

Ultrasound-based Dynamic Bone Tracking to Enhance Clinical Assessments of Knee Kinematics

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INTRODUCTION: Measurements of joint kinematics are crucial for diagnosing injuries, tracking healing, and guiding treatments. Current methods for clinical assessments (e.g., arthrometers, motion capture, and stress radiographs) are limited in accuracy by soft tissue motion¹ and/or in frequency of use by radiation exposure². The gold-standard method for measuring joint kinematics in a research setting is biplane fluoroscopy³. However, fluoroscopy is limited in wide-spread use by cost, processing time, and radiation exposure. Therefore, a method to track bone motion that (1) is not limited by soft tissue motion and radiation exposure, and (2) can be implemented by both clinicians and researchers, would enhance assessments of joint kinematics in both clinical and research settings. Ultrasound is a promising imaging modality to overcome the limitations of other methods⁴. Accordingly, our objectives were to (1) develop and validate an ultrasound (US)-based bone-tracking algorithm to measure knee kinematics using clinical laxity exams as an example use case, and (2) determine how loading rate and repositioning of the ultrasound transducer alters kinematics measured using our US-based bone-tracking algorithm.

METHODS: Robotic testing: In five fresh-frozen human cadaveric knees (1F/4M, 66.2 ± 3.4 years), we simulated anterior and posterior (±89 N at 3.3 N/s), and varus and valgus (±15 Nm at 0.52 Nm/s) laxity assessments at 0°, 20°, and 45° of knee flexion using a six degree-of-freedom (DOF) robotic simulator (KR300 2700-2, KUKA; **Figure 1a**). In addition to the primary load, each laxity assessment included smaller off-axis loads to represent those present during a manual laxity exam⁵. During each assessment, we placed an US transducer (LF11-5H60-A3, ArtUS, TELEMED) over the lateral (during varus loading), medial (during valgus loading), or anterolateral (during anterior-posterior (A-P) loading) aspect of the knee. US-based bone-tracking algorithm: We used B-mode cine loops and a custom, normalized cross-correlation method to track bone motion (**Figure 1a**). To determine the A-P translation changes, we divided the bone motion by the cosine of the angle between the transducer plane and the A-P axis. To determine the V-V angle changes, we converted bone motion to rotation by assuming the V-V rotation occurred about an axis through the middle of the tibial plateau⁶.

Analysis of effect of loading rate: To simulate the errors introduced by measuring kinematics at different loading rates, we downsampled the ultrasound data by different factors to simulate joint velocity during a one second load-unload laxity exam (Case 1) and previously reported velocities during pathologic gait (e.g., ACL rupture for A-P⁷ and varus thrust for V-V⁸) (Case 2). For each case of each assessment, we computed the errors between the US-measured kinematics and the time-synched robot-measured kinematics at each US frame. We pooled errors across specimens and flexion angles and computed the bias, precision, and root-mean-square errors (RMSE). Analysis of effect of transducer repositioning: To characterize the errors introduced by repositioning the ultrasound transducer, we replayed the kinematics from the 20° laxity assessments to maintain consistent bone motion. For the A-P trials, we conducted six additional tests, which consisted of three tests at two different transducer locations: on the anterolateral and on the anteromedial aspects of the knee. For the V-V trials, we conducted nine additional tests, which consisted of three tests at three different locations: over the collateral ligament, shifted anteriorly, and shifted posteriorly. We used interclass correlation coefficients (ICC) to test the reproducibility of repositioning the transducer.

RESULTS SECTION: The maximum RMSEs were 1.45 mm and 0.68° during slow A-P and V-V loading, respectively (**Figure 1b**). After downsampling the data to mimic A-P and V-V velocities during laxity assessments (Case 1) and pathologic gait (Case 2), we found small changes in the RMSEs for kinematics in all four loading directions, with a common trend of under predicting kinematic motions (**Figure 1b**). ICCs for transducer repositioning ranged from 0.72 (Valgus) to 0.98 (Varus) (**Figure 1c**).

DISCUSSION: Our first key finding was that our US-based bone-tracking algorithm can measure A-P and V-V kinematics to within 1.46 mm and 0.68° during slow A-P and V-V loading, respectively. These errors were minimally affected by simulated changes in the loading rate (**Figure 1b**). Additionally, the errors in measuring total A-P laxity in our study (RMSE = 2.8 mm) are lower than those from a previous study⁹ comparing KT-1000 measurements to the gold-standard, Roentgen Stereophotogrammetric Analysis (RSA) (mean errors = 4.2 to 5.2 mm). Furthermore, although not a direct comparison because we measured kinematics during laxity testing in the present study, the errors in V-V are on par with previous errors determined for biplane fluoroscopy during walking³ (RMSEs in V-V = 0.77°). Our ongoing work is expanding this evaluation to include a variety of functional daily activities (e.g., walking, stair ascent/descent) to compare errors in measuring kinematics during dynamic activities to other imaging modalities (e.g., optical motion capture and biplane fluoroscopy). Our second key finding was that our US-based bone-tracking algorithm ranged from moderate to excellent reliability¹⁰ when repositioning the transducer (**Figure 1c**). Indeed, the ICC values computed in this study (ICC = 0.86 for A-P and 0.72 to 0.98 for V-V) are similar to those reported for devices that are currently used in clinical assessments (e.g., KT-1000^{11,12} = 0.55 to 0.70 and stress radiographs¹³ = 0.70 to 0.96).

SIGNIFICANCE/CLINICAL RELEVANCE: Using ultrasound to measure kinematics should enable widespread assessments of knee mechanics because ultrasound is a safe, non-radiating imaging technique that is familiar to both clinicians and researchers. This study showed that our bone-tracking algorithm is a promising approach to assess kinematics for a range of applications, such as diagnosing disorders, monitoring healing, and informing rehabilitation.

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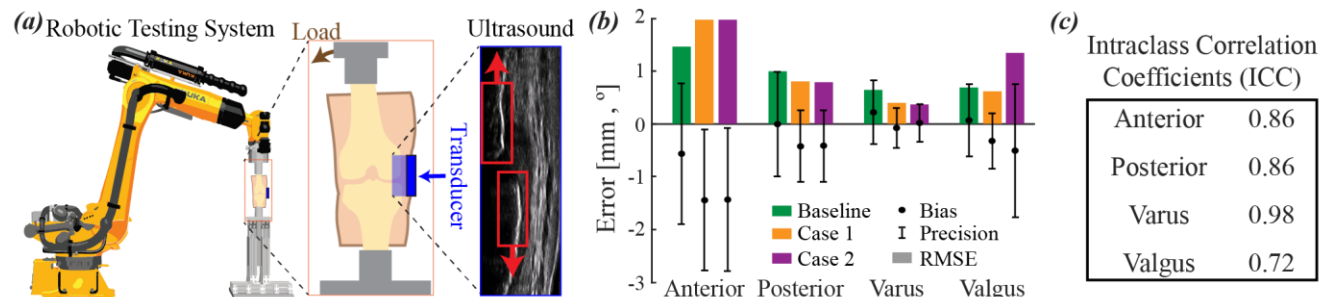


Figure 1: (a) We evaluated knee kinematics measured using our ultrasound-based bone-tracking algorithm against the gold-standard kinematics measured by our robotic testing system. (b) We determined that bias (mean, scatter points), precision (standard deviation, error bars) and root-mean-squared errors (RMSE, bars) were small for our bone-tracking algorithm regardless of effective loading rate (Baseline: robotic experimental speed, Case 1: laxity assessment, and Case 2: pathologic gait). (c) We determined that the intraclass correlation coefficients (ICCs) were moderate to excellent in reliability, which demonstrates that our tracking algorithm is largely insensitive to transducer placement.