[Reprinted from THE JOURNAL OF ORTHOPAEDIC RESEARCH
Vol. 14, no.1, pp. 144-151, January 1996]

Hamstrings and Psoas Lengths During Normal and Crouch Gait: Implications for Muscle-Tendon Surgery

Scott L. Delp, Allison S. Arnold, Rosemary A. Speers, and *Carolyn A. Moore

*Departments of Biomedical Engineering and Physical Medicine and Rehabilitation, Northwestern University and Sensory Motor Performance Program, Rehabilitation Institute of Chicago, and *Gait Analysis Laboratory, Children's Memorial Hospital, Chicago, Illinois, U.S.A.*

Summary: Crouch gait, one of the most common movement abnormalities among children with cerebral palsy, is characterized by persistent flexion of the knee during the stance phase. Short hamstrings are thought to be the cause of crouch gait; thus, crouch gait is often treated by surgical lengthening of the hamstrings. In this study, a graphics-based model of the lower extremity was used in conjunction with three-dimensional kinematic data obtained from gait analysis to estimate the lengths of the hamstrings and psoas muscles during normal and crouch gaits. Only three of 14 subjects with crouch gait (four of 20 limbs with knee flexion of 20° or more throughout stance) had hamstrings that were shorter than normal by more than 1 SD during walking. Most (80%) of the subjects with crouch gait had hamstrings of normal length or longer, despite persistent knee flexion during stance. This occurred because the excessive knee flexion was typically accompanied by excessive hip flexion throughout the gait cycle. All of the subjects with crouch gait had a psoas that was shorter than normal by more than 1 SD during walking. These results emphasize the need to consider the geometry and kinematics of multiple joints before performing surgical procedures aimed at correcting crouch gait.

Crouch gait is one of the most common movement abnormalities among children with cerebral palsy. Although crouch gait is characterized primarily by persistent flexion of the knee during stance, children who walk with a crouch often exhibit exaggerated flexion, adduction, and internal rotation of the hip in addition to excessive knee flexion.

Tight hamstrings due to muscle spasticity or static contracture are reputed to be the cause of crouch gait; thus, persistent crouch is often treated by surgical lengthening of the hamstrings. Although a hamstrings lengthening procedure usually decreases stance phase knee flexion, it can lead to other problems, such as decreased knee flexion during swing or increased hip flexion during stance (1,2,6,7,10,16,17). In an attempt to avoid such complications, it is now common practice for surgeons to perform additional procedures, such as a rectus femoris transfer or iliopsoas lengthening, in conjunction with hamstrings lengthening (5,8,12).

The complications that can result from lengthening the hamstrings, as well as the difficulties involved in planning and subsequently evaluating concomitant procedures, have motivated us to better understand the causes of crouch gait and the methods by which surgical decisions are made. At present, a patient is a candidate for hamstrings lengthening if one limb exhibits persistent knee flexion of 20-30° during stance, a popliteal angle greater than 45°, and evidence of hamstrings overactivity as determined from electromyographic recordings (15). However, satisfying these criteria does not necessarily imply that the hamstrings are too short, for several reasons. First, the length of a biarticular muscle such as the hamstrings does not follow intuitively from joint kinematics; rather, it depends on the angular changes of multiple joints and on the muscle's moment arms about these joints. Second, the relationship between static measures of hamstrings tightness, such as popliteal angle (defined in Table 1), and length of the hamstrings during movement has not been established. Finally, electromyographic recordings indicate only that a muscle is active—they do not indicate why a muscle is active. Premature or prolonged activity of the hamstrings could reflect spasticity of the hamstrings, as is often assumed, or could instead indicate that the hamstrings are activated to compensate for some other abnormality. Since the hamstrings can generate a substantial hip extension moment (18), they may be activated, for example, to compensate for a hip flexion contracture or spasticity of the hip flexors.

Using a computer model of the lower limb, Hoffin-

Received December 29, 1994; accepted April 25, 1995.
Address correspondence and reprint requests to S. L. Delp at Sensory Motor Performance Program, Rehabilitation Institute of Chicago (Room 1406), 345 East Superior Street, Chicago, IL 60611, U.S.A.

TABLE 1. *Characteristics of the subjects with crouch gait*

Subject[a]	Sex	Age (yrs + mos)	Maximum knee extension during stance[b] (R/L knee flexion) (°)	Maximum hip extension during stance[c] (R/L hip flexion) (°)	Popliteal angle[d] (R/L knee flexion) (°)	Hip flexion contracture[e] (R/L hip flexion) (°)
1	F	11 + 9	61/60	31/43	70/55	25/10
2	F	10 + 5	52/58	22/30	55/65	20/20
3	M	13 + 6	55/41	27/6	70/65	15/0
4	M	10 + 4	37/32	30/47	45/40	10/20
5	M	8 + 3	36/34	2/14	45/55	0/5
6	F	15 + 6	30/26	29/26	70/60	15/10
7	M	8 + 7	29/16	6/–7	45/45	15/10
8	M	8 + 6	26/12	23/7	25/40	0/0
9	M	10 + 1	25/17	8/1	45/40	0/0
10	M	9 + 11	14/24	9/8	35/50	0/5
11	F	9 + 4	23/16	29/1	50/80	10/0
12	M	12 + 11	21/9	19/12	50/65	10/15
13	M	7 + 2	21/13	1/–2	50/50	20/10
14	M	10 + 9	14/20	1/13	N.M.	0/0

[a] Subjects are ordered according to the maximum knee extension attained during stance. Subjects 1-6 exhibited knee flexion of 20° or more throughout stance in both limbs; subjects 7-14 exhibited knee flexion of 20° or more throughout stance in one limb.

[b] Knee flexion/extension angle is the angle formed between the long axis of the thigh and the shank. Knee flexion is represented by a positive joint angle and is 0° at the anatomical position.

[c] Hip flexion/extension angle is the angle formed between the long axis of the thigh and a line perpendicular to the plane formed by the left and right anterior superior iliac spine and posterior superior iliac spine (as estimated by a sacral wand marker). Hip flexion is represented by a positive joint angle and is approximately 13° at the anatomical position.

[d] A popliteal angle test measures the degree to which the knee can be passively extended with the hip flexed 90°. This test is performed with the patient supine, the pelvis stabilized, and the contralateral limb extended. The popliteal angle is defined as the angle between the shank and a vertical line. A popliteal angle of 0° indicates that the knee is fully extended; a popliteal angle greater than 45° may indicate tightness of the hamstrings. N.M. = not measured.

[e] A hip flexion contracture test measures the degree to which the hip can be extended without arching the spine. This test is performed with the patient supine, the pelvis stabilized, and the contralateral limb fully flexed. Hip flexion contracture is determined by measuring the angle between the patient's extended limb and the examining table.

ger et al. (9) estimated hamstrings and psoas lengths during crouch gait to investigate why some patients exhibit increased anterior pelvic tilt following lengthening of the hamstrings. They found that most (12 of 16 subjects; 28 of 32 limbs) of the subjects' hamstrings were "long" rather than "short" during walking due to the subjects' excessive hip flexion and to the hamstrings' relatively large moment arm at the hip as compared with the knee. These authors subsequently proposed lengthening the hip flexors as an alternative to lengthening the hamstrings. Hoffinger et al. modeled the knee joint as a simple hinge, which could have caused errors in their estimates of muscle length. They also included patients who had undergone a number of previous surgeries. Nevertheless, the results of their study are interesting and warrant further consideration.

The objectives of this study were to (a) estimate the lengths of the hamstrings and psoas during normal and crouch gait on the basis of a computer model of the lower limb that accurately characterizes knee kinematics and patients who have not had previous surgery, and (b) compare the lengths of subjects' hamstrings and psoas muscles during walking with their lengths during static muscle tests. Our goal was to determine whether the hamstrings are indeed short in patients with crouch gait, as is often inferred from measures of knee flexion and popliteal angle, or whether the hamstrings might actually be longer than normal, as suggested by Hoffinger et al.

MATERIALS AND METHODS

Fourteen subjects with crouch gait (mean age 10.5 years) and 10 subjects without movement disorders (mean age 12.6 years) underwent gait analysis at the Children's Memorial Hospital in Chicago. A five-camera VICON motion measurement system (Oxford Metrics, Oxford, England) was used to track the three-dimensional positions of 15 reflective markers during walking. These marker positions were used, along with estimates of the joint center locations (3), to calculate subjects' three-dimensional joint kinematics as described by Kadaba et al. (11).

Subjects with crouch gait were included in this study if they exhibited a minimum of 20° of knee flexion in one or both limbs throughout the stance phase (Table 1). Eight of the subjects walked with knee flexion of 20° or more in one limb, and six walked with knee flexion of 20° or more in both limbs. All had

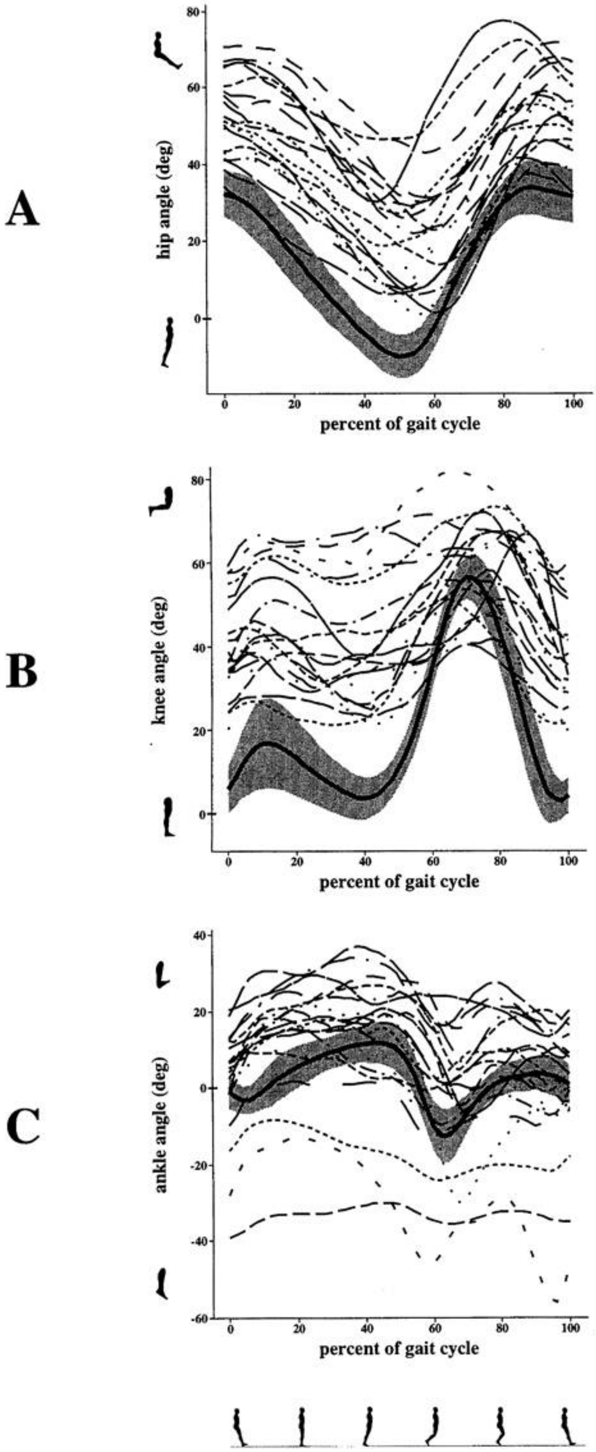

FIG. 1. Plots of (**A**) hip flexion/extension, (**B**) knee flexion/extension, and (**C**) ankle plantar/dorsiflexion angles for the 14 subjects with crouch gait (20 "crouched" limbs) during walking. Averaged curves for the normal subjects (shaded areas) ±1 SD are shown for comparison. To be included in this study, subjects with crouch gait had to exhibit knee flexion of 20° or more in one or both limbs throughout stance. Some subjects were crouched considerably more than this and walked with more than 60° of knee flexion during stance. Variability was also observed in subjects' ankle angles. Although most of the subjects with crouch gait walked with a certain amount of dorsiflexion, three of the subjects had excessive plantar flexion. Regardless of knee or ankle kinematics, all subjects with crouch gait exhibited exaggerated hip flexion for at least part of the gait cycle.

been diagnosed with spastic cerebral palsy, were over age 7, had not undergone previous orthopaedic surgery, and walked without orthoses or other assistance. A comparison of the sagittal plane kinematics during walking for the normal subjects and for the subjects with crouch gait (Fig. 1) illustrates some of the important characteristics of the latter group.

A graphics-based biomechanical model of the lower extremity (4) was used in conjunction with subjects' kinematic data to estimate the changes in hamstrings and psoas lengths that occur during crouch gait and normal walking (Fig. 2). This model characterizes the origin-to-insertion paths of the muscles and the kinematics of the joints for a nominal male subject (height approximately 1.8 m) so that the lengths and moment arms of the muscles can be estimated for a wide range of body positions. The hip model, which defines relative motions between the pelvis and femur, is assumed to be a ball-and-socket joint. The knee model, which is based on the work of Yamaguchi and Zajac (19), accounts for the kinematics of the tibiofemoral and patellofemoral joints in the sagittal plane.

Attachment coordinates for the semitendinosus, semimembranosus, biceps femoris long head, and psoas muscles in the lower extremity model were defined by Delp et al. (4). A single "hamstrings" muscle path was constructed using an average of the attachment coordinates for the semitendinosus, semimembranosus, and biceps femoris long head, weighted by the physiologic cross-sectional areas of the muscles. A single psoas muscle path was constructed on the basis of the average of its origin sites along the lumbar vertebrae. Intermediate "via points" were introduced so that the psoas path wrapped over the pelvic brim before inserting on the lesser trochanter. Although the psoas is a multijoint muscle, its origin was fixed to the model's pelvic reference frame rather than to a separate sacral or lumbar reference frame; hence, changes in psoas length reflect changes in hip angles only.

The length of a muscle for a given limb position was calculated as the distance from origin to insertion along the muscle path. This length was normalized by the computer model's muscle length at the anatomical position (hamstrings 43.2 cm; psoas 25.8 cm) so that comparisons could be made among subjects of different sizes. To obtain estimates of hamstrings and psoas lengths during walking, muscle lengths were calculated at limb positions corresponding to subjects' body positions at approximately 50 evenly spaced points in their gait cycles. Maximum and minimum lengths were noted. For the subjects with normal gait, muscle lengths for the right limbs were averaged at each point in the gait cycle to obtain representative "normal" curves; normal maximum and minimum muscle lengths were taken from these averaged curves. For the subjects with crouch gait, muscle lengths for the right and left limbs were estimated and evaluated on a limb-by-limb basis. Our results focus on the 20 "crouched" limbs (i.e., limbs with knee flexion of 20° or more throughout stance) since these are the limbs most likely to undergo surgery to lengthen the hamstrings.

The lengths of the hamstrings and psoas muscles during static tests were compared with estimated lengths during walking. The computer model was used to calculate the length of the hamstrings at limb positions corresponding to a range of popliteal angles. The lengths corresponding to subjects' measured popliteal angles were then compared with the subjects' maximum hamstring lengths during walking. Similarly, the psoas lengths corresponding to measured hip flexion contracture angles were compared with the maximum psoas lengths during walking. The hamstrings and psoas lengths were calculated with the model's pelvis at 0° of pelvic tilt (the position at which the popliteal angle and hip flexion contracture are ideally measured) and at ±5° of pelvic tilt to account for our uncertainty about the actual orientation of subjects' pelves during the static tests.

The musculoskeletal model was used to determine which joint rotations have the greatest influence on hamstrings and psoas

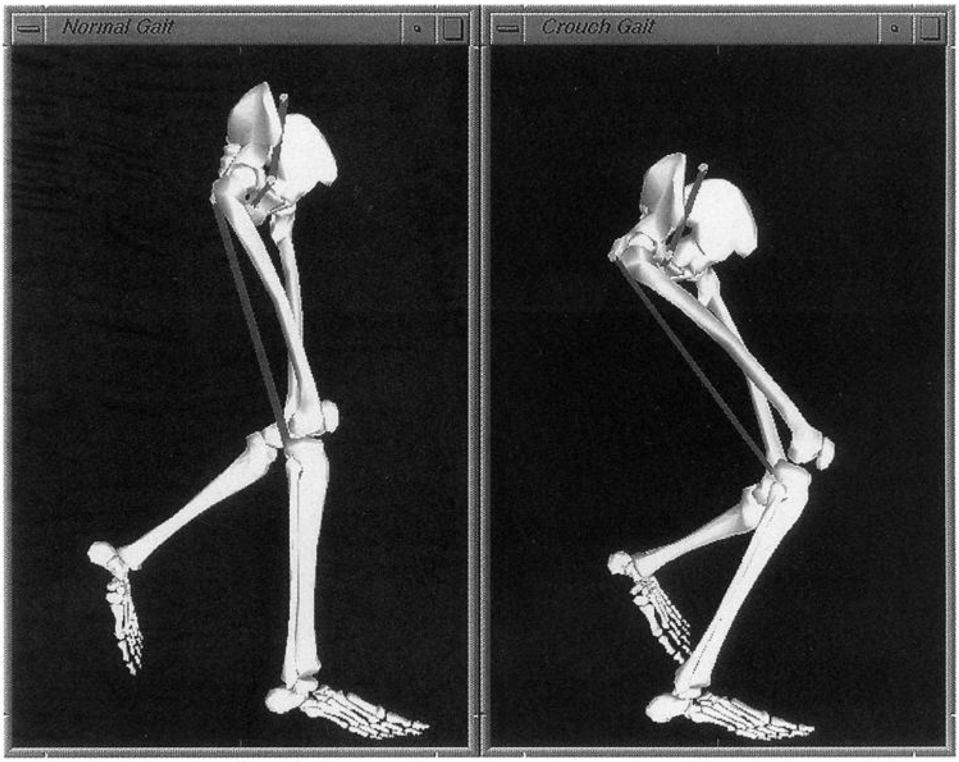

FIG. 2. Graphics-based model of the lower extremity depicting (**A**) normal and (**B**) crouch gaits at 16% of the gait cycle (midstance). The paths of the hamstrings and psoas used to estimate the muscle-tendon lengths are highlighted.

lengths during walking. The maximum and minimum hip flexion/extension, abduction/adduction, internal/external rotation, and knee flexion/extension angles were recorded for the group of subjects with normal gait and for the group of subjects with crouch gait, to obtain an estimate of the range of motion of each joint during normal and crouch gait. The change in muscle length over each range of motion was expressed as a percentage of the muscle's length at the anatomical position, and the relative importance of each joint rotation on hamstrings length and on psoas length was assessed.

RESULTS

Only three of the 14 subjects with crouch gait (both limbs of subject 3 and the "crouched" limbs of subjects 7 and 9; Table 1) had maximum hamstring lengths that were shorter than normal by more than 1 SD (Fig. 3, at approximately 95% of gait cycle). Only one subject with crouch gait (the right limb of subject 3; Table 1) had a maximum hamstring length that was shorter than normal by more than 2 SDs. None had a minimum hamstring length (approximately 60% of gait cycle) that was shorter than normal by more than 1 SD. Thus, for the majority of the subjects with crouch gait, the hamstrings appeared to reach normal or longer-than-normal lengths during walking despite excessive knee flexion during stance. This occurred because the hamstrings span the hip as well as the knee, and the excessive knee flexion was accompanied by excessive hip flexion throughout the gait cycle.

All of the subjects with crouch gait (all limbs with knee flexion of 20° or more and the other limbs of subjects 8-12; Table 1) had a maximum psoas length that was shorter than normal by more than 2 SDs (Fig. 4 at approximately 50% of gait cycle). Most of the subjects with crouch gait (all limbs with knee flexion of 20° of more except the left limbs of subjects 3 and 10 and the right limbs of subjects 7 and 9; Table 1) had a minimum psoas length (approximately 90% of gait cycle) that was shorter than normal by more than 2 SDs, and all subjects with crouch gait (all 28 limbs) had a minimum psoas length that was shorter than normal by more than 1 SD. These findings can also be attributed to excessive hip flexion during walking.

Comparison of subjects' hamstring lengths during the popliteal angle tests with their maximum hamstring lengths during walking yielded two important findings. First, for all but one subject (both limbs of subject 6; Table 1), the hamstrings were considerably shorter during walking than during the popliteal angle test (most circles are below the dark shaded area in Fig. 5A). Second, on the basis of measured popliteal angles, all of the subjects' hamstrings were seemingly long enough for normal gait (all circles are to the right of where the shaded areas intersect in Fig. 5A). These observations suggest that measurements of the popliteal angle are not related to hamstring lengths during walking and thus may not be highly relevant when deciding whether a patient's hamstrings need to be lengthened.

Comparison of subjects' psoas lengths during the

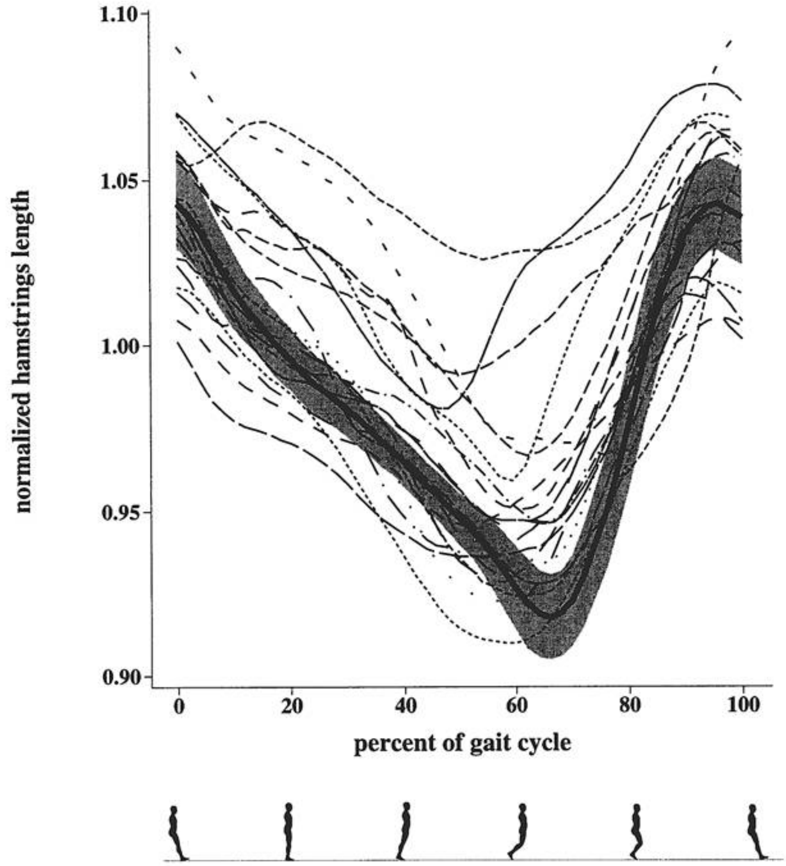

FIG. 3. Normalized hamstring length for the 14 subjects with crouch gait (20 limbs with knee flexion of 20° or more) during walking. The averaged curve for the normal subjects (solid dark line) ±1 SD (shaded area) is shown for comparison. Curves above the shaded area represent hamstrings that are longer than normal; curves below the shaded area represent hamstrings that are shorter than normal. Lengths were normalized by the model's hamstring length at the anatomical position.

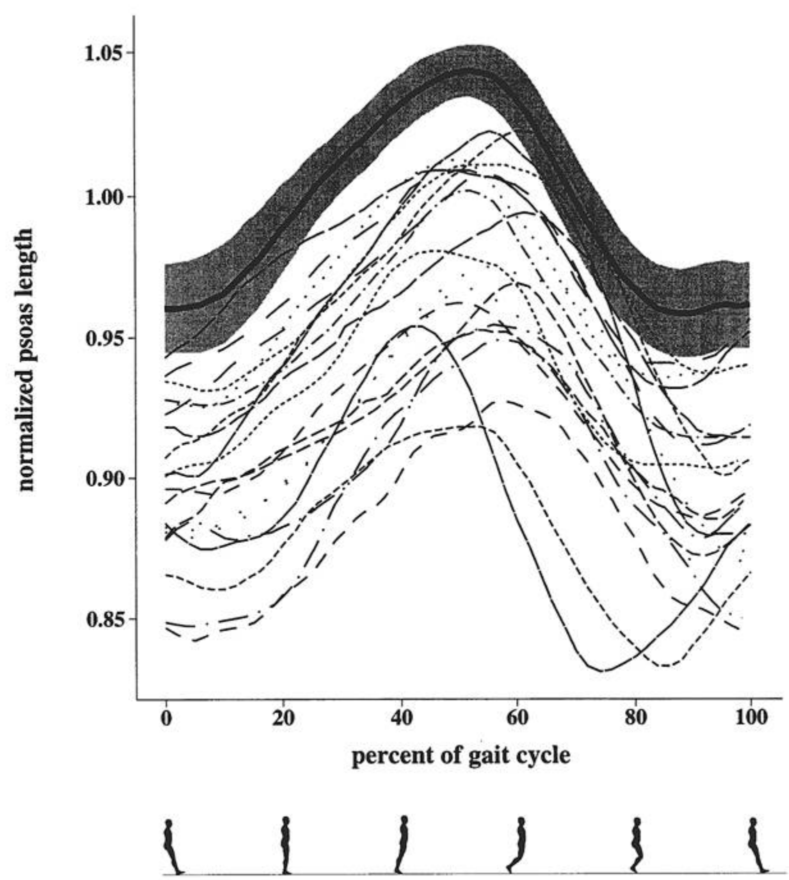

FIG. 4. Normalized psoas length for the 14 subjects with crouch gait (20 limbs with knee flexion of 20° or more) during walking. The averaged curve for the normal subjects (solid dark line) ±1 SD (shaded area) is shown for comparison. Note that all crouched limbs have maximum psoas lengths that are shorter than normal (below the shaded region) by more than 1 SD. Lengths were normalized by the model's psoas length at the anatomical position.

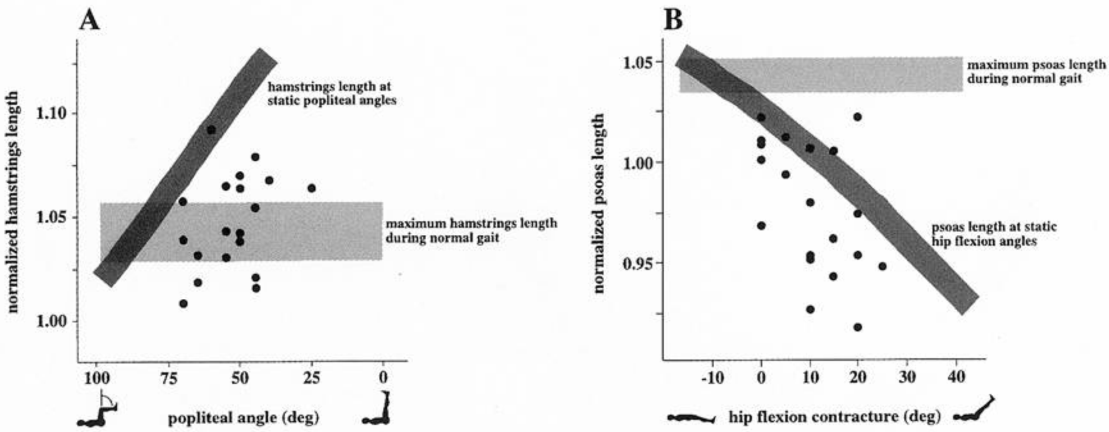

FIG. 5. Comparison of hamstrings and psoas lengths during static muscle tests with maximum lengths during walking. **A:** The dark shaded area shows hamstring length at static limb positions corresponding to a range of popliteal angles, estimated at pelvic tilt angles of 0 ± 5°; the light shaded area indicates the maximum hamstring length ± 1 SD during normal gait; and the circles represent plots of maximum hamstring length (during walking) versus popliteal angle for each of the "crouched" limbs. **B:** The dark shaded area shows psoas length at static limb positions corresponding to a range of hip flexion angles, estimated at pelvic tilt angles of 0 ± 5°; the light shaded area indicates the maximum psoas length ±1 SD during normal gait; and the circles represent plots of maximum psoas length (during walking) versus hip flexion contracture angle for each of the "crouched" limbs. Note that the maximum length of the hamstrings during normal walking, as estimated from the model, is equal to its length at a popliteal angle of about 80°.

hip flexion contracture tests with their maximum lengths during walking similarly revealed that most subjects' psoas muscles were shorter during walking than during their hip flexion contracture test (most circles are below the dark shaded area in Fig. 5B). This finding suggests that spasticity or other dynamic factors—not just static muscle contracture—contribute to the abnormal movement patterns of subjects with crouch gait.

DISCUSSION

In this study, three-dimensional kinematic measurements and a computer model of the musculoskeletal system were used to investigate whether the hamstrings are short in patients with crouch gait, or whether the hamstrings might instead be longer than normal due to the excessive hip flexion that typically accompanies knee flexion in these patients. Our analysis indicates that 11 of the 14 subjects with crouch gait (16 of 20 limbs with knee flexion of 20° or more throughout stance) had hamstrings that were of normal length or longer during walking, despite excessive knee flexion during stance. In contrast, our estimates suggest that the psoas was shorter than normal in all of the subjects with crouch gait. These results are consistent with the findings of Hoffinger et al. (9) and suggest that short hip flexors—not short hamstrings—may be the primary muscle abnormality in most children with crouch gait.

Before discussing the clinical implications of these results, it is important to consider some of the limitations of this study. First, the musculoskeletal model used represents an adult subject, whereas the kinematic data were obtained from children. Hamstrings and psoas lengths were normalized to the length of the muscle at the anatomical position in an effort to account for the differences in size. This normalization scheme assumes, however, that the ratio of a muscle's moment arm to its length at the anatomical position is constant among subjects. Unfortunately, there are insufficient data in the literature to determine how muscle moment arms vary between subjects of different sizes and ages; thus, this assumption cannot currently be tested. Perhaps of greater concern is the fact that the same model was used to analyze muscle lengths for both normal and pathological gait, even though some children with cerebral palsy have bone deformities. If bone deformities substantially alter the moment arms of the muscles about the hip and knee, then our model would not provide accurate estimates of muscle lengths. Certainly, future work is needed to determine how muscle moment arms vary among subjects of different sizes and ages and to understand how bone deformities affect the moment arms of various muscles. Fortunately, our basic conclusions are not sensitive to small errors in calculations of muscle length.

A second limitation of our analysis results from fixing the origin of the psoas in the pelvic reference frame and therefore assuming that changes in psoas length due to rotations at the lower lumbar spine and lumbosacral joint are negligible. We considered fixing the origin of the psoas to a reference frame attached to the sacrum or one of the lumbar vertebrae; however, this would have required knowledge of the relative motion between the spine and the pelvis and hence would have necessitated devising a system capable of accurately measuring the kinematics of the lumbar spine during walking.

Finally, the accuracy of our calculations of muscle

TABLE 2. *Effects of joint motions on muscle lengths during normal walking and crouch gait*

	Range of motion[a] (°)	Change in length[b] (%) Hamstrings	Psoas
Normal walking			
Hip flexion/extension[c]	45 to –16	12.8	13.0
Hip abduction/adduction[d]	–11 to 11	1.7	0.6
Hip internal/external rotation[e]	24 to –14	0.2	0.5
Knee flexion/extension[c]	68 to –3	10.8	—
Crouch gait			
Hip flexion/extension	77 to 0	18.2	19.6
Hip abduction/adduction	–20 to 18	3.0	0.9
Hip internal/external rotation	45 to –10	0.4	0.7
Knee flexion/extension	82 to 20	11.1	—

[a] Range of motion for each degree of freedom during walking is based on the maximum and minimum joint angles for the group of subjects with normal gait and the group with crouch gait (limbs with knee flexion of 20° or more throughout stance).

[b] Changes in muscle-tendon length are expressed as percentages of the muscle-tendon lengths at the anatomical position.

[c] Hip flexion/extension and knee flexion/extension angles are defined in Table 1.

[d] Hip abduction/adduction angle is the angle formed between the long axis of the thigh and a line perpendicular to the line joining the left and right anterior superior iliac spines in the coronal plane. Hip adduction is represented by a positive joint angle and is 90° at the anatomical position.

[e] Hip internal/external rotation angle is the angle formed by a line joining the medial and lateral condyles (as estimated by a thigh wand marker) and a line joining the left and right anterior superior iliac spines in the transverse plane. Internal rotation is represented by a positive joint angle and is 0° at the anatomical position.

length depends on the accuracy of our measurements of joint kinematics. Our analysis indicates that changes in hamstrings and psoas lengths during normal and crouch gait can be attributed primarily to joint rotations in the sagittal plane (Table 2). Because these degrees of freedom undergo relatively large rotations during gait, we are reasonably confident in our kinematic measurements. The accuracy of our measured gait kinematics is also confirmed by the fact that the averaged kinematics for the normal subjects reported here are within 1 SD of data published in the literature (13,14).

The length of a multijoint muscle during movement depends on the angular changes of multiple joints and on the muscle's moment arms about these joints. The most visible sign of crouch gait is flexed knees; however, flexed knees are often accompanied by excessively flexed hips. Flexing the knees shortens the hamstrings but flexing the hips lengthens them. Since the hip extension moment arm of the hamstrings is greater than its knee flexion moment arm, the lengths of the hamstrings are affected more by hip flexion than by knee flexion. In this study, the hamstrings of most subjects with crouch gait appeared to be of normal or longer-than-normal lengths despite excessive knee flexion during stance. This suggests that lengthening the hamstrings may be inappropriate in some patients with crouch gait.

In contrast, all of the subjects with crouch gait had a psoas that was shorter than normal throughout the gait cycle, even though the subjects were admitted to this study on the basis solely of their excessive knee flexion during the stance phase. This suggests that the coupling between the knee and hip, via the hamstrings, may be an important factor contributing to abnormalities of movement. If hip flexion were reduced, then perhaps the knee flexion would improve, since decreasing excessive hip flexion may decrease hamstrings tension and enable knee extension.

Certainly, short hip flexors are not necessarily the only problem in these limbs. Crouch gait could arise from a multitude of other causes including weak plantar flexors, weak hip extensors, external tibial torsion, or difficulties with balance. It is also important to recognize that overlengthening or weakening the hip flexors could cause other problems, as the hip flexors serve to initiate swing and contribute to limb advancement. Thus, aggressive lengthening or tenotomy of the iliopsoas is not recommended. Nevertheless, this study emphasizes the need to consider musculoskeletal geometry and the kinematics of multiple joints when assessing the causes of crouch gait.

Calculation and examination of muscle lengths during walking could aid in surgical decision-making and planning. A computer model of the musculoskeletal system provides information that is not immediately evident from kinematic gait analysis or static muscle tests but which is relevant to muscle lengthening surgeries. Interestingly, we found that the three subjects with crouch gait whose hamstrings were shorter than normal during walking were not distinguishable from the other subjects in this study on the basis of their gait kinematics and static tests. Analysis of our model, in fact, indicated that subjects' measured popliteal angles did not correlate well with their estimated hamstring lengths during crouch gait; on the basis of measured popliteal angles, all subjects had hamstrings of adequate length for normal walking. We believe that the use of musculoskeletal models in conjunction with quantitative motion analysis will help to uncover other factors that contribute to crouch gait and could provide a more effective means of selecting appropriate patients for surgery. Further work to test this hypothesis is needed.

Acknowledgment: This work was supported by the Baxter Foundation, Whitaker Foundation, National Science Foundation Grant BCS-9257229, and National Science Foundation Graduate Research Fellowships (A.A. and R.S.). We are grateful to Steve Vankoski, Claudia Kelp-Lenane, and Tony Weyers for help with the data collection, Abraham Komattu for assistance with computer programming and data analysis, and Norris Carroll, Luciano Dias, and George Rab for the many discussions we have had regarding crouch gait.

REFERENCES

1. Baumann JU, Ruetsch H, Schürmann K: Distal hamstring lengthening in cerebral palsy. *Int Orthop* 3:305-309, 1980
2. Damron TA, Breed AL, Cook T: Diminished knee flexion after hamstring surgery in cerebral palsy patients: prevalence and severity. *J Pediatr Orthop* 13:188-191, 1993
3. Davis RB, Ounpuu S, Tyburski D, Gage JR: A gait analysis data collection and reduction technique. *Hum Mov Sci* 10:575-587, 1991
4. Delp SL, Loan JP, Hoy MG, Zajac FE, Topp EL, Rosen JM: An interactive, graphics-based model of the lower extremity to study orthopaedic surgical procedures. *IEEE Trans Biomed Eng* 37:757-767, 1990
5. DeLuca P, Davis R, Ounpuu S, Walsh J: Distal hamstring lengthening and effects on pelvic tilt in spastic diplegic cerebral palsy. *Dev Med Child Neurol* 36(Suppl 70):10, 1994
6. Dhawlikar SH, Root L, Mann RL: Distal lengthening of the hamstrings in patients who have cerebral palsy. *J Bone Joint Surg [Am]* 74:1385-1391, 1992
7. Gage JR, Fabian D, Hicks R, Tashman S: Pre- and postoperative gait analysis in patients with spastic diplegia: a preliminary report. *J Pediatr Orthop* 4:715-725, 1984
8. Gage JR: Surgical treatment of knee dysfunction in cerebral palsy. *Clin Orthop* 253:45-54, 1990
9. Hoffinger SA, Rab GT, Abou-Ghaida H: Hamstrings in cerebral palsy crouch gait. *J Pediatr Orthop* 13:722-726, 1993
10. Hsu LCS, Li HSY: Distal hamstring elongation in the management of spastic cerebral palsy. *J Pediatr Orthop* 10:378-381, 1990
11. Kadaba MP, Ramakrishnan HK, Wootten ME: Measurement of lower extremity kinematics during level walking. *J Orthop Res* 8:383-392, 1990
12. Nene AV, Evans GA, Patrick JH: Simultaneous multiple operations for spastic diplegia. *J Bone Joint Surg [Br]* 75:488-494, 1993
13. Ounpuu S, Gage JR, Davis RB: Three-dimensional lower extremity joint kinetics in normal pediatric gait. *J Pediatr Orthop* 11:341-349, 1991
14. Perry J: *Gait Analysis: Normal and Pathological Function.* Thorofare, New Jersey, Slack, 1992
15. Rab G: Consensus on crouched gait. In: *The Diplegic Child: Evaluation and Management,* pp 337-339. Ed by MD Sussman. Park Ridge, Illinois, American Academy of Orthopaedic Surgeons, 1992
16. Ray RL, Ehrlich MG: Lateral hamstring transfer and gait improvement in the cerebral palsy patient. *J Bone Joint Surg [Am]* 61:719-723, 1979
17. Thometz J, Simon S, Rosenthal R: The effect on gait of lengthening of the medial hamstrings in cerebral palsy. *J Bone Joint Surg [Am]* 71:345-353, 1989
18. Waters RL, Perry J, McDaniels JM, House K: The relative strength of the hamstrings during hip extension. *J Bone Joint Surg [Am]* 56:1592-1597, 1974
19. Yamaguchi GT, Zajac FE: A planar model of the knee joint to characterize the knee extensor mechanism. *J Biomech* 22:1-10, 1989