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Six First Metatarsal Shaft Osteotomies

Mechanical and Immobilization Comparisons

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Because malunion (usually with dorsal elevation of the first metatarsal) has been reported after the treatment of severe hallux valgus deformities by proximal osteotomies, the current study was designed to compare the sagittal stability of six different metatarsal shaft osteotomies: the proximal crescentic, proximal chevron, Mau, Scarf, Ludloff, and biplanar closing wedge osteotomies. A plate was used in the biplanar closing wedge osteotomy; all others used screws for fixation. Ten fresh-frozen, human anatomic lower extremity specimens were used for each osteotomy. Failure loads were measured as units of force (newtons) and converted to pressure (kilopascals). Then the F-Scan system, which uses a thin insole to measure plantar pressure, was used to evaluate the pressure under the first metatarsal of seven volunteers using four types of shoes. According to the results, in patients with normal bone stock who are compliant, any of the four shoe types tested may be used after a Ludloff, Scarf, biplanar wedge (plantar screw fixation), or Mau osteotomy, but the wedge-based shoe should be used after a proximal crescentic or chevron osteotomy or for patients with severe osteopenic bone.

In Western society, hallux valgus deformity has become an increasingly bothersome condition for which more than 130 surgical procedures have been described as treatment.[13] Distal osteotomies of the first metatarsal primarily are advocated for mild to moderate hallux valgus deformities. For more severe deformities, more proximal first metatarsal osteotomies have been performed because they have been proven mathematically to achieve greater correction.[12] The proximal crescentic,[10,17,32] proximal chevron,[10,26] Mau,[18,21] Scarf,[1,28] Ludloff,[8,16,27] and biplanar closing wedge osteotomies[6,22,24,33] are currently the most commonly used proximal metatarsal osteotomies.

Adequate fixation of osteotomies is necessary to ensure osseous union, and screw fixation generally is sufficient. However, despite adequate fixation, dorsiflexion of the first metatarsal is a complication after proximal metatarsal osteotomies in 28% to 82% of patients.[2,17,31–33] Dorsiflexion and shortening of the first metatarsal predisposes patients to develop new transfer lesions.[10] Progressive metatarsal elevation has been observed in several patients treated with adequate standard screw fixation. Pearson et al[23] stated that

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dorsal angulation frequently was not seen on early postoperative radiographs. Strausser et al[30] and Thompson[31] stated that dorsal displacement might occur intraoperatively because of poor technique, but that it also occurs postoperatively secondary to inadequate fixation or noncompliance with the postoperative regimen. Pedobarographic analysis has shown that substantial pressure exists under the first metatarsal head in stance and during normal walking. The literature reports that high peak pressure under the first metatarsal during walking varies from 147 to 311 kPa.[3–5,7,11,14]

The current study assesses the relative strength of the six most common proximal metatarsal osteotomies for correction of metatarsus primus varus, and correlates these results with the pressures measured under the first metatarsal in a normal shoe, a soft-soled postoperative shoe, a wooden-soled postoperative shoe, and a wedge-based postoperative shoe.

MATERIALS AND METHODS

Sample Preparation and Surgical Techniques

Sixty fresh-frozen, human anatomic lower extremity specimens were kept frozen at −20°C until use, at which point they were thawed at room temperature. The same experienced foot and ankle surgeon (H-JT) then performed each procedure, with no variance in the technique. All specimens were dissected out of the foot en bloc as the first metatarsal medial cuneiform complex. All soft tissues were dissected off the specimens with the exception of the metatarsocuneiform joint capsule, which was left intact.

Proximal Crescentic Osteotomy

For the proximal crescentic osteotomy[10,17,32] (Fig 1A), the dorsal metatarsal cortex was predrilled with a 3.5-mm drill bit 10 mm distal to the proposed osteotomy site, which was 12 mm distal to the metatarsocuneiform joint. The osteotomy then was performed with an oscillating saw and a crescentic saw blade, with the concavity facing proximally. The cut was made with the saw blade positioned at an angle halfway between perpendicular to the plantar surface of the foot and perpendicular to the dorsal cortex of the metatarsal. The distal fragment was rotated to achieve correction and temporarily fixed in place with a 0.062-inch Kirschner (K) wire. The osteotomy then was drilled through the near cortex pilot hole with a 2.5-mm drill bit through the plantar cortex, followed by insertion of a 4-mm cancellous lag screw.

Proximal Chevron Osteotomy

The proximal chevron osteotomy[10,26,30] (Fig 1B) was performed on the medial aspect of the first

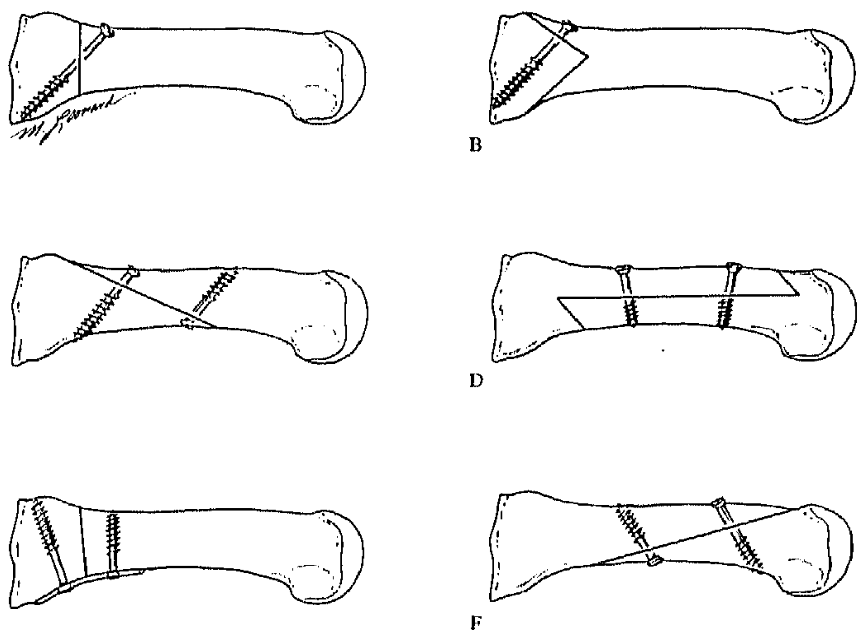


Fig 1. The six osteotomy techniques. (A) Proximal crescentic; (B) proximal chevron; (C) Ludloff; (D) Scarf; (E) biplanar closing wedge; and (F) Mau.

metatarsal, 15 mm distal to the metatarsocuneiform joint. The apex of the osteotomy was directed distally, and a 0.045-inch K wire was inserted to mark the apex. A microsagittal saw was used to complete the osteotomy, and the distal fragment was shifted laterally. A guide wire for the 3.5-mm cannulated screw was inserted across the osteotomy, overdrilled with a 2.5-mm drill bit through the plantar cortex, and followed by insertion of a 3.5-mm cortical screw.

Ludloff Osteotomy

For the Ludloff osteotomy[8,16,27] (Fig 1C), an oblique osteotomy was made at the first metatarsal, beginning dorsally 5 mm distal to the metatarsocuneiform joint, aiming distally and ending proximal to the sesamoid apparatus; the dorsal ⅔ of the osteotomy were completed first. A guide wire for the 3.5-mm cannulated screw was inserted across the osteotomy, overdrilled with a 2.5-mm drill bit through the plantar cortex, and followed by insertion of a 3.5-mm cortical screw without total closing of the osteotomy. The osteotomy then was finished distally, and a second 3.5-mm cortical screw was inserted from plantar to dorsal.

Scarf Osteotomy

For the Scarf osteotomy[1,20,28] (Fig 1D), two 0.045-inch K wires were inserted from medial to lateral at the site of the apices of the three arms of the Z. The first arm of the osteotomy was performed between the two guide wires from medially to laterally with a 20° plantar tilt. The proximal cut was angled 70° plantarly and distally with respect to the horizontal limb, and the distal cut was aimed 70° dorsally and plantarly. The dorsal fragment was transposed laterally, and fixation was achieved with two 3.5-mm cannulated cortical screws.

Biplanar Wedge Osteotomy

The biplanar wedge osteotomy[22,24,33,34] (Fig 1E) was performed 12 mm distal to the metatarsocuneiform joint. The cuts were performed from the medial side with a microsagittal saw blade. A biplanar wedge with approximately 3- to 5-mm bases laterally and plantarly was removed, and rotation was performed, closing the site. Temporary fixation was achieved with a 0.062-inch K wire. The plantar aspect of the metatarsal was contoured with the saw blade to allow flush seating of the plate. A ⅓ tubular two hole AO plate was affixed to the specimen, with a 4-mm cancellous screw in the proximal fragment and a 3.5-mm cortical screw in the distal fragment.

Mau Osteotomy

For the Mau osteotomy[18,21] (Fig 1F), an oblique osteotomy was made at the first metatarsal from dorsal at the metatarsal neck area, aiming proximal to the base of the first metatarsal, and the dorsal ⅔ of the osteotomy were completed first. A guide wire for the 3.5-mm cannulated screw was inserted across the osteotomy, overdrilled with a 2.5-mm drill bit through the plantar cortex, and followed by insertion of a 3.5-mm cortical screw without total closing of the osteotomy. The osteotomy was finished proximally, and a second 3.5-mm cortical screw was inserted from plantar to dorsal.

Mechanical Testing

All specimens then were prepared for mechanical testing. Three 0.062-inch K wires were placed to transfix the metatarsocuneiform joint, with care to assure that no wire crossed the osteotomy site.[6,19] Each specimen was potted in a 2-inch polyvinyl chloride tube with polyester resin so that the resin held the cuneiform and metatarsal base fragment but did not incorporate the osteotomy site or fixation hardware. An extensometer was placed into predrilled holes in the proximal and distal fragments to allow measurement of the fracture gap (deflection) across the osteotomy without interfering with loading of the specimen. The polyvinyl chloride pipe was clamped with the metatarsal specimen inclined 15° to simulate the anatomic position. The plantar aspect of the metatarsal head then was loaded in a cantilever bending mode with a moment arm of 34 mm, using a servohydraulic MTS Mini Bionix test frame (MTS Systems Corp, Eden Prairie, MN) at a rate of 5 mm/minute. Load was applied continuously until failure (gross bony fracture, screw pull out, or gapping greater than 2 mm at the osteotomy site) (Fig 2). Failure loads were measured as units of force (N) and converted to pressure (kPa) based on a constant contact area of 2.5 cm^2 [e.g., $(100\ \text{N}/0.25) \times 10^{-3}\ \text{m}^2 = 400{,}000\ \text{N/m}^2 = 400\ \text{kPa}$] to allow comparison with the in-shoe pressure measurements.

Data Analysis

Data collection was performed with Testware (MTS Systems) and analysis was performed with Microsoft Excel (Microsoft Corp, Bellevue, WA). Load deflection curves were generated for each specimen, resulting in values for strength and

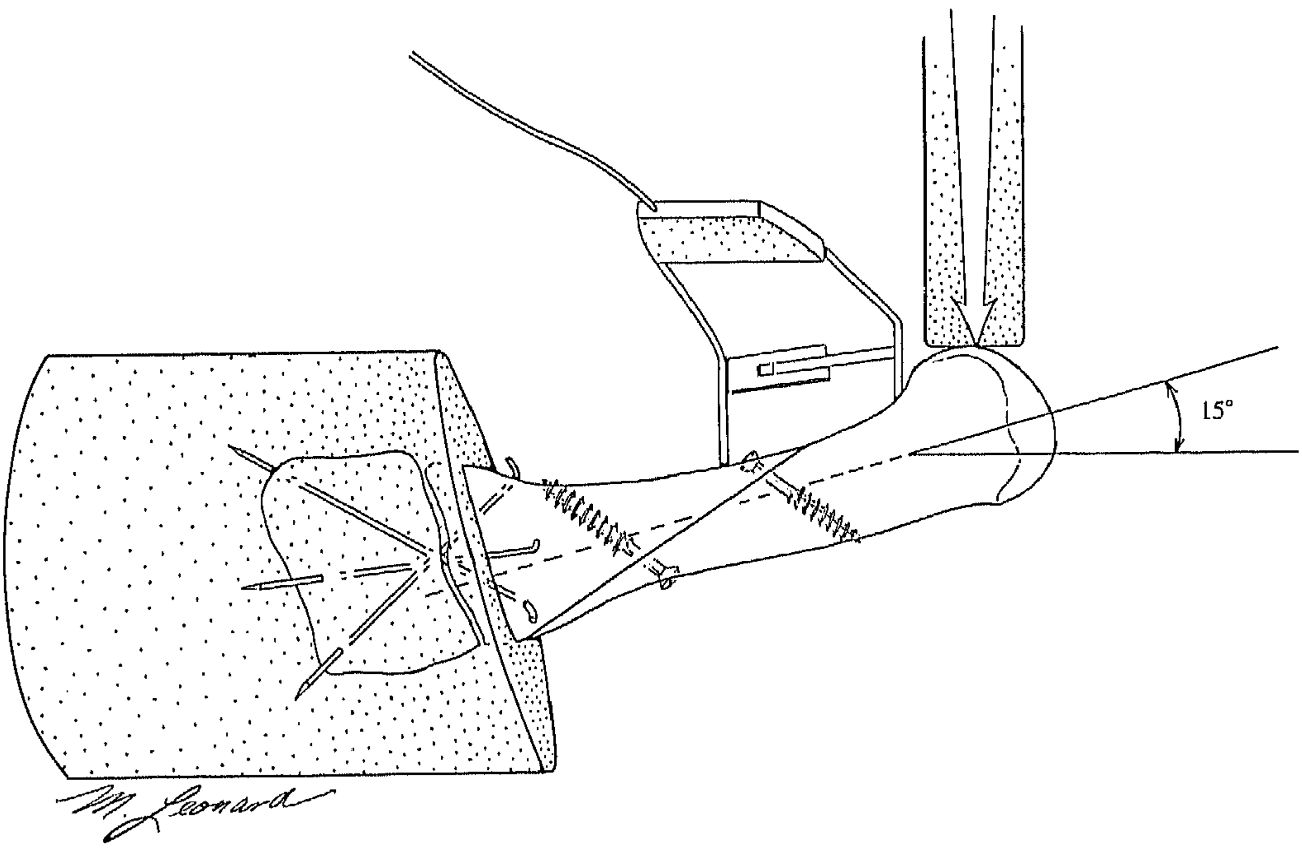


Fig 2. The mechanical test setup.

stiffness at the initial portion of the load deflection curve for all osteotomies. Statistical analysis of the data[6] consisted of a two-tailed Student's t test with significance set at $p < 0.05$.

In-Shoe First Metatarsal Plantar Pressure Measurements

To measure pressure under the first metatarsal during walking, seven control subjects who were asymptomatic were chosen and the F-Scan system (Tekscan, Boston, MA) was used as described by Rose et al.[25] The seven subjects (six men, one woman) had no previous history of foot problems and had normal feet. Their average age was 34.1 years (range, 29–45 years) and their average weight was 185.3 pounds (range, 140–305 pounds). The F-Scan system consists of a flexible pressure sensitive insole sensor, a 9-volt battery powered transducer unit, a 9.25-m long coaxial cable, gait analysis software, and a personal computer. The sensor is connected to the transducer unit, which is strapped to the patient's leg, and the coaxial cable connects the transducer to the computer. The sensor is designed in a grid of rows and columns. Each sensing trace is coated with pressure sensitive resistive ink so that a sensing cell is created at every grid intersection. The sensor may be trimmed to fit various shoes and various participants' shoe sizes (Fig 3). Using the area display mode, the area of peak pressure under the first metatarsal was identified and marked on a grid for each participant.

The F-Scan system was calibrated according to manufacturer's specifications for each participant before measuring. Each subject was tested in: (1) his/her normal shoes (those worn on a daily basis), (2) a soft-soled postoperative shoe (Medical-Surgical Shoe, Darco, Hungtington, WV; Fig 4A), (3) a wooden-soled postoperative shoe (Post-Op Shoe, State Medical Corp, Powel, TN; Fig 4B), and (4) a wedge-based postoperative shoe (OrthoWedge Healing Shoe, Darco; Fig 4C).

RESULTS

Osteotomy Testing

The strength of each osteotomy specimen was measured. The average strengths were: proximal crescentic osteotomy, 199.6 kPa (range, 48–600

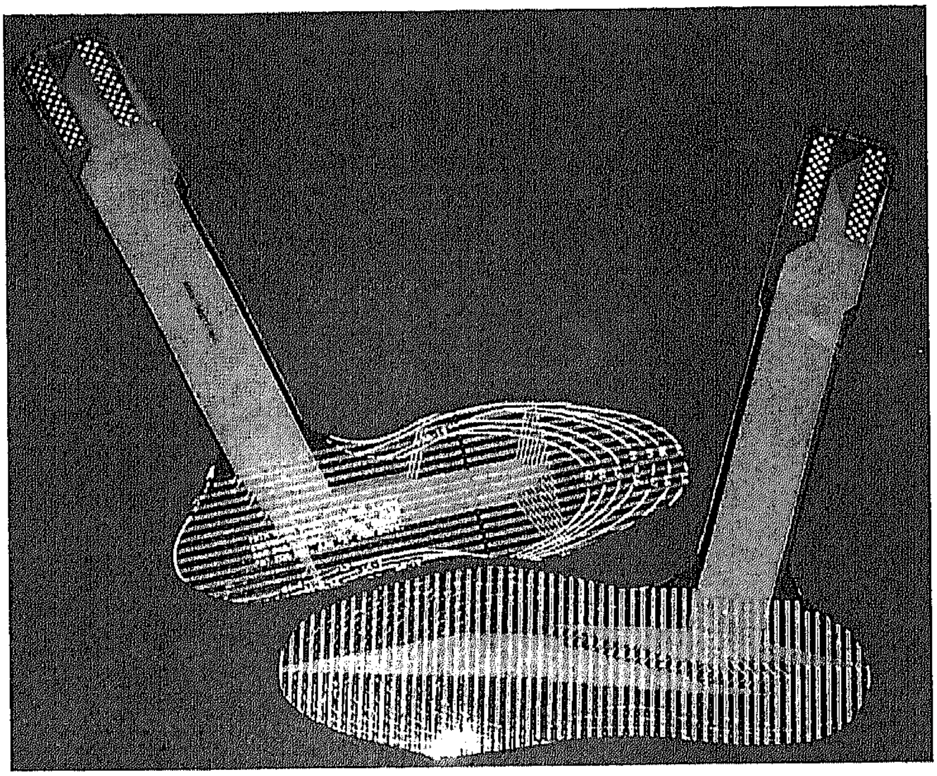
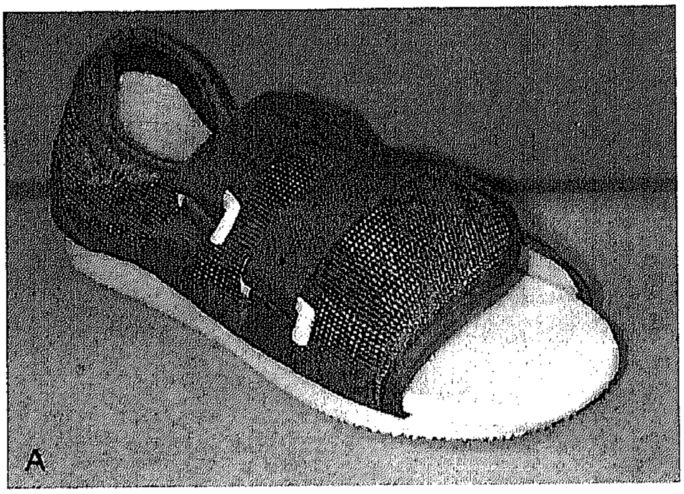
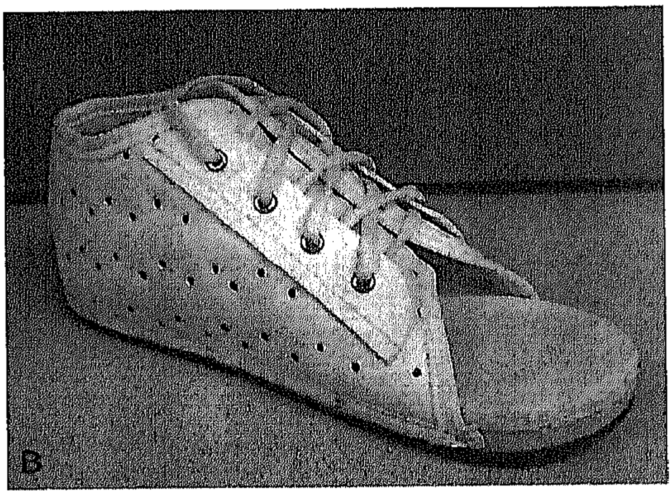


Fig 3. Flexible, pressure sensitive insoles, F-Scan system.





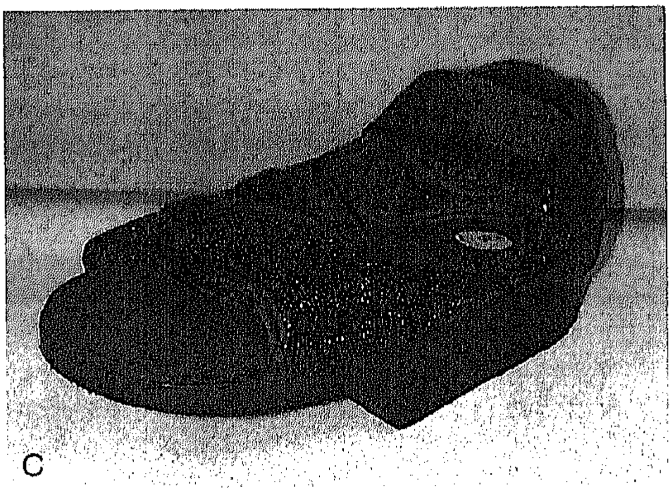


Fig 4. Postoperative shoes. (A) A soft-soled postoperative shoe (Medical-Surgical Shoe); (B) a wooden-soled postoperative shoe (Post-Op Shoe); and (C) a wedge-based postoperative shoe (OrthoWedge Healing Shoe).

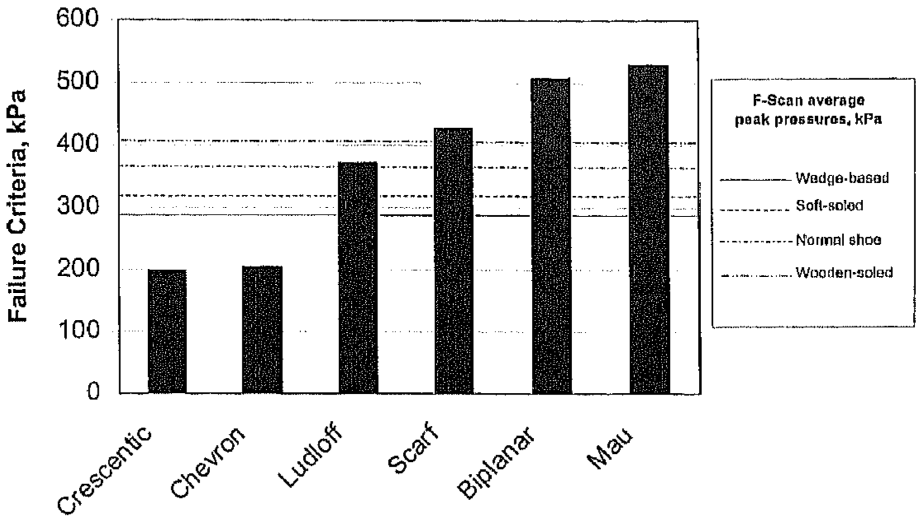


Fig 5. The mean strengths (measured in kPa) of the six osteotomies compared with pressure in a normal shoe.

kPa); proximal chevron osteotomy, 205.3 kPa (range, 96–332 kPa); Ludloff osteotomy, 372 kPa (range, 172–636); Scarf osteotomy, 428.4 kPa (range, 140–820 kPa); proximal closing wedge osteotomy (plantar plate), 508.8 kPa (range, 88–1044 kPa); and Mau osteotomy, 530.0 kPa (range, 248–856 kPa) (Fig 5).

There was no significant difference ($p = 0.86$) between the strength of the proximal crescentic and proximal chevron osteotomies, but that of the Ludloff value was significantly different from both ($p = 0.002$ and $p = 0.004$, respectively). The Scarf value was significantly higher than that of the proximal crescentic ($p = 0.008$) and proximal chevron osteotomies ($p = 0.002$), but not significantly different ($p = 0.49$) from that of the Ludloff osteotomy.

In terms of strength, the proximal crescentic ($p = 0.02$) and the proximal chevron ($p = 0.004$) osteotomies were significantly less stable than the proximal wedge osteotomy; the Ludloff ($p = 0.054$) and the Scarf ($p = 0.25$) osteotomies also were less stable than the proximal wedge osteotomy, but not significantly so. The Mau osteotomy was significantly stronger than the proximal crescentic ($p = 0.0004$) or the proximal chevron ($p = 0.00008$) osteotomies; the Ludloff ($p = 0.054$), Scarf ($p = 0.25$), and the proximal closing wedge osteotomies (plantar plate fixation) ($p = 0.86$) were less stable than the Mau osteotomy, but not significantly so (Table 1).

The average stiffnesses of the osteotomies were: Mau osteotomy, 180 N/mm (range, 50–337 N/mm); Ludloff osteotomy, 131 N/mm (range, 31–342 N/mm); Scarf osteotomy, 111 N/mm (range, 29–245 N/mm); proximal closing wedge osteotomy (plantar plate), 83 N/mm

TABLE 1. Statistical Comparison (p Value) of Average Strengths of the Six Osteotomy Types[a]

Type of Osteotomy	Mau	Biplanar	Scarf	Ladluff	Chevron
Mau					
Biplanar	0.86				
Scarf	0.25	0.52			
Ludloff	0.054	0.24	0.49		
Chevron	0.0002[b]	0.016[b]	0.007[b]	0.017[b]	
Crescentic	0.0008[b]	0.02[b]	0.0016[b]	0.04[b]	0.93

[a]Average strengths: Mau, 530 kPa; biplanar, 508 kPa; Scarf, 428 kPa; Ludloff, 372 kPa; chevron, 205 kPa; crescentic, 199 kPa.

[b]Statistically significant ($p \leq 0.05$).

TABLE 2. Statistical Comparison (p Value) of Average Stiffness of Six Osteotomy Types[a]

Type of Osteotomy	Mau	Biplanar	Scarf	Ludloff	Chevron
Mau					
Biplanar	0.02[b]				
Scarf	0.083	0.41			
Ludloff	0.245	0.21	0.59		
Chevron	0.001[b]	0.20	0.02[b]	0.02[b]	
Crescentic	0.0006[b]	0.11	0.02[b]	0.01[b]	0.52

[a]Average stiffness: Mau, 180 N/mm; biplanar, 83 N/mm; Scarf, 111 N/mm; Ludloff, 131 N/mm; chevron, 48 N/mm; crescentic, 35 N/mm.

[b]Statistically significant ($p \leq 0.05$).

(range, 16–227 N/mm); proximal chevron, 48 N/mm (range, 7–112 N/mm); and proximal crescentic osteotomy, 25 N/mm (range, 5–139 N/mm).

Statistical analysis of stiffness revealed significant differences between the Mau osteotomy and the proximal chevron osteotomy ($p = 0.001$) and between the Mau osteotomy and the proximal crescentic osteotomy ($p = 0.0006$). The differences in stiffness between the other osteotomies were not statistically significant (Table 2).

First Metatarsal Pressure Testing

Mean peak pressures (± standard deviation) under the first metatarsal were: normal shoe, 367.9 kPa ± 35.3 (range, 145–1040 kPa); soft-soled postoperative shoe, 328.7 kPa ± 16.1 (range, 197–561 kPa); wooden-soled postoperative shoe, 402.3 kPa ± 37.6 (range, 160–926 kPa); and wedge-based postoperative shoe, 290.8 kPa ± 14.5 (range, 132–610 kPa). Using the Tukey's range test, there was a statistically significant difference between the wooden-soled postoperative shoe and the wedge-based postoperative shoe ($p = 0.0389$) (Table 3).

DISCUSSION

Metatarsus primus varus is a common component in the hallux valgus deformity. More severe hallux valgus deformity with marked metatarsus primus varus (intermetatarsal angle > 15°) is corrected inadequately by distal osteotomies, and therefore proximal osteotomies

TABLE 3. Average Pressure by Shoe Type and Test Subject

Subject (weight)	Average Pressure in			
	Normal Shoe (kPa)	*Soft-Soled Shoe (kPa)*	*Wooden-Soled shoe (kPa)*	*Wedge-Based shoe (kPa)*
1 (145 pounds)	677	470	617	474
2 (165 pounds)	255	262	213	240
3 (166 pounds)	215	243	219	142
4 (305 pounds)	320	415	577	335
5 (182 pounds)	266	378	302	273
6 (185 pounds)	264	245	240	169
7 (158 pounds)	581	344	608	388
Overall average	368	329	402	290

are indicated. Numerous proximal metatarsal osteotomies have been described,[13] each with its own potential complications and problems.[31]

The first objective of the current study was to assess the relative strength of the six most common proximal metatarsal osteotomies for correction of metatarsus primus varus. The popular crescentic and the proximal chevron osteotomies are the gold standards for treatment of metatarsus primus varus. The proximal closing wedge technique with a modified plantar plate fixation was reported recently by Campbell et al.[6] Because of its stability, they recommended this technique for treatment of patients at risk for fixation failure, such as those with severe osteopenic bone or those deemed at risk for noncompliance with postoperative weightbearing restrictions on the forefoot. The Ludloff and Mau procedures first were described at the beginning of this century,[16,18] but lack of adequate hardware for fixation led to failures, causing these two techniques to fall from favor for several decades. More recently, however, development of new hardware has led surgeons to reconsider using these techniques.[8,21] The Scarf procedure[1,20,28] is very popular with podiatrists and among orthopaedic surgeons in Europe. Because of the particular geometry of the cut, this technique is considered inherently stable, and many surgeons allow their patients to wear sneakers 2 weeks after surgery.

Vertical stability of the first ray is an important consideration after hallux valgus surgery. Proximal metatarsal osteotomies are much more unstable than distal metatarsal osteotomies.[29] A major complication after hallux valgus surgery is transfer metatarsalgia secondary to dorsal angulation of the first metatarsal and loss of correction. This may be caused by the inherent instability of the procedure, by poor bone stock in patients with osteopenia, or by patient noncompliance with postoperative regimens.[31] The incidence of dorsal angulation after proximal metatarsal osteotomies varies. In a long-term followup study of proximal closing wedge osteotomies, Trnka et al[33] reported 25% dorsal angulation, whereas Mann et al[17] found 28% in a series of 109 proximal crescentic osteotomies and reported that dorsiflexion of the first metatarsal did not influence the presence of transfer lesions. This latter statement could not be confirmed by the study of Trnka et al,[33] who stated that 40% of the patients with dorsal angulation had metatarsalgia of the adjacent metatarsal heads. Sammarco et al[26] presented a series of 51 proximal metatarsal chevron osteotomies without dorsal angulation and transfer lesions. Reports of results of the Mau,[21] Ludloff,[8,27] and Scarf[28] techniques suggest that these three procedures entail a lower risk of dorsal angulation.

The question arises, at what time does dorsal angulation occur? Pearson et al[23] reported dorsal angulation after proximal crescentic osteotomy in 23 of 28 feet, but they also stated that angulation frequently was not evident on early postoperative radiographs. This observation leads to the conclusion that dorsal angulation is a result of the pressure applied to the healing osteotomy during walking in the postoperative period. Various postoperative immobilization devices are used to protect the fixation and to reduce the patient's discomfort.

The current authors found that the gold standard osteotomies (the proximal crescentic and the proximal chevron osteotomies) were the least stable techniques. These findings correlate with those of Lian et al,[15] who compared the fixation bending strength of the proximal crescentic osteotomy with that of the proximal chevron and Ludloff osteotomies. They found that the proximal crescentic osteotomy provided fewer stable constructs than did the proximal chevron or the Ludloff osteotomy; however, only the latter comparison was statistically significant. McCluskey et al[19] compared the strength of the proximal crescentic osteotomy with that of the proximal chevron osteotomy and found the difference to be statistically significant (134 and 321 kPa, respectively). The current study confirmed those results, although the mean strengths were different (199 and 205 kPa, respectively) ($p = 0.02$). The Scarf osteotomy, the biplanar closing wedge osteotomy (plantar plate fixation), and the Mau osteotomy had even higher mean strength values. All three osteotomies revealed a statistically significant higher mean strength than that of the proximal crescentic and the proximal chevron osteotomies, but not the Ludloff osteotomy (Table 1). Although the current results were consistent for the pairs of bones used, information about the age and bone quality of the human anatomic specimens (which might have affected those results) was not available.

The second objective of the current study was to determine which postoperative regimen would prevent dorsal angulation and loss of correction after each of the six osteotomy techniques studied, that is, to determine the fixation strength necessary to withstand the forces generated during protected postoperative weightbearing. To avoid putting patients at risk for fixation failure during testing of different postoperative devices after osteotomy, the current authors elected to use healthy volunteers without preexisting foot disorders to test high peak pressures to the first metatarsal during walking in different types of postoperative devices and in normal shoes. As previously reported by Cavanagh et al,[7] there is no relationship between body weight and peak pressure (Table 3).

The current results indicated that the device affording the most protection, that is resulting in the lowest average peak pressure under the first metatarsal, was the wedge-based postoperative shoe (290 kPa), followed by the soft-soled postoperative shoe (329 kPa), normal shoes (368 kPa), and the wooden-soled shoe (402 kPa), which commonly is used for postoperative immobilization.

These findings correlate with the results of Glod et al.[11] Using the F-scan system, they compared peak pressures on the forefoot during walking in eight different postoperative devices and walking barefoot. The results showed that the wooden-soled shoe decreased the average pressure compared with walking barefoot by 16.8%, but six of the 20 test subjects had increased pressure of up to 54%. Excluding the below knee removable walkers, the wedge-based postoperative shoe, which benefits from a cantilevered effect, was the most efficient device in reducing forefoot pressures (average decrease, 51.2%; range, 11%–76%). Corbett et al[9] also reported an increase of peak pressures in five of 10 test subjects using the wooden-soled postoperative shoe, but a wooden-soled shoe with a first metatarsophalangeal cutout orthotic insole had an average decrease of 42.7%, which was more than was measured using a cast (31.25%).

A patient who is compliant may partially weightbear on the surgically treated foot during the postoperative recovery. According to the current study results, such a patient may use a wooden-soled shoe, a soft-soled postoperative shoe, a wedge-based shoe, or even a normal shoe after a Ludloff, a Scarf, a biplanar wedge (with plantar screw fixation), or a Mau osteotomy. However, the wedge-based postoperative shoe may be preferable after a proximal crescentic or a chevron osteotomy. In addition, patients with severe osteopenic bone or those at risk for noncompliance should use the wedge-based postoperative shoe after any of the six osteotomies. A surgeon should base the choice of osteotomy type and postoperative treatment decisions on knowledge of the patient, clinical and radiographic information, and the stability of fixation at the time of surgery.

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