Development of a Finite Element Model of a Modular Revision Total Hip Arthroplasty Stem with Connecting Pin

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INTRODUCTION: Total Hip Arthroplasty (THA) is a very successful and cost-effective treatment for various terminal diseases of the hip[1]. However, complications can prompt the need for revision total hip arthroplasty (rTHA)[2]. Uncemented, tapered, fluted stems allow bridging proximal bone defects of the femur. Modularity of such stems improves clinical outcomes, as reconstruction of length and torsion can be separated from seating of the stem[3]. However, recent reports have demonstrated a unique failure mode of such modular stems, with loosening of the connection pin from the distal component, a shrink fit connection[4]. A finite element analysis (FEA) model was developed to better understand this new failure mode and investigate implant behavior under *in vivo* loads. The FEA models were verified against bench failure data.

METHODS: Publications, manufacturer brochures and caliper measurements were used to develop ten (10) models of the femoral stem of a modular, tapered, fluted, uncemented stem (Revitan, Zimmer Biomet) in Inventor/2022 (Autodesk, San Francisco, CA). The system consisted of a connecting pin (CoCr28Mo6, E = 210 GPa, v = 0.3, Y = 824 MPa) and femoral stem (Ti6Al7Nb, E = 105 GPa, v = 0.35, Y = 900 MPa) (Fig. 1). Elastic-perfectly plastic behavior was modeled. Five femoral stem nominal diameters (14 to 24 mm) were evaluated at high (42 micron) and low (23 micron) interference fits, corresponding to estimated manufacturing tolerances. Models were meshed and evaluated in Abaqus/2019 Standard (Dassault Systèmes, Waltham, MA) using quadratic tetrahedral elements. A mesh convergence study was completed to determine the appropriate element length, with less than 5% change in reaction moment as output, described below. The final mesh edge length was ~1.3 mm. The outside surface of the distal femoral stem was fixed. The first step in all models simulated stem-pin assembly during manufacturing where the initial cylindrical interference overlap between the distal connecting pin and the femoral stem was resolved to contact with no overlap. Next, two studies were performed. The first followed experimental torque to failure tests for model verification, the second simulated *in vivo* load processes. Experimental torque to failure tests (Zwick TL 500, Zwick Roell) were performed on fifteen (15) rTHA assemblies (14 to 24 mm nominal diameter) with an angular velocity of 30°/min until a peak torque was achieved. In the torque to failure study for model verification, a rotation of 0.01 rad/s was applied to the pin to elicit the maximum reaction moment. The coefficient of friction between stem and pin was iterated to correlate with the reaction moment achieved during bench failure analysis. Twenty-six (26) models were run during the first study, evaluating maximum reaction moment at the connecting pin. After model verification and with the best-fit coefficient of friction, the next study investigated model behavior under *in vivo* loads applied as moments to the connecting pin. A fixed stem to head height of 75 mm was used for calculation and translation of moments from a femoral coordinate system to an implant coordinate system[5]. Moments corresponded to the 85% percentile of bodyweight for the average male population in the United States or 95% for the average European male population[4]. The *in vivo* moments correspond to the point in an activity cycle at which a maximum axial moment acts on the femoral stem. Evaluated *in vivo* moments include walking, standing up, sitting down, walking up stairs, walking down stairs, and jogging. Sixty (60) models were run during the *in vivo* study evaluating for tangential contact slip and maximum stress. Failure at the distal connection pin was evaluated by exceeding the material yield stress, excess contact tangential slip, or a reaction moment greater than bench failure data.

RESULTS: Over all five femoral stem sizes investigated, the average difference in reaction moment due to high or low interference tolerances during verification was 66.34 Nm (Fig. 2). The coefficient of friction iterated to 0.36 corresponding to the best fit between linear regressions of the high and low interference cases and the experimental data. The average nodal tangential slip at the shrink fit interface in the low interference model increased as the implant diameter decreased, with notable slip above 1 micron with *in vivo* forces corresponding to walking up stairs, walking down stairs, and jogging (Fig. 3). The average nodal tangential slip in the high interference model was decreased in all modes assessed, with notable slip above 1 micron with *in vivo* forces corresponding to jogging only (Fig. 3). The maximum stress occurred at the neck of the connecting pin and had an average value of 524.3 MPa, 420.6 MPa, 463.0 MPa, 705.8 MPa, 681.0 MPa, and 936.5 MPa corresponding to the *in vivo* loads of walking, standing up, sitting down, stairs up, stairs down, and jogging, respectively. In all cases, the maximum stress at the contact surface was less than the maximum stress at the neck of the connecting pin.

DISCUSSION: The results of FEA model verification suggest that interference tolerance has a significant effect on the holding torque capacity between the connecting pin and femoral stem. While no single interference tolerance or coefficient of friction in the model represents averages of bench failure data for all five femoral stem sizes, the chosen coefficient of friction and high and low interference tolerance results in model-predicted reaction moments that represent the variability in the experimental data well. The increased tangential slip that occurred with the *in vivo* loads of stairs up, stairs down, and jogging suggests that the lower interference fit may not be suitable for these activities. In addition, the increased tangential slip that occurred with *in vivo* loads of jogging for both high and low interference cases may indicate that jogging should be restricted outright with use of modular rTHA components. The stress concentration at the neck of the connection pin provides additional support to other documented failure modes involving fatigue fracture of the connection pin at the neck[5]. The stress at the neck of the connecting pin during the *in vivo* load of jogging exceeded the yield stress of CoCr28Mo6 and suggests that yielding could occur during this activity. In addition, the maximum stress at the connecting pin neck approaches 83% and 80% of yield stress with the *in vivo* loads of walking up and down stairs, respectively. The developed FEA model can explain the instances of implant failure by distal connecting pin loosening during typical physiological loads. Further, the model suggests that a change to manufacturing tolerances which result in a greater interference fit may reduce this mode of failure in the future.

SIGNIFICANCE/CLINICAL RELEVANCE: Loosening of the distal connecting pin in the modular Revitan stem has not been previously analyzed as a new failure mode. The presented FEA model can be used to estimate physiological activity limitations to minimize the chance of distal pin loosening and yielding and provide insight into manufacturing improvements.

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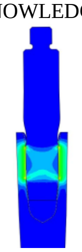

Fig. 1: Abaqus model (cross section) of femoral stem and distal connecting pin.

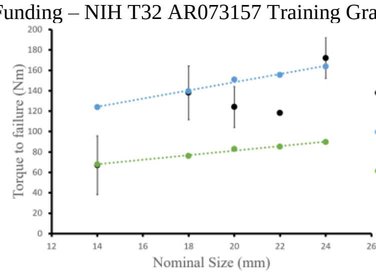

Fig. 2: Model verification with friction coefficient of 0.36 at high/low interference.

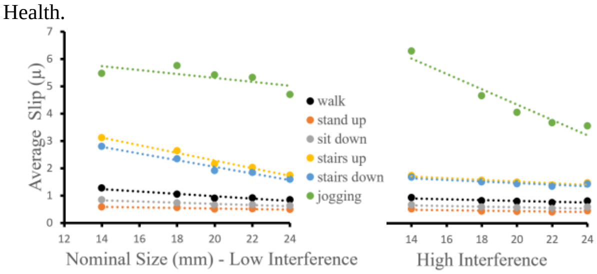

Fig. 3: Average contact nodal tangential slip during *in vivo* loading at high/low interference.