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# EFFECTS OF TENSIONING ERRORS IN SPLIT TRANSFERS OF TIBIALIS ANTERIOR AND POSTERIOR TENDONS

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**Background:** Split transfers of the tibialis anterior and posterior tendons are commonly performed to address hind-foot varus deformities in patients with cerebral palsy, stroke, or brain injury. Poor outcomes from these procedures are often attributed to a failure to tension the transferred tendon properly, but the mechanical effects of this aspect of the procedure have not been quantified, to our knowledge. The purpose of the present study was to use a cadaver model to examine changes in the actions of these muscles that occur when the tensions in the halves of the split tendon are intentionally balanced or unbalanced to varying degrees.

**Methods:** Tendon excursion was measured in seven cadaveric specimens before and after split tendon transfer with experimentally controlled tensions in the halves of the split tendon. The muscle moment arm, a quantitative indicator of the action of a muscle about a joint axis, was calculated as the derivative of tendon excursion with respect to the subtalar joint angle.

**Results:** The tibialis anterior had an eversion moment arm with the subtalar joint in a neutral position following surgery, but the tibialis posterior had virtually no action in the neutral position. Following the split transfers with ideally balanced tension, subtalar joint rotations of  $>5^\circ$  strongly influenced the moment arm of the tibialis posterior ( $p < 0.0002$ ), indicating that its action depends on the position of the hindfoot. The moment arm of the tibialis anterior, however, was influenced only by rotations of  $\geq 20^\circ$  ( $p > 0.1741$  for each angle pair comparison of  $< 20^\circ$ ). Moment arms were generally insensitive to imbalances in tension between the medial and lateral tendon halves; significant differences in the moment arm ( $p < 0.05$ ), compared with that in the balanced condition, were seen only when one half was slack or nearly so.

**Conclusions:** These results suggest that it is possible for a split tendon transfer to be successful over a large range of tensionings. Split transfer of the tibialis posterior tendon produced the desired mechanical outcome in that the tibialis posterior had an eversion moment arm when the foot was inverted and an inversion moment arm when the foot was everted. Split transfer of the tibialis anterior to the cuboid, however, produced a muscle that consistently functioned as an everter regardless of the position of the hindfoot.

**Clinical Relevance:** Residual varus and overcorrection following a split tendon transfer are often attributed to technical errors in balancing the tension between the medial and lateral tendon halves. The findings of the present study, however, suggest that such surgical failures are likely caused by only the largest of imbalances in tendon tension.

Split transfers of the tibialis anterior or posterior tendon are commonly performed to correct the varus deformity of the hindfoot that often accompanies cerebral palsy, stroke, and brain injury. These procedures involve splitting the distal part of the tendon longitudinally, detaching half of the tendon from its medial insertion, and reattaching it to the lateral side of the foot<sup>1-3</sup>. Both of these split transfers are designed to alter the muscle-tendon unit in such a way that it neither inverts nor everts the foot but instead maintains a stable but flexible neutral posture. With insertions on both the medial

and the lateral side of the foot, the split tendon is meant to return the foot to a neutral position regardless of whether the foot is inverted or everted. Kaufer called this arrangement a "mechanical servo-mechanism."<sup>2</sup>

The reported clinical outcomes of split transfer of the tibialis anterior and posterior tendons have generally been good but have varied considerably<sup>4-11</sup>. One factor repeatedly mentioned by authors to explain poor and fair results is difficulty in achieving a proper tension balance between the medial and lateral halves of the transfer<sup>4,7,9,10,12</sup>. Balanced mediolateral ten-

sion in a split tendon transfer is achieved by positioning the foot and ankle in a neutral position or slight dorsiflexion and pulling the transferred (lateral) half of the tendon until it is taut and then suturing it in place. If the lateral half is left too long and slack, the transfer will have little or no effect on muscle action. Conversely, if the lateral half is pulled too tight, the treated muscle may be converted to an everter that overcorrects the varus deformity.

Split transfers of the tibialis anterior and posterior tendons were designed to radically alter the actions of those muscles at the subtalar joint, yet there have been few biomechanical investigations of the results of those procedures. The purpose of the present study was to measure, in cadaver specimens, the subtalar joint moment arms of the tibialis anterior and posterior following split tendon transfers in which the tensions in the medial and lateral tendon halves were (1) made equal to simulate optimal surgical technique and (2) purposely unbalanced to simulate surgical errors. We hypothesized that the subtalar joint moment arms of both muscles would be negligible in the neutral position when the medial and lateral tensions had been made equal and that the moment arms would be significantly altered when the tensions had been substantially unbalanced. For the purposes of this study, the tensions were considered to be substantially unbalanced when the medial half of the split tendon had only 50% of the tension that was present in the lateral half, or vice versa.

### Materials and Methods

Seven fresh-frozen cadaver legs (from four female and three male donors who had been fifty-three to eighty-seven years old at the time of death) were thawed and were sectioned approximately 23 cm proximal to the plantar surface of the foot, and the tibialis anterior and posterior were identified. Except for the tibialis anterior and posterior tendons, all soft tissues proximal to a transverse plane 5 cm superior to the malleoli were removed, but tissues distal to this level, including the extensor retinaculum, were initially left intact. Each specimen was secured to an aluminum foot-plate by two 3.1-mm-diameter steel pins inserted mediolaterally through the posterior aspect of the calcaneus, a 25.4-mm-long screw driven into the inferior aspect of the calcaneus, and taping of the forefoot. Proximally, the specimen was fixed to the top of the testing apparatus with a bolt inserted into the medullary canal of the tibia and secured with bone cement as well as a 3.1-mm-diameter steel pin driven transversely through the tibia, the fibula, and a hole in the bolt (Fig. 1).

Steel cables (0.5 mm in diameter) were sutured to the insertional tendons of the tibialis anterior and posterior at the level of the musculotendinous junction. To reproduce physiological lines of action, these cables were passed through appropriately positioned pulleys attached to the tibial mounting shaft. Cable extension transducers (PT101; Celesco Transducer Products; Canoga Park, California) permitted measurement of the excursion of each tendon to within  $\pm 0.025$  mm, while torsional springs incorporated into these devices maintained a constant cable tension of approximately 18 N.

Specimens were first tested with the tibialis anterior and posterior tendons intact and then were retested following split transfer of both tendons. The surgical techniques were previously described by Hoffer et al.<sup>1</sup> and Kling et al.<sup>8</sup> To monitor and control tendon tensions, miniature load cells (2CT; Precision Measurement, Ann Arbor, Michigan) were placed in series with the medial and lateral halves of each tendon. A 1-cm-wide aluminum block replaced the natural junction between the medial and lateral halves (Fig. 2). Set screws mounted in this block permitted adjustment of the lengths of the cables sutured to the medial and lateral tendon halves and passed through the block. Relative tension between the medial and lateral halves of the tendons was established by adjusting the lengths of the cables passing through the block while the foot and ankle were held in their anatomically neutral positions.

The position and orientation of the foot were measured with use of an instrumented spatial linkage<sup>13</sup> that connected the movable foot-plate to the fixed base of the testing device. This linkage was fitted with six potentiometers used to transduce rotations at each of its six joints. Voltage outputs from each potentiometer, both cable transducers, and each of the

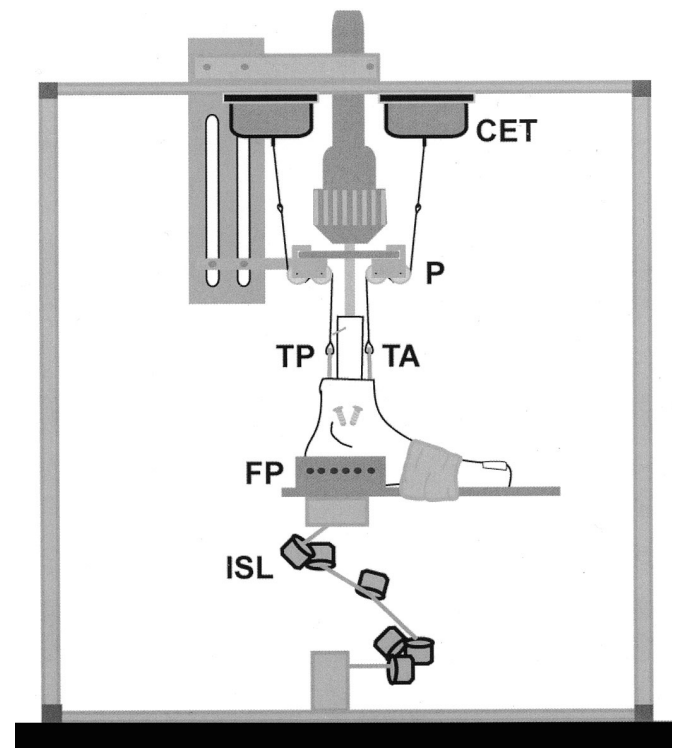


Fig. 1  
Cadaver specimens were mounted in the test apparatus by attachment to the foot-plate and tibial mounting shaft. The motion of the foot-plate (FP) was monitored with use of an instrumented spatial linkage (ISL), and tendon excursions were measured with use of cable extension transducers (CET). Cables were sutured to the insertional tendons of the tibialis anterior (TA) and tibialis posterior (TP) and routed through pulleys (P) that approximated physiological lines of action.

four load cells were sampled at 120 Hz with use of a personal computer and LabVIEW data acquisition software (National Instruments, Austin, Texas). All data were subsequently low-pass filtered with use of a fourth-order Butterworth filter with a cutoff frequency of 5 Hz implemented in the MATLAB software package (MathWorks, Natick, Massachusetts).

Prior to testing, the talocrural joint was fixed in a neutral position by driving one or two screws through the medial malleolus into the talus. Proper screw placement was verified when each specimen was dissected following the experiment. The foot was held in a static, anatomically neutral position and then slowly rotated manually to the extremes of its range of inversion and eversion. The foot was moved to maximum eversion, then to maximum inversion, and then back to eversion. Each specimen was moved in each direction until the onset of resistance to the motion was noted. All but one specimen exhibited  $>10^\circ$  of eversion and  $>15^\circ$  of inversion, mo-

tions that, as a result of the constraints created by our test system, were considered to occur at the subtalar joint. These angles defined the range of angles over which the subtalar joint moment arms were calculated. Three trials were performed with the tibialis anterior and posterior tendons intact, and thirty-three trials were performed following split transfer of both tendons. The thirty-three experiments done after the split tendon transfers consisted of three trials at each of eleven evenly spaced medial-to-lateral tension balances that ranged from the medial tendon half being taut while the lateral half was completely slack to the reverse situation, in which the lateral side was taut and the medial side was slack. One of these sets of three trials was performed with the medial and lateral tendon tensions approximately equal (within 5%).

Inversion-eversion angles were calculated from the potentiometer voltage output from the instrumented spatial linkage with use of techniques that we described previously<sup>14</sup>. Helical axis decomposition<sup>15</sup> was used to locate the subtalar joint axis, and a Euler-angle decomposition<sup>16</sup> was employed in which the first rotation occurred about the subtalar joint axis, so that the first of the Euler angles was interpreted as a subtalar joint rotation. Trials were excluded from analysis if either the second or the third of these Euler angles reached  $\pm 10^\circ$  during the test, indicating play in the joint or a poorly defined joint axis. Joint angles were calculated with use of custom-written routines in MATLAB.

Muscle moment arm, a geometric indicator of the capacity of a muscle-tendon unit to produce or resist rotation about a joint axis, is the perpendicular distance from the joint axis to the line of action of a muscle crossing the joint. In the present study, muscle moment arms were measured indirectly in the cadaver specimens with use of the tendon excursion method<sup>17</sup> (Fig. 3). Tendon excursion data from each trial were fit by polynomial functions of joint angle that varied in degree. With use of the method proposed by Hughes et al.<sup>18</sup>, polynomial regressions were performed on tendon excursion versus subtalar joint angle data sets to find the lowest-order polynomial that resulted in root-mean-squared error for each fit that was smaller than 0.5 mm. Effective muscle moment arms were calculated as the analytical derivative of each tendon excursion polynomial with respect to joint angle multiplied by  $-1$ <sup>17,19</sup>. The resulting moment arm polynomials were then evaluated and averaged at  $5^\circ$  intervals between  $10^\circ$  of eversion and  $15^\circ$  of inversion.

One-sample t tests were performed to establish whether the mean subtalar joint moment arms of the tibialis anterior and tibialis posterior were different from zero in the neutral position following equally balanced split tendon transfers. One-way analyses of variance were performed to determine whether the subtalar joint angle ( $-10^\circ$ ,  $-5^\circ$ ,  $0^\circ$ ,  $5^\circ$ ,  $10^\circ$ , and  $15^\circ$ , with a positive value indicating inversion) influenced the subtalar joint moment arms of the intact tibialis anterior and posterior. Two-way analyses of variance were used to investigate the dependence of the subtalar joint moment arms of the tibialis anterior and posterior on the subtalar joint angle (with testing at the same angles described above) and on the per-

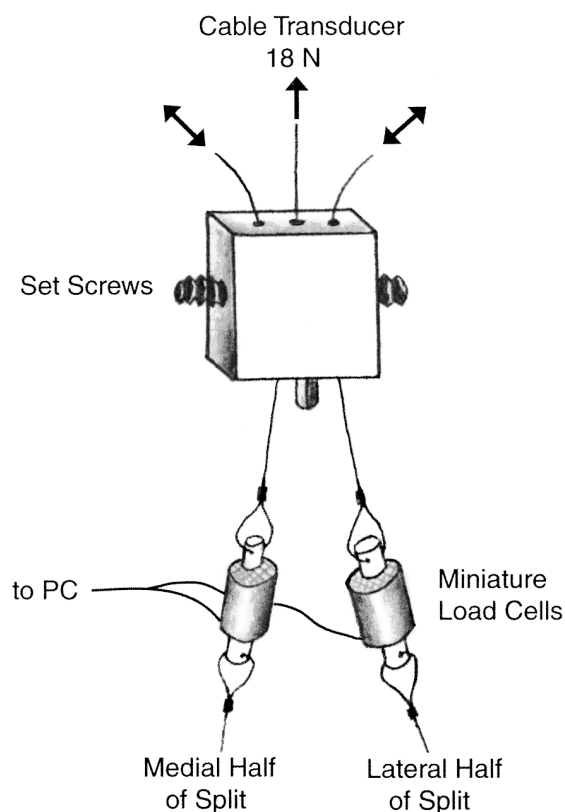


Fig. 2

Illustration of the 1-cm-wide aluminum block that simulated the natural junction of the medial and lateral tendon halves. Tension was adjusted in each tendon half by altering the length of the cable passing through the block. Set screws locked the cable in place, and miniature load cells were used to monitor tensions. Cable transducers applied a constant 18-N force to each common tendon.

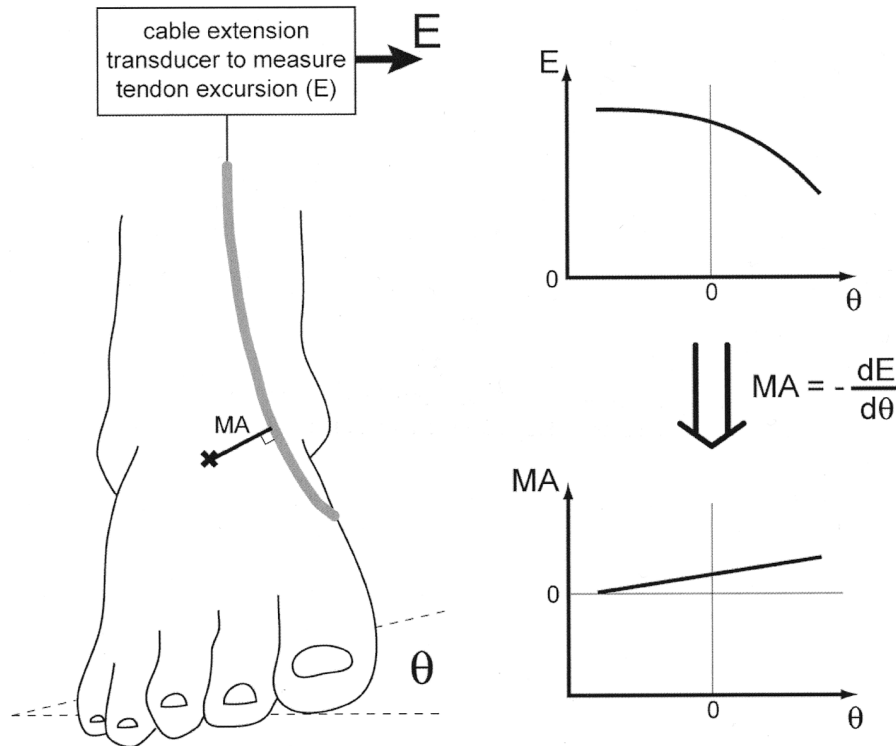


Fig. 3

Schematic representation of the muscle moment arm and its measurement with the tendon excursion method. The foot is rotated about the subtalar joint axis (X), as both the subtalar joint angle ( $\theta$ ) and tendon excursion (E) are monitored. The muscle moment arm (MA) may then be calculated as the negative slope of the excursion versus angle curve. This moment arm is a quantitative indicator of the rotational effect of a muscle about a specific joint axis at a given level of force production; it is the perpendicular distance from the joint axis to the line of action of the muscle-tendon unit.

centage change in medial-lateral tension balance (with testing of eleven evenly spaced tension levels). Tukey pairwise comparisons were performed following each analysis of variance to identify the tension levels and joint rotations that produced significant changes in subtalar joint moment arms. The level of significance was set at  $\alpha = 0.05$  for all analyses.

## Results

Analysis of variance and subsequent post hoc mean comparisons showed that the moment arms of the intact tibialis anterior and posterior were significantly influenced only by subtalar rotations of  $\geq 20^\circ$  ( $p > 0.0542$  for all other angle pair comparisons) (Figs. 4, A, and 6, A). The intact tibialis posterior was found to have a larger mean inversion moment arm (ranging from 1.6 to 2.1 cm over the range of motion) than the intact tibialis anterior (ranging from 0.3 to 0.8 cm).

Subtalar joint rotations of  $> 5^\circ$  significantly altered the subtalar joint moment arm of the tibialis posterior ( $p < 0.0002$  for each angle pair comparison of  $> 5^\circ$ ) following an ideally balanced split transfer (Fig. 4, B). After the split transfer, the tibialis posterior had an inversion moment arm of 1.8 cm when the foot was everted and an eversion moment arm of 2.6 cm

when the foot was inverted. The subtalar joint moment arm of the tibialis posterior was found to vary with the degree of medial-lateral tension balance (Fig. 5). This variation was not, however, found to be uniform over the range of imposed tension balances; the changes in moment arm that resulted from transitions from slack to slightly taut were larger than the changes that occurred between tension balances in which both tendon halves carried loads.

In contrast, the moment arms of the tibialis anterior after the balanced split transfers were not significantly altered by subtalar joint rotations of  $< 20^\circ$  ( $p > 0.1741$  for each angle pair comparison of  $< 20^\circ$ ) (Fig. 6, B). After the split transfer, the tibialis anterior consistently functioned as an everter, with eversion moment arms of 0.6 cm in the most inverted position and 1.2 cm in the most everted position. The moment arms of the tibialis anterior varied with medial-to-lateral tension balance in a manner similar to that of the tibialis posterior (Fig. 7), but they were offset in the direction of eversion by approximately 1 cm.

T tests showed that the mean moment arm of the tibialis posterior (an eversion moment arm of  $0.05 \pm 0.16$  cm) in the neutral subtalar position was not significantly different from

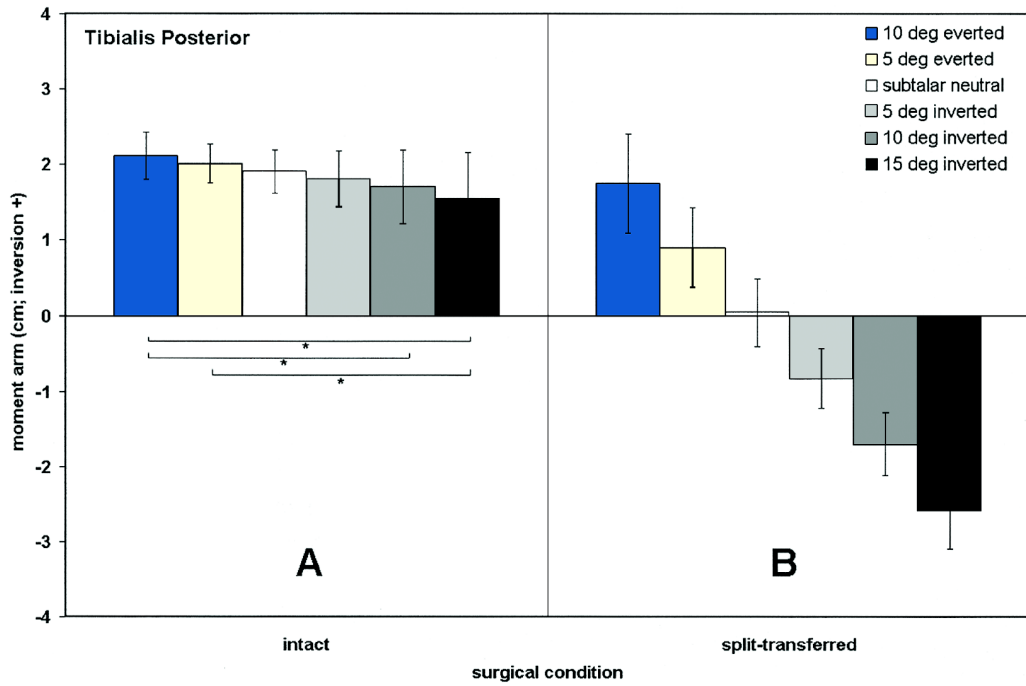


Fig. 4  
Subtalar moment arms of the tibialis posterior, measured at six subtalar joint angles, prior to surgery (A) and following an ideally balanced split tendon transfer (B). Asterisks denote significant ( $p < 0.05$ ) differences between moment arms. In B, all angle comparisons revealed significant differences except for those that represented  $5^\circ$  of subtalar joint rotation.

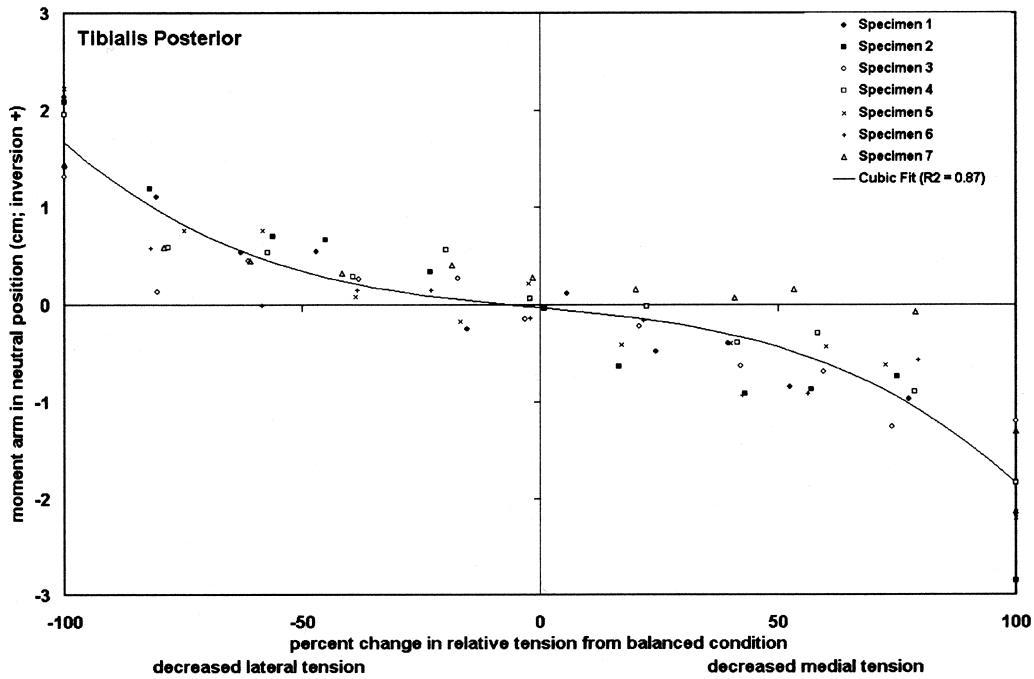


Fig. 5  
Subtalar joint moment arms of the tibialis posterior in the neutral position plotted against the percent change in tension balance. Positive values for the percent change in tension balance indicate that the lateral tendon half is more taut than the medial half, and negative values indicate a more taut medial half.

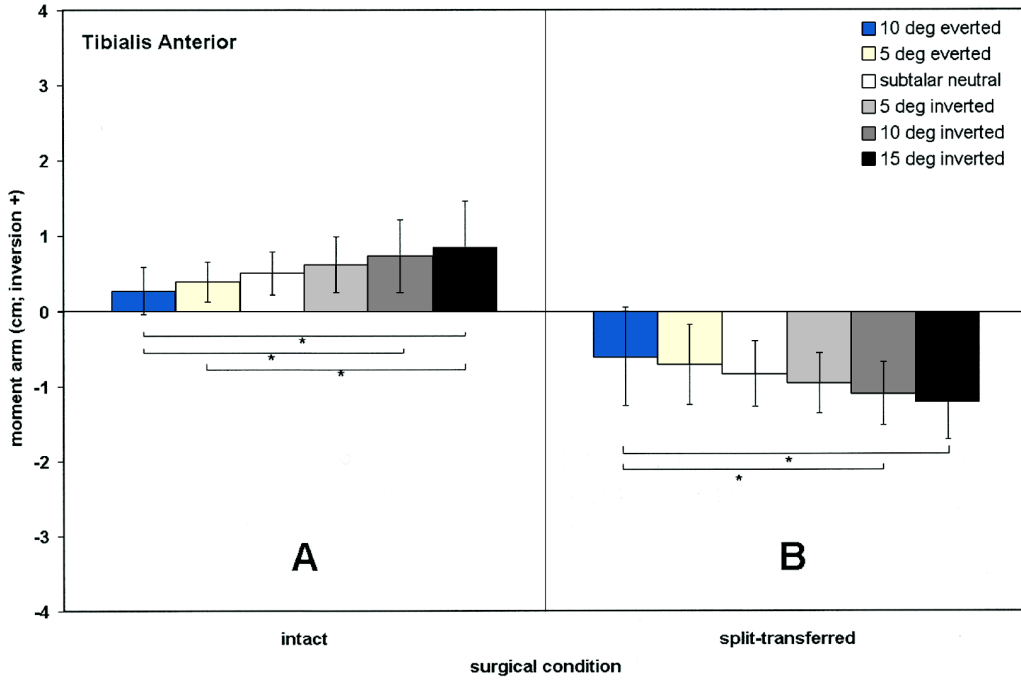


Fig. 6 Subtalar moment arms of the tibialis anterior, measured at six subtalar joint angles, prior to surgery (A) and following an ideally balanced split tendon transfer (B). Asterisks denote significant ( $p < 0.05$ ) differences between moment arms.

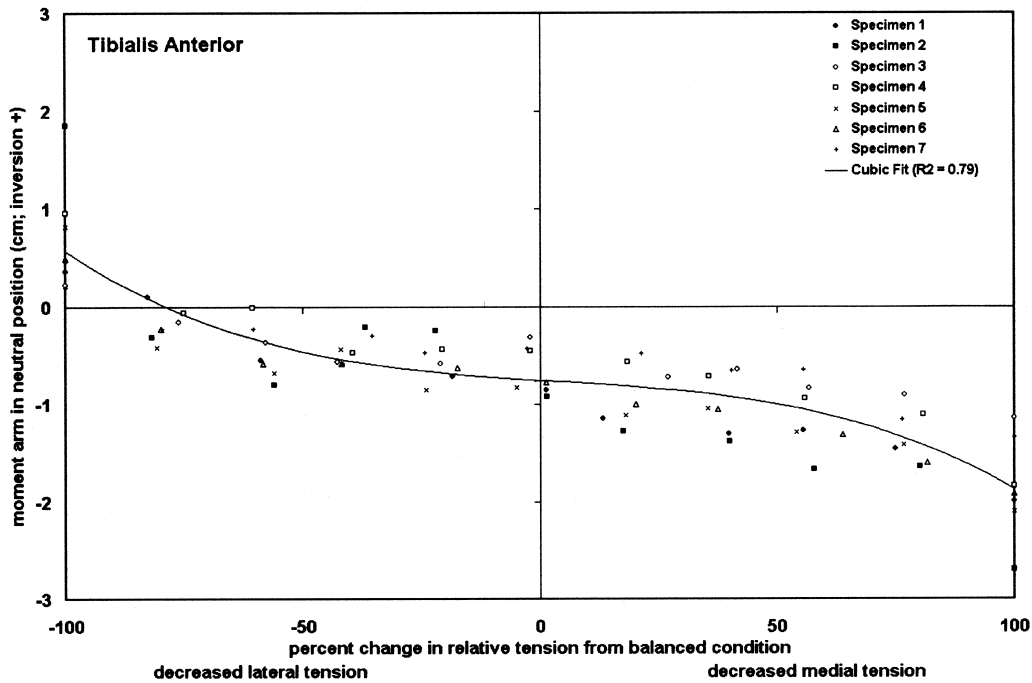


Fig. 7 Subtalar joint moment arms of the tibialis anterior in the neutral position plotted against the percent change in tension balance. Positive values for the percent change in tension balance indicate that the lateral tendon half is more taut than the medial half, and negative values indicate a more taut medial half.

zero ( $p = 0.4712$ ) after an equally balanced split tendon transfer, but the mean eversion moment arm of the tibialis anterior ( $0.84 \pm 0.44$  cm) was significantly different from zero ( $p = 0.0024$ ). Subtalar joint moment arms in the neutral position were significantly affected only by large changes in the relative tensions in the medial and lateral halves of the transfer (Figs. 5 and 7).

Mean comparisons following analysis of variance showed significant differences (all  $p < 0.0001$ ) between moment arms measured after equal tensioning and those measured with either the lateral or the medial side slack. A significant difference ( $p = 0.0216$ ) was also noted between the moment arms of the tibialis posterior measured after equal tensioning and those measured with the medial tension equal to 20% of the lateral tension. However, no other comparisons after the equal balance transfers showed a significant difference in moment arm (all  $p > 0.081$ ).

Third-order polynomial fits ( $r^2 = 0.79$  for the tibialis anterior and  $r^2 = 0.87$  for the tibialis posterior) were performed to characterize the dependence of subtalar joint moment arms on the change in relative tension from the balanced condition (Figs. 5 and 7). The effects of tension imbalances of 50% were estimated by interpolating these polynomials. The tibialis anterior moment arm changed by 0.29 cm when the lateral tension was half of the medial tension and by  $-0.24$  cm when the medial tension was half of the lateral tension. The corresponding changes in the tibialis posterior moment arm were 0.37 and  $-0.40$  cm.

## Discussion

Split transfer of the tibialis posterior tendon to the distal part of the peroneus brevis tendon produced the desired mechanical outcome when the tensions in the medial and lateral halves of the transfer were made equal. Following transfer, the tibialis posterior was found to have an eversion moment arm when the foot was inverted, an inversion moment arm when the foot was everted, and no action when the foot was in the neutral position. Split transfer of the tibialis anterior performed with an ideal medial-lateral tension balance, however, caused the muscle to become a slight everter throughout the range of subtalar joint motion. Subtalar joint moment arms after the split transfers of the tibialis anterior and posterior were significantly affected when the medial or lateral half of the transfer was made completely slack, but the moment arms were relatively insensitive to smaller, but still substantial, changes in tension balance. Only small changes in the subtalar joint moment arm ( $<0.5$  cm) resulted when the split transfers were unbalanced such that the tension in one tendon half was 50% of the tension in the other half. This finding suggests that split tendon transfer is a robust procedure and its desired mechanical effects are jeopardized by only the largest of technical errors.

In previous biomechanical studies of split tendon transfer, the investigators either have not examined changes in muscle moment arms resulting from these procedures or have not controlled the relative tendon tensions. Hui et al.<sup>20</sup> per-

formed split transfers of the tibialis anterior tendon to various sites on the lateral aspect of the foot and monitored angular displacement of the foot while applying tension to the tibialis anterior proximally in cadaver specimens. They concluded that split transfer to the fourth metatarsal axis maximized dorsiflexion while minimizing supination and pronation. We previously measured changes in musculotendinous moment arms that resulted from split tendon transfers performed *in vitro*<sup>14</sup>. Using this method, we found that split transfer of the tibialis posterior to the distal part of the peroneus brevis tendon consistently converted it from a strong inverter into a muscle with little action in the neutral position. The results of split transfer of the tibialis anterior to the cuboid were more variable but, on the average, produced an everter of the subtalar joint over the range of subtalar joint motion; similar results for the tibialis anterior were found in the present study. Neither we (in our previous study<sup>14</sup>) nor Hui et al. measured or controlled the relative tensions in the two halves of the split transfer, as was done in the present study, despite previous assertions that clinical outcome is sensitive to the balance of tensions<sup>4,7,9,10,12</sup>.

This study had certain limitations. The muscle moment arms were measured in cadaver specimens rather than in living subjects and thus were not subject to the effects of muscle adaptation<sup>21</sup>. The specimens came from older or elderly donors and thus differed from the feet of children with cerebral palsy, who are often the recipients of split tendon transfers. The experimental apparatus did not reproduce physiological loading of the ankle joint, and no loads were applied to tendons of muscles other than those studied. No attempt was made to apply a compressive load across the ankle, and the joint may even have been distracted by the weight of the foot, foot-plate, and instrumentation. Motions were applied manually, increasing the possibility that they might have been applied inconsistently. Such nonphysiological loading and subjective application of motion had the potential to cause the subtalar joint to move in a manner not consistent with that of an ideal hinge. However, the magnitudes of deviations from hinge-like behavior were consistently found to be small, and the joint axes were generally found to be repeatable within  $5^\circ$  between trials on a given specimen, suggesting that motion similar to that of a hinge did occur at the subtalar joints.

Anatomical positioning of each specimen had to be approximated because there is no definitive method of determining anatomical position. Since tendon tensions were sensitive to this positioning of the foot, the medial-lateral tendon tension ratios that we reported should be considered approximations. Only light loads were applied during the tests. Recent studies by Maganaris et al.<sup>22</sup> and Ito et al.<sup>23</sup> suggested that the dorsiflexion moment arm of the tibialis anterior increases between conditions of rest and maximum contraction. Ito et al., however, reported no changes in moment arm between 30% and 100% of maximum contraction, suggesting that submaximal contraction may be sufficient to produce such changes in moment arm.

The present study was also limited in that artificial means were used to simulate the split tendon junction. This method



permitted the introduction of load cells to monitor and control tensions but may have resulted in unnatural load sharing between the medial and lateral tendon halves. Finally, the inverting and everting capacities of only two muscles were considered. The tibialis anterior and tibialis posterior were chosen for investigation because split transfers of these tendons are commonly used to correct varus deformity; other muscles, however, have the potential to contribute to the problem of varus deformity as well as to its overcorrection. These muscles include the triceps surae, the peroneals, and the extrinsic toe extensors.

The results of the present study suggest that the outcome of split tendon transfer is not sensitive to the imposed medial-lateral tension balance between the tendon halves. The slight everting action that was evident when half of the tibialis anterior was transferred to the dorsum of the cuboid may contribute to overcorrection of hindfoot varus, but it might also improve surgical outcome by counteracting other offending muscles. If, for example, both the tibialis anterior and the tibialis posterior contribute to the varus deformity but only the tibialis anterior is transferred, its postoperative everting action might reduce or overcome the deforming influence of the tibialis posterior. It is also important to note that the slight everting action of the tibialis anterior following split transfer is due, in part, to the choice of the cuboid as the lateral insertion site. Split transfer of the tibialis anterior to a more medial location, such as the lateral cuneiform<sup>3</sup>, might be more likely to produce a muscle that neither inverts nor everts with the subtalar joint in the neutral position. Conversely, split transfer of

the tibialis anterior more laterally, such as to the distal part of the peroneus brevis tendon, would probably produce a stronger everter. The outcome of split transfer of the tibialis posterior also depends on the choice of insertion site; our results suggest that transfer to a location medial to the distal part of the peroneus brevis tendon would probably result in a muscle that everts in the neutral position. ■

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