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Preserving Plantar Flexion Strength After Surgical Treatment for Contracture of the Triceps Surae: A Computer Simulation Study

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Summary: Contractures of the triceps surae commonly are treated by surgical lengthening of the gastrocnemius aponeurosis or the Achilles tendon. Although these procedures generally relieve contractures, patients sometimes are left with dramatically decreased plantar flexion strength (i.e., decreased capacity to generate plantar flexion moment). The purpose of this study was to examine the trade-off between restoring range of motion and maintaining plantar flexion strength after surgical treatment for contracture of the triceps surae. A computer model representing the normal moment-generating characteristics of the triceps surae was altered to represent two conditions: isolated contracture of the gastrocnemius and contracture of both the gastrocnemius and the soleus. The effects of lengthening the gastrocnemius aponeurosis and the Achilles tendon were simulated for each condition. The simulations showed that nearly normal moment-generating characteristics could be restored when isolated gastrocnemius contracture was treated with lengthening of the gastrocnemius aponeurosis. However, when isolated gastrocnemius contracture was treated with lengthening of the Achilles tendon, the moment-generating capacity of the plantar flexors decreased greatly. This suggests that lengthening of the Achilles tendon should be avoided in persons with isolated gastrocnemius contracture. Our simulations also suggest that neither lengthening of the gastrocnemius aponeurosis nor lengthening of the Achilles tendon by itself is an effective treatment for combined contracture of the gastrocnemius and soleus. Lengthening the gastrocnemius aponeurosis did not decrease the excessive passive moment developed by the contracted soleus. Lengthening the Achilles tendon restored the normal passive range of motion but substantially decreased the active force-generating capacity of the muscles. Our simulations indicate that independent lengthening of the contracted gastrocnemius and soleus, rather than lengthening of their common tendon, accounts for differences in the architecture of these muscles and may be a more effective means to restore range of motion and maintain plantar flexion strength when combined contracture of the gastrocnemius and soleus is present.

Ankle equinus, one of the most common deformities in cerebral palsy, can be caused by shortening of the fibers (contracture) of the triceps surae (2,7,9,12). Isolated gastrocnemius contracture or combined contracture of the gastrocnemius and soleus may be present. When isolated gastrocnemius contracture is present, the ankle can be dorsiflexed with the knee flexed but not with the knee extended. If both the gastrocnemius and the soleus are contracted, there is resistance to dorsiflexion even when the knee is flexed because of excessive pas-

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sive force developed by the contracted soleus (2).

Gastrocnemius aponeurosis lengthening and Achilles tendon lengthening are commonly used to treat equinus deformities, and several clinical studies have evaluated the effectiveness of these procedures (5,9,11,12,15,17). When only the gastrocnemius is contracted, lengthening the gastrocnemius aponeurosis usually is effective in restoring the normal range of ankle motion and maintaining the moment-generating capacity of the plantar flexors (plantar flexion strength). However, lengthening of the Achilles tendon, a procedure commonly used to treat combined contracture of the gastrocnemius and soleus, is less effective. If the Achilles tendon is lengthened too much, the active force-generating capacity of the muscles can be greatly reduced, resulting in disabling muscle weakness. By contrast, if the Achilles tendon is not lengthened enough, passive plantar flexion moment continues to cause ankle equinus after surgery.

The moment generated by a muscle is the product of its force and moment arm. Passive moment is generated when muscle is inactive and the muscle fibers are stretched beyond their resting lengths. Active moment is generated when muscle is excited by a motoneuron and calcium-mediated binding of actin to myosin causes muscle force to develop; the active force developed depends on the extent of the actin-myosin overlap (8). Operations performed to correct ankle equinus aim to restore the range of ankle motion by decreasing excessive passive moment while maintaining the active moment-generating capacity of the muscles.

Muscle architecture (the lengths and arrangement of muscle fibers in a muscle-tendon complex) can influence the effects of tendon lengthening on muscle force production (4). Since the gastrocnemius and soleus have different architectures, one would expect these muscles to respond differently to tendon lengthening. These effects are difficult to quantify in clinical studies, however, because individual muscle forces cannot be measured without invasive techniques. Therefore, we developed a computer model to examine how tendon lengthenings affect the force-generating and moment-generating characteristics of the triceps surae.

The goals of this study were to analyze how lengthening the gastrocnemius aponeurosis and the Achilles tendon affects passive and active moments about the ankle and to determine an effective means to restore normal moment-generating characteristics after muscle contracture. We first developed a computer model that represents the normal moment-generating characteristics of the major muscles crossing posterior to the ankle. The model then was altered to represent two conditions: isolated contracture of the gastrocnemius and contracture of both the gastrocnemius and the soleus. The effects of gastrocnemius aponeurosis and Achilles tendon lengthening were simulated for each condition. The theoretical effectiveness of the simulated procedures was evaluated on the basis of their ability to restore normal passive and active moment-generating characteristics about the ankle.

METHODS

The Normal Model

A computer model was developed that included representations of the soleus, medial and lateral gastrocnemius, tibialis posterior, peroneus longus, peroneus brevis, flexor hallucis longus, and flexor digitorum longus (3). This model consisted of three-dimensional representations of the bones and muscle-tendon paths, kinematic descriptions of the ankle and knee, and a biomechanical model of each muscle-tendon complex (Fig. 1).

The length-tension characteristic of each muscle-tendon complex was derived by scaling a Hill-type

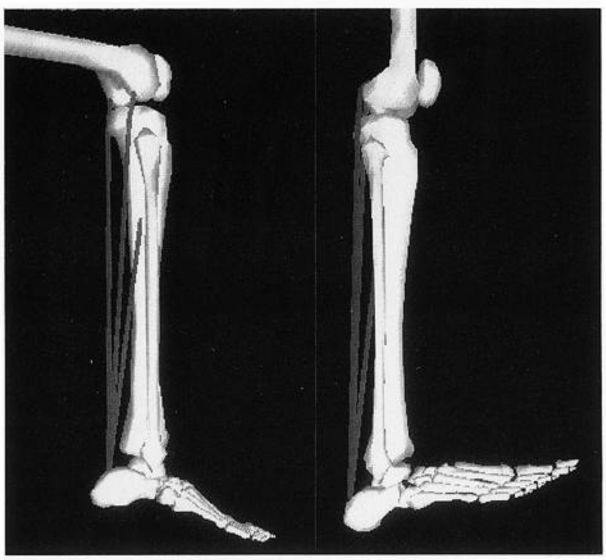

FIG. 1. Three-dimensional representation of the musculotendinoskeletal geometry used to calculate the lengths and moment arms of the muscles. The left frame shows a posterolateral view of the medial and lateral gastrocnemius and the soleus with the knee flexed and the ankle plantar flexed (the position with the shortest muscle-tendon lengths). The right frame shows the model with the knee extended and the ankle dorsiflexed. When the knee is extended, the path of the gastrocnemius is constrained to wrap over the distal femur.

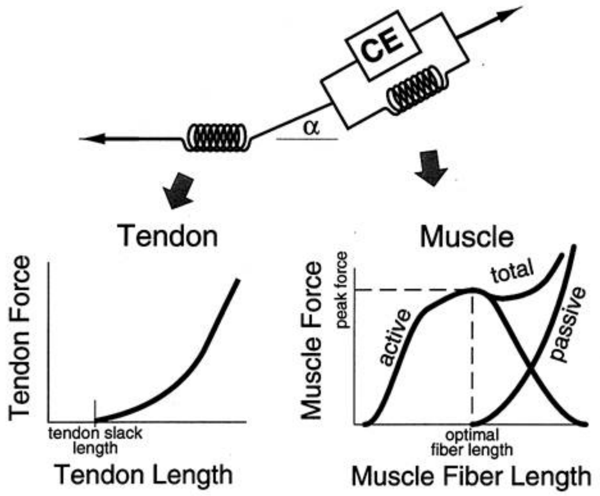

FIG. 2. Muscle-tendon model. The length-tension property of muscle is represented by an active contractile element (CE) in parallel with a passive elastic element. Total isometric muscle force is assumed to be the sum of muscle force when it is inactive (passive) and when it is maximally excited (active). The muscle is in series with the tendon, which is represented by a nonlinear spring. The pennation angle (α) is the angle between tendon and muscle fibers. Tendon slack length is the length of tendon at which force initially develops during tendon stretch. This model was scaled to represent each muscle by specification of the muscle's peak force, optimal fiber length, tendon slack length, and pennation angle.

model of muscle and tendon (28), as described previously (3). Four parameters scale the muscle-tendon model to represent a specific muscle-tendon complex (Fig. 2). The four parameters—peak isometric force, optimal muscle fiber length, tendon slack length, and pennation angle—were derived from data collected in anatomical studies. (6,25) Peak isometric force is based on the physiologic cross-sectional area of the muscle. Optimal muscle-fiber length is the fiber length at which active muscle force peaks. Tendon slack length is the length of tendon beyond which force develops on elongation. Pennation angle specifies the angle between the tendon and the muscle fibers when the fibers are at the optimal length.

Passive moment was calculated as the product of moment arm and passive muscle force. Total moment was calculated as the product of moment arm and active plus passive muscle forces. To study how tendon lengthening affects the moment-generating capacity of the plantar flexors, muscles were assumed to be at their maximum level of activation when the total moment was calculated. Thus, the total moment represents the maximum isometric moment-generating capability of the muscles, which is a measure of muscle strength. Passive and total moments calculated with the model were compared with experimentally measured plantar flexion moments to test the accuracy of the normal model (see Results section).

Simulation of Muscle Contracture

Ziv et al. (29) reported that muscle fiber lengths were reduced 45% in spastic mice, whereas bone growth was relatively normal. Clinical studies of children with cerebral palsy also have suggested that muscle contractures result from a decreased number of sarcomeres. Light and electron microscopy of muscle biopsies taken from children with cerebral palsy have shown that the number of sarcomeres decreases but the muscle and connective tissue is otherwise normal (22,23).

On the basis of the data of Ziv et al. (29), we characterized isolated gastrocnemius contracture by decreasing the optimal fiber lengths of the medial and lateral gastrocnemius by 45%, while the fiber length of the soleus was not altered. To characterize contracture of the entire triceps surae, the optimal fiber lengths of the gastrocnemius and the soleus were reduced by 45%. In the computer model, the decrease in fiber lengths resulted in a substantial increase in passive moment about the ankle. With the knee extended, the computer model had an onset of passive moment at 30° of plantar flexion for the isolated gastrocnemius contracture and combined contracture of the gastrocnemius and soleus. This is consistent with the observations of Tardieu and Tardieu (23), who reported that the average onset of passive moment occurs at approximately 30° of plantar flexion in children with equinus when the knee is extended. The computer model also showed that the passive moment developed by the triceps surae with isolated gastrocnemius contracture was approximately normal when the knee was flexed. However, simulated contracture of both the gastrocnemius and the soleus resulted in excessive passive moment, even with 90° of knee flexion. Thus, the representations of muscle contracture are consistent with clinical observations (2).

Simulation of Gastrocnemius Aponeurosis Lengthening

Procedures for lengthening the gastrocnemius aponeurosis have been described by Strayer (19) and Baker (1). In the Strayer method, a transverse tenotomy is made in the gastrocnemius aponeurosis proximal to its junction with the common tendon of the soleus. The ankle is dorsiflexed, and the aponeurosis is sutured in the new position. The Baker modification (1) of the Strayer technique uses a tongue-in-groove incision in the gastrocnemius aponeurosis. The gastrocnemius aponeurosis is dissected off the soleus, the foot is dorsiflexed, and the aponeurosis is sutured in the new position.

Since the site of lengthening is distal to the fibers of the gastrocnemius but proximal to the juncture of the gastrocnemius and soleus tendons, gastrocnemius aponeurosis lengthening was simulated by elongating the tendon of the gastrocnemius while the soleus tendon remained unaltered. The tendon of the contracted gastrocnemius was lengthened until the onset of passive moment occurred at 10° of plantar flexion with the knee in full extension, representing a conservative lengthening of the gastrocnemius aponeurosis. The sum of the passive moments developed by the contracted gastrocnemius and the normal soleus was used to determine the proper amount of lengthening to simulate treatment of isolated gastrocnemius contracture. The elongation for contracture of both the gastrocnemius and the soleus was determined from the sum of the passive moments developed by the contracted gastrocnemius and the contracted soleus. In both cases, a 2 cm elongation of the gastrocnemius aponeurosis produced an onset of passive moment at 10° of plantar flexion with the knee in extension.

Simulation of Achilles Tendon Lengthening

Lengthening of the Achilles tendon usually is performed with use of one of the sliding techniques proposed by White (24) or Hoke (2). Both techniques lengthen the tendon distal to the fibers of the gastrocnemius and soleus. To simulate lengthening of the Achilles tendon, the lengths of the gastrocnemius and soleus tendons were increased. The amount of tendon elongation needed to create an onset of passive moment at 10° of plantar flexion with the knee in extension was determined with use of the computer model. This represented a conservative lengthening of the Achilles tendon. The amount of tendon lengthening for isolated gastrocnemius contracture was determined from the sum of the passive moments developed by the contracted gastrocnemius and the normal soleus with the knee in full extension. The tendon lengthening for combined contracture of the gastrocnemius and soleus was determined from the sum of the passive moments developed by the contracted gastrocnemius and the contracted soleus with the knee in full extension. In both cases, a 2 cm elongation of the Achilles tendon produced an onset of passive moment at 10° of plantar flexion. To simulate lengthening of the Achilles tendon for isolated gastrocnemius contracture, 2 cm was added to the tendon lengths of the contracted gastrocnemius and the normal soleus. To simulate lengthening of the Achilles tendon for combined contracture of the gastrocnemius and soleus, 2 cm was added to the tendon lengths of the contracted gastrocnemius and the contracted soleus.

The effects of the simulated tendon lengthenings were evaluated by comparing the moment-generating characteristics of the contracted triceps surae be-

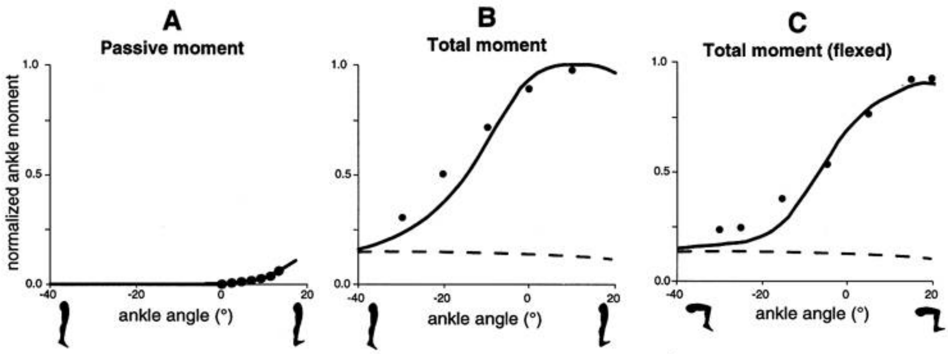

FIG. 3. Ankle moment versus ankle angle for the normal model. The passive moment with the knee extended (**A**) was calculated with the model (solid curve) and compared with the passive plantar flexion moment reported by Siegler et al. (18) (dots). The total moments with the knee extended (**B**) and flexed 90° (**C**) were calculated with the model (solid curve) and compared with the maximum isometric moments reported by Sale et al. (16) (dots). The broken-line curves in **B** and **C** represent the sum of the moments produced by the tibialis posterior, peroneus longus, peroneus brevis, flexor hallucis longus, and flexor digitorum longus. The difference between the solid and broken-line curves in **B** and **C** therefore represents the moment produced by the triceps surae. Experimental and calculated moments are normalized by the maximum active moment with the knee extended. Total moment represents the maximum moment-generating capacity of the muscles.

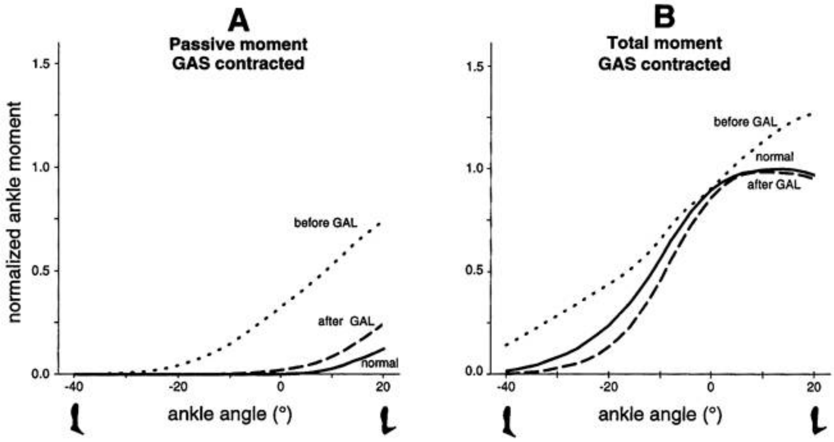

FIG. 4. Ankle moment versus ankle angle before and after simulated gastrocnemius aponeurosis lengthening (GAL) with isolated gastrocnemius (GAS) contracture. Lengthening restores the passive moment developed by the triceps surae to slightly greater than normal when only the gastrocnemius is contracted (**A**). The total moment is normal with the ankle in dorsiflexion but slightly less than normal with the ankle in plantar flexion after gastrocnemius aponeurosis lengthening (**B**). Moments were calculated with the knee extended and were normalized by the maximum active moment of the normal triceps surae. Total moment represents the maximum moment-generating capacity of the muscles.

fore and after the simulated tendon lengthenings to the moment-generating characteristics of the normal triceps surae.

RESULTS

The passive plantar flexion moment calculated with the model of normal muscles corresponds closely to measured passive moments (18) (Fig. 3A). Total plantar flexion moments calculated with the model also correspond closely to maximal plantar flexion moments measured by Sale et al. (16) with the knee extended (Fig. 3B) and flexed (Fig. 3C). The sum of the moments developed by the tibialis posterior, peroneus longus, peroneus brevis, flexor hallucis longus, and flexor digitorum longus is relatively constant with ankle angle and contributes only a small fraction of the plantar flexion moment when the ankle is between 10° of plantar flexion and 20° of dorsiflexion (broken line in Fig. 3B and C). Since the gastrocnemius and soleus provide such a large percentage of the plantar flexion moment and are the only muscles affected by lengthening of the Achilles tendon and gastrocnemius aponeurosis, the subsequent presentation includes moments generated by these muscles only.

With isolated gastrocnemius contracture, lengthening of the gastrocnemius aponeurosis such that passive moment begins at 10° of plantar flexion results in only slightly greater than normal passive moment about the ankle (Fig. 4A). Since the soleus develops very little passive moment when only the gastrocnemius is contracted, passive moment can be decreased further with additional lengthening of the gastrocnemius aponeurosis. After simulated lengthening, the total moment-generating capacity of the triceps surae is approximately 95% of normal when the ankle is in dorsiflexion (Fig. 4B). Although the total plantar flexion moment is approximately normal after lengthening of the gastrocnemius aponeurosis, the contribution of passive moment is slightly greater than normal.

By contrast, lengthening of the gastrocnemius aponeurosis does not restore normal passive moment about the ankle with combined contracture of the gastrocnemius and soleus. Passive moment remains greater than normal because lengthening the gastrocnemius aponeurosis does not alter the excessive passive force developed by the contracted soleus. After simulated lengthening, the total moment generated by the triceps surae is greater than normal, primarily because of the excessive passive moment, which makes up 75% of the total moment at 15° of dorsiflexion.

When only the gastrocnemius is contracted, lengthening of the Achilles tendon so that the passive moment begins at 10° of dorsiflexion restores the passive moment of the triceps surae to approximately normal (Fig. 5A). However, lengthening of the Achilles tendon produces a major decrease in the moment-generating capacity of the triceps surae (Fig. 5B). The total plantar flexion moment generated by the triceps surae with isolated gastrocnemius contracture reaches only 36% of the normal value at 0° of dorsiflexion and 48% at 15° of dorsiflexion. These simulations demonstrate that plantar flexion strength decreases greatly when Achilles tendon lengthening is used to treat isolated gastrocnemius contracture because the uncontracted soleus is weakened unnecessarily.

When both the gastrocnemius and the soleus are contracted, lengthening the Achilles tendon so that the onset of passive moment occurs at 10° of plantar flexion restores the passive moment of the triceps surae to approximately normal (Fig. 5C). However, this increase in tendon length also decreases the moment-generating capacity of the triceps surae substantially (Fig. 5D). After simulated lengthening of the Achilles tendon, the total plantar flexion moment generated by the triceps surae with combined gastrocnemius and soleus contracture reaches only 37% of the normal value at 0° of dorsiflexion and 70% at 15° of dorsiflexion.

Passive moment decreases after the Achilles tendon is lengthened because the increase in tendon length causes the muscle fibers to relax and develop less passive force at a given ankle angle. This shifts the onset of passive moment toward dorsiflexion. The shift in passive moment is accompanied by a shift in the peak active moment toward dorsiflexion. Because the soleus has shorter fibers than the gastrocnemius, it is weakened more by the same tendon elongation. Consequently, in the computer model, a 2 cm lengthening of the Achilles tendon restores the moment-generating characteristics of the contracted gastrocnemius to approximately normal but overcorrects the soleus and weakens it unnecessarily. If the Achilles tendon were lengthened less, so that the soleus was not overcorrected, the passive moment developed by the gastrocnemius would remain much greater than normal.

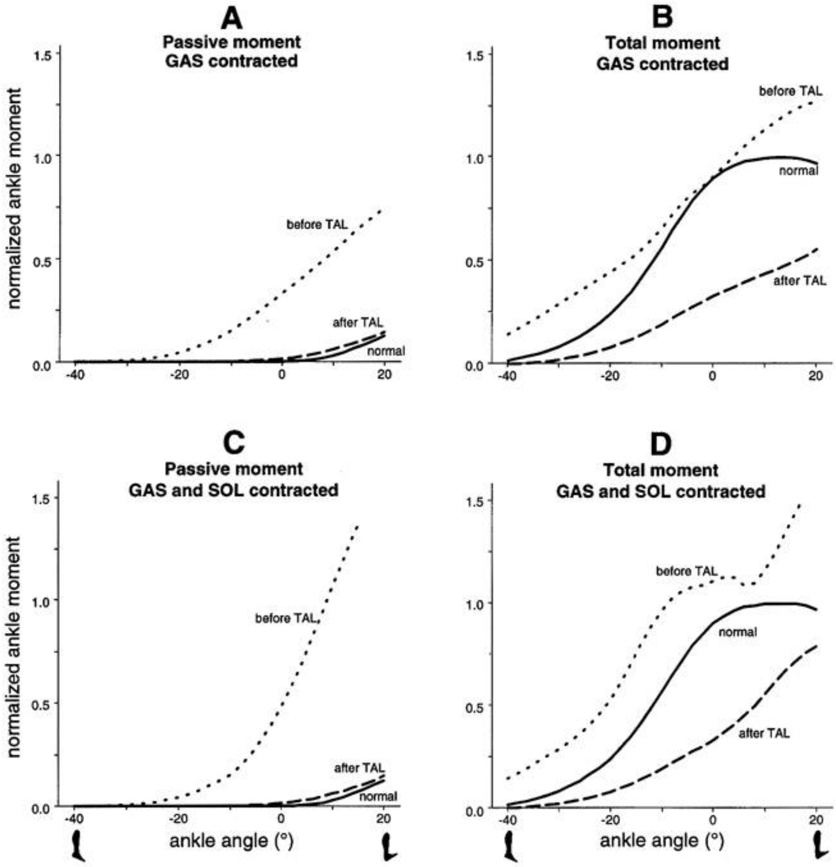

FIG. 5. Ankle moment versus ankle angle before and after simulated Achilles tendon lengthening (TAL) with isolated gastrocnemius (GAS) contracture (**A** and **B**) and with contracture of both the gastrocnemius and the soleus (SOL) (**C** and **D**). After Achilles tendon lengthening, the passive moment developed by the triceps surae is restored to approximately normal (**A** and **C**); however, the total moment is substantially less than normal (**B** and **D**). Moments were calculated with the knee extended and were normalized by the maximum active moment of the normal triceps surae. Total moment represents the maximum moment-generating capacity of the muscles.

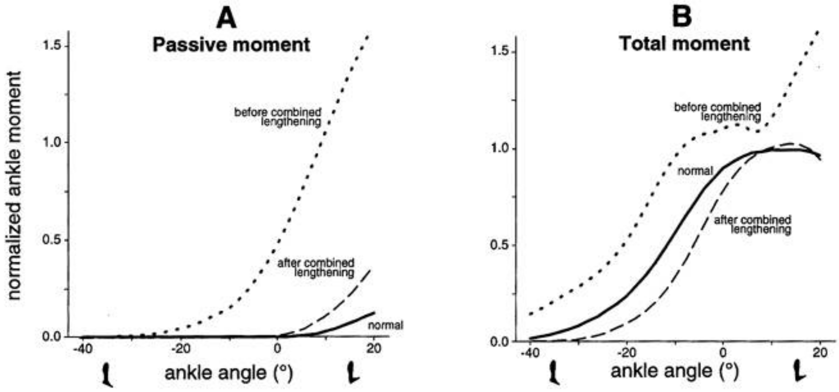

FIG. 6. Ankle moment developed by the triceps surae with contracture of both the gastrocnemius and the soleus before and after the Achilles tendon and gastrocnemius aponeurosis were lengthened by 1 cm. After combined lengthening, the passive moment developed by the triceps surae is somewhat greater than normal (**A**); however, the total moment is nearly normal (**B**). Moments were calculated with the knee extended and were normalized by the maximum active moment of the normal triceps surae. Total moment represents the maximum moment-generating capacity of the muscles.

The computer simulations indicate that active and passive moment-generating characteristics of the contracted triceps surae can be restored more effectively by combined lengthening of the Achilles tendon and gastrocnemius aponeurosis. A simulation in which both the Achilles tendon and the gastrocnemius aponeurosis are lengthened by 1 cm results in a passive moment that is slightly greater than normal (Fig. 6A). However, the total moment-generating capacity is much greater than after Achilles tendon lengthening alone (compare broken-line curves in Figs. 6B and 5B). These simulations suggest that combined lengthening of the gastrocnemius aponeurosis and Achilles tendon may be more effective because it accounts for differences in the architecture of the gastrocnemius and soleus and allows more independent correction of contracture of these two muscles.

DISCUSSION

The aim of this study was to examine how lengthening the gastrocnemius aponeurosis and the Achilles tendon affects passive and active moments developed about the ankle. Simulations showed that nearly normal passive and active moments could be restored when isolated gastrocnemius contracture was treated with gastrocnemius aponeurosis lengthening. However, with combined contracture of the soleus and gastrocnemius, Achilles tendon lengthening alone was not an effective treatment. If the Achilles tendon was lengthened enough to restore nearly normal passive moment, the active moment-generating capacity was greatly reduced. Our results suggest that independent correction of the contracted gastrocnemius and soleus potentially is a more effective method to restore normal passive and active moments about the ankle.

Before the technical details of achieving independent correction are discussed, the effects of several limitations of this study should be considered. When calculating total moments, we assumed that the muscles were fully activated. However, patients with spasticity often are unable to activate the muscles fully due to lack of voluntary control. Our simulations do not account for the complexities associated with activation of spastic muscle, such as potential alterations in recruitment or rate modulation, which could affect the force output of muscle (21). The total moments reported here therefore should be interpreted as the maximum moment-generating capacity of the triceps surae. Similarly, it was assumed that muscles were completely inactive when passive moments were calculated. Passive moments therefore represent the minimum moment developed by the triceps surae.

The biomechanical muscle model used here represents the major features of isometric muscle force generation. As discussed in detail by others, however, such models incorporate several simplifications (28). For example, all fibers within a muscle are assumed to be at the same length for a given muscle-tendon length. Herzog and ter Keurs (10) suggested that this may result in underestimating the range of joint angles over which a muscle produces active force. Even with the simplifications associated with the muscle model used here, the computer model reproduces the major features of the passive and total moments over a range of knee and ankle positions. Since the moments calculated with the computer model correspond well with experimentally measured ankle moments, use of the model to study the effects of tendon lengthening on ankle moments is a reasonable approach.

Although we have accounted for the decrease in muscle fiber lengths that may occur before tendon lengthening, the simulations presented here do not account for the effects of muscle-tendon remodeling that can occur after lengthening. For instance, immobilization after tendon lengthening can decrease the peak force of a muscle (26), alter the number of sarcomeres in a muscle fiber (20,26), and change the elasticity of tendon (27). In the simulations, peak force, fiber length, and tendon elasticity of each muscle-tendon complex were kept constant. Our results therefore should be used to understand the *acute* changes in the joint moments that result from tendon lengthening and not the changes that may occur after growth and adaptation.

The forces calculated with the computer model were based on the architectural parameters of muscle used in the model (6,25). These parameters were taken from anatomical studies during which muscle fiber lengths, pennation angles, and cross-sectional areas were measured in adult anatomical specimens, because architectural parameters for children have not been reported. If muscle architecture differs greatly in children, then our results could be affected. For example, our simulations suggest that ankle moments can be restored more effectively by independent correction of the contracted gastrocnemius and soleus because the muscle fiber lengths are different in these two muscles. If the gastrocnemius and soleus had the same muscle fiber lengths in children with contractures, then ankle moments may be restored effectively by lengthening of their common tendon (the Achilles tendon). However, we expect that instances in which the contracted gastrocnemius and soleus could be corrected with exactly the same increase in tendon length occur infrequently and that independent correction is a better solution in most cases.

Finally, even with precise knowledge of how the moments about the ankle change with tendon lengthening, the results of these operations still would be somewhat unpredictable because of the abnormal patterns of muscle activation that often accompany pathology of the central nervous system (13,14). This study focused on the moment-generating capacity of the triceps surae because it is affected directly by tendon lengthening. More complex issues, such as how tendon lengthening indirectly affects production of muscle force through its influence on neural control patterns, are not discussed here, although other studies using kinetic analysis have begun to address this issue (15).

The results presented here have several important clinical implications. Computer simulations revealed that equinus due to isolated gastrocnemius contracture can be treated effectively by lengthening the gastrocnemius aponeurosis. Lengthening the gastrocnemius aponeurosis such that the onset of passive moment occurs at 10° of plantar flexion decreases the resistance to dorsiflexion and preserves the moment-generating capacity of the plantar flexors. This conclusion is consistent with the findings of Rose et al. (15). Although lengthening the Achilles tendon also restores normal passive moments about the ankle, it reduces the active moment-generating capacity of the plantar flexors dramatically. This suggests that Achilles tendon lengthening should not be used to treat isolated gastrocnemius contracture because doing so may decrease the strength of the plantar flexors greatly.

Our results suggest that, theoretically, independent adjustment of contracted gastrocnemius and soleus muscles is more effective than lengthening the Achilles tendon in restoring normal passive and active moment-generating characteristics about the ankle. Independent adjustment of the muscles may be accomplished in several ways. With the patient prone and the knee flexed 90°, the Achilles tendon first is lengthened such that the contracted soleus is corrected. The knee then is extended, and the gastrocnemius aponeurosis is lengthened to relieve any additional contracture of the gastrocnemius. Alternatively, the soleus and gastrocnemius can be adjusted independently by lengthening only the aponeurosis of the soleus and the aponeurosis of the gastrocnemius, leaving the Achilles tendon unaltered. Independent correction of the two contracted muscles is slightly more complicated than lengthening of the Achilles tendon; however, the potential to better preserve plantar flexion strength in patients with contracture of both the gastrocnemius and soleus by independent lengthening of the two muscles is an important concept that should be considered in the treatment of ankle equinus.

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