Towards Validating a Computational Workflow for Predicting Micromotion in Total Ankle Replacements

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INTRODUCTION

Total ankle replacements (TARs) are increasingly effective in treating end-stage ankle arthritis, offering improved mobility and quality of life when compared to arthrodesis. However, relative to hip and knee replacements, TARs fail at significantly higher rates, mainly due to mechanical issues such as poor initial fixation of the tibial implant. Micromotion at the bone-implant interface is a metric often used to indicate risk of aseptic loosening and early failure, as large micromotion leads to fibrous tissue formation instead of osseointegration. Accurate prediction of bone-implant micromotion under known loading would improve evaluation of current implants and allow for optimization of implant fixation designs to increase stability. Our objective was to develop a computational workflow to predict specimen-specific implant micromotion and directly validate with experimental measurements of implant micromotion during simulated level walking in a cadaver model.

METHODS

A computational workflow was developed to predict micromotion in an implanted cadaveric specimen using outputs from robotic simulations of gait. The experimental method using the robotic gait simulator and digital image correlation to experimentally measure micromotion is described in further detail in an associated abstract. The pilot cadaver chosen was implanted with the Infinity TAR (Stryker, Mahwah, NJ) and represented as such in the computational models. While experimental testing encompassed ten matched pairs (N = 20), computational modeling blinded to the experimental results of one specimen has been completed. A specimen-specific OpenSim musculoskeletal model was created from pre- and postoperative CT scans in neutral alignment with ankle ligaments represented as tension-only springs with properties approximated from literature and with uncertainty in reference length incorporated. Experiment outputs that served as inputs to the computational models included ground reaction forces, primary kinematics (ankle plantarflexion/dorsiflexion rotation) during gait, and muscle-tendon forces measured during simulated gait. Ankle eversion/inversion and internal/external rotation were measured experimentally to compare kinematics for additional validation. Forward dynamic simulations were performed using the Joint Articular Mechanics (JAM) toolbox to solve for secondary kinematics and contact forces. Joint contact forces were mapped to corresponding finite element models (**Fig 1**) with heterogeneous bone properties derived from preoperative CT. Micromotion was calculated at the implant surface relative to the bone. Direct validation was preliminarily performed by comparing the peak micromotion and micromotion pattern calculated from the experiment and computational models.

RESULTS

Forward dynamic simulations estimated the secondary ankle joint kinematics, including eversion/inversion, internal/external rotation, and ankle translations. In our pilot analysis, the predicted internal/external rotation showed moderate agreement with the experimental kinematics measured (RMSE=2.07°, r=0.33), while eversion/inversion exhibited limited correspondence with observed trends (RMSE=1.56°, r=0.13). Bone-implant micromotion analysis revealed peak micromotion at 97 % of stance, with component movements of 20μm anterior-posterior, 186 μm superior-inferior, and 6 μm medial-lateral (**Fig 2**). The peak micromotion reached 187 μm, occurring at the posterolateral edge of the tibial implant, reflecting the maximum instability during simulated level walking. Peak experimental micromotion of 336 μm occurred at 90% of stance, demonstrating a slight increase compared to predicted values, but matching the pattern and point of stance well experimentally (**Fig 2**).

DISCUSSION

This study presents our preliminary attempt at validating a computational workflow for evaluating specimen-specific implant micromotion following TAR. Peak micromotion was localized to the posterolateral region of the tibial implant, with the largest displacements occurring predominantly in the superior-inferior direction. These findings highlight clinically relevant regions of potential instability that may contribute to aseptic loosening. While micromotion patterns are influenced by patient-specific anatomy, implant design, and gait characteristics, this preliminary study was limited to a single gait condition and one implant type. Future work will expand the sample size and include additional implant designs to strengthen the validation and to investigate variability in fixation stability and loading patterns, with the goal of improving patient-specific risk assessment and implant performance.

SIGNIFICANCE/CLINICAL RELEVANCE

This study provides a validated computational approach to predict implant micromotion, a key factor associated with early loosening under physiologic gait loading conditions. By enabling patient-specific evaluation of implant stability before clinical implantation, this method has the potential to guide implant design improvements and optimize surgical techniques. Ultimately, this computational workflow may reduce failure rates, improve long-term implant survivorship, and enhance functional outcomes for patients undergoing total ankle arthroplasty.

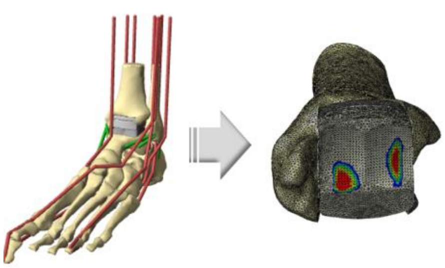

Figure 1. Musculoskeletal model with total ankle implant and corresponding tibial contact force distribution during 96.6% of stance

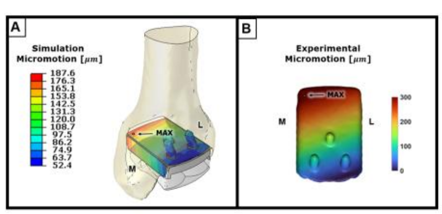

Figure 2. Comparison of total micromotion between simulation at 96.6 percent of stance (A) and experimental measurement (B). "M" and "L" indicate medial and lateral sides