TRANSFERABILITY OF A PREVIOUSLY VALIDATED IMU SYSTEM FOR LOWER EXTREMITY KINEMATICS

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This study tested transferability and validity of an Inertial Measurement Unit (IMU) system for estimation of lower limb kinematics. Peak hip, knee, and plantarflexion angles and sagittal plane range of motion (ROM) were compared during body weight squats (BWSQ) and countermovement jumps (CMJ) in 16 participants using root mean square error (RMSE) and intraclass correlation coefficients (ICC). RMSE was <15° for all but peak hip flexion in BWSQ and CMJ, and CMJ hip and ankle ROM. High ICC was observed in BWSQ knee ROM (0.927) and peak flexion (0.722), with moderate ICC in for peak hip flexion in BWSQ (0.469) and CMJ (0.595), and CMJ knee ROM (0.460). The IMU system produced acceptable lower limb kinematics in a novel environment. Future work will aim to minimize system-based differences and expand planes of motion.

KEYWORDS: Wearables, kinematics, sensors, validation, algorithm development

INTRODUCTION: Advancements in both technology and sensor algorithms may enable researchers to quantify kinematics outside a laboratory environment. Optical motion capture (OMC) has long been the industry gold standard, capturing both valid movements and enabling researchers to compare findings given the general standardisation. While 3D marker-based OMC systems are the gold standard, they require large financial and time investment. Moreover, analysis of complex movements may prohibit use of OMC due to potential marker occlusion. Wearable sensors are increasing in prominence and facilitating biomechanical analyses of clinical measures, gait parameters, and military-specific tasks (Antunes et al., 2021; Fusca et al., 2018; Mavor et al., 2020). IMU systems are capable of quantifying spatiotemporal variables and joint kinematics in complex movements and may be employed outside of a controlled, laboratory environment (Hindle et al., 2020). To improve device applications for analysing movement patterns, validating IMU systems during dynamic movements commonly undertaken in performance and injury screening (e.g., BWSQ and CMJ) is necessary. Analysis of peak angles and ROM is important to biomechanics researchers, clinicians, and coaches in quantifying injury risk, rehabilitation, and performance with minimal equipment. Specifically, increasing peak sagittal plane angles reportedly reduces deleterious ground reaction forces, and changes in joint ROM throughout rehabilitation may serve as a marker for return-to-activity after injury (Nagelli et al., 2019; Seymore et al., 2019). Analyses of these discrete measures using wearable sensors may allow clinicians and coaches to make informed decisions regarding practices to reduce risk of injury and structure rehabilitation. Implementation of a previously validated methodology in a new space highlights the transferability from the laboratory to practical application of an IMU system (Hindle et al., 2020). As such, the purposes of this study were 1) to employ a previously validated IMU placement and algorithm methodology to test transferability of the system between sites, and 2) to validate peak hip, knee, and plantarflexion angles and sagittal plane ROM against the industry standard of OMC during dynamic movements. It was hypothesised that 1) the methodology would be transferrable to a laboratory separate from the initial validation site, and 2) the IMU system would produce valid lower extremity kinematics during a BWSQ and CMJ.

METHODS: Sixteen recreationally active individuals (1.74 ± 0.10 m, 75.35 ± 14.93 kg, 24.90 ± 4.58 years) self-reportedly free from injury were recruited and provided written, informed consent prior to participation (University of Pittsburgh IRB, STUDY21040030). Participants completed five trials of a BWSQ and CMJ while standing on bilateral force plates (Kistler, Model 9286BA). The BWSQ required participants to stand with their feet shoulder-width apart and complete one squat to a self-selected depth. For the CMJ, participants started with their hands above their head and executed a CMJ with arm swing (to a self-selected squat depth), landing with both feet simultaneously on the force plates. A CMJ was considered unsuccessful if participants failed to take off and land on the force plates. OMC data were captured using 12 infrared cameras (MX T20-S, MX 13, MX13+) at 200 Hz (Nexus v.2.12, Vicon Motion Systems Ltd., Oxford, UK), and a modified University of Western Australia marker set using 42 retroreflective markers and clusters (Besier et al., 2003). The participant-based kinematic model was generated in Visual 3D (C-Motion, v.2021.11.3), comprising a pelvis and bilateral thighs, shanks, and feet. Functional joint centers were used to calculate hip and knee kinematics (Schwartz & Rozumalski, 2005). The ankle joint center was defined as the midpoint between the lateral and medial malleoli (Wu et al., 2002). All rotations were defined as rotations away from the anatomical position, distal segment relative to the proximal segment. Data were low pass filtered (4th order Butterworth) at 12 Hz. Missing marker data were filled using the spline and rigid body filters in Nexus. The IMU system used in the current study was developed by Hindle et al. (2020). Blue Trident IMUs (iMeasureU, Vicon Ltd., London, UK) were placed on the pelvis and bilateral thighs, shanks, and feet (seven total) and collected data from a tri-axial accelerometer (±16 g, 1125 Hz), magnetometer (±4900 µT, 112.5 Hz), and gyroscope (±2000°/s, 1125Hz), synchronized via Bluetooth with OMC data in Vicon Nexus (v2.12.1). Relative joint angles were derived with a sensor fusion and pose estimation algorithm, using raw magnetic, angular rate, and gravitational data (Hindle et al., 2020). Analysis of IMU data required that each trial had approximately 1 second of static subject data, and joint angles were reported relative to this initial static position at commencement of each trial. For both OMC and IMU data, hip, knee, and ankle peak angles and ROM were calculated for BWSQ, and from the start of the CMJ to toe-off. Toe-off was defined using a force-based threshold (< 20 N) for OMC data, and as peak ankle joint extension for the IMU data. RMSE (Jamovi, v.1.6.23.0) and ICC (IBM SPSS Statistics 27) were used to compare right hip, knee, and ankle peak flexion and sagittal plane ROM between systems. ICC with two-way mix effects for a single measurement were performed and interpreted as excellent (≥ 0.9), good (0.9-0.75), moderate (0.75-0.5), and poor (< 0.5) (Koo & Li, 2016).

RESULTS: There were insufficient data for IMU calibrations in some trials which necessitated removal of 18 hip, 9 knee, and 13 ankle trials for BWSQ, and 7 hip, 6 knee, 21 ankle trials out of the 80 possible trials per task. Results from data analyzed are presented in Table 1. The highest level of ICC agreement was observed for peak knee flexion angle (0.722) and ROM (0.927) in the BWSQ (Figure 1). Hip ICC agreement was low for both peak angle (0.469) and ROM (0.194) in the bodyweight squat, but moderate for CMJ peak flexion (0.595). Ankle ICC peak flexion and ROM were extremely low (<0.110).

Table 1: Mean Difference ± 95% CI, RMSE, ICC, and Range (of Differences) for OMC vs. IMU.

	Flex	RMSE	ICC	ROM	RMSE	ICC
BWSQ						
HIP	17.9±5.8°	15.7°	0.47*	18.1±3.9°	14.9°	0.19
Range	0.1°-16.7°			0.2° - 27.9°		
KNEE	11.2±3.0°	12.2°	0.72*	5.2±2.1°	12.6°	0.93*
Range	0.1°-26.2°			0.2°-22.9°		
ANKLE	14.1±1.9°	11.0°	-0.11	8.8±2.4°	8.29°	0.25
Range	0.2°-25.4°			0.7°-36.2		
CMJ						
HIP	11.1±3.7°	18.1°	0.60*	13.2±3.0°	17.7°	0.27
Range	0.5°-25.2°			0.4°-25.9°		
KNEE	7.7±2.3°	14.8°	0.18	10.7±3.3°	12.2°	0.46*
Range	0.0°-15°			0.0°-29.1°		

ANKLE Range	13.4±3.6° 0.0°-26.8°	12.3°	0.11	9.2±2.4° 0.6°-26.5°	15.3°	≤ 0.02

***p < 0.05**

In the CMJ, peak hip angle ICC was highest (0.595), followed by knee ROM (0.460). BWSQ and CMJ peak angle RMSE was lowest for hip (16-20% of OMC and IMU averages), followed by the knee (19-24% of OMC and IMU averages), and greatest for the ankle (46-79% of OMC and IMU averages). The knee had the lowest ROM RMSE for both movements (10-12% of the averages) followed by the hip (16-22% of the averages). Ankle ROM RMSE was lower than peak plantarflexion angle for both movements (23-57% of the averages), but still greatest among all joints.

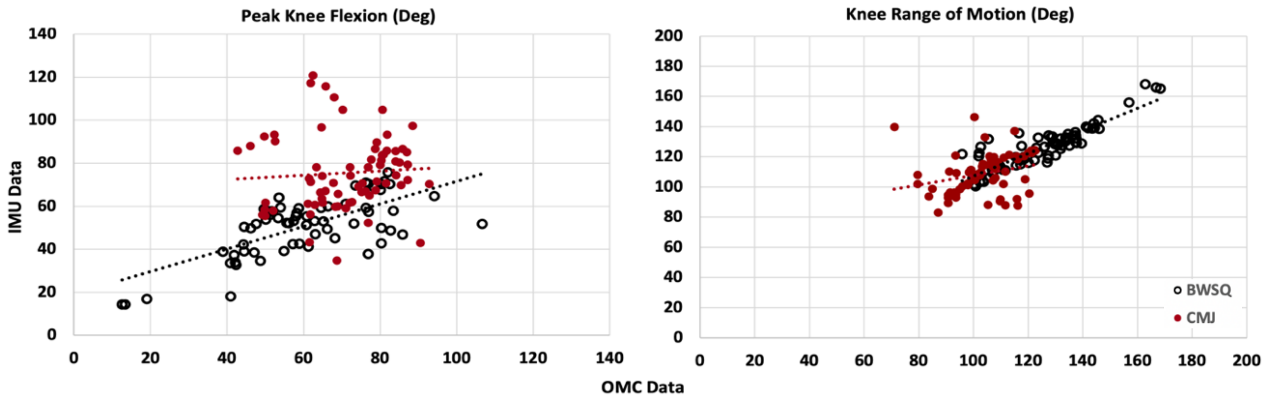

Figure 1: Peak knee flexion (left) and ROM (right) of OMC (x-axes) vs. IMU system (y-axes). The dotted lines represent line of best fit.

DISCUSSION: The purpose of the study was twofold: 1) to replicate the use of a previously validated and novel IMU placement and algorithm, and 2) to compare lower extremity flexion angles and ROM to gold-standard OMC during dynamic movements. The observed values align with previous work published by Hindle et al. (2020), whose methodology was employed in the current study. Moderate to high ICC for hip and knee peak angles and excellent agreement for knee ROM indicate transferability of this methodology across research sites. The ability to measure knee kinematics is imperative, as the knee is a common injury site for acute and chronic injuries (Eagle et al., 2019; Messier et al., 2008). Implementing this system in real-world scenarios where high-risk, complex, dynamic movements occur can enable quantification of knee mechanics that contribute to understanding musculoskeletal injury. Many of the differences observed between the systems may stem from differences in the definition of the reference position. OMC generates a participant-based kinematic model using a single static trial as its reference that is applied to all trials for that participant. Conversely, the IMU algorithm sets an anatomically neutral position at the start of every trial, making all rotations relative to that trial's static position. Specifically, the largest differences observed via ICC are in the ankle, which were likely due to divergence from the neutral position while participants prepared for each movement. The nature of the ankle was also likely to influence the consistency of the starting position for each movement. While standing in the anatomical position, the hip and knee are less susceptible to angular variation and will often remain around zero degrees, while a slight bend in the knee, for instance, will alter the tibial position and impact the ankle angle. Such differences in defining neutral position may make comparisons of peak angles between systems difficult, while ROM variables remain similar. The higher ICC and lower mean differences in BWSQ compared to CMJ were unsurprising given the faster movement velocity in the CMJ than the BWSQ. The current IMU placement and algorithm methodology were originally developed for slower movement patterns (e.g., shuffle walk, bear crawl) (Hindle et al., 2020). IMUs will capture more noise in ballistic than slow movements, largely due to movement artefact that occurs as a consequence of the large proximal musculature of the limb. As such, the system may be refined to allow for its implementation in more dynamic movements, such as the CMJ. In the BWSQ, RMSE and ICC were high to moderate for knee peak flexion and ROM, indicating validity of the system for quantifying sagittal knee kinematics. The high RMSE for the hip and the knee relative to the ankle may have been due to the greater functional range of motion of the hip and knee compared to the ankle during a squat. Even in a more ballistic movement, like the CMJ, hip peak flexion and knee ROM were valid according to ICC values. This is very promising for the progression of IMU algorithm development as hip and knee joints may be hard to quantify due to large range of motion and movement artefact due to soft tissue. While angles from the IMU system diverged from OMC for ankle plantarflexion and ROM in the BWSQ, and for all measures but hip peak flexion in CMJ, future work may reduce these errors by optimizing methodologies and refining the algorithm for ballistic movements. A consistent static start to a movement is vital for repeatable output from this IMU method. A method for ensuring consistency may be marking a single starting position for each task, and utilizing that position for definition of the OMC static model. Future work should aim to refine the algorithm to allow for the quantification of bilateral and multi-planar kinematics, both of which are invaluable to the continuously improving approach of sensor-based biomechanics.

CONCLUSION: An IMU system produced acceptable knee and hip kinematics as characterized by ICC values, while joint angles and ROM exhibited at the ankle had low agreement with an OMC system. Differences between systems may have been caused by the defined calibration used by each system. Optimizing system methodologies could enable this previously validated IMU system and algorithm to be used across different laboratories.

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