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Relationship of medial gastrocnemius relative fascicle excursion and ankle joint power and work performance during gait in typically developing children

A cross-sectional study

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Abstract

Muscle fascicles lengthen in response to chronic passive stretch through in-series sarcomere addition in order to maintain an optimum sarcomere length. In turn, the muscles' force generating capacity, maximum excursion, and contraction velocity is enhanced. Thus, longer fascicles suggest a greater capacity to develop joint power and work. However, static fascicle length measurements may not be taking sarcomere length differences into account. Thus, we considered relative fascicle excursions through passive ankle dorsiflexion may better correlate with the capacity to generate joint power and work than fascicle length. Therefore, the aim of the present study was to determine if medial gastrocnemius relative fascicle excursions correlate with ankle joint power and work generation during gait in typically developing children. A sample of typically developing children (n=10) were recruited for this study and data analysis was carried out on 20 legs. Medial gastrocnemius relative fascicle excursion from resting joint angle to maximum dorsiflexion was estimated from trigonometric relations of medial gastrocnemius pennation angle and thickness obtained from B-mode real-time ultrasonography. Furthermore, a three-dimensional motion capture system was used to obtain ankle joint work and power during the stance phase of gait. Significant correlations were found between relative fascicle excursion and peak power absorption (–) $r(14)=-0.61$, $P=.012$ accounting for 31% variability, positive work $r(18)=0.56$, $P=.021$ accounting for 31% variability, and late stance positive work $r(15)=0.51$, $P=.037$ accounting for 26% variability. The large unexplained variance may be attributed to mechanics of neighboring structures (e.g., soleus or Achilles tendon mechanics) and proximal joint kinetics which may also contribute to ankle joint power and work performance, and were not taken into account. Further studies are encouraged to provide greater insight on the relationship between relative fascicle excursions and joint function.

Abbreviations: CP = cerebral palsy, MG = medial gastrocnemius, RFE = relative fascicle excursion, TD = typically developing.

Keywords: kinetics, muscle architecture, plantarflexion, ultrasound

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1. Introduction

With longitudinal bone lengthening and the consequent muscle fascicle strain observed during growth, structures of the muscle-tendon unit need to adapt in order to maintain an optimum sarcomere length for force production.[1] As such, an in-series sarcomere addition has been reported to occur in response to chronic fascicle stretch.[2,3] Therefore, an increase in fascicle length through in-series sarcomere addition would contribute to an increase in muscle force generation and maximum muscle excursion and contraction velocity.[4] Thus, longer fascicles would suggest a greater capacity to develop joint power and work, essential for every-day activities.[5] Accordingly, knee extensor fascicle length has shown significant correlations to rate of force development and impulse in typically developing (TD) children.[5] Conversely, when children with spastic type cerebral palsy (CP) were assessed, no correlations were observed.[5]

This lack of correlation may be attributed to differences in spastic muscle morphology and mechanical properties of the CP muscle relative to the TD muscle.[6] The scientific literature suggests that regulation of sarcomere length is impaired in children with CP[7] due to observations of over-stretched sarcomeres at fixed joint positions[8–12] while having equal fascicle length.[13] Thus, we may not infer force generating capacity from static fascicle length measurements, nor should isometric strength tests be used as the optimal joint position for force generation between subjects would be different.[14,15] We believe dynamic and more functional assessments such as power generation during gait should be used instead.[16]

Furthermore, passive fascicle strain of the medial gastrocnemius (MG) has been reported to be significantly smaller in CP.[17,18] Authors suggested this may be attributed to reduced and over-stretched sarcomeres, and as such may correlate with the ability to generate power and work.[17] Similarly, when a group of TD subjects was separated on the basis of MG muscle stiffness and maximum passive torque during passive ankle dorsiflexion, those with greater stiffness showed smaller MG fascicle excursions at maximum angles.[19] Authors suggest this may be attributed to structures preventing fascicle and sarcomere overstretch. Thus, we believe that relative fascicle excursions (RFE) through passive ankle dorsiflexion may better correlate with the capacity to generate joint power and work than fascicle length. Therefore, the aim of the present study was to determine if MG RFEs would correlate with ankle joint power and work generation during gait in TD children. We hypothesized that MG RFE would be significantly correlated to ankle plantarflexion power and work generation during gait.

2. Methods

The present was a cross-sectional study in which a sample of participants attending our hospital were recruited and tested on one occasion on the same date as the recruitment took place.

2.1. Subjects

Subjects were recruited from those who attended our hospital for an ultrasound test and met the following inclusion criteria: no lower-limb impairment or impairments affecting locomotion such as impaired components of the postural control system; no cognitive impairment; and ages between 5 and 18 years.

A convenience sample of TD children (n = 10), 7 men and 3 women, aged (mean ± SD) 10.98 ± 3.41 years, weight (mean ± SD) 38.57 ± 16.90 kg, and height (mean ± SD) 141.71 ± 21.05 cm were recruited for this study and were tested bilaterally (20 legs). From the 20 legs analyzed, 3 outliers were detected that were related to measurement error and were thus discarded. Children and parents or legal guardians signed an informed consent prior testing. This study was approved by the Scientific Research Committee of our hospital and was in accordance with the Declaration of Helsinki on human research.

2.2. Procedures

Regarding muscle architecture assessments, we performed B-mode real-time ultrasonography of the MG muscle using a MyLabClassC (Esaote, Italy) with a linear transducer (LA523, scanning frequency: 7–16 MHz; sector size: 60 mm). In addition, a three-dimensional motion capture system (BTS Bioengineering, Milan, Italy) synchronized with 2 force platforms (Kistler 9286AA, Winterthur, Switzerland) were used to measure joint kinetics. Sampling frequency was set at 200 Hz for both motion and force recordings.

For the ultrasound measurements, subjects were asked to lay prone on a plinth, with their feet hanging from the edge, and their knees in extension. Then, resting ankle joint angle (°), and maximum ankle dorsiflexion (°) were measured through standard manual goniometry. Subsequently, a modified Walker R.O.M. ankle orthosis (PRIM, Móstoles, Spain) with an integrated goniometer was placed on each ankle in order to fix the joint at 3 predefined testing positions (−10°, 0°, and +10°) in which the subject was instructed to relax as much as possible (Fig.1).

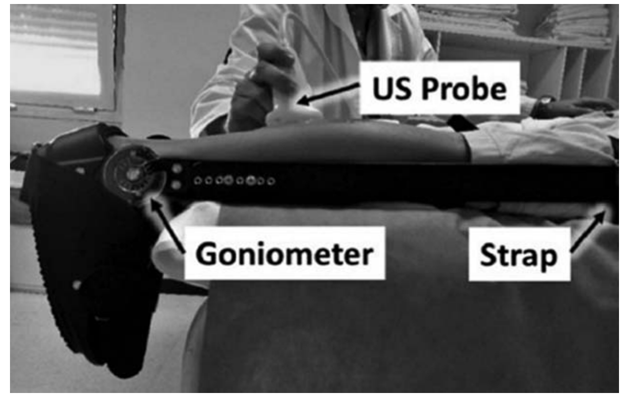

Figure 1. Scheme of experimental setup including ankle joint positioning device with integrated goniometer, strap to fix the thigh to the device, and ultrasound probe.

In order to assess RFE, fascicle length at each of the predefined joint positions was estimated using fascicle angle and muscle thickness. Thus, for each joint position, 6 images were taken: 3 images proximal to the muscle-tendinous junction to measure fascicle angle, and 3 images at the MG mid-belly where superficial and deep aponeuroses were parallel to each other to measure muscle thickness. The ultrasound probe was aligned over the mid-longitudinal plane of the MG and manually adjusted until deep and superficial aponeurosis and muscle fascicles were clearly identified on the monitor. Additionally, a substantial amount of gel was placed on the probe and pressure was kept minimal throughout the assessment. An experienced radiologist performed all the ultrasound assessments. Visual inspection of the child and ultrasound monitor was performed simultaneously in order to discard trials in which child or muscle structure movement occurred.

Clearly visible muscle fascicles adjacent to the muscle-tendinous junction were used for analysis.[18,20–22] The following muscle structure parameters were extracted from the ultrasound images: muscle thickness (mm): perpendicular distance between deep and superficial aponeuroses at the MG mid-belly, with a 90° angle from the deep aponeurosis[22,23]; fascicle angle (degrees): angle between fascicular and deep aponeurosis direction[22–25] proximal to the muscle-tendinous junction. Subsequently, fascicle length (mm) was measured: linear distance between the insertions of the fascicle into the lower and upper aponeuroses[21–25] and from that RFE (%): fascicle excursion throughout the range of motion (fascicle length at 10° dorsiflexion − fascicle length at 10° plantarflexion) as a percentage of fascicle length at 0°.[26] The following trigonometric relations were used to calculate fascicle length (fascicle length [mm] = muscle thickness [mm]/sin fascicle angle [rad]). Three measures were taken at each site to assess intra-session reliability and averages were used for statistical analyses.

In order to obtain gait kinetics, a set of reflective markers were placed over the skin on discrete anatomical sites according to the Helen Hayes Model.[27] After calibration, the subject was asked to walk normally throughout the calibrated volume until at least 10 walking trials were completed. No instructions regarding foot

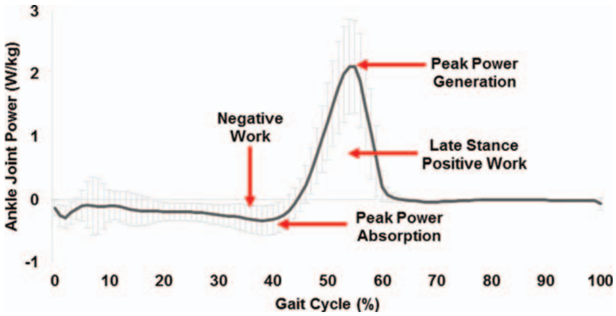

Figure 2. Ankle joint power throughout the gait cycle (mean ± SEM). Arrows indicate negative work area, late stance positive work area (same as total positive work area), location of peak power generation and absorption.

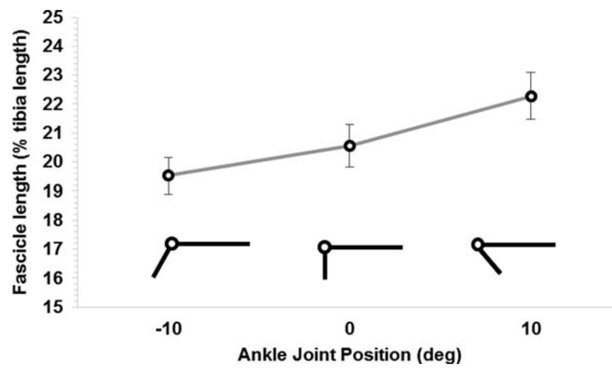

Figure 3. Fascicle length change throughout ankle joint position.

placement were given, however, only those trials in which the subject stepped within at least 1 force platform with each foot were used for analysis.

Kinetic variables were obtained from bilateral ground reaction forces and kinematic data (Fig. 2): peak ankle joint plantarflexion power absorption and generation (W/kg): peak ankle joint power during the single limb stance of phase was calculated from inverse dynamics; positive and negative ankle work (J/kg): integration of positive and negative phase power data; late stance positive work (J/kg): integration of positive phase power data during push-off; and net work (J/kg): difference between positive and negative work throughout the stance phase.

2.3. Statistical analysis

The Statistical Package for Social Sciences (SPSS 22.0, IBM; Corp., Armonk, NY) was used for statistical analyses. In order to determine intra-rater reliability of estimated fascicle length, intraclass correlation coefficients (ICC) were measured. Moreover, to test for correlations between RFE and ankle joint power and work, correlation coefficients were calculated. The following potential confounding variables were included in the analysis: age for its effect on muscle architecture, gait velocity for its effect on gait kinetics, resting joint angle for its effect on relative fascicle excursion, and maximum dorsiflexion for its effect on relative fascicle excursion. First of all, outliers were detected and were checked for possible measurement errors. In order to determine how these outliers affected the mean, comparison of original means and 5% trimmed means were performed. The Shapiro-Wilk test for normality indicated normal distribution for all parameters except for peak power absorption. Part correlations and bivariate Pearson correlations were used to determine the effect of RFE on peak power absorption and negative work; and residuals of peak power generation, net work, positive work, and late stance work respectively. In order to determine significant correlations, P was set at .05.

3. Results

Summary of muscle structure and gait kinetic data is reported on Table 1. Fascicle length used to measure RFE showed good reliability with ICC scores ranging from 0.70 to 0.78. Results show that from 10° ankle plantarflexion to 10° ankle dorsiflexion, fascicle length increased (14.06%) resulting in a RFE of 13.31 ± 2.66% (mean ± SEM) (Fig. 3). Regarding correlations between RFE and gait kinetics, RFE was significantly correlated to peak power absorption (–) controlling for the effects of age on RFE, r (14) = −0.61, P = .012 accounting for 31% variability in peak power absorption; RFE was significantly correlated to positive work controlling for the effects of age, velocity, and resting joint angle on positive work r (18) = 0.56, P = .021 accounting for 31% variability in positive work; and RFE was significantly correlated to late stance positive work controlling for the effects of age, velocity, and resting joint angle

Table 1

Summary of sample muscle structure and gait kinetic data.

Parameter	Mean	SEM	95% CI lower bound	95% CI upper bound
RJA,°	−37.26	1.38	−40.16	−34.36
MDF,°	23.25	2.60	17.81	28.69
Peak power absorption, W/kg	−0.60	0.07	−0.74	−0.46
Peak power generation, W/kg	2.22	0.17	1.86	2.57
Total negative work, J/kg	−10.09	0.79	−11.74	−8.45
Total positive work, J/kg	19.73	1.59	16.40	23.06
Net work, J/kg	9.64	1.61	6.28	13.00
Late stance positive work, J/kg	18.81	1.53	15.62	22.01
RFE, %	13.31	2.66	7.68	18.94
Ankle PF fL (%tibia length)	19.53	0.63	18.20	20.86
Ankle N fL (%tibia length)	20.56	0.73	19.02	22.10
Ankle DF fL (%tibia length)	22.28	0.82	20.54	24.01

CI = confidence interval, DF fL = fascicle length at 10° dorsiflexion, MDF = maximum dorsiflexion, N fL = fascicle length at 0° or neutral, PF fL = fascicle length at 10° plantarflexion, RFE = relative fascicle excursion, RJA = resting joint angle, SEM = standard error of mean.

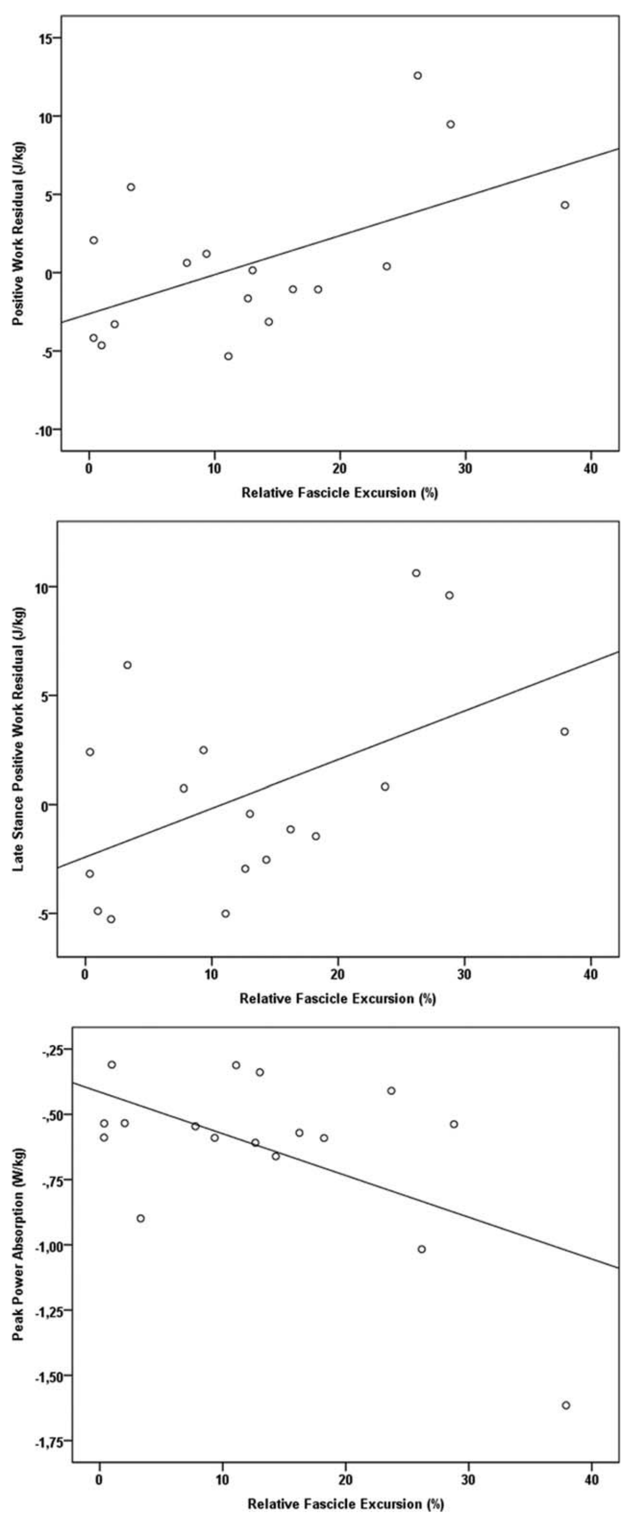

Figure 4. Scatter plots of significant correlations between relative fascicle excursion and peak power absorption (A), positive work residual (B), and late stance positive work residual (C).

on late stance positive work $r\,(15)=0.51$, $P=.037$ accounting for 26% variability in late stance positive work (Fig. 4). These results imply that larger RFEs account for greater peak power absorption and concentric work generation throughout the stance phase of gait. Conversely, no correlations were found between RFE and peak power generation $r(15)=0.41$, $P=.100$; RFE and net-work $r(15)=0.35$, $P=.173$; or RFE and negative work $r(14)=-0.32$, $P=.221$.

4. Discussion

The present study showed that fascicle length increased in response to passive ankle dorsiflexion. Furthermore, this RFE was found to be significantly, and moderately to strongly related to total and late stance positive ankle joint work, thus supporting our initial hypothesis that larger RFEs would correlate with greater ankle work generation during the stance phase of gait. Furthermore, we found a significant correlation between RFE and peak power absorption, meaning that larger RFEs correlate with more negative power, thus more energy absorption.

As would be expected, fascicle length increased in response to passive ankle dorsiflexion, which yielded a mean RFE of 13.31 ± 2.66% (mean ± SEM), similar to the 10.81% reported for children over the same range of motion.[18] However, other reports have observed larger excursions which may be attributed to the range over which RFE was measured.[17,26] While Barber et al[17] reported a RFE of 20.3 ± 1.40% (mean ± 1SEM) from slack ankle angle to maximum dorsiflexion, and Matthiasdottir et al[26] reported a RFE of approximately 23.4% throughout a common range of motion, we measured RFE over a 20° range of motion, much lower than those previously reported. Furthermore, Hirata et al[28] reported that the MG slack angle of TD adults was 20.7° ± 6.7 plantarflexion and that passive forces increased exponentially with ankle dorsiflexion, hence the increase in fascicle length throughout dorsiflexion.[17,18,26] Therefore, using a range of motion starting before or past the slack angle would ultimately affect RFE. Unfortunately slack angle was not measured in the present study, but fascicle excursions were measured starting at 27.26° past resting joint angle which was −37.26° ± 1.38 (mean ± SEM), possibly underestimating excursions and overestimating the reference fascicle length, resulting in an underrated RFE. Regarding gait kinetics, similar values to those previously reported in the literature were found.[29]

Interestingly, while correlations were found between RFE and peak power absorption, RFE did not correlate with total eccentric work. On the other hand, while correlations were found between RFE and concentric work, RFE did not correlate with peak power generation. This can be explained by the essential difference between peak power and work performance. Peak joint power may be defined as the greatest rate of doing work over a movement, while work performance refers to the total work developed over that same movement. Thus, the relationship between RFE and peak power absorption and the lack of correlation to eccentric work performed can be translated by stating that fascicles undergoing greater relative excursions are able to absorb large amounts of power but not necessarily maintain power absorption through time. Furthermore, the present study computed eccentric work performance throughout the entire stance phase and was not limited to the second rocker, where most power is absorbed.[30]

Moreover, the relationship between RFE and concentric work performed and the lack of correlation to peak power generation can be translated by stating that fascicles undergoing greater relative excursions are able to maintain power generation over time, however this would not affect the capacity to generate large amounts of power. RFE only accounted for 31% and 26% variability in concentric ankle work during total stance phase and push-off phase of gait respectively. The large unexplained variance may be attributed to mechanics of neighboring structures (e.g., soleus or Aquilles tendon mechanics) and proximal joint kinetics which contribute to ankle joint power and work performance and were not taken into account.[30] Furthermore, dynamic ultrasound analyses in TD children have shown that fascicle length is maintained throughout mid-stance, where power is absorbed at the tendon, thus, passive RFE would not be related to power absorption throughout this phase but may be somewhat indicative of peak power absorption. Then, during late stance, fascicle length shortens due to the concentric contraction, thus, RFE would only indicate the transfer of potential energy to kinetic energy, and would not account for the maximum capacity of power generation, which would be related to other mechanisms such as neural mechanisms.[29] Ultimately, this would also affect net-work which was also unrelated to RFE.

Further limitations include the large muscle architecture variability observed in the present study which may due to the large age range of the sample (6.09–16.71 years).[1,31] From 10 to 20 years of age, fascicle length has shown to be unrelated to age, hence, MG growth during this age range has been based on pennation angle and aponeuroses length increase.[31] Similarly, tendon length, which is fundamental for joint work and power generation, has been correlated to age in children ranging from 5 to 12 years of age,[1] more so than from 10 to 20 years of age.[31] In addition, despite good reliability of fascicle length intra-rater measurements, reported ICCs were smaller than those reported in the literature.[32] We believe this may be attributed to the use of conventional error reduction techniques used in the present ultrasound measurement protocol.[33,34]

The present study revealed that MG RFE is significantly related to peak power absorption and concentric work performance at the ankle during the stance phase of gait in TD children. This is the first study to report RFE as a measure of function and, despite study limitations, we believe it may reveal underlying muscle mechanics contributing to power and work performance during gait. The understanding of how passive mechanisms provide for energy storage and return throughout the stance phase of gait may further elucidate how impairments which disrupt normal passive mechanisms in other populations affect gait,[35] and contribute to the design and improvement of treatments targeting gait performance.[36] Nevertheless, future studies are needed in order to understand the nature of the relationship between RFE and joint power and work performance during gait and increase external validity.

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