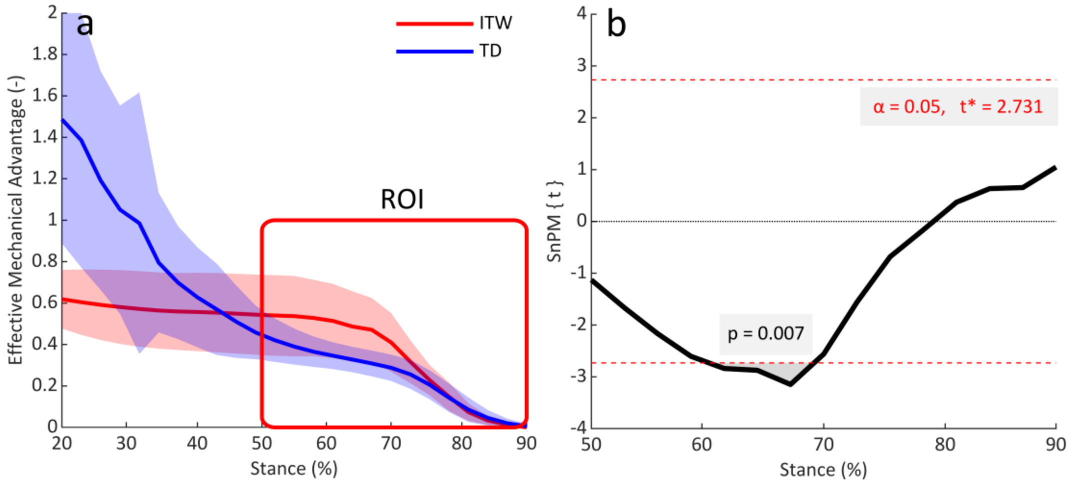

Figure 6.3. (a) Plantarflexor effective mechanical advantage throughout 20-90% of stance. Red box represents region of interest between 50-90% of stance, where meaningful plantarflexor moments (≥0.5Nm·kg^{-1}) are generated in both groups. (b) SnPM1D output for comparisons of plantarflexor effective mechanical advantage from 50-90% of stance between groups. ITW: children who idiopathically toe-walk; TD: typically developing children; ROI: region of interest.

It was notable that in the period of active plantarflexion (Region of Interest, Figure 6.3a) the within-group variability of EMA was greater in children who ITW than TD children (0.2 *vs* 0.1). Examination of individual data showed that children who ITW with the highest severity of equinus (consistently more plantarflexed throughout stance) had the greatest EMA during propulsion (Figure 6.4). Although statistical significance was not quite achieved (p = 0.059) when correlating plantarflexion angle and EMA at peak plantarflexor moment, a trend towards a high negative correlation (r3 = -0.864) was observed.

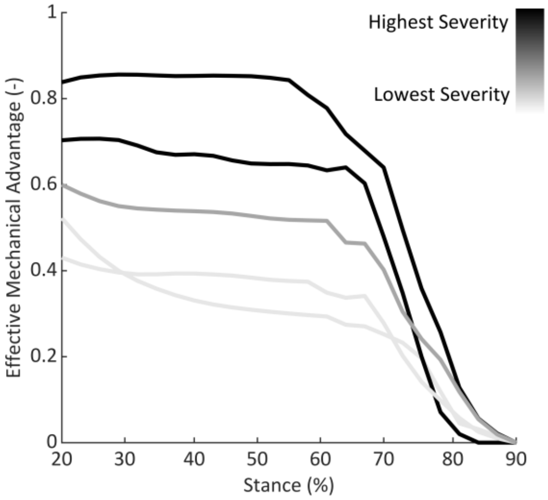

Figure 6.4. Individual plantarflexor effective mechanical advantage curves throughout 20-90% of stance for children who idiopathically toe-walk.

Discussion

This study is the first to quantify plantarflexor EMA in children who ITW. Children who ITW had, on average, a greater plantarflexor EMA than TD children in the period of stance where meaningful plantarflexion moments were generated in both groups. Consequently, the muscle force required for gait was estimated to be less in children who ITW. Therefore, clinical decision making should fully consider that interventions which restore a typical heel-to-toe gait pattern risk compromising this advantageous leverage and thus, may increase the plantarflexor muscle force requirements for gait.

Previous studies using 2-dimensional sagittal plane models have shown that equinus gait decreases the GRF moment arm length, leading to a reduction in the plantarflexor muscle force requirements for gait (Hampton et al., 2003; Kerrigan et al., 2000). In the present study, it was confirmed that this mechanism applies in 3-dimensional measurements. In TD children, the normalised$_{\text{height}}$ GRF moment arm length increased throughout stance from 2.6 to a peak of 7.7cm·m^{-1} (Figure 6.2a), due to the natural progression of the GRF vector along the foot. This is consistent with previous work in typically developed adults (Giddings et al., 2000). However, in children who ITW, the normalised$_{\text{height}}$ GRF moment arm was longer than typical at initial contact (5.2cm·m^{-1}) but only increased to a peak of 6.1cm·m^{-1} (Figure 6.2a), as the GRF vector did not progress along the foot in the same manner and remained more vertically orientated than for TD children. Consequently, comparable to previous work in other populations (Hampton et al., 2003; Kerrigan et al., 2000), equinus gait reduced the GRF moment arm length for children who ITW and thus, reduced the plantarflexor joint moment requirements for propulsion. As there was no significant difference in self-selected walking speed, this therefore suggests that toe-walking may be a strategy to control the GRF and the magnitude of its effect on joint moments.

However, it has also been suggested that reducing the GRF moment arm length may be to compensate for anatomical changes in the Achilles tendon moment arm in children with CP (Kalkman et al., 2017). In this study, differences in both the absolute and $\text{normalised}_{\text{height}}$ Achilles tendon moment arm length were not significant between children who ITW and TD children. However, the $\text{normalised}_{\text{height}}$ Achilles tendon moment arm length was slightly larger in children who ITW. It is known that increased plantarflexion angle (Maganaris et al., 2000) and load (Maganaris et al., 1998) increase the Achilles tendon moment arm length. Therefore, between 20-50% of stance, where children who ITW were more plantarflexed and produced larger plantarflexion moments than TD children, this difference was more prominent (%Δ = 21%; Figure 6.1a). However, between 50-90% of stance, where meaningful plantarflexion moments were generated in both groups, the difference in $\text{normalised}_{\text{height}}$ Achilles tendon moment arm length was small (%Δ = 4%; Figure 6.1a). Therefore, data from the present study suggests that the Achilles tendon moment arm lengths during gait are not functionally different between groups. Consequently, this may suggest that unlike children with CP (Kalkman et al., 2017), children who ITW do not have an anatomical change in the Achilles tendon moment arm, and toe-walking is likely not a compensation to achieve typical EMA. This interpretation is further supported by the fact EMA was larger in children who ITW and causes us to reject our hypothesis.

Plantarflexor EMA was compared between 50-90% of stance, as this corresponded to the period of stance where meaningful plantarflexor moments were generated in both groups of children. The combination of a slightly greater Achilles tendon moment arm length with a significantly reduced GRF moment arm length led to a significantly (67%) greater plantarflexor EMA in children who ITW compared to TD children (60-70% of stance; Figure 6.3a). Consequently, the required muscle force for any given propulsion force would be less for children who ITW. Indeed, the required plantarflexor muscle force at peak plantarflexion moment was 30% smaller in children who ITW than TD children. The EMA was also negatively associated with toe-walking severity for children who ITW. However, in chapter 4, it was shown that these children who ITW were not weaker than TD children, and indeed operated close to their optimal joint angle during gait. Therefore, it is unlikely that equinus is a strategy to reduce the muscle force requirements of gait for children who ITW, and rather, it appears more likely to be an additional consequence of the altered gait kinematics. Moreover, although a large EMA is beneficial when walking, it may be less favourable at higher speeds or when running (Ray & Takahashi, 2020), and this should be investigated further with children who ITW to improve their participation.

All clinical interventions for children who ITW have a primary aim to restore dorsiflexion range of motion and a typical heel-toe gait pattern (Engström et al., 2013; Fox et al., 2006; Jahn et al., 2009; Satila et al., 2016). This will cause an increase in the GRF moment arm length during propulsion by restoring the natural progression of the GRF vector along the foot. Therefore, the plantarflexor EMA will inadvertently be compromised through clinical intervention. It is currently unknown what effect this will have on the required plantarflexor muscle force for gait, but data from this study indicate that if the gait kinematics matches those of TD children, the required muscle force could increase by up to 42% in children who ITW. Furthermore, clinical interventions may also, in the short-term, shift children who ITW away from their optimal joint angle (chapter 4). Consequently, if the child does not have adequate muscle strength or endurance to meet the compound effects of reduced EMA and impaired utilisation of the force-length properties post-intervention, this may be a reason why current clinical interventions have poor medium to long term outcomes and high rates of recurrence (Dietz & Khunsree, 2012; van Kuijk et al., 2014). Thus, future work should quantify how plantarflexor EMA and thus, the muscle force requirements and movement economy are altered through clinical intervention, so that clinicians can decide on the appropriate treatment with full consideration of the implications. Until now, it has not been feasible to quantify the EMA in children who walk in equinus. However, in this thesis, the proposed, simple method has been easily adopted in both young adults (chapter 5) and children who ITW. Therefore, this could facilitate the implementation of such measurements into clinical practice.

The specific limitations for this experimental chapter should be acknowledged. Although care was taken in the placement of motion capture markers and in the acquisition of static ultrasound images, it cannot be ruled out that small errors may have been introduced by marker misplacement and skin movement artefact (Peters et al., 2010), or by alignment and pixelation errors (Goldstein, 2000) impacting the correction of motion capture markers. However, this method has previously been shown to have good reliability (chapter 5). The trans-malleolar axis was used to define the ankle joint axis of rotation, whereas the true ankle axis operates around the talo-crural joint (Barnett & Napier, 1957; Lundberg et al., 1989). The talo-crural joint is located further distally and anteriorly than the transmalleolar axis, emphasised during loaded plantarflexion. Therefore, whilst the true plantarflexor EMA may have been underestimated in both groups of children, it is likely that this has been underestimated more so in children who ITW than in TD children, as children who ITW operated at significantly greater plantarflexed positions. Consequently, as the EMA of children who ITW was significantly greater than TD children during propulsion, it is likely that the difference between groups should actually be larger than quantified here. The use of a functional joint calibration may provide closer estimates to the true ankle joint axis of rotation (Wade et al., 2019), however this was not feasible for these children who ITW. Therefore, future work is required to confirm this notion. Future work is also required to determine if joint remodelling occurs in children who ITW due to continual loading at extreme joint positions.

To conclude, it was shown that children who ITW do not present with alterations in the Achilles tendon moment arm length during gait. Thus, plantarflexor EMA is greater in children who ITW than TD children, due to a reduced GRF moment arm length. Consequently, children who ITW required 30% less estimated plantarflexor muscle force for propulsion. However, it is unlikely that equinus is a strategy to purposely reduce the muscle force requirements of gait, as underlying weakness does not present in these children who ITW. Further work should quantify the plantarflexor EMA pre and post clinical intervention, to assess alterations in this leverage and the resultant impact on muscle function. Future work can also utilise the data from the current study to inform comprehensive musculoskeletal models of children who ITW.

CHAPTER 7: GENERAL DISCUSSION

The overall purpose of this thesis was to improve our understanding of the musculoskeletal mechanisms which may contribute to the pathology of children who ITW. The information provided can guide the clinical decision-making process around the treatment options that are prescribed for idiopathic toe-walking.

Summary of Experimental Findings

The hypothesised mechanical reasons why children who ITW may walk in equinus were (1) they cannot achieve the necessary ankle joint ROM due to altered muscle and tendon structures, or that equinus is a compensation strategy to meet the mechanical demands of the task due to (2) muscle weakness, or (3) inadequate EMA. Therefore, four main studies were performed to test these mechanical hypotheses.

Firstly, in chapter 2, the gait kinematics and kinetics of children who ITW and TD children were presented. Children who ITW operated at greater plantarflexed positions throughout most of the gait cycle compared to TD children. Children who ITW also produced a significantly greater plantarflexion moment between 0-24%, and a significantly smaller plantarflexion moment between 50-59% of the gait cycle than TD children. No differences were found in the frontal or transverse planes at the ankle joint, or in any cardinal plane for the knee and hip joints between groups. Consequently, the findings of this study support the common notion that idiopathic toe-walking is truly a sagittal plane ankle joint pathology. Therefore, it was suggested that clinical treatments should, as currently prescribed, target the ankle joint in isolation.

To test hypothesis (1), the muscle architecture and passive lengthening properties of the gastrocnemius medialis muscle and Achilles tendon were assessed in children who ITW and TD children (chapter 3). It was found that some children who ITW had restricted ankle joint ROM. However, this restricted ROM was likely caused by a shorter Achilles tendon, not a shorter muscle as is often clinically assumed to be the cause of contracture. The shorter, which typically corresponds to a stiffer, Achilles tendon may contribute to a greater ankle joint stiffness and cause the reduced ROM observed in children who ITW. Additionally, a shorter, stiffer Achilles tendon length would increase the stretching stimulus experienced by the in-series muscle and may therefore explain why the gastrocnemius muscle and fascicle lengths of children who ITW have remodelled to longer lengths than TD children.

To test hypothesis (2), muscle strength of the hip, knee, and ankle, and the *in-vivo* operating lengths of the gastrocnemius medialis muscle were assessed during typical and equinus gait (chapter 4). Children who ITW did not present with muscle weakness around the hip, knee, or ankle joints. Moreover, children who ITW operated at more plantarflexed angles and at longer fascicle lengths than TD children during gait. These ranges used during gait coincided with the observed differences in the peak of the plantarflexor moment-angle and -length relationships. Therefore, it was found that the altered muscle functional properties, and underlying muscle architecture (chapter 3), allowed children who ITW to operate where they are functionally strong during gait.

Finally, chapter 5 and 6 were conducted to test hypothesis (3). Specifically, in chapter 5, a new and novel method was developed to quantify the Achilles tendon moment arm length during equinus gait. In chapter 6, this method was adopted to quantify the plantarflexor EMA of children who ITW and TD children. It was found that children who ITW had a greater plantarflexor EMA than TD children in the period of stance where meaningful plantarflexor moments were generated in both groups. This could be explained by a smaller GRF moment arm length observed in children who ITW, combined with no functional alterations in the Achilles tendon moment arm between groups. Although the greater EMA observed in children who ITW led to a reduction in the plantarflexor muscle force requirements for gait, it appears unlikely that equinus is a strategy to actively reduce the muscle force demands for these children, as they do not present with plantarflexor weakness (chapter 4). Therefore, it appears more likely that the reduced force requirements are purely a consequence of the altered gait kinematics.

Clinical Relevance

Overall, the findings of these experimental studies have shown that children who ITW present with substantial alterations in their underlying gastrocnemius muscle architecture, functional properties, and leverage about the ankle joint, that are different to what is often clinically assumed. Moreover, these alterations appear well adapted to the characteristic demands of equinus gait, allowing function close to optimum joint angle and fascicle length during gait. As current treatments aim to restore dorsiflexion ROM, with the aim of achieving typical joint angles during gait, this may suggest that children who ITW will be shifted away from these optimal positions following intervention. Therefore, there are some important clinical implications when considering the potential effect of current treatments on gait and/or muscle function, which may help to explain their overall effectiveness.

Children who ITW are often compared to children with CP, as they both present with a similar locomotor dysfunction which results in habitual use of the MTU at shorter lengths than typical. Moreover, significant equinus contractures can develop in both groups of children if the equinus gait is not corrected. Therefore, similar clinical interventions are often prescribed to both groups of children to lengthen the MTU, either by increasing the length of the muscle, or the Achilles tendon. It is often clinically assumed that children who ITW will have undergone similar musculoskeletal alterations as children with CP, due to a similar atypical loading of the ankle joint. However, although commonly associated, the findings of this thesis suggest that CP and idiopathic toe-walking are completely different conditions and thus, will likely require different treatment approaches. In CP, equinus contractures are often caused by a shorter and stiffer gastrocnemius muscle (Barrett & Lichtwark, 2010; Fry et al., 2004; Willerslev-Olsen et al., 2018). However, it appears that this is not the case for children who ITW. Indeed, it appears that it is a shorter, and potentially stiffer, Achilles tendon that contributes to the reduced ROM in these children (chapter 3). Therefore, it may be more appropriate to use the term “fixed deformity” as opposed to equinus contracture when describing the restricted ROM of children who ITW. Moreover, clinical treatments to lengthen the MTU may be better targeted at the Achilles tendon, rather than the gastrocnemius muscle for children who ITW.

Current conservative treatments to restore dorsiflexion ROM, such as stretching or serial casting, are likely targeting the gastrocnemius muscle. In chapter 3, it was shown that the muscle of children who ITW lengthened significantly more than the tendon to achieve joint rotation. Therefore, as the muscle is the relatively more compliant structure within the MTU, it would likely be the structure to “see” the physiological stimulus of an MTU stretch and thus, be the structure to increase in length. Consequently, increasing the length of an already long muscle (chapter 3), either through these conservative treatments or through zone 1 surgical procedures (Figure 1.1), may have implications for gait and/or muscle function in these children. Children who ITW were shown to operate at joint angles that corresponded close to optimal fascicle length during gait (chapter 4) and that resulted in a greater plantarflexor EMA than TD children (chapter 6). Therefore, further lengthening of the muscle to increase MTU length and restore dorsiflexion ROM, could cause the muscle of children who ITW to operate at longer lengths than optimal post-intervention. Moreover, restoring dorsiflexion ROM during gait would increase the GRF moment arm length and thus, worsen the plantarflexor EMA. Consequently, it is possible that children who ITW would be required to function at joint positions and muscle lengths that would cause them to be weaker following intervention, yet the muscle force requirements for gait would be greater. If true, these interventions which target the gastrocnemius muscle may therefore make it harder for these children to walk post-intervention. Thus, this may help to explain why conservative treatments often have poor medium to long term outcomes with high rates of recurrence for children who ITW (Hirsch & Wagner, 2004; Dietz & Khunsree, 2012; van Kuijk et al., 2014).

The alternative is therefore to increase MTU length by lengthening and reducing the stiffness of the Achilles tendon. The findings of this thesis suggest that these interventions would be more appropriate for children who ITW than those targeting the muscle. By increasing the length of the Achilles tendon, this may allow the absolute muscle length to remain close to optimal during gait, despite the altered joint position and increased MTU length post-intervention (chapter 4). Whilst inevitably the GRF moment arm length would still be greater, and plantarflexor EMA worse post-intervention, preserving optimal muscle length may ensure that children who ITW would still have the strength capacity to overcome the increased force demands associated with a more typical gait pattern (chapter 6). If true, this may therefore explain why surgical procedures performed in anatomical zones 2 and 3 (Figure 1.1) have been shown to be more effective in treating idiopathic toe-walking in the long-term compared to conservative treatments (Hemo et al., 2006; McMulkin et al., 2006; McMulkin et al., 2016; Jahn et al., 2009).

Finally, it was hypothesised that a shorter, and therefore stiffer, Achilles tendon may allow children who ITW to better control the position of the ankle joint during loading of stance (Alexander, 2002) without the requirement of greater muscle shortening. Lengthening the Achilles tendon through intervention will likely reduce its stiffness, which may have implications on force transmission (Reeves, 2006). Therefore, alterations to tendon stiffness should also be considered in the clinical decision-making process for children who ITW. However, if treatments are successful in their aim to restore a more typical heel-to-toe gait pattern, then the specific control of the ankle joint associated with an increased tendon stiffness may no longer be required. An increased tendon stiffness during typical heel-to-toe gait may hinder the storage and recovery of elastic energy and impede improvements to overall gait efficiency (Lichtwark & Wilson, 2008). Moreover, reducing the Achilles tendon stiffness would likely remove the stretching stimulus on the distal end of the muscle, and may therefore prevent further lengthening of the gastrocnemius muscle away from its optimal length.

Limitations

In addition to the specific limitations identified for each experimental chapter, there are some general limitations that should be acknowledged. Primarily, the sample size of children who ITW included within this thesis may appear small (n = 5). However, this is representative of the small population of children who remain in equinus beyond early childhood (Engström et al., 2012), and who have not undergone any recent orthopaedic intervention. Although small, the sample includes children with good variability in age, stature, mass (Table 2.1), and equinus severity (Figure 2.3), yet statistically significant and clinically meaningful differences have still been detected. Secondly, all measures of muscle architecture and function were obtained from the gastrocnemius muscle only, yet joint moments of the whole plantarflexor muscle group during MVC and gait were reported. Therefore, it is unclear as to the potential mechanical contributions of other plantarflexor muscles, particularly the soleus, to overall MVC and gait performance. Thus, further work is required to establish the muscle-tendon architecture of other synergist muscles in the plantarflexor group, the respective contribution of these muscles to MVC and gait performance, and how these change throughout the development of idiopathic toe-walking and in response to treatment. Finally, observational cross-sectional studies, such as those completed as part of this thesis, are unable to identify cause-effect relationships. Therefore, this will likely limit the potential reach of impact for clinical practice. Thus, confirmatory, and longitudinal studies are always important when studying clinical populations. Nonetheless, the measurements performed throughout this thesis are biomechanically sound, therefore we can be confident in these novel findings.

Future Research

As this thesis is the first to document the musculoskeletal adaptations of children who ITW, there is naturally a need for future research to be conducted. Firstly, measurements of the gastrocnemius muscle architecture and *in vivo* operating lengths during gait have shown that the MTU of children who ITW consists of a longer muscle and a shorter tendon length than TD children. This allows children who ITW to function close to where they are optimally strong. However, at present, the cause-effect relationship between the altered muscle properties and gait kinematics remains unclear. Therefore, longitudinal studies of the development of muscle in children who ITW are needed. This would allow us to determine whether muscle remodelling has occurred due to the habitually altered gait pattern, or whether these are underlying neuro-structural alterations in the muscle that cause children who ITW to adapt functionally. Knowledge of this cause-effect relationship may enable early intervention for children who ITW, which would likely prevent secondary symptoms from developing, such as a fixed deformity.

It was also suggested that the function of a shorter, and therefore stiffer Achilles tendon, may allow children who ITW to better control the position of the ankle joint during gait (Alexander, 2002) and maintain plantarflexion during loading of stance without the requirement of greater muscle shortening. However, this hypothesis is dependent on knowledge of the muscle-tendon interaction during gait. In this thesis, only the *in vivo* fascicle lengths were measured, therefore future studies are required to directly measure the *in vivo* operating lengths of the whole muscle and tendon during gait, as well as directly quantifying Achilles tendon stiffness in children who ITW. This would allow us to confirm or reject the notion that children who ITW would benefit from a stiffer Achilles tendon.

The findings of this thesis have suggested that clinical interventions to lengthen the Achilles tendon would be better suited to children who ITW than those that target the muscle, based on their potential impact to muscle and/or gait function. However, the muscle architecture, functional properties, and leverage about the ankle joint need to be assessed post-intervention, with long-term follow ups, to confirm whether these notions are true. Longitudinal intervention studies would not only enable us to measure these muscle properties following treatment, but they could also allow for predictive measures to be identified pre-intervention. This would potentially allow for individualised treatment options to be prescribed based on their likeliness to result in typical/good gait function following intervention. Moreover, if indeed future studies do confirm the notion that treatments to target the tendon are most appropriate for children who ITW, then conservative treatments to increase tendon length, without the need for risky and invasive surgical procedures, should be developed.

Conclusions

Overall, the findings of this thesis have shown that children who ITW present with substantial alterations in their underlying gastrocnemius muscle architecture, functional properties, and leverage about the ankle joint, which appear well adapted to the characteristic demands of equinus gait. Therefore, given that many clinical interventions likely compromise these advantageous characteristics, considerations of muscle and/or gait function should be included in the decision-making process for children who ITW. The data from this thesis suggest that interventions to lengthen the Achilles tendon may be more appropriate than those that lengthen the muscle for children who ITW, based on the assumption that optimal muscle length could be preserved. If so, this may ensure that children who ITW would have the strength capacity to meet the additional force demands associated with typical gait kinematics. However, future studies are first required to assess the resultant impact of these clinical interventions on gait function and the muscle force producing capabilities before strong clinical recommendations can be given.

APPENDIX A

Fast-Fourier Transformation

To determine the appropriate cut-off frequency for the low-pass filter applied to gait data, a Fast Fourier Transformation (FFT) was performed on the raw unfiltered ankle, knee and hip joint kinematics and ground reaction force data. The frequency spectrum output for each FFT are shown in Figure A.1. The standard 6Hz filter, commonly applied to gait data, was deemed appropriate for all data.

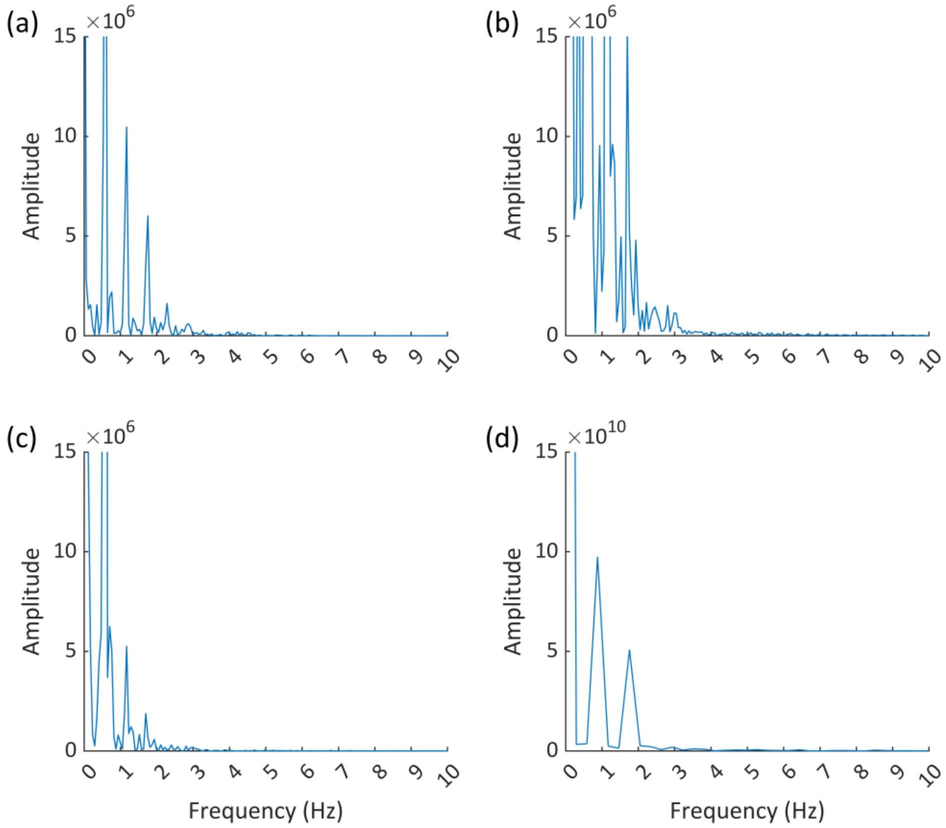

Figure A.1. Frequency spectrum output following a Fast Fourier Transformation performed on the raw unfiltered (a) ankle, (b) knee, and (c) hip joint angle, and (d) ground reaction force data.

APPENDIX B

Measured fascicle length – Phillips Epiq 7 *vs.* Telemed

During the isokinetic dynamometry measurements, children struggled to perform ramped maximum voluntary contractions (MVC). Therefore, often the time taken to reach MVC was extremely quick. Thus, the superior sample frequency and image quality of the Phillips Epiq 7 ensured that fascicle length could be tracked and measured during these movements. In contrast, it was not possible to use the Phillips Epiq 7 during the gait measurements. Firstly, the system in general is large and bulky, therefore this would have blocked the view of several motion capture cameras. Moreover, the design and orientation of the Phillips Epiq 7 transducer did not allow for the probe to be securely fastened to the medial gastrocnemius muscle, and it was not possible to walk without the contralateral leg hitting the transducer wire, hindering gait, and introducing noise within the data. Therefore, the flat probe of the Telemed Echoblaster, combined with its small and compact hardware overcame these methodological issues.

To ensure that the data was not confounded by using two different ultrasound systems, a pilot study was conducted on two young adults. Firstly, resting fascicle lengths were compared using the Phillips Epiq 7 and Telemed Echoblaster. Three ultrasound images were captured using each ultrasound system. Measured fascicle length data are shown in table A.1.

Table A.1. Measured resting fascicle lengths (mm) of two young adults using the Phillips Epiq 7 and Telemed Echoblaster ultrasound systems.

	Fascicle Length (mm)						
	Phillips Epiq 7			Telemed Echoblaster			Av. Difference
	1	2	3	1	2	3	
YA 1	70.92	69.87	70.54	71.20	71.34	71.44	0.88
YA 2	56.23	56.42	55.99	55.59	55.87	55.73	0.48

Abbreviations: YA, young adult.

Secondly, to ensure that ultrasound measurements would also not be affected by differences in fascicle length and/or ankle joint position, fascicle excursion across the full ankle ROM was measured three times using each ultrasound system. Excursion ranges are shown in Table A.2.

Table A.2. Fascicle excursion range (mm) of two young adults across their full range of motion using the Phillips Epiq 7 and Telemed Echoblaster ultrasound systems.

Fascicle Excursion Range (mm)							
	Phillips Epiq 7			Telemed Echoblaster			Av. Difference
	1	2	3	1	2	3	
YA 1	19.62	21.17	21.04	21.88	20.24	21.45	0.58
YA 2	25.75	24.48	24.53	25.61	25.33	26.02	0.73

Abbreviations: YA, young adult.

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