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Length Changes of the Hamstrings and Adductors Resulting from Derotational Osteotomies of the Femur

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Summary: Derotational osteotomies of the femur are frequently performed to treat persons with cerebral palsy who walk with excessive internal rotation of the hip. However, whether these procedures stretch or slacken the surrounding muscles appreciably is unknown. Determination of how muscle lengths are altered by derotational osteotomies is difficult because the length changes depend not only on the osteotomy site and the degree of derotation, but also on the anteversion angle of the femur and the rotational position of the hip. We have developed a three-dimensional computer simulation of derotational osteotomies, tested by anatomical experiments, to examine how femoral anteversion, hip internal rotation, and derotation affect the lengths of the semitendinosus, semimembranosus, biceps femoris long head, adductor longus, adductor brevis, and gracilis muscles. Simulation of derotational osteotomies at the intertrochanteric, subtrochanteric, or supracondylar levels decreased the origin-to-insertion lengths of the hamstrings and gracilis in our model by less than 8 mm (1.8%). Hence, the lengths of the hamstrings and gracilis are not likely to be altered substantially by these procedures. The origin-to-insertion lengths of the adductor longus and adductor brevis decreased less than 4 mm (1.9%) with subtrochanteric correction in our model, but the length of adductor brevis increased 8 mm (6.3%) with 60° of intertrochanteric derotation. These muscles are also unlikely to be affected by derotational osteotomies, unless a large degree of intertrochanteric derotation is performed.

Persons with cerebral palsy who have increased anteversion of the femur frequently walk with excessive internal rotation of the hip. Excessive internal rotation causes tripping and may lead to lateral patellar subluxation or external tibial torsion (16,18). Hence, derotational osteotomies of the femur are often performed in an effort to improve the rotational alignment of the limb (4,18). This procedure involves division of the femur perpendicular to the femoral shaft and external rotation of the distal limb segment such that the knee and foot are aligned with the direction of forward progression.

Whether derotational osteotomies stretch or slacken the surrounding muscles appreciably is unknown. This information is important for surgical planning for three reasons. First, if a muscle's origin-to-insertion length is decreased substantially as a result of surgery, then the muscle's active force-generating capacity may be compromised. Alternatively, if derotation of the femur stretches a muscle, then the muscle may generate excessive passive force or its spastic response may be exaggerated. In such cases, it has been suggested that the muscle may need to be lengthened surgically to prevent internal rotation of the hip in the short term or recurrence of excessive anteversion in the long term (8). Finally, if derotation alters the lengths of the muscles targeted for concomitant soft-tissue procedures, then these length changes may need to be considered when estimating the amount of surgical lengthening needed to improve function. Because persons with cerebral palsy often walk with increased knee flexion and hip adduction in addition to excessive internal rotation, concomitant lengthenings of the hamstrings and adductors are commonly performed.

Currently, there is no consensus as to how derotational osteotomies affect the lengths of the hamstrings or adductors. Gage has suggested that derotation increases the origin-to-insertion distances of the medial hamstrings and decreases the origin-to-insertion distance of the lateral hamstring (8). In contrast, Rab has reported that the medial hamstrings are not stretched appreciably following external rotation of the femur, but the adductor longus may be tightened as much as 10% (14).

Analysis of muscle length changes with derotation is complex. Derotation of the femur can be performed at the intertrochanteric, subtrochanteric, or supracon-

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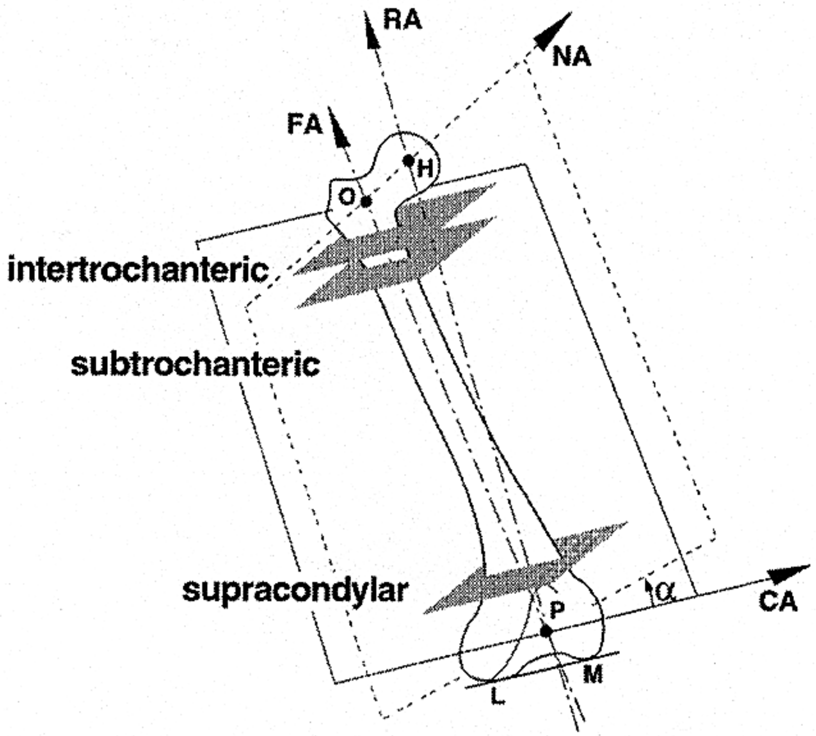

FIG. 1. Description of femoral geometry. H is the center of the femoral head, O is the center of the femoral neck, P is the attachment of the posterior cruciate ligament, and L and M are the posterior aspects of the lateral and medial condyles, respectively. Anteversion (α) is the angle between the plane of the neck axis (NA) and the plane of the condylar axis (CA). Hip rotation occurs about the axis (RA), which is defined by the point H and the midpoint of a line joining the medial and lateral condyles. Derotation occurs about an axis parallel to the femoral shaft axis (FA) but located at the centroid of the intertrochanteric, subtrochanteric, or supracondylar cutting planes. (Adapted with permission from Murphy SB, Simon SR, Kijewski PK, Wilkinson RH, Griscom NT: Femoral anteversion. *J Bone Joint Surg [Am]* 69:1171, 1987.)

dylar levels, and these procedures alter the femoral geometry and muscle lines of action in different ways. In addition, the anteversion angle of the femur, the rotational position of the hip, and the amount of femoral derotation all potentially influence muscle lengths, and their effects are not entirely independent. The length change of a muscle with derotation depends on the distance between the muscle line of action and the axis of derotation; the muscle line of action, in turn, depends on the anteversion angle of the femur and the rotational position of the hip (Fig. 1). These length changes are difficult to assess on the basis of radiographic measurements because the planar projections do not accurately characterize the three-dimensional musculoskeletal geometry.

The purpose of our study was to determine how surgical correction of anteversion deformities affects muscle lengths. We have developed a three-dimensional computer simulation of derotational osteotomies to examine how femoral anteversion, hip internal rotation, and external rotation of the distal limb segment affect the lengths of the muscles about the hip. We focused on the semitendinosus, semimembranosus, biceps femoris long head, adductor longus, adductor brevis, and gracilis because these muscles are often lengthened surgically to treat gait abnormalities in persons with cerebral palsy.

METHODS

A computer model of the lower extremity (2,6) was used to estimate the length changes of the hamstrings and adductor muscles for a range of anteversion deformities and the corresponding corrective derotational osteotomy procedures. We simulated derotational osteotomies at the intertrochanteric, subtrochanteric, and supracondylar levels. The length changes of the hamstrings predicted by the model for supracondylar derotation were compared with the length changes determined experimentally. Osteotomies were performed on two anatomical specimens, and the origin-to-insertion paths of the muscles were digitized for a 0-60° range of derotation angles.

Description of the Computer Model

Our computer model characterizes the three-dimensional bone geometry, the paths of the hamstrings and adductors, and the kinematics of the hip for a nominal adult subject. The hip was assumed to be a ball-and-socket joint, and each muscle was represented as a series of line segments as specified by Delp et al. (6).

Anteversion of the femur was defined as the angle between the plane of the femoral neck axis and the plane of the condylar axis (Fig. 1). Our undeformed model has an anteversion angle of 20°. We altered the anteversion angle of the model to represent a range of deformities by rotating the bone vertices that comprise the femoral head and neck about the femoral shaft axis. We assumed that the deformity takes place entirely within the femoral neck and not along the femoral shaft. Derotational osteotomies at the intertrochanteric, subtrochanteric, and supracondylar levels were simulated by cutting the femur perpendicular to the femoral shaft axis (Fig. 1). The distal segment was externally rotated about an axis oriented parallel to the femoral shaft axis and located at the centroid of the bone at the cutting plane.

TABLE 1. *Skeletal dimensions for the two specimens and the model*

Skeletal dimension	Specimen 1	Specimen 2	Model
Maximum anterior-posterior dimension of lateral condyle (mm)	66	59	58
Maximum medial-lateral dimension of distal femur (mm)	80	78	80
Superior-inferior dimension from greater trochanter to lateral epicondyle (mm)	374	343	379
Anteversion angle[a] (°)	10	5	0-60

[a] A tabletop measurement of femoral anteversion (11) was taken for each specimen.

Verification of Length Changes with Derotation

An anatomical study was performed on two fresh-frozen lower limb specimens to determine if the muscle paths in our model reasonably estimated the length changes of the hamstrings with derotation. We wondered if fascial connections might constrain the hamstrings proximally and if this would cause greater length changes with derotation than predicted by our model. To investigate this issue, we manually digitized the paths of the hamstrings in the two anatomical specimens for supracondylar derotation angles of 0-60°. We performed the osteotomies at the supracondylar level because an analysis of our model suggested that the addition of a constraining point in the proximal part of each muscle path would most alter the length changes for supracondylar derotation. The adductors were not included in the anatomical study, because their paths were well represented by straight lines extending from origin to insertion.

Each specimen was prepared by removing the skin while leaving the fascia and surrounding musculature intact. The hip was fused at 0° of rotation, adduction, and flexion, and the knee was constrained to full extension. The specimen was then mounted in an Ilizarov apparatus (5) consisting of two sets of concentric rings connected by threaded rods (Fig. 2). A supracondylar osteotomy was performed with a lateral approach while the apparatus maintained the relative positions of the bone segments. The cutting plane for the osteotomy was oriented perpendicular to the femoral shaft axis and was located approximately 2 cm proximal to the distal femoral physis (18). Derotation occurred at the distal set of rings and was accomplished by rotating the outer ring connected to the distal segment with respect to the inner ring attached to the proximal segment.

A three-dimensional localizer (Flashpoint 5000; Image Guided Technology, Boulder, CO, U.S.A.) was used to track the coordinate locations of small infrared emitters located on a digitizing probe and on two rigid plastic frames (Fig. 2). One frame was mounted near the pubic symphysis, and the other was mounted on the tibia distal to the hamstring insertions. The paths of the hamstrings were carefully marked with use of small fishhooks that were straightened and inserted into the muscles. These markers were manually digitized for the three muscle paths in 10° increments of external derotation from 0 to 60°. Our digitized points were repeatable within 0.7 ± 0.2 mm on average, with a maximum repeatability error of 2.5 mm. The muscle paths were digitized three times at each increment of derotation. The length of each muscle was calculated as the sum of the distances between the averaged muscle path markers. The derotation angle was calculated based on the relative orientation of the distal emitter triad with respect to the original orientation of this triad at 0° of derotation.

The muscle attachment sites and 18 landmarks on the pelvis, femur, and tibia were digitized to facilitate registration and display of the digitized muscle paths relative to the bones of our computer model. Key dimensions of the specimens and our lower limb model are given in Table 1.

The length changes of the hamstrings measured experimentally compared favorably with the length changes predicted by our computer model (Fig. 3). The biceps femoris long head shortened more in the simulation than during the experiment for either specimen. This difference may arise from the relatively simple muscle path representation in the model or because no mechanism exists to take up slack in cadaveric muscle. Examination of the digitized hamstring paths on a computer graphics display revealed that, in general, the distal portion of each muscle moved further with derotation than did the proximal portion. However, this did not cause the overall length changes to deviate substantially from the length changes calculated with the muscle paths in our computer

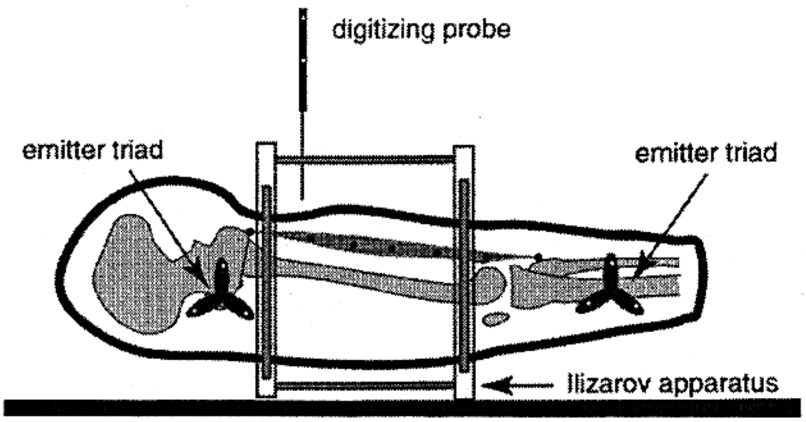

FIG. 2. Experimental set-up. The specimen was secured in an Ilizarov apparatus with use of six cortical half-pins. One set of rings was placed in the region of the proximal femur, and the other was placed near the supracondylar cutting plane. We attempted to position the femur with the shaft axis at the center of the Ilizarov rings to produce pure rotation. Frames housing emitter triads were attached to the pubic symphysis and to the tibia distal to the hamstring insertions. The emitters on the two frames and on a digitizing probe were tracked by infrared cameras. The paths of the semitendinosus, semimembranosus, and biceps femoris long head were digitized with use of the probe. The coordinate systems established by the emitter triads were used to calculate the derotation angle.

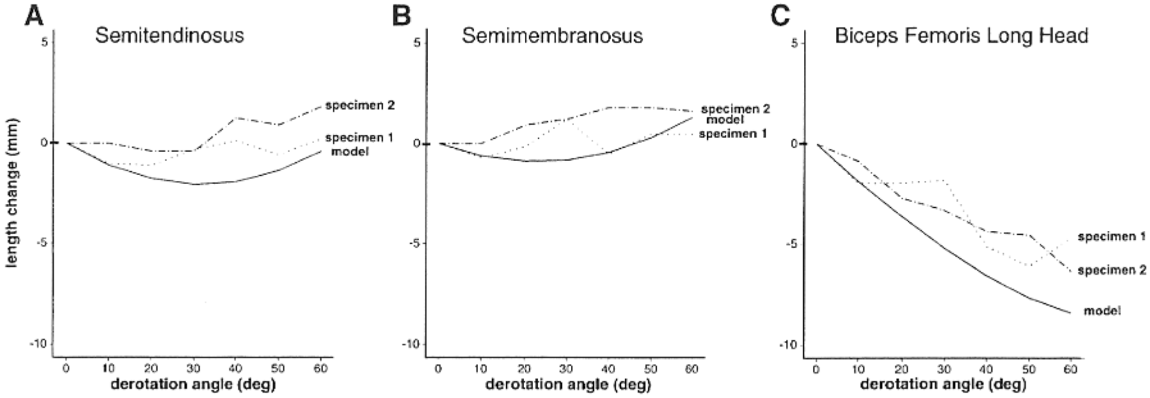

FIG. 3. Length change versus supracondylar derotation angle for the semitendinosus (**A**), semimembranosus (**B**), and biceps femoris long head (**C**) measured experimentally and calculated with the computer model with 10° of anteversion and 0° of hip internal rotation.

simulation. For this reason, we decided to represent both the hamstrings and adductors as a series of straight-line segments in our computer simulation.

Simulation of Derotational Osteotomy Procedures

We simulated corrective derotational osteotomy procedures at the intertrochanteric, subtrochanteric, and supracondylar levels using equal amounts of anteversion, hip internal rotation, and derotation (Fig. 4). We first altered the anteversion angle of the model from 0 to 60° (Fig. 4B). To "correct" the deformity at each anteversion angle and at each level, we (a) internally rotated the hip such that the neck axis was in the coronal plane (Fig. 4C), and (b) externally rotated the segment of the femur distal to the cutting plane such that the condylar axis was coplanar with the neck axis (Fig. 4D). These simulations resulted in corrected femurs with 0° of anteversion. Hip flexion, hip adduction, and knee flexion angles were kept constant at angles corresponding to the anatomical position.

Planning of derotational osteotomies, particularly with respect to the amount of derotation, may be based on a number of different factors. Some surgeons derotate the femur to an anteversion angle of 0°, as has been described, which realigns the knee to the anatomical position with the greater trochanter in the most lateral position. Others base the degree of derotation on the patient's abnormal hip rotation or foot progression angles measured during gait analysis (9) or on the patient's passive range of hip rotation measured on clinical examination (18,19). For this reason, we performed additional simulations to examine the independent effects of anteversion, hip rotation, and derotation on the muscle lengths. We also performed a sensitivity study to determine whether the length changes with correction varied with hip or knee flexion.

RESULTS

The simulated osteotomy procedures altered the lengths of the hamstrings and gracilis less than 8 mm (Fig. 5A and B). This corresponds to a 1.7-1.8% change from the anteverted lengths at the anatomical position. The maximum length changes occurred for 60° of anteversion corrected by 60° of hip internal rotation and 60° of supracondylar derotation. Intertrochanteric and subtrochanteric osteotomies showed the same trends as supracondylar correction but with smaller length changes. The origin-to-insertion lengths of the hamstrings and gracilis decreased in these simulations.

The length changes of the hamstrings with hip internal rotation and derotation were relatively insensitive to the degree of anteversion, hip flexion, or knee flexion in our simulations. In general, the medial and

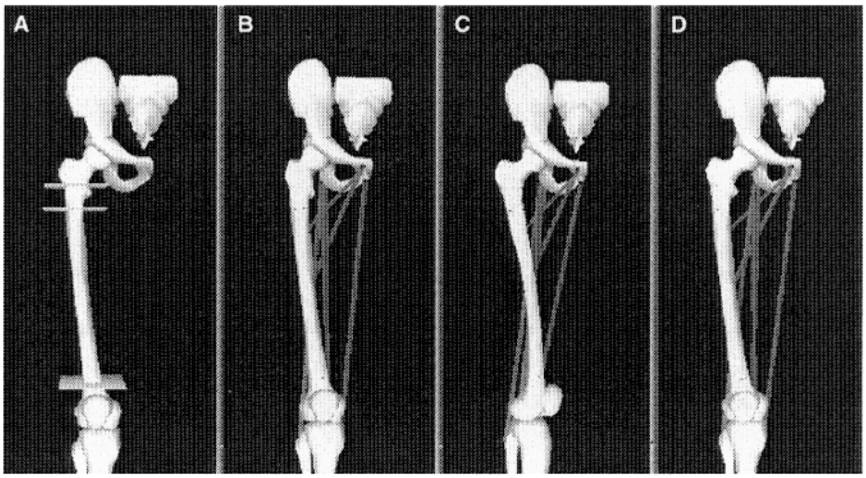

FIG. 4. Derotational osteotomy simulation. The locations of the intertrochanteric, subtrochanteric, and supracondylar cutting planes are displayed on the undeformed lower extremity model (**A**). For illustration, a femur with 50° of anteversion (**B**) is corrected by internal rotation of the hip, resulting in an inward position of the patella (**C**), and intertochanteric derotation of the distal segment, producing a realigned limb (**D**). The muscle insertions on the distal limb segment move with the bones; hence, the muscle lines of action are potentially altered as a result of these rotations.

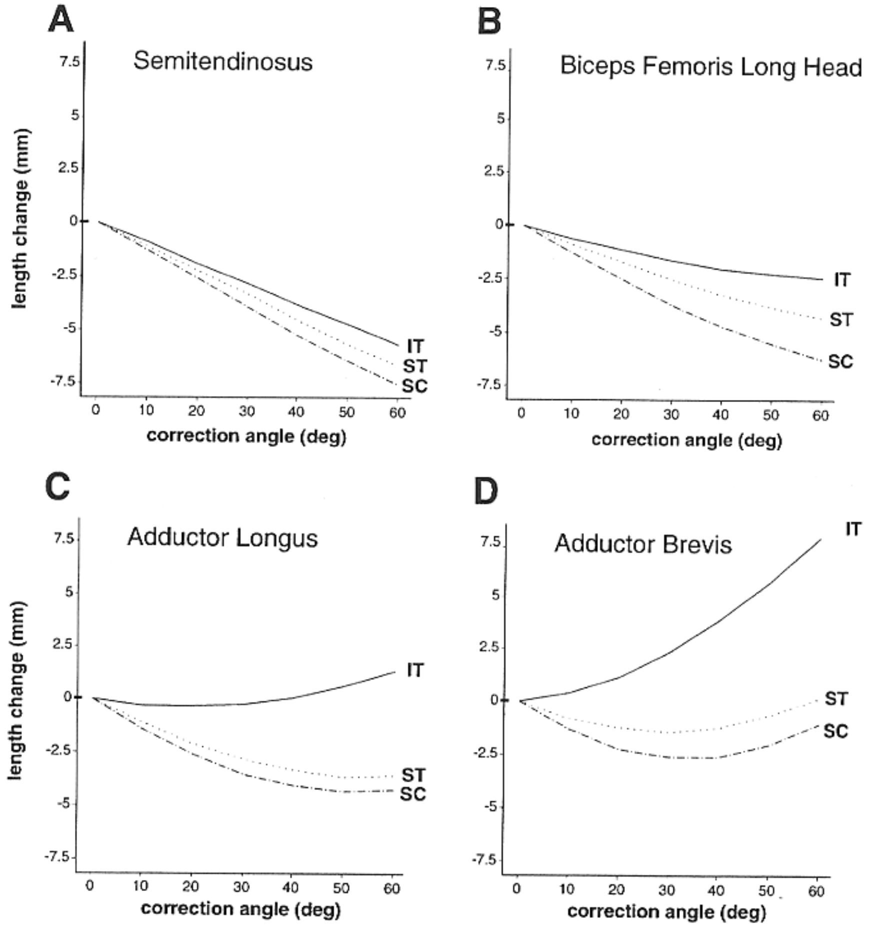

FIG. 5. Changes in length with correction angle for the semitendinosus (**A**), biceps femoris long head (**B**), adductor longus (**C**), and adductor brevis (**D**) at the intertrochanteric (IT), subtrochanteric (ST), and supracondylar (SC) levels. All length changes were measured from the anteverted state. Length changes for the semimembranosus and gracilis were similar to those for the semitendinosus.

lateral hamstrings were stretched by internal rotation of the hip and slackened by external rotation of the distal limb segment. The amount of shortening with derotation was influenced by the amount of hip internal rotation. With hip rotation of 0°, derotation shortened the hamstrings by about 1 mm, but with hip rotation of 60°, derotation shortened these muscles as much as 1 cm. The angle of anteversion had only a minimal influence on the lengths of the hamstrings in our model, in agreement with Schutte et al. (17). Hip or knee flexion of 90° altered the length changes of the hamstrings and gracilis with correction at most 2 mm from the length changes reported at the anatomical position.

The adductor longus and adductor brevis were slightly shortened by correction at the subtrochanteric or supracondylar levels, but were lengthened by large degrees of correction at the intertrochanteric level (Fig. 5C and D). The maximum length change of the adductor longus occurred with 60° of supracondylar correction, which decreased the length of the muscle by 4 mm (1.9%) in our model. The maximum length change of the adductor brevis was 8 mm (6.3%), an increase that occurred with 60° of intertrochanteric correction. The adductor longus also increased in length with intertrochanteric correction but only by 1.4 mm (0.7%). Both the adductor longus and adductor brevis insert proximal to the supracondylar cutting plane. Therefore, their length changes for supracondylar correction depended only on the internal rotation of the hip in the procedure (i.e., internal rotation of the hip such that the femoral neck axis is in the coronal plane, Fig. 4C) and not on the external rotation of the distal segment.

The length changes of the adductor longus and adductor brevis with derotation remained relatively constant for a range of anteversion and hip rotation angles but increased slightly with hip flexion. These muscles were, in general, slackened by internal rotation of the hip and stretched by external rotation of the distal segment at the subtrochanteric and intertrochanteric levels. The adductor longus and adductor brevis lengthened 2 and 4 mm more, respectively, when correction was simulated with the hip flexed to 45°.

DISCUSSION

It has been postulated that derotational osteotomies of the femur increase the origin-to-insertion lengths of the medial hamstrings (8). Our computer simulations suggest that derotational osteotomies at any of the three levels do not appreciably lengthen the medial hamstrings or biceps femoris long head but, instead, may shorten these muscles a few millimeters. To gauge whether these length changes are significant, we calculated the changes in hamstring lengths for a 30° decrease in popliteal angle, a typical improvement that might result from hamstring lengthening surgery. Popliteal angle measures the degree to which the knee can be passively extended with the hip flexed 90° (4,10). Several authors have reported average preoperative popliteal angles near 60° and average postoperative popliteal angles near 30° following surgical lengthening of the hamstrings in persons with cerebral palsy (3,7,12). Using our computer model, we found that a decrease in popliteal angle from 60 to 30° increased the origin-to-insertion lengths of the hamstrings by about 2.5 cm. This is three times larger than the length changes produced for any combination of anteversion, internal hip rotation, and derotation in our simulations. Hence, hamstring lengthenings performed prior or concurrent to a derotational osteotomy are not likely to be affected substantially by the bone correction.

The origin-to-insertion lengths of the adductor longus and adductor brevis increased with intertrochanteric correction in our simulations; however, the length changes were less than those predicted by Rab (14). For subtrochanteric correction, the adductor longus and adductor brevis were shortened slightly. We compared these length changes with the length changes corresponding to a 15° increase in passive range of abduction that might result from an adductor tenotomy (15). We found that an increase in abduction from 15 to 30° in our computer simulation lengthened the adductor longus and adductor brevis by 1.8 cm. This length change is 10 times the maximum length change for the adductor longus and more than twice that for the adductor brevis in our osteotomy simulations. Therefore, the adductor longus is not likely to be stretched appreciably by derotational osteotomy. The adductor brevis may be stretched, but only when a large degree of intertrochanteric derotation is performed.

It is important to keep in mind the limitations of this study. We have used a computer model of an adult-sized subject to estimate the length changes of muscles resulting from derotational osteotomies of the femur. However, surgeries to correct rotational deformities are frequently performed on children. Currently little information is available in the literature describing how muscle paths vary with size and age. Although we believe that the trends shown in our results are representative of the muscle length changes that occur in children, more information is needed about pediatric bone geometry and muscle paths to determine the accuracy of predictions based on an adult-sized model.

There are also limitations inherent to our representation of anteversion deformities. The actual distribution of the torsion within the neck and shaft of the femur in persons with cerebral palsy is unknown. In this study, we assumed that the deformity occurs within the femoral neck and not along the femoral shaft. The hamstrings do not insert on the femur, so the descriptions of these muscles are insensitive to our method of representing anteversion. If some of the torsion does occur along the femoral shaft, the results for the adductors may be affected.

The length changes of the muscles with intertrochanteric, subtrochanteric, and supracondylar derotation depend on the locations of the cutting planes used in our simulations. The locations of the intertrochanteric and subtrochanteric cutting planes were based on the position of the lesser trochanter. The location of the supracondylar cutting plane, however, was not as well defined. To assess the sensitivity of the results to the position of the cutting plane, we moved the supracondylar cutting plane superiorly by as much as 6 cm. This changed the derotated lengths of the medial hamstrings by 0.1 mm, the length of the biceps femoris long head by 0.4 mm, and the length of the gracilis by 0.8 mm. It was concluded that the length changes due to derotation at the supracondylar level are relatively insensitive to variations in the location of the cutting plane.

We simulated ideal procedures with the derotation axes parallel to the femoral shaft axis resulting in pure rotation and no translation of the bone segments. Actual surgery may involve translations of the bone fragments or rotational deviations that could stretch or slacken the muscles. To bound the effects of translational displacements, we translated the derotated distal segment by one-half of the bone radius at each osteotomy site. Anterior-posterior and medial-lateral translations at all three levels affected the resulting lengths of the hamstrings by less than 1 mm. The adductors were influenced most by anterior-posterior translations; however, the lengths changed at most 5 mm from the lengths reported without any translation. We also examined the effects of varus/valgus and flexion/extension rotations on the results of the simulated osteotomy procedures. We found that a 10° deviation in the orientation of the cutting plane could more than double the maximum length changes from those reported with the cutting plane perpendicular to the femoral shaft axis. Therefore, a 10° variation in the orientation of the cutting plane at any level is likely to produce greater length changes than those estimated in our simulations.

We have not attempted to estimate postoperative length changes of the muscles during functional tasks such as walking. This would require knowledge of whether patients hold their hips in the same rotational positions postoperatively as they did preoperatively during walking or whether the patients adopt new hip positions following the realignment of their limbs. For example, derotation at the supracondylar level will not affect the lengths of the adductor longus or adductor brevis if the rotational position of the femoral head with respect to the pelvis is not changed. However, if derotation acts proximally to reposition the femoral head in its hip rotation arc during walking, then derotation at any of the levels will alter the functional lengths of these muscles. Aiona et al. (1) and Orendurff et al. (13) studied the hip rotation patterns of 10 patients with cerebral palsy following isolated derotational osteotomies of the femur and observed that hip rotation patterns during walking changed less than the passive ranges of hip rotation measured on clinical examination. This suggests that a portion of the derotation was realized proximally in these patients. Additional studies that quantify the postoperative changes in patients' anteversion angles and hip rotation angles during walking are needed to understand how the functional lengths of the muscles are altered by these procedures. Currently, the results of our study are limited to the effect of the surgery and cannot be extended to estimate postoperative hip rotation during walking or functional outcomes of patients following surgery.

Despite these limitations, our three-dimensional computer simulation can provide new insight. Gage (8) stated that when a derotational osteotomy is performed, the insertions of the medial hamstrings are rotated laterally and anteriorly while the insertion of the lateral hamstring is rotated posteriorly and medially. He suggested that this will separate the attachments of the medial hamstrings, increasing the tension in these muscles, while concurrently decreasing the origin-to-insertion distance and tension in the lateral hamstring. This statement is accurate if the medial hamstring insertions are anterior to their origins prior to external derotation. However, with excessive anteversion of the femur and internal rotation of the hip, the insertions of the medial hamstrings are slightly lateral and posterior to their origins prior to derotation. In this case, external derotation of the femur moves the insertions medially and anteriorly and hence more directly inferior to their origins, effectively decreasing the origin-to-insertion distance by a small amount. Derotation moves the insertion of the lateral hamstring posteriorly and medially as suggested by Gage (8); this decreases the origin-to-insertion distance and reduces the tension on this muscle. This analysis demonstrates the complexity of the musculoskeletal geometry and the need for three-dimensional analysis of orthopaedic surgical corrections.

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