

# Achilles Tendon Length and Medial Gastrocnemius Architecture in Children With Cerebral Palsy and Equinus Gait

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**Background:** The aim of this study was to examine both the tendon and muscle components of the medial gastrocnemius muscle-tendon unit in children with cerebral palsy (CP) and equinus gait, with or without contracture. We also examined a small number of children who had undergone prior surgical lengthening of the triceps surae to address equinus contracture. **Methods:** Ultrasound was used to measure Achilles tendon length and muscle-tendon architectural parameters in children of ages 5 to 12 years. Muscle and tendon parameters were compared among 4 groups: Control group (N = 40 limbs from 21 typically developing children), Static Equinus group (N = 23 limbs from 15 children with CP and equinus contracture), Dynamic Equinus group (N = 12 limbs from 7 children with CP and equinus gait without contracture), and Prior Surgery group (N = 10 limbs from 6 children with CP who had prior gastrocnemius recession or tendo-achilles lengthening). The groups were compared using analysis of variance and Scheffe post hoc tests.

**Results:** The CP groups had longer Achilles tendons and shorter muscle bellies than the Control group ( $P < 0.001$ ). Normalized tendon length was also longer in the Prior Surgery group compared with the Static Equinus group ( $P < 0.001$ ). The Prior Surgery group had larger pennation angles than the CP groups ( $P \leq 0.009$ ) and tended to have shorter muscle fascicle lengths ( $P \leq 0.005$  compared with Control and Static Equinus,  $P = 0.08$  compared with Dynamic Equinus). Similar results were observed for pennation angles and normalized muscle fascicle lengths throughout the range of motion.

**Conclusions:** Children with spastic CP and equinus gait have longer-than-normal Achilles tendons and shorter-than-normal muscle bellies. These characteristics are observed even in children with dynamic equinus, before contracture has developed. Surgery further lengthens the tendon, restoring dorsiflexion but not normal muscle-tendon architecture. These architectural

features likely affect function, possibly contributing to functional deficits such as plantarflexor weakness after surgery.

**Level of Evidence:** Level II, prospective comparative study.

**Key Words:** toe walking, contracture, spasticity, ultrasound, muscle-tendon lengthening

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Equinus is one of the most common problems leading to gait and functional limitations in children with cerebral palsy (CP).<sup>1,2</sup> Dynamic equinus can usually be addressed with bracing, physical therapy, or botulinum toxin injections. Static contractures may require splinting, serial casting, or, in many cases, surgical lengthening of the triceps surae. Surgery usually improves ankle kinematics and kinetics, but both recurrence of contracture and over-lengthening are significant problems in some patients. Recurrence of equinus occurs in up to 41% of patients after gastrocnemius recession (GR) or tendo-achilles lengthening (TAL) surgery.<sup>3–5</sup> In contrast, calcaneal deformity because of over-lengthening occurs in up to 36% of patients after surgery.<sup>5–8</sup> The reasons for these divergent responses remain unknown. Proposed explanations include age at the time of surgery, distribution of involvement of CP, and development of contractures at other levels.

There is emerging evidence that muscle structure differs between spastic and normally innervated muscle.<sup>9,10</sup> Spastic muscle contains shorter sarcomeres and cells of greater stiffness than normally innervated muscle tissue.<sup>11</sup> Despite the increased stiffness of the spastic muscle cells, the extracellular matrix in spastic muscle tissue may be of lesser mechanical strength than in normal muscle tissue.<sup>12</sup> There may also be differences in the architecture of the musculotendinous unit between normal muscle and spastic muscles with and without contracture. These differences need to be studied as they may impact the outcome of treatment.

Ultrasound imaging is a well-established noninvasive technique for characterizing muscle architecture.<sup>13</sup> Several studies have focused on ultrasound imaging of the gastrocnemius in children with CP. Results have shown that children with spastic diplegic CP have shorter and

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smaller muscle bellies than typically developing children.<sup>14–16</sup> Similar findings have been obtained in children with spastic hemiplegic CP comparing the paretic limb versus the nonparetic limb.<sup>16,17</sup> The shortened length of the muscle belly (MB) appears not to be due to large reductions in fascicle length<sup>18,19</sup> although small differences have been reported in some studies.<sup>16,20</sup> After surgical intramuscular lengthening, MB and fascicle length decrease and do not recover.<sup>15,19</sup> Muscle volume does not change immediately after surgery and increases during the following year.<sup>15</sup>

Much less is known about the tendinous component of the muscle-tendon unit (MTU). To our knowledge, the tendon has not been directly studied in children with CP even though it is the primary target of surgical intervention for equinus contracture. Computational and animal studies have suggested that immobilization during growth will lead to the development of a longer tendon and shorter MB.<sup>21–23</sup> It is possible that the abnormal ankle positioning during equinus gait will produce a similar effect.

The purpose of the current study was to examine both the tendon and muscle components of the medial gastrocnemius MTU in children with CP and equinus gait, with or without contracture. We also examined a small number of children who had undergone prior surgical lengthening of the triceps surae to address equinus contracture. We hypothesized that children with equinus would have longer Achilles tendons and shorter muscle bellies and fascicles than typically developing children and that these effects would be even more pronounced in children who had undergone surgical lengthening of the triceps surae.

## METHODS

### Study Participants

This study examined a convenience sample of typically developing children (N = 21), children with CP, calf spasticity (grade 1 or higher on the Modified Ashworth Scale<sup>24</sup>), and equinus gait (with or without equinus contracture) but no prior surgery to the triceps surae (N = 20), and children with CP who had prior surgical lengthening of the triceps surae through TAL or GR (N = 6). All participants were required to be 5 to 12 years old and able to comply with instructions. Additional requirements for the participants with CP included a diagnosis of spastic CP with no evidence of athetosis or ataxia and no prior rhizotomy or use of a Baclofen pump. The study was approved by the Institutional Review Board at our institution, and written informed consent and assent were obtained for all participants.

### Procedures

Each participant underwent a physical examination to measure femur (top of greater trochanter to lateral knee joint line) and tibia (lateral knee joint line to lateral malleolus) length. Maximum dorsiflexion and plantarflexion were measured by standard goniometry with the knee fully extended. The hindfoot was inverted for the

dorsiflexion measurements. Any knee joint contracture was measured by goniometry and recorded.

For the ultrasound imaging, a Kin-Com isokinetic dynamometer was used to hold the ankle in place to maximize the reliability of the ankle positioning. The dynamometer provided much more reliable positioning than could be achieved using a standard goniometer.<sup>25</sup> With the participant lying prone, the dynamometer was used to passively dorsiflex and plantarflex the participant's ankle through the range of motion (ROM) 3 times, stopping at 5-degree or 10-degree increments depending on the available ROM. A portable ultrasound system (Terason, Burlington, MA) with a standard 5 to 10 MHz linear transducer was used for image acquisition. The transducer was aligned along the middle of the medial gastrocnemius just proximal to the distal toe of the muscle. A sagittal-plane image was recorded at each stop, so that a total of 3 images were collected at each stop angle. Three ultrasound images were also collected with the ankle hanging at its natural position out of the dynamometer, with the body remaining prone, and this resting ankle angle was measured by standard goniometry. Length of the Achilles tendon ( $L_{\text{tend}}$ ) was measured by locating the musculotendinous junction of the medial gastrocnemius and the superior posterior calcaneal surface with the ultrasound probe and measuring the distance between these 2 points.

### Analysis

The ultrasound images were analyzed using MATLAB (MathWorks Inc, Natick, MA) to determine pennation angle ( $\alpha$ ) and muscle thickness (Fig. 1). Muscle fascicle lengths ( $L_f$ ) were estimated as  $L_f = (\text{muscle thickness}) / \sin(\alpha)$  for each image. Each image was analyzed 3 times, and the average  $\alpha$  and  $L_f$  at each ankle angle were calculated. The accuracy of the muscle measures has been established previously through comparison with direct measurements on cadavers.<sup>26,27</sup> Reliability has also been established, with ourselves and others reporting coefficients

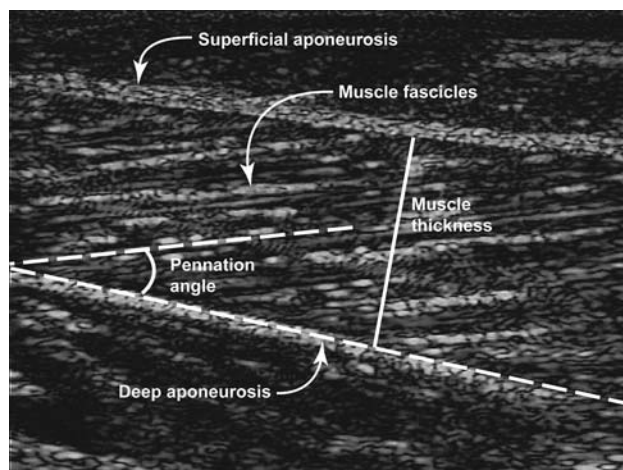


FIGURE 1. Sample ultrasound image showing measurement of muscle thickness and pennation angle.

**TABLE 1.** Demographics of the Study Participants

|                        | Control (N = 21 Subjects) | Equinus (N = 20 Subjects)                 | Prior Surgery (N = 6 Subjects)           |
|------------------------|---------------------------|---|--|
| Sex                    | M = 7, F = 14             | M = 10, F = 10                            | M = 2, F = 4                             |
| Age (y)                | 8.8 ± 2.3                 | 8.5 ± 1.9                                 | 9.0 ± 2.5                                |
| Cerebral palsy subtype | N/A                       | 4 hemiplegic, 15 diplegic, 1 quadriplegic | 2 hemiplegic, 2 diplegic, 2 quadriplegic |

of variation of 0% to 5%.<sup>25,26,28</sup> Software for Interactive Musculoskeletal Modeling (SIMM; Motion Analysis Corporation, Santa Rosa, CA)<sup>29</sup> was used to estimate the medial gastrocnemius MTU length at the resting ankle angle based on the femur and tibia lengths and knee angle measured during the physical examination. MB length was then calculated by subtracting tendon length from MTU length ( $L_{MB} = L_{MTU} - L_{tend}$ ). All lengths were normalized by tibia length to account for differences in body size among the participants. Achilles tendon length and MB length were also expressed as a percentage of MTU length.

For children with CP and equinus, limbs were subdivided into Static Equinus (< 0 degrees) and Dynamic Equinus (≥ 0 degrees) groups based on whether the ankle could dorsiflex to neutral with the knee extended and ankle inverted. Only the affected side was included for hemiplegic participants. Differences between the groups were examined using analysis of variance with a significance level of 0.05 and Scheffe post hoc tests with a Bonferroni correction for multiple comparisons.

**RESULTS**

Demographics of the study participants are presented in Table 1. Only 1 side was tested in 2 typically developing children due to time constraints during their test session and in 1 diplegic child due to an inability to cooperate with the testing for an extended period of time. For the equinus groups, all bilaterally involved participants had both limbs in the same group except for 2 children who had 1 limb in each group. Thus, the Static Equinus group consisted of 23

limbs from 15 children, and the Dynamic Equinus group consisted of 12 limbs from 7 children. In the Prior Surgery group, 3 subjects had bilateral Strayer-type GR, 1 subject had bilateral open TAL, and 2 subjects had unilateral TAL. The time since surgery ranged from 4 months to 7 years, with a median of 16 months.

As expected, the maximum dorsiflexion, maximum plantarflexion, and resting ankle angles were all significantly more plantarflexed in the Static Equinus group compared with the Control, Dynamic Equinus, and Prior Surgery groups ( $P < 0.001$ ) (Table 2). No difference in ankle angles was found among the other groups ( $P > 0.17$ ). Reflecting the more plantarflexed resting position of the Static Equinus group, normalized MTU length at the resting angle was significantly shorter in the Static Equinus group compared with all the other groups ( $P < 0.001$ ) (Table 2).

Normalized resting tendon length was longer in all of the CP groups compared with the Control group (Table 2) although the difference did not achieve statistical significance for the Static Equinus group after the Bonferroni correction ( $P = 0.03$ ). The marginal result for the Static Equinus group was likely due to the more plantarflexed ankle position, which shortened the overall MTU length. All of the CP groups had significantly longer tendon lengths than the Control group when expressed as a percentage of MTU length ( $P < 0.001$ ). Normalized tendon length was also longer in the Prior Surgery group compared with the Static Equinus group ( $P < 0.001$ ).

Resting MB length was shorter in all of the CP groups than in the Control group both when normalized

**TABLE 2.** Mean (SD) Physical Examination Results and Muscle-Tendon Architecture at the Resting Ankle Angle

|                                       | Control (N = 40 Sides) | Static Equinus (N = 23 Sides*) | Dynamic Equinus (N = 12 Sides*) | Prior Surgery (N = 10 Sides) |
|---------------------------------------|------------------------|--------------------------------|---------------------------------|------------------------------|
| Maximum dorsiflexion (degrees)        | 10.9 (6.3)             | - 15.8 (7.5)†                  | 6.3 (4.8)‡                      | 8.0 (11.1)‡                  |
| Maximum plantarflexion (degrees)      | - 35.6 (5.2)           | - 51.7 (6.5)†                  | - 35.8 (6.7)‡                   | 34.5 (12.3)‡                 |
| Resting ankle angle (degrees)         | - 18.0 (5.1)           | - 40.8 (7.8)†                  | - 23.8 (8.8)‡                   | - 16.5 (8.2)‡                |
| Resting MTU length (normalized)       | 1.06 (0.02)            | 0.98 (0.02)†                   | 1.04 (0.03)‡                    | 1.07 (0.02)‡                 |
| Tendon length (normalized)            | 0.47 (0.04)            | 0.51 (0.04)                    | 0.55 (0.04)†                    | 0.59 (0.05)†‡                |
| Tendon length (% of MTU length)       | 45 (4)                 | 52 (4)†                        | 53 (4)†                         | 55 (5)†                      |
| Muscle belly length (normalized)      | 0.58 (0.05)            | 0.47 (0.04)†                   | 0.49 (0.04)†                    | 0.48 (0.06)†                 |
| Muscle belly length (% of MTU length) | 55 (4)                 | 48 (4)†                        | 47 (3)†                         | 45 (5)†                      |
| Pennation angle (degrees)             | 17.9 (2.5)             | 18.6 (4.0)                     | 17.4 (4.2)                      | 23.8 (5.3)†§                 |
| Fascicle length (normalized)          | 0.12 (0.02)            | 0.11 (0.03)                    | 0.10 (0.01)                     | 0.07 (0.03)†‡                |

\*Two subjects had 1 limb in each equinus group (Static and Dynamic).

†Significant difference from Control group.

‡Significant difference from Static Equinus group.

§Significant difference from Dynamic Equinus group.

MTU indicates muscle-tendon unit.

and as a percentage of MTU length ( $P < 0.001$ ) (Table 2). Resting MB lengths did not differ significantly among the CP groups ( $P > 0.24$ ).

Resting pennation angle was greater in the Prior Surgery group compared with the other groups (Table 2) although the difference narrowly missed statistical significance for the Static Equinus group after the Bonferroni correction ( $P = 0.009$ ). Pennation angle did not differ among the Control, Static Equinus, and Dynamic Equinus groups ( $P > 0.92$ ). The Prior Surgery group had shorter normalized resting fascicle lengths than the Control and Static Equinus groups ( $P \leq 0.005$ ) and showed a trend toward shorter fascicle lengths compared with the Dynamic Equinus group ( $P = 0.08$ ).

Similar results were observed for pennation angle and normalized fascicle length across the ROM. Pennation angles were larger in the Prior Surgery group, with little difference between the Control, Static Contracture,

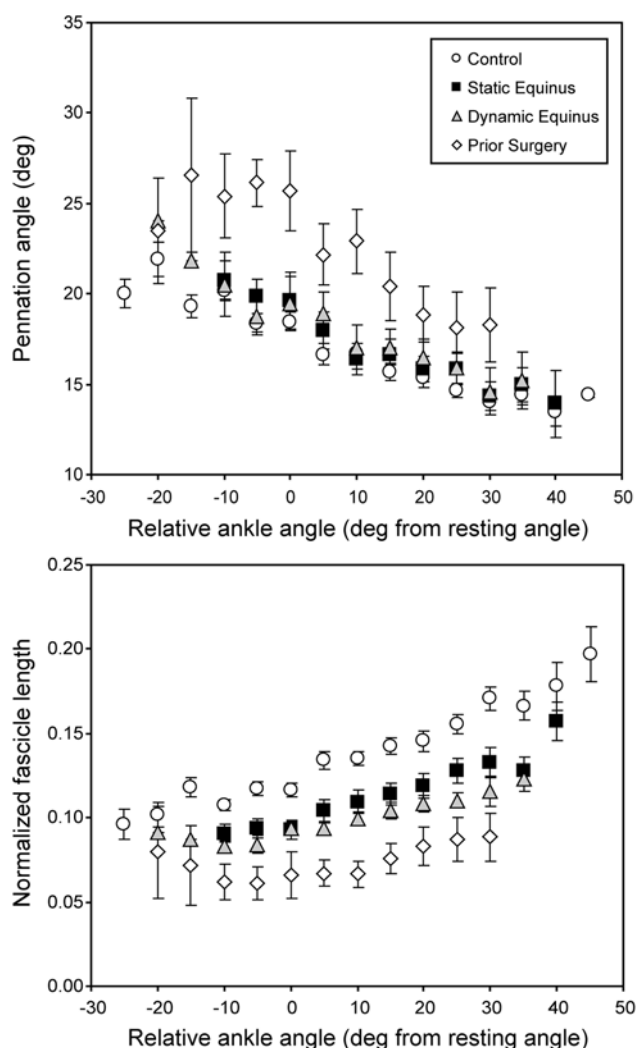
and Dynamic Contracture groups. Normalized fascicle lengths were shortest in the Prior Surgery group and longest in the Control group. Pennation angles decreased and fascicle lengths increased as the ankle position became more dorsiflexed. These results are best visualized in terms of ankle angle relative to the resting angle as this provides a reference position where the muscle and tendon should be lightly loaded by the weight of the foot (Fig. 2).

### DISCUSSION

In this study, we directly measured the length of the Achilles tendon in children with CP and equinus gait and found that the tendons were longer than normal, even in children with dynamic equinus. Normalized tendon length was also longer in children who had undergone prior triceps surae lengthening compared with the children who had static equinus. These results suggest that architecture of the MTU is altered before contractures develop and that surgery lengthens an already longer-than-normal tendon. Although it has been qualitatively observed that the muscle is shorter and the tendon longer after surgery,<sup>30</sup> the quantitative findings of this study are original as tendon lengths were not reported in previous studies. The results for the equinus groups are also provocative as they suggest that the differences appear even without surgery.

For the muscle, our results are generally consistent with the findings of previous studies. Shortened muscle bellies have been observed in children with spastic diplegic CP<sup>14</sup> and in the affected limbs of children with spastic hemiplegic CP.<sup>17</sup> No differences were found for normalized fascicle lengths in children without prior surgery<sup>18</sup> although moderate decreases have been reported for absolute fascicle lengths by a different group of investigators.<sup>16,20</sup> After GR, Shortland and colleagues<sup>19</sup> observed decreased fascicle lengths and increased pennation angles similar to our findings. However, they also reported decreased MB length after GR,<sup>15</sup> whereas MB length was shorter than normal, but not shorter than in subjects without surgery, in our prior surgery cohort. The discrepancy may result from differences in measurement technique as Fry and colleagues directly imaged the entire MB using 3-dimensional ultrasound, whereas we estimated it based on MTU and Achilles tendon length. In either case, surgery failed to restore normal gastrocnemius muscle structure. Decreased fascicle lengths would be expected to decrease muscle velocity and excursion, and increased pennation angles would be expected to decrease force production, although the former is a much larger effect.<sup>31,32</sup>

Our surgery results should be considered preliminary as we studied only a small number of subjects with a wide range of time to follow-up. The surgeries were also performed using a variety of surgical techniques. Within this group, we observed similar results for GR and TAL and were not able to identify differences in muscle-tendon architecture between these 2 procedures, possibly due to the small number of operated limbs studied. There may



**FIGURE 2.** Pennation angle and normalized fascicle length (mean  $\pm$  standard error) as a function of ankle angle relative to the resting ankle angle (0=resting angle, negative angles indicate relative plantarflexion).

also be little difference in the effects of GR and TAL on the medial gastrocnemius because lengthening occurs distal to the medial gastrocnemius MB in both procedures. Results might differ more for the soleus, which is affected differentially by GR and TAL.

A limitation of the current study is its cross-sectional nature. It would be interesting to examine longitudinal changes in muscle-tendon architecture in the same individuals as contracture develops and after surgery. It would also be informative to study other muscles as the mechanisms of contracture development may be different in different muscle groups.<sup>33,34</sup> Despite these limitations, clear differences were observed between the groups, providing a basic understanding of the differences in muscle and tendon architecture associated with equinus gait and its surgical correction.

Much of our knowledge about changes in the MTU in CP has been derived from in vivo ultrasound studies. Previous ultrasound studies have focused on muscle architecture as discussed above. These studies have identified shorter and smaller muscle bellies with possible reductions in fascicle lengths in the affected limbs of children with CP.<sup>15–20,34,35</sup> Additional insight regarding spastic muscle has been obtained through in vitro studies.<sup>9,10</sup> Spastic muscle cells are shorter and stiffer than normal<sup>11</sup> and are surrounded by abundant but poorly organized extracellular matrix.<sup>12</sup> Spastic muscle tissue exhibits increased variability in fiber diameter and altered fiber type distribution,<sup>36,37</sup> with large variations among different muscles.<sup>38</sup> Studies of the entire MTU have mainly involved computer simulations.<sup>29,31,39–41</sup> These studies incorporate assumptions about muscle-tendon structure, for example, modeling contractures by reducing muscle fiber lengths.<sup>39</sup> The current study combines in vivo ultrasound measurements with musculoskeletal modeling to study the individual muscle and tendon components within the MTU. Additional research is needed employing all of these approaches to broaden our understanding of the complex muscle-tendon changes associated with CP.

In summary, in children with spastic CP and equinus gait, the gastrocnemius MTU exhibits a longer-than-normal tendon with a shorter-than-normal MB. These differences are evident even in children with CP who exhibit dynamic equinus, before contracture has developed. Surgery restores dorsiflexion ROM but does not restore normal muscle-tendon architecture, with longer tendon lengths, shorter muscle fascicles, and larger pennation angles being observed in children who have had surgery. These architectural features likely affect function, possibly contributing to functional deficits such as plantarflexor weakness after surgery. The biomechanical consequences of these architectural differences need to be further evaluated to better understand the etiology and treatment of contractures in children with CP.

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