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Motion of the Hindfoot after Simulated Arthrodesis*

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ABSTRACT: Arthrodesis of the subtalar joint, triple arthrodesis (involving the subtalar, talonavicular, and calcaneocuboid joints), double arthrodesis (involving the talonavicular and calcaneocuboid joints), arthrodesis of the talonavicular joint, and arthrodesis of the calcaneocuboid joint were simulated in a cadaver model, and the range of motion of each joint not involved in the simulated arthrodesis was measured with a three-dimensional magnetic space tracking system. The excursion of the posterior tibial tendon was also measured under all of these conditions. We found that any combination of simulated arthrodeses that included the talonavicular joint severely limited the motion of the remaining joints to about 2 degrees and limited the excursion of the posterior tibial tendon to 25 per cent of the preoperative value. Simulated arthrodesis of the calcaneocuboid joint had little effect on the range of motion of the subtalar joint, and it reduced the range of motion of the talonavicular joint to a mean of 67 per cent of the preoperative value; a mean of 73 per cent of the excursion of the posterior tibial tendon was retained. After simulated arthrodesis of the subtalar joint, a mean of 26 per cent of the motion of the talonavicular joint, 56 per cent of the motion of the calcaneocuboid joint, and 46 per cent of the excursion of the posterior tibial tendon was retained.

The talonavicular joint is the key joint of the triple joint complex. The talonavicular joint had the greatest range of motion, and simulated arthrodesis of this joint essentially eliminated motion of the other joints of the complex.

CLINICAL RELEVANCE: Arthrodesis of any of the joints of the so-called triple joint complex (the subtalar, talonavicular, and calcaneocuboid joints) limits the motion of the remaining, unfused joints. However, clinical estimates of these limitations are imprecise and motion of the individual joints cannot be specifically

measured clinically. It is important to be able to measure the limitation of motion of each joint after arthrodesis of the other joints in order to understand the clinical implication of the arthrodesis. Also, it is necessary to ascertain the effect of limiting the motion of these joints on the excursion of the posterior tibial tendon in order to determine when it is appropriate to reconstruct the tendon concomitantly with these arthrodeses.

Motion of the so-called triple joint complex (the subtalar, talonavicular, and calcaneocuboid joints) is necessary for the foot to accommodate variations in ground surface and rotation from the lower extremity. Although gross differences in the amount of motion of the triple joint complex remaining after different arthrodeses has been recognized *in vivo* and *in vitro*^{2-4,9}, the amount of motion remaining has not been measured accurately, to our knowledge.

While it is difficult to measure this motion precisely in the clinical setting, Mann and Baumgarten estimated clinically that about 50 per cent of the motion of the transverse tarsal joint remained after arthrodesis of the subtalar joint. They therefore advocated the use of isolated arthrodesis of the subtalar joint rather than triple arthrodesis, when possible, to leave the foot as flexible as possible. Fogel et al. found that isolated arthrodesis of the talonavicular joint provided satisfactory results but clinically limited subtalar motion compared with that of the contralateral foot. With use of a standard manual goniometer and reference pins in the tibia, calcaneus, and second metatarsal, Gellman et al. measured the motion of the foot and the ankle *in vitro* after various combinations of simulated arthrodeses of the ankle and tarsal joints. Those authors did not include arthrodesis of the talonavicular or calcaneocuboid joints, or both, or measure the motion of individual joints.

Unlike motion of the major joints of the lower extremity, motion of the joints of the foot cannot be measured accurately with an external goniometer. It is possible, however, to measure the change in position of individual bones of the foot in three-dimensional space with a three-dimensional magnetic space tracking system; the range of motion of the joints can then be calculated. This system has been used in the past to study the mechanics of the wrist^{7,8}.

Most pronation and supination of the foot occurs in

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the triple joint complex. The posterior tibial muscle and the peroneal muscles are the principal muscles acting on these joints. Arthrodesis of any one of the joints of the triple joint complex affects the excursion of the posterior tibial tendon.

The purpose of the present study was to quantify, *in vitro*, the effect of simulated arthrodesis of selected joints of the triple joint complex on both the range of motion of the remaining, unfused joint or joints and the excursion of the posterior tibial tendon. We believe that these *in vitro* data will help a practitioner to determine when to perform a transfer of the flexor digitorum longus tendon to replace the function of a ruptured or otherwise non-functional posterior tibial tendon concomitantly with arthrodesis.

Materials and Methods

Ten fresh-frozen cadaveric foot specimens, amputated at the middle of the tibia, were used in this study. All of the specimens had a grossly normal posterior tibial tendon and had no radiographic evidence of osteoarthritis. The exact ages of the donors were not known, but all feet were from adults and all growth plates were closed.

The soft tissue about the ankle and the malleoli was left intact, and the more proximal soft tissue was cleared from the tibia and the fibula. The ankle was fixed in a neutral position with three large screws. Elimination of motion of the ankle was necessary to isolate motion of the triple joint complex and to allow reliable and reproducible measurement of the tendon excursion.

The three-dimensional locations of the talus, calcaneus, navicular, and cuboid were monitored with a magnetic space tracking system (Fastrak; Polhemus Navigational Sciences Division, Colchester, Vermont). This system consists of a source that generates a magnetic field and four sensors, the positions of which are detected within the magnetic field. The accuracy of the system is dependent both on the amount of metal in the field and on the distance between the sensor and the source¹⁰. Metal objects of a certain composition, size, and shape can be used in the space tracking system without causing interference. The metal components (screws, wires, and threaded pins) used during this experiment were placed in various locations about the source to verify that they did not create any detectable distortion. The manufacturer determined the accuracy of the tracking system (0.8 millimeter along each of the three translational axes and 0.15 degree about each of the three rotational axes) with the sensor thirty inches (76.2 centimeters) from the source. The present study was conducted with the sensor no more than twelve inches (30.5 centimeters) from the source. The accuracy with the shorter distance was determined, before the study was conducted, to be 0.1 millimeter along each translational axis and 0.1 degree about each rotational axis.

The magnetic source of the space tracking system was fixed to the test frame, and the sensors were attached to each of the four bones (Fig. 1). The position of the sensor in each bone was selected so that the sensors did not come into contact with each other throughout the range of motion of the foot. To attach the sensors rigidly to each bone, each sensor was mounted on a small Plexiglas plate that was connected to two 3.0-millimeter carbon vinyl ester pins. The pins were press-fit into two undersized holes in the bone six millimeters apart. Two pins were used with each sensor to prevent rotation at the pin-bone interface.

The specimens were placed plantar side up in the testing apparatus, which stabilized the tibia and allowed unrestricted motion of the foot (Fig. 1). Placement of the foot plantar side up also simplified the use of weights and wires for the application of loads.

Tendon pulls were used to move the foot through a reproducible range of motion without imposing an artificial axis of motion. The tendons of the posterior tibial and peroneus brevis muscles were

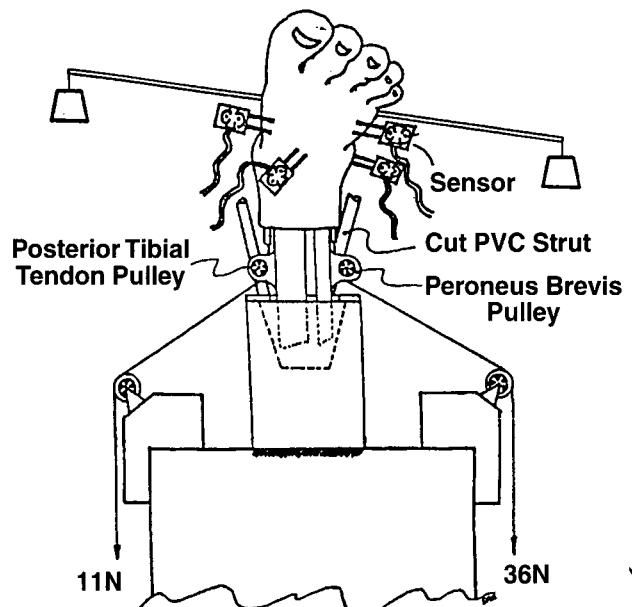


FIG. 1

Illustration of the foot in the apparatus used to test the range of motion of the subtalar, talonavicular, and calcaneocuboid joints as well as excursion of the posterior tibial tendon.

selected because they are antagonists and the principal muscles acting on the triple joint complex. In preliminary testing, a pull on the peroneus longus tendon did not cause greater motion in the triple joint complex than a pull on the peroneus brevis tendon did.

Stainless-steel wires were sutured to the posterior tibial and peroneus brevis tendons proximal to the malleoli. The sutures were attached to gauges that measured linear displacement through wire cables threaded through pulleys. Use of the pulleys allowed a direct line of pull on each tendon and allowed the excursion of these tendons to be measured as the foot was moved (Fig. 1).

As neither the peroneus brevis tendon nor the posterior tibial tendon inserts into the calcaneus, testing of the initial specimens was performed with a load placed on the calcaneus to stabilize it against the talus and to prevent it from acting as a free body. Subsequent testing showed no difference in joint motion or tendon excursion with or without a load on the calcaneus. However, for consistency, all of the specimens were tested with the calcaneus loaded.

For the purpose of this study, the motion produced in the triple joint complex by placement of a load on the peroneus brevis tendon is defined as pronation and the motion produced by placement of a load on the posterior tibial tendon is defined as supination. To achieve the pronated position of the foot, a thirty-six-newton load was placed on the peroneus brevis tendon and an eleven-newton load was placed on the posterior tibial tendon (Fig. 1). The loads were exchanged to achieve the supinated position of the foot. These loads were chosen because preliminary testing had demonstrated that greater loads did not produce noticeable additional motion of the joints under investigation.

After each simulated arthrodesis, the linear displacement reading for the excursion of the posterior tibial tendon and the three-dimensional position of the bones were recorded for each of three supination trials and three pronation trials. The simulated conditions included no arthrodesis, arthrodesis of the subtalar joint, triple arthrodesis (involving the subtalar, talonavicular, and calcaneocuboid joints), double arthrodesis (involving the talonavicular and calcaneocuboid joints), arthrodesis of the talonavicular joint, and arthrodesis of the calcaneocuboid joint. The order of the simulated arthrodeses was maintained to minimize the number of times that hardware was placed into the bones to be fixed together, thereby allowing more rigid stabilization of the bones. During the experiment, the foot was

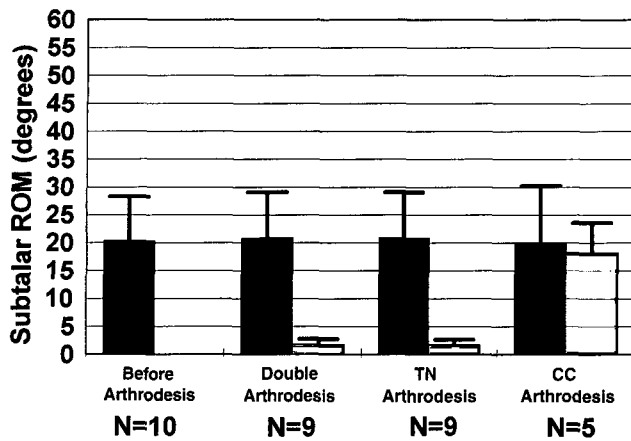


FIG. 2

Graph of the mean range of motion (ROM) (and standard deviation) of the subtalar joint before the simulated arthrodeses (black bars) and after simulated arthrodeses (gray bars) of the talonavicular (TN) joint, the calcaneocuboid (CC) joint, and both joints (double arthrodesis). The numbers below the bars are the number of feet included for each simulated arthrodesis.

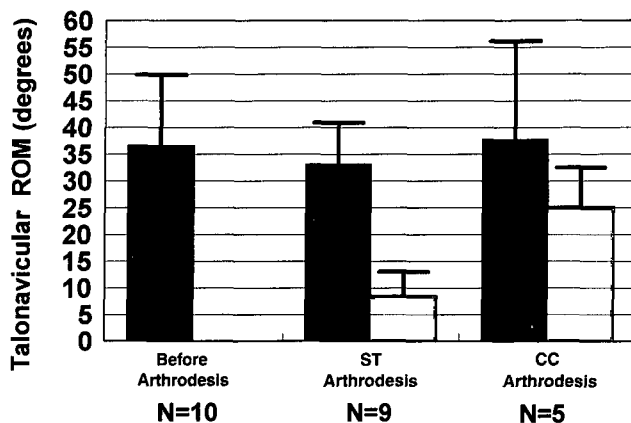


FIG. 3

Graph of the mean range of motion (ROM) (and standard deviation) of the talonavicular joint before the simulated arthrodeses (black bars) and after simulated arthrodeses (gray bars) of the subtalar (ST) joint and the calcaneocuboid (CC) joint. The numbers below the bars are the number of feet included for each simulated arthrodesis.

held in a neutral plantigrade position while each joint was fixed. The subtalar joint was fixed with the heel in the neutral position, as fixing of this joint in varus results in more restricted motion of the talonavicular and calcaneocuboid joints¹¹. To simulate an arthrodesis, a combination of at least two screws or threaded pins, with a firm hold in bone, were placed across the joint to be fixed. No cartilage was removed from the joints.

From the data collected, the range of motion of the subtalar, talonavicular, and calcaneocuboid joints and the excursion of the posterior tibial tendon were calculated for each condition from full supination to full pronation of the foot.

Statistical Analysis

Statistical analysis was performed with each foot acting as its own control. Analysis of variance with pair-wise comparisons with Bonferroni corrections were applied to account for multiple measurements. A level of significance of $p \leq 0.05$ was used. If 3 degrees of motion or more occurred at the site of a simulated arthrodesis, data from that arthrodesis as well as data from subsequent conditions

that included the inadequately fixed site, were excluded. For example, if excessive motion was present after the simulated subtalar arthrodesis, this condition as well as the simulated triple arthrodesis were excluded for that foot. However, if excessive motion occurred after simulated arthrodesis of the calcaneocuboid joint (the last condition simulated), the measurements of the previous simulations were not excluded.

Results

Before the simulated arthrodeses, the talonavicular joint had the greatest range of motion (36.7 ± 13 degrees [mean and standard deviation]), followed by the subtalar joint (20.4 ± 8 degrees) and the calcaneocuboid joint (14.4 ± 6 degrees), in all ten feet.

Simulated arthrodesis of the talonavicular joint and simulated double arthrodesis significantly limited the range of motion of the subtalar joint, in the nine feet for which it was recorded, to a mean of 8 and 9 per cent, respectively, of the subtalar motion before the simulated arthrodeses ($p < 0.0001$ for both) (Fig. 2). Simulated arthrodesis of the subtalar joint resulted in a significant decrease in the range of motion of the talonavicular joint ($p < 0.0001$) and the calcaneocuboid joint ($p = 0.005$), in the nine feet for which it was recorded, to a mean of 26 per cent (Fig. 3) and 56 per cent (Fig. 4), respectively, of the range of motion before the simulated arthrodeses. Simulated arthrodesis of the calcaneocuboid joint had little effect on the range of motion of either the talonavicular joint, which retained a mean of 67 per cent of the motion that it had had before the simulated arthrodeses (Fig. 3), or the subtalar joint, which retained a mean of 92 per cent of its motion (Fig. 2), in the five feet for which these data were recorded.

The mean excursion of the posterior tibial tendon in the ten feet was 17 ± 5 millimeters (range, ten to twenty-seven millimeters) before the simulated arthrodeses. In

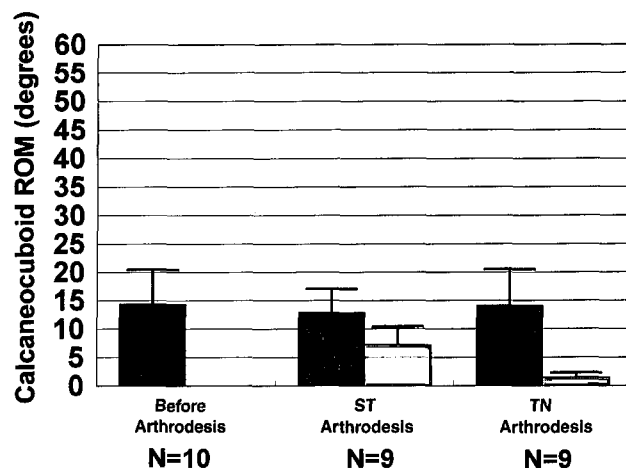


FIG. 4

Graph of the mean range of motion (ROM) (and standard deviation) of the calcaneocuboid joint before the simulated arthrodeses (black bars) and after simulated arthrodeses (gray bars) of the subtalar (ST) joint and the talonavicular (TN) joint. The numbers below the bars are the number of feet included for each simulated arthrodesis.

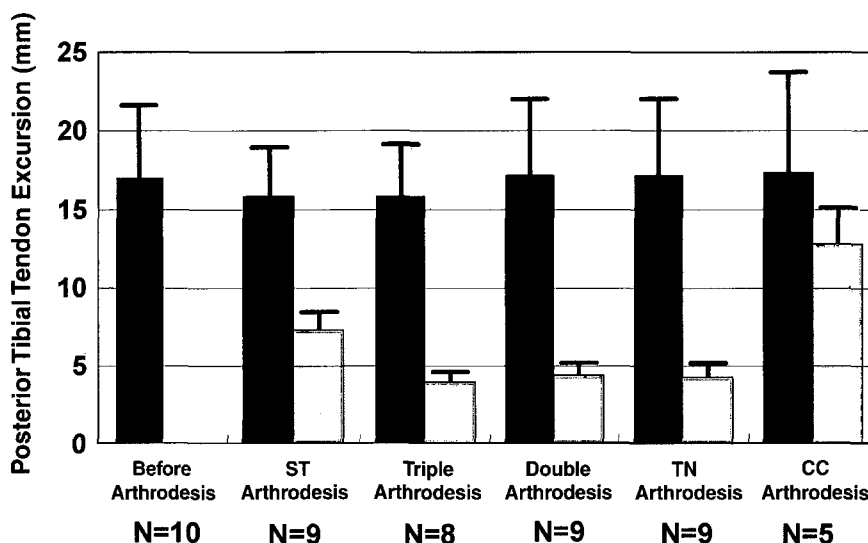


FIG. 5

Graph of the mean excursion (and standard deviation) of the posterior tibial tendon before the simulated arthrodeses (black bars) and after simulated arthrodesis (gray bars) of the subtalar (ST) joint, triple arthrodesis, double arthrodesis, arthrodesis of the talonavicular (TN) joint, and arthrodesis of the calcaneocuboid (CC) joint. The numbers below the bars are the number of feet included for each simulated arthrodesis.

the five feet for which it was recorded, a mean of 73 per cent of the excursion was maintained after simulated arthrodesis of the calcaneocuboid joint (Fig. 5). With the number of specimens in this study, we could not show a significant difference between the tendon excursion before the simulated arthrodesis of the calcaneocuboid joint and that after it. However, the excursion of the posterior tibial tendon was significantly decreased, compared with before the simulated arthrodeses, after all of the simulated arthrodeses that involved the talonavicular joint (arthrodesis of the talonavicular joint, double arthrodesis, and triple arthrodesis) ($p < 0.0001$ for all). Simulated arthrodesis of the subtalar joint and simulated arthrodesis of the talonavicular joint decreased the tendon excursion, in the nine feet for which it was recorded, to a mean of 46 and 25 per cent, respectively, of the excursion before the simulated arthrodeses. After simulated double arthrodesis (in the nine feet for which it was recorded) and after simulated triple arthrodesis (in the eight feet for which it was recorded), the remaining excursion was a mean of 25 per cent of that before the simulated arthrodeses (Fig. 5).

Discussion

There have been several clinical studies involving patients who had various arthrodeses of the triple joint complex. Lapidus reported on a patient who had arthrodesis of the subtalar joint in one foot and arthrodesis of the talonavicular joint in the other. He reported that the foot that had had arthrodesis of the subtalar joint had better compensatory motion compared with the foot that had had arthrodesis of the talonavicular joint; however, the amount of motion remaining was not quantified in either foot. Mann and Baumgarten retrospectively evaluated eleven feet that had iso-

lated arthrodesis of the subtalar joint. With use of the contralateral side for comparison, they estimated that about 50 per cent of the transverse tarsal (talonavicular and calcaneocuboid) motion had been maintained. Hall and Pennal clinically estimated that 25 to 50 per cent of transverse tarsal motion remained after arthrodesis of the subtalar joint. In the present study, a mean of 26 per cent of the motion of the talonavicular joint and 56 per cent of the motion of the calcaneocuboid joint remained after simulated arthrodesis of the subtalar joint. Fogel et al., in their follow-up study of patients who had had arthrodesis of the talonavicular joint, noted that subtalar as well as transverse tarsal motion was severely limited. This clinical result is in accordance with our *in vitro* finding that the subtalar and calcaneocuboid joints retained 3 degrees of motion or less after simulated arthrodesis of the talonavicular joint. Our *in vitro* measurements are consistent with the *in vivo* estimates of motion retained by the transverse tarsal joint after arthrodesis of the subtalar joint and by the subtalar joint after arthrodesis of the talonavicular joint.

The mean range of motion of the subtalar joint (20.4 degrees) before the simulated arthrodeses in the present study was within the 18-to-24-degree range determined by Inman in two cadaveric studies¹¹. The results of the present study, however, cannot be compared with those reported by Gellman et al. because those authors determined the motion remaining in the foot as a whole after various simulated arthrodeses. Also, Gellman et al. moved the foot manually in a predetermined direction, whereas we used tendon pulls with constant loads to move the feet.

With our experimental model, we were able to quantify several important clinical observations. The degree to which simulated arthrodesis of a joint of the

triple joint complex affects motion of the remaining joints is associated with the amount of motion that the joint had before the arthrodesis. The calcaneocuboid joint had the least motion before the simulated arthrodeses, and the simulated arthrodesis of this joint had the least effect on the motion of the other joints. Conversely, the talonavicular joint had the most motion before the simulated arthrodeses and the simulated arthrodesis of this joint restricted motion more than the simulated arthrodesis of any of the remaining joints did. Simulated arthrodeses that included fixation of the talonavicular joint (arthrodesis of the talonavicular joint or double arthrodesis) eliminated nearly all motion of the remaining joint or joints. After either simulated arthrodesis of the talonavicular joint or simulated double arthrodesis, the motion of the subtalar joint was limited to about 2 degrees (about 9 per cent of the motion of the subtalar joint before the simulated arthrodeses), which was the same as the motion of the subtalar joint after simulated arthrodesis of the subtalar joint. After simulated arthrodesis of the subtalar joint, 26 per cent of the motion of the talonavicular joint (about 9 degrees) remained and 56 per cent of the motion of the calcaneocuboid joint (about 7 degrees) remained. Simulated arthrodesis of the calcaneocuboid joint affected the motion of the remaining joints the least. We previously demonstrated that most of the motion of the subtalar and talonavicular joints was retained after simulated arthrodesis of the calcaneocuboid joint with a bone block (lengthening of the lateral column)¹.

The mean excursion of the posterior tibial tendon before the simulated arthrodeses in the present study is consistent with that determined by Hintermann et al. In their study, the excursion of all of the extrinsic muscles of the plantigrade foot were determined in various degrees of plantar flexion and dorsiflexion with varying degrees of inversion and eversion. Those authors demonstrated that the excursion of the posterior tibial tendon was less affected by flexion of the ankle from -20 to 30 degrees (mean, 4.4 millimeters of excursion; range, 1.8 to 9.3 millimeters of excursion) than by inversion and eversion of the foot. With 0 degrees of plantar flexion, they found the mean excursion of the posterior tibial tendon to be 16.3 millimeters (range, 6.8 to 22.3 millimeters) from inversion to eversion. In the present study, the mean excursion of the posterior tibial tendon before the arthrodeses was 17 ± 5 millimeters (range, ten to twenty-

seven millimeters) with the ankle fixed in neutral.

As far as we know, the effect of various arthrodeses on excursion of the posterior tibial tendon has not been studied previously. In the present study, the amount of excursion remaining after a particular simulated arthrodesis was associated with the amount of motion remaining in the triple joint complex. A mean of 73 per cent of the excursion of the posterior tibial tendon was retained after simulated arthrodesis of the calcaneocuboid joint, whereas a mean of 46 per cent was retained after simulated arthrodesis of the subtalar joint. Excursion was most restricted by simulated arthrodeses that included the talonavicular joint (a mean of 25 per cent remained after arthrodesis of the talonavicular joint, after double arthrodesis, and after triple arthrodesis). These data suggest that excursion of the posterior tibial tendon is most related to mobility of the talonavicular joint and that any arthrodesis that preserves mobility of the talonavicular joint, such as arthrodesis of the calcaneocuboid or subtalar joint, also preserves excursion of the posterior tibial tendon. It follows that transfer of the flexor digitorum longus tendon to the navicular tuberosity, to restore the function of a ruptured or otherwise non-functional posterior tibial tendon, will also maintain its excursion if the talonavicular joint remains mobile. Therefore, this tendon transfer can be performed to restore the function of the posterior tibial tendon in conjunction with arthrodesis of the calcaneocuboid joint or, possibly, arthrodesis of the subtalar joint, both of which preserve motion of the talonavicular joint.

In summary, this cadaveric study demonstrated that motion of the talonavicular joint is the key to motion of the triple joint complex. Any simulated arthrodesis that includes fixation of the talonavicular joint essentially eliminates the motion of the other joints in the complex and severely limits excursion of the posterior tibial tendon. After simulated arthrodesis of the subtalar joint, some motion of the talonavicular and calcaneocuboid joints is retained, as is a mean of 46 per cent of the excursion of the posterior tibial tendon. Simulated arthrodesis of the calcaneocuboid joint preserves a good deal of the motion of the talonavicular joint, most of the motion of the subtalar joint, and most of the excursion of the posterior tibial tendon. These results are consistent with clinical observations that the amount of motion remaining in these joints influences the patient's postoperative function.

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