Comparison of Proximal and Distal Oblique Second Metatarsal Osteotomies with Varying Achilles Tendon Tension

Biomechanical Study in a Cadaver Model

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Background: The optimal surgery for reducing pressure under the second metatarsal head to treat metatarsalgia is unknown. We tested our hypothesis that a proximal oblique dorsiflexion osteotomy of the second metatarsal would decrease second-metatarsal plantar pressures in a cadaver model with varying Achilles tendon tension. We also tested the plantar pressure effects of two popular techniques of distal oblique osteotomy.

Methods: Twelve fresh-frozen feet from six cadavers were randomly assigned to either the distal osteotomy group (a classic distal oblique osteotomy followed by a modified distal oblique osteotomy) or proximal metatarsal osteotomy group. Each specimen was tested intact and then after the osteotomy or osteotomies. The feet were loaded with 0, 300, and 600 N of Achilles tendon tension and a 400-N ground reaction force. Plantar pressures were measured by a pressure sensitive mat and analyzed in sections located under each metatarsal.

Results: The proximal metatarsal osteotomy significantly reduced average pressures beneath the second metatarsal head during both 300 and 600 N of Achilles tendon loading by an average of 19.4 and 29.7 kPa, respectively ($p < 0.05$). The modified distal oblique osteotomy significantly decreased these pressures during 600 N of Achilles tendon loading, by a mean of 20.2 kPa, which was to a lesser extent than the proximal metatarsal osteotomy. Interestingly, the classic distal oblique osteotomy was not found to have significant effects on pressures beneath the second metatarsal head.

Conclusions: The proximal oblique dorsiflexion metatarsal osteotomy may be the most effective procedure for decreasing plantar pressures under the second metatarsal. The modified distal oblique osteotomy may be the second most effective.

Clinical Relevance: The findings of this biomechanical study help shed light on which of the common second metatarsal osteotomies are best for decreasing plantar pressures.

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Metatarsalgia is a common chief symptom among patients presenting to foot and ankle clinics. Gagnon¹ and Helal² provided early descriptions of metatarsal

osteotomy techniques for the treatment of metatarsalgia. Weil and Barouk popularized the distal metatarsal shortening osteotomy in Europe in 1992³. The distal oblique osteotomy

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gained popularity in the United States in the next decade and is sometimes referred to as the Weil osteotomy. The role of this osteotomy in the treatment of metatarsalgia was described as bringing the metatarsal head behind the callus, thus decreasing the plantar pressure underneath³. Both distal and proximal oblique osteotomies have been found to be fairly effective for treating this condition⁴⁻⁷, but there is uncertainty as to which of the operations is optimal. The biomechanical effects of these procedures on plantar pressures are complex, especially when considering active muscle forces such as those via the Achilles tendon, and there are conflicting reports in the biomechanical literature regarding whether distal oblique osteotomy has any therapeutic effect on the increased plantar pressures⁸. A serious complication of distal oblique osteotomy is “floating toe” due to plantar flexion of the metatarsal head and dorsal pull of the intrinsic muscle, which conflicts with the aim of the osteotomy⁹. Segmental resection of bone resulting in dorsal translation (modified distal oblique osteotomy) is currently recommended to reduce the risk of this complication and provide better results¹⁰.

Previous biomechanical cadaver studies of the effects of osteotomies for metatarsalgia on plantar pressures have had mixed results. Snyder et al.¹¹ demonstrated no significant

change due to distal oblique osteotomy, whereas Khalafi et al.¹² found a significant decrease in second-metatarsal plantar pressure that was magnified with simulated heel rise. Cadaveric modeling of modified distal oblique osteotomies by Lau et al.⁸ did not show that these modifications affected plantar pressure, although the study did not include loading of any muscles. Trask et al. examined the effect of the obliquity of proximal diaphyseal osteotomies with regard to off-loading of the second metatarsal head and found that osteotomies directed from dorsal proximal to plantar distal were more effective than the reverse¹³. Primary limitations of some previous investigations include not using a stable fixation (e.g., screw) method for the osteotomy and the exclusion of muscle forces such as those via the Achilles tendon. The force of the Achilles tendon varies for different activities and disease states that may be related to metatarsalgia^{14,15}.

In this study, we tested the effects of the proximal oblique dorsiflexion osteotomy and two distal oblique osteotomies on plantar pressures beneath the first, second, and third metatarsals in the presence of a controlled ground reaction force and different static Achilles tendon tensions. Our primary hypothesis was that the proximal metatarsal osteotomy would decrease second-metatarsal plantar pressures.

Fig. 1

Schematics of the distal oblique, modified distal oblique, and proximal oblique dorsiflexion osteotomies. In the distal oblique osteotomy, the metatarsal head is translated 3 mm proximally. In the modified distal oblique osteotomy, a 3-mm section of bone is also resected, resulting in both dorsal and proximal translation of the metatarsal head. In the proximal oblique osteotomy, a 3-mm dorsally based wedge is resected at a 45° angle. The horizontal dotted reference line assists visualization of potential changes in the height of the metatarsal head in relation to the plantar surface. (Reproduced with permission of Devon Stuart, MA, CMI, Devon Medical Art.)

Materials and Methods

Specimens

Twelve matched fresh-frozen cadaver feet from six donors were tested. The sample size was chosen on the basis of similar sample sizes used in previous cadaver studies of osteotomies for metatarsalgia^{11,12}. There were four female and two male donors, ranging in age from forty-seven to fifty-eight years (mean age, 51.3 years) at the time of death. The specimens had no discernible signs of a previous surgical procedure or deformity related to arthritis. The left and right feet from the same donor were each randomly assigned to either the distal oblique osteotomy group (classic followed by modified distal oblique osteotomy, $n = 6$) or the proximal oblique shortening group ($n = 6$). Each specimen was tested intact and then after the osteotomy or osteotomies.

Osteotomies

The osteotomies were performed by the first author (U.A.), a foot and ankle fellowship-trained orthopaedic surgeon, or by a foot and ankle fellow (B.M.) under the direction of the first author. All distances were measured with use of a ruler, and a headless compression screw was used for fixation. The stability of the fixation following the osteotomy was manually confirmed; no failure of the fixation sites was observed during testing.

The distal oblique osteotomy was performed with a microsagittal saw parallel to the floor through the dorsal one-third of the metatarsal head 2 mm distal to the articular surface and translated proximally 3 mm. The site was fixed with a 2.4-mm cannulated screw (Fig. 1).

The modified distal oblique procedure was performed with a parallel resection of 3 mm of bone, equal to the proximal translation. This created an overall 5-mm dorsal translation of the metatarsal head (3-mm bone thickness + 2×1 -mm saw thickness), compared with the 1 mm resulting from the saw thickness in the traditional distal oblique osteotomy (Fig. 1). The resected bone was visually checked for parallelism of the cut surfaces. This procedure was performed following the distal oblique osteotomy in the same specimens, and with use of the same screw hole to secure the fragments.

The proximal oblique dorsiflexion osteotomy was performed with a microsagittal saw, and a 3-mm dorsally based wedge was resected at a 45° angle. The osteotomy started 1 cm distal to the metatarsal base and proceeded proximal to distal. It was fixed with a 2.4-mm cannulated screw (Fig. 1).

Load Application Setup

The feet were statically loaded by downward force on the tibia and simultaneous tensioning of the Achilles tendon while the foot rested on a pressure mat (Fig. 2). The exposed proximal part of the tibia was potted in a PVC (polyvinyl chloride) pipe and then rigidly fastened, with use of a fixture and set screws, to the vertical actuator of a servohydraulic mechanical testing machine (FlexTest 40 Controller; MTS Systems). The Achilles tendon was fastened with a liquid nitrogen freeze clamp to a wire cable that passed over a pulley to create a physiologic line of action of the tendon¹⁶. The cable was tensioned by a pneumatic cylinder with an in-line S-type load cell (LC101-500; Omegadyne), which was precalibrated with static weights. Pressure was adjusted by a regulator until the desired Achilles tendon force was confirmed by the load cell.

Pressure Mat and Ground Reaction Force

The plantar surface of the foot rested on a pressure mat (emed; novel) (2 sensels/cm²). The mat was fastened to an axial load cell (model 1010ACK-500-B, 2224-N capacity, eccentric load compensated; Interface) beneath it, which measured ground reaction force. The load cell was fastened to a horizontal bearing (four ball transfers) beneath it. After the tibia was attached to the actuator in a vertical orientation, load was gradually increased on the tibia until the ground reaction force reached 400 N, approximately half of the average body weight of humans. The horizontal bearing removed constraint in the mediolateral and anteroposterior directions and in horizontal plane rotation during axial loading, allowing the foot to find a more natural position.

Anatomical Trial

Without Achilles tendon load applied, a series of anatomical landmarks were manually compressed while pressure mat data were recorded. Landmarks included the head of each metatarsal, the posteriormost point of the heel, and the medial and lateral aspects of the forefoot. These pressure data were used for segmentation of the plantar pressure data as described below.

Achilles Tendon Loading

The Achilles tendon force was gradually set to 0, 300, or 600 N, while plantar-oriented tibial force (servohydraulic actuator displacement) was simultaneously adjusted to maintain a constant ground reaction force of 400 N. Once the desired

Fig. 2

Schematic and photograph of the experimental apparatus for mechanical loading of the cadaver feet. The Achilles tendon is loaded with 0, 300, or 600 N while the tibia is pressed down to induce a ground reaction force of 400 N. The bearing enables unconstrained mediolateral and anteroposterior translation and horizontal plane rotation to enable the foot to find a more natural position during loading.

TABLE I Comparison Among Osteotomy Groups of Post-Osteotomy Minus Pre-Osteotomy Pressures in the Same Foot

	Mean Pressure Change (Standard Deviation) (kPa), P Value					
	300-N Achilles Tendon Force			600-N Achilles Tendon Force		
	First Metatarsal	Second Metatarsal	Third Metatarsal	First Metatarsal	Second Metatarsal	Third Metatarsal
Average pressure						
Distal oblique osteotomy	-1.9 (10.2), 1.0	+0.4 (6.2), 1.0	+2.8 (6.8), 1.0	-5.0 (10.7), 1.0	+0.7 (11.7), 1.0	+2.5 (11.3), 1.0
Modified distal oblique osteotomy	+3.8 (10.5), 1.0	-12.7 (15.5), 0.17	+1.8 (8.4), 1.0	+4.2 (14.0), 1.0	-20.2 (20.7), 0.044*	+2.2 (7.2), 1.0
Proximal oblique osteotomy	+12.9 (7.3), 0.031*	-19.4 (9.7), <0.001*	-9.1 (10.0), 0.24	+16.5 (11.9), 0.46	-29.7 (20.7), 0.017*	-15.9 (22.3), 0.53
Peak pressure						
Distal oblique osteotomy	+5.0 (28.1), 1.0	+13.3 (19.1), 1.0	+7.5 (15.4), 1.0	-15.0 (30.5), 1.0	+23.3 (19.4), 0.35	+16.7 (29.4), 1.0
Modified distal oblique osteotomy	+16.7 (18.9), 1.0	-17.5 (27.3), 1.0	+15.0 (33.0), 1.0	+15.0 (35.8), 1.0	-36.7 (59.6), 1.0	+26.7 (54.3), 1.0
Proximal oblique osteotomy	+60.0 (39.5), 0.011*	-26.7 (22.7), 0.83	-1.7 (42.6), 1.0	+92.5 (106.1), 0.10	-49.2 (29.7), 1.0	-13.3 (78.9), 1.0

*A significant difference ($p < 0.05$) from zero (with zero indicating no change due to surgery).

forces were reached, plantar pressures were recorded over a ten-second trial. The foot maintained a flat position during testing. Each specimen was tested intact and then after the osteotomy or osteotomies.

Plantar Pressure Analysis

Average pressures, peak pressures, and contact areas were computed for the first, second, and third metatarsal regions with use of the emed software accompanying the pressure mat. Foot masks were automatically defined by the automask program and confirmed or adjusted by using the anatomical landmark trials.

Statistical Analysis

Differences in average pressures, peak pressures, and contact areas were determined between the pre-osteotomy and post-osteotomy conditions for each type of surgery and for each metatarsal region. A linear mixed-effects statistical model (SAS software, version 9.4; SAS Institute) was used to test if differences were significantly different from zero. The linear mixed-effects model takes into account the within-subject correlation inherent in this repeated-measures design involving twelve matched feet from six cadavers. P values were adjusted for multiple comparisons by using the Bonferroni method to account for up to nine tests (three types of surgery $\times$ three metatarsal regions) to ensure that the family-wise type-I error was 0.05. The above analysis was repeated for each of the three Achilles tendon force levels.

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Results

Before the surgical procedures, with 300 N of Achilles tendon force applied, the average plantar pressures (over each metatarsal zone) were a mean (and standard deviation) of 53.3 ± 14.3 , 58.0 ± 16.6 , and 49.5 ± 9.9 kPa under the first, second, and third metatarsals, respectively (Fig. 3). Peak pressures averaged 111.7 ± 43.3 , 100.8 ± 27.4 , and 90 ± 17.6 kPa, respectively.

The classic distal oblique osteotomy had only small, non-significant effects on plantar pressures under the first, second, and third metatarsals (Table I and Fig. 4). The modified distal oblique osteotomy significantly decreased the average pressure

by a mean of 20.2 ± 20.7 kPa beneath the second metatarsal under a 600-N Achilles tendon load ($p = 0.044$), but the pressure decrease was not significant under a 300-N Achilles tendon load ($p = 0.17$).

The proximal oblique osteotomy significantly decreased the average pressure under the second metatarsal by a mean of 19.4 ± 9.7 kPa when the Achilles tendon force was 300 N ($p < 0.001$) and 29.7 ± 20.7 kPa when the Achilles tendon force was 600 N ($p < 0.017$) (Table I and Fig. 4). This surgery significantly increased the average and peak pressures under the first metatarsal when the Achilles tendon load was 300 N (Table I and Fig. 4). There were trends of decreased pressure under the third metatarsal following this surgery, but these decreases were not significant.

No significant differences in contact areas due to the osteotomies were detected. There were several trends between increasing Achilles tendon force and increasing effects

Fig. 3

Average pressures (± 1 standard deviation) under the first, second, and third metatarsals measured before the osteotomies, with application of the three different Achilles tendon forces. For all test conditions, the total ground reaction force was constant.

Fig. 4
Effects of the three different osteotomies on the average plantar pressures under the first, second, and third metatarsals (met). The bars indicate the difference relative to pre-osteotomy pressures measured in the same foot. Error bars indicate the standard error, and significance is indicated by an asterisk.

of the osteotomies (Fig. 4), but these effects were not statistically analyzed.

Discussion

Our results show that the proximal oblique osteotomy of the second metatarsal significantly reduced plantar pressures under the second metatarsal head in the presence of both 300 N and 600 N of Achilles tendon loading (Table I and Fig. 4). Pressures under the first metatarsal head were increased, indicating that the proximal oblique osteotomy may be effective in shifting load from the second to the first metatarsal head. The modified distal oblique osteotomy resulted in significant decreases in average pressures under the second metatarsal head, but only in the presence of the higher Achilles tendon force.

The distal oblique osteotomy was shown clinically to have good-to-excellent results in 88% of cases at the time of midterm follow-up in a prospective study⁶. Interestingly, that study did not show that classic distal oblique osteotomy is

effective in reducing plantar pressure under the second metatarsal head. Our study provides data suggesting that the proximal metatarsal osteotomy may be more effective in off-loading the second metatarsal than either the classic or the modified distal oblique osteotomy. The distal oblique osteotomy may act through a different mechanism in the treatment of metatarsalgia, perhaps not decreasing pressure but shifting pressure posteriorly to a more favorable location, or decreasing stress at the metatarsophalangeal joint. Furthermore, our data suggest that, if a distal osteotomy is indicated, the modified—instead of the classic—distal oblique osteotomy should be chosen to reduce pressure under the second metatarsal.

Our findings contrast somewhat with those of Khalafi et al.¹², who reported that the classic distal oblique osteotomy decreased pressure beneath the second metatarsal head associated with a 500-N tibial load. They performed a classic distal oblique osteotomy with 5 mm of proximal translation of the metatarsal head and utilized a Kirschner wire for fixation. Differences with our study's findings may be explained partly by differences in the amount of proximal translation and Achilles tendon loading. In our study, we shortened the metatarsal by only 3 mm (as is done in the original technique), compared with 5 mm in the procedures performed by Khalafi et al.; overshortening in the clinical scenario can lead to transfer metatarsalgia. Their study simulated both a plantigrade and a heel-rise position, but the Achilles tendon force was applied by a turnbuckle, which produced an unquantified force magnitude. It is also notable that Khalafi et al. performed the osteotomies in only three pairs of specimens. The results of the classic distal oblique osteotomy in our study are more in agreement with those of Lau et al.⁸. In that study, a classic oblique Weil osteotomy, a modified Weil osteotomy with a wedge resection, and a metatarsal head resection were compared in a cadaver model with 700 N of cyclical tibial loading and the ankle dorsiflexed 30°. Lau et al. found that only the metatarsal head resection significantly reduced plantar pressure.

Our findings are generally in agreement with those in a recent cadaver study by Trask et al.¹³, who used a complex, realistic gait simulator that included Achilles tendon load and other muscles. Their study focused on the influence of the osteotomy plane and magnitude of shortening on plantar pressures, and showed proximal osteotomy to have greater efficacy than distal osteotomy. We chose a proximal-to-distal oblique osteotomy angulation in our study to use metaphyseal bone for better fixation and hypothetical fusion of the osteotomy site.

The Achilles tendon provides the largest muscle force acting on the foot, and previous studies have demonstrated that increased Achilles tendon tension shifts pressures from the hindfoot to the forefoot^{15,17}. In our study, we applied several different magnitudes of Achilles tendon force because the influence of the Achilles tendon varies during different activities and across disease states. Our study provides data trends (Figs. 3 and 4) regarding the importance of Achilles tendon loading, and these data have implications for patients with Achilles tendon contracture in conjunction with metatarsalgia. Diabetic

patients with Achilles tendon contracture have higher peak plantar pressures than those without ankle equinus¹⁸, and forefoot pressure has been found to decrease after Achilles tendon lengthening¹⁴. A prospective randomized study showed that patients with diabetes who had undergone Achilles tendon lengthening had a decreased rate of forefoot reulceration, transiently decreased forefoot pressure, and increased heel pressure¹⁹. Evidence from these studies and ours supports the concept that Achilles tendon or gastrocnemius lengthening should be added to any metatarsal head off-loading procedure in the presence of a contracted Achilles tendon.

There is retrospective evidence that the distal oblique osteotomy is often safe and effective despite a modest rate of complications^{4,7,20}. Common complications include nonunion, malunion, transfer metatarsalgia if the metatarsal is over-shortened, continued pain if it is undershortened, metatarsophalangeal joint stiffness, and floating toe^{21,22}. Miguez et al.²² found a rate of floating toe of 54% (thirty-eight of seventy) when a distal oblique osteotomy had been combined with a proximal interphalangeal arthroplasty. Most of the problems, such as joint stiffness and floating toe, associated with distal oblique osteotomies may result from plantar flexion of the metatarsal head and the intra-articular approach used for the osteotomy. Dorsal translation by using a modified distal oblique or proximal oblique osteotomy technique likely minimizes the rate of the floating-toe complication. A proximal oblique osteotomy also decreases the rate of joint stiffness as it is performed through an extra-articular approach. The proximal osteotomy is a more technically demanding procedure, however, because of the need to avoid neurovascular structures, to use fluoroscopy, and to obtain more exposure than is needed for the distal osteotomy procedures. Furthermore, the site of the proximal osteotomy is probably exposed to higher forces during gait and requires more off-loading after surgery to allow adequate healing²³.

This study was limited by the testing of only six matched pairs of cadaver feet (twelve feet in total). An increased sample size might have resulted in additional significant associations, such as between the modified distal oblique osteotomy and a reduction in pressure under the second metatarsal during application of a 300-N Achilles tendon force. Even though our sample size was limited, however, we corrected for multiple

hypothesis testing to better control type-I error. Another limitation is that we only tested a static position with the foot flat; testing in the heel-rise position would be very useful in future studies. Although a heel-rise position was not tested in this study, when we applied the larger (600-N) Achilles tendon force it was noted that the plantar pressures shifted anteriorly and heel pressures tended to diminish, indicating a state nearer to heel rise. Our experimental design was based on the assumption that the results of the modified distal oblique osteotomy were not affected by the initial testing of the classic distal oblique osteotomy in the same foot. The rationale for this assumption was that the modified osteotomy was similar to the classic distal oblique osteotomy except that it removed more bone. Our experimental design did not directly compare these two procedures with one another. Reproducibility of results within individual specimen(s) was not formally tested, and the Achilles tendon was loaded but no other, smaller extrinsic or intrinsic muscle forces were applied. Biomechanical studies of multiple osteotomies in tandem are an interesting area for future study. It is important to confirm our findings in this controlled, simplified cadaver model with clinical studies measuring plantar pressures in this patient population before and after these procedures. ■

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References

- Gagnon PA. [Oblique metatarsal osteotomy in the surgical treatment of plantar keratosis]. *Union Med Can.* 1968 Jan;97(1):32-6. French.
- Helal B. Metatarsal osteotomy for metatarsalgia. *J Bone Joint Surg Br.* 1975 May;57(2):187-92.
- Barouk LS. [Weil's metatarsal osteotomy in the treatment of metatarsalgia]. *Orthopade.* 1996 Aug;25(4):338-44. German.
- Beech I, Rees S, Tagoe M. A retrospective review of the Weil metatarsal osteotomy for lesser metatarsal deformities: an intermediate follow-up analysis. *J Foot Ankle Surg.* 2005 Sep-Oct;44(5):358-64.
- Espinosa N, Maceira E, Myerson MS. Current concept review: metatarsalgia. *Foot Ankle Int.* 2008 Aug;29(8):871-9.
- Hofstaetter SG, Hofstaetter JG, Petroutsas JA, Gruber F, Ritschl P, Trnka HJ. The Weil osteotomy: a seven-year follow-up. *J Bone Joint Surg Br.* 2005 Nov;87(11):1507-11.
- Trnka HJ, Mühlbauer M, Zettl R, Myerson MS, Ritschl P. Comparison of the results of the Weil and Helal osteotomies for the treatment of metatarsalgia secondary to dislocation of the lesser metatarsophalangeal joints. *Foot Ankle Int.* 1999 Feb;20(2):72-9.
- Lau JT, Stamatis ED, Parks BG, Schon LC. Modifications of the Weil osteotomy have no effect on plantar pressure. *Clin Orthop Relat Res.* 2004 Apr;421:194-8.
- Perez HR, Reber LK, Christensen JC. The role of passive plantar flexion in floating toes following Weil osteotomy. *J Foot Ankle Surg.* 2008 Nov-Dec;47(6):520-6. Epub 2008 Sep 27.
- Garg R, Thordarson DB, Schrupp M, Castaneda D. Sliding oblique versus segmental resection osteotomies for lesser metatarsophalangeal joint pathology. *Foot Ankle Int.* 2008 Oct;29(10):1009-14.
- Snyder J, Owen J, Wayne J, Adelaar R. Plantar pressure and load in cadaver feet after a Weil or chevron osteotomy. *Foot Ankle Int.* 2005 Feb;26(2):158-65.

- 12.** Khalafi A, Landsman AS, Lautenschlager EP, Kelikian AS. Plantar forefoot pressure changes after second metatarsal neck osteotomy. *Foot Ankle Int.* 2005 Jul;26(7):550-5.
- 13.** Trask DJ, Ledoux WR, Whittaker EC, Roush GC, Sangeorzan BJ. Second metatarsal osteotomies for metatarsalgia: a robotic cadaveric study of the effect of osteotomy plane and metatarsal shortening on plantar pressure. *J Orthop Res.* 2014 Mar;32(3):385-93. Epub 2013 Nov 14.
- 14.** Armstrong DG, Stacpoole-Shea S, Nguyen H, Harkless LB. Lengthening of the Achilles tendon in diabetic patients who are at high risk for ulceration of the foot. *J Bone Joint Surg Am.* 1999 Apr;81(4):535-8.
- 15.** Aronow MS, Diaz-Doran V, Sullivan RJ, Adams DJ. The effect of triceps surae contracture force on plantar foot pressure distribution. *Foot Ankle Int.* 2006 Jan;27(1):43-52.
- 16.** Sharkey NA, Smith TS, Lundmark DC. Freeze clamping musculo-tendinous junctions for in vitro simulation of joint mechanics. *J Biomech.* 1995 May;28(5):631-5.
- 17.** Jones RL. The human foot. An experimental study of its mechanics, and the role of its muscles and ligaments in the support of the arch. *Am J Anat.* 1941;68(1):1-39.
- 18.** Lavery LA, Armstrong DG, Boulton AJ; Diabetex Research Group. Ankle equinus deformity and its relationship to high plantar pressure in a large population with diabetes mellitus. *J Am Podiatr Med Assoc.* 2002 Oct;92(9):479-82.
- 19.** Mueller MJ, Sinacore DR, Hastings MK, Strube MJ, Johnson JE. Effect of Achilles tendon lengthening on neuropathic plantar ulcers. A randomized clinical trial. *J Bone Joint Surg Am.* 2003 Aug;85(8):1436-45.
- 20.** Vandeputte G, Dereymaeker G, Steenwerckx A, Peeraer L. The Weil osteotomy of the lesser metatarsals: a clinical and pedobarographic follow-up study. *Foot Ankle Int.* 2000 May;21(5):370-4.
- 21.** Highlander P, VonHerbulis E, Gonzalez A, Britt J, Buchman J. Complications of the Weil osteotomy. *Foot Ankle Spec.* 2011 Jun;4(3):165-70. Epub 2011 Apr 13.
- 22.** Migués A, Slullitel G, Bilbao F, Carrasco M, Solari G. Floating-toe deformity as a complication of the Weil osteotomy. *Foot Ankle Int.* 2004 Sep;25(9):609-13.
- 23.** Pearce CJ, Calder JD. Metatarsalgia: proximal metatarsal osteotomies. *Foot Ankle Clin.* 2011 Dec;16(4):597-608. Epub 2011 Oct 8.