

Nothing but a Knee Thing: Wearable Motion Sensors versus Optical Motion Capture Measuring Knee Range of Motion before and after TKA

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INTRODUCTION: In the US, ~800,000 total knee arthroplasties (TKA) are performed annually. Post-TKA, range of motion (ROM) recovery is compulsory for successful outcomes (e.g. patient satisfaction, activity completion). However, knee ROM is often quantified using simplified, imprecise techniques (e.g. goniometry) in controlled settings that do not consider how patients function in the ‘real-world.’ Therefore, methods for capturing knee ROM in more realistic settings are necessary. One recently developed modality for doing so is wearable inertial measurement units (IMU). Several commercially available IMU systems exist on the marketplace for quantifying knee ROM before/after TKA. However, the accuracy of these wearables is inadequately described. Accordingly, the objectives of this study were to evaluate 1) wearable sensor accuracy pre/post-TKA and 2) patient sensor self-application accuracy.

METHODS: This IRB approved prospective cohort study compared two sagittal knee angle measurement techniques (wearable IMU sensors vs. optical motion capture (MOCAP)) in 20 patients undergoing unilateral TKA. Patients were assessed at our biomechanics laboratory ~3 weeks pre-TKA having self-applied wearables (unaligned sensors) per their surgeon’s instructions (lateral shank/thigh, Figure 1A). Optical MOCAP markers were placed on their pelvis/bilateral lower extremities (Figure 1B). Wearable sensor sagittal knee angles ($f_s=50\text{Hz}$) and optical MOCAP position data ($f_s=100\text{Hz}$) were captured simultaneously during all activities including heel/wall slides, standing knee bends, seated march, long arc quads, sit-to-stand, timed up-and-go, and treadmill gait. Unaligned sensor data were mathematically rotated *in-silico* to correct for sensor-to-leg alignment errors and stored as a new knee angle measurement (aligned sensors). All patients then underwent TKA via the medial parapatellar approach by one surgeon using the same implant make/model. Three weeks post-TKA, patients repeated the data capture process. All MOCAP 3D position data were 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).

RESULTS: 20 TKA patients (10M, 67.7 ± 7.4 yrs, $\text{BMI} = 32.0 \pm 7.1$) were enrolled. Wearable IMU accuracy was equal pre-/post-TKA, and data were combined accordingly. An example subject walking (Figure 2) highlights typical knee angle DC offset errors in unaligned sensors versus aligned sensors and optical MOCAP. Across all subjects/activities (Figure 3A), unaligned sensors yielded strong, significant correlations with MOCAP with a high coefficient of determination ($R^2 > 0.94$). However, 11.4° of extra knee flexion was erroneously present with unaligned sensors. Mathematically correcting unaligned sensors to aligned sensors yielded a similar R^2 but reduced the offset error to $< 1.0^\circ$ erroneous knee flexion. Throughout all activities, mean/mean absolute value error (Figure 3B) for unaligned sensors vs. MOCAP were $-13.7 \pm 8.0^\circ$ and $14.2 \pm 7.1^\circ$, respectively. Comparing aligned sensors vs. MOCAP resulted in mean/mean absolute value error $-0.6 \pm 7.0^\circ$ and $4.4 \pm 5.5^\circ$, respectively.

DISCUSSION: Wearable sensors capturing data outside of well-controlled clinical/laboratory settings provide richer information regarding patient recovery, facilitating improved clinical decision making. However, sensor and patient variability need to be assessed for these novel wearables. This wearable sensor was accurate across a variety of activities when aligned with the leg mechanical axes ($< 5^\circ$ error). However, patient wearable sensor self-application induced a significant DC offset error ($> 13^\circ$). Thus, patient sensor application training and sensor-to-leg alignment procedures are critical for accurate knee angle measurements.

SIGNIFICANCE/CLINICAL RELEVANCE: The present efforts highlight the potential power of using wearable IMUs to monitor postoperative knee ROM following TKA. The sensors offer a low cost option to acquire relatively accurate ($< 5^\circ$ error) knee ROM across a wide array of different typical activities using self-applied wearable sensors.

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