An Experimental and Computational Approach for Evaluation of In-Vivo Knee Mechanics

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Introduction: Dynamic, in-vivo evaluations of knee mechanics are important for understanding knee injury and repair and developing successful treatment pathways. Combined experimental and computational methodologies have been employed to improve our understanding of knee mechanics and enable the testing of new treatments in ways that are impractical with in vivo and in vitro experiments alone. The goal of the current study was to combine high-speed stereo radiography, musculoskeletal modeling, and finite element (FE) analysis for evaluation of subject-specific, in-vivo knee mechanics in a healthy subject performing a knee extension and lunge activity, and to further validate the model for evaluation of implanted knee mechanics.

Materials and Methods: Simultaneous high-speed stereo radiography (HSSR) images, marker-based motion capture, and ground reaction forces were collected for a healthy, older adult male (age=52 years, height=172 cm, weight=126 lbs, BMI=19.3) performing a seated knee extension and single-leg lunge [1] (Figure 1a). Tibiofemoral (TF) and patellofemoral (PF) joint kinematics were computed by registering CT-reconstructed bones to the 2D HSSR images. Subject-specific, whole-body, musculoskeletal models were developed in OpenSim, and consisted of 12 body segments (torso, pelvis, femurs, tibiae, tali, calcanei, toes), and 92 Hill-type musculotendon units [2] (Figure 1b). HSSR kinematics, motion capture and ground reaction forces were input into the musculoskeletal model for prediction of muscle forces. Subject-specific finite element models were developed in Abaqus (Simulia, Providence, RI) for the knee extension and lunge activity (Figure 1c). Models included bone, cartilage, TF and PF ligaments, meniscus, and quadriceps and hamstrings muscles. FE model loading and boundary conditions replicated the experimental motion for knee extension and lunge activities using a combination of hip, ankle, and muscle loading derived from HSSR kinematics and musculoskeletal models. Soft tissue calibration was performed in simulations of the knee extension activity to match experimental joint kinematics; model validation was performed using direct comparison to experimental knee kinematics in the lunge activity. Load-controlled simulation of the lunge activity was used to predict implanted (Scorpio NRG, Stryker) knee mechanics.

Results and Discussion: The subject achieved knee flexion angles as large as 135° (Figure 2a). In simulation of the knee extension activity, the calibrated model was effective in matching experimental knee kinematics. The model was successfully validated through direct comparison to lunge experimental TF (RMS diff. of F-E<2°, I-E<3°, A-P<2 mm) and PF kinematics (RMS differences of F-E<5°, I-E<4°, M-L<4 mm). The virtually implanted model of the lunge activity had good agreement with fluoroscopy kinematics from the literature [3], verifying the model for evaluation of implanted knee mechanics.

Figure 1. Experiment and computational workflow including a) HSSR, motion capture, and GRF data collection, b) musculoskeletal modeling, and c) finite element modeling

Figure 2. Comparison of experiment, natural and implanted model, and literature [3] TF internal-external kinematics during lunge

Translational Impact: The current modeling framework may be used to optimize implant design and surgical alignment for improved kinematics during everyday activities.

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