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ORIGINAL ARTICLE

Reliability and Validity of Maximum Lower Limb Angle During Countermovement Jump: Comparing 3D Motion Capture with Inertial Measurement Units

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KEYWORDS
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ABSTRACT
Background. Movement assessment is vital in physical therapy for injury prevention. Although 3D motion capture provides precise measurements, its high cost and complexity limit practical application. Inertial measurement units (IMUs) present a more feasible alternative; however, their reliability in complex movements, such as the countermovement jump (CMJ), remains underexplored. **Objectives.** To assess the reliability and concurrent validity of IMUs in measuring maximum lower limb angles during CMJs compared to 3D motion analysis. **Methods.** An observational cross-sectional design was employed with 36 participants (18 males, 18 females; mean age 23.25 years). Participants performed CMJs while fitted with reflective markers for 3D analysis and IMUs. Peak joint angles were measured in the sagittal, frontal, and transverse planes. Reliability was assessed using intraclass correlation coefficients (ICCs), and concurrent validity was determined through Pearson correlation coefficients. **Results.** Results indicated moderate to excellent reliability for joint angle measurements, with ICCs ranging from 0.51 to 0.95 across planes. Concurrent validity demonstrated moderate to high correlations, particularly in the sagittal (hip: r=0.74, knee: r=0.73) and frontal planes (ankle: r=0.94). However, lower correlations were noted in the transverse plane for the ankle (r=0.40). **Conclusion.** These findings suggested that while IMUs were effective for assessing joint angles during CMJs, caution was warranted when interpreting transverse plane data, particularly for the ankle. This study underscored the potential of IMUs as a practical alternative to 3D motion analysis in clinical and athletic settings.

INTRODUCTION

Movement assessment is a critical component of physical therapy, allowing practitioners to detect abnormalities and inefficiencies in patient movement. This detection informs the creation of targeted treatment plans, essential for preventing recurrent injuries and minimizing the risk of future ones. Accurate movement evaluation is thus integral to injury prevention strategies and effective rehabilitation (1, 2).

Traditionally, three-dimensional (3D) motion analysis has been considered the gold standard for assessing movement patterns. This method employs at least six infrared cameras to track markers placed on anatomical landmarks, producing detailed movement models across various postures.

Despite its precision, 3D motion analysis has several limitations, including high costs, maintenance complexity, and the need for large, specialized spaces—factors that reduce its feasibility for routine clinical or field-based applications (3, 4).

In recent years, inertial measurement units (IMUs) have emerged as a promising alternative for movement analysis. Comprising accelerometers, gyroscopes, and magnetometers, IMUs can assess various movement parameters, including joint angles, velocity, and acceleration. Their advantages—affordability, portability, ease of use, and applicability in outdoor settings—make them attractive for clinical and athletic contexts (5, 6). Previous research supports the use of IMUs for capturing specific movement patterns, showing that they provide reliable data across various movement types (7, 8).

Jumping, a fundamental skill in many sports, is crucial for enhancing athletic performance, as it directly influences muscular power, agility, and neuromuscular coordination. The countermovement jump (CMJ), in particular, is commonly used to evaluate lower limb strength and power. CMJ analysis is widely employed in rehabilitation settings and injury risk assessments (9, 10). CMJ measures, such as force-time characteristics, indicate an athlete's lower-body strength and neuromuscular function (11).

Previous studies have explored the validity and reliability of IMUs compared to 3D motion capture systems, particularly in analyzing simpler movement tasks like walking. For example, research has demonstrated that IMUs provide accurate and reliable kinematic data during gait analysis (7, 12). However, studies also show that while IMUs perform well in measuring temporal gait variables, such as stride frequency and phase timing, they are less precise in capturing spatiotemporal variables (12). Additionally, while IMUs can effectively assess straight walking, they encounter limitations when analyzing more complex movements, such as turning, especially in populations with gait impairments like elderly individuals or patients with Parkinson's disease (13).

Despite the growing evidence supporting IMU use in simple movement tasks, challenges remain when applying this technology to more dynamic and complex sports movements, such as jumping (6, 8). Given these challenges, this study aims to evaluate the reliability and concurrent validity of IMUs in assessing kinematic parameters of the lower limbs during CMJs, comparing their performance to the gold-standard 3D motion capture system in healthy adults.

MATERIALS AND METHODS

Study Design. This observational cross-sectional study was approved by the University Human Research Ethics Committee (COA No. 073/2565).

Participants. Healthy male and female participants, aged 20 to 35 years, fluent in Thai, and able to follow instructions, were recruited. Individuals with musculoskeletal disorders, such as recent muscle tears or ankle sprains within the week prior to data collection, or those unable to perform a CMJ, were excluded (14).

A power analysis determined that a minimum of 36 participants would be required to achieve statistical significance, detecting a medium effect size with 80% power at a significance level of 0.05 (15). Participants were recruited via social media and flyers distributed at local colleges, with recruitment materials providing detailed information about the study's purpose, procedures, and eligibility criteria (14).

Procedure. Participants were fitted with sixteen reflective markers for 3D motion analysis using a lower limb plug-in gait marker set (Vicon, Oxford, UK). Additionally, IMUs were attached to capture movement data. The motion analysis utilized ten SMART-DX cameras (BTS Bioengineering, Italy) and Ultium Motion IMUs (Noraxon, USA), both set to a sampling frequency of 200 Hz. All equipment was calibrated according to the manufacturers' specifications before data collection to ensure measurement accuracy (BTS Bioengineering, 2020; Noraxon, 2020). During the static calibration process, participants stood in a standardized anatomical stance, with feet shoulder-width apart, arms relaxed at their sides, and bodies aligned in a neutral posture. This positioning allowed the motion analysis system to establish a baseline for each marker's location relative to the participant's anatomical landmarks.

Participants completed a standardized warm-up routine before performing the CMJ (16). The jump procedure involved standing with feet shoulder-width apart, placing hands on the hips, rapidly bending the knees and hips, and jumping as high as possible (10). After landing, participants flexed their knees and hips slightly to absorb the impact. Participants practiced the CMJ until they demonstrated proficiency in the movement (11).

Each participant performed three CMJ trials, with motion data recorded simultaneously by the SMART-DX and Ultium Motion systems. Trials were conducted under controlled conditions to ensure consistent timing and environmental factors (14).

Data Analysis. Data from the motion capture system were analyzed using Smart Tracker and Smart Analyzer software (BTS Bioengineering, Italy). The raw marker data were filtered with a low-pass Butterworth filter at 20 Hz and processed through Visual 3D software (C-Motion, Germantown, USA) (17). Peak hip, knee, and ankle joint angles were extracted for each jump, and average values were calculated for each participant.

Statistical Analysis. All statistical analyses were performed using IBM SPSS Statistics (version 22.0; IBM Corp., Armonk, NY, USA). The Shapiro-Wilk test assessed the normality of the data distribution. To evaluate reliability between the IMU and 3D motion capture systems, intraclass correlation coefficients (ICC (3,1)) were calculated with the following interpretation guidelines: excellent (>0.90), good (0.75–0.90), moderate (0.50–0.74), and poor (<0.50) (14).

The standard error of measurement (SEM) was computed using the formula $SEM = SD \times \sqrt{(1 - ICC)}$, where SD represents the standard deviation of the data and ICC represents the correlation coefficient (18). The minimal detectable change (MDC) was calculated using $MDC = 1.96\sqrt{2} \times SEM$ or $2.77 \times SEM$ (19).

Concurrent validity between the IMU and 3D motion capture systems was assessed using Pearson correlation coefficients, interpreted as follows: 0.00–0.30 (no significant correlation), 0.30–0.50 (low correlation), 0.50–0.70 (moderate correlation), 0.70–0.90 (high correlation), and 0.90–1.00 (very high correlation) (20). Statistical significance was set at $p<0.05$ (14).

RESULTS

Thirty-six healthy participants (18 females and 18 males) were enrolled in this study. The mean age of the cohort was 23.25 years (±2.80), with an average body weight of 64.19 kg (±14.44), a mean height of 1.67 m (±0.23), and a body mass index (BMI) of 20.77 kg/m² (±3.93) (Table 1).

Lower limb joint angles during the CMJ were assessed across three planes of motion using both IMU and a 3D motion capture system (Table 2). In the sagittal plane, the IMU recorded a hip angle of 79.81° (±13.06), while the 3D motion capture system measured 83.29° (±12.56). For knee flexion, the IMU recorded 82.89° (±10.89) compared to 89.98° (±11.23) measured by the 3D system. Ankle flexion angles were 8.72° (±40.21) for the IMU and 10.27° (±38.97) for the 3D system.

Table 1. Mean and Standard Deviation of Physical Characteristics of Research Participants.

Characteristics	Mean ± Standard Deviation
Gender	
- Male	18
- Female	18
Age (years)	23.25 ± 2.80
Weight (kilograms)	64.19 ± 14.44
Height (meters)	1.67 ± 0.23
Body Mass Index (kg/m²)	20.77 ± 3.93

In the frontal plane, the IMU measured a hip angle of 10.61° (±10.18) compared to 10.53° (±9.49) with 3D analysis. Knee angles were -0.25° (±8.15) and -0.46° (±11.33) for IMU and 3D systems, respectively. Ankle angles were -10.22° (±11.65) for the IMU and -8.99° (±11.96) for 3D motion analysis.

In the transverse plane, hip rotation angles were 15.48° (±12.18) using IMU and 14.18° (±10.99) with 3D motion capture. Knee angles were 0.15° (±20.06) for IMU and 2.13° (±20.20) for the 3D system. Ankle rotation angles were 20.18° (±4.74) for IMU and 22.04° (±5.62) for 3D motion analysis.

The reliability of peak joint angle measurements during the CMJ was assessed using intraclass correlation coefficients (ICCs) (Table 3). In the sagittal plane, the hip showed ICC values ranging from 0.71 to 0.92 (p<0.001), indicating moderate to excellent reliability. The knee displayed ICC values between 0.82 and 0.95 (p<0.001), while the ankle showed values between 0.70 and 0.92 (p<0.001). In the frontal plane, the hip and ankle demonstrated moderate to excellent reliability, with ICCs ranging from 0.68 to 0.91 (p<0.001) and 0.72 to 0.91 (p<0.001), respectively. The knee showed good to excellent reliability, with ICC values ranging from 0.84 to 0.95 (p<0.001). In the transverse plane, the hip and knee demonstrated moderate to good reliability, with ICC values ranging from 0.51 to 0.84 (p<0.001) and 0.62 to 0.88 (p<0.001), respectively. The ankle showed lower reliability in the transverse plane, with ICC values ranging from 0.16 to 0.78 (p=0.007).

Concurrent validity was evaluated using Pearson correlation coefficients (Table 3). For the hip, moderate correlations were observed across all planes: sagittal (r=0.74, p<0.001), frontal (r=0.72, p<0.001), and transverse (r=0.80, p<0.001). Similarly, the knee demonstrated moderate correlations in the sagittal (r=0.73, p<0.001), frontal (r=0.89, p<0.001), and transverse planes (r=0.90, p<0.001). The ankle showed high correlations in both the sagittal (r=0.94, p<0.001) and frontal (r=0.92, p<0.001) planes but exhibited a lower correlation in the transverse plane (r=0.40, p=0.014).

Table 2. Peak Joint Angles of the Lower Limbs during Countermovement Jump (CMJ) in Three Planes Between IMU and 3D Motion Analysis.

Peak Joint Angle (Degrees)	IMU (Mean ± SD)	3D Motion (Mean ± SD)
Hip joint		
Flexion (+) /Extension (-)	79.81 ± 13.06	83.29 ± 12.56
Abduction (+) /Adduction (-)	10.61 ± 10.18	10.53 ± 9.49
External (+) /Internal (-) rotation	15.48 ± 12.18	14.18 ± 10.99
Knee joint		
Flexion (+) /Extension (-)	82.89 ± 10.89	89.98 ± 11.23
Abduction (+) /Adduction (-)	0.25 ± 8.15	-0.46 ± 11.33
External (+) /Internal (-) rotation	0.15 ± 20.06	2.13 ± 20.20
Ankle joint		
Plantarflexion(+) /Dorsiflexion (-)	8.72 ± 40.21	10.27 ± 38.97
Abduction (+) /Adduction (-)	-10.22 ± 11.65	-8.99 ± 11.96
Inversion (+) /Eversion (-)	20.18 ± 4.74	22.04 ± 5.62

Table 3. Reliability and Concurrent Validity of Peak Joint Angles of the Lower Limbs during Countermovement Jump (CMJ) in Three Planes Between IMU and 3D Motion Analysis Using Interclass Correlation Coefficient (ICC 3,1) and Correlation Coefficient.

Movement	ICC (95% CI)	SEM (Degree)	MDC (Degree)	Correlation Coefficient
Sagittal plane				
- **Hip joint**	0.85 (0.71 – 0.92)*	2.35	6.53	0.74*
- **Knee joint**	0.90 (0.82 – 0.95)*	10.34	28.66	0.73*
- **Ankle joint**	0.84 (0.70 – 0.92)*	0.63	1.77	0.94*
Frontal plane				
- **Hip joint**	0.83 (0.68 - 0.91)*	0.01	0.02	0.72*
- **Knee joint**	0.92 (0.84 – 0.95)*	0.07	0.20	0.89*
- **Ankle joint**	0.84 (0.72 – 0.91)*	0.35	0.97	0.92*
Transverse plane				
- **Hip joint**	0.72 (0.51 – 0.84)*	0.33	0.93	0.80*
- **Knee joint**	0.78 (0.62 – 0.88)*	0.78	2.17	0.90*
- **Ankle joint**	0.57 (0.16 – 0.78)*	1.13	3.13	0.40**

ICC: Intraclass Correlation Coefficient; SEM: Standard Error of Measurement; MDC: Minimal Detectable Change; *: p<0.001; **: p=0.014.

DISCUSSION

This study evaluated the reliability and concurrent validity of maximum joint angle measurements of the lower extremities during the CMJ using IMUs and 3D motion analysis in healthy adults aged 18 to 35. A total of 36 participants were included, providing a robust dataset for comparing the two measurement methods.

The results indicated that the reliability of joint angle measurements in the sagittal plane ranged from moderate to excellent (ICC: 0.71 to 0.92), with the knee exhibiting robust reliability (ICC: 0.82 to 0.95) (1, 12). These findings are consistent with previous literature, which supports using IMUs for reliable measurements during dynamic movements (6, 7). However, lower reliability was observed in the transverse plane (ICC: 0.51 to 0.84 for the hip and knee; ICC: 0.16 to 0.78 for the ankle), underscoring potential challenges in accurately capturing complex joint angles during rapid movements. This outcome is corroborated by Baek et al. (2022), who noted similar difficulties in the transverse plane (3). The lower reliability may be attributed to the anatomical complexity of the ankle joint and the effect of sensor placement on measurement precision (21).

The concurrent validity analysis revealed moderate to high correlations between IMUs and 3D motion analysis across the sagittal and frontal planes for the hip (r = 0.74–0.80) and knee (r = 0.73–0.90) (4, 10). Notably, the ankle exhibited high correlations in the sagittal (r = 0.94) and frontal planes (r = 0.92) but a substantially lower correlation in the transverse plane (r = 0.40) (8). These results suggest that while IMUs are reliable for assessing joint angles in certain planes, their utility may be limited in capturing multidimensional movements, particularly in the ankle during dynamic tasks.

The reduced reliability and validity in the transverse plane could be explained by the intricate structure of the ankle joint, which enables simultaneous movements across multiple planes. As Hall (2012) emphasized, the talocrural and subtalar joints contribute to the complexity of ankle movements, making accurate sensor placement and angle measurement more challenging (21). Additionally, the high-impact forces experienced by the ankle during jumping may introduce vibrations that affect sensor accuracy, a problem less pronounced in the hip and knee, where joints are more stabilized during movement (11).

Despite these challenges, the results demonstrate that IMUs are a feasible tool for assessing joint angles during physical activities. Their portability, ease of use, and real-time data transmission capabilities offer distinct advantages for field applications (5). However, as Teufl et al. (2019) pointed out, optimal sensor placement and secure attachment are essential for minimizing measurement errors, particularly during high-velocity movements. Future research should address the limitations of this study, which was confined to healthy young adults performing vertical CMJs (8). Broadening the sample to include individuals of varying ages and fitness levels would improve the generalizability of the findings. Furthermore, investigating the impact of movement speed on the accuracy of IMU measurements across a range of athletic tasks could provide deeper insights into the reliability and applicability of these devices in clinical and sports settings (22).

CONCLUSION

This study demonstrates that IMUs can reliably and validly assess maximum joint angles in the sagittal and frontal planes during the CMJ in healthy young adults. However, caution is warranted when interpreting data from the transverse plane, particularly for the ankle. As the use of IMUs continues to grow in physical activity analysis, further exploration of their efficacy across varied movements and populations will be essential to optimizing their application in both clinical and athletic contexts.

APPLICABLE REMARKS

- IMUs were reliable for measuring joint angles in the sagittal and frontal planes, particularly for the knee, but showed limitations in the transverse plane, especially for ankle movements.
- Accurate sensor placement and secure attachment were essential for improving IMU measurement precision, especially during high-speed movements.
- IMUs offer practical advantages for field applications due to their portability and real-time data capabilities, making them valuable for dynamic movement analysis in sports and clinical settings.

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AUTHORS' CONTRIBUTIONS

Study concept and design: Chuanpis Boonkerd, Thanawat Kitsuksan, Teerapat Laddawong. Acquisition of data: Chuanpis Boonkerd, Thanawat Kitsuksan, Suteera Jaidee, Teerapat Laddawong. Analysis and interpretation of data: Chuanpis Boonkerd, Thanawat Kitsuksan, Suteera Jaidee, Teerapat Laddawong. Drafting the manuscript: Chuanpis Boonkerd, Thanawat Kitsuksan, Suteera Jaidee, Teerapat Laddawong. Critical revision of the manuscript for important intellectual content: Chuanpis Boonkerd, Thanawat Kitsuksan, Suteera Jaidee, Teerapat Laddawong. Statistical analysis: Chuanpis Boonkerd, Thanawat Kitsuksan, Suteera Jaidee, Teerapat Laddawong. Administrative, technical, and material support: Chuanpis Boonkerd, Thanawat Kitsuksan, Suteera Jaidee, Teerapat Laddawong. Study supervision: Chuanpis Boonkerd, Thanawat Kitsuksan, Teerapat Laddawong.

CONFLICT OF INTEREST

The authors hereby declared that they had no conflicts of interest concerning this research.

FINANCIAL DISCLOSURE

The authors declare no conflicts of interest. This disclosure promotes transparency, indicating that no financial or personal factors influenced the study.

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ETHICAL CONSIDERATION

The study was approved by the University Human Research Ethics Committee (COA No. 073/2565), following guidelines to protect participants' rights and confidentiality in line with the Declaration of Helsinki. Informed consent was obtained, and participants could withdraw at any stage.

ROLE OF THE SPONSOR

The sponsor had no role in the study's design, data collection, analysis, or manuscript preparation, ensuring the research's independence.

ARTIFICIAL INTELLIGENCE (AI) USE

No AI tools were used in designing, analyzing, or drafting this study. This disclosure affirms that the authors conducted all work without AI assistance.

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