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Proximal Metatarsal Osteotomies: A Comparative Geometric Analysis Conducted on Sawbone Models

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ABSTRACT

We evaluated the change in position of the first metatarsal head using a three-dimensional digitizer on sawbone models. Crescentic, closing wedge, oblique shaft (Ludloff 8° and 16°), reverse oblique shaft (Mau 8° and 16°), rotational "Z" (Scarf), and proximal chevron osteotomies were performed and secured using 3-mm screws. The 16° Ludloff provided the most lateral shift (9.5 mm) and angular correction (14.5°) but also produced the most elevation (1.4 mm) and shortening (2.9 mm). The 8° Ludloff provided lateral and angular corrections similar to those of the crescentic and closing wedge osteotomies with less elevation and shortening. Because the displacement osteotomies (Scarf, proximal chevron) provided less angular correction, the same lateral displacement, and less shortening than the basilar angular osteotomies, based upon this model they can be more reliably used for a patient with a mild to moderate deformity, a short first metatarsal, or an intermediate deformity with a large distal metatarsal articular angle. These results can serve as recommendations for selecting the optimal osteotomy with which to correct a deformation.

Key Words: Hallux Valgus; Osteotomy; Geometry, Sawbone Models

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INTRODUCTION

The greatest number of procedures for hallux valgus corrections include soft-tissue release and bony correction of the deformity of the first metatarsal using proximal or distal osteotomies.[25]

Mild hallux valgus deformities can be corrected using a distal metatarsal osteotomy whereas moderate to severe deformities are corrected more predictably using a proximal metatarsal osteotomy. When osteotomies aimed at correcting the varus deformity are performed, other changes in the configuration of the first metatarsal, such as elevation, depression, shortening, elongation, or rotation (pronation or supination), can occur.[27] The ideal osteotomy should include correction of the varus angle and pronation, without other undesired changes. The degree of correction achieved can be evaluated by determining the clinical improvements subjectively or objectively using radiographic parameters or plantar foot pressure systems.[5,7-9,18,20,21,23] However, radiographic evaluations are subject to inherent large deviations and are therefore inaccurate. Mathematical models based on data obtained from radiographic measurements provide a more precise method of determining the amount of correction achieved. Other factors that play a role in performing the osteotomy (such as shortening owing to the width of the saw, displacement during the fixation method or amount of rotation). The biomechanical studies of different osteotomies usually evaluate the strength of the construct that holds the osteotomy in place and do not address changes in position between the proximal and distal segments.[4,7,8,13-15,19,20,26] Only the amount of shortening secondary to the closing wedge osteotomy has been evaluated in a sawbone model.[1]

The current study evaluated different osteotomies in terms of the associated three-dimensional geometric changes in the relative positions of the proximal and digital segments in each osteotomy such as lateral displacement, angular rotation, elevation, and shortening. The ultimate objective was to determine which osteotomy is best suited for optimal correction of hallux valgus

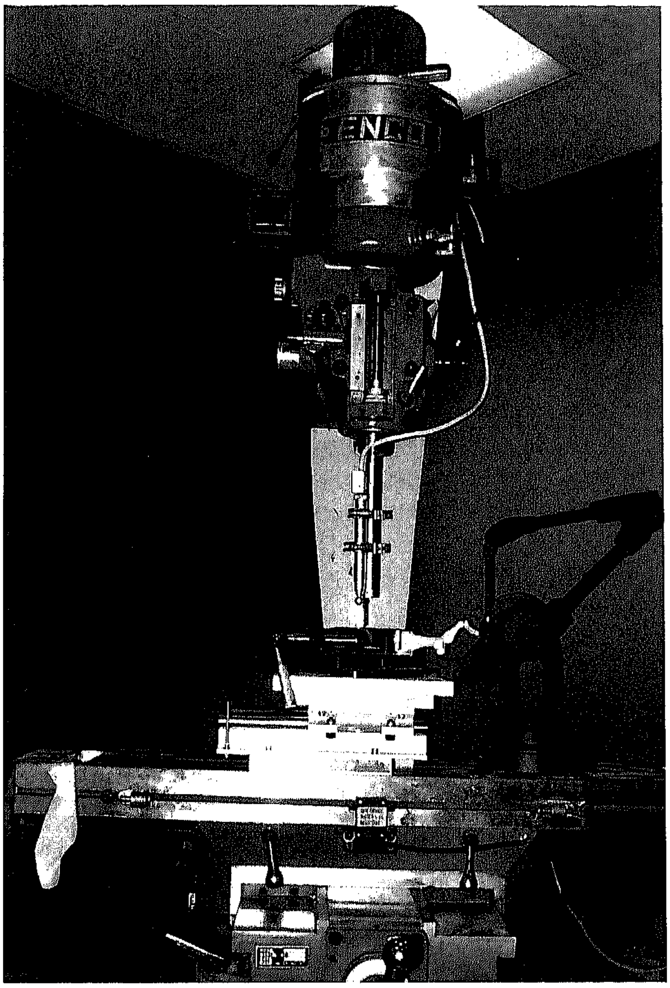

Fig. 1: Experimental set-up.

deformities based on variations in patient anatomy and condition severity.

MATERIALS AND METHODS

We used first metatarsal sawbone models (Pacific Research Laboratories, Vashon, WA). A cubicle block on the proximal aspect of each model allowed it to be securely fastened in a vise. The vise was mounted on a linear slide secured to the table of the test frame. The test frame was a vertical milling machine that provided x, y, and z motion of the table on which the sawbone model was positioned. Above the table, a saw was rigidly mounted to the upper head of the milling machine (Fig. 1), which allowed it to move up and down in the z direction and to be angled to produce cuts in different planes. The bone models could then be positioned under the saw blade and moved in a straight line to produce accurate, reproducible cuts in any required plane.

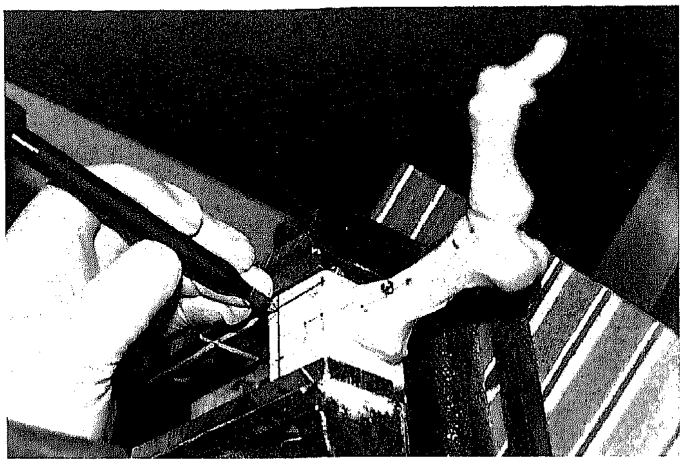

Fig. 2: Reference frame undergoing digitization.

A Microscribe 3D digitizer (Immersion Corp., San Jose, CA) was used to obtain the x, y, and z coordinates of selected points on the model. Three points on the proximal end of each sample provided the reference frame. Three other points over the center of the metatarsal head and an additional two points (1 cm apart along the midline, in between the reference frame and distal points) were used to measure relative position changes before and after the osteotomies were performed (Fig. 2).

After securing the model in the vise, the digitizer was used to establish the reference frame at the proximal end and to obtain preoperative data at the metatarsal head. Each osteotomy was then performed using a standard saw blade (Hall 5023-138 blade, 0.4 mm thick, 0.4 mm wide; Zimmer, Warsaw, IN) mounted on a standard mini Hall sagittal (or dome) saw. We used six different osteotomy techniques: two displacement osteotomies, the rotational "Z" (Scarf) (Fig. 3a) and the proximal chevron (Fig. 3b), and four angular osteotomies, the crescentic (Fig. 3c), the closing wedge (Fig 3d), the reverse oblique shaft (Mau) (Fig. 3e), and the oblique shaft (Ludloff) (Fig. 3f). The crescentic,[18] closing wedge,[29] Ludloff,[16,22] Mau,[19] proximal chevron,[5,21] and Scarf[2,24] osteotomies were performed with a correction of 8°. The Ludloff and Mau osteotomies were also performed for a correction of 16°. The osteotomies were secured using cannulated 3-mm screws (AO, Synthes, Paoli, PA). The 8° and 16° corrections were performed using a template to verify that the angle was correct. After the osteotomy was secured, a second set of data points was obtained. Reference frame data points were taken before and after the osteotomies in case the base moved during the procedure. Five models were used for each osteotomy. The following parameters were calculated for each sample: change in elevation of the metatarsal head; medial/lateral shift of the distal compared with the proximal segments; angular change in the transverse plane (medial/lateral); rotation of the metatarsal head in the coronal plane; and shortening of the first metatarsal.

Description of Osteotomies

Scarf Osteotomy: The first cut of the Scarf osteotomy[2,24] (Fig. 3a) was made longitudinally, aiming 10° plantarly from the medial side to the lateral side, at the mid width of the bone. Then a transverse dorsal cut was made 1 cm proximal to the metatarsophalangeal joint line, and a proximal plantar cut was made just at the flare of the base of the bone (1.5 cm from the metatarsocuneiform line). The distal segment was then shifted 5 mm laterally and secured with a 3-mm cannulated screw inserted from the dorsal cortex, aiming laterally and plantarly to engage the osteotomy. A second screw was

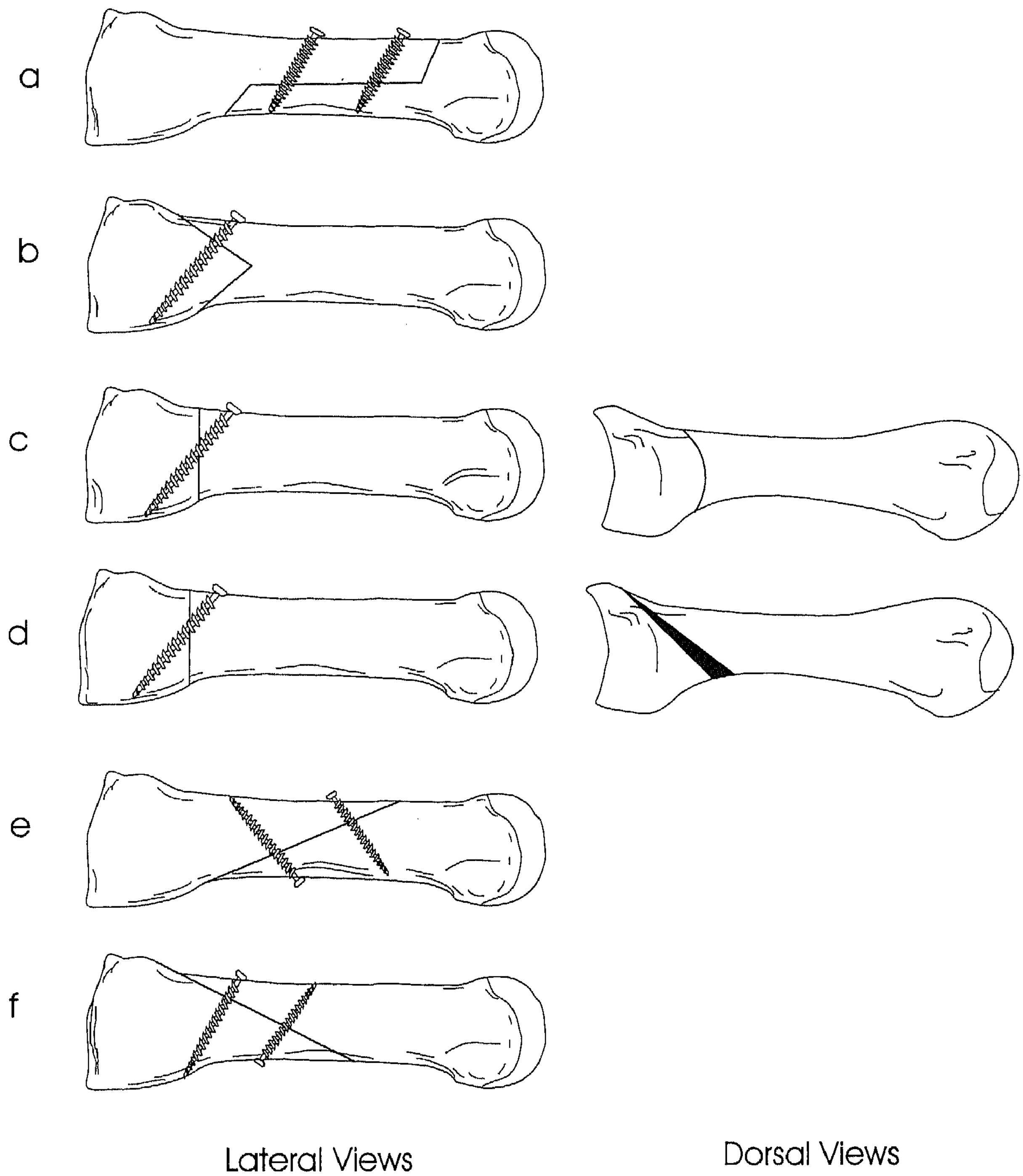

Fig. 3: Displacement osteotomies: **(a)** rotational "Z" (Scarf), and **(b)** proximal chevron; angular osteotomies: **(c)** crescentic, **(d)** closing wedge, **(e)** reverse oblique shaft (Mau), and **(f)** oblique shaft (Ludloff).

inserted just proximal to the first for further stabilization of the osteotomy.

Chevron Osteotomy: For the chevron osteotomy[5,21] (Fig. 3b), the dorsal cut was started 1 cm from the metatarsocuneiform line, aiming distally at 50°, and was finished aiming proximally at the same inclination. It was performed perpendicularly to the sagittal plane, and the distal segment was displaced laterally 0.5 cm. The distal segment was then secured with a screw inserted dorsally, midline in the distal fragment, aiming laterally to engage the proximal fragment.

Crescentic Osteotomy: For this crescentic osteotomy[18] (Fig. 3c), the saw cut was performed perpendicularly to the long axis of the metatarsal and tilted 10° laterally, as recommended in 1991 by Lippert and McDermott.[15] The concave side of the saw (Hall, 5053-176 blade, Zimmer) faced proximally according to Mann et al.,[18] and the edge of the convexity was 1.5 cm from the metatarsocuneiform line.[18]

Closing Wedge Osteotomy: For the closing wedge osteotomy[29] (Fig. 3d), the first cut was performed in the coronal plane at 45° to the long axis of the bone, from proximal-medial at the metatarsocuneiform line, aiming distal-lateral. The second cut was performed at 53° to achieve 8° of correction. A single screw was inserted directed from dorsal-lateral to plantar medial.

Mau Osteotomy: The Mau osteotomy[19] (Fig. 3e) started 1 cm proximal to the metatarsophalangeal joint line, dorsal to the pitch of the proximal lateral cortex of the bone plantarly. It was performed perpendicularly to the sagittal plane, thus creating a 30° angle with the apex pointing toward the metatarsophalangeal joint. Just before completion of the osteotomy, a proximal 3-mm cannulated screw was inserted from the plantar side. Upon completion of the procedure a second screw was inserted dorsally and just distal to the first screw. Both screws then were tightened at a corrected position of 8° (8° Mau) or 16° (16° Mau) according to a template.

Ludloff Osteotomy: The Ludloff osteotomy[16,22] (Fig. 3f) started at the metatarsocuneiform line dorsally and finished 3 mm proximal to the sesamoids.[22] It was performed perpendicularly to the sagittal plane, thus creating a 30° angle with the apex pointing toward the metatarsocuneiform joint. Just before completion of the osteotomy, a proximal 3-mm cannulated screw was inserted from the dorsal cortex. Upon completion of the procedure a second screw was placed plantarly, just distal to the first screw. Both screws then were tightened at a corrected position of 8° (8° Ludloff) or 16° (16° Ludloff) according to a template.

Statistical Analysis

An analysis of variance was used to determine if the differences in the measured parameters between each osteotomy were significant. A Student-Newman-Keuls post hoc analysis was performed when significant differences were determined. The level of significance in the current study was set at $P \leq 0.05$.

RESULTS

Lateral Displacement

The osteotomies provided an average of approximately 5 mm of lateral displacement, ranging from a high of 9.5 mm (SD, 2.8 mm), by the 16° Ludloff, to a low of 2.5 mm (SD, 0.3 mm) by the 8° Mau (Table 1). Compared with the 16° Ludloff, all other osteotomies provided smaller lateral displacement. Additionally, the 8° Mau had significantly less displacement than the crescentic and proximal chevron osteotomies.

Angles

The 16° Ludloff osteotomy provided the largest angle, i.e. 14.7° (SD, 1.1°) and the proximal chevron provided the smallest angle, i.e. 0.03° (SD, 2.9°) (Table 1). Compared with the 16° Ludloff osteotomy, all other osteotomies provided significantly smaller angles.

Elevation

All elevations provided by the osteotomies were minimal (<1.5 mm), ranging from 0.02 (SD, 0.6 mm) by

Table 1: Average Changes After Osteotomy

Type of Osteotomy	Lateral Shift [mm (SD)]	Angle [° (SD)]	Elevation [mm (SD)]	Rotation [° (SD)]	Shortening [mm (SD)]
Crescentic	6.9 (1.5)	8.6 (2.9)	0.6 (1.0)	2.7 (4.2.)	1.9 (0.9)
8° Ludloff	4.6 (1.8)	6.2 (1.9)	0.3 (0.5)	1.2 (0.8)	1.4 (0.5)
16° Ludloff	9.5 (2.8)	14.7 (1.1)	1.4 (0.3)	1.9 (1.3)	2.9 (0.4)
Closing wedge	4.8 (0.6)	5.0 (3.8)	0.7 (0.5)	-0.9 (2.3)[b]	2.0 (0.6)
8° Mau	2.5 (0.3)	2.3 (2.2)	0.08 (0.4)	-2.2 (1.9)[b]	0.3 (0.4)
16° Mau	5.4 (0.9)	9.4 (4.7)	0.02 (0.6)	-0.9 (3.2)[b]	0.9 (0.5)
Proximal chevron	6.0 (3.0)	0.03 (2.9)	-0.2 (1.0)[a]	1.6 (3.1)	0.7 (0.3)
Scarf	4.0 (1.4)	0.6 (1.6)	-0.2 (0.4)[a]	0.6 (1.6)	0.4 (0.3)

[a] Negative elevation values indicate depression.
[b] Negative rotation values indicate supination.

the 16° Mau to 1.4 mm (SD, 0.3 mm) by the 16° Ludloff (Table 1). The 16° Ludloff osteotomy provided significantly more elevation than did the Scarf, closing wedge, 16° Mau, and 8° Mau osteotomies. No other significant difference was observed. The proximal chevron and Scarf procedures provided a minimal depression of 0.2 mm (SD, 1.0 mm) and 0.2 mm (SD, 0.4 mm), respectively, rather than elevation.

Rotation

Minimal rotation of the metatarsal head occurred after all the osteotomies. With the exceptions of the crescentic procedure, which produced a pronation of 2.7° (SD, 4.2°), and the 8° Mau procedure, which produced a supination of 2.2° (SD, 1.9°), all osteotomies resulted in less than 2° of rotation (either pronation or supination) (Table 1). The only statistically significant difference was that between the crescentic and 8° Mau osteotomies. The Scarf osteotomy resulted in the least rotation, i.e. 0.6° of pronation (SD, 1.6°).

Shortening

The 8° Mau, 16° Mau, proximal chevron, and Scarf osteotomies yielded the least shortening (Table 1), each <1 mm. The proximal angular osteotomies yielded more shortening, ranging from 1.4 mm (SD, 0.5 mm) by the 8° Ludloff, to 2.9 mm (SD, 0.4 mm) by the16° Ludloff. Shortening from the proximal angular osteotomies (8° and 16° Ludloff, crescentic, and closing wedge) was significantly different than that from the Mau and displacement osteotomies.

DISCUSSION

In the current study, we measured the geometric changes that occurred at the distal metatarsal head with different types of osteotomies. We used synthetic anatomic sawbone models that were consistent in size, material, and configuration. The dimensions of the models were similar to those of the average adult bone: 60 mm long and 15 mm wide at the base and the flare of the neck.[10,11] We used a serial linkage digitizing device with an accuracy of 0.1 mm, and the test frame gave a solid and accurate method of aiming and performing the exact cuts we planned. Nevertheless, there were sometimes wide variations in the results, indicating that even under strict laboratory conditions, there are variations in the technique itself. The variations in the angles were 30% to 50%. In the crescentic osteotomy, the variation was higher than that in the 8° and 16° Ludloff osteotomies, which may indicate that the variations are caused by the fixation technique and not to the cut surface. It is obvious that the smaller the deviations, the better the technique. For most of the parameters, the Ludloff osteotomies had the least variations.

We found one study in the literature that analyzed only the shortening of the first metatarsal.[1] No study was found that compared the three-dimensional geometric changes of different osteotomies. Mathematical models can predict the amount of correction very accurately, but they do not account for important variations in performing the osteotomy such as the width of the saw cut and the amount of compression and displacement while inserting and securing the screw for fixation. In analyzing our osteotomies, we found that, although we measured 5 mm of displacement in the chevron and Scarf osteotomies, securing the screw displaced the osteotomy backward by at least 1 mm in most of the specimens.

Lateral Displacement

In this model we have used the proximal chevron osteotomy as one in which predominantly lateral displacement occurs. Mild angulation may be obtained by impacting the osteotomy laterally, or by inserting a bone graft medially as previously described.[3] As most commonly performed and described, however, angulation of the osteotomy is not routinely performed, and therefore it was not used in this sawbone model. The displacement osteotomies (chevron and Scarf procedures) produced approximately 5 mm of lateral displacement, as expected. There was no possibility of more correction because of the risk of fixation failure. The width of each sawbone in the distal and proximal thirds was 15 mm. The width in the middle third was approximately 10 mm. These measurements were similar to those reported in other studies.[9,10,12] However, three of the basal angular osteotomies (closing wedge, 8° Ludloff, and 16° Ludloff) each yielded less than the desired correction. Although the osteotomies were performed under optimal laboratory conditions, technical errors (affecting the postoperative results) were to be expected. The lateral displacements obtained in the basal angular osteotomies depended on the amount of correction to be achieved and were limited only by the length of the distal segment.

In both Mau osteotomies, large angular corrections produced relatively mild displacements because the center of angulation about which each correction was made was located between the middle and distal third. Compared with the other rotational osteotomy types studied, the Mau osteotomies are the most distal and should be used only for the correction of minor deformations.

Angles

Each of the Mau osteotomies behaved like a distal osteotomy. Instead of the large correction desired, each

Mau produced only minimal correction distally when measured from the base of the first metatarsal. The displacement osteotomies provided minimal angular correction, and the angular osteotomies produced the most correction, as expected. The higher the angle of correction during the procedure, the greater was the amount of shortening of the first metatarsal.[1,10,11,30]

In the study by Banks et al.,[1] a shortening of 1.7 mm was found after a 10° closing wedge osteotomy. We used sawbone models similar to those in the study by Banks et al.[1] and a template of 8°. After securing the closing wedge osteotomy with the screw, the tracked corrected angle was only 5.0°(SD, 3.8°). Although the experiment was performed under laboratory conditions using precise devices, we could not achieve the exact expected result with minimal deviation in the closing wedge osteotomy. The osteotomies that provided the smallest deviations from the planned corrections were the 8° Ludloff, i.e. 6.2° (SD, 1.9°) and the 16° Ludloff, i.e. 14.7° (SD, 1.1°). We attribute the relatively small deviations of the Ludloff osteotomies to the operative procedure in which only a partial osteotomy was performed on the proximal side, a screw was inserted and not tightened, the osteotomy was completed, a second screw was inserted, and then both screws were tightened at a corrected position of 8° or 16°. This technique enables control of the fragments at all stages of the procedure.

Elevation

An elevation of 2 mm or more can be of clinical relevance and can cause transfer metatarsalgia. None of the osteotomies we performed, however, produced an elevation of clinical relevance. These findings led us to conclude that the published elevations observed during clinical studies (for example, 6.7 mm for the closing wedge[23] and an unreported amount of elevation after crescentic osteotomy in 28% of the patients[18]) are caused by technical problems in fixation or premature full weightbearing. A study conducted at our laboratory[20] indicated that, biomechanically, these osteotomies are not strong enough to bear full weight. Although plantar displacement of the distal fragment at the time of fixation or the use of a biplanar cut in the frontal plane can depress the distal fragment, this was not investigated in this study. In performing substantial corrections, the closing wedge osteotomy or the Ludloff osteotomy are at risk for pathologic elevation. However, meticulous technique and careful postoperative management can reduce the risk of transfer metatarsalgia in these osteotomies. Saxena and McCammon[22] commented that when directing the osteotomy plantarly, the head will translocate plantarly. However, no data were presented to substantiate this claim. Clinical studies in evaluating transfer metatarsalgia owing to elevation in the metatarsal head are more important in the evaluation of such patients.

Rotation

In the current study, we could not demonstrate a statistically significant correction of metatarsal head pronation. To achieve better correction, there is a need to investigate differing angles of the plantar cut surfaces. Lippert and McDermott[15] demonstrated that in the crescentic osteotomy, tilting the saw position obliquely toward the sesamoids results in metatarsal external rotation.

Shortening

In the current study, a clinically and statistically significant shortening of approximately 2 mm was found in each of the three proximal angular osteotomies, as expected: the 16° Ludloff produced 2.9 mm (SD, 0.4 mm), the closing wedge produced 2.0 mm (SD, 0.6 mm), and the crescentic produced 1.9 mm (SD, 0.9 mm).

In another sawbone model, Banks et al.[1] showed a shortening of 1.7 mm at 10° of correction with a closing wedge osteotomy. Their smaller amount of shortening, when compared with our results with the closing wedge osteotomy, was probably caused by their use of a bone clamp, rather than a screw, to secure the osteotomy; the screw yields more compression at the osteotomy site. In addition, our proximal cut was at 45°, whereas that in the study of Banks et al.[1] was at 52°. In a mathematical model of the closing wedge osteotomy, Kummer[12] found a shortening of 2.6 mm. Based on his formulas, a first metatarsal 60 mm long would be shortened by 1.4 mm after removal of a 10° wedge. Mann et al.[18] found a shortening of approximately 2 mm with 8° of correction of the intermetatarsal angle after a crescentic osteotomy. They did not give clinical importance to this shortening although the patients had transfer lesions attributed to the elevation change.

In a patient with an already short metatarsal or with metatarsalgia, further shortening of the metatarsal may increase the central forefoot loading. Therefore, when selecting a suitable procedure for such patients, displacement osteotomies that give the least amount of shortening should be considered. These displacement osteotomies also caused minimal depression of the metatarsal head. They may be successful only for patients with mild or intermediate deformities because the angular correction was found to be minimal, although the lateral displacement was similar to that of the rest of the osteotomies (approximately 5 mm).

According to our results, the procedure of choice for patients with severe deformities is an angular osteotomy, preferably the Ludloff procedure, in which there is good control of the angle corrected. The angle can be easily increased, and pronation of the head can be corrected as well. Increasing the angle of correction in the Ludloff osteotomy, however, increases elevation and shortening of the metatarsal head. The elevation might be overcome by aiming the osteotomy plantarly, but more investigation is needed to verify this suggestion. Shortening is inherent in angular corrections and is common to all angular osteotomies, as was found in the experimental and mathematical model by Banks et al.[1] and in a clinical study by Zlotoff.[30] Because the crescentic osteotomy gave somewhat more elevation and shortening than did the 8° Ludloff, we suggest the Ludloff as the preferred method for moderate to severe deformities.

In angular osteotomies, the distal metatarsal articular angle increases as the angle of correction is increased. However, if the intermetatarsal angle is not severe, displacement base osteotomies may be used. According to our results, lateral displacement from displacement osteotomies was the same as that with the other osteotomies, but there was no increase in the angle and, therefore, no increase in the distal metatarsal articular angle. The 8° and 16° Mau procedures gave the least amount of correction because the geometric behavior of this osteotomy is like that of a distal osteotomy; therefore, the Mau procedure should be reserved for mild deformities.

CONCLUSION

In conclusion, in our laboratory study, we found the following:

1. the displacement osteotomy gives an accurate, expected correction for patients with mild or intermediate hallux valgus deformity;
2. for patients with more severe deformities, angular osteotomies should be used;
3. the closing wedge, 16° Ludloff, and crescentic osteotomies all provided good correction but also yielded clinically significant shortening;
4. the 8° Ludloff osteotomy yielded good angular and lateral shift correction with virtually no change in elevation and little change in shortening;
5. displacement osteotomies are preferred for patients with large distal metatarsal articular angles or short metatarsals; and
6. the Mau osteotomy, which provides the least amount of correction, should be reserved for mild deformities.

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