Biomechanics of Fracture Repair Applied to the Lapidus Procedure

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STATEMENT OF PURPOSE

Fracture repair is influenced by biologic and mechanical factors. The choice of therapy directly impacts interfragmentary zone stability.[1] As demonstrated in clinical and experimental investigations, large gaps cause a delay in fracture healing.[2]

The Lapidus arthrodesis procedure can correct hallux valgus through modification of the distal medial cuneiform and proximal first metatarsal to achieve a stable fusion with angular correction. Following cartilage resection at the 1st tarsometatarsal (TMT) joint, the bones must be held in alignment using hardware such as staples, screws, a plate/screw construct or an intramedullary (IM) nail. The purpose of this study is to evaluate bone stability to encourage primary bone healing with and without interfragmentary compression.

METHODOLOGY & HYPOTHESIS

In order to understand the impact of joint compression on the mechanical environment for TMT fusion, a computational biomechanics model was developed. A foot and ankle specimen from a middle-aged female was CT scanned to capture the anatomic bone and soft tissue structures in 3 dimensions. The 0.5 mm image slices were segmented using 3DSlicer (http://www.slicer.org), converted to a 3D vector format (IGS or Initial Graphics exchange Specification), and imported into Computer-Aided Design (CAD) software, SOLIDWORKS 17.

Fig. 1

PROCEDURES

The CAD software was used to manually add ligamentous structures (Fig 1). Anthropometric cortical shells, trabecular cores, and cartilaginous endplates were captured for all 28 bones of the foot and ankle. The 1st metatarsal and cuneiform along with the associated cartilage was imported into finite element analysis (FEA) software, ANSYS 17, to build the computational models with linear elastic tissue properties referenced from other research simulations[3].

To test the hypothesis that additional compression imposed by an implant/instrument system would produce a more favorable mechanical environment for primary bone healing in Lapidus arthrodesis patients, two finite element models were created. Both models implemented the normal adult anatomy noted above and a 5.5 mm IM nail implanted across the 1st TMT joint. TMT joint preparation was simulated in both computational models by removing approximately 1.5 mm of cuneiform tissue and 1.5 mm of metatarsal tissue, as would be expected in clinical practice. The operative removal of cartilage and a portion of the subchondral plate promotes fusion by creating planar contact joint surfaces for proper bony alignment and direct bone-to-bone contact at the fusion site.

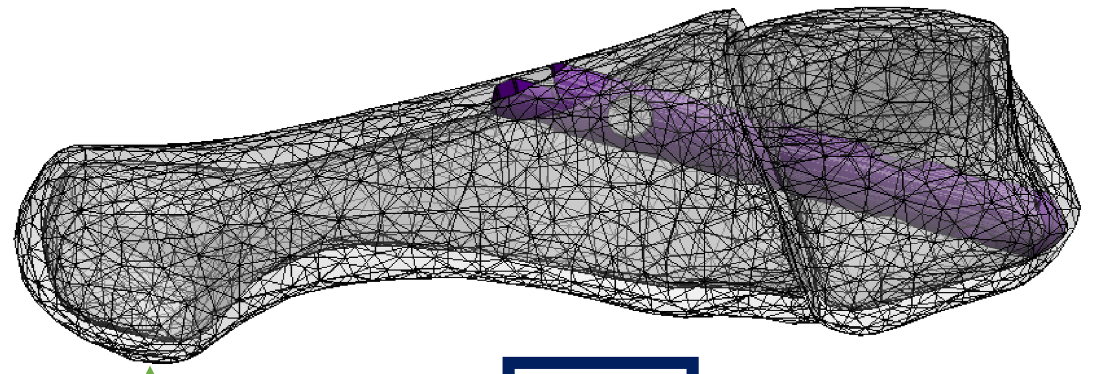


Fig. 2

Boundary conditions were applied to both computational models to simulate loading that could be anticipated to occur during activities of daily living. In particular, a vertical ground reaction force of 274 N was applied to the distal end of the 1st metatarsal to simulate loading of the 1st metatarsal expected during ambulation. The first of the two models applied zero N of IM nail compression and the second model applied 100 N of compression along the axis of the IM nail. Maximum von Mises stress in the IM nail, maximum joint contact stress, and the magnitude of interframentary motion at the inferior aspect of the TMT joint were quantified for both models and compared.

LITERATURE REVIEW

Primary bone healing is only possible with gap reduction and rigid fixation at the fracture site.[1] Relative displacement occurs between fracture surfaces when implants are used without application of compression. The amount of displacement is inversely proportional to the device stiffness and directly proportional to the load applied when studied with a finite element model.[4] In joint healing, compression is best achieved by keeping the strain value between 2-10%. Strain is calculated as displacement divided by fracture gap width. Too much compression can lead to necrosis and too little compression can lead to non-union. At optimum compression, osteons can cross the compressed surfaces, resulting in primary bone healing.[1] Applying this research to the surface area of the 1st TMT joint, suggested compression is 80-100 N.

RESULTS

The computational models showed substantial differences in both stress magnitudes and interfragmentary motion (Figs 3 and 4).

Fig. 3: 0 N Compression Across the TMT Joint

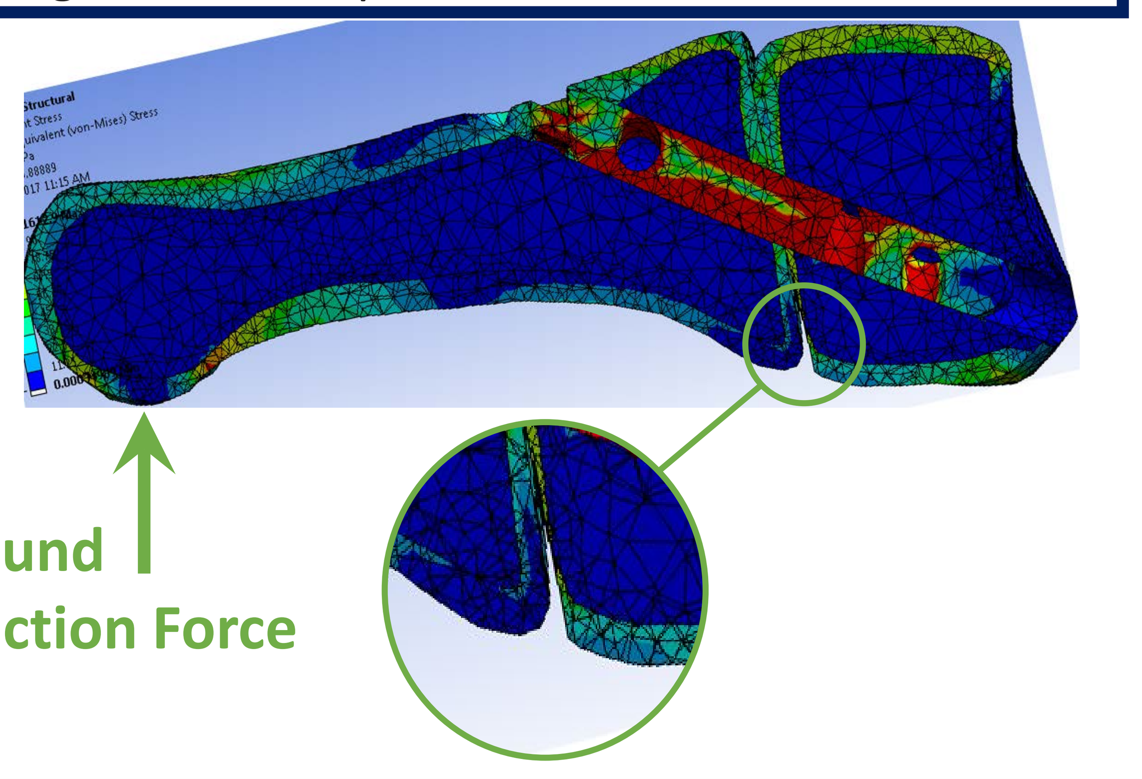
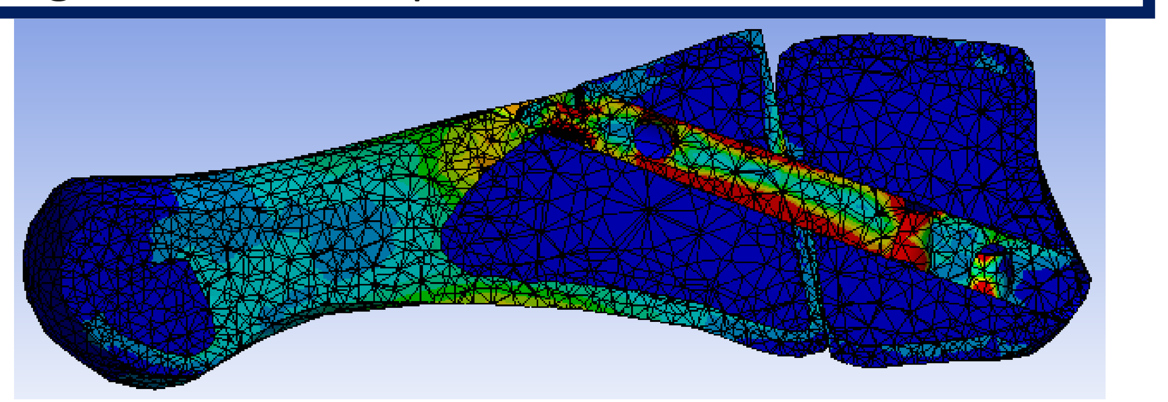


Fig. 4: 100 N Compression Across the TMT Joint



RESULTS

The peak von Mises implant stress in the zero N compression model was 1613 MPa (Fig 3). The peak von Mises stress in the 100 N compression model was 206 MPa (Fig 4), a factor of 7.8 less. In addition to the substantially higher implant stresses, the compressive contact stress at the dorsal surface of the TMT joint was a factor of 7.0 higher for the scenario without the 100N compression applied to the IM nail.

Lastly, the prevention of micro-motion at the arthrodesis site is necessary for primary bone repair. As shown in Fig 3 inset, plantar gapping of 0.75 mm was calculated for the scenario without compression applied to the IM nail, in contrast to negligible gapping with 100 N of IM nail compression in Fig 4.

DISCUSSION

Low implant stress levels are important to ensure clinical success in patients with risk factors for bony repair such as a history of smoking, diabetes, or morbid obesity. Nonunion or delayed union in these patients, combined with high hardware stress when joint compression is not applied intra-operatively increases the risk of implant fractures. High compressive stresses may cause pressure necrosis or bony failure in patients with osteopenia. Likewise, fusion site motion will increase the likelihood of nonunion and cannot support primary bone healing. All three factors support application of 100 N of IM nail compression in patients undergoing a Lapidus arthrodesis.

REFERENCES

1. Perren, S. M. (2002). Evolution of the internal fixation of long bone fractures: the scientific basis of biological internal fixation: choosing a new balance between stability and biology. Bone & Joint Journal, 84(8), 1093-1110.
2. Claes, L., Eckert-Hübner, K., & Augat, P. (2003). The fracture gap size influences the local vascularization and tissue differentiation in callus healing. Langenbeck's archives of surgery, 388(5), 316-322.
3. Williams, L.L. (2017). *A Finite Element Model of a Realistic Foot and Ankle for Flatfoot Analysis* (Thesis submission). *Used with permission from the author.*
4. Chao, E.Y., Kasman, R. A., & An, K. N. (1982). Rigidity and stress analyses of external fracture fixation devices—a theoretical approach. Journal of biomechanics, 15(12), 971-983.

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