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A biomechanical analysis of posterior tibial tendon dysfunction, medial displacement calcaneal osteotomy and flexor digitorum longus transfer in adult acquired flat foot

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ABSTRACT

Background: Biomechanical models have been used to study stress in the metatarsals, subtalar motion, lateral column lengthening and subtalar arthroereisis. Posterior tibial tendon dysfunction has been associated with increased loads in the arch of the acquired flat foot. We examine whether a 10 millimeter (mm) medial displacement calcaneal osteotomy and flexor digitorum longus transfer to the navicular reduces these increased loads in the flat foot.
Methods: The response of a normal foot, a foot with posterior tibial tendon dysfunction, and a flat foot to an applied load of 683 Newton was analyzed using a multi-segment biomechanical model. The distribution of load on the metatarsals, the moment about each joint, the force on each of the plantar ligaments and the muscle forces were computed.
Findings: Posterior tibial tendon dysfunction results in increased load on the medial arch, which may cause the foot to flatten. A 10 mm medial displacement calcaneal osteotomy substantially decreases the load on the first metatarsal and the moment at the talo-navicular joint and increases the load on the fifth metatarsal and the calcaneal-cuboid joint. Adding the flexor digitorum longus transfer to the medial displacement calcaneal osteotomy has only a small effect on the flattened foot.
Interpretation: Our biomechanical analysis illustrates that when the foot becomes flat, the force on the talo-navicular joint increases substantially from its value for the normal foot, and that medial displacement calcaneal osteotomy can reduce this increased force back toward the value occurring in the normal foot. This study provides a biomechanical rationale for medial displacement calcaneal osteotomy treatments for posterior tibial tendon dysfunction.

1. Introduction

Posterior tibial tendon dysfunction is associated with adult acquired flat foot deformity. Although posterior tibial tendon dysfunction may result from trauma, it is more often due to a progressive degenerative condition that leads to weakening of the posterior tibial tendon. Since this tendon is one of the main supporters of the medial arch, as it weakens it places additional stress on other supporting structures, which in turn become weakened over time (Lapidus, 1943; Manter, 1946). The result may be a progressive flattening of the foot, leading to increased load on the first metatarsal, the ligaments supporting the joints of the medial arch, plantar medial rotation of the talus, hind foot valgus, forefoot abduction, and decreased medial arch height (Arangio et al., 1998; DeLand et al., 2005; Huang et al., 1993; Jahss, 1982; Kitaoka et al., 1998). The Achilles tendon may shorten and exert a valgus moment on the calcaneus (Mann, 1993). Treatment for posterior tibial tendon dysfunction includes medial slide calcaneal osteotomy, alone and in combination with flexor digitorum longus transfer to the navicular, and lateral column lengthening, alone and in conjunction with medial slide calcaneal osteotomy (Horton et al., 1998; Myerson et al., 1995).

In this study, we use our biomechanical model of the foot (Salathe and Arangio, 2002) to test the hypothesis that posterior tibial tendon dysfunction increases the load on the medial arch of the foot and increases the forces on the talo-navicular joint, the spring ligament, the long plantar ligament, the first metatarsal and the plantar aponeurosis. We also use this biomechanical model to test the hypothesis that a 10 mm medial slide calcaneal osteotomy, isolated and combined with flexor digitorum transfer to the navicular, reduces the load on the medial longitudinal arch in the flattened foot. The biomechanical model has been used previously to examine the effect of lateral column lengthening calcaneal osteotomy (Arangio et al., 2007) and the effect of subtalar arthroereisis (Arangio et al., 2004) on the adult flexible flat foot.

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2. Methods

We used a three dimensional multi-segment biomechanical model of the foot developed and described previously (Salathe and Arangio, 2002). The biomechanical model regards the foot as a three dimensional structure consisting of rigid bones held together at their articulating surfaces by flexible ligaments. The plantar aponeurosis, which extends from the base of the calcaneus to each of the five rays, provides further support to this structure. The body weight, applied at the dome of the talus, the ground reaction forces, concentrated under the five metatarsal heads and the heel, and the muscles acting at various locations on the foot are the external forces acting on this structure.

The requirement that the muscle forces balance the body weight, preventing rotation about the ankle joint axis and the subtalar joint axis, determines their magnitude. When standing on one foot, the ground reaction forces must satisfy three equations of static equilibrium. Their sum must equal the body weight, and the moments of these forces and of the body weight about two perpendicular axes in the transverse (horizontal) plane must balance. Equilibrium provides only these three equations to determine the six support forces, because only three points are required to support an object. If there are more than three points of support, the structure is statically indeterminate and the manner in which it deforms under applied forces determines how the support is distributed.

Various ligaments and the plantar aponeurosis resist the deformation of the foot, preventing the bones from moving relative to each other. Under loading, the first three metatarsals rotate relative to their corresponding cuneiforms about a pivot point on the dorsal side of the joint, and plantar tarsometatarsal ligaments resist this rotation. Plantar cuneonavicular ligaments resist rotation of the cuneiforms relative to the navicular, and the plantar calcaneonavicular ligament, or spring ligament, extending from the navicular to the calcaneus, resists rotation of the navicular relative to the talus about a point on the dorsal side of the talo-navicular joint. Plantar tarsometatarsal ligaments resist rotation of the fourth and fifth metatarsals relative to the cuboid, and both the plantar calcaneocuboid ligament and a portion of the long plantar ligament resist rotation of the cuboid relative to the calcaneus. While a large portion of the long plantar ligament, which originates on the calcaneus, extends only to the cuboid, there is also a portion extending from its origin on the calcaneus to the base of the second, third, fourth and fifth metatarsals. This restrains the rotation of the metatarsals relative to the cuneiforms, the cuneiforms relative to the navicular and the navicular relative to the talus for the medial arch, and of the metatarsals relative to the cuboid and the cuboid relative to the calcaneus for the lateral arch. The plantar aponeurosis, which originates on the calcaneus and extends to the phalanges, also resists the flattening of the arch and the deformation of the foot. It does so by resisting relative motion of each of the joints in the same manner as described for the long plantar ligament, except that the joints of the first ray are included as well. Knowing the location of the pivot points on the dorsal side of each joint, and the location of the points of insertion of each of the ligaments and their mechanical properties, deformation of the foot under the action of the external forces acting on it can be determined. The requirement that after deformation the metatarsal heads remain coplanar, or deviate from a common plane by an amount related to the compression of the foot pad under each metatarsal head, provide additional equations for determining the ground reaction forces.

Modeling a specific foot requires input data that describe the shape of that foot. These data include the coordinates of the points where the support forces are applied under the heel and metatarsal heads, and of the insertion on the bones for the PA and for each of the ligaments. It also includes the coordinates of the points of insertion of the tendons on the foot, the points at which the flexor hallucis longus tendon enters and exits the sustentaculum tali, the extensor digitorum longus and tibialis posterior tendons leave the medial malleolus, the peroneus longus and peroneus brevis tendons leave the lateral malleolus, and the peroneus longus tendon passes under the cuboid. These data were obtained by two different methods, described below, and we used each of these methods to obtain data from a cadaver foot in both the normal and flat foot configuration. The cadaver foot was used only to obtain data describing the shape of the foot so that the difference between a normal and a flat foot could be realistically represented. No experiments were performed using the cadaver foot and all results presented here are mathematical predictions of the biomechanical model. The additional data required in the model, such as Young's modulus for the ligaments and the physiological cross sectional areas for the muscles, were obtained from the literature as described previously (Salathe and Arangio, 2002). The arch height was measured from the inferior margin of the navicular to a line drawn from the inferior margin of the first metatarsal to the calcaneus. The lateral column length was measured from the anterior inferior margin of the calcaneus to the fifth metatarsal head.

The first method for obtaining the data that describe the shape of the foot used X-rays and computerized axial tomography (CAT) scans (Arangio et al., 2004) to find the required anatomical landmarks for the biomechanical model. A fresh frozen cadaver foot specimen from a 77-year-old Caucasian female with no history of foot problems was used. The tibia and fibula were amputated at the junction of the middle and distal third of the leg and the skin, subcutaneous tissues, and proximal muscles were dissected from the specimen. The tibia, fibula and foot were attached to a specially designed frame and metal beads were inserted at the anatomical sites described above (Fig. 1). X-rays (Picker Cleveland, Ohio, USA) and a CAT scan (CT General Electric Light Speed: Milwaukee, Wisconsin, USA) of the specimen were taken in three mutually perpendicular planes and used to determine the spatial location of the beads to obtain the data describing the foot in its normal configuration. In order to obtain the corresponding data for this foot when it is in the flat foot configuration, the talo-navicular capsule, tibio-navicular portion of the deltoid ligament, spring ligament and plantar aponeurosis of one cadaver specimen were cut, and the foot was manually loaded until flat foot deformity was produced. The locations of the anatomical landmarks were again determined in order to represent the behavior of a flat foot in our biomechanical model.

The second method for obtaining data used direct linear transformation, a procedure that locates spatial points using two or more cameras, to obtain the locations of the anatomical landmarks (Arangio et al., 2007). A thin pointed plastic rod was constructed and five white balls were attached along its length. The distance of these balls from the tip of the rod was precisely determined. The tip of the rod was placed on each of the anatomical landmarks. Fig. 2 illustrates the rod accessing a landmark on the dorsal side of the foot. The spatial location of the centers of the balls along the rod was found from the camera images using the direct linear transformation method, and used to determine the coordinates of the tip of the rod. The location of each landmark was determined twice, with the rod in two different orientations and results were compared to ensure consistency and averaged to increase accuracy. The locations of the anatomical landmarks were first determined with the foot in its normal configuration. Additional photographs were taken of the foot to determine its arch height. The foot was then deformed into a flat foot configuration as described above and the locations of the anatomical landmarks were again obtained to represent the flat foot in our biomechanical

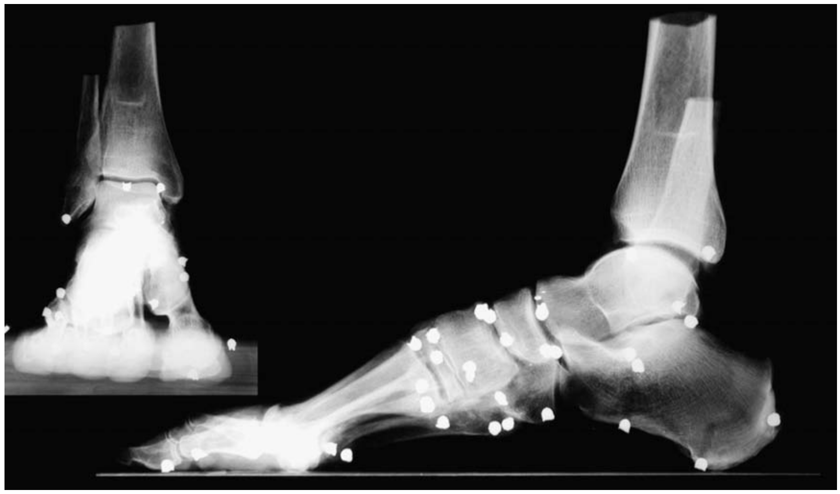

Fig. 1. X-ray of cadaver foot showing metal beads inserted at anatomical sites.

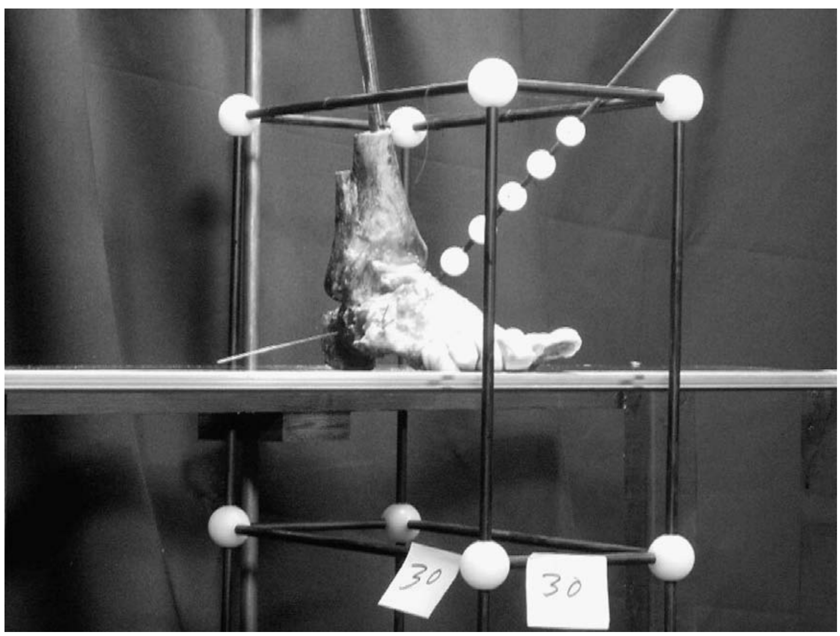

Fig. 2. The DLT method used to access a data point on the dorsal side of the foot.

model. Photographs were again taken to determine the arch height of the flattened foot

The effect of a 10 mm medial displacement calcaneal osteotomy was determined mathematically from our biomechanical model by shifting the location of the support force under the calcaneus and the point of attachment of the Achilles tendon on the calcaneus 10 mm laterally from the location they were determined to have for the flat foot. The effect of flexor digitorum longus transfer was also determined mathematically by setting the force that the digitorum longus exerts on the rays of the foot equal to zero in our biomechanical model, and having this muscle exert its force on the navicular instead.

3. Results

When the foot from which the data was collected using X-rays and CAT scans was made flat, the lateral talo-first metatarsal angle decreased 10°, the lateral talo-calcaneal angle decreased 7°, arch height decreased 5 mm, and the talo-navicular coverage angle increased 30°. In the foot from which data were collected using the digitorum longus transfer (DLT) method, the arch height, measured from the photographs, decreased from 28 mm in its normal configuration to 25 mm after it was made flat.

The results of the biomechanical analysis are presented for a body weight of 683 N. When the foot is flat, the portion of the body weight supported by the rays of the medial arch increased and the portion of the body weight supported by the fifth metatarsal decreased relative to the values obtained for the normal foot. MDCO reduced the load on the first and second metatarsal and increased the load on the fifth metatarsal, shifting the weight distribution back toward that occurring in the normal foot. The addition of FDLT to the MDCO had minimal effect on the body weight distribution in the flattened foot. These results are summarized in Table 1. Column A data is from the CAT-scan method and column B data is from the DLT method.

PTTD increased the force exerted by the Achilles tendon and decreased the force exerted by the peroneus longus and peroneus

Table 1
The percent of the body weight supported by each metatarsal and the heel for various cases. *Column A*: using the data from the foot that was CAT scanned. *Column B*: using the data obtained from the DLT method.

	Normal		PTTD		Weakened		Flat		MDCO + FDLT		MDCO + FDLT	
	A (%)	B (%)	A (%)	B (%)	A (%)	B (%)	A (%)	B (%)	A (%)	B (%)	A (%)	B (%)
First	10	11	10	10	11	11	18	15	9	5	9	6
Second	5	6	5	7	4	5	7	9	3	5	3	4
Third	5	6	5	6	4	5	2	5	5	6	5	6
Fourth	8	6	8	6	9	8	7	6	12	13	12	13
Fifth	6	5	6	5	6	5	1	1	8	11	8	11
Heel	66	66	66	66	66	66	65	64	63	60	63	60

brevis relative to the normal foot. The force provided by the Achilles tendon, the hallucis longus and the flexor digitorum longus decreased when the foot was made flat. MDCO further decreased the force exerted by the Achilles tendon while increasing the force exerted by the peroneus brevis and peroneus longus. Adding the FDLT resulted in minimal changes in the muscle forces. These results are shown in Table 2.

PTTD results in an increased load on the ligaments supporting the talo-navicular joint and the other joints of the medial arch. When these ligaments weaken as a result of the increased load they bear due to PTTD, this load increases even further. When the foot becomes flat there is a large increase in the moment on the talo-navicular joint and on the joints of the first and second rays, substantially increasing the load on the ligaments supporting these joints. The 10 mm MDCO reduced these moments considerably, but not back to the values occurring in the normal foot. These results are shown in Table 3. With the anatomical data obtained from the cadaver foot using CAT scans (column A in Table 3), the moment provided by the ligament supporting the talo-navicular joint increased from 4.35 Newton meters (N m) for the normal foot to 9.90 N m in the flat foot and decreased to 4.74 N m with MDCO. The moment provided by the ligament supporting the naviculo-first cuneiform joint increased from 0.30 N m for the normal foot to 3.98 N m in the flat foot and MDCO decreased this moment to 0.26 N m. A large increase in the moment at the talo-navicular joint was also found when the foot was made flat in the case where the data was obtained using the DLT method. This moment increased from 4.88 N m to 12.72 N m and then decreased back to 5.97 N m after MDCO (column B in Table 3).

We also modeled the flexor digitorum longus transfer when applied to the normal foot with PTTD and weakened ligaments. The result was that FDL transfer decreased the moment at the talo-navicular joint from 5.23 N m to 5.03 N m for the data that was obtained from the foot by CAT scanning and from 5.96 N m to 5.75 N m for the data that was obtained from the foot using the DLT method.

4. Discussion

The two methods used in our study provided independent data sets for the anatomical landmarks that characterize the shape of the normal and the flat foot for use in the biomechanical model. In the first method, metal beads were inserted into the foot at

Table 2
The force (in Newtons) in each of the extrinsic muscles acting on the foot. *Column A*: using the data from the foot that was CAT scanned. *Column B*: using the data obtained from the DLT method.

	Normal		PTTD		Weakened		Flat		MDCO		MDCO + FDLT	
	A	B	A	B	A	B	A	B	A	B	A	B
tc	215	239	240	269	240	269	107	128	96	122	96	119
tp	43	48	0	0	0	0	0	0	0	0	0	0
fhl	21	24	24	27	24	27	11	13	10	12	10	12
fdl	11	12	12	13	12	13	5	6	5	6	10	12
pb	55	33	43	21	43	21	46	17	57	27	57	28
pl	109	67	85	41	85	41	92	34	114	54	114	56

tc = Achilles tendon, tp = tibialia posterior, fhl = flexor hallucis longus, fdl = flexor digitorum longus, pb = peroneus brevis, pl = peroneus longus.

Table 3
The moment (in Newton meters) that must be provided by the ligaments at each of the joints of the foot. *Column A*: using the data from the foot that was CAT scanned. *Column B*: using the data obtained from the DLT method.

	Normal		PTTD		Weakened		Flat		MDCO		MDCO + FDLT	
	A	B	A	B	A	B	A	B	A	B	A	B
1M, 1C	0.18	0.09	0.20	0.07	0.45	0.37	2.75	2.87	0.34	0.05	0.37	0.10
1C, NV	0.30	0.88	0.95	1.54	1.36	2.06	3.98	5.06	0.26	0.65	0.19	0.46
2M, 2C	0.57	0.39	0.65	0.47	0.66	0.54	1.09	1.57	0.42	0.82	0.41	0.79
2C, NV	0.88	0.90	1.01	1.06	1.00	1.07	1.61	2.19	0.64	1.14	0.61	1.09
3M, 3C	0.63	0.48	0.66	0.49	0.62	0.47	0.15	0.74	0.80	1.08	0.80	1.07
3C, NV	1.09	1.10	1.15	1.15	1.03	1.01	0.39	1.27	1.44	1.75	1.43	1.72
NV, TA	4.35	4.88	4.92	5.49	5.23	5.96	9.90	12.72	4.74	5.97	4.77	5.92
4M, CU	1.70	1.31	1.72	1.34	1.99	1.64	1.53	1.45	2.53	3.21	2.53	3.22
5M, CU	1.40	0.98	1.32	0.91	1.35	0.93	0.09	0.30	2.04	2.61	2.04	2.63
CU, CA	4.12	3.65	4.08	3.57	4.54	4.11	2.38	2.78	5.92	8.67	5.93	8.71

M = metatarsal, C = cuneiform, NV = navicular, TA = talus, CU = cuboid, CA = calcaneus.

the location of the desired landmarks, and these locations could be determined accurately from the X-rays and the cat-scans of the foot. For beads in close proximity it was sometimes difficult to determine which bead corresponded to the desired location. Another disadvantage is that it requires access to a CAT scanner, along with the associated expense. With the DLT method the anatomical locations are determined sequentially, and there is no difficulty in discerning anatomical landmarks. In addition, the DLT method does not require any expensive equipment: only digital cameras are required. However, extensive computer software needs to be developed for the analysis of the data, and the calibration cage must be constructed. When the data was obtained using the CAT-scan method, the foot was stiffer and the flattened geometry was different than when the data was collected using the DLT method. The data reflect these different conditions. Both methods proved highly accurate in obtaining the spatial location of the anatomical landmarks and provided two distinct data sets to represent both the normal and the flat foot.

The results from our biomechanical model support the hypothesis that loss of the tibialis posterior muscle force increases the load on the ligaments supporting the first metatarsal–medial cuneiform, medial cuneiform–navicular and talo-navicular joints, and on the medial segments of the long plantar ligament and plantar aponeurosis. Our model predicts that when these ligaments are weakened, the load increases further and after the foot becomes flat, there is a large increase in the load on the medial arch. In flat foot, the mid-foot break may occur at the navicular–medial cuneiform joint (Greisberg et al., 2003; Vertullo and Nunley, 2002). This is consistent with the increased moments we calculated at the navicular–medial cuneiform joint for the flat foot. These predictions support experimental and clinical observations and suggest that acquired flat foot may be a time dependent multifactor sequence of events (Ananthakrisnan et al., 1999; Arangio and Salathe, 2001; Huang et al., 1993; Niki et al., 2003; Thordarson et al., 1995).

Our model predicts that a 10 mm medial slide calcaneal osteotomy reduces the percent of the body weight supported by the first and second metatarsals, increases the support provided by the fourth and fifth metatarsals, decreases the moments at the talo-navicular joint and decreases the force in the Achilles tendon in the flattened foot. This supports reported experimental data (Hadfield et al., 2003; Havenhill et al., 2005; Nyska et al., 2003; Scott et al., 2007). Medial slide calcaneal osteotomy results in a medial shift in the insertion of the Achilles tendon and the location of the support force under the calcaneus. This decreases the valgus moment of the Achilles tendon, decreasing as well the moments on the ligaments supporting the first metatarsal–medial cuneiform, medial–cuneiform–navicular and talo-navicular joints. The MDCO may not increase arch height and it does not correct forefoot abduction. In an earlier study (Arangio and Salathe, 2001) we used a simpler biomechanical model to study the effect of medial slide calcaneal osteotomy on the support distribution under the foot. That model did not include the muscles, tendons and ligaments, and so could not account for the medial shift in the insertion of the Achilles tendon or the alteration in the muscle forces resulting from medial slide calcaneal osteotomy, and it could not determine the forces in the ligaments supporting the joints of the foot.

In the present report, we also studied the effect of combining medial slide calcaneal osteotomy with flexor digitorum transfer to the navicular in the flattened foot condition. Our results indicate that flexor digitorum transfer to the navicular after medial slide calcaneal osteotomy had minimal effect on the percent load supported by each metatarsal head and the calcaneus, the moment at the joints of the medial column, the force provided by the long plantar ligament and plantar aponeurosis and forces in each of the six muscles studied. This is consistent with experimental observation (Watanabe et al., 2003). Rosenfeld et al. (2005) reported that the flexor digitorum longus (FDL) muscle hypertrophies 44% one year after transfer in response to posterior tibial tendon dysfunction. We simulated hypertrophy of the flexor digitorum transfer to the navicular by doubling the physiological cross sectional area of the digitorum longus. The simulated hypertrophied flexor digitorum transfer to the navicular had minimal effect on the flattened foot condition. Hui et al. (2007) reported, "in contrast to the clinical proposition that FDL transfer to the navicular or medial cuneiform increases this muscle's advantage to invert the hindfoot, this cadaver study suggests that to the contrary, FDL muscle arms decrease after transfer." We also analyzed the flexor digitorum transfer to the navicular in the weakened ligament condition before the foot was made flat and found a small decrease in the medial arch moments from 6.84 N m to 6.81 N m.

Our study is limited in that we used a normal foot made into a flat foot and our model is applicable only during stance phase. More studies and modeling are required to calculate the precise amount of medial slide and calcaneal lengthening necessary in a given patient with heel valgus, decrease in arch height and forefoot abduction.

5. Conclusions

Our analysis shows that as posterior tibial tendon and medial arch ligament insufficiency develops the forces on the medial arch increase, and as the foot becomes flat the moments at the joints of the medial rays show very large increases. A 10 mm medial slide calcaneal osteotomy substantially decreases the moments on the talo-navicular joint and the load on the medical arch in the flat foot toward normal. Our analysis also shows that adding the flexor digitorum longus transfer to the navicular further decreases the load on the talo-navicular joint by less than 1% beyond that achieved with the MDCO alone.

Conflict of Interest

There are no sources of funding or other conflicts of interest associated with this work.

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