A Computational Workflow to Holistically Assess Total Knee Arthroplasty Biomechanics Identifies Subject-Specific Effects of Joint Mechanics on Implant Fixation

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INTRODUCTION: Approximately two thirds of total knee arthroplasty (TKA) failures are related to either joint mechanics (e.g., instability) or fixation mechanics (e.g., aseptic loosening) [1]. While joint and fixation mechanics are interrelated [2], biomechanical studies often treat them separately, hampering our understanding of how joint kinematics and forces combine to influence implant fixation. Therefore, we asked whether subjects who experience larger tibiofemoral joint forces or more tibiofemoral translation in their TKA knee place greater burden on the fixation of the implant? We hypothesized that larger joint forces and more anterior-posterior (AP) translation would lead to greater burden on implant fixation.

METHODS: We developed a subject-specific computational workflow that integrates a multibody musculoskeletal model to evaluate joint mechanics with a finite element (FE) model to evaluate fixation mechanics (Fig.1). We implemented our workflow using data from the third, fourth, fifth, and sixth Grand Challenge Competitions to Predict In Vivo Knee Loads (GC3-GC6) [3], which include preoperative and postoperative CT-scans and motion analysis data of gait trials from patients with an instrumented TKA. We adapted a generic lower extremity musculoskeletal model [4] to the anatomies and TKA implantations of each subject. We utilized an enhanced static optimization algorithm (https://simtk.org/projects/opensim-jam) to determine the subject-specific tibiofemoral joint forces, contact locations, and kinematics throughout the stance phase of gait, from heel strike (0% of gait) to toe-off (60% of gait), which we directly transferred to corresponding subject-specific FE models to evaluate the implant fixation. For the FE models, the tibia was fixed 150 mm distal to the resection and modeled with non-homogenous elastic moduli (E) determined from the preoperative CT-scan, using proximal tibia density-modulus relationships [5,6] and a Poisson's ratio (υ) of 0.3. The tibial component, insert, and cement were modeled as a titanium alloy (E=114 GPa, υ=0.33), ultra-high molecular weight polyethylene (E=463 MPa, υ=0.46), and polymethylmethacrylate (E=2.2 GPa, υ=0.33), respectively. We tied the bone-cement interface and considered cohesive contact between implant and cement [7]. Because all subjects received cemented implants, we assessed the burden on the implant fixation by computing the interfacial failure index (FI) which represents the risk of implant interface disruption due to debonding between the cement and the implant [8].

RESULTS: Across subjects, the joint forces predicted by the musculoskeletal model matched the corresponding experimentally measured forces from the instrumented TKA (Fig. 2a-b). The models captured the inter-subject variability in force magnitude, with peaks occurring at 47% (GC3), 44% (GC4), 49% (GC5), and 13% (GC6) of gait. Similarly, the models captured the variability in AP contact locations (Fig. 2c), where the most posterior AP contact occurred at 16% (GC3), 60% (GC4), 0% (GC5), and 50% (GC6) of gait for the medial compartment and at 43% (GC3), 22% (GC4), 60% (GC5), and 0% (GC6) of gait for the lateral compartment. Such variability in joint mechanics translated to the fixation mechanics (Fig. 3) in which the FI peaked at 11% (GC3), 47% (GC4), 50% (GC5), and 47% (GC6) of gait, which did not coincide with the greatest joint loading nor the most posterior contact locations.

DISCUSSION: From our holistic evaluation of TKA biomechanics during the stance phase of gait using our computational workflow, we found that the greatest risk of debonding did not coincide with either the peak joint forces or the extreme tibiofemoral contact positions. This underscores the combined influence of joint kinematics and forces on fixation mechanics. Our approach also allowed us to identify important inter-subject variability in the risk of implant debonding.

SIGNIFICANCE/CLINICAL RELEVANCE: Using our computational workflow to evaluate both joint and implant fixation mechanics of TKA, we identified subject-specific effects of joint kinematics and forces on implant fixation that would otherwise have gone unnoticed. We aim to use our workflow to quantify the impact of patient factors, surgical factors (e.g., implant alignment), and implant factors (e.g., articular constraint) on TKA biomechanics.

REFERENCES: [1] AJRR Annual Report (2022). [2] Teeter et al., *J Arthroplasty* (2017). [3] Fregly et al., *J Orthop Res* (2011). [4] Arnold et al., *Ann Biomed Eng* (2010). [5] Morgan et al., *J Biomech* (2003). [6] Snyder & Schneider. *J Orthop Res* (1991). [7] de Ruiter et al., *J Exp Orthopaed* (2017). [8] Zelle et al., *J Biomech* (2011).

Fig. 1: Computational workflow overview:

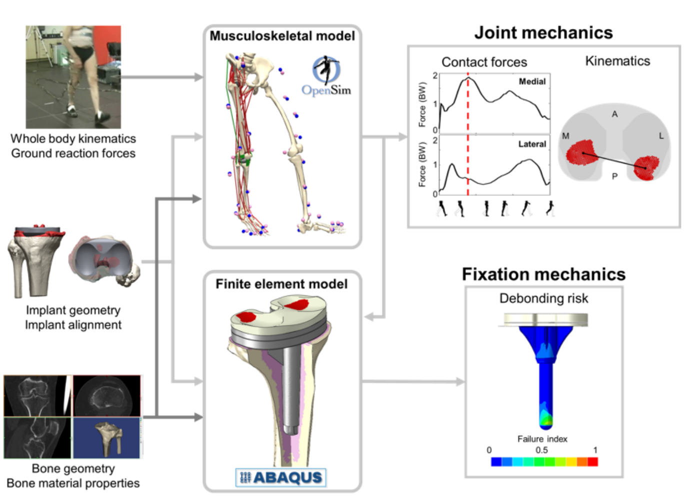

Fig. 2: Joint mechanics:

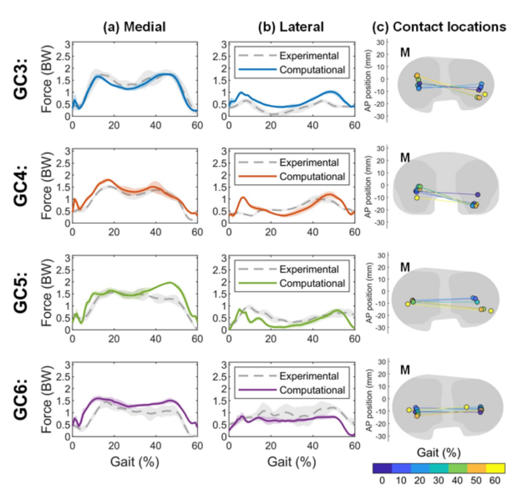

Fig. 3: Fixation mechanics:

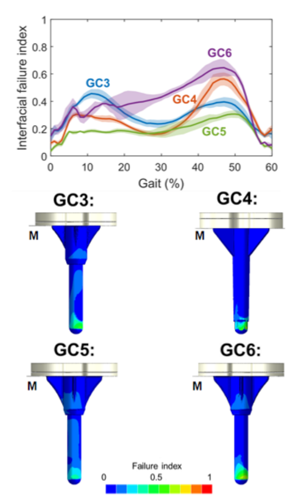

Figure 1: Overview of the computational workflow. **Figure 2:** Subject-specific **(a)** medial and **(b)** lateral tibiofemoral contact forces (in bodyweight, BW) during the stance phase of gait and **(c)** anterior-posterior contact locations in the medial (M) and lateral compartments of the tibial insert averaged throughout the stance phase of the gait trials. **Figure 3: Top:** Subject-specific evolution of the highest interfacial failure index (FI) during the stance phase of gait. **Bottom:** Subject-specific contour plots of the composite FI accumulated at the posterior bone-cement interface throughout stance across all trials.