this analysis (forces on the joints had to be slightly rotated in order to get equilibrium conditions). Table **1** contains the *x-y* force components in Newtons. More specifically, F_2 is the external ground force, F_h equals $F_{hl} + F_{hb}$ where F_{hl} and F_{hb} are the forces acting along the tendons of the flexor hallucic longus and flexor hallucic brevis muscles respectively; F_{pl} is the *xy*-component of the peroneus longus force, and R_4 and R_2 are equilibrium forces on the tarsometatarsal and metatarsophalangeal joints from the neighboring bones. In order to calculate the maximum stresses on the cuts, the bone is drawn with a 35^0 angle to the floor (Fig. **1**), which is the angle the bone takes [4] during the push-off phase (second force peak during stance).

Table 1. Forces (in Newtons) at the Metatarsal Bone Model Presented in Fig. (3)

Symbol	*x*-Value	*y*-Value	Origin
F_2	0	290	External ground force
F_{hl}	-475	221	Flexor hallucis longus muscle
F_{hb}	-329	133	Flexor hallucis brevis muscle
F_{pl}	-371	0	Peroneus longus force
R_2	-62.1	145	Tarsometatarsal joint
R_4	1237	-789	Metatarsophalangeal joint

The ANSYS bone model was divided in 14000 elements in total, with 8300 nodes on the *xy* plane, whereas the OOF bone model was divided in 8000 elements with 8000 nodes on the *xy* plane. Bone dimensions were 66 × 37 × 10mm and bone volume was 12.8 cm^3. The following bone material constants were used [9]: Elastic modulus 20 GPa, Poisson's ratio 0.3, density 1.94g/cm^3 (average values). Calculated bone mass was 24.3 g.

RESULTS

Followup data from clinical application of this new method were collected an average 32.7 months after the operation (Table **2**). Mean preoperative HVA was 34.1 degrees (range, 22 to 56 degrees) and mean preoperative IMA was 15.5 degrees (range, 10 to 29 degrees). At the last follow-up examination, mean postoperative HVA angle was 14.2 degrees (range, 0 to 28 degrees), mean postoperative IMA angle was 8.1 degrees (range, 6 to 22 degrees), and mean AOFAS score was 94.3 (range 67 to 100). Results were rated as excellent in fifty feet (80.64%), good in 8 feet (12.9%) and fair in 4 feet (6.45%). All osteotomies were fused and there were no cases of non-union, loosening, avascular metatarsal head necrosis or wound infection. Two patients with fair results experienced late recurrence of the deformity, but this was not clinically significant, and they refused any further treatment.

Both software packages (ANSYS and OOF) performed linear static structural FEA calculations and their outputs consist of sets of stress vector components along specific coordinate axes on each node of the model. Both data sets can be found as supplementary info at the web links listed in the Appendix [16, 17]. From these values, the average

Table 2. Results of the Modified Chevron Osteotomy and Herbert Screw Fixation at Follow-Up (Mean Follow-Up Time 32.7 Months, Range 24-54 Months)

Age - yr*	54.9 (17-70)†
Female (%)	100
Hallux valgus angle (degrees)	14.2 (0-28)
Intermetatarsal angle (degrees)	8.1 (6-22)
AOFAS score (%)	
Excellent	80.64
Good	12.90
Fair	6.45
Poor	0

*At time of operation.
†Numbers in parentheses indicate ranges.

normal and average shear stress was calculated on the nodes of the 60^0 and the 90^0 osteotomies (Figs. **4**, **5**). In general, normal compressive (positive) stresses along an interface tend to keep the two parts together, while shear stresses tend to slide the two parts apart. Therefore better bonding is expected where the normal-to-shear stress ratio λ is positive and greater than 1. Table **3** shows the average λ produced by the two methods along the segments AC, CA', BC and CB' (Fig. **1**) of the two osteotomies. For ease of comparison, all ratios are normalized in the 0 to 1 range. In general, FEA methods are complex and their results include some degree of uncertainty; however, in the present work we only attempted qualitative analysis, with no emphasis on detailed numerical data. In this qualitative fashion, results obtained with the ANSYS and OOF methods agree reasonably well. In particular, both methods predict that the largest λ occurs along the CA segment of the ACA' (Fig. **1**) osteotomy and it is 2 to 3 times larger than the second largest λ which occurs along the CB' segment of the BCB' osteotomy. Therefore a stronger bonding is expected for the 90^0 ACA' osteotomy compared to the classical 60^0 Chevron osteotomy BCB', and this finding may explain our excellent clinical results. However, the CA' and the BC segments should also be taken into account, and both methods predict low normal stresses on these segments (Table **3**). These interfaces will also influence healing time, but we believe that the strong bonding of the CA segment is the prevailing factor.

DISCUSSION

Our results indicate that the 90^0 angle may be a good choice for Chevron osteotomy. Good clinical results have been reported in 80-90% of patients having the typical 60^0 osteotomy [4, 6, 9] with recurrences or under-corrections occurring in 10-14% of cases [5, 7, 8]. However, a recent study by Torkki *et al.* [10] reported inferior results, probably due to the number of different surgeons (including trainees) who performed these operations and the unselected study population.

Data obtained from applying FEA analysis to a bone model seem to explain the good clinical results observed in our patient cohort. These results are easier to explain

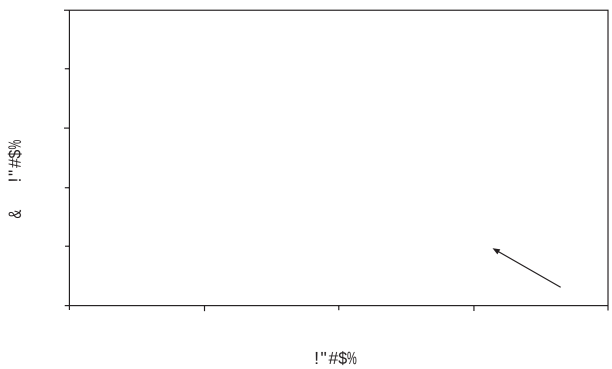

Fig. (4). A plane x-y view of the bone model shown in Fig. (**3**), with Finite Element Analysis nodes (tiny dots) created by the ANSYS software while evaluating normal and shear stresses with the 60^o and 90^o osteotomies. Due to the discrete nature of the analysis, the two osteotomies cannot be represented by exact straight segments. Filled triangles indicate the nodes chosen to represent the 90^0 osteotomy, whereas filled circles indicate the nodes chosen to represent the 60^0 osteotomy. Point C (arrow) is the center of the circle shown in Fig. (**1**).

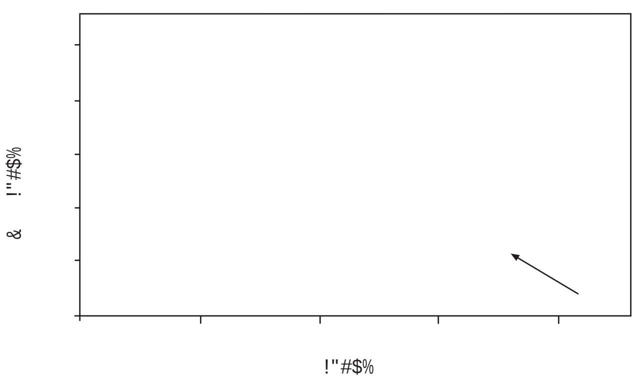

Fig. (5). A plane x-y view of the bone model shown in Fig. (**3**), with Finite Element Analysis nodes (tiny dots) created by the OOF software while evaluating normal and shear stresses with the 60^o and 90^o osteotomies. Due to the discrete nature of the analysis, the two osteotomies cannot be represented by exact straight segments. Filled triangles indicate the nodes chosen to represent the 90^0 osteotomy, whereas filled circles indicate the nodes chosen to represent the 60^{0}osteotomy. Point C (arrow) is the center of the circle shown in Fig. (**1**).

Table 3. Normalized Normal-to-Shear Stress Ratio Calculated by the Two FEA Packages for the Two Osteotomies of Fig. (1)

Section	ANSYS	OOF
AC	1.00	1.00
CA	0.20	0.08
BC	0.32	0.03
CB	0.35	0.47

physically if the bone is approximated by a straight long beam under longitudinal compression. This is a well known example in the theory of elasticity, with maximum and zero normal stress along the directions of 0^0 and ± 90^0 with respect to the beam axis, and maximum shear stress at ± 45^0. In the case of the metatarsal bone, all forces in Fig. (**3**) (except F_2) are almost parallel to the long axis of the bone. Because the metatarsal bone has an elongated shape, this bone can be approximated by a beam, and this crude approximation can help us understand the distribution of stresses along the bone. As the ± 30^0 BCB' osteotomy (Fig. **1**) is close to the ± 45^0 case, a large shear stress is to be expected. In contrast, as the AC and CA segments resemble the 90^0 and 0^0 cases, normal stresses are expected to be maximum and zero respectively.

CONCLUSION

In this manuscript we present our experience with the 90-degree Chevron osteotomy on a patient cohort of 51 women who had surgery for 62 Hallux Valgus deformities, and we also present results of Finite Element Analysis (FEA) of the 90^o Chevron osteotomy. Compared to the 60^o method, FEA predicts enhanced mechanical bonding, with stronger compressive stresses and weaker shearing stresses with the 90^0 Chevron osteotomy. Our good long-term clinical results, together with results of Finite Element Analysis, suggest that the 90^0 angle Chevron osteotomy is a good alternative to the classic 60^o method in patients with mild to moderate Hallux Valgus who need surgery.

AUTHOR CONTRIBUTIONS

Charalambos Matzaroglou, performed many operations, collected data and drafted manuscript.

Panagiotis Bougas, assisted with most operations and collected data.

Elias Panagiotopoulos, supervised most operations, directed patient care and revised manuscript.

Alkis Saridis performed many operations, collected data and revised manuscript.

Menelaos Karanikolas provided anesthesia for many procedures, organized, revised and submitted manuscript.

Dimitris Kouzoudis provided data, conducted Finite Element Analysis, and revised manuscript.

CONFLICT OF INTEREST

This work was supported solely by Department Funds. All authors declare that they have no conflict of interest to report.

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APPENDIX

The outputs of two packages ANSYS and OOF consist of sets of stress vector components along specific coordinate axes which can be found at the web links

http://www.ephysics.des.upatras.gr/chevron90fea/ansysExport.xls

and

http://www.ephysics.des.upatras.gr/chevron90fea/oofExport.xls

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