Finite Element Analysis for First Metatarsophalangeal Joint Arthrodesis Demonstrates Reduction in Stress Across Bio-Integrative Fixation Over Traditional Metal Fixation

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Introduction/Purpose: During each step-in gait, the first metatarsophalangeal joint (MTPJ) is stressed by 90% of body weight, while loading the metatarsal head and base with up to 29% (228N/80Kg patient) of body weight (188N) during each foot push-off. To withstand these high mechanical forces, a successful fusion is dependent on joint preparation and rigid fixation. In this study we assessed a novel bio-integrative fiber-reinforced screw and nail construct. This material technology may provide improved mechanical fixation profile through its high flexural strength and flexural modulus that is closely matched to that of cortical bone. Finite Element Analysis (FEA) was performed to evaluate the mechanical strength and stress concentrations acting on the 1st MTPJ fusion following the use of these implants, compared to conventional metal fixation.

Methods: CT-based FEA of the 1st MTPJ fusion fixed by two fixation methods was simulated for mechanical strength and stress concentrations acting on the surrounding cortical bone. The 1st MTPJ of an adult male weighing 80kg was segmented from a left foot CT scan (120 KVP, SL 1mm) and was incorporated in a 3-dimensional CAD model. Bio-integrative fiber-reinforced 4.0mm partially threaded headless compression screw, and a 3.0mm fiber-reinforced cannulated nail were inserted in this computational model in crossed fashion (Fig. 1A). The bio-integrative implants are composed of continuous reinforcing mineral fibers (50% w/w), comprised of elements found in native bone and bound together by a degradable polymer [poly (L-lactide-co- D,L-lactide), PLDLA]. Two 4.0mm partially threaded headless titanium screws were inserted in similar trajectories and served as control (Fig. 1B). The FEA algorithm was based on published known forces acting on the first ray during push-off. Post-processing was performed on FEA results.

Results: The relative displacement between the Metatarsal and Phalangeal heads upon simulated loading was 1.6mm for metal fixation and 0.2mm for the fiber-reinforced bio-integrative fixation, demonstrating this technology to be mechanically stable at least as conventional metal fixation. In both models, the Von-Mises maximum stresses were found between the implant thread and shank. However, maximum localized stresses in cortical bone regions interacting with the metal implants were substantially higher (up to 8 times) compared to the bio-integrative implant-bone interactions. Moreover, stresses in the implant body were remarkably higher with metal implants compared to bio-integrative fixation (Fig. 1C, D&E). These results indicate that for physiological loading conditions applied on the 1st MTPJ, the use of bio-integrative fixation construct may reduce stress concentrations at the implant-cortical bone interface.

Conclusion: FEA results indicate that bio-integrative screw-nail construct provides equivalent mechanical fixation strength to metal fixation, while resulting in lower bone-implant stress concentrations. The closely matched flexural modulus of the bio-integrative material to that of cortical bone, decreases implant-bone resistance level and the probability of bone/implant failure and risk for implant loosening, all common complications in foot and ankle surgery. This study demonstrates a new methodology of CT-FEA for the evaluation of 1st MTPJ fusion arthrodesis and suggests the bio-integrative screw-nail combination as an alternative to traditional metal fixation. This model is currently being investigated in an ongoing clinical series.
Figure 1A & B: Implants incorporation in a 3-dimensional computational joint model. Yellow dots indicate hard contact (tie) for bio-integrative nail and screw construct (1A) and metal screws construct (1B). Figure 1C, D & E: Von-Mises stress. Mapping at Implant-Bone contact surfaces (regions are marked in yellowed circles) of bio-integrative nail and screw construct (1C) and metal screws construct (1D). Maximum stress at regions of interest (Difference in %) (1E).