Bone Stress Relaxation and Abrasion in Press-Fit Femoral Knee Implant Fixation: Experimental and Computational Analysis

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INTRODUCTION: Aseptic loosening is the leading cause of revision in cementless total knee arthroplasty (TKA), highlighting the importance of strong initial stability. Pre-clinical evaluations are essential for understanding implant fixation mechanics. Finite element (FE) models typically use linear elastic bone material models, which inadequately represent bone behavior. While incorporating bone plasticity improves predictions of primary stability, it may overestimate fixation by neglecting bone viscoelasticity and abrasion [1]. This study aims to integrate bone relaxation and bone abrasion into simulations of fixation strength for femoral TKA components and compare them with experimental measurements.

METHODS: Six femoral knee components were implanted onto cadaveric femurs, and strain gauges measured the implant outer surface strain from implantation to 24 hours post-implantation, providing a surrogate for bone relaxation in the femur. After 24 hours, a pull-off test was conducted. The reconstructions were recreated in FE analysis using CT data for geometrical and material properties and optical scans for implant position relative to the bone. With these models, incorporating a plastic- viscoelastic bone material model, the experiments were simulated [2]. Bone abrasion was estimated at varying levels and simulated virtually (0, 0.5, 0.75 mm) (Figure 1), and the experimental implant strain, strain reduction, and pull-off force were compared to the simulated values.

RESULTS SECTION: The computational model without abrasion predicted implant strain 350% higher than experimental measurements (Figure 2a). Virtual abrasion of 0.75 mm considerably improved the agreement with experimental findings, but an overestimation of strains by 150% remained. Experimental strain reductions due to bone relaxation varied per reconstruction from 17% to 37%, while computational strain reductions were on average 41% lower (Figure 2c). Simulations without abrasion showed 180% to 360% higher pull-off forces than the experiments (Figure 2c). Including 0.5 mm of virtual abrasion reduced pull-off forces, aligning them more closely with experimental values, though 0.75 mm led to underestimation of the pull-off force in some cases.

DISCUSSION: Without accounting for bone abrasion, simulations overestimated implant strains and fixation strength, with less pronounced strain reductions over time compared to experimental observations. Incorporating virtual bone abrasion notably improved the agreement between experimental and computational results. These findings highlight the critical role of bone plasticity, stress relaxation, and abrasion in simulating implant fixation and offer a foundation for optimizing implant design and surgical outcomes.

SIGNIFICANCE/CLINICAL RELEVANCE: Computational modeling is an essential part of pre-clinical evaluation of new orthopaedic implants. The current work increases the fidelity of computational modeling of press-fit fixation of cementless total knee arthroplasty components, thereby contributing to the clinical safety upon the introduction of new implant systems.

REFERENCES: [1] Berahmani et al., J Biomech 61:137-143,2017. [2] Gersie et al., SSRN E-Journal, 2024.

ACKNOWLEDGEMENTS: This collaboration project is co-funded by the PPP Allowance made available by Health~Holland, Top Sector Life Sciences & Health, to stimulate public-private partnerships, and DePuy Synthes Knee Research and Development (Leeds, UK).

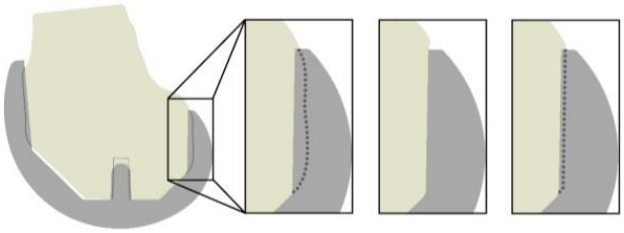

Figure 1: Coronal cross-section showing bone penetration. During implantation, bone nodes are retracted to the implant surface, with virtual abrasion leaving 0.5 mm of 0.75 mm bone penetration.

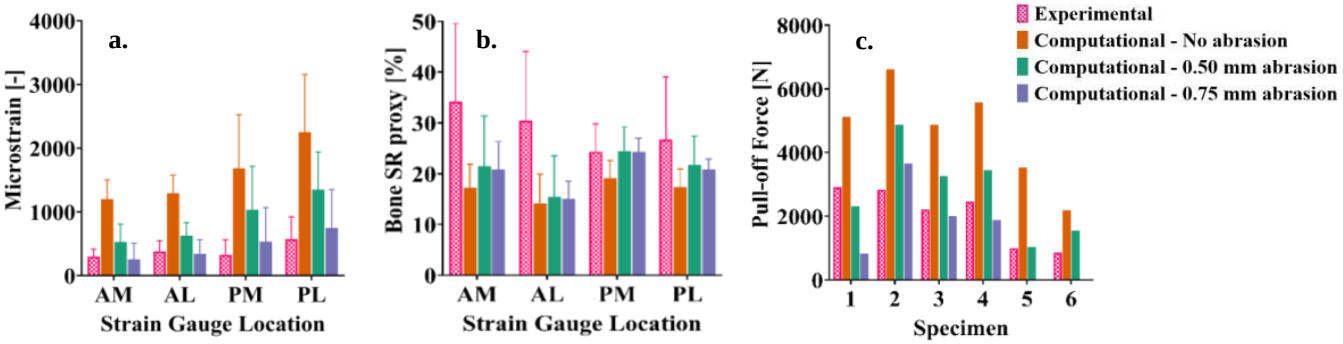

Figure 2: a) Implant surface strain after implantation at strain gauge locations: AM (anterior-medial), AL (anterior-lateral), PM (posterior-medial), and PL (posterior-lateral). b) Average reduction, representing bone stress relaxation (SR), 24 hours post-implantation. c) Average pull-off forces for experimental and simulated tests. No forces were calculated for specimens 5 and 6 with 0.75 mm virtual abrasion due to minimal contact causing non-convergence.