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Comparative biomechanical study of different screw fixation methods for minimally invasive hallux valgus surgery: A finite element analysis

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ABSTRACT

Background: There are different screw configurations utilised for minimally invasive hallux valgus (HV) deformity despite limited biomechanical data assessing the stability and strength of each construct. We aimed to compare the strength of various screw configurations for minimally invasive HV surgery using finite element analysis (FEA).
Methods: A FEA model was developed from a CT of a female with moderate HV deformity. Five screw configurations utilizing one or two bicortical or intramedullary screws were tested. Stress analysis considered osteotomy displacement, maximum and minimum principal stresses, and von Mises stress for both implants and bone for each screw configuration.
Results: Fixation with two screws (one bicortical and one intramedullary) demonstrated the lowest values for osteotomy displacement, minimum and maximum total stress, and equivalent von Mises stress on the bone and screws in both loading conditions.
Conclusion: The optimal configuration when performing minimally invasive surgery for moderate HV is one bicortical and one intramedullary screw.
Level of evidence: Level III

1. Introduction

Minimally invasive or percutaneous surgery has become a popular procedure to treat hallux valgus (HV) deformity due to the significant improvement in clinical and radiographic outcomes following surgery[1–6]. The possibility of a large metatarsal head translation of > 100 % has made this technique versatile for the management of severe HV deformities[7,8]. Fig. 1.

A large metatarsal head translation requires stable and rigid internal fixation to maximize bony union[9]. The operative technique principles have evolved to the current fourth generation, which describes a specific internal fixation with two screws: a proximal screw reaching two cortices before fixing the metatarsal head and a distal parallel screw that can reach only one cortical before fixing the head as shown in Fig. 1 [10–12]. However, some authors have questioned the need for two screws and demonstrated good results using only one screw to fix the osteotomy[13,14]. There is a lack of basic science biomechanical studies investigating the stability or strength of the constructs used for minimally invasive HV surgery[15–18].

There are different methods of testing the fixation strength of constructs, including cadaveric specimens and finite element analysis. Finite element analysis (FEA) in biomechanical studies uses computational models to simulate and analyze the mechanical

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Fig. 1. Post-operative radiograph of minimally invasive hallux valgus correction demonstrating the classical MICA fixation configuration.

behavior of bone, soft tissues, and implants and has previously been used in studies of hallux valgus[8,19–22]. FEA helps clarify the stress distribution, deformation, and overall biomechanical performance of the foot and ankle structures under various conditions.

This study aimed to perform a biomechanical analysis based on FEA to compare the strength of different screw fixation configurations of minimally invasive HV surgery. We hypothesize that fixation with one bicortical proximal screw and one intramedullary distal screw is biomechanically the strongest with least risk of secondary complications such as metatarsal fracture or metalwork failure.

2. Methods

2.1. Study design

A FEA model was designed and performed following the Considerations for Reporting Finite Element Analysis Studies in Biomechanics guidelines [9].

2.2. Finite element analysis model

A 3D foot finite element model was developed based on non-weight bearing computer tomography (CT) images with a slice thickness of 0.5 mm of a 46 years old female patient (164 cm, 60 kg) foot with a moderate hallux valgus deformity who underwent minimally invasive HV surgery. A female patient with moderate hallux valgus deformity was chosen as this is the most common deformity severity treated with minimally invasive HV surgery in a number of studies [3,11]. The hallux valgus angle (HVA) was 30 degrees; First and second intermetatarsal angle (IMA) was 14 degrees. The CT images were imported into the InVesalius™ program for three-dimensional reconstruction of the anatomical structure. After three-dimensionally reconstructed the DICOM images, the 3D files in the Stereo Lithography (STL) format were created. Three-dimensional virtual models of each system (bone, ligaments, and screws) were made using the Rhinoceros™ 6 program (Robert McNeel & Associates, United States), and the FEA was performed with the SimLab™ program (HyperWorks, United States) using the Optistruct solver [16]. The discretization of the geometric domain was performed using second-order tetrahedral elements with an average edge length of 3 mm in the cortical and trabecular bones, 0.5 mm in the area, 2 mm in the ligaments with refinement in the contact regions with average edge size of 0.8 mm. All tissues were defined as homogeneous, isotropic, and linearly elastic. Young's modulus and Poisson's ratio for the modeled structures were identified from a previous study [16]. The properties of the materials are listed in Table 1. A standard mesh sensitivity analysis was performed to ensure that the mesh density used in the FEM was sufficient to reach the converged numerical results and that no further mesh refinement was necessary.

From these 3D virtual models, an extracapsular short chevron "V′-shaped osteotomy with 130 degrees of inclination with 75 % of lateral translation was made and fixed using five different screw configurations. The corrected HVA was 5 degrees, and IMA was 4 degrees (Fig. 2) based on typical corrections of the HVA, IMA and the intermetatarsal angle between the proximal fragment of the osteotomy and the second ray (IAPF) described in the literature[1,3,23]. An Akin osteotomy is only performed if there is residual hallux valgus deformity[3,24,25], in this case, this was not was not modelled as it was not required in the case the model was based on and this is important to note as it may affect the generalisability of the results to other techniques that incorporate an Akin osteotomy.

2.3. Fixation configuration

Fixation configuration was based on previous surgical studies and techniques reported in the literature[3,14,15,26–28]. The implants used were formatted as indicated by the manufacturer's dimensional characteristics (Novastep®, Rennes, France). Five internal fixation configurations with 4.0 mm chamfered screws were used for fixation of Minimally Invasive Hallux Valgus Surgery and assessed by finite element model (Fig. 3): original MICA fixation with two screws (proximal bicortical and a distal intramedullary screw), two intramedullary screws, two bicortical screws, one intramedullary screw, and one bicortical screw. These screw configurations represent the common scenarios in which a minimally invasive chevron osteotomy might be stabilized. The entry point for each screw was chosen based on the technical descriptions of the MICA technique as described by Redfern, Vernois and Lam[12,24,29]. For models B and E (Fig. 3) proximal screw entry placement was identical with the entry point at point specified midway in the sagittal

Table 1
Material properties for each material.

	Elastic modulus (MPa)	Poisson's ratio
Cortical Bone	7300	0,3
Trabecular Bone	1000	0,3
Titanium Screw	186400	0,3
Ligaments	260	0

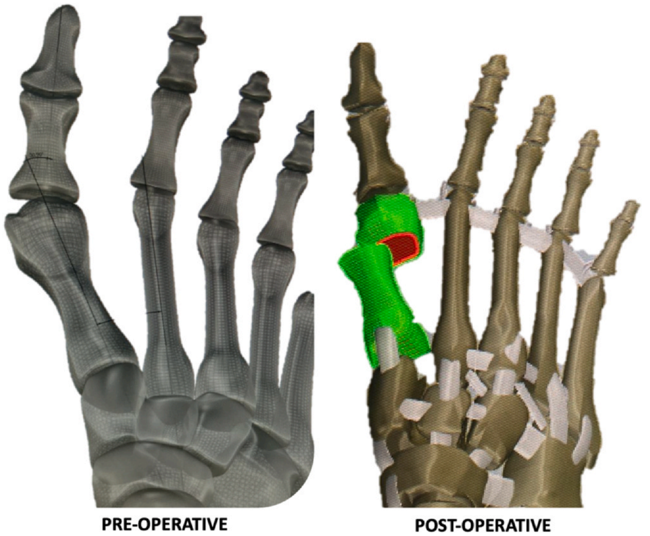

Fig. 2. Graphical representation of the pre and and post-operative simulated model for the finite element analysis.

plane of the first MT at the apex where the medial edge of the proximal first MT and first TMTJ so that the screw passed through the proximal metaphysis and then out through the lateral wall proximal to the osteotomy site. For model C, screw entry point was 5 mm distal to the TMTJ at the mid point of the sagittal plane of the first MT through the proximal metaphysis angled to achieve intramedullary fixation. For model D screw entry point was 2 mm distal to the TMTJ at the mid point of the sagittal plane of the first MT through the proximal metaphysis angled to achieve cortical (rather than intramedullary) fixation. For model F, the entry point was located at the mid point of the sagittal plane of the first metatarsal 18 mm distal to the first TMTJ aimed to achieve intramedullary fixation. With regards to the distal screw placement, model B used the same screw entry point and configuration as model F. For model C and D, distal screw entry point was located 12 and 10 mm distal to the proximal entry point and parallel in the sagittal plane respectively.

2.4. Loading conditions

With the forefoot and hindfoot fixed, a vertical ground reaction force (GRF) was applied to the midfoot as shown in Fig. 4. The upward vertical force of the Achilles tendon was also created with half of the value of the GRF. Simulated 150 N and 300 N loads were applied to the model. These loads were chosen based on work published by Cheung et al. who previously developed a FEA model of the foot[30]. They noted that a person with a body mass of 70 kg applies a vertical force of 350 N on each foot during balanced standing. This value of Achilles' tendon loading was approximately 50 % of the force

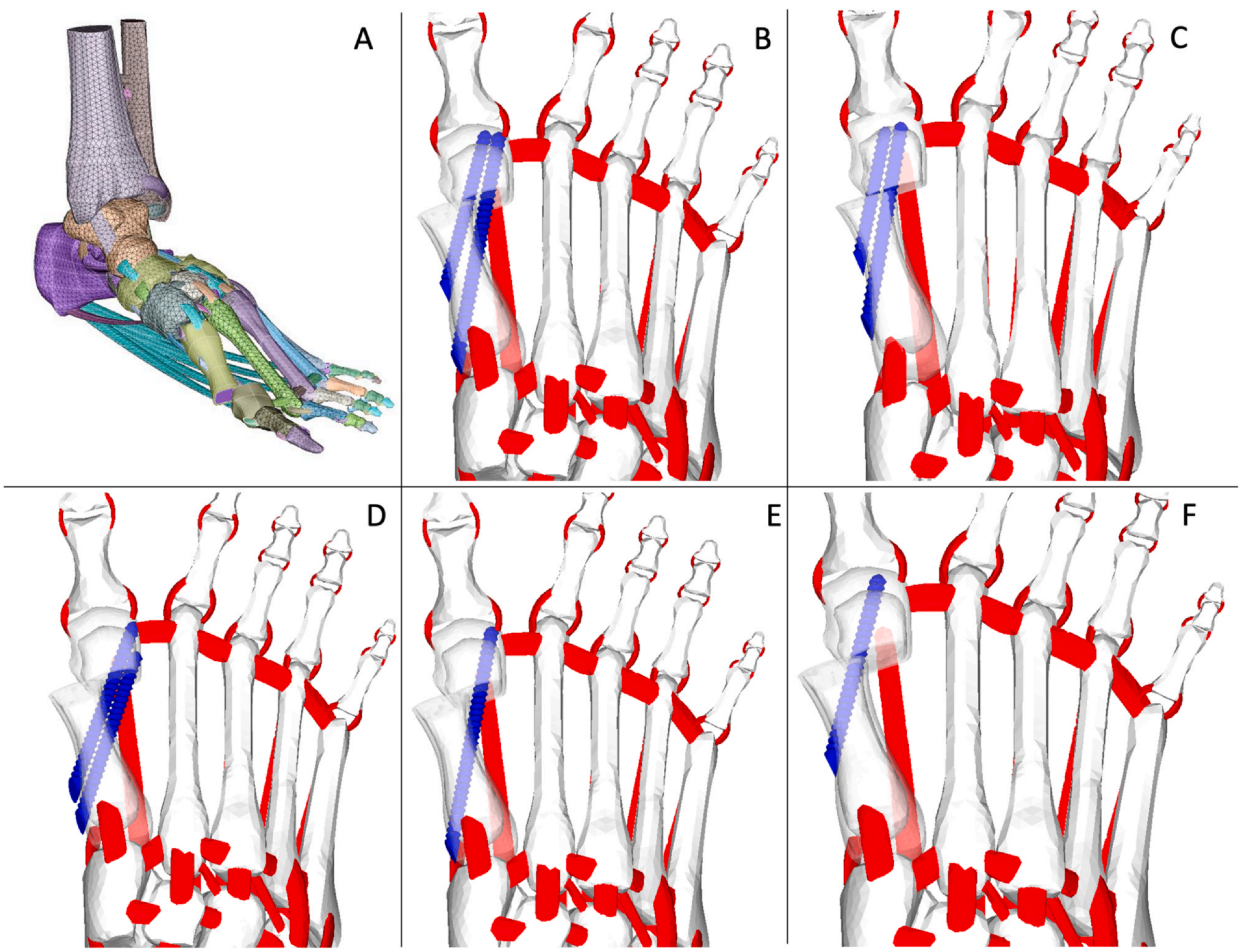

Fig. 3. Screw fixation configuration tested as art of the finite element analysis model: (A) Representation of model (B) Fourth-generation configuration with one bicortical and one intramedullary screw (C) Two intramedullary screws (D) Two bicortical screws (E) one bicortical screw (F) one intramedullary screw.

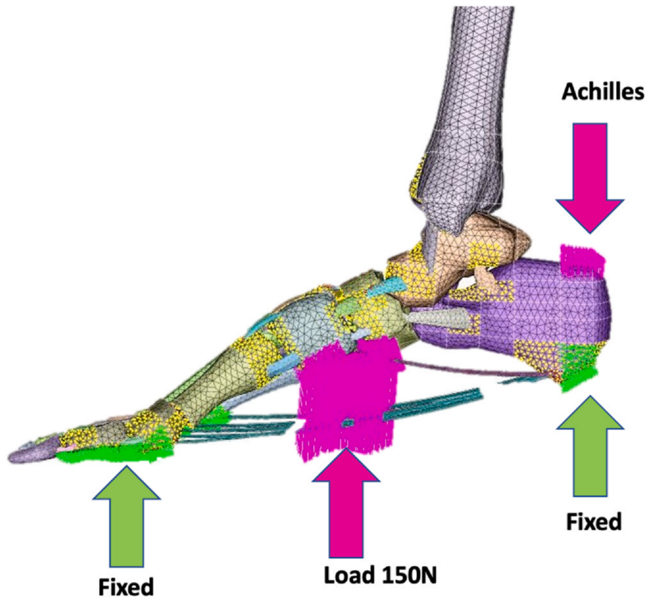

Fig. 4. Loading conditions for the finite element analysis.

applied on the foot during balanced standing on one foot. As our patient was 60Kg, we calculated the force vector to be 300 N. We then halved this to simulate weightbearing with both feet. The FEA evaluated the localized displacement of the osteotomy site, the von mises stresses on the first metatarsal and the screws.

2.5. Stress analysis

For the analysis of stresses, the maximum and minimum principal stresses (Pmax, Pmin) and von Mises stress values for the screws (VMS) and the bone (VMB) were used. The Pmax demonstrates the areas with the most traction forces, while the Pmin the areas with compression forces. Stress analysis of the first metatarsal bone was explicitly performed to assess the fracture risk. A similar stress analysis of the screw configuration was conducted to identify which configuration carried the highest risk of screw fatigue and failure. The displacement of the osteotomy under stress was also measured.

2.6. Declarations

There was no funding to support this study. RR and GN report fees from Novastep outside the scope of this study. RR also reports fees from Marquardt and Medartis beyond the scope of this study. GFF reports fees from Arthrex beyond the scope of this study. None of the other authors have any conflicts of interest to declare.None of the other authors have any conflicts of interest to declare. ICJME forms are available for all authors. Ethical approval was not required for this biomechanical study.

3. Results

A load with 150 and 300 N was conducted for the five fixation models. The osteotomy displacement, maximum and minimum principal stresses, and equivalent von Mises stress for both implants and bone were calculated. The results are summarized in Tables 2 and 3.

3.1. Displacement osteotomy

The MICA fixation had 0.4 mm displacement of the osteotomy under 150 N and 1.5 mm under 300 N. The highest osteotomy displacement occurs with one intramedullary screw fixation with 1.3 and 2.6 mm under 150 and 300 N (Fig. 5).

3.2. Maximum principal stresses

The MICA fixation showed the lowest values (34.3 and 71.0 MPa) under 150 and 300 N, respectively. The fixation with one bicortical screw showed the highest values (46.2 and 91.2 MPa) under 150 and 300 N as shown in Fig. 6.

3.3. Minimum principal (Compression)

The MICA fixation showed the highest value (−73.5 and −144.8 MPa) under 150 and 300 N. The fixation with one intramedullary screw showed the highest value (−75.2 MPa) and under 150 N, while the fixation with two intramedullary screws had the highest value (−153.5 MPa) under 300 N as shown in Fig. 6.

3.4. Von mises bone stress

The highest stress on the bone at 150 N occurs when using one intramedullary screw fixation (78.2 MPa), while the fixation with

Table 2
Finite Element Analysis of Different Configurations for Fixation of Minimally Invasive Hallux Valgus Surgery at 150 N of loading.

	MICA	2 Intramedullary Screws	2 Bicortical Screws	1 Intramedullary Screw	1 Bicortical Screw
Displacement - Osteotomy (mm)	0,46	1,21	1,15	1,34	1,26
MaxP(MPa) - Tension	34,3	35,85	40,79	35,39	46,24
MinP(MPa) - Compression	−73,56	−74,33	−73,67	−75,24	−74,72
Von Mises Bone(MPa)	68,45	70,75	64,93	78,82	71,99
Von Mises Screw(MPa)	791,31	867,79	795,2	805,12	861,14

Table 3
Finite Element Analysis of Different Configurations for Fixation of Minimally Invasive Hallux Valgus Surgery at 300 N of loading.

	MICA	Two Intramedullary Screws	Two Bicortical Screws	One Intramedullary Screw	One Bicortical Screw
Displacement - Osteotomy (mm)	1,59	2,59	2,56	2,68	2,61
MaxP(MPa) - Tension	71,04	73,65	82,47	74,98	91,24
MinP(MPa) - Compression	−144,89	−153,51	−152,14	−151,05	−152,35
Von Mises Bone(MPa)	135,24	142,14	138,54	153,74	186,57
Von Mises Screw(MPa)	1032,19	1735,58	1590,4	1863,06	2019,37

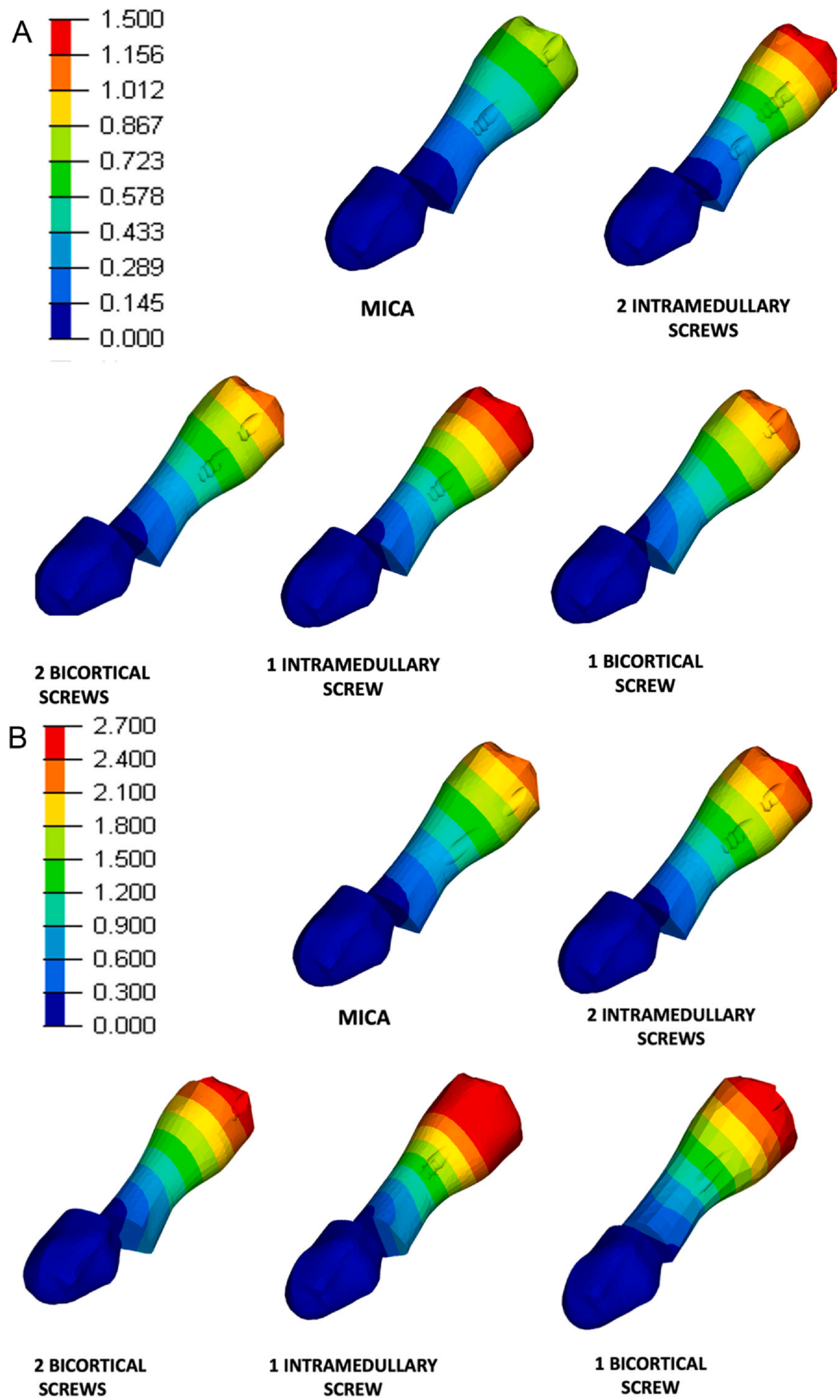

Fig. 5. Osteotomy displacement (mm) under 150 N (A) and 300 N (B) of load demonstrating the distance the osteotomy moved when subject to different loading conditions.

one bicortical screw has the highest value (186.5) at 300 N. The MICA fixation demonstrated the lowest bone stresses at both 150 and 300 N (64.9 and 135.2 MPa) as shown in Fig. 7.

3.5. *Von mises screw stress*

The highest stress on the screw at 150 N occurs when the fixation used two intramedullary screws (867.7 MPa), while the fixation with two bicortical screws had the highest value (2019.3 MPa) at 300 N. The MICA showed the lowest screw stresses at both 150 and 300 N (791.3 and 1032.1 MPa) as shown in Fig. 8.

4. Discussion

This computational FEA study has found that the MICA screw configuration technique, as described in the original technique, was biomechanically the most effective and safe, with the lowest displacement on the osteotomy site and a lower risk of fracture or metalwork failure.

The Pmax (traction or tensile forces) evaluates the amount of deformation that occurs in the model. MICA showed the lowest values, representing less probability of lateral wall fracture of the metatarsal bone. It is important to note that the medial and plantar area of the proximal fragment concentrated the tensile forces with one intramedullary screw

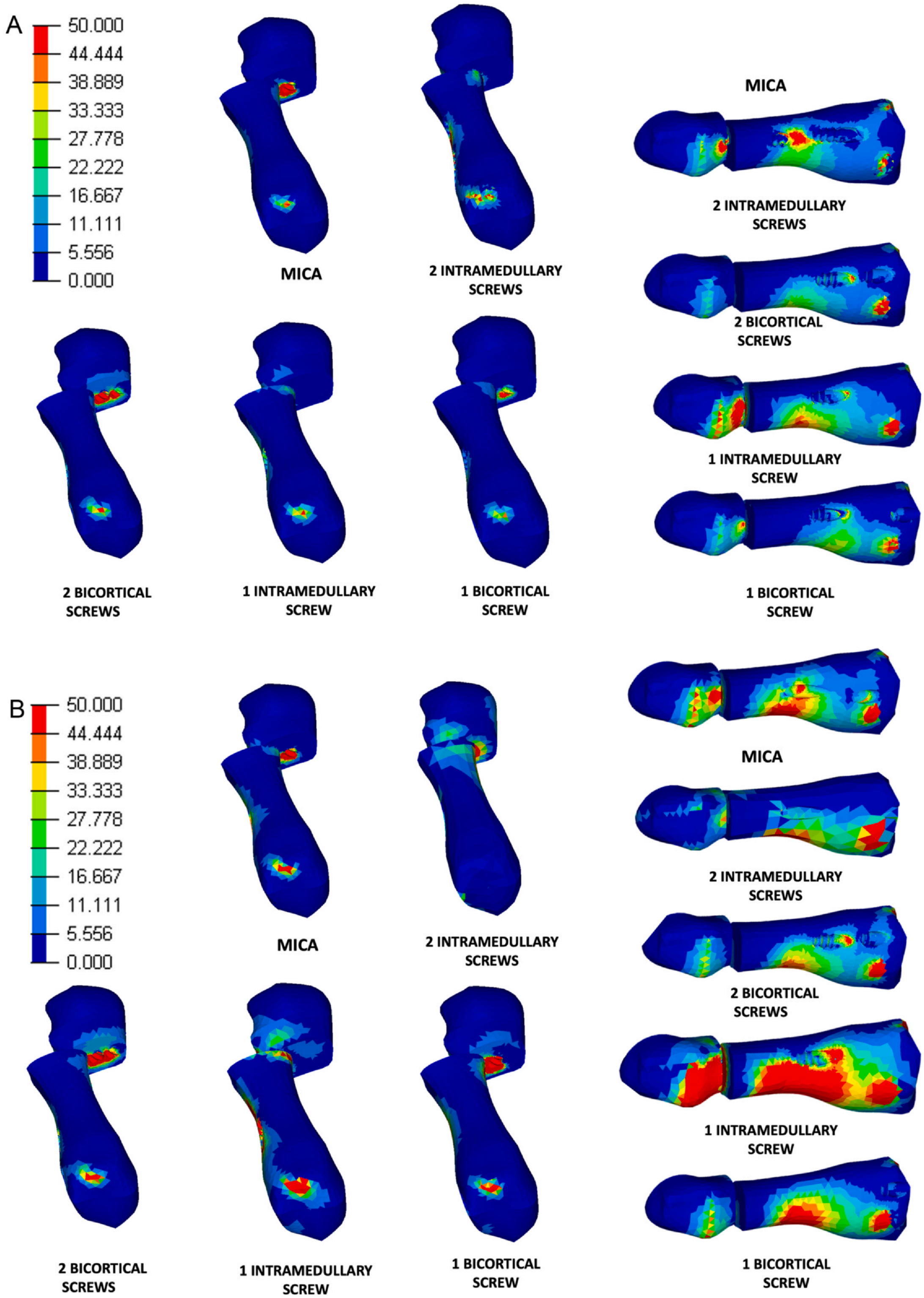

Fig. 6. Maximum principal traction stresses (MPa) under 150 N (A) and 300 N (B) and compression with 150 N (C) and 300 N (D) of load showing how the traction and compression stresses affecting the first metatarsal in response to different loading conditions.

fixation. In contrast, the lateral and distal parts of the proximal fragment concentrated the tensile forces in the fixation with two bicortical screws. The fracture of the proximal lateral wall fragment of the osteotomy is a known complication related to MICA[31–33] and we hypothesise that in cases where the head of the metatarsal is 100 % translated, the fixation is made with two bicortical screws thereby increasing the stress on the proximal fragment and increasing risk of fracture.

There is some debate in the literature discussing the need for two screws to MICA. Li et al. performed a study comparing the clinical and radiographic outcomes of MICA fixed with a single screw versus a dual screw[13]. A total of 103 patients with mild to moderate HV-treated MICA were retrospectively evaluated, with at least 12 months of follow-up. 51 patients underwent single-screw fixation procedures, and 52 received dual-screw fixation procedures. Both

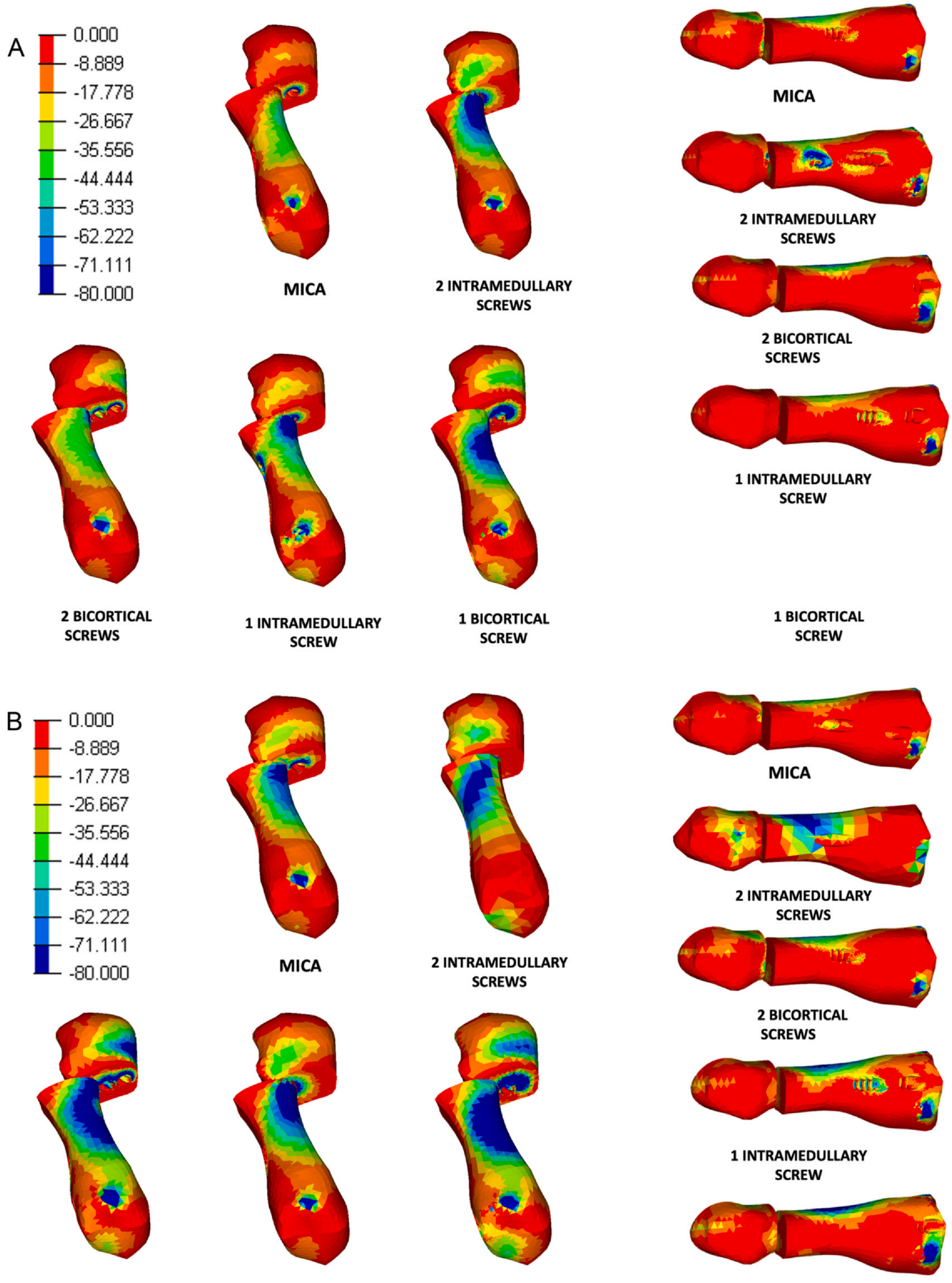

Fig. 6. (*continued*)

groups had good to excellent clinical and radiographic outcomes during the final follow-up and a similar rate of complications. The present study showed higher values of stress in the bone (represented by the VMB) on fixations with a single screw. It is important to emphasize that the finite element model was made with 75 % lateral displacement of the metatarsal head and potentially these results may demonstrate greater difference in osteotomies with 100 % translation.

The stresses on the screw analysed by the VMS showed a lower risk of screw breakage in the MICA original fixation with greater discrepancies noted when load increased to 300 N. The single screw used for the bicortical model showed almost two times of stress compared with the screws on the MICA original fixation. It is interesting to note that the area that had higher stress values corresponded to the point where the screw crossed the lateral cortex of the proximal fragment, suggesting this area is at risk of failure (as seen in clinical practice by lateral wall fractures). It seems that the intramedullary screw in MICA is important to increase the stability and also to share the bicortical screw stresses in this area and by extension reduce the risk of fracture.

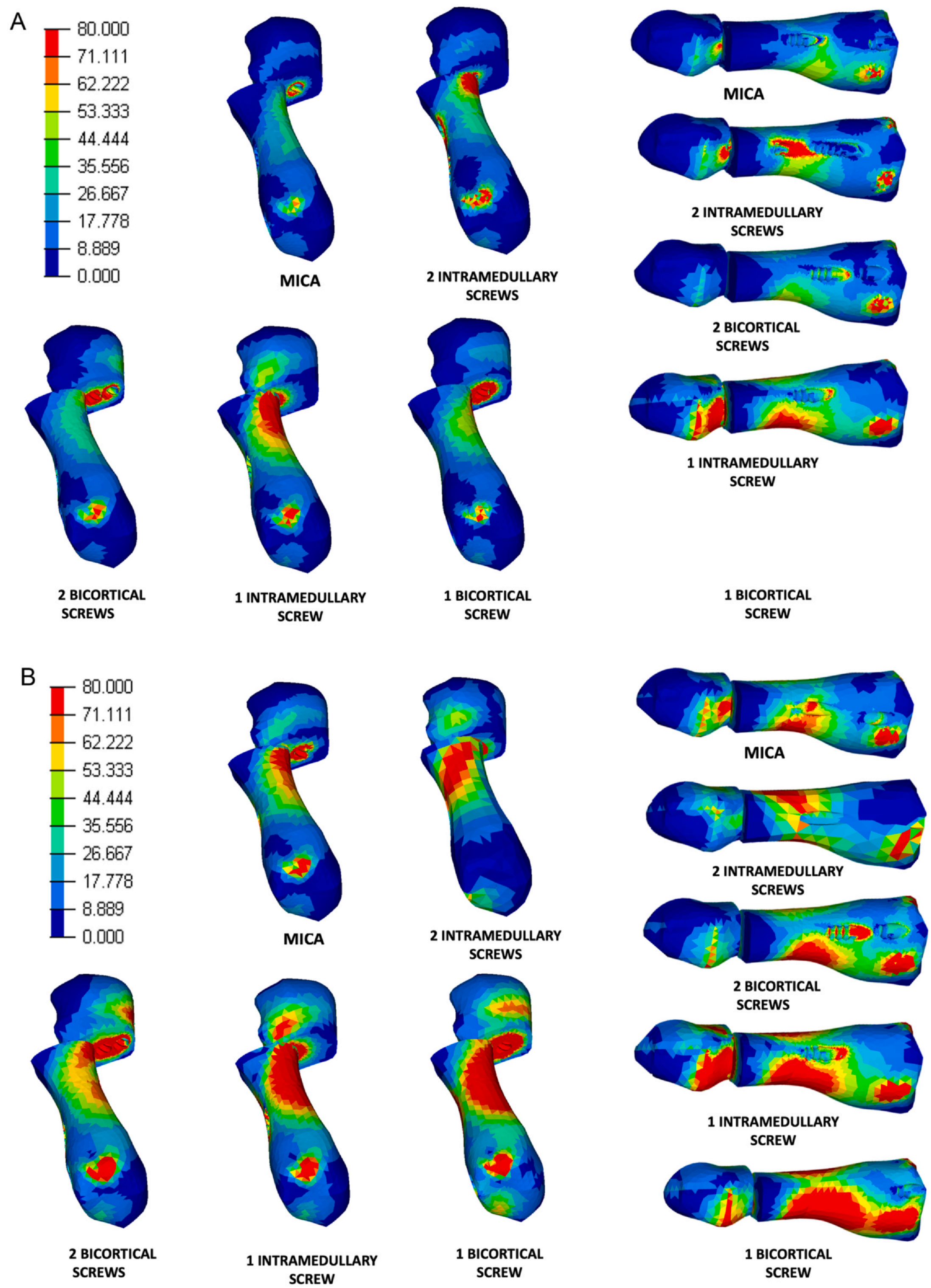

Fig. 7. Von Mises stress analysis for each foot for different fixation configurations under 150 N (A) and 300 N (B) of load demonstrating lowest stress when the combination of one intramedullary and one bicortical screw used for fixation.

This study expands upon work performed by Xie et al. investigating fixation methods after minimally invasive hallux valgus surgery[34]. Xie et al. used FEA to simulate and analyze the biomechanical characteristics of three different fixation methods (bandage, k-wire, herbert screw) after minimally invasive osteotomy for hallux valgus. This study found that Kirschner wire and Herbert screw were better than bandage fixation in fixation strength and stability. Still, there was no significant difference between Kirschner wire and Herbert screw although they also found there was a potential risk of fracture when using a k-wire[34].

This study found that the MICA fixation configuration optimised the tension and compression stress at the osteotomy level. This is important as a previous finite element analysis that used a two-dimensional FE model of the first metatarsal compared the traditional

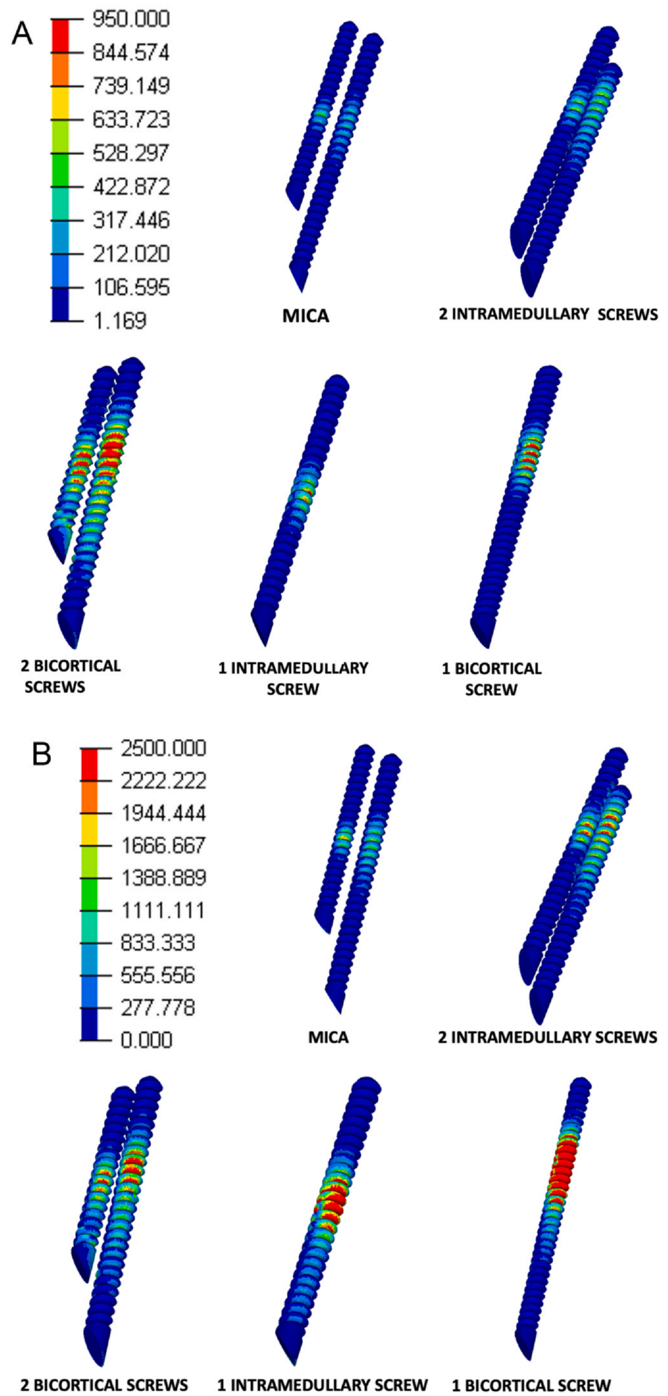

Fig. 8. Von Mises stress analysis focusing on each screw for different fixation configurations under 150 N (A) and 300 N (B) of load demonstrating lowest stress when the combination of one intramedullary and one bicortical screw used for fixation.

sixty-degree chevron to a ninety-degree chevron osteotomy and found improved mechanical bonding owing to stronger compressive stresses at the osteotomy site and weaker shear stresses that tend to slide the two bone parts apart[19].

Several studies utilized FEA to investigate various aspects of HV including: force compensation mechanism[19], generalized ligament laxity[35], fixation method[34,36], role of footwear[37] proximal phalanx geometry[38] and assessment of first ray properties. [7,8,16,21,22,39]. Few studies are reporting the finite element analysis on osteotomy technique or fixation in HV deformity correction; Zhang et al. demonstrated, using a moderate HV model, that a 4 mm osteotomy displacement using a chevron osteotomy resulted in the lowest stresses across the first MTPJ[22].

Biomechanical studies investigating fixation methods in MIS HV are very limited. Clinical studies are reporting the outcomes of both single screw fixation and two screw fixation which report both the single- and dual-screw fixation groups had comparable clinical and radiographic outcomes, as well as a similar incidence of complications[14]. There are understandable advantages of single screw fixation including reduction of overall surgical cost, number of intraoperative fluoroscopy images and operation duration. However, these short-term advantages may be mitigated if there is a higher risk of failure, as suggested by the results of this study. A recent cadaveric study also found that three-point proximal screw fixation has superior biomechanical properties compared to intramedullary fixation which is in keeping with the results of this study[18].

4.1. Interpretation

Within the constraints of the underlying clinical case and model, the clinical implications of this finite element analysis demonstrate the fixation method for MICA using one bicortical and one intramedullary screw is biomechanically superior, with lower total and localized displacement, reduced Von Mises stresses, and potentially reduced risk of implant failure. Surgeons should aim to achieve fixation using the classical construct for MICA HV procedures as this may lead to improved stability, decreased risk of complications, and potentially overall better treatment outcomes although should be aware the results from this study only apply to moderate deformity and may not necessarily be reproduced with different deformity severities or osteotomy configurations. Further studies should investigate different osteotomy configurations, the impact of metatarsal head translation, and the clinical implications of different osteotomy fixation configurations.

4.2. Strengths

FEA modeling enables insight into the foot and ankle mechanics during various surgical interventions. The detailed stress analysis offered by FEA is a reliable method for assessing fixation configuration. Finite element analysis has been widely used in the field of foot and ankle surgery, which provides strong support for clinical research on the etiology, pathological mechanism, surgical treatment, and rehabilitation intervention of hallux valgus.

4.3. Limitations

There are important limitations to recognise in this study. From a clinical perspective, this study focused on a single case of moderate HV deformity without an Akin osteotomy. It is therefore not possible to generalise the findings in this study for different osteotomy configurations (eg transverse vs chevron), deformity severity (mild vs moderate vs severe) or percentage metatarsal head shifts. Readers should note that this case did not incorporate an Akin osteotomy in the modelling and therefore the addition of an Akin osteotomy, or other forefoot/lesser toe deformities may change the loading in the foot and potentially affect the stress across the first metatarsal and affecting the results. There are also recognized limitations of FEM analysis. For modelling purposes, it was considered that the mechanical properties of the materials, cortical bone, trabecular bone, ligaments, and syntheses were continuous, isotropic and uniform linear elastic materials and therefore do not reflect changes in bone density or morphology (as is often the case for FEA models). The accuracy of FEA results depends on the input parameters and assumptions made during model development, and precise material properties can vary in clinical situations. Simplifications in modelling, such as assuming linear material behaviour or limited anatomy, may affect the accuracy of predictions and readers should be aware of this when considering the results of this study with regards to clinical practice.

5. Conclusion

Whilst acknowledging the limitations of the FEA model, fixation of MICA using one intramedullary and one bicortical screw yielded better results regarding osteotomy displacement, minimum and maximum total stress, VMB, and VMS in both conditions. These results demonstrate that the classical fixation for MICA described in the original technique may be biomechanically most efficient and safe compared with alternative screws configurations.

Declaration of Competing Interest

There was no funding to support this study. RR and GN report fees from Novastep outside the scope of this study. RR also reports fees from Marquardt and Medartis beyond the scope of this study. GFF reports fees from Arthrex beyond the scope of this study. None of the other authors have any conflicts of interest to declare. None of the other authors have any conflicts of interest to declare. Ethical approval was not required for this biomechanical study.

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