The Implant Fixation Biomechanics of Total Knee Arthroplasty are Influenced by the Knee Joint Moments during Gait: A Computational Study

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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 component fixation. Therefore, our goal was to investigate the influence of joint kinematics and forces on TKA component fixation. To this end, we developed a subject-specific computational workflow to holistically assess TKA biomechanics and posed the research question: how do joint forces and joint kinematics influence the risk of cement-implant debonding?

METHODS:

Our computational workflow 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 with an instrumented TKA. We adapted a generic lower extremity musculoskeletal model [4] to the anatomy and TKA implantation of each subject. We utilized an enhanced static optimization algorithm [5] to determine the subject-specific tibiofemoral joint forces, contact locations, and kinematics throughout the stance phase 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 modulus (E) determined from the preoperative CT-scan, using proximal tibia density-modulus relationships [6,7] 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 [8]. We computed the risk of cement-implant debonding by computing the interfacial failure index (FI) [9].

RESULTS:

Across subjects, the contact forces predicted by the musculoskeletal model matched the corresponding experimentally measured forces from the instrumented TKA (Fig. 2a-c), capturing the inter-subject variability in force magnitude and anterior-posterior (AP) contact locations during stance (Fig. 2d). The variability in joint mechanics translated to fixation mechanics (Fig. 3); FI peaked at 11% (GC3), 47% (GC4), 50% (GC5), and 47% (GC6) of gait but this did not coincide with the greatest joint loading, which occurred at 47% (GC3), 44% (GC4), 49% (GC5), and 13% (GC6) of gait nor the most posterior AP contact locations, which occurred at 43% (GC3), 22% (GC4), 60% (GC5), and 0% (GC6) of gait for the lateral compartment. However, we found that the varus-valgus moment, which was the product of the joint force and the distance of the contact point to the knee center in the coronal plane, was correlated (R^2=0.37, β=-0.01, p=0.006) with the peak FI (Fig. 4).

DISCUSSION AND CONCLUSION:

Our computational workflow identified inter-subject variability in the risk of cement-implant debonding during gait that was only directly attributed to the varus-valgus moment, which was a combination of the AP contact locations and the joint contact forces. This underscores the combined influence of joint kinematics and forces on fixation mechanics. Our holistic workflow to evaluate TKA biomechanics will allow us to quantify the impact of implant alignment and design 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] Smith et al., *J Biomech Eng*. 2016 [6] Morgan et al., *J Biomech* 2003. [7] Snyder & Schneider. *J Orthop Res* 1991. [8] de Ruiter et al., *J Exp Orthopaed* 2017. [9] Zelle et al., *J Biomech* 2011.

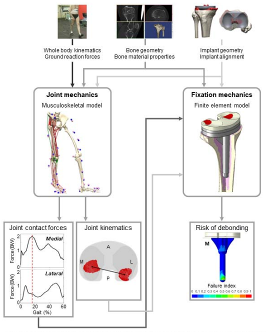

Figure 1: Overview of the computational workflow. Our workflow integrates a multibody musculoskeletal model to determine joint mechanics with a finite element model that then uses these joint mechanics as inputs to determine fixation mechanics.

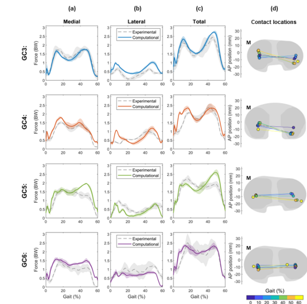

Figure 2: Subject-specific **(a)** medial, **(b)** lateral, and **(c)** total tibiofemoral contact forces (in bodyweight, BW) during the stance phase of gait from heel strike (0% gait) to toe-off (60% gait). The solid-colored lines represent the average contact force predicted across all trials and the corresponding shaded region represents ± 1 standard deviation. The dashed-grey line represents the average contact force measured by the instrumented TKA across all trials and the corresponding shaded region represents ± 1 standard deviation. **(d)** subject-specific anterior-posterior (AP) contact locations in the medial (M) and lateral compartments of the tibial insert averaged throughout the stance phase of the gait trials.

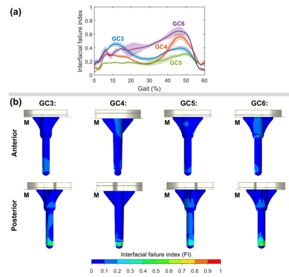

Figure 3: **(a)** subject-specific evolution of the highest interfacial failure index (FI) during the stance phase of gait from heel strike (0% gait) to toe-off (60% gait). The solid-colored lines represent the average FI predicted across all trials and the corresponding shaded region represents ± 1 standard deviation. **(b)** subject-specific anterior and posterior contour plots of the highest FI accumulated at the bone-cement interface across all trials.

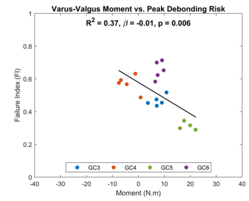

Figure 4: Scatter plot of the total varus-valgus moment (in N.m) across the joint at the instant of the peak risk of cement-implant debonding (quantified by the interfacial failure index, FI) during the stance phase of gait for each subject. Each colored dot represents a gait trial performed by the subject and the solid black line represents the linear regression line.