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The role of estimating muscle-tendon lengths and velocities of the hamstrings in the evaluation and treatment of crouch gait

Allison S. Arnold [a,*], May Q. Liu [a], Michael H. Schwartz [c], Sylvia Õunpuu [d], Scott L. Delp [a,b]

[a] *Department of Mechanical Engineering, Stanford University, Stanford, CA 94305-5450, USA*
[b] *Department of Bioengineering, Stanford University, Stanford, CA, USA*
[c] *Center for Gait and Motion Analysis, Gillette Children's Specialty Healthcare, St. Paul, MN, USA*
[d] *Center for Motion Analysis, Connecticut Children's Medical Center, Hartford, CT, USA*

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Abstract

Persons with cerebral palsy frequently walk with excessive knee flexion during terminal swing and stance. This gait abnormality is often attributed to ''short'' or ''spastic'' hamstrings that restrict knee extension, and is often treated by hamstrings lengthening surgery. At present, the outcomes of these procedures are inconsistent. This study examined whether analyses of the muscle-tendon lengths and lengthening velocities of patients' hamstrings during walking may be helpful when deciding whether a candidate is likely to benefit from hamstrings surgery. One hundred and fifty-two subjects were cross-classified in a series of multi-way contingency tables based on their pre- and postoperative gait kinematics, muscle-tendon lengths, muscle-tendon velocities, and hamstrings surgeries. The lengths and velocities of the subjects' semimembranosus muscles were estimated by combining kinematic data from gait analysis with a three-dimensional computer model of the lower extremity. Log-linear analysis revealed that the subjects who walked with abnormally ''short'' or ''slow'' hamstrings preoperatively, and whose hamstrings did not operate at longer lengths or faster velocities postoperatively, were unlikely to walk with improved knee extension after treatment ($p < 0.05$). Subjects who did not walk with abnormally short or slow hamstrings preoperatively, and whose hamstrings did operate at longer lengths or faster velocities postoperatively, tended to exhibit unimproved or worsened anterior pelvic tilt after treatment ($p < 0.05$). Examination of the muscle-tendon lengths and velocities allows individuals who walk with abnormally short or slow hamstrings to be distinguished from those who do not, and thus may help to identify patients who are at risk for unsatisfactory postsurgical changes in knee extension or anterior pelvic tilt.

Keywords: Cerebral palsy; Gait; Hamstrings; Musculoskeletal model

1. Introduction

Crouch gait, one of the most prevalent and troublesome movement abnormalities among children with cerebral palsy, is characterized by excessive knee flexion during the terminal swing and stance phases. Abnormally ''tight'' hamstrings, due to spasticity [1–3] or static contracture [3,4], are thought to cause the excessive knee flexion in many cases. Thus, crouch gait is commonly treated by surgical lengthening of the hamstrings, typically in combination with other orthopaedic procedures.

Unfortunately, it is difficult to predict which patients will benefit from hamstrings surgery. Many individuals achieve dramatic improvements in knee extension, stride length and walking efficiency following surgery, while others show little improvement or get worse. Previous studies have attempted to explain these inconsistent outcomes by categorizing patients on the basis of preoperative gait kinematics and/or surgical interventions and comparing postoperative changes in knee, hip and pelvis angles during walking across the patient groups (e.g. [5–8]). These studies have provided valuable

* Corresponding author. Tel.: +1 650 724 7086; fax: +1 650 724 1922.
E-mail address: asarnold@stanford.edu (A.S. Arnold).

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documentation of patients' gait kinematics and kinetics before and after surgery; however, these analyses have identified only a few of the factors that potentially influence outcomes, and the reported findings have been contradictory. One reason is that several factors in addition to tight hamstrings may contribute to crouch gait, and determining whether an individual's gait abnormality is due to short or spastic hamstrings [6,9–11], spastic hip flexors [9,12,13], weak knee extensors [14], weak ankle plantarflexors [15], torsional deformities of the tibia [16,17], problems with balance or another source is not straightforward. To improve the outcomes of treatments for crouch gait, more efficacious strategies for making treatment decisions are needed.

The purpose of this study was to assess whether analyses of the muscle-tendon lengths and lengthening velocities of patients' hamstrings during crouch gait may be helpful when deciding whether a patient is likely to benefit from hamstrings surgery. We reasoned that if hamstrings contracture is the source of a patient's excessive knee flexion (i.e. if crouch gait is caused by excessive passive forces that are generated when abnormally short hamstrings are stretched), then the patient's hamstrings are likely to operate at abnormally short muscle-tendon lengths, particularly in terminal swing, when the hamstrings are stretched to their maximum lengths during walking. In such cases, surgical lengthening of the hamstrings may improve knee extension by decreasing the passive forces generated by the muscles, thereby enabling short hamstrings to operate at longer muscle-tendon lengths. Alternatively, if hamstrings spasticity is the source of a patient's excessive knee flexion (i.e. if crouch gait is caused by an exaggerated, velocity-dependent resistance of the hamstrings to stretch), then the patient's hamstrings are likely to lengthen at abnormally slow muscle-tendon velocities, particularly during the mid-swing phase, when the hamstrings are rapidly stretched. In such cases, surgical lengthening of the hamstrings may improve knee extension by attenuating the muscles' exaggerated response to stretch, thereby enabling spastic hamstrings to lengthen at greater muscle-tendon velocities. We also reasoned that if a patient's hamstrings are not operating at short lengths or slow velocities during walking, and are not restricting knee extension, then surgical lengthening of the muscles may not alleviate excessive knee flexion, or may unnecessarily compromise hamstrings strength. These arguments suggest that estimates of patients' hamstrings lengths and velocities, as determined from gait analysis and a computer model that accurately characterizes the musculoskeletal geometry, may help to distinguish those who have short or spastic hamstrings from those who do not, and thus may augment the techniques currently used to identify candidates for surgery.

Several research groups have estimated the muscle-tendon lengths [18–23] and/or velocities [2,24] of the hamstrings during normal and crouch gait. A consistent finding from these studies is that not all persons with crouch gait walk with hamstrings that are shorter than normal [18–24] or slower than normal [2,24]. Previous analyses have also shown that subjects with abnormally "short" hamstrings tend to walk with longer muscle-tendon lengths, and subjects with abnormally "slow" hamstrings tend to walk with longer muscle-tendon velocities, when knee extension is improved following hamstrings surgery; by contrast, subjects whose hamstrings do not operate at short lengths or slow velocities preoperatively do not tend to walk with longer or faster hamstrings postoperatively [24]. The results of these studies are encouraging, and suggest that analyses of the muscle-tendon lengths and velocities warrant further investigation.

The analyses of muscle-tendon lengths and velocities performed in each of the previous studies [2,18–24] had important limitations. Most studies relied on generic models of the lower extremity with normal adult musculoskeletal geometry. However, many individuals who undergo surgery to treat crouch gait are children with bone deformities, and only Schutte et al. [20] and Arnold et al. [24] evaluated whether variations in musculoskeletal geometry due to age or bone deformities may have compromised the accuracy of the muscle-tendon lengths or velocities estimated with their models. Only a small number of subjects were analyzed in previous studies (typically 10–30 subjects), and only Cosgrove et al. [21] examined whether the subjects' gait deviations were systematically altered after surgery. Hence, important questions remain unanswered, and the role of muscle-tendon lengths and velocities in surgical decision-making remains unclear.

In this study, we retrospectively determined the muscle-tendon lengths and lengthening velocities of the medial hamstrings for 152 subjects, at the body positions corresponding to each subject's measured gait, using a well-tested computer model of the lower extremity [25]. The following questions were addressed:

- What percentage of patients walk with hamstrings that are operating at abnormally short muscle-tendon lengths?
- What percentage of patients walk with hamstrings that is lengthening at abnormally slow muscle-tendon velocities?
- Is knee extension during terminal swing and early stance more likely to be improved after surgery when the hamstrings are operating at abnormally short lengths or slow velocities preoperatively? Is knee extension more likely to be improved when the hamstrings operate at longer lengths or faster velocities postoperatively?
- Is anterior pelvic tilt more likely to be exaggerated after surgery when the hamstrings are not operating at abnormally short lengths or slow velocities preoperatively? Is anterior pelvic tilt more likely to be exaggerated when the hamstrings operate at longer lengths or faster velocities postoperatively?
- If the hamstrings are not operating at abnormally short lengths or slow velocities preoperatively, is it possible to improve knee extension without hamstrings lengthening surgery?

This work examines these questions and critically evaluates the utility of analyzing muscle-tendon lengths and velocities of the hamstrings in a large sample of subjects before and after surgery.

2. Methods

The 152 subjects were selected from the motion analysis laboratory databases at two children's medical centers (hereafter referred to as Center A and Center B). All had spastic cerebral palsy, were able to ambulate without orthoses or other assistance, and were 6 years of age or older (mean 10 years, range 6–22 years) preoperatively. All had undergone at least two gait analyses as part of their routine medical care, and all but one had undergone intervening orthopaedic surgery and physical therapy.

To be included, a subject had to walk with at least 20° of knee flexion in one or both limbs at initial contact (averaged over 0–4% of the gait cycle) or terminal swing (averaged over 96–100% of the gait cycle) preoperatively. We included subjects with varying levels of involvement, and with varying degrees of knee flexion in mid-stance (i.e. ''jump-knee'' gait or crouch gait [4,26,27]). One limb per subject, the limb with the greater degree of knee flexion that met all other inclusion criteria, was selected for analysis. A limb was excluded if its musculoskeletal geometry about the hip or knee had been surgically altered prior to the preoperative exam, or if a varus, valgus or extension osteotomy had been performed prior to the postoperative exam, or if botulinum toxin had been injected into the hamstrings, psoas or adductors within 6 months prior to either exam. Subjects who had previously undergone a tendo-Achilles lengthening (27 subjects) or other soft-tissue surgery at the ankle (9 subjects) were included if the procedure had been done at least 24 months prior to the preoperative exam. None of the subjects had undergone a selective dorsal rhizotomy or a neurectomy, and none were on baclofen.

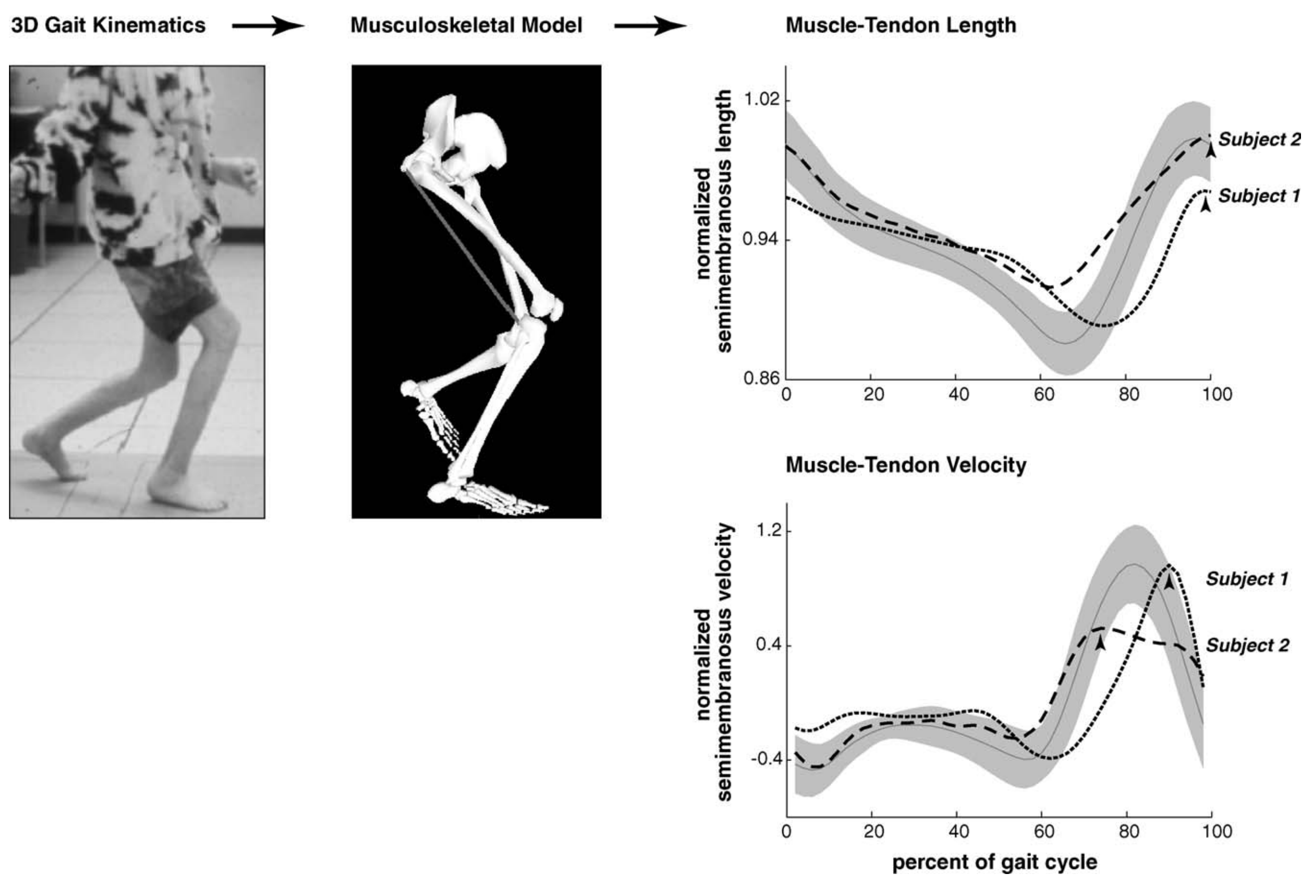

Fig. 1. Estimation of subjects' semimembranosus muscle-tendon lengths and velocities during walking. A computer model of the lower extremities (center) was used in combination with the subjects' joint angles and stride durations measured during gait analysis (left) to plot the muscle-tendon lengths and lengthening velocities of the semimembranosus vs. gait cycle (right). The muscle-tendon lengths and velocities corresponding to each subject's abnormal gait (e.g. Subjects 1 and 2, dashed lines) were normalized and were compared to the lengths and velocities averaged for unimpaired individuals (mean ± 2 S.D., shaded region) to determine if the subjects' hamstrings were operating at peak muscle-tendon lengths shorter than normal, or peak muscle-tendon velocities slower than normal (peak lengths and velocities indicated by arrows). Some of the subjects, such as Subject 1, walked with semimembranosus lengths that were substantially shorter than normal. Other subjects, such as Subject 2, walked with semimembranosus velocities that were substantially slower than normal. Such analyses may help to distinguish patients who have ''short'' or ''spastic'' hamstrings from those who do not, and thus may augment conventional methods used to describe patients' neuromusculoskeletal impairments and gait abnormalities.

In total, 77 individuals from Center A who were examined between 1988 and 2002 and 75 individuals from Center B who were examined between 1994 and 2002 met these inclusion criteria. Each subject underwent three-dimensional gait analysis [28] and clinical assessment. The subjects' joint angles during walking were computed as described by Kadaba et al. [29], and one representative barefoot trial from each subject's pre- and postoperative exam was selected for further study. All subjects and/or their parents provided informed written consent for the collection of these data. Retrospective analyses of the data were performed in accordance with the regulations of all participating institutions.

A computer model of the lower extremity [25] was used in combination with the subjects' joint angles and stride durations obtained from gait analysis to estimate the muscle-tendon lengths and velocities of the hamstrings at the body positions corresponding to each subject's pre- and post-operative gait (Fig. 1). The model characterizes the three-dimensional geometry of the pelvis, femur and proximal tibia, the kinematics of the hip and tibiofemoral joints and the paths of the semimembranosus and semitendinosus muscles. The model has been described and tested extensively in previous studies [25,30].

The muscle-tendon lengths and velocities of the semimembranosus were determined for each subject at every 2% of the gait cycle. Because the length changes of the semimembranosus and semitendinosus are similar during walking [20,25], we considered the semimembranosus to be representative of the medial hamstrings for this analysis. Muscle-tendon length was calculated as the distance along the modeled path of the semimembranosus between the muscle's origin and insertion. Muscle-tendon velocity was estimated by computing the numerical derivative of the muscle-tendon length data with respect to time and applying a zero-phase digital filter with a cutoff frequency of 8 Hz (second order Butterworth filter, MATLAB, The MathWorks, Natick, MA). We identified the maximum, or "peak" lengths and velocities of the subjects' muscles during walking, since these measures correspond to times in the gait cycle when abnormally short or spastic hamstrings are most likely to restrict knee extension.

We normalized the muscle-tendon lengths and velocities based on the averaged peak length and averaged peak velocity, respectively, of the semimembranosus during normal gait. The means and standard deviations of the peak lengths and velocities during normal gait were determined from the gait kinematics of 45 unimpaired subjects. About half of the unimpaired subjects were evaluated at Center A, the other half were evaluated at Center B. Data from both groups of unimpaired subjects were pooled after t-tests confirmed that the peak muscle-tendon lengths averaged for the unimpaired subjects were not significantly different for the two centers ($p < 0.05$). The model was not scaled to the subjects prior to normalization; this decision was based on a previous study [25], which showed that scaling the model along its anatomical axes did not improve the accuracy of the normalized lengths estimated with the model. Hence, differences in the subjects' muscle-tendon lengths and velocities before and after surgery reflect differences in their measured gait kinematics, not changes in size.

We answered our research questions by cross-classifying the 152 subjects in a series of $2 \times 2 \times 2$ contingency tables [31]. Each subject was categorized on the basis of seven dichotomous variables: preoperative muscle-tendon length (short, not short) and muscle-tendon velocity (slow, not slow), hamstrings surgery (lengthened, not lengthened), postoperative change in muscle-tendon length (longer, not longer) and muscle-tendon velocity (faster, not faster) and postoperative change in knee extension (satisfactory, unsatisfactory) and anterior pelvic tilt (satisfactory, unsatisfactory). Three-way hierarchical log-linear analyses were performed to assess whether the subjects' outcome classifications were related to their length/velocity classifications or to their surgery classifications. The subjects from each center were analyzed separately and then pooled as appropriate. A test statistic was considered to be significant for p-values less than 0.05.

The length/velocity variables were derived from our estimates of the subjects' muscle-tendon lengths and velocities during walking. A subject's hamstrings were classified as "short" preoperatively if the peak length of the semimembranosus during walking was less than the peak length during normal gait by 2 S.D. or more; otherwise, a subject's hamstrings were classified as "not short." A subject's hamstrings were classified as "slow" preoperatively if the peak velocity of the semimembranosus during walking was less than the peak velocity during normal gait by 2 S.D. or more; otherwise, a subject's hamstrings were classified as "not slow." A subject's hamstrings were classified as "longer" if the maximum postoperative length of the semimembranosus during walking was greater than the preoperative length by an amount corresponding to a 10° change in knee angle at initial contact, as averaged for the unimpaired subjects; otherwise, the subject's hamstrings were considered to be "not longer." A subject's hamstrings were classified as "faster" if the maximum postoperative velocity of the semimembranosus during walking was greater than the preoperative velocity by 2.7 cm/s; otherwise, the subject's hamstrings were considered to be "not faster." This velocity change corresponds to a 10° increase in knee extension computed over 250 ms, the approximate time interval of terminal swing.

The surgery variable indicated whether the subjects did or did not undergo hamstrings surgery. A subject was classified as having undergone a hamstrings lengthening if the intervening surgery included one or more of the following procedures: intramuscular tenotomy or z-lengthening of the semitendinosus (82 and 12 subjects, respectively), transfer of the semitendinosus to the adductor magnus or lateral femoral condyle (4 and 7 subjects, respectively), lengthening of the semimembranosus (93 subjects) or lengthening of the biceps femoris long head (11 subjects).

The outcome variables indicated whether relevant aspects of the subjects' gait kinematics changed in a satisfactory or unsatisfactory manner after surgery. A subject's knee extension was classified as ''satisfactory'' if it was improved by at least 10° during terminal swing or early stance, or if it was within 2 S.D. of the average knee angles during normal gait; otherwise, knee extension was classified as ''unsatisfactory.'' We used a 10° threshold for deciding whether improvements in the knee angles were large enough to be considered satisfactory because this value corresponds to approximately 2 S.D. of the knee angles averaged for the unimpaired subjects and it represents a clinically significant change. A subject's mean pelvic tilt was classified as ''satisfactory'' if the subject walked with excessive anterior tilt preoperatively that was diminished by at least 7°, or if the subject walked with excessive posterior tilt that was increased by at least 7°, or if the subject's pelvic tilt was within 2 S.D. of the average pelvic tilt during normal gait. A subject's mean pelvic tilt was classified as ''unsatisfactory'' if the subject walked with excessive anterior tilt preoperatively that was not diminished by at least 7°, or if the subject walked with normal pelvic tilt preoperatively and this tilt was shifted anteriorly by 7° or more. We used a 7° threshold for deciding whether changes in pelvic tilt were large enough to be considered satisfactory because this value corresponds to approximately 2 S.D. of the pelvic tilt averaged for the unimpaired subjects. We used a 19° threshold for deciding whether a subject's anterior pelvic tilt was ''excessive;'' this value is 2 S.D. above the pelvic tilt averaged for the unimpaired subjects.

3. Results

Approximately one-third of the subjects walked with abnormally short semimembranosus muscle-tendon lengths (54 of 152 subjects, 35%); in most cases, these subjects also walked with abnormally slow muscle-tendon velocities. Another one-third of the subjects had hamstrings that operated at abnormally slow muscle-tendon velocities, but not short lengths (45 of 152 subjects, 30%). The remaining one-third of the subjects (53 of 152 subjects, 35%) walked with peak semimembranosus lengths and velocities that were neither shorter nor slower than normal; in these cases, contracture or spasticity of the hamstrings may not have been the source of the excessive knee flexion. The subjects' preoperative length/velocity classifications were not immediately evident from gait analysis or from static clinical tests (Table 1). This suggests that these classifications, which account for the moment arms of the hamstrings at the hip and the knee as well as the subjects' three-dimensional motions about these joints during walking, have the potential to augment conventional gait analysis and provide new information. The percentages of subjects classified as having short or slow hamstrings from Center A (50 of 77 subjects, 65%) and from Center B (49 of 75 subjects, 65%) were not different.

A majority of the subjects underwent surgical lengthening of the hamstrings (Table 2), frequently in combination with other procedures. At neither center was the decision to surgically lengthen the hamstrings, in general, consistent with the peak muscle-tendon lengths or lengthening velocities of the subjects' semimembranosus muscles during walking. Nearly one-third of the subjects who underwent

Table 1
Characteristics of the subjects classified by their preoperative semimembranosus muscle-tendon lengths and velocities during walking

	Neither[a]	*Slow*[a]	*Short*[a]	*Both*[a]	Correlation[b] with length	Correlation[b] with velocity
Number of subjects ($n = 152$)	53 (35%)	45 (30%)	13 (8%)	41 (27%)		
From center A ($n = 77$)	27	24	6	20		
From center B ($n = 75$)	26	21	7	21		
Variables from preoperative exam[c]						
Age (years)	9 ± 2	10 ± 3	9 ± 4	10 ± 4		
Popliteal angle[d] (°)	46 ± 11	51 ± 10	52 ± 9	55 ± 14	−0.34	−0.29
Mean walking speed (m/s)	1.1 ± 0.2	0.9 ± 0.2	1.0 ± 0.3	0.9 ± 0.2	0.29	0.54
Mean pelvic tilt[e] during walking (°)	20 ± 5	20 ± 4	14 ± 3	14 ± 5	0.75	
Maximum hip extension in stance phase[e] (°)	4 ± 8	9 ± 6	0 ± 7	6 ± 10		−0.38
Knee flexion at initial contact[e] (°)	27 ± 8	30 ± 9	32 ± 9	34 ± 10	−0.29	
Maximum knee extension in stance phase[e] (°)	10 ± 12	14 ± 12	14 ± 11	22 ± 14	−0.38	−0.28
Maximum ankle dorsiflexion in stance phase[e] (°)	9 ± 10	7 ± 12	13 ± 9	7 ± 15		

[a] Slow defined as peak muscle-tendon velocity slower than 2 S.D. from the peak velocity averaged for 45 unimpaired subjects during walking; short defined as peak muscle-tendon length shorter than 2 S.D. from the peak length averaged for 45 unimpaired subjects during walking; neither defined as neither peak muscle-tendon velocity slow nor peak muscle-tendon length short; both defined as both peak muscle-tendon velocity slow and peak muscle-tendon length short.

[b] Pearson's product-moment correlation coefficient between variables of interest and subjects' peak semimembranosus muscle-tendon lengths and velocities during walking; only correlations that are significant for p-values <0.01 are noted.

[c] Mean ± 1 S.D.

[d] Popliteal angle quantifies the degree to which the knee can be passively extended with the pelvis stabilized, the ipsilateral hip flexed 90°, and the contralateral limb flexed; a value of 0° indicates full knee extension.

[e] Positive values indicate anterior pelvic tilt, hip flexion, knee flexion and ankle dorsiflexion.

Table 2
Hamstrings surgeries[a] classified by subjects' preoperative muscle-tendon lengths and velocities

	Neither[b]	Slow[b]	Short[b]	Both[b]
Number of subjects ($n = 152$)	53	45	13	41
Lengthening of medial and lateral hamstrings	3	3	1	4
Lengthening of medial hamstrings only	28	23	6	26
Lengthening or transfer of semitendinosus only	1	5	1	3
No hamstrings surgery	21	14	5	8

[a] The time between each subject's preoperative exam and intervening surgery was not more than 16 months (mean 4 months), the time between the surgery and the postoperative exam was at least 8 months and not more than 35 months (mean 13 months), and the cumulative time between each subject's two exams was not more than 40 months (mean 18 months).
[b] Neither, slow, short and both are defined in Table 1.

hamstrings surgery did not walk with abnormally short or slow hamstrings preoperatively (32 of 104 subjects, 31%). More than half of the subjects who did not undergo hamstrings surgery walked with hamstrings that were shorter than normal or slower than normal preoperatively (27 of 48 subjects, 56%).

Log-linear analysis revealed several statistically significant associations between the subjects' pre- and postoperative muscle-tendon lengths and velocities, hamstrings surgeries, and the subjects' postoperative changes in gait kinematics. Not surprisingly, different associations were found for the subjects whose hamstrings were classified as short or slow (i.e. whose crouched gait may have been caused by short or spastic hamstrings), and for the subjects whose hamstrings were classified as neither short nor slow (i.e. whose crouched gait may have been caused by other factors). Results for both groups of subjects are summarized below.

3.1. Analysis of subjects whose hamstrings were classified as short or slow

Subjects who walked with abnormally short or slow hamstrings preoperatively tended to walk with improved knee extension during the terminal swing and early stance phases postoperatively when the hamstrings operated at longer lengths or faster velocities ($p < 0.05$, Fig. 2, white bars). When short hamstrings did not operate at longer muscle-tendon lengths, or when slow hamstrings did not lengthen at faster muscle-tendon velocities, the subjects' changes in knee extension were less likely to be satisfactory ($p < 0.05$, Fig. 2, shaded bars).

Short hamstrings were more likely to operate at longer muscle-tendon lengths, and slow hamstrings were more likely to lengthen at faster muscle-tendon velocities, when the intervening treatment included hamstrings lengthening surgery ($p < 0.05$, Fig. 2, compare ratios of white and shaded bars for subjects who did/did not undergo hamstrings surgery). Most of the subjects with short or slow hamstrings who underwent hamstrings surgery walked with longer peak semimembranosus lengths or faster peak semimembranosus velocities postoperatively (57 of 72 subjects, 79%) and 70% of these subjects walked with improved knee extension. By contrast, many of the subjects who did not undergo hamstrings surgery did not walk with longer or faster hamstrings postoperatively (14 of 27 subjects, 52%) and only 14% of these subjects walked with improved knee extension. These data suggest that patients with short or slow hamstrings, if not treated appropriately, may be at risk for unsatisfactory changes in knee extension.

3.2. Analysis of subjects whose hamstrings were classified as neither short nor slow

When subjects' hamstrings were not operating at abnormally short lengths or slow velocities preoperatively, no statistically significant associations between the subjects' hamstrings surgeries, their postoperative changes in muscle-tendon length or velocity, or their postoperative changes in knee extension were detected (Fig. 3). Most of the subjects who underwent hamstrings surgery walked with improved knee extension during the terminal swing and early stance phases postoperatively (22 of 32 subjects, 69%), regardless

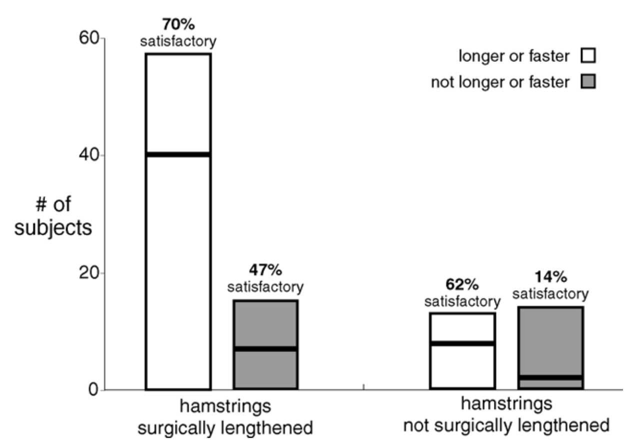

Fig. 2. Number of subjects who walked with abnormally short and/or slow hamstrings preoperatively, cross-classified by hamstrings surgery and by the subjects' postoperative changes in muscle-tendon length and velocity. The percentages of subjects who walked with satisfactory changes in knee extension in each category are indicated (thick horizontal line and text label). Log-linear analysis showed that two of the two-way associations were significant (likelihood ratio χ^2 with three degrees of freedom = 23.25, $p < 0.05$). First, the subjects who underwent hamstrings surgery were more likely to walk with longer or faster hamstrings postoperatively than those who did not. Second, the subjects who walked with longer or faster hamstrings postoperatively were more likely to achieve a satisfactory change in knee extension than those who did not.

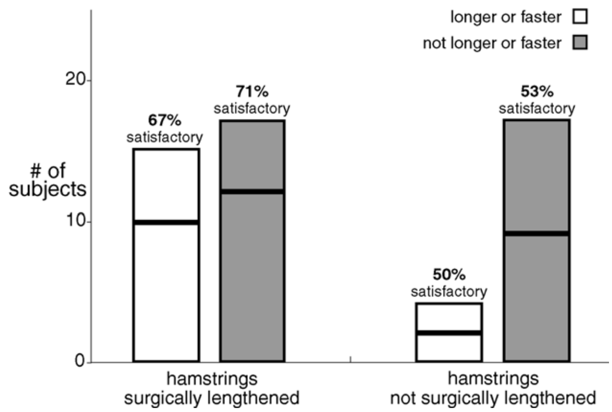

Fig. 3. Number of subjects who walked with neither short nor slow hamstrings preoperatively, cross-classified by hamstrings surgery and by the subjects' postoperative changes in muscle-tendon length and velocity. The percentages of subjects who walked with satisfactory changes in knee extension in each category are indicated (thick horizontal line and text label). Log-linear analysis showed that neither the three-way nor the two-way associations were significant.

of whether the hamstrings operated at longer lengths or faster velocities (Fig. 3, compare white and shaded bars for subjects who underwent hamstrings surgery). Many of the subjects (11 of 21 subjects, 52%) achieved satisfactory changes in knee extension without hamstrings surgery (Fig. 3, compare bars for subjects who did/did not undergo hamstrings surgery). In these subjects, the changes in knee extension may have been related to concomitant procedures.

Subjects whose hamstrings were neither short nor slow preoperatively, who underwent hamstrings surgery, tended to walk with unimproved or worsened anterior pelvic tilt postoperatively when the hamstrings operated at longer lengths or faster velocities ($p < 0.05$, Fig. 4, compare white and shaded bars for subjects who underwent hamstrings surgery). Changes in pelvic tilt were more likely to be satisfactory when hamstrings that were neither short nor slow were not surgically lengthened ($p < 0.05$, Fig. 4, compare outcomes for the subjects who did/did not undergo hamstrings surgery). These data suggest that patients who do not walk with short or slow hamstrings may be at risk for unsatisfactory changes in anterior pelvic tilt.

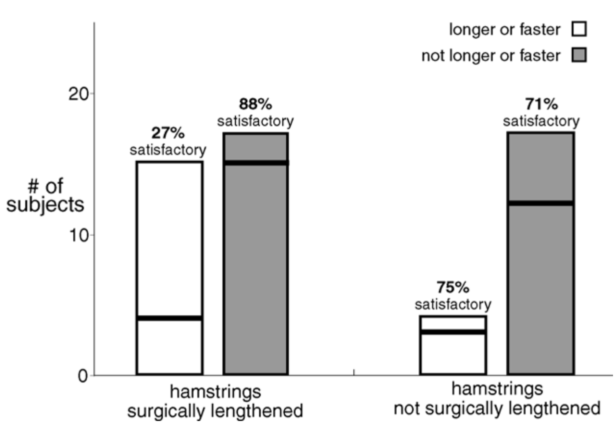

Fig. 4. Number of subjects who walked with neither short nor slow hamstrings preoperatively, cross-classified by hamstrings surgery and by the subjects' postoperative changes in muscle-tendon length and velocity. The percentages of subjects who walked with satisfactory changes in pelvic tilt in each category are indicated (thick horizontal line and text label). Log-linear analysis showed that the three-way association was significant (likelihood ratio χ^2 with one degree of freedom = 4.78, $p < 0.05$). The subjects who underwent hamstrings surgery, and who walked with longer or faster hamstrings postoperatively, were less likely to achieve a satisfactory change in pelvic tilt than those who did not.

4. Discussion

Analyses of muscle-tendon lengths and lengthening velocities alone, like any other variable measured during gait analysis, cannot predict the outcome of multi-level orthopaedic surgery. However, estimates of the peak lengths and velocities of patients' hamstrings during crouch gait may be helpful when assessing if abnormally tight hamstrings are limiting a patient's knee extension, and thus may help to identify patients who are at risk for unsatisfactory postsurgical changes in knee extension or anterior pelvic tilt. This study is the first to demonstrate the potential utility of such analyses in a large sample of subjects before and after surgery.

In previous studies of the muscle-tendon lengths during crouch gait, Schutte et al. [20] found that most subjects had hamstrings that operated at abnormally short lengths (14 of 21 limbs, 67%), while Delp et al. [18] estimated that only 20% (4 of 20 limbs) had hamstrings that operated at abnormally short lengths. We believe that the 35% incidence (54 of 152 subjects) calculated in this study provides a more accurate estimate of the percentages of patients who walk with short hamstrings than previously reported. We evaluated the muscle-tendon lengths for a greater number of subjects than had been examined in previous studies. Also, we refined the geometric paths of the muscles in our model based on magnetic resonance images of persons with cerebral palsy and on experimental measurements of the length changes in cadaveric specimens [25,30].

Estimates of the muscle-tendon lengths and velocities during crouch gait, as calculated in this study, have the potential to augment conventional gait analysis. Because these estimates are based on a detailed computer model of the musculoskeletal geometry and the joint kinematics, they simultaneously account for the muscle moment arms at the hip and the knee as well as patients' three-dimensional motions about these joints during walking. It is important to emphasize that this model does not include descriptions of the muscle architecture, and it does not represent the nervous system. Hence, the model cannot be used to estimate patients' passive or active muscle-tendon forces, muscle fiber lengths or reflex thresholds. In other words, analyses of the muscle-tendon lengths can indicate whether a patient's hamstrings are operating at lengths shorter or longer than normal, but such analyses cannot explain why a patient's hamstrings are operating at those lengths. Analysis of the muscle-tendon velocities, similarly, can indicate whether a patient's hamstrings are lengthening at velocities slower or faster than normal, but such analyses cannot explain why a patient's hamstrings are lengthening at those rates. Certainly, more work is needed to clarify the actions of the hamstrings and other muscles during walking, and to understand how surgical lengthening alters the forces produced by the hamstrings in the presence of spasticity and contracture.

Several other limitations of this study should be considered. First, we did not account for variations in surgical technique or postoperative physical therapy when categorizing the subjects' treatments. Our gait data were collected over a 14-year period at two different institutions. If variations in operative technique, treatment philosophy, or other factors systematically led to differences in the subjects' postoperative gait kinematics, the effects of these variations would not have been elucidated by the analyses performed here. Despite the variability, our analyses revealed several statistically significant associations between the subjects' pre- and postoperative muscle-tendon lengths and velocities, hamstrings surgeries and postoperative changes in gait kinematics.

Second, factors in addition to short or spastic hamstrings may have contributed to the excessive knee flexion of some of the subjects during walking. In such cases, improvements in the subjects' gait patterns after surgery may have depended not only on whether the hamstrings were surgically lengthened, but also on whether other contributing factors were corrected.

Third, nearly all of the subjects in this study underwent concomitant procedures between their pre- and postoperative exams, typically in addition to hamstrings lengthening. Most notably, 110 subjects underwent a gastrocnemius and/or soleus lengthening, 96 subjects had a rectus femoris transfer and 83 subjects had a derotational osteotomy of the femur. Also, 27 subjects had a tendo-Achilles lengthening (TAL) prior to their preoperative exam. We verified that the proportion of subjects who walked with improved knee extension was similar for the subjects who had a prior TAL and those who did not; thus, a prior TAL did not seem to predispose the subjects in this study to unsatisfactory changes in knee extension. Nevertheless, when interpreting the results of this study, the confounding effects of the subjects' concomitant and prior treatments must be considered.

Fourth, we used relatively simple measures of outcome, based on changes in the subjects' knee and pelvis angles during walking. We purposely focused on subjects' knee and pelvis angles because these measures are often thought to be influenced by hamstrings lengthening surgery. These measures do not necessarily reflect the success or failure of the subjects' multi-level interventions.

Given these limitations, what is the role of estimating muscle-tendon lengths and velocities of the hamstrings in the evaluation and treatment of crouch gait? Our study revealed that subjects who walk with abnormally short or slow hamstrings preoperatively, and whose hamstrings do not operate at longer lengths or faster velocities postoperatively, are unlikely to walk with improved knee extension after treatment. Subjects who do not walk with abnormally short or slow hamstrings preoperatively, and whose hamstrings operate at longer lengths or faster velocities postoperatively, are likely to exhibit unimproved or worsened anterior pelvic tilt after treatment. Thus, we believe that examination of the muscle-tendon lengths and velocities during crouch gait, in combination with clinical examination, gait analysis and perhaps other assessments [1,32], have the potential to provide important insights.

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