ORIGINAL ARTICLE

Axial rotation of the first metatarsal head in a normal population and hallux valgus patients

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Summary
Hypothesis: Does metatarsal pronation exist and, if so, what is its impact?
Introduction: Hallux valgus is a deformity associating angulation and a rotational component. The present study sought to investigate the nature and origin of the coronal plane displacement.
Materials and methods: A prospective single-center radiological and anatomic study was conducted on 100 feet operated for hallux valgus. Baseline X-ray determined the preoperative position of the 1st metatarsal head in the coronal plane. The range of motion (ROM) of the cuneometatarsal joint in pronation—supination was measured peroperatively. An anatomic study investigated possible diaphyseal torsion.
Results: Mean radiologic pronation in hallux valgus was 12.7° (range, 0°—40°). Cuneometatarsal rotational ROM was determined by adding peroperative ROM in pronation (mean, 9.3°; range, 0°—30°) and in supination (mean, 8.7°; range, 0°—20°). Intermetatarsal divergence showed no correlation with radiologic pronation or ROM in pronation. Radiologic pronation showed no correlation with peroperative ROM in pronation. Pronation of the metatarsal head was never observed without associated sesamoid pronation; the latter, however, was in some cases observed without the former. Twenty randomly selected metatarsal cadaver specimens from the anatomy laboratory of the University of Nice (France) showed diaphyseal torsion in 80% of cases, with the metatarsal head in neutral position or in supination with respect to the base.
Discussion: In hallux valgus, 1st ray pronation appears to be systematic, in contrast to the typical supination found in the general population. Metatarsal rotation is always associated with sesamoid rotation, whereas the converse is not the case: displacement of the sesamoids appears to displace the metatarsal head via the metatarsosesamoid ligaments. This “drive-belt” effect, however, varies in its mechanical properties and the transmission is imperfect and likely subject to progressive ligament stretching, so that head rotation does not exactly follow and may even become independent of the sesamoid displacement. Radiologic and clinical rotation thus do not
Introduction

Hallux valgus is a deformity caused by pathological displacement of the 1st ray of the foot. The vertical and horizontal components have been widely explored [1] and are routinely taken into account in the various procedures of surgical correction; the frontal rotation component, in contrast, has been generally overlooked except in a few studies [2–4]. Phalangeal pronation, however, is an almost systematic clinical finding in hallux valgus. The present study investigated the possible existence of pathologic 1st metatarsal rotation, its mechanism, and its possible impact on the cuneometatarsal (C1M1) joint.

A novel radiographic (Bernard) view enabled preoperative measurement of head orientation in the frontal plane. C1M1 range of motion (ROM) was quantified peroperatively. Finally, a short anatomic study investigated whether head positioning in the frontal plane might be subject to diaphyseal torsion.

Material and methods

Clinical study

A continuous prospective single-center study included 94 female and six male patients (mean age, 54 years; range, 19–82 yrs) undergoing surgical correction of hallux valgus between January 8, 2001 and February 3, 2003. All patients considering their deformity to be disabling were included, allowing for the usual surgical contraindications.

Dorsoplantar and lateral weight-bearing X-ray views were taken. Diaphyseal axes between the center of the head and the middle of the proximal epiphysis were calculated in the radiology department of the institution, to determine the metatarsophalangeal (MTP1) and M1-M2 divergence angles.

AP views were taken to determine metatarsal head rotation and the spatial relations between the sesamoids and metatarsal facets [5]. As bone architecture varies depending on whether the foot is slack or in weight-bearing, a non-dynamic weight-bearing view was considered necessary. This is not provided by the Muller-Guntz view or by MRI or CT; a novel incidence was therefore designed (Fig. 1). So as to visualize the distal extremity of the 1st metatarsal, it was taken, unlike in the Guntz view, in the axis not of the foot but of the shaft, the divergence of which correlates with the abduction displacement of M1. Patients were X-rayed standing, with the cassette placed vertically behind the foot. To avoid superimposition, the heel and toes were raised by radio-transparent wedges of respectively 40mm and 10mm. The foot was positioned in external rotation to obtain a vertical projection of the metatarsal shaft, with horizontal alignment to a mark on the cassette.

On an isosceles triangle with the crista as apex and the sides tangential to the lateral and medial sesamoid facets of the metatarsal head, metatarsal rotation was measured as the angle subtended by the base and the horizontal (Fig. 2). Reproducibility required the projection of the shaft to be strictly vertical in order to ensure exact measurement of rotation.

Passive C1M1 rotational ROM was measured peroperatively during oblique basal plane osteotomy. Two basal K-wires, both parallel to the plantar plane, were inserted on either side of the joint. One joined the 1st cuneiform to the rest of the tarsus; this was the only variant with respect to the usual technique (Fig. 3). A third 1.8 mm distal wire in the M1 head served as a lever to move the head into forced pronation–supination, with a constant force limited by the curvature. The angle was assessed on goniometry after the

match any longer. The anatomic study showed that, while diaphyseal torsion cannot be ruled out, the metatarsal pronation mainly derives from cuneometatarsal joint rotational instability, the evolution of which does not parallel lateral instability, no correlation being found between degree of varus and rotational instability.

Conclusion: The present study found metatarsal pronation to be associated with hallux valgus, making a preoperative AP view useful; the underlying mechanism was generally cuneometatarsal instability. Although difficult to specify exactly without correlation between radiological and clinical data, any such pronation raises the question of whether replacing the metatarsal head on its sesamoid supports is sufficient to achieve stability in all planes, or whether on the contrary derotation should be associated to metatarsal valgization osteotomy to restore horizontal support.

Level of evidence: Level IV.
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two proximal wires had diverged, and was systematically checked by the both surgeons (JPM and JLB). Data were analyzed on Pearson correlation coefficients with a significance threshold set at 2.5°, corresponding to the estimated uncertainty of measurement.

Anatomical study

As a search of the literature found no references as to a possible impact of M1 shaft torsion on head positioning, 20 M1 bone specimens (11 right, nine left) were taken at random from the Nice University anatomy laboratory.

To measure the frontal angulation (pronation and supination) of the proximal and distal extremities of the metatarsal, the single vertical part of the lateral side of the metatarsal at the junction of the mid and proximal thirds, which is specific to M1, was taken as a reference plane. The horizontal and frontal planes were determined from this reference plane and the metatarsal axis. The position of the proximal extremity of the metatarsal base in the frontal plane was determined by the angle subtended by the axis through the dorsal and plantar extremities and the vertical reference plane (Fig. 4). The medial and lateral sulci bordering the sesamoid facets served as references for the horizontal plane at the distal extremity (Fig. 5). For the

### Table 1

Radiology results for 100 operated cases of hallux valgus.

<table>
<thead>
<tr>
<th>Results</th>
<th>Peroperative pronation</th>
<th>Peroperative supination</th>
<th>Peroperative instability</th>
<th>Radiologic pronation</th>
<th>Metatarsus Varus</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>9.3°</td>
<td>8.7°</td>
<td>18°</td>
<td>12.7°</td>
<td>15.4°</td>
<td>53.8</td>
</tr>
<tr>
<td>Range</td>
<td>0° – 30°</td>
<td>0° – 20°</td>
<td>0° – 40°</td>
<td>0° – 40°</td>
<td>5° – 25°</td>
<td>19 – 82</td>
</tr>
<tr>
<td>% ≥ 10°</td>
<td>45%</td>
<td>49%</td>
<td>90%</td>
<td>70%</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Peroperative rotational instability is calculated as the sum of peroperative pronation and supination; 90% of patients showed instability > 10° and 70% radiologic pronation > 10°.
Results

Clinical study

Mean radiologic pronation was $12.7 \pm 7.7^\circ (0–40^\circ)$, mean M1M2 divergence was $15^\circ \pm 4.2^\circ (5–25^\circ)$ (Tables 1 and 2).

Mean peroperative ROM was $9^\circ (0–30^\circ)$ in pronation, and $9.4^\circ \pm 6.1^\circ (0–20^\circ)$ in supination. Mean overall cuneometatarsal instability, calculated as the sum of the above, was thus $18^\circ$.

No correlation was found between M1M2 divergence and either radiologic pronation or clinical cuneometatarsal rotational instability. Radiologic pronation was a mean $5.4^\circ$ less than the clinical value.

Metatarsal pronation was never found without at least equal parallel sesamoid rotation. On the other hand, five patients showed no metatarsal pronation despite the presence of sesamoid rotation (Figs. 4 and 6).

Age correlated with M1M2 divergence (R = 0.36) and ROM in pronation (R = 0.35) but not with radiologic pronation (R = 0.05).

Anatomic study

The purpose of the anatomic study was to determine whether, in the frontal plane, the 1st metatarsal may undergo rotation due not to joint instability but to diaphyseal torsion (Table 3). Thirteen of the 20 heads were in supination, three in neutral position and 4 in pronation with respect to the base. In parallel, the sesamoid facets showed a wide range of angular values (from $-18^\circ$ to $+15^\circ$) which, however, varied with head position (Table 3 and Fig. 4). The plane of the head (plane 4 in Fig. 4) remained parallel to the sesamoid facets (plane 5 in Fig. 4). Head pronation correlated with supination of the base ($P < 0.001$).

Discussion

The radiologic study showed a clear predominance of M1 pronation in hallux valgus, systematically associated with at least as great a parallel displacement of the sesamoids, whereas conversely considerable sesamoid rotation may still be associated with a horizontal metatarsal. The clinical study confirmed that this rotation entailed mobilization of the cuneometatarsal joint. Finally, the anatomic study showed that diaphyseal torsion could impact the axial positioning of the M1 head.

The root cause of the rotational displacement thus seems to lie in an axial displacement of the sesamoids, moving the entire metatarsophalangeal complex [6,7]. The “drive belt” is the ligaments (Fig. 6), the resistance of which is variable [8], being stronger at phalangeal-sesamoid level, transmitting rotation toward the phalangeal apparatus [9,10] rather than to the metatarsal head, where the metatarsosesamoid ligaments distend as the metatarsophalangeal deformity increases. This differential resistance may explain how a horizontal metatarsal head can be associated with considerable sesamoid displacement (Fig. 7, n° 4 and n° 7), and may also account for the non-correlation between radiologic pronation and cuneometatarsal instability: freed from sesamoid traction, the head recovers a horizontal position despite a very unstable C1M1 joint.

There are many reports of the motor function of the flexors and its impact on the sesamoids, subjected to excessive strain. Snijders [11], in a biomechanical model, demonstrated that, in the transverse plane, two main forces impact the MP joint: firstly, a midfoot reaction to the upward pressure of the ground, pushing the 1st metatarsal into varus abduction, and secondly the flexor hallucis longus (FHL)
displacing the phalangeal apparatus in valgus adduction. Gianini and Catani [12] stressed that, despite metatarsophalangeal joint dorsiflexion, the FHL tends to induce subluxation of the potentially unstable sesamoids while the phalangeal apparatus remains in pronation.

The present study demonstrated the consequences of this pronation for the cuneometatarsal joint, which is where the rotation occurs [13] rather than, as usually, in the talonavicular joint, where its amplitude is 4.1° in pronation and 6.2° in supination [14]. Clinically, this results in an abnormal 18° C1M1 rotational ROM and 9.3° ROM in pronation. It is noteworthy that, unlike in the study by Eustace et al. [3], there was no radiological correlation between rotation and metatarsal varus. According to Suzuki et al. [15], C1M1 instability is at the origin of metatarsal abduction, stability being required for effective locking of the foot in gait. Gebo [16] pointed out that stability of the 1st ray, and of the cuneometatarsal joint in particular, is what distinguishes the prehensile function in other primates and the weight-bearing function in humans, and that humans alone among existing primates are unable to move their 1st ray. Le Floch-Frigent [17] likewise reported that the main 1st-ray motor muscle in the four hominoid primates is the fibularis longus (FL), which induces eversion of the foot by acting on a mobile ray, whereas in humans the ray is immobile. C1M1 instability disturbs harmonious muscle action on the metatarsal head, which can no longer fulfill its function [1] due to combined vertical instability and frontal displacement. The FL, which is inserted in the M1 base, is no longer well-anchored and is unable to varize the calcaneus as required to provide a rigid 1st ray. Tendon displacement also impacts the action of the flexors which, no longer vertical, shows impaired response to the counter-pressure of the ground. Talbot et al. [18], using a piezoelectric device to compare flexor force vectors at 0°, 15° and 30° of flexion in healthy subjects and subjects with phalangeal pronation, measured the resultant obliqueness (Fig. 8). And finally, displacement deprives the metatarsal head of a horizontal support for its articular facets.

The limitations of the present study firstly concern possible diaphyseal torsion in the frontal plane, confirmed by the anatomic correlation between pronation of the head and supination of the base of the 1st metatarsal. The verticality of the reference plane chosen for the metatarsal base in the anatomic study of specimens may not be the same ...
Figure 7  Metatarsal head and sesamoid positioning. Sesamoid pronation may occur without metatarsal pronation. However, metatarsal rotation is systematically associated with a parallel displacement of the sesamoid band.

Figure 8  Change in force vectors according to pronation. The horizontal vector pushes the metatarsal head inward. Decreased vertical vector induces defective weight-bearing.
in a bone joined to the rest of the foot, but the study nevertheless showed that metatarsal head pronation can occur without cuneometatarsal instability. This could be a morphological adaptation, as in the tibia or femur, but could also be a reaction to early congenital hallux valgus during growth. This could account for the difference between radiologic pronation (13°) and C1M1 instability (18°). It follows that preoperative radiography fails to determine cuneometatarsal instability precisely.

Another source of error may lie in radiographic approximation in tracing the sesamoid facets from a worn crista, although this does not cast doubt on the prevalence of pronation. Phalangeal rotation (concerning which no reports could be found in the literature) results from sesamoid traction, even if the metatarsal impact is uncertain. It would no doubt have been useful to compare sesamoid and metatarsal rotation quantitatively.

Conclusion

The present study confirmed the existence of pathological pronation of the metatarsophalangeal apparatus in hallux valgus. AP radiographs make an important diagnostic contribution to preoperative assessment, shedding light on the support of the metatarsal head and its relation to the sesamoids. However, they provide only partial assessment of cuneometatarsal instability, which is related to but does not correlate with metatarsal pronation. The study raises the question of the choice between simple translation—valgization osteotomy to raise the head up to the level of the sesamoids and metatarsal osteotomy associating varization to derotational supination.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

References