

Gastrocnemius and soleus lengths in cerebral palsy equinus gait— differences between children with and without static contracture and effects of gastrocnemius recession

Tishya A.L. Wren^{a,b,c,*}, K. Patrick Do^a, Robert M. Kay^{a,b}

^aChildrens Orthopaedic Center, Childrens Hospital Los Angeles, 4650 Sunset Blvd., No. 69, Los Angeles, CA 90027, USA

^bDepartment of Orthopaedics, University of Southern California, Los Angeles, CA, USA

^cDepartments of Radiology and Biomedical Engineering, University of Southern California, Los Angeles, CA, USA

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Abstract

Equinus gait is one of the most common abnormalities in children with cerebral palsy. Although it is generally assumed that the calf muscles are abnormally short in equinus gait, no studies have been done to confirm that the muscles are short and that this shortness contributes to the equinus. This study used musculoskeletal modeling combined with computerized gait analysis to examine medial gastrocnemius (MGAS), lateral gastrocnemius (LGAS), and soleus (SOL) musculotendinous lengths during equinus gait in children with cerebral palsy. All three muscles were abnormally short during equinus gait whether or not the children had equinus contractures ($P \leq 0.005$). Children with static contractures had shorter maximum static MGAS and LGAS lengths than children with dynamic equinus ($P \leq 0.002$). The children with static contractures had ratios of peak dynamic length to maximum static length close to 1.0 for MGAS and LGAS (1.005 ± 0.015) but lower ratios for SOL (0.984 ± 0.024). For the children with static contracture, these ratios did not change significantly after gastrocnemius recession ($P \geq 0.14$) because both static and dynamic lengths increased postoperatively ($P \leq 0.04$). These results support the current clinical understanding of the role of calf “tightness” in equinus gait, including the appropriateness and effectiveness of gastrocnemius recession for children with equinus contracture.

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1. Introduction

Equinus gait or “toe walking” is one of the most prevalent abnormalities in children with cerebral palsy (CP). Initially, the equinus is dynamic and can be managed with orthoses, physical therapy, stretching, strengthening of the dorsiflexors, and/or botulinum toxin injections. Even with treatment, however, a fixed contracture often develops, which may necessitate surgical correction. During surgery, the calf muscles are lengthened based on the assumption that short calf muscles play an important role in the equinus contracture. However, no studies have been done to confirm

that the muscles are indeed short and that this shortness contributes to equinus gait.

During equinus gait, abnormal ankle plantarflexion may be accompanied by either knee hyperextension or by excessive knee flexion. Excessive knee flexion occurs in patients with static or dynamic hamstring contracture, while knee hyperextension occurs in patients without hamstring contracture (Gage, 1991). This could result in normal gastrocnemius lengths since the gastrocnemius crosses both the knee and the ankle. In contrast, the soleus crosses only the ankle and is therefore expected to be short during equinus gait regardless of knee position.

Musculoskeletal modeling can be combined with computerized gait analysis to study musculotendinous lengths during gait. Several studies have used musculoskeletal modeling to examine hamstring lengths during crouch gait in children with CP. These studies have

*Corresponding author. Childrens Orthopaedic Center, Childrens Hospital Los Angeles, 4650 Sunset Blvd., #69, Los Angeles, CA 90027, USA. Tel.: +1-323-660-2450 X433; fax: +1-323-666-4409.

E-mail address: twren@chla.usc.edu (T.A.L. Wren).

shown that most children with crouch gait walk with normal hamstring lengths despite excessive knee flexion throughout the gait cycle (Hoffinger et al., 1993; Delp et al., 1996; Thompson et al., 1998, 2001). However, children selected for hamstring lengthening surgery to correct crouch gait do have abnormally short dynamic hamstring lengths which become normal after surgery (Olsen et al., 2002). Botulinium toxin injections also increase dynamic hamstring length whether or not the hamstrings are short before injection (Thompson et al., 1998). These studies illustrate the importance of examining musculotendinous lengths since the lengthening of muscles that are not short could possibly have deleterious consequences.

To our knowledge, similar studies have not yet been conducted to study calf muscle length in equinus gait. The current study addressed this void by examining gastrocnemius and soleus lengths during equinus gait in children with CP. Children with dynamic equinus were studied, along with children who had static contractures. For the children with static contractures, muscle lengths were examined both before and after calf muscle lengthening via gastrocnemius recession. The purposes of the study were (1) to determine whether the gastrocnemius is abnormally short during equinus gait, (2) to examine the efficacy of gastrocnemius recession surgery in altering dynamic muscle lengths, and (3) to assess the degree to which gastrocnemius and soleus “tightness” contribute to equinus gait in children with and without static contracture.

2. Materials and methods

The study protocol was approved by the Committee for Clinical Investigations (institutional review board) at Childrens Hospital Los Angeles. The study involved two groups of children with cerebral palsy and one control group (Table 1). The control group consisted of 10 limbs from 10 able-bodied children (Normal group). The first

CP group consisted of 6 limbs from 4 children who had undergone isolated gastrocnemius recession to correct fixed contracture and equinus gait with no other simultaneous surgeries (GR group). The second CP group consisted of 10 limbs from 8 children who walked in equinus but did not have fixed contractures (Dynamic Equinus group). Fixed (static) contracture was defined as inability to dorsiflex the ankle to neutral with the knee maximally extended during physical examination. Equinus gait was defined as peak ankle dorsiflexion during the stance phase of gait more than 1 standard deviation (SD) below normal. Isolated foot drop during swing was not considered equinus gait. All subjects had passive knee extension within $\pm 10^\circ$ of neutral. Children with bony deformities, ankle varus/valgus, or midfoot breaks were excluded from this study.

All subjects underwent gait examinations which included comprehensive physical examination and computerized gait analysis. Subjects in the GR group had both pre- and postoperative gait examinations, while subjects in the Dynamic Equinus and Normal groups had only one examination. For the GR group, the average time between surgery and postoperative evaluation was 1.1 ± 0.6 (mean \pm SD) years.

During the physical examination, an experienced physical therapist dorsiflexed the ankle to the end of its range with the knee flexed at 90° to assess soleus contracture and with the knee extended to the end of its range to assess gastrocnemius contracture. The hindfoot was positioned in neutral varus/valgus during all measurements. Measurements were taken using a standard goniometer. One arm of the goniometer was placed laterally along the long axis of the shank (aligned from the lateral malleolus to the head of the fibula, with the axis just distal to the lateral malleolus), and the other along the lateral aspect of the calcaneus. The forefoot was not used for alignment of the goniometer so dorsiflexion could be measured at the ankle joint alone without any contribution from the mid-tarsal or tarso-metatarsal joints.

Table 1
Subject demographics

	Gastrocnemius recession (<i>N</i> = 4 subjects)	Dynamic equinus (<i>N</i> = 8 subjects)	Normal (<i>N</i> = 10 subjects)
Age (yr)	5.1 \pm 1.5	6.7 \pm 2.3	7.4 \pm 1.1
Sex	4 male, 0 female	4 male, 4 female	5 male, 5 female
CP subtype	1 hemiplegic 3 diplegic	2 hemiplegic 6 diplegic	None
Previous surgeries	None	Tendo-achilles lengthening (1 subject); Hip adductor & gastrocnemius lengthening (1 subject); Tendo-achilles & hamstring lengthening (1 subject)	None
Static dorsiflexion, knee flexed (deg)	1.3 \pm 6.6 (<i>N</i> = 6 limbs)	19.2 \pm 7.3 (<i>N</i> = 10 limbs)	Not measured
Static dorsiflexion, knee extended (deg)	-12.2 \pm 4.2 (<i>N</i> = 6 limbs)	10.2 \pm 5.3 (<i>N</i> = 10 limbs)	Not measured

Computerized gait analysis was performed following standard procedures using a 7 camera Vicon (Oxford Metrics, Oxford, England) motion analysis system. This system uses a set of 15–19 passive retro-reflective markers attached over specific bony landmarks of the pelvis and lower extremities (Kadaba et al., 1990; Davis et al., 1991). Subjects made several passes down a 15 m path with the markers in place. Kinematic (joint angle) data from at least three consistent trials were averaged, as is standard in our laboratory. Since the averaged trials were consistent (no “outlier” trials were included), use of the average should give similar results to using a representative trial, as done in many other laboratories.

Musculotendinous lengths were calculated using the Software for Integrated Musculoskeletal Modeling (SIMM) (Musculographics Inc., Chicago, IL) and a graphics-based model of the lower extremity (Delp et al., 1990). This model defines the musculoskeletal geometry of a normal adult male, including the location of muscle origins and insertions (Delp et al., 1990). It has been used previously in many studies to represent both adults and children, including children with CP (Delp and Zajac, 1992; Delp et al., 1996; Thompson et al., 1998; Schmidt et al., 1999; Arnold and Delp, 2001; Olsen et al., 2002). As joint angles change, the distance between a muscle’s origin and insertion also changes, allowing calculation of musculotendinous length (subsequently referred to as “muscle length”). One change was made to the model—the allowable plantarflexion range was increased from 40° to 75° to accommodate the ankle motion observed in our subjects. Soleus (SOL), medial gastrocnemius (MGAS), and lateral gastrocnemius (LGAS) lengths were calculated throughout the gait cycle using the kinematic data from the computerized gait analyses. Maximum static muscle lengths were calculated using the joint angles measured during physical examination. Maximum static SOL length was calculated from the knee flexed measurement, and maximum static MGAS and LGAS lengths were calculated using the knee extended measurement. The ratio of peak muscle length during gait to maximum static muscle length was calculated. Muscle lengths were normalized by the muscle lengths in the anatomic position (ankle neutral, knee fully extended) for results presentation.

Non-parametric statistics were used to account for the relatively small number of subjects. Unpaired Mann–Whitney *U* tests were used for comparisons between the GR, Dynamic Equinus, and Normal groups. Paired Wilcoxon signed rank tests were used to compare the pre- versus postoperative results for the GR group. The significance level was set at $P < 0.05$.

3. Results

The dynamic equinus group had abnormally short peak muscle lengths during gait ($P = 0.0002$ for MGAS; $P = 0.0002$ for LGAS; $P = 0.003$ for SOL) (Fig. 1). The GR group had abnormally short peak muscle lengths during gait preoperatively ($P = 0.001$ for MGAS; $P = 0.001$ for LGAS; $P = 0.005$ for SOL) but not postoperatively ($P = 0.45$ for MGAS; $P = 0.45$ for LGAS; $P = 0.28$ for SOL) (Fig. 2). There were no

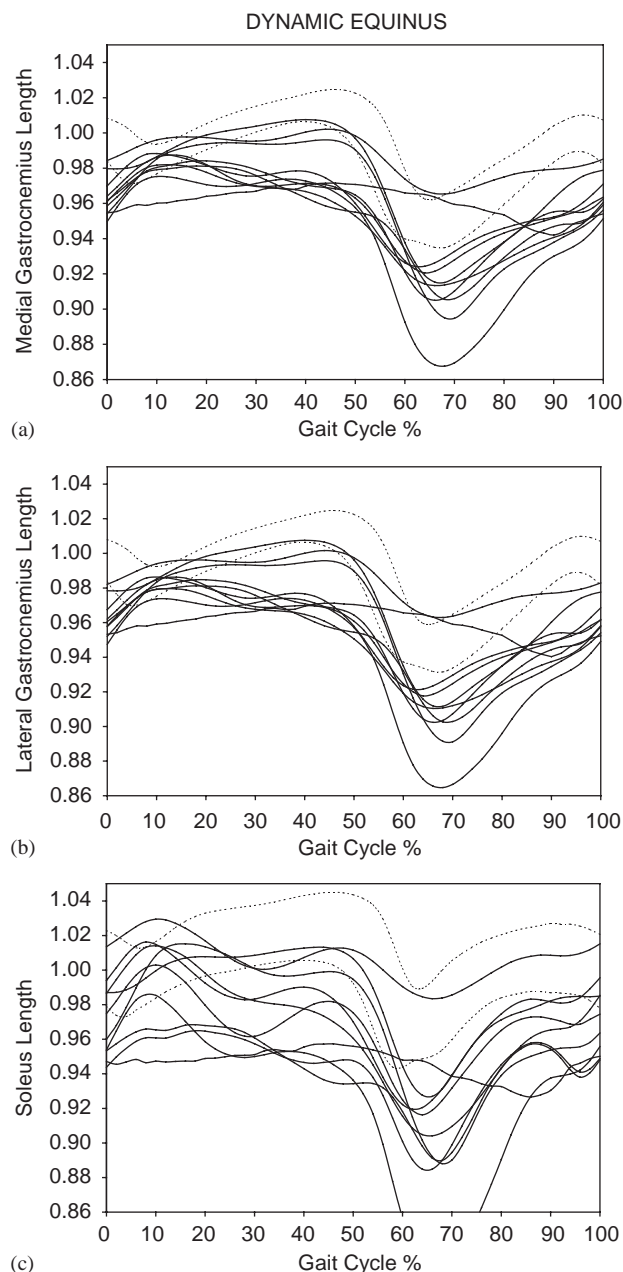


Fig. 1. Normalized musculotendinous lengths for (a) medial gastrocnemius, (b) lateral gastrocnemius, and (c) soleus for subjects in the dynamic equinus group. Dashed lines represent ± 2 SD from the mean of the Normal group. Muscle–tendon lengths are abnormally short throughout the gait cycle.

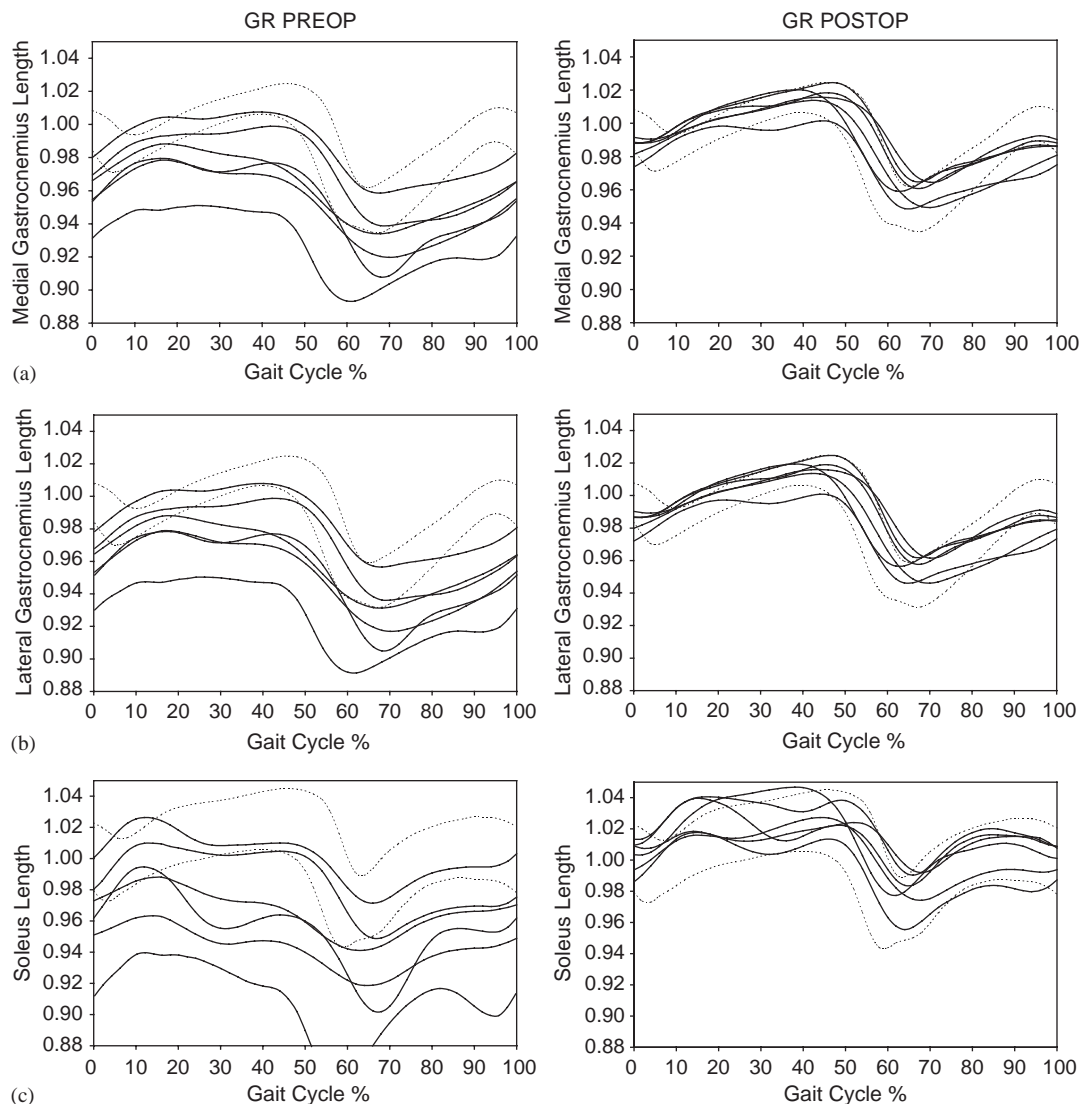


Fig. 2. Pre- and postoperative normalized musculotendinous lengths for (a) medial gastrocnemius, (b) lateral gastrocnemius, and (c) soleus for subjects in the GR group. Dashed lines represent ± 2 SD from the mean of the Normal group. Surgery leads to correction of short dynamic lengths, particularly during stance (first 60% of gait cycle).

significant differences in dynamic muscle lengths between the Dynamic Equinus group and the preoperative GR group ($P=0.66$ for MGAS; $P=0.74$ for LGAS; $P=0.39$ for SOL).

Compared with the Dynamic Equinus group, the GR group had shorter static muscle lengths preoperatively ($P=0.001$ for MGAS; $P=0.001$ for LGAS; $P=0.002$ for SOL) but not postoperatively ($P=0.47$ for MGAS; $P=0.47$ for LGAS; $P=0.71$ for SOL) (Table 2). The ratio of dynamic-to-static muscle length differed significantly between the two groups for MGAS ($P=0.007$) and LGAS ($P=0.007$), but not for SOL ($P=0.06$). The average ratios for the GR group were close to 1.0 for MGAS and LGAS but lower for SOL preoperatively (Fig. 3a). The ratios were also lower for the Dynamic Equinus group. The ratios did not change significantly in the GR group after surgery ($P=0.35$ for MGAS and

LGAS; $P=0.14$ for SOL) (Fig. 3b) since both static ($P=0.03$ for MGAS and LGAS; $P=0.04$ for SOL) and dynamic ($P=0.03$ for MGAS, LGAS, and SOL) muscle lengths increased postoperatively.

4. Discussion

The results of this study demonstrate that gastrocnemius and soleus lengths are abnormally short during equinus gait in children with cerebral palsy. These findings contrast with previous investigators' findings for crouch gait, in which hamstring length is normal in the majority of subjects (Hoffinger et al., 1993; Delp et al., 1996; Thompson et al., 1998, 2001). This occurs because the abnormal knee flexion, which shortens the hamstrings, is accompanied by excessive hip flexion,

Table 2
Peak normalized musculotendinous lengths (mean ± SD)

	GR		Dynamic Equinus	Normal
	Preop	Postop		
MGAS				
Peak static length	0.979 ± 0.007 ^a	1.017 ± 0.009	1.014 ± 0.006	N/A
Peak length in gait	0.984 ± 0.020	1.016 ± 0.008	0.987 ± 0.012	1.015 ± 0.005
Ratio	1.005 ± 0.015 ^a	0.998 ± 0.014	0.972 ± 0.015	N/A
LGAS				
Peak static length	0.979 ± 0.007 ^a	1.018 ± 0.009	1.014 ± 0.006	N/A
Peak length in gait	0.984 ± 0.020	1.016 ± 0.008	0.987 ± 0.012	1.015 ± 0.005
Ratio	1.005 ± 0.015 ^a	0.998 ± 0.014	0.972 ± 0.015	N/A
SOL				
Peak static length	1.003 ± 0.016 ^a	1.038 ± 0.013	1.041 ± 0.016	N/A
Peak length in gait	0.987 ± 0.031	1.033 ± 0.011	0.995 ± 0.028	1.027 ± 0.010
Ratio	0.984 ± 0.024	0.998 ± 0.010	0.955 ± 0.028	N/A

Bold indicates significant difference from Normal.

GR subjects had shorter static lengths than Dynamic Equinus subjects pre- but not postoperatively.

Dynamic lengths were abnormally short for the Dynamic Equinus and preoperative GR subjects. Dynamic-to-static ratios were close to 1.0 for MGAS and LGAS in the GR group but lower for SOL and for the Dynamic Equinus group.

^a indicates significant difference from Dynamic Equinus group.

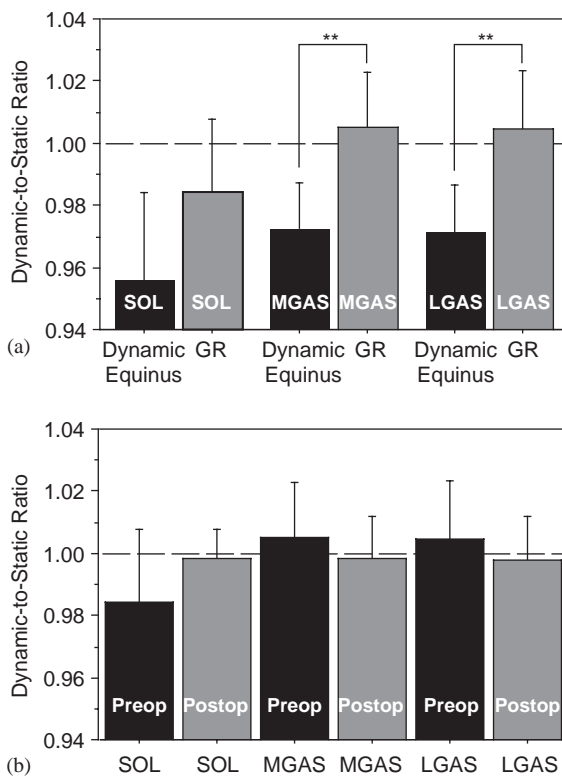


Fig. 3. (a) Preoperative ratios (mean ± SD) of peak dynamic to maximum static musculotendinous lengths, (b) Pre- and postoperative ratios (mean ± SD) for the GR group. The gastrocnemii have higher ratios in the GR group compared with the dynamic equinus group. The ratios did not change significantly after surgery.

which lengthens the hamstrings. Since soleus length is solely a function of ankle joint angle, the soleus is naturally short during equinus gait in which the ankle is abnormally plantarflexed. However, the gastrocne-

mius, which crosses two joints, could have normal length if shortening due to ankle plantarflexion were offset by lengthening due to greater knee extension or hyperextension. Our results indicate that this is not the case for the study subjects, who generally had knee hyperextension in stance. Gastrocnemius lengths would be expected to be even shorter in patients who have equinus gait with excessive knee flexion.

Children with static equinus contracture differ from children with dynamic equinus in that they reach their maximum static gastrocnemius lengths during gait. This implies that the gastrocnemius is a limiting factor in equinus gait for children with static ankle contractures but not for children without static contractures. This supports the current clinical understanding of the role of calf “tightness” in equinus gait. Since children with CP may have different degrees of static or dynamic equinus deformity, gastrocnemius and soleus length deficits will vary along a continuum from mild to severe shortness.

After gastrocnemius recession, the calf muscles are no longer abnormally short during gait. Because the GR procedure lengthens the gastrocnemii more than the soleus, both the gastrocnemii and soleus reach close to their maximum static lengths during gait postoperatively when only the gastrocnemii did so preoperatively. While one might expect higher soleus dynamic-to-static length ratios in limbs with greater soleus contracture, no relationship was found between this ratio and static dorsiflexion angles with the knee flexed. The ratio was highest in two limbs that dorsiflexed to 0° and +6°, lowest in two limbs that dorsiflexed to -5° and +12°, and intermediate in two limbs that dorsiflexed to 0° and -5°. Maximum static soleus length increased following GR even though this procedure theoretically affects only the gastrocnemius. This may result from the close

coupling of the muscles through fascia, tendon, and other connective tissues.

This study used strict inclusion criteria for subjects in the GR group to eliminate the confounding effects of multiple surgeries which many children with CP undergo. Because of the strict inclusion criteria, only a relatively small number of subjects was available. Nevertheless, these subjects yielded significant results. While it is possible that the results were biased by requiring subjects to have no other simultaneous surgeries, we have found similar results in children with CP who underwent GR as part of multilevel surgery and for subjects who underwent tendo-achilles lengthening (Wren et al., 2003). This suggests that the findings of this study apply more generally to children with CP who exhibit equinus gait.

We did not calculate static muscle lengths for the Normal group because static dorsiflexion angles were not available for these subjects. Although subjects in the Normal group were older than the subjects with CP, this should not affect the normalized muscle length results examined in this study. The normalized muscle lengths depend only on kinematics which become stable by age $3\frac{1}{2}$ years (Sutherland, 1997). All subjects in this study were older than $3\frac{1}{2}$ years.

Both the physical examination and gait analysis measurements are subject to possible measurement inaccuracies. Previous studies have found high intrarater reliability for static ankle dorsiflexion measurements but only moderate interrater reliability, primarily due to differences in the bony landmarks used by different therapists (Elveru et al., 1988; Youdas et al., 1993). We have not performed formal reliability testing in our laboratory, but all therapists are highly experienced and work together using the same measurement standards to maximize consistency. To assess potential errors in the static muscle lengths and dynamic-to-static muscle length ratios due to inaccuracies in the static dorsiflexion measurements, we performed a sensitivity analysis. For the dorsiflexion angles measured in this study, a 5° error in the measured angle would change the static muscle length by up to 1.4% for the soleus and up to 0.9% for the gastrocnemii. A 5° error in knee angle would change the gastrocnemius lengths by less than 0.4% and would have no effect on soleus length. Based on the average lengths from this study, these potential errors could change the dynamic-to-static length ratios by up to 1.3% for the soleus and 0.9% for the gastrocnemii. While the possibility of such errors needs to be recognized, they should not bias the overall results since they would not systematically increase or decrease all measurements.

With regard to the gait analysis measurements, only sagittal plane knee and ankle motions were used in the muscle length calculations. Motion in other planes should have little effect on calf muscle lengths, as

observed previously for hamstring and psoas lengths (Delp et al., 1996). Since sagittal plane kinematics are highly repeatable (Kadaba et al., 1989), errors associated with the gait analysis measurements should be minimal. To further protect against errors due to the motion analysis system, kinematic data from at least three consistent trials were averaged to obtain representative results for each subject.

The musculoskeletal model used in this study has several limitations. First, it represents the musculoskeletal geometry of a normal adult male (Delp et al., 1990). This model has been used in many previous studies of children, including children with CP, but it remains largely unknown how well this model represents children (Delp and Zajac, 1992; Delp et al., 1996; Thompson et al., 1998; Schmidt et al., 1999; Arnold and Delp, 2001; Olsen et al., 2002). The use of an adult sized model should not affect the normalized muscle lengths examined in this study because, as noted previously, these lengths depend only on kinematics, which become stable at age $3\frac{1}{2}$ years (Sutherland, 1997). However, differences in body proportions and muscle attachment locations between adults and children could affect the muscle length results. Currently, we do not know if any such differences exist. Perhaps more importantly, we have not modeled musculoskeletal deformities for the children with CP. Such deformities can affect the length of some muscles but not others. For example, femoral anteversion affects psoas length but not hamstring length (Schutte et al., 1997; Arnold et al., 2001). No studies have yet been done to determine if skeletal deformities such as femoral anteversion, tibial torsion, or ankle varus/valgus affect calf muscle lengths. To minimize possible errors due to skeletal deformities, subjects with bony deformities were excluded from this study.

A second limitation of the model is that it does not reveal why the calf muscles are short during equinus gait. We examined dynamic-to-static muscle length ratios in an attempt to gain insight into the role of muscle contracture in equinus gait. The results suggested that gastrocnemius “tightness” contributes to equinus gait in children with static contractures. The physiological basis for this “tightness” is not yet known, but recent studies have suggested that it may be related to increased passive stiffness of the muscle fibers (Friden and Lieber, 2003) and/or deficiencies of aponeurotic length (Shortland et al., 2002). For children with dynamic equinus, the primary cause is thought to be calf spasticity and/or dorsiflexor weakness (Engsberg et al., 2000; Goldstein and Harper, 2001).

In summary, we have confirmed that the gastrocnemius and soleus are abnormally short during equinus gait in children with CP. This finding applies both to static equinus contracture and dynamic equinus in the absence of contracture. In children with equinus due to

static contracture, lengthening of the calf musculature through gastrocnemius recession reestablishes normal static and dynamic muscle lengths. These results suggest that gastrocnemius recession may be an appropriate and effective treatment for children with equinus contractures.

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