KINEMATICS COMPARISON OF OPENCAP AND IMU WITH MARKER-BASED MOTION CAPTURE IN TREADMILL RUNNING: A PILOT STUDY

Muhammad Nur Shahril Iskandar[1], Phillis Soek Po Teng[1*]

Physical Education and Sports Science Academic Group National Institute of Education, Nanyang Technological University, Singapore[1]

The purpose of this pilot study was to compare lower-limb running kinematics measured using a markerless system, OpenCap, and inertial measurement units (IMUs) against the marker-based motion capture (mocap) system. One participant ran at 2.22 m/s on a treadmill for one minute. Mean absolute error (MAE) and root mean square error (RMSE) of hip, knee, and ankle flexion were calculated independently for all 3 devices. Time synchronization of devices was facilitated by performing a 'kick' and identifying its peak knee angle prior to running. Offset correction was also applied to OpenCap and IMUs data to match those of marker-based mocap data at the start of time synchronization. OpenCap exhibited a higher degree of error than IMUs in all joint angles compared to marker-based mocap both before and after an offset correction was applied, with errors exceeding 10°.

KEYWORDS: markerless, gait analysis, joint angles, accuracy

INTRODUCTION: Gait analysis provides critical insights into pathological movement patterns associated with various neurological, musculoskeletal, and other disorders. While observational assessments offer valuable qualitative perspectives, instrumented motion analysis enables more precise quantitative measurements of kinematics and kinetics - critical for diagnosis and treatment planning. However, specialized equipment required for such analysis tends to be expensive and constrained to laboratory settings, limiting accessibility and generalizability to practitioners.
Recent advancements in markerless motion capture (mocap) technology, such as OpenCap, aim to address these barriers. OpenCap utilizes pose-estimation algorithms and muscle-driven simulations to estimate 3D movement kinematics and kinetics through a web-based platform (Uhlrich et al., 2023). Initial validation shows that its accuracy is comparable to other markerless systems and inertial measurement units (IMUs) for walking, squatting, and other movements. However, it remains unclear whether OpenCap retains the accuracy in faster dynamic motions like running. This pilot study's primary aim was to assess the accuracy of OpenCap in analyzing treadmill running kinematics. IMUs were also used to provide an additional basis for comparison. The results will inform practitioners of its appropriate usage to obtain kinematic data in running gait analysis.

METHODS: This study was approved by the Nanyang Technological University Institutional Review Board (IRB-2023-1013). One healthy 27-year-old male participant (height: 159.8 cm; body mass: 56.5 kg) provided informed consent and participated in this study.
The participant performed a single treadmill (h/p cosmos saturn®) running session, while an 8-camera marker-based mocap system (Vicon MX T-Series, Vicon Motion Systems Ltd, UK, 200 Hz), 6 wireless IMUs (Noraxon, USA, 100 Hz), and 2 iOS devices (iPhone 13 and iPad 9, 60Hz) were simultaneously recorded. Reflective markers were placed on anatomical landmarks (anterior/posterior superior iliac spine, lateral/medial epicondyle, lateral/medial malleolus, 2nd metatarsal head, heel), while IMUs were attached to the pelvis and bilaterally on the thigh, shank, and foot segments using velcro straps. A static standing trial was collected to calibrate IMUs orientations. For the OpenCap system (version 1.6), the rear cameras of the 2 iOS devices were positioned in front facing the participant and about 45° to each side of the treadmill. Calibration was performed using a 210 mm × 175 mm checkerboard. Another static trial, where the participant stood in a neutral pose, was collected for model calibration used in OpenCap.

Data collection: The participant stood by the side of the treadmill while recording started on all devices. This ensures the participant was seen in the marker-based mocap and OpenCap cameras. The participant then performed a ‘’kick’ where the right knee was extended and flexed rapidly, to facilitate the time synchronization of all devices by utilizing the peak knee kinematics. Subsequently, the participant immediately stepped onto the treadmill and ran at a self-selected speed for 1 minute. Kinematics data from the marker-based mocap system were obtained using inverse kinematics in OpenSim with the same musculoskeletal model used in OpenCap. IMUs kinematics data were derived from the commercial MyoRESEARCH software (version 3.2, Noraxon, USA). Marker-based and IMUs data were low-pass filtered (12 Hz, 4th order Butterworth) and downsampled to 60 Hz to match OpenCap’s default setting. Kinematic analysis of the hip, knee, and ankle flexion was compared using mean absolute error (MAE) and root mean square error (RMSE) between IMUs and OpenCap with the criterion marker-based mocap system without segmenting individual gait cycles to avoid introducing additional errors. Additionally, a systematic offset correction was applied to IMUs and OpenCap by aligning their values at time synchronization with the marker-based mocap system. For example, if there is a +2° deviation in IMU data compared to marker-based data at time synchronization, applying a systematic offset involves adjusting the IMU data by -2° throughout the time series.

RESULTS: The participant ran a self-selected speed of 2.22 m/s. The accuracy analysis revealed substantial differences between the IMUs and OpenCap when compared to the marker-based mocap system, with OpenCap showing greater error overall (Table 1) both before and after offset correction. IMU errors improved considerably compared to OpenCap after applying the offset correction. However, the offset correction impacted OpenCap minimally while substantially increasing right ankle flexion error.

Table 1: Comparison of MAE and RMSE values between IMUs and OpenCap with a marker-based mocap system. Bold values indicate a lower error comparing IMU and OpenCap.

	MAE (°)		**RMSE (°)**	
	Before	After	Before	After
IMUs				
Left				
Hip flexion	**19.3**	**9.1**	**20.7**	**11.5**
Knee flexion	**3.2**	**4.4**	**3.9**	**5.3**
Ankle flexion	**4.3**	**2.4**	**5.1**	**3.1**
Right				
Hip flexion	24.3	**6.1**	25.4	**7.8**
Knee flexion	**5.4**	**5.1**	**6.9**	**6.3**
Ankle flexion	**10.9**	**8.1**	**11.6**	**8.9**
Overall	**11.2**	**5.9**	**12.3**	**7.2**
OpenCap				
Left				
Hip flexion	21.1	13.6	23.6	16.0
Knee flexion	14.0	12.0	17.3	14.3
Ankle flexion	14.8	20.1	17.6	23.9
Right				
Hip flexion	**20.4**	11.3	**22.9**	13.5
Knee flexion	15.7	13.4	19.0	16.0
Ankle flexion	18.0	29.1	21.6	33.7
Overall	17.3	16.6	20.3	19.6

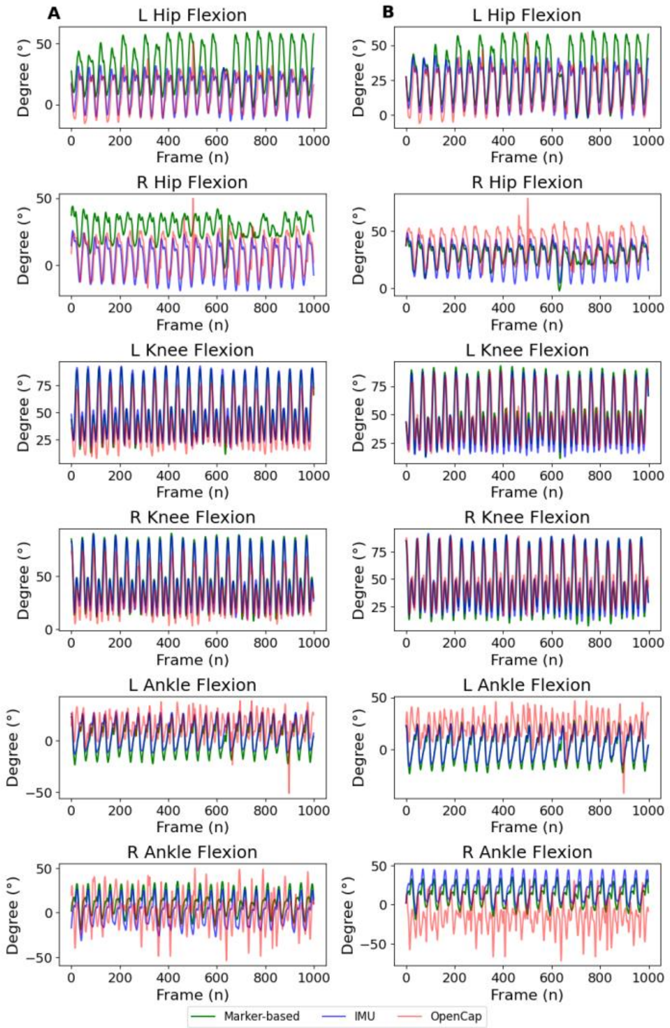

Figure 1: The kinematic waveforms of lower-limb kinematics in the first 1000 frames comparing marker-based mocap, IMU, and OpenCap (A) before offset, and (B) after offset correction.

DISCUSSION: This study aimed to compare the lower-limb running kinematics obtained from marker-based mocap, IMUs, and the markerless system, OpenCap. The key findings revealed that using OpenCap and IMUs to obtain accurate running kinematics remains challenging.

Prior to any offset correction, the IMUs demonstrated better accuracy than OpenCap in most joint angles compared to the marker-based mocap system. Nonetheless, both OpenCap and IMUs exhibited overall MAE exceeding 10° across several joint angles. Following the application of an an offset correction, the IMU's overall MAE was reduced to 5.9°, whereas OpenCap's overall MAE remained above 10°, greater than previously OpenCap validated movements in walking (Uhlrich et al., 2023). This level of inaccuracy may be unacceptable for clinical gait analysis applications.

Interestingly, the differences in left and right ankle angles derived from the IMUs were more than twice the magnitude of each other, possibly attributed to placement issues. However, the offset corrections seemed to resolve device alignment or placement issues, as evidenced by a dramatic reduction in the error ankle and hip flexion angle as well. This aligns with findings from other IMU study where offset correction substantially reduced the RMSE between 18°-28° to 5°-8° degrees (Nüesch et al., 2017) for all joint angles during treadmill running. This also supports previous IMU studies that sagittal plane kinematics had higher validity measurements compared to other planes (Park & Yoon, 2021).

Examining the kinematic waveforms revealed that knee flexion is the most consistent parameter in IMUs and OpenCap, with no random spikes observed as seen in hip and ankle

flexion (Figure 1). However, OpenCap's knee flexion errors were still greater than 10°, potentially limiting its suitability for clinical applications. In addition, the offset corrections had a negligible impact on OpenCap's accuracy. In fact, the right ankle flexion angle error increased markedly after the offset correction, clearly showing that the kinematic waveform was off throughout when compared with both the marker-based mocap system and IMUs. A potential source of error includes suboptimal calibration procedures which could have affected the data unknowingly as there is no way for users to verify the model post-calibration prior to data collection. While users can troubleshoot by reprocessing their data locally, such issues can only be discerned after data collection. Additionally, some programming skills are required to navigate the OpenCap application locally. Given that OpenCap was designed to democratize gait analysis use for practitioners, this could limit the practicality for practitioners.
Some potential sources of error and limitations that could have affected the measurements in this study should be addressed. First, the camera positioning could be suboptimal. While Uhlrich et. al (2023) found no major improvements with multiple cameras in walking analysis, future research should evaluate if this applies to running analysis. Second, time synchronization relied on identifying peak knee flexion at the start of data collection. Our preliminary analysis revealed that it was superior compared to utilizing foot-related marker positioning data. As presented earlier, the OpenCap ankle kinematics were indeed off while the knee kinematics was the most stable. However, it is acknowledged that more robust synchronization procedures could reduce timing errors. Additionally, this pilot study focuses only on sagittal plane kinematics. Further validation could include other kinematics such as hip adduction and rotation to determine if OpenCap is a feasible method for assessment as well.
To our knowledge, this is the first study examining OpenCap accuracy for running. As a case study, it highlights substantially greater errors compared to walking when recording at 60 Hz and utilizing 2 cameras. Future studies on running are recommended to utilize more cameras, vary the camera heights to reduce occlusion-related errors, and include participants running at different speeds to validate the accuracy across various velocities. Researchers could also explore recording at 120 Hz but should be mindful of the limited recording duration of 30 seconds. A potential exploration would also be to utilize fusion sensor algorithms by combining markerless motion capture data with IMUs data as initial evidence has shown a considerable improvement in the joint centers and kinematics accuracy (Pearl et al., 2023).

CONCLUSION: Overall, both systems demonstrate challenges in analyzing running kinematics. While OpenCap shows promise as an accessible gait analysis tool, the findings suggest it would benefit from further refinement and optimization to match the marker-based mocap system. Additional validation across a range of movements, subjects, and environments could provide a clearer understanding of its suitable applications. Markerless video solutions like OpenCap have immense potential for democratization but likely need improvement for robust clinical implementation in high-speed running.

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ACKNOWLEDGEMENTS: This research / project is supported by the National Institute of Education, Singapore, under its Academic Research Fund (RI 3/22 PT). Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not reflect the views of the National Institute of Education, Singapore.