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The Reliability of Three-Dimensional Inertial Measurement Units in Capturing Lower-Body Joint Kinematics during Single-Leg Landing Tasks

JACOB M. THOMAS† and ROGER O. KOLLOCK‡

Oxley College of Health Science, University of Tulsa, Tulsa, OK, USA

†Denotes graduate student author, ‡Denotes professional author

ABSTRACT

International Journal of Exercise Science 15(1): 1306-1316, 2022. 3-D inertial measurement units (IMUs) have advantages over other types of motion capture systems, as IMUs cannot be obstructed by equipment and gear. Therefore, the purpose of this study was to assess the reliability of IMUs in measuring joint angles at the hip, knee, and ankle during two types of single-leg landings: 1) drop-landing (DL) and 2) leap-landing (LL). Nineteen subjects, both males (n = 9, 21.88 ± 1.64 yrs, 178.36 ± 9.68 cm, 185.68 ± 16.63 kg) and females (n = 11, 22.45 ± 4.32 yrs, 171.57 ± 6.55 cm, 70.95 ± 14.99 kg) participated in this study. Participants performed three trials of both tasks. The DL required the participant to drop onto their dominant leg from a 30 cm box onto force plate. The LL task required participants to leap over a 20 cm hurdle onto the force plate. ICC values and SEM calculations were used to assess the IMU's reliability. Overall, IMUs displayed fair-to-excellent reliability for both tasks (ICC = 0.442-0.962), aside from ankle inversion (ICC = 0.290) & ankle abduction (ICC = 0.216) at initial ground contact and ankle abduction (ICC = 0.234) at maximum vertical ground reaction force, both during the LL task. IMUs can be a reliable measurement tool for lower extremity motion during dynamic landing, so long as factors related to reliability at the ankle are considered.

KEY WORDS: IMU, biomechanics, hurdle

INTRODUCTION

Traditionally, scientists have employed the use of tethered, or infrared camera motion capture systems when exploring human motion. While these types of motion capture systems are reliable (27), valid (10), and considered by many to be the gold standard of motion capture, (24) they do have several limitations (28). As it relates to tethered systems, they require the attachment of sensors with leads connected to a data acquisition module. This may result in restriction of the subject's pattern of movement while also confining them to a small area in order to maintain an appropriate distance from the source of the leads (12). With regard to infrared motion capture systems, the use of reflective markers on top of, or underneath garments is often a limiting factor. This is because placing the reflective markers underneath clothing would result in concealment of the markers from the cameras. Placing reflective markers on top of clothing would result in the creation of artifacts, due to the shifting or movement of garments, which would skew the measurements (28). It is for these reasons that 3-D inertial measurement units (IMU) have become prominent in the biomechanical research field for the measurement of joint angle and acceleration data (22).

Three-dimensional inertial measurement units (IMU) are a cost-effective alternative to large laboratory setups, such as tethered or infrared systems, when taking biomechanical measurements during movement tasks (16, 21). IMUs use accelerometers, gyroscopes, and magnetometers to measure joint acceleration and rotation in 3 planes of motion (sagittal, frontal, transverse) (7). This technology gives the researcher freedom to perform measurements under a variety of different testing conditions. As readings from IMUs are typically transmitted via radio signals directly to a receiver, IMUs can also be placed under garments or protective equipment and attached directly to the skin at specific anatomical landmarks. This unique attribute lends itself well to research applications within tactical populations, as workers employed in tactical occupations often wear restrictive garments and equipment, which may affect their patterns of movement during job-related duties. This necessitates the use of valid and reliable instrumentation capable of capturing alterations in movement patterns. Such instrumentation is necessary to determine the influence this specialized equipment and gear may have on a tactical operator's quality of movement and its potential for increasing injury susceptibility.

IMU sensors have been found to be valid when measuring joint angles during, simple rotational movement, trunk movement, jumping, squatting, craniocervical movement, and during gait analysis tasks (1, 4, 7, 9, 11, 25, 29). As it specifically relates to the measurement of joint angles, IMUs have been found to produce valid measurements at the hip, knee, and ankle in the frontal, sagittal, and transverse planes of motion (1, 9, 11, 29). Prior research has compared the ability of IMU sensors in capturing lower body joint angles, to those of infrared and reflective marker-based systems (3, 5, 14). This earlier research has reported that the two systems produce comparable results (3, 5, 14).

The reliability of IMUs has also been examined in prior studies. Most of the research assessing the reliability of IMU sensors for monitoring lower extremity motion has focused on gait (1, 8, 9, 11, 17, 16). Cho et al. examined the reliability of an IMU system in measuring hip, knee, and ankle motion in the frontal, sagittal, and transverse planes during a walking task, finding ICC values ranging from 0.864-0.999 for the measures of knee valgus/varus and flexion/extension (9). Other studies have reported similarly high reliability of IMU sensors when measuring walking gait (1, 11). As it relates to tasks other than walking gait, Al-Amri et al. examined the reliability of IMU sensors in measuring knee, ankle and hip motion in the frontal, transverse, and sagittal planes during both a counter-movement jump and squatting task (1). It was observed that for all planes of motion, except transverse, *ICC* values were between 0.6 and 0.95. (1). This contrasts with their findings at the transverse plane, in which ankle motion was observed to have poor reliability (ICC $< .6$) for both tasks. They also observed that for the squat, hip and knee motion in the transverse plane also demonstrated poor reliability. The group reported that ankle abduction in transverse plane demonstrated poor reliability for the measurement of both tasks (1). For the squat task, transverse plane measures for knee ROM, knee maximum angle, and hip minimum angle displayed ICC values less than .06 (1). The results of these studies suggest that IMU sensors may be less reliable in measuring transverse plane motion. To date there is no evidence suggesting similar reliability outcomes with the measurement of lower body landing kinematics. Arguably, the mechanical shock imposed on the human body at ground contact during single leg landing tasks as compared to normal walking gait could cause artifacts resulting in greater measurement error (17, 20). It remains to be seen whether IMUs can produce reliable data when performing higher order movement tasks, which involve landing from a jump or height. Therefore, the purpose of this study was to assess the reliability of IMUs in measuring joint angles at the hip, knee, and ankle during two types of single-leg landings: 1) drop-landing (DL) and 2) leap-landing (LL). Based on earlier research, we hypothesize that IMU sensors will demonstrate fair to excellent reliability, with the exception of ankle motion.

METHODS

The study was a cross-sectional design. All data were collected at the University of Tulsa biomechanics laboratory by the same evaluator. The University of Tulsa Institutional Review Board (Protocol 19-28) granted approval for this study. All participants read and signed an approved Institutional Review Board consent document prior to participation. This research was carried out fully in accordance to the ethical standards of the International Journal of Exercise Science (19).

Participants

Nineteen subjects, both males (n = 9, 21.88 ± 1.64 yrs, 178.36 ± 9.68 cm, 185.68 ± 16.63 kg) and females (n = 11, 22.45 ± 4.32 yrs, 171.57 ± 6.55 cm, 70.95 ± 14.99 kg) were recruited for this study. All subjects were 18 or older. Post hoc power analysis determined that, with a minimal acceptable reliability of ICC = 0.40 and expected reliability of ICC = 0.74, 19 participants was sufficient to achieve 80% power (2).

Protocol

Participants reported to the laboratory wearing athletic attire, and were issued appropriately sized military combat boots (Belleville 390 Hot weather boots, Belleville, IL) for one test session. This footwear was selected in order to reduce variability associated with differences in footwear, and to represent footwear donned by tactical athletes, for whom IMU measurements may be useful. Participants were allowed to move about the laboratory until they were satisfied with the comfort of the boots, in order to familiarize themselves with the footwear. Height and weight were collected for each participant. Height was measured using a portable stadiometer (Invicta Plastics ltd., Leicester, England). Weight was measured using the Tanita TBF-300A scale and body composition analyzer (Tanita Corporation of America, Inc., Arlington Heights, Illinois). Patients were then fitted with IMU sensors (myoMOTION Research Sensors, Noraxon U.S.A., Scottsdale, Arizona) at the pelvis, left and right thigh, left and right shank, and left and right foot that transmitted data to a receiver (myoMOTION Research Receiver, Noraxon U.S.A., Scottsdale, Arizona) at a sampling rate of 100 Hz, the maximum sampling rate of the device used for this study. The foot sensors were placed on the dorsal aspect of the feet at the metatarsal region of the foot, equidistant between the head of the first and fifth metatarsals using a shoe adapter and rubber strapping system (Noraxon U.S.A., Scottsdale, Arizona) (18, 13). The shank sensors were placed according to a tibia fitting template (dorsaVi Ltd, New York, NY) (26). The tibia fitting template was used to standardize the sensor placement across participants. The tool was placed on the inferior edge of the medial malleolus and provided reference for sensor placement based on the height of the participant beginning at 16.5 cm (for those <165cm in height) and increasing sensor placement height on the shank by 2 cm for every additional 10 cm of participant height. The thigh sensors were placed halfway between the greater trochanter and the lateral condyle of the femur on the lateral portion of the thigh, while the pelvis sensor was placed posteriorly, equidistant between right and left posterior superior iliac spine. This placement protocol was developed within our laboratory to ensure consistency of sensor placement. IMU sensors were then calibrated using the Polhemus Patriot Calibration Stylus configuration (Polhemus, Colchester, Vermont), and Myomotion motion capture software version 3.14 (Noraxon U.S.A., Scottsdale, Arizona).

The IMU sensors were calibrated by having the participants stand on a 30 cm box, with feet shoulder width apart and hands on hips. Following sensor calibration, the digital model was improved using anthropometrics obtained through the palpation, and subsequent digitization of bony landmarks using the Polhemus Patriot Calibration Stylus. These bony landmarks included the: anterior superior iliac spine, posterior superior iliac spine, medial and lateral femoral condyles, medial and lateral malleoli, as well as the 1st and 5th metatarsal joints on both sides of the body. Per the manufacturer, these readings were only reliable for 5 minutes post calibration. Thus, stylus calibrations were performed prior to each individual task. Joint angle measurements included hip flexion, hip abduction, hip external rotation, knee flexion, knee abduction, ankle dorsiflexion, ankle inversion, ankle abduction, pelvic tilt, and pelvic obliquity. Each of these measures were recorded at initial ground contact (IC), which was defined as the instant the vertical ground reaction force exceeded 10 N and at maximum vertical ground reaction force (VGRF) for each of the three trials. VGRF was collected using a 40 cm x 60 cm force plate (Bertec, Columbus, OH). Force plate data were sampled at 1500 Hz. All force plate data was filtered using a low pass Butterworth filter with 20 Hz cutoff frequency. Force plates were synchronized with IMUs using a synchronization system (MyoSync, Noraxon U.S.A., Scottsdale, Arizona). Synchronization allowed for joint angle analysis at the timepoints of IC and maximum VGRF.

Following the placement and calibration of sensors, participants performed three DL trials (Figure 1). The DL task required the participant to drop onto their dominant leg from a 30 cm box placed approximately 10% of their height away from a 40 cm x 60 cm force plate (Bertec, Columbus, OH). Upon landing, the participants had to "stick" the landing by maintaining stability, and subsequently remained motionless for a ten-second period. If this condition was not met, trials were repeated until successfully performed. The participants performed three DL trials (13).

Following the DL task, participants were asked to complete three trials of a LL task (Figure 2). The LL task required participants to stand in a staggered stance placing their dominant foot at a distance of 60% of the participant's height away from a force plate (Bertec, Columbus, OH), with their non-dominant foot at a distance of 40% of the participant's height away from the force plate. A hurdle 20 cm in height was placed at 20% of the participant's height away from the force plate necessitating a leap over the hurdle onto the force plate. Similarly, to the DL, the participants had to "stick" the landing and remain motionless for a ten-second period.

Figure 1. Drop Landing (DL) Task

Figure 2. Leap Landing (LL) Task

Statistical Analysis

Intra-class correlation coefficients ($ICC_{3,1}$) were run to determine the inter-trial reliability of the IMUs. ICC values were calculated for hip flexion, hip abduction, hip external rotation, knee flexion, knee abduction, ankle dorsiflexion, ankle inversion, ankle abduction, pelvic tilt, and pelvic obliquity at IC (defined as the moment VGRF surpassed 10N) and max VGRF (as measured by force plates). These data points were grouped by trial for all participants, and compared between trials to calculate ICC. ICC values were interpreted according to the scale set forth by Shrout & Fleiss (23) which states that ICC ≥ 0.75 is excellent, ICC 0.40-0.74 is fair-to-high, and ICC ≤ 0.39 is poor. Standard error of measurement (SEM) values were calculated to determine the precision of each measure (see Equation 1). SEM values less than 3° were considered excellent, *SEM* values less than 5° were considered acceptable (15). These analyses were completed for both the LL and DL tasks. Alpha level was set at a priori .05. All data was analyzed using SPSS Statistic 24 (IBM, Somers, NY).

Equation 1. Standard Error of Measure

$$SEM = SD \times \sqrt{1 - ICC}$$

RESULTS

Drop- Landing Task: At IC the inter-trial ICC values for the pelvis, hip, knee and ankle ranged from 0.943-0.959 (SEM = 0.271°-0.360°), 0.899-0.956 (SEM = 0.363°-0.770°), 0.896-0.949 (SEM = 0.182°-0.552°), and 0.563-0.829 (SEM = 1.055°-2.257°) respectively (Table 1). At maximum VGRF the inter-trial ICC values for the pelvis, hip, knee and ankle ranged from 0.874-0.962 (SEM = 0.690°-1.751°), 0.680-0.880 (SEM = 0.849°-1.875°), 0.796-0.823 (SEM = 0.598°-1.178°), and 0.569-0.873 (SEM = 1.121°-2.535°), respectively (Table 1).

Leap-Landing Task: At IC inter-trial ICC values for the pelvis, hip, knee and ankle ranged from 0.927-0.956, (SEM = 0.326°-0.429°) 0.869-0.936 (SEM = 0.674°-1.105°), 0.796-0.823 (SEM = 0.627°-1.188°), and 0.216-0.915 (SEM = 1.924°-6.657°), respectively (Table 2). At Maximum VGRF, the inter-trial ICC values for the pelvis, hip, knee and ankle ranged from 0.880-0.922 (SEM = 0.626°-0.688°), 0.758-0.910 (SEM = 0.878°-1.789°), 0.715-0.884 (SEM = 0.533°-2.111°), and 0.234-0.960 (SEM = 1.145°-6.846°), respectively (Table 2). Table 1 & 2 also report p-values associated with ICC tests.

Table 1. Drop-landing Inter-trial $ICC_{3,1}$ Results

Measure	*ICC*	*95% CI* Lower	Upper	*SEM*	*p-value*
			Initial Ground Contact		
Hip Flexion	0.956	0.909	0.981	0.363	< .001*
Hip Abduction	0.905	0.810	0.959	0.461	< .001*
Hip External Rotation	0.899	0.799	0.956	0.770	< .001*
Knee Flexion	0.896	0.793	0.955	0.552	< .001*
Knee Abduction	0.949	0.894	0.978	0.182	< .001*
Ankle Dorsiflexion	0.776	0.589	0.898	1.901	< .001*
Ankle Inversion	0.829	0.675	0.924	1.055	< .001*
Ankle Abduction	0.563	0.297	0.781	2.257	< .001*
Pelvic Tilt	0.943	0.883	0.976	0.360	< .001*
Pelvic Obliquity	0.959	0.915	0.983	0.271	< .001*
			Maximum Vertical Ground Reaction Force		
Hip Flexion	0.884	0.771	0.949	0.850	< .001*
Hip Abduction	0.851	0.712	0.934	0.849	< .001*
Hip External Rotation	0.680	0.448	0.848	1.875	< .001*
Knee Flexion	0.796	0.621	0.908	1.178	< .001*
Knee Abduction	0.823	0.665	0.921	0.598	< .001*
Ankle Dorsiflexion	0.873	0.751	0.944	1.155	< .001*
Ankle Inversion	0.569	0.304	0.785	1.121	< .001*
Ankle Abduction	0.610	0.354	0.809	2.535	< .001*
Pelvic Tilt	0.874	0.705	0.932	0.690	< .001*
Pelvic Obliquity	0.962	0.921	0.984	1.751	< .001*

*$p<.05$

Table 2. Leap-landing Inter-trial $ICC_{3,1}$ Results

Measure	*ICC*	*95% CI* Lower	Upper	*SEM*	*p-value*
		Initial Ground Contact			
Hip Flexion	0.936	0.869	0.973	0.674	< .001*
Hip Abduction	0.869	0.743	0.942	0.859	< .001*
Hip External Rotation	0.895	0.792	0.955	1.105	< .001*
Knee Flexion	0.794	0.618	0.907	1.188	< .001*
Knee Abduction	0.812	0.646	0.915	0.627	< .001*
Ankle Dorsiflexion	0.915	0.829	0.964	1.924	< .001*
Ankle Inversion	0.290	0.012	0.592	4.331	0.020*
Ankle Abduction	0.216	-0.052	0.531	6.657	0.061
Pelvic Tilt	0.956	0.908	0.981	0.326	< .001*
Pelvic Obliquity	0.927	0.851	0.969	0.429	< .001*
		Maximum Vertical Ground Reaction Force			
Hip Flexion	0.910	0.820	0.961	0.878	< .001*
Hip Abduction	0.758	0.561	0.889	1.798	< .001*
Hip External Rotation	0.889	0.781	0.952	0.930	< .001*
Knee Flexion	0.715	0.497	0.867	2.111	< .001*
Knee Abduction	0.884	0.770	0.949	0.553	< .001*
Ankle Dorsiflexion	0.960	0.916	0.983	1.145	< .001*
Ankle Inversion	0.442	0.160	0.703	2.221	0.001*
Ankle Abduction	0.234	-0.029	0.554	6.846	0.042*
Pelvic Tilt	0.922	0.843	0.967	0.626	< .001*
Pelvic Obliquity	0.880	0.764	0.948	0.688	< .001*

*$p<.05$

DISCUSSION

The main findings of this study were that IMUs displayed fair to excellent inter-trial reliability for all variables, except LL ankle abduction at IC and maximum VGRF, as well as ankle inversion at IC. To the authors' knowledge, this was the first study to evaluate the reliability of IMU sensors while performing drop landing and leap landing tasks. In the present study it was hypothesized that IMU sensors would demonstrate fair to excellent reliability, with the exception of ankle motion. This hypothesis was supported. Aside from the three variables at the ankle during the LL task, the IMU sensor system displayed fair to excellent reliability overall. Various prior studies have examined the reliability of IMU sensors while performing simple movement or gait analysis tasks, and have found overall reliability to be fair to excellent (7, 9, 11). However, this is the first study to the authors' knowledge which has investigated higher order movement tasks involving landing such as the LL and DL. Al-Amri et al. examined the reliability of IMUs during squatting and jumping tasks, which are more functional in nature than some other tasks examined in prior research, but do not involve the same levels of dynamic control or landing as are observed in the DL and LL tasks (1).

The findings of this present study indicate that the reliability of angular measurement of IMUs at the ankle may deteriorate as higher order movement tasks are performed. This is likely because the foot sensor is the only one which cannot be adhered directly to the skin but must, instead, be strapped to the shoe. Mechanical shock created as a result of ground contact may cause sensor movement, resulting in the creation of artifacts, and therefore, sensor readings may become less representative of motions occurring at the ankle joint as the tasks performed increase in complexity. Due to the ankle sensor's proximity to the point of ground contact, it likely experiences the mechanical shock of landing to a greater degree than sensors which are more proximal. Future research should continue to focus on the reliability of IMU sensors while performing complex movement tasks in order to detect excess variability which could skew the findings of research involving these sensors. It is also possible that the footwear worn in this study was restrictive, and contributed to the poor reliability at the ankle. These factors should be considered when using IMUs to measure higher order body transport tasks.

The present study is not the first to report poor ICC values at the ankle joint using IMUs. In their examination of the reliability of the Xsens MTw Awinda IMU sensor system, Al-Amri et al. also reported poor repeatability (ICC<0.01) of transverse plane ankle angle in the heel strike phase of gait (1). Standard error of measure for transverse ankle angle at heel strike was reported to be acceptable (between 3º and 5º) (1). The group noted that the poor ankle repeatability was one of only two variables which were categorized as poor, the other being frontal plane knee angle at heel strike (ICC < 0.04; SEM < 3º) (1). In the present study, no ICC values were reported below 0.2, however, SEM values above 5º were found for ankle abduction angle at both time-points during the LL task. These findings suggest that the IMU system used in the current study produced better repeatability for the tasks and angles observed, but also created a greater standard error of measure, indicating a lower level of absolute reliability for these specific measurements. Conversely, Cho et al. reported excellent ICC values (all greater than 0.912) using the Motion Track IMU sensor system in measuring angular change at the ankle in the frontal, sagittal, and transverse planes, when performing gait analysis (9). These excellent ICC values could be related to differences in the IMU systems. Both Cho et al. and Al-Amri et al. used straps to secure IMUs to the foot, similar to the methods used in the present study.

Charlton et al. examined the reliability of an IMU sensor which was embedded in participants' shoes during a walking task, and reported excellent reliability when measuring foot progression angle, a term for the average transverse motion at the ankle throughout the gait cycle (toe-in/toe-out) (8). However, it should be noted that this was the only angle measured in the study, and only one sensor was required to measure foot progression angle (8). Prior research has found that IMU sensors may become less reliable as more sensors are added to the configuration (6) Differences between these prior studies and the present one may be due to the IMU system, the methods of sensor placement, placement position of sensors, and the researcher administering the test. Any of these factors could influence the reliability of IMU readings. Future research should continue to focus on the validity of IMU sensors for measures at the pelvis, hip, knee and ankle.

Two main practical applications can be taken from the present study. First, because pelvis markers were always concealed under clothing, depending on the length of shorts worn, as were thigh markers, high ICC values in these locations suggest that IMU sensors may be a viable option in testing scenarios in which reflective markers may be occluded from infrared cameras by clothing, gear or equipment (e.g. firefighters, military, police). However, further IMU research is required within tactical populations to assess reliability while wearing personal protective equipment. Second, IMU sensors' mobility may allow for more flexibility as compared to infrared camera systems with regard to types of the testing environments. This aspect of mobility provides the ability to reliably capture motion in more natural settings than the controlled environment of a laboratory, leading to more applicable findings, particularly within tactical occupations and other athletic populations.

Two limitations should be noted within the present study. First, the calibration tool used to improve the IMU anatomical model (Polhemus Patriot Calibration Stylus, Polhemus, Colchester, Vermont) was only valid, per the manufacturer, for 5-minutes post-calibration. This should be noted for future studies using the device, as results may vary if this time limit is not observed. The calibration method used in the present study is also time intensive and should be considered by clinicians wishing to use the IMU sensor system. Calibration time may vary (5-7 minutes) based upon the clinician's calibration experience and proficiency. Second, reduced sensor reliability at the ankle could be due to sensor placement, or attachment technique. This presents a future area of study to determine a method of sensor placement at the ankle which produces more reliable results.

The findings of this present study indicate that IMU devices are a reliable tool for measuring kinematics during single leg drop landing and leap landing tasks, so long as factors related to the ankle are taken into consideration. Further research should examine methods for reducing the variability of readings at the ankle during higher order movement tasks via different placement strategies or improved wearable options.

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