



Measuring sagittal plane hip and knee joint kinematics during swing phase: reliability of a webcam-based approach

JUNG-HOON AHN^{1#}, HYE-KANG PARK^{2#}, CHANG-YOON BAEK^{2, 3*}

¹ Department of Sports Rehabilitation, College of Health and Medical Science, Cheongju University, Cheongju, Republic of Korea.

² Department of Rehabilitation Center, National Health Insurance Ilsan Hospital, Ilsan, Republic of Korea.

³ Graduate School of Sports Medicine, CHA University, Gyeonggi-do, Republic of Korea.

These authors have contributed equally to this study.

Purpose: Joint angle analysis during gait is crucial for identifying pathological conditions and estimating joint loading, thereby supporting clinical decision-making for injury prevention. Although various methods are available for analyzing joint angles, webcam-based motion capture systems (MoCap) are gaining attention due to their affordability and user-friendliness. This study aimed to evaluate and compare the inter-rater and intra-trial reliability of a webcam-based MoCap with that of a conventional inertial measurement unit (IMU)-based system. **Methods:** Gait analysis was conducted on 15 participants (6 males, 9 females; mean age: 28.1 ± 5.26 years). While participants walked a 3-meter distance, hip and knee joint angles in the sagittal plane were simultaneously recorded using both inertial measurement unit (IMU) sensors and a webcam-based MoCap. Inter-rater and intra-trial reliability were assessed using intraclass correlation coefficients (ICCs), and agreement between the two systems was evaluated using Bland–Altman analysis. **Results:** For intra-trial reliability, most IMU-based systems demonstrated excellent reliability ($ICC > 0.8$). Although slightly lower, the webcam-based MoCap also achieved substantial to almost perfect reliability ($ICC = 0.652 - 0.838$). Inter-rater reliability between the IMU and webcam-based MoCap generally showed moderate to substantial agreement ($ICC = 0.466 - 0.696$). **Conclusions:** These findings suggest that the webcam-based MoCap may serve as a viable alternative in settings where IMU systems are unavailable or impractical. Future studies should aim to refine webcam-based tracking algorithms to improve event detection, assess reliability across diverse populations and movement tasks, and further validate such systems against gold-standard marker-based 3D optical MoCap.

Key words: webcam-based motion capture, inertial measurement unit, gait analysis, joint angle

1. Introduction

Gait analysis is an effective method widely used in both clinical and research settings to evaluate human movement and musculoskeletal function, providing critical insights that aid diagnosis, treatment planning and rehabilitation [4], [13], [34]. Joint angle analysis during gait is crucial for enhancing clinical decision-making in injury prevention by identifying deviations associated with pathological conditions and predicting joint loading [2], [6], [7], [29]. To analyze joint angles during gait,

both marker-based motion capture systems (MoCap) and inertial measurement unit (IMU)-based systems are commonly used as standard methodologies [10], [14]. While marker-based MoCap are considered the gold standard for gait analysis, they have notable limitations, including high operational costs, time-intensive setup procedures and operator-dependent technical requirements requiring specialized expertise [10]. IMU-based gait analysis systems offer distinct advantages over traditional MoCap, notably eliminating the need for extensive external infrastructure and allowing real-world gait assessment in ecological settings [14], [15]. However,

* Corresponding author: Chang-Yoon Baek, Department of Rehabilitation Center, National Health Insurance Ilsan Hospital, Ilsan, Republic of Korea, Graduate School of Sports Medicine, CHA University, Gyeonggi-do, Republic of Korea e-mail: nhimc504359@naver.com

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these systems still face persistent challenges, such as the need for strict sensor placement protocols, meticulous calibration procedures, and susceptibility to signal degradation in environments with ferromagnetic materials or electromagnetic interference [15]. As a result, smartphone- and webcam-based analytical methods are being actively explored as alternatives to both traditional MoCap and IMU-based systems [9], [20], [28], [33]. Webcam-based systems offer substantial advantages as low-cost solutions, with operational simplicity, a high level of agreement with conventional systems, and good-to-excellent reliability [4], [32], [33]. The integration of artificial intelligence (AI)-driven computational platforms into webcam-based systems provides two major advantages: (1) enhanced analytical capabilities for detailed spatiotemporal parameter extraction and (2) improved measurement accuracy through automated pattern recognition algorithms [16], [23]. Previous study demonstrated that machine learning-enhanced webcam systems achieve substantial to near-perfect reliability (intraclass correlation coefficients [ICC] ranging from 0.64 to 0.95) in hip joint angle assessments, offering performance comparable to optical MoCap technologies [35]. Furthermore, the COVID-19 pandemic has accelerated interest in tele-assessment modalities, with webcam-based systems gaining prominence due to their cost-effectiveness and reduced accessibility barriers compared to traditional MoCap technologies [21, 35].

Analysis of lower-limb joint kinematics in the sagittal plane during gait provides critical insights into locomotor asymmetry and limitations in joint mobility [31]. Moreover, sagittal plane analysis offers superior measurement repeatability compared to frontal or transverse plane evaluations, establishing it as a key component in clinical decision-making protocols derived from gait assessments [26]. Although prior studies have compared three-dimensional (3D) MoCap and webcam-based systems for analyzing lower extremity joint angles during gait, few have evaluated these systems against IMU-based systems. Furthermore, there remains a lack of studies thoroughly assessing the reliability and concurrent validity of webcam-based methods for measuring sagittal plane hip and knee joint kinematics during the swing phase of gait. Therefore, the aim of this study is to investigate the potential of webcam-based systems as a viable alternative to traditional IMU-based systems for quantifying lower-limb joint kinematics during the swing phase of human gait. These approaches have the potential to produce clinically actionable data comparable to conventional systems, potentially transforming gait evaluation frameworks by enhancing global accessibility and enabling innovative remote assessment and monitoring solutions.

2. Materials and methods

2.1. Participants

Twenty-one healthy adult volunteers were prospectively recruited. Inclusion criteria were defined as adults aged 19–50 years, with exclusion criteria encompassing a history of musculoskeletal surgery affecting ambulatory function, neurological impairments, and cognitive deficits that may compromise comprehension or communication during experimental protocols. Among the recruited participants, three individuals withdrew due to inability to complete the experimental protocol, and three were excluded owing to data loss, resulting in a final analytical cohort of 15 participants (6 males, 9 females). After receiving detailed verbal and written disclosures regarding the study's purpose, all participants formally documented their consent through signed agreements. The study protocol received approval from the Institutional Review Board of Korea University (IRB No. KUIRB-2024-0108) and was conducted in accordance with the Declaration of Helsinki, ensuring ethical compliance for human subject research.

The sample size for this study was determined using a sample size calculator, incorporating a 20% attrition rate, which yielded a minimum required enrollment of 20 participants [3]. For sample size calculation, based on previous studies, the minimum acceptable reliability (ICC) of $\rho_0 = 0.64$, an expected reliability (ICC) of $\rho_1 = 0.90$, a significance level (α) of 0.05, and a power ($1 - \beta$) of 90% were set [31], [35].

2.2. Experimental setup

2.2.1. Inertial measurement unit

An IMU was used for gait analysis (Xsens MTw Awinda, Movella, Inc., Henderson, NV, USA). Each sensor incorporated a 3-axis accelerometer, 3-axis magnetometer and 3-axis gyroscope [12]. The sensors, measuring 47 mm × 30 mm × 13 mm and weighing 16 g, were attached to the pelvis and both lower limbs (bilateral thighs, shanks, and feet) according to the standard Xsens gait protocol [11] (Table S1).

2.2.2. Webcam-based motion capture system

A webcam-based MoCap was employed (4DEYE, SYM Healthcare, Inc., Seoul, South Korea). The system

includes five red-green-blue (RGB) sensor webcams (HD20, Joytron, Seoul, South Korea) and a custom analysis program based on the open source computer vision (OpenCV) library for image analysis [1], [5]. For motion analysis, 27 landmarks of the human body are automatically recognized in images captured at 12 Hz by five cameras, and the 3D coordinates of the landmarks are tracked in real time (Table S2). Based on the defined landmarks, the analysis program created a skeleton model and calculate each joint and joint angle in real time (Fig. 1). Hip flexion/extension is defined as the femoral shaft relative to the trunk, and knee flexion/extension is defined as the angle between the femoral and tibial shafts [22].

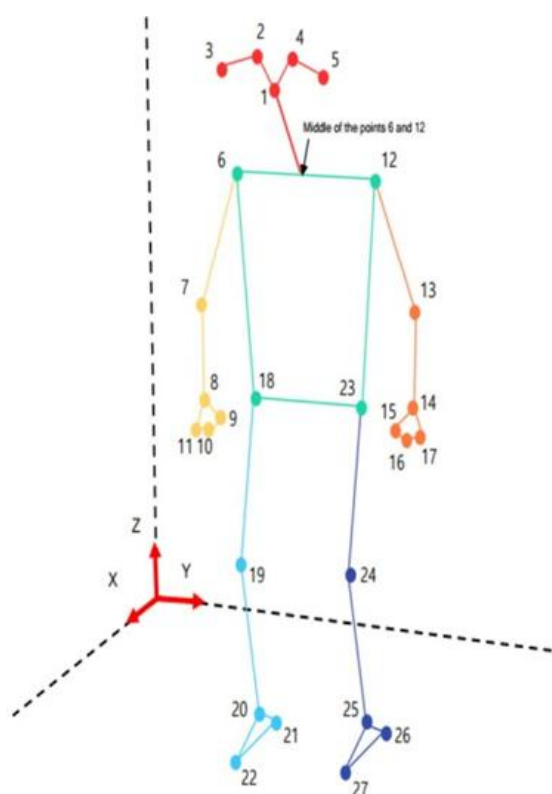


Fig. 1. Skeleton model of 4DEYE with 27 landmarks.
27 landmarks for calculating each joint and joint angle in real time

2.3. Procedures

Gait analysis was conducted in a dedicated space measuring 315 cm in length and 90 cm in width. The webcam-based MoCap was positioned at the end of the walking path. Participants wore IMU sensors on seven body regions and stood in a neutral position at the starting point for system calibration. Upon hearing a verbal cue, participants began walking with their right foot and proceeded at a self-selected, comfortable pace along the 3-meter walkway. Each participant completed three

trials: the first served as a practice trial for adaptation, and the second and third trials were used for data collection (Fig. 2).

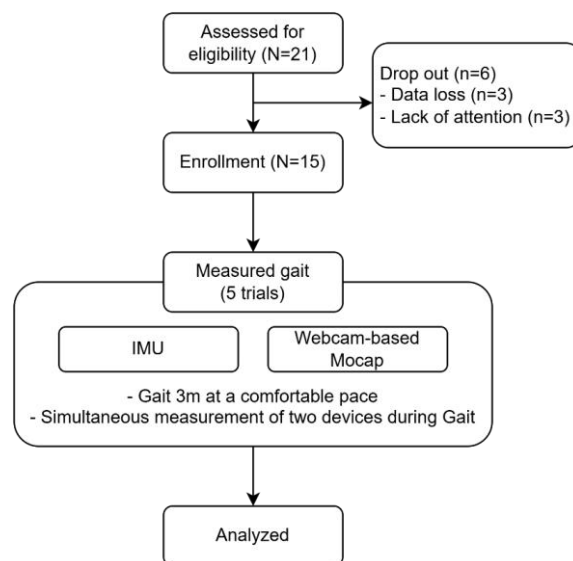


Fig. 2. Flowchart of study process

2.4. Data processing

During gait trials, both the IMU and webcam-based MoCap recorded sagittal plane hip and knee joint angles using their respective proprietary software. Each system provided real-time visualization of landmark positions and joint angles, eliminating the need for post-processing or manual data modification. To isolate the swing phase, toe off was defined by the minimum hip flexion angle, and heel strike by the maximum hip flexion angle. At each event, the corresponding hip and knee joint angles, as well as the total joint excursion during the swing phase, were extracted and compared between the two systems.

2.5. Statistical analysis

ICC and 95% confidence intervals (CIs) were used for inter-rater reliability (ICC 3,k) and intra-trial reliability (ICC 3,1) between IMU and webcam-based MoCap. The ICC value uses the six-level nomenclature suggested by Landis and Koch: poor agreement ≤ 0.00 ; slight agreement = 0.00 to 0.20; fair agreement = 0.21 to 0.40; moderate agreement = 0.41 to 0.60; substantial agreement = 0.61 to 0.80 and almost perfect agreement = 0.81 to 1.00 [19].

The Bland–Altman analysis was utilized to assess the agreement between the two devices for hip and knee

joint angles and joint excursion during the swing phase at toe off and heel strike. For analysis, the differences in mean, standard deviation, and 95% limits of agreement between IMU and webcam-based motion capture are calculated [24].

The demographic details and joint angle data used in this study were expressed as mean and standard deviation. All statistical analyses were performed using PASW statistics 18 (SPSS, Inc., Quarry Bay, Hong Kong), and $p < 0.05$ was considered statistically significant.

3. Results

Data were collected from a total of 15 subjects, consisting of 6 males and 9 females. The mean age was 28.1 ± 5.26 years, the mean height was 170.5 ± 9.13 cm, the

mean weight was 69.4 ± 12.96 kg, and the mean body mass index was 20.9 ± 9.16 kg/m².

Inter-rater reliability demonstrated moderate agreement (ICC = 0.466–0.578) between the hip joint angle at toe off and heel strike, and the knee joint excursion angle during the swing phase. Additionally, the knee joint angle and hip joint excursion angle in toe off and heel strike showed substantial agreement (ICC = 0.620–0.696) (Table 1).

The mean of the differences between the two measurements showed a hip joint angle of 0.35 degree, knee joint angle of 0.45 degree at toe off, and hip joint angle of 1.45 degree, knee joint angle of 5.61 degree at heel strike. In the swing phase, excursion was shown as hip joint angle 1.79 degree and knee joint angle 0.36 degree. In Bland–Altman plots, the limit of agreement for hip and knee angles was shown to be hip joint angle 2.72 to –3.42 degree and knee joint angle 3.7 to –4.61 de-

Table 1. Inter-rater reliability between the IMU and webcam-based mocap

	Angle [°]		ICC (2, k)	95% CI	SEM [°]
	IMU	Webcam-based mocap			
Hip					
Toe off	1.33 ± 1.78 (133.8%)	1.67 ± 0.61 (36.5%)	0.466*	−0.121–0.746	1.11
Heel strike	28.15 ± 4.06 (14.4%)	26.71 ± 4.61 (17.3%)	0.578*	0.113–0.799	3.35
Excursion	26.82 ± 4.8 (17.9%)	25.03 ± 4.56 (18.2%)	0.696**	0.360–0.855	3.20
Knee					
Toe off	2.9 ± 2.32 (80.0%)	3.35 ± 1.72 (51.3%)	0.629**	0.220–0.823	1.50
Heel strike	−1.87 ± 3.6 (192.5%)	3.73 ± 2.03 (54.4%)	0.620**	0.202–0.819	2.17
Excursion	62.52 ± 3.38 (5.4%)	62.88 ± 4.72 (7.5%)	0.503*	−0.044–0.764	3.34

* $p < 0.05$, ** $p < 0.01$. Values are presented as mean $\pm$ SD (CV%). ICC – intraclass correlation coefficient, CI – confidence interval, SEM – standard error of measurement.

Table 2. Intra-trial reliability of the IMU and webcam-based mocap

	Measurement	Angle [°]		ICC (3, 1)	95% CI	SEM [°]
		Trial 1	Trial 2			
Hip						
Toe off	IMU	1.46 ± 1.82 (124.66%)	1.19 ± 1.78 (149.58%)	0.635*	−0.087–0.877	1.32
	Webcam-based mocap	1.55 ± 0.38 (24.52%)	1.79 ± 0.76 (42.46%)	0.652*	−0.037–0.883	0.43
Heel strike	IMU	28.42 ± 4.33 (15.23%)	27.88 ± 3.89 (13.95%)	0.837**	0.516–0.945	2.18
	Webcam-based mocap	26.18 ± 4.52 (17.27%)	27.23 ± 4.80 (17.63%)	0.663*	−0.004–0.887	3.31
Excursion	IMU	26.96 ± 5.39 (19.99%)	26.69 ± 4.32 (16.19%)	0.848**	0.548–0.949	2.51
	Webcam-based mocap	24.63 ± 4.55 (18.47%)	25.44 ± 4.69 (18.43%)	0.668*	0.011–0.889	3.26

Table 2 continued

Knee						
Toe off	IMU	2.90 ± 2.29 (79.00%)	2.90 ± 2.42 (83.45%)	0.918**	0.755–0.972	0.92
	Webcam-based mocap	3.22 ± 1.54 (47.83%)	3.47 ± 1.92 (55.33%)	0.696*	0.094–0.898	1.19
Heel strike	IMU	−1.58 ± 3.89 (246.20%)	−2.17 ± 3.40 (156.68%)	0.912**	0.739–0.971	1.47
	Webcam-based mocap	3.72 ± 1.89 (50.81%)	3.74 ± 2.23 (59.63%)	0.697*	0.097–0.898	1.41
Excursion	IMU	62.23 ± 3.43 (5.51%)	62.80 ± 3.42 (5.44%)	0.799**	0.401–0.933	1.98
	Webcam-based mocap	62.65 ± 3.98 (6.36%)	63.11 ± 5.49 (8.70%)	0.838**	0.519–0.946	2.53

* $p < 0.05$, ** $p < 0.01$. Values are presented as mean ± SD (CV%). ICC – intraclass correlation coefficient, CI – confidence interval, SEM – standard error of measurement.

gree at toe off, and hip joint angle 10.72 to −7.83 degree and knee joint angle 0.41 to −11.62 degree at heel strike. In the swing phase, excursion showed hip joint angle of 10.66 to −7.08 degree and knee joint angle of 8.9 to −9.63 degree (Fig. 3).

Intra-trial reliability showed substantial agreement (ICC = 0.635–0.799) between the hip joint angle at toe off and the knee joint excursion angle during the swing phase in the IMU. Additionally, almost perfect agreement (ICC = 0.837–0.918) was shown in the knee joint angle at toe off, hip joint angle and knee joint angle at heel strike, and hip joint excursion angle during the swing phase (Table 2).

Webcam-based MoCap showed substantial agreement (ICC = 0.652–0.697) in hip and knee joint angles during toe off and heel strike. In the swing phase, the knee joint excursion angle showed almost perfect agreement (ICC = 0.838) (Table 2).

4. Discussion

This study aimed to evaluate the intra- and inter-trial reliability of IMU and webcam-based MoCap, as well as the agreement between the two devices. The hip and knee joint angles at toe off and heel strike during the swing phase of gait were measured in the sagittal plane. The results demonstrated that both systems achieved acceptable levels of reliability; however, variations were observed depending on the measurement phase and specific joint assessed.

Intra-trial reliability within each system was notably higher for the IMU-based system. Most measurements exceeded an ICC value of 0.80, indicating almost per-

fect reliability, particularly for knee joint angles at toe off and heel strike, where ICC values exceeded 0.90. These findings align with previous reports; for example, Cho et al. reported nearly perfect intra-rater reliability (ICC = 0.998) when using IMUs to assess sagittal plane hip and knee angles during gait in healthy adults [8]. IMUs have also shown excellent reliability (ICC = 0.80–0.98) compared to camera-based 3D MoCap, which are considered the gold standard, supporting their suitability for both clinical and real-world applications [14], [17]. Additionally, the ICC values for hip and knee joint angles at heel strike and toe off reported in optical MoCap study (ICC = 0.814–0.880) were comparable to the reliability levels of the IMU observed in the present study [27]. These findings, consistent with prior research, demonstrate that the intra-trial reliability of the IMU is sufficient to serve as a reference standard. The webcam-based MoCap, although slightly less consistent, still demonstrated substantial to near-perfect reliability (ICC = 0.652–0.838). A previous study found moderate to high reliability (ICC = 0.773–0.918) for hip and knee joint angles measured by webcam-based MoCap during a standing squat task [22]. This study shows lower reliability in comparison to earlier research. The reduced accuracy of the analysis is attributed to two primary factors: visual occlusion resulting from the crossing of the lower extremities during dynamic tasks such as gait, and geometric distortion that occurs when converting a 2D image captured by the webcam into a 3D representation [18], [36]. Inter-rater reliability between the IMU and webcam-based MoCap was generally moderate to substantial agreement (ICC = 0.466–0.696), indicating acceptable consistency between the two systems for comparative gait analysis.

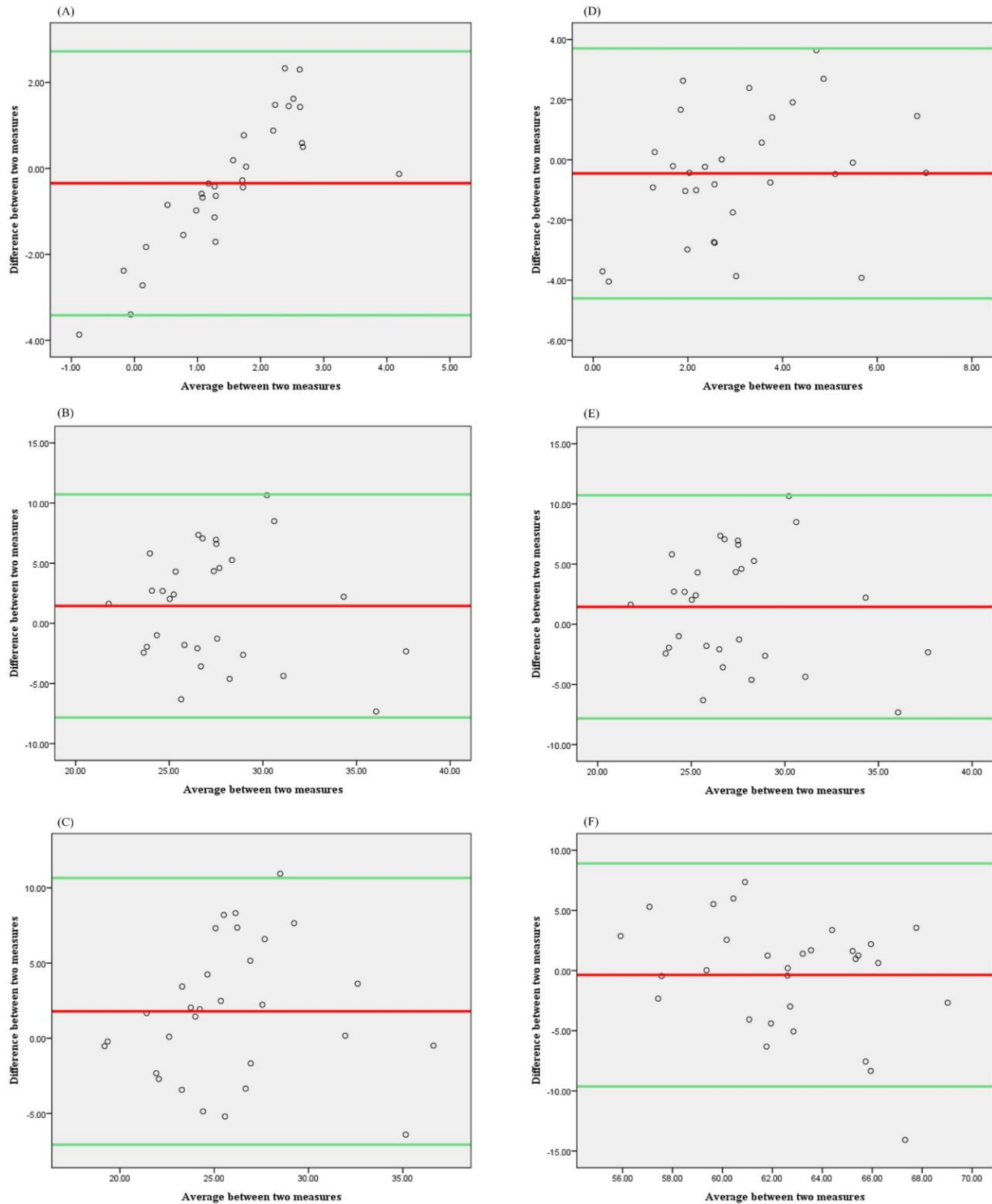


Fig. 3. Bland–Altman plots. The red line in the middle indicates the mean of differences, and the upper and lower green line show 95% limit of agreement (mean of differences ± 1.96 standard deviations of the difference): (A) to (C) represent hip joint angles, (D) to (F) represent knee joint angles. (A) and (D) represent toe off, (B) and (E) represent heel strike, (C) and (F) represent joint excursion angles

Other low-cost motion capture technologies, such as 3D markerless MoCap and virtual reality-based systems, are available as potential alternatives; however, consistent biases in hip and knee joint angles, discrepancies in peak values due to direct kinematic compu-

tation, and limitations in pose estimation, restricted field of view, and surface-based depth estimation can collectively reduce their reliability for gait analysis [10], [37]. In contrast, the webcam-based MoCap demonstrated substantial to near-perfect reliability (ICC =

0.652–0.838) without requiring complex calibration or costly hardware, indicating its practicality and suitability for basic clinical gait assessment. Given its comparable reliability and ease of implementation, the webcam-based MoCap may serve as a viable alternative to IMU-based systems, particularly in environments constrained by cost, accessibility, or setup limitations.

Bland–Altman plots were additionally used to assess the agreement between the IMU and webcam-based MoCap. The mean differences between the two devices were generally minimal, typically less than 2 degrees. However, there was a notable exception with the knee joint angle at heel strike, which exceeded 5 degrees. The limits of agreement (LOA) for the hip and knee joint angles at toe off remained low, under 5 degrees. Conversely, the LOA for both joints was widely dispersed, exceeding 10 degrees at heel strike and during swing phase excursion angles. In 3D gait analysis, the acceptable range of error for joint angles is 2 to 5 degrees. Errors exceeding 5 degrees may lead to misleading clinical interpretations [25]. In this study, the discrepancies between the two measurement methods were predominantly less than 2 degrees, suggesting that webcam-based MoCap can serve as a suitable alternative to IMU. Nevertheless, to establish a wider LOA, future research should focus on evaluating the algorithmic corrections and frame rates associated with webcam-based MoCap.

Overall, the IMU demonstrated superior intra-trial reliability, while the webcam-based system also provided sufficiently reliable performance, particularly for measuring joint excursions. These findings support the growing viability of low-cost, accessible MoCap technologies in clinical and research settings, while also emphasizing the need for careful consideration of measurement context and intended use.

Several limitations should be considered in this study. First, the relatively small sample size may limit the generalizability of the findings. Second, the experiments were conducted under controlled laboratory conditions, and reliability may differ in real-world clinical or daily living environments. Third, the webcam-based system relies on 2D video analysis, which may lack depth information necessary for accurately capturing complex 3D joint movements. Fourth, the relatively low frame rate of the webcam-based system may have led to slight phase-shift errors or underestimation of peak joint excursions at specific gait events. However, the use of multiple cameras and high-resolution video helped to enhance landmark tracking stability, thereby minimizing these effects. Moreover, given the moderate to substantial agreement observed between the two measurement systems, the webcam-based approach appears to pro-

vide sufficiently accurate data for clinical assessment or gait screening purposes. Fifth, although presenting mean joint angle–time curves with standard deviations over the gait cycle is generally informative, this visualization was omitted from the results. This decision was due to the different frame rates and independent internal clocks of the two measurement systems, which rendered direct temporal alignment unreliable. Consequently, an event-based analysis focusing on specific gait events (toe off and heel strike) and excursion angles was adopted as a more robust and system-independent approach. Lastly, the absence of validation across diverse populations, such as older adults and individuals with disabilities, necessitates caution in broadly applying these results.

Future studies should focus on optimizing webcam-based tracking algorithms to improve event detection, evaluating reliability across diverse populations and movement tasks, and further validating these technologies against gold-standard marker-based 3D optical MoCap.

5. Conclusions

This study demonstrated that both IMU and webcam-based MoCap offer acceptable reliability for measuring sagittal plane hip and knee joint angles during gait, particularly at toe off and heel strike. The IMU-based system showed superior intra-trial reliability and can be considered a reference standard. Despite slightly lower consistency, the webcam-based system also achieved substantial reliability and showed promise as an accessible alternative, especially in resource-limited settings. However, limitations such as small sample size, controlled environment, and 2D data constraints should be considered. Future research should aim to enhance algorithmic accuracy, validate performance across diverse populations, and compare findings with gold-standard 3D optical systems.

Availability of data and materials

In accordance with the conditions set by the ethics committee, the data collected in this study are not available for sharing with third parties.

Authors' contributions

Conceptualization, C.Y.B. and J.H.A.; Method, H.K.P.; Software, H.K.P.; Validation, C.Y.B. and J.H.A.; Formal analysis, H.K.P.;

Investigation, H.K.P. and C.Y.B.; Resources, J.H.A.; Data curation, H.K.P.; Writing – original draft preparation, H.K.P.; Writing – review and editing, C.Y.B. and J.H.A.; Visualization, H.K.P.; Supervision, C.Y.B. and J.H.A.; Project administration, C.Y.B. and J.H.A. All authors have read and agreed to the published version of the manuscript.

Conflict of interests

The authors declare no conflict of interest.

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Supplement

Table S1. Location of IMU sensor

Location	Optimal position
Pelvis	Flat on sacrum
Upper leg	Lateral side above knee
Lower leg	Flat on the shin bone (medial surface of the tibia)
Foot	Middle of bridge of foot

Table S2. Landmarks of the human body

Number	Landmark
1	Nose
2	Right side eyes
3	Right side ears
4	Left side eyes
5	Left side ears
6	Center of shoulder joint on the right side
7	Center of elbow joint on the right side
8	Center of wrist joint on the right side
9	Right side metacarpal I
10	Right side metacarpal II
11	Right side metacarpal V
12	Center of shoulder joint on the left side
13	Center of elbow joint on the left side
14	Center of wrist joint on the left side
15	Left side metacarpal I
16	Left side metacarpal II
17	Left side metacarpal V
18	Center of hip joint on the right side
19	Center of knee joint on the right side
20	Center of ankle joint on the right side
21	Right foot heel
22	Right foot toe
23	Center of hip joint on the left side
24	Center of knee joint on the left side
25	Center of ankle joint on the left side
26	Left foot heel
27	Left foot toe