A COMPUTATIONAL APPROACH TO ORTHOPEDIC IMPLANT DESIGN OPTIMIZATION

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Introduction Unlike fasteners used in mechanical assemblies, cancellous bone screws used in orthopedics typically anchor objects within the bone material, rather than mate two surfaces together. Hence, tensile loads may be applied at the bone-implant interface at large angles with respect to the screw axis. While both computational[1,2] and benchtop results[1] have been reported for a wide range of screw designs, few published results exist evaluating screw-thread dimensions when loaded in off-axis directions. The purpose of this study was to elucidate mechanisms for failure of bone material at the bone-implant interface, and to determine which, if any, screw designs of different materials could minimize the stress concentrations and propensity for early failure of the bone-implant interface.

Methods Planar finite-element models were created of anterior vertebral screws[2] implanted in bone tissue. The screws and the surrounding bone tissue were defined as separate contact bodies. Screws varied by material type: 316L stainless steel ($E \cong 193$GPa), titanium ($E \cong 116$GPa), and poly-L lactic acid (PLLA) resorbable polymer ($E \cong 3.6$GPa); and thread diameter: 5mm, 6mm, and 7mm. Each design variation was loaded to 100N of tension at load case parameters of 0°, 30°, 60° and 90° angles with respect to the screw axis. Bone tissue was modeled as isotropic elements of stiffness 100MPa. Simple quad elements were employed in linear plane-stress analysis because of the multiple loadcases and screw design variations. Von Mises stress and Strain Energy Density were calculated at each node for each load case and screw design.

Results Two representative nodes within the bone were selected to compare the loads imparted to the bone across different load cases. Typically, in all load cases, the highest Von Mises stresses and Total Strain Energy Density values were found on the nodes at the tips of the outermost threads. Situations where these nodes did not demonstrate the highest stress values were when certain bone elements underwent bending loads, and the simplicity of the quad element type resulted in singularly high stresses.

When loaded at 0° (axial pullout) by stainless steel or by titanium screws, Von Mises Stresses in the bone varied from 2.1MPa, 2.4MPa, and 2.8MPa at the tips of the outermost threads for 5mm, 6mm, and 7mm screws. Polymer screws underwent more elongation, and imparted elevated loads to the surrounding bone (4.5MPa, 4.2MPa, 4.2MPa). As loading angle deviated from the screw axis, the trends in both metallic screws were towards higher imparted stresses with respect to load angle and implant diameter (Figure 1). At orthogonal (90°) loading, Von Mises stresses at the left-side characteristic node were 15MPa, 17MPa, and 26MPa for 7mm steel, titanium, and polymer screws respectively.

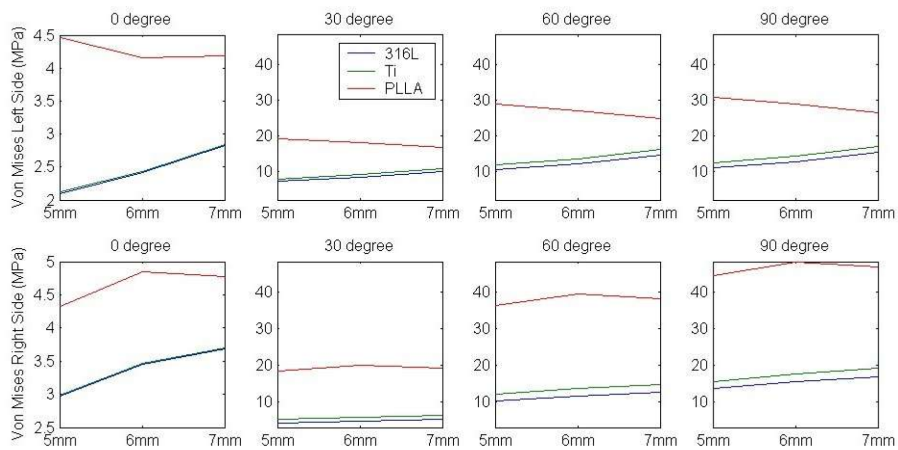

Figure 1 Plots of Von Mises Stresses at two characteristic nodes for each loadcase, by implant diameter

Polymer implants, in off-axis loading conditions, underwent significantly more bending than did metallic screws. As such the resulting stress imparted to bone were higher across all loadcases and implant diameters. Also in polymer implants the tendency was for maximum stresses to decrease with respect to implant diameter (Figure 1).

Discussion For the metallic screws at axial pullout loading; stress distribution patterns, deformation, and trends with respect to screw thread diameter were in keeping with previously published results.[1,2] Larger diameter screws imparted higher stress than smaller diameter screws, and stresses were distributed evenly throughout the bone material, along the entire length of the screw. In polymer screws, for any given loadcase, larger diameter screws did not impart higher stresses to the surrounding bone tissue. This phenomenon was possibly because the larger threads themselves underwent deformation to alleviate the increased load transfer due to greater bending and elongation of the screw shaft

Compared to axial pull on the implant, small deviations in loading angle resulted in dramatically different stress distributions, with large stress gradients in the bone surrounding the implant stem immediately within the bone. What screw designs are less likely to damage surrounding tissue depend greatly on the material utilized, as well as the type of loading experienced by the implant-bone interface. In this study, off-axis loading resulted in significantly higher stresses - indicating higher system stiffness, but also a possibly higher propensity for bone fracture. In orthogonal or oblique-loading; rigid, small-thread screws seem to impart the safest loading profile to bone. In order to achieve similar results with softer implant materials, a much different thread design is indicated.

[1]Hsu C.-C., Chao C.-K., Wang J.-L., Hou S.-M., Tsai Y.-T., Lin J. Increase of pullout strength of spinal pedical screws with conical core: biomechanical tests and finite element analyses. Journal of Orthopedic Research. 23 (2005) 788-794.
[2]Zhang Q.H., Tan S.H., Chou S.M. Investigation of fixation screw pull-out strength on human spine. Journal of Biomechanics. 37 (2004) 479-485.