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RESEARCH ARTICLE

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Atypical triceps surae force and work patterns underlying gait in children with cerebral palsy

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Abstract

The purpose of this study was to quantitatively assess Achilles tendon mechanical behavior during gait in children with cerebral palsy (CP). We used a newly designed noninvasive sensor to measure Achilles tendon force in 11 children with CP (4F, 8–16 years old) and 15 typically developing children (controls) (9F, 8–17 years old) during overground walking. Mechanical work loop plots (force-displacement plots) were generated by combining muscle-tendon kinetics, kinematics, and EMG activity to evaluate the Achilles tendon work generated about the ankle. Work loop patterns in children with CP were substantially different than those seen in controls. Notably, children with CP showed significantly diminished work production at their preferred speed compared to controls at their preferred speed and slower speeds. Despite testing a heterogeneous population of children with CP, we observed a homogenous spring-like muscle-tendon behavior in these participants. This is in contrast with control participants who used their plantar flexors like a motor during gait. Statement of Clinical Significance: These data demonstrate the potential for using skin-mounted sensors to objectively evaluate muscle contributions to work production in pathological gait.

KEYWORDS

Achilles tendon force, cerebral palsy gait, motor disorders, muscle-tendon work loops, shear wave tensiometer

1 | INTRODUCTION

Children with cerebral palsy (CP) use substantially more metabolic energy to walk than typically developing children.[1,2] The elevated energetic demands are often attributed to the abnormal gait patterns that children with CP adopt. For example, equinus gait induces heightened ankle torques in early stance, while crouch gait dramatically amplifies knee extensor torques.[3] However, net joint kinetic and kinematic measures are not strong determinants of the variability in metabolic cost observed in children with CP.[4] Thus, it seems that other factors, such as spasticity, selective motor control or altered muscle properties, may contribute to elevated and variable metabolic costs in CP.[4–6]

Much of the metabolic cost of normal walking has been linked to the work done by the limbs during step-to-step transitions.[7,8] The trailing limb does positive work on the center-of-mass (COM) during propulsion, which offsets the simultaneous negative work done by the leading limb.[7] Children with CP are remarkably inefficient in generating work during the step-to-step transition,[6] a phase where much of the work is typically generated by the ankle plantarflexors.[9,10] Indeed, biomechanical studies have shown that children with CP produce less positive ankle power and work during pushoff.[11–13] However, net joint measures do not necessarily reflect the output of individual muscle-tendon units, particularly when contractures and co-contraction are present.

Our laboratories are investigating the use of shear wave tensiometry to track muscle-tendon kinetics during walking.[14,15] Tensiometers measure wave propagation speed along with the tissue, which can be used to infer the tensile load (stress or force) transmitted by the tendon.[16] We applied a calibration to estimate tendon force from squared wave speed, and plotted force against muscle-tendon length to characterize the work loop.[17–20] Work loops can distinguish the functional behavior of the muscle-tendon unit. For example, a net positive work loop over a gait cycle indicates the unit is acting like a motor.[19] In contrast, an upward sloped force-length curve with no net work is indicative of more spring-like behavior.

Here, we investigate the use of shear wave tensiometry to assess the work done by the triceps surae about the ankle in typically developing children and CP patients who exhibit equinus and/or crouch gait. We show that EMG amplitudes can be overlaid onto the work loop to visualize the coupling between excitation timing and work generation. We hypothesized that, compared to typically developing children, individuals with CP would exhibit abnormal excitation timing and atypical work loop patterns with diminished net work done by the triceps surae muscle-tendon units during walking. The data illustrate how tensiometry can facilitate quantitative assessment of muscle-tendon behavior in gait pathologies, which could prove useful in planning treatments for gait disorders.

2 | METHODS

All study procedures for this case-control study (Level of Evidence III) were approved by the University of Minnesota IRB (STUDY00002326).

2.1 | Participants

Eleven children with CP (4 F, 8–16 years old) and 15 typically developing children (controls) (9 F, 8–17 years old) participated in this study (Table 1). All participants were recruited from the Gillette Children's Specialty Healthcare in St. Paul, MN. Participants were included if they were between the ages of 8 and 17 years old, were capable of following instructions and providing informed assent, and were able to walk across a 30 ft. walkway at least 10 times. Children with CP were included if they had been diagnosed with spastic diplegic cerebral palsy without dystonia/ataxia/athetosis, had had no surgical procedure or pharmacological spasticity treatments (e.g., botulinum toxin, baclofen, etc.) in the 3 months before participating in the study, were without acute or chronic pain in lower-extremities, were not currently taking pharmacological agents that impact neuromuscular control, were GMFCS Levels I or II status, and had evidence of equinus (less than 5 degrees mean stance dorsiflexion angle) or crouch (more than 20 degrees mean stance knee flexion angle) gait patterns in a prior visit to the gait lab. Typically developing children (controls) were included if they had no previous Achilles tendon injury, and no significant cardiovascular, pulmonary, neurological, or musculoskeletal impairments.

2.2 | Experimental procedures

Anthropometric measurements were taken by an experienced physical therapist for all participants. Leg length was measured as the sum of the distance from the ASIS to the medial femoral condyle and the distance from the medial femoral condyle to the medial malleolus for the tested limb. Reflective markers were placed bilaterally over the lower limbs of all participants for motion capture analysis.[21] Surface EMG sensors were placed bilaterally on the following muscles following SENIAM guidelines[22]: rectus femoris, medial hamstring, vastus lateralis, tibialis anterior, and medial gastrocnemius. A shear wave tensiometer[14–16] was secured over the Achilles tendon of the more affected limb of the children with CP at the time of testing, as defined by spasticity scores (modified Ashworth[23]), and on the right limb in the controls.[24] All participants walked over-ground at their preferred speed; additionally, typically developing children were asked to walk at a faster-than-preferred and a slower-than-preferred speed. A minimum of three strides were analyzed for each participant.

2.3 | Shear wave tensiometry

A shear wave tensiometer, consisting of a custom tapping device and accelerometer array in series, was secured over the Achilles tendon with a self-adherent wrap. The piezo-actuated (PK4JQP2) tapping device was driven by a 50 Hz square wave via an open-loop piezo controller (MDT694B). The accelerometer array consisted of two miniature accelerometers (Model 352C23, PCB Piezotronics, Depew, NY) mounted 8 mm apart in a silicone mold (Mold Star 15 SLOW, Smooth-On). Accelerometry data were collected at 100 kHz and then bandpass filtered using a fourth-order, zero-lag Butterworth filter with 150 and 1500 Hz cutoff frequencies. For each tap, we computed the time between wave arrival at the two accelerometers by finding the delay that maximized the normalized cross-correlation between the first and second accelerometer signals using the first millisecond after the tap. Sub-sample interpolation was performed using a local 3-point cosine fit of the normalized cross-correlation values.[25] Shear wave speed was calculated by dividing the distance between the accelerometers by the time delay. Performing this analysis for each tap resulted in a 50 Hz tendon wave speed signal.

Achilles tendon force (F) was estimated from wave speed (c) using a prediction model of the form $F = \beta(c^2 - c_{min}^2)$, where β is the tensiometer calibration gain, and c_{min} is the minimum wave speed measured over all preferred speed walking trials for a given

TABLE 1 Participant demographics for children with cerebral palsy (CP) (n = 11), as well as average values from the CP and control groups.

	Age (years)	Mass (kg)	Leg Length (m)	GMFCS	Velocity (normalized) Slow	Pref	Fast	Plantarflexor spasticity (Ashworth score)	Max dorsiflexion angle (degrees) knee 90	knee 0	Equinus (E), Crouch (C)
Controls (n = 15)											
Avg	13	47.3	0.83	N/A	0.30	0.42	0.58	-			-
SD	3	14.2	0.10	N/A	0.05	0.05	0.08	-			-
Child with CP (n = 11)											
1	14	48.4	0.83	II		0.42		1	0	−4	-
2	13	71.9	0.82	I		0.22		1	8	0	-
3	16	52.1	0.81	II		0.32		4	15	10	C
4	16	40.2	0.79	II		0.38		2	8	6	E
5	8	43.9	0.78	I		0.43		1	20	10	C
6	12	55.0	0.77	II		0.32		1	4	−2	-
7	10	29.0	0.76	II		0.29		1	14	10	C
8	11	36.7	0.79	I		0.29		3	0	−18	C,E
9	14	36.1	0.83	II		0.38		1	22	10	C
10	13	57.6	0.76	I		0.33		1	−4	−7	C
11	15	47.1	0.82	II		0.37		2	0	−4	C
Avg	13	47.1	0.80			0.34					
SD	3	12.0	0.03			0.06					

Note: All participants walked at their preferred speed, and controls additionally walked slower and faster than preferred speeds. All speeds were normalized as a function of leg length.[21] Children with CP went through a physical exam where several measures, including plantarflexor spasticity and maximum dorsiflexion ankle angle, were recorded with the knee flexed to 90 degrees and extended to 0 degrees. Presence of equinus or crouch during walking at preferred speed in this study are noted, and data are presented for the more affected limb (tested limb). All subjects were recruited based on presence of crouch or equinus from a prior visit; "-" indicates neither crouch nor gait present at the time of data collection.

individual. β was defined as $\beta = (T_{peak}/r_{Ach}(\theta))/\left(c^2_{peak}\right)$, where T_{peak} was the peak ankle torque at the participant's preferred speed, $r_{Ach}(\theta)$ was the estimated Achilles tendon moment arm at the ankle angle at which peak ankle torque occurred, and c_{peak} was the wave speed at the instance of peak ankle torque. T_{peak} and c_{peak} were averaged across all preferred speed walking strides. The regression equation used to estimate Achilles tendon moment arm $r_{Ach}(\theta)$ was taken from a prior study on typically developing children,[26] using methods published on healthy adults.[14,15] A similar calibration approach has previously been used for calibrating to tendon stress,[26] but the same can be done with tendon force given the constant tendon cross-sectional area.

2.4 | Excursion

Triceps surae muscle-tendon excursion about the ankle was defined as the muscle-tendon length relative to its upright posture. This excursion represented the change in length from an upright posture due to ankle rotation, and was computed by integrating the average Achilles tendon moment arm with respect to the ankle dorsiflexion angle during gait.[26] Excursion was normalized to leg length.

2.5 | Work loops

Achilles tendon work loops[18] were created by plotting force versus excursion. Power was calculated as the time derivative of excursion multiplied by force. Work was calculated over the interval from the minimum excursion during early stance (corresponding to the inflection point after loading response when the muscle-tendon begins to lengthen) to the minimum muscle-tendon unit length in initial swing. Positive and negative work values were calculated by integrating the positive and negative portions of the power curve, respectively, over this interval. Positive and negative work were summed to estimate net work. Independent samples t-tests were performed to compare net work between children with CP at their preferred speed and controls at each speed ($p < 0.05$). A one-way repeated measures ANOVA was performed to compare net work across speeds among controls ($p < 0.05$).

2.6 | EMG processing

EMG data were recorded at 1800 Hz using wireless sensors (MA300-XVI, Motion Lab Systems, Inc.). Data were processed using a 10–500 Hz bandpass filter and signals were full wave rectified. Processed data were then passed through a 10 Hz lowpass filter to obtain a linear envelope and were normalized to the maximum value of the trial signal.

The medial gastrocnemius and tibialis anterior muscles were deemed "on" at any point during the gait cycle where the normalized EMG signal was greater than a normalized value of 0.4 (or 40% of the peak).

3 | RESULTS

The children with CP exhibited less triceps surae excursion about the ankle and lower Achilles tendon force during pushoff than the control group (Figure 1A). There was also greater variability in excursion and force patterns between subjects, which is indicative of the

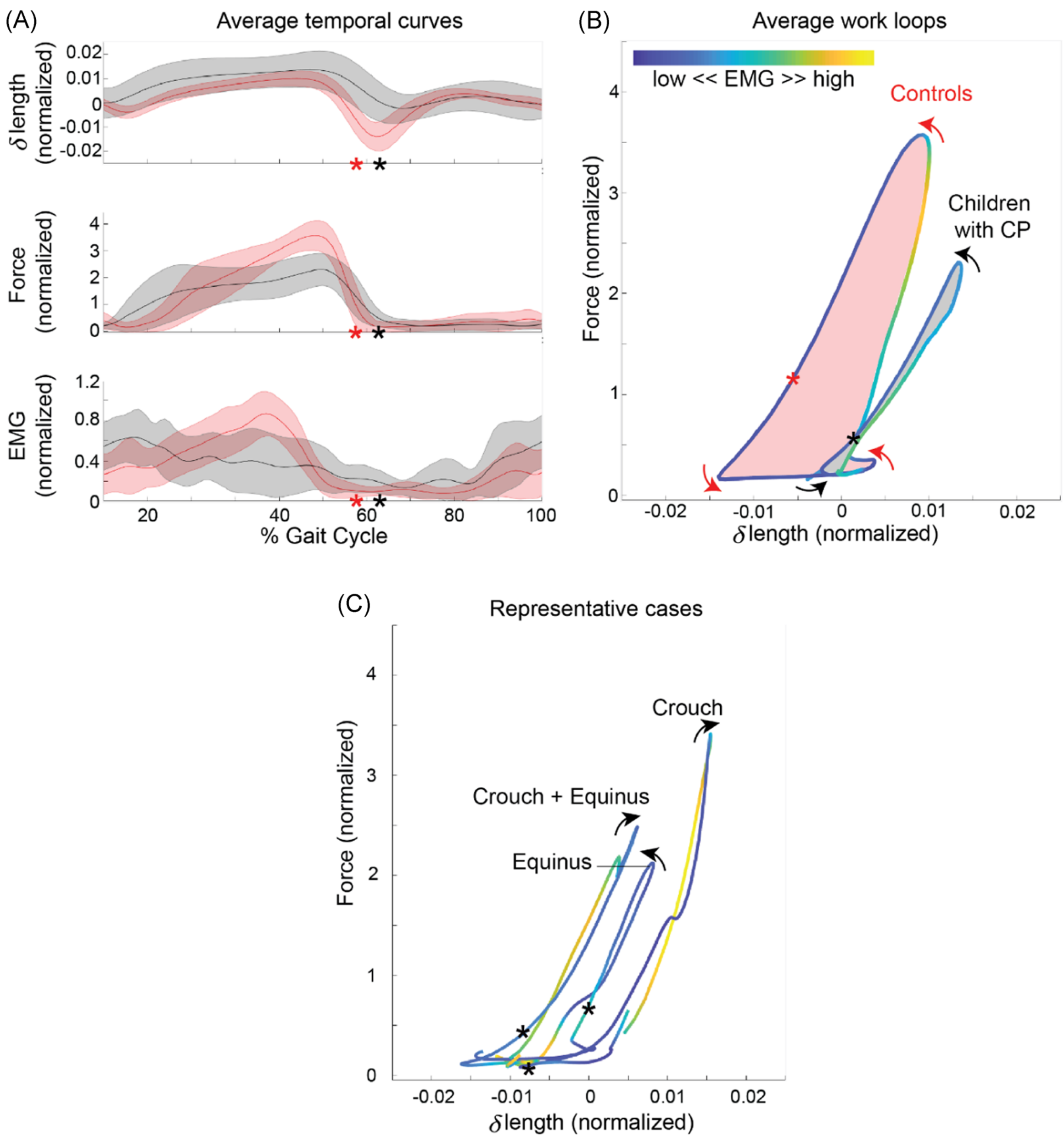

FIGURE 1 For the group of children with cerebral palsy (CP—black) and the typically developing children (controls—red) walking at their preferred walking speed, we show (A) normalized excursion about the ankle (top), Achilles tendon force (middle), and medial gastrocnemius EMG (bottom) over the gait cycle, and (B) average work loops for triceps surae about the ankle. Medial gastrocnemius activation (EMG) is overlaid in color and timing of contralateral foot off (*) are denoted. (C) Representative cases of children in CP who walked in equinus, crouch, or both crouch and equinus each showed similar spring-like work loops. Arrows indicate direction of work loops.

heterogenous CP patients and gait patterns that were included in this study. Children with CP produced nearly zero net work by the triceps surae about the ankle as is evidenced by their average work loop (Figure 1B). A similar spring-like pattern is observed independent of gait posture (e.g., crouch, equinus, or a combination of both) (Figure 1C).

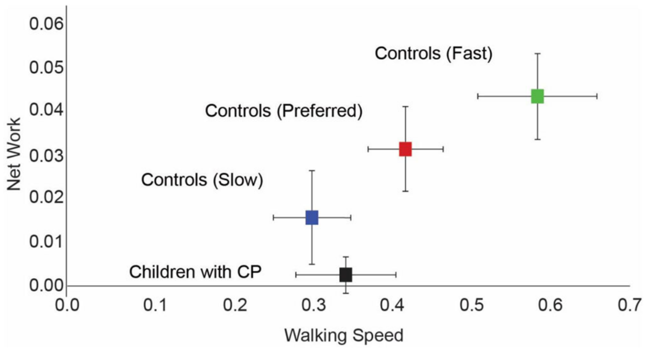

FIGURE 2 Net work for children with cerebral palsy was significantly lower at comparable normalized walking speeds to controls walking at slow ($p = 0.02$) and preferred speeds ($p = 0.03$). Net work increased with walking speed in controls ($p < 0.001$).

The average normalized net work of children with CP (0.002 ± 0.004) is 92% lower than the network produced by controls at their preferred speed (0.031 ± 0.010, $p = 0.03$) and 85% lower than the controls at their slow speed (0.016 ± 0.011, $p = 0.02$) (Figure 2). Controls did more net work with increased speed ($p < 0.001$).

In the average work loop curves (Figure 1B), medial gastrocnemius EMG activity is overlaid in color. At their preferred speed, most controls showed medial gastrocnemius activity just before peak lengthening and loading (Figures 1B and 3). However, the children with CP showed a completely different phasing pattern, often activating early in loading response along with simultaneous tibialis anterior activation (Figure 3).

4 | DISCUSSION

This study utilized shear wave tensiometry, kinematics, and EMG to objectively assess triceps surae work loop patterns underlying gait in children with CP. These analyses revealed profound differences in triceps surae behavior among a heterogenous group of children with CP, when compared to typically developing children. Most notably, the triceps surae operated at shorter lengths, exhibited abnormal timing of activation, and generally produced little to no work about

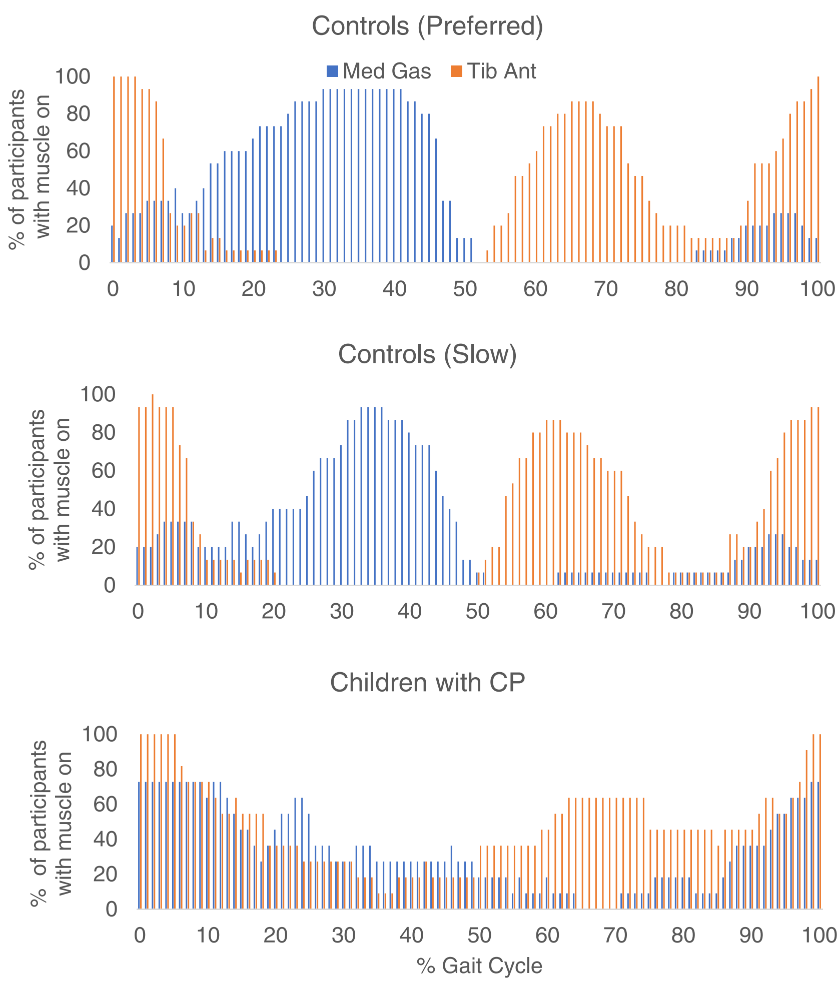

FIGURE 3 Medial gastrocnemius and tibialis anterior EMG signal timing over the gait cycle. Note the larger percentage of overlap in activity between the two muscles in the children with cerebral palsy, indicating co-contraction, and the early timing of the medial gastrocnemius activation relative to controls.

the ankle during push-off. In contrast, the triceps surae of the typically developing children acted as a motor generating a substantial amount of net work, as expected.[27] The work loop approach leverages tensiometry-based measures of tendon load to assess the neuromechanics of the plantar flexors, thereby providing insights that extend traditional motion analysis metrics. Work loop plots could additionally be used to reveal mechanical features of the muscle-tendon unit behavior that may be helpful in the discussion of treatment planning for correcting gait disorders. Features of interest include the functional operating length (muscle lengths at which forces are transmitted[28]), muscle-tendon quasi-stiffness during early stance,[29–31] and the phasing of muscular activation relative to stretch.[20] Muscle-tendon behavior could be investigated before and after treatment as well, and could provide more objective treatment planning and outcome evaluation for gait disorders.

Despite a heterogenous range of gait pathologies and treatment history (Table S1), all CP participants generated almost no net positive work from the plantarflexors during pushoff (Figure 1). The representative cases (Figure 1C) correspond to subjects #4 (equinus only), #11 (crouch only), and #8 (crouch and equinus) in Table S1. Notably in the crouch only case, the participant presented with more excursion and force than the equinus cases, yet still showed a spring-like work loop behavior. Looking at excursion or force temporally and independently might show this participant was walking within normative ranges, but the work loop reveals no net positive work done by the triceps surae about the ankle. The individual work loop plots revealed that all the CP subjects tended to exhibit early gastrocnemius activation during muscle-tendon stretch, when compared to the control subjects. The timing of muscle activation is particularly important in the efficiency of gait, as previous researchers have noted.[32] Prior studies have indicated that mis-timed muscle activation is associated with reduced net limb mechanical work in individuals with hemiplegia.[33] Several factors related to CP could cause affected muscles to fire earlier, including poor volitional motor control,[34,35] spasticity,[36] and altered central pattern generators/synergies.[3] In this study, we found peak medial gastrocnemius activation occurred earlier in children with CP with more TA co-contraction compared with our control group (Figure 3).

Secondary impairments in children with CP, including altered muscle-tendon kinematics and muscle morphology, also contribute to the limited triceps surae work. For example, children with CP have smaller and weaker muscles,[37,38] and often develop muscle-tendon contractures.[39] One study showed a correlation between reduced ankle range-of-motion and increased energy expenditure in children with CP.[40] However, we still observed reduced work production even in participants without a contracture. Children with CP have been shown to exhibit altered muscle-tendon properties. Notably, they have shorter muscle fascicle lengths[41] and longer Achilles tendons.[42] These longer tendon lengths compared to typical may act to counteract the smaller muscle belly lengths and mass in children with CP, and may serve to enhance energy storage/return of the Achilles tendon.[28,42]

The work loop approach presented here provides a bridge between physical exam metrics and quantitative gait analyses, which have become part of many standard evaluations for children with CP.[43,44] Physical exams which evaluate contractures and spasticity by moving the joint through different postures at various speeds[45] do not provide information on muscle behavior during an active functional task, such as walking. Conversely, quantitative gait analysis provides functional metrics of joint kinematics and kinetics yet lacks muscle-group specific information. The shear wave tensiometers are wearable and noninvasive, thus also providing opportunities for their application outside of the traditional motion capture space.[46] Of note, we have not observed a change in kinematics or kinetics due to wearing the shear wave tensiometer (Figure S1) and a previous study showed no significant change in postural sway due to the tapping device.[47] While the research presented here focused on the use of tensiometry to evaluate triceps surae behavior, tensiometery has successfully been used on the patellar tendon in children[26] and may be able to measure hamstring loading as well.[16] These tendons could be particularly pertinent to study given the high incidence of interventions at these tendons for children with CP walking in crouch gait (e.g. hamstring lengthening, patellar tendon advancement). Furthermore, since the technology is noninvasive and compact, there is possibility for intraoperative applications as well (e.g. comparing tendon loading pre- and post- muscle-tendon lengthening).

We acknowledge there are several assumptions and limitations inherent in the work loop approach. Our calibration procedure for the tensiometer requires an estimate of Achilles tendon force, which we estimated from peak ankle torque and an average Achilles tendon moment arm measurement during a distinct phase of walking. This assumes that the triceps surae are contributing solely to the ankle torque at that instant. While the children with CP did show some evidence of co-contraction about the ankle (Figure 3), the triceps surae are disproportionately stronger than the tibialis anterior. Also, this approach is limited to interpretation of the triceps surae work about the ankle only; we cannot parse the contribution of the soleus and gastrocnemius without further assumptions. Our muscle-tendon excursions were based on ankle moment arms of typically developing children.[26] Bony deformities that are present in children with CP were not accounted for. Further, excursion about the ankle was based only on the dorsi-plantarflexion ankle angle, which doesn't account for movement of the midfoot. Ultimately, the interpretation of the study findings, particularly that of less net work done by the children with CP, is not likely to be substantially altered by these assumptions or limitations.

In conclusion, these data demonstrate the potential for using shear wave tensiometers to objectively evaluate the effect of pathology on muscle-tendon loading and to characterize objective metrics of muscle-tendon mechanical behavior during pathological gait. The work loop approach provides a visual tool that summarizes modifiable factors that underlie gait disorders in children with CP (Figure 1). This study establishes a biomechanical assessment technique which can aid in the goal of translating novel biomechanical assessments into targeted treatments for gait disorders.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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