

# Don't Sweat the Technique: Accurately Measuring Knee Range of Motion using Poorly Placed Wearable Sensors

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**INTRODUCTION:** Nearly 800,000 total knee arthroplasty (TKA) procedures occur in the US each year. Following TKA, recovery is measured a number of ways including but not limited to strength, stability, and range of motion (ROM). ROM recovery is crucial for completing a variety of activities of daily living (ADL), like gait. However, ROM recovery metrics are often captured in well-controlled settings (e.g. clinic) using methods that are frequently imprecise (e.g. goniometry). Recently, commercially available methods have been developed to increase both the portability and precision of measuring knee ROM in real-world settings. One such method is wearable inertial measurement units (IMUs). While wearable IMUs offer the possibility of accurately, remotely monitoring patient ROM post-TKA, accurate ROM measurements require patients to correctly self-apply those sensors. If patients fail to do so, ROM measurement error may increase. However, to our knowledge no comprehensive analyses exist evaluating the impact incorrectly placing sensors has on the accuracy of knee ROM measurements. Thus, we conducted a prospective study to evaluate the impact 1) sensor placement and 2) software calibration compliance have on knee ROM measurement accuracy of a commercially available wearable IMU system. We hypothesized 1) compliance with software calibration would significantly reduce knee ROM error, 2) compliance with software calibration would remove sagittal but not transverse plane sensor placement error, & 3) transverse plane sensor placement error would impact knee ROM error more than sagittal plane placement error.

**METHODS:** This IRB approved prospective cohort study compared knee angles during gait measured with a commercially available wearable IMU system to our 'gold standard' knee angle measurements collected via optical motion capture (MOCAP) across a range of IMU sensor positions in the sagittal and transverse planes with and without software calibration compliance. 10 healthy individuals consented to participate in 1 visit to our biomechanics laboratory. Optical MOCAP markers were placed on their pelvis/bilateral lower extremities (Figure 1A). Wearable IMU sensors were then placed on the dominant lateral thigh and shank (Figure 1B) across a range of sagittal/transverse positions (Figure 1C) to simulate possible errors in patient self-application of sensors. To account for the potential of patients improperly performing the appropriate software based calibration procedures at home, wearable sensor ( $f_s=50\text{Hz}$ ) and optical MOCAP data ( $f_s=100\text{Hz}$ ) were captured once after completing 'leg alignment' calibration procedures ('aligned knee ROM') and repeated without completing that process ('unaligned knee ROM'). All data were collected for 60s at each sensor position/calibration compliance during walking at a self-selected pace. MOCAP 3D position data were then processed in Visual3D computing sagittal knee angles. Unaligned sensor, aligned sensor, and optical MOCAP sagittal knee angles were compared using correlation analyses and generated cross-plots (optical MOCAP vs. IMU-based sagittal knee angle). Additional statistics compared error categories based on sensor misalignment plane, bony segment (thigh vs. shank), & misalignment category.

**RESULTS:** 10 healthy individuals (5M,  $24 \pm 1.2$  years) were enrolled. Both aligned and unaligned IMU knee angle matched the overall shape of optical MOCAP knee angle as shown by an example subject's walking data (Figure 2C). Aligned and unaligned IMU data were both strongly correlated with optical MOCAP knee ROM with high coefficients of determination (Figure 2B;  $R^2=0.84$  and  $0.93$ , respectively). However,  $16.4^\circ$  of average erroneous knee flexion was present in unaligned sensors. Across all sensor positions, correctly following 'leg alignment' calibration procedures reduced knee ROM error (Figure 2C;  $13.8 \pm 4.5^\circ$  vs.  $4.5 \pm 1.8^\circ$ ). Analyzing knee ROM error by sensor placement error types showed significant differences in the error induced by sagittal vs. transverse plane sensor misalignment (Figure 3A) as well as specifically comparing transverse plane errors (anterior/posterior turn) to sagittal plane errors (anterior/posterior tilt) (Figure 3C). No significant differences were noted between errors on the thigh sensor versus errors on the shank sensor (Figure 3B) or comparing sensor placement errors that added 'false flexion' versus sensor placement errors that added 'false extension' (Figure 3D).

**DISCUSSION:** Wearable sensors are capable of capturing rich datasets outside of well-controlled clinical or laboratory settings. This is necessary to provide a more 'real-world' perspective on patient recovery following TKA. However, many commercially available systems are reliant on patients to appropriately apply the sensors and complete necessary calibration processes. The evaluated wearable system quantified knee ROM accurately (error compared to optical MOCAP  $< 5^\circ$ ) regardless of sensor placement error when sensor-to-leg alignment was completed. Accordingly, with proper use, wearable IMU systems offer a way to achieve moderate accuracy in measuring knee ROM ( $< 5^\circ$ ) continuously in real-world settings. Moreover, compared to current gold standard methods for measuring knee motion (e.g. optical MOCAP, fluoroscopy), these types of sensor systems are lower cost and portable, facilitating continuous remote data capture. Future studies should more fully explore errors induced by patient sensor placement errors and failing to complete calibration processes.

**SIGNIFICANCE/CLINICAL RELEVANCE:** Our investigation provides further evidence that wearable sensors afford clinical teams and patients a low cost, portable, and accurate mechanism to monitor recovery following TKA. Care should be taken during patient education and on-boarding to ensure that patients fully understand the necessary steps for successfully using these types of wearable IMU systems.

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**IMAGES AND TABLES:**

