Implant Design Optimization Applied to the Carpometacarpal Joint of the Thumb
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Introduction: The manufacturing flexibility of 3D printing has allowed for new approaches in designing total joint replacement implants. In addition to the implant’s shape, designers can now consider optimizing the distribution of material properties thanks to 3D printed materials with tailored porosity1. Moreover, shape and/or material optimization can be patient-specific. In this work, we focused on the carpometacarpal (CMC) joint of the thumb. We first examined the biomechanical performance of the Moje Acamo uncemented implant, for which revisions due to early aseptic loosening reach 52%2. We then examined whether the Moje Acamo performance could be improved by 1) optimizing its shape, 2) optimizing its distribution of material properties, or 3) simultaneously optimizing both shape and material property distribution.

Materials and Methods: We combined finite element analysis (FEA) with the multi-objective optimization algorithm NSGA-II to optimize the likelihood of bone ingrowth in the immediate post-operative scenario by minimizing the peak bone-implant micromotion and the failure of bone at the bone-implant interface. We generated a 2D FEA model from CT-scans of the first metacarpal bone of an 82 year-old male diagnosed with late-stage osteoarthritis. We reproduced an implantation of the Moje Acamo that had loosened at two years3. For shape optimization, we parameterized the implant stem’s geometry with 8 variables, allowed to vary between 0.6 mm and an upper limit only constrained to avoid cortex perforation and ensure a tapered stem shape. For material optimization, the stem’s elastic modulus was obtained by linear interpolation between a proximal and a distal elastic modulus, allowed to vary between 1.1 GPa and 200 GPa. These moduli correspond to the lowest of porous materials clinically used in orthopedics (i.e., TrabecularTitanium, LimaCorporate) to the highest (i.e. zirconia, the material of the Moje Acamo). The implant’s articular geometry was not altered from that of the Moje Acamo. Meshing was done with 0.1 mm linear elements, and the coefficient of friction between implant and bone was set to 0.6. Loading was consistent with the activity of key pinch4.

Results and Discussion: The Moje Acamo yielded a peak micromotion of 38 μm and high bone strains dorso-distal to the stem, consistent with the reported failures of this design. Optimizing stem shape resulted in the greatest reduction in micromotion and bone failure (Fig. 1 - a), while optimizing the material resulted in little-to-no improvements. The elastic modulus of the optimized stems was either homogeneous or decreasing from proximal to distal (Fig. 1 – b). The optimized shapes of the stems were wider than the Moje Acamo, aiming for cortical bone contact (Fig. 1 – b).

Translational Impact: We took a novel approach to implant design by combining shape and material optimization. Our results show that the bone-implant interaction can be improved by carefully choosing the stem shape and materials, which could be done in a patient specific basis.

Disclosure Statement: None of the authors have conflicts to disclose.