Accuracy of IMU-Based Upper-Extremity Kinematics During the Barbell Upright Row

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Abstract

Wearable inertial measurement units (IMUs) are a portable alternative to optical motion capture for monitoring joint kinematics in training, but their accuracy for upper-extremity resistance exercises is not well established. Elbow flexion and shoulder adduction during the barbell upright row were estimated from low-cost IMUs (WT901C, 10 Hz) with OpenSense and compared with eight-camera optical motion capture processed in OpenSim. In a preliminary study (n = 2), the forearm IMU was placed at distal, middle, and proximal locations. RMSE was 9.2–21.9° for elbow flexion and 8.7–18.4° for shoulder adduction, so no condition met the 5° criterion. Errors arose mainly from calibration offsets and an underestimated elbow range of motion. The middle forearm location gave the lowest error, and initial guidelines for IMU use are proposed.

Keywords: IMU, OpenSense, OpenSim, upright row, upper-extremity kinematics, sensor placement.

Introduction

Indonesia's Grand Design of National Sports (Presidential Regulation No. 86/2021) calls for measurable, evidence-based athlete development. Accurate joint kinematics allow training decisions to rest on objective data rather than on visual observation alone.

Marker-based optical motion capture with OpenSim musculoskeletal modeling is the reference standard, but it is confined to the laboratory. Wearable IMUs can be used in the training environment, yet their joint angles are affected by gyroscope drift, magnetic disturbance, sensor placement, and sensor-to-segment calibration.

IMU validity is well documented for gait, but the multiaxial shoulder makes the upper extremity more challenging. OpenSense computes IMU-based joint angles with the same model definitions as marker-based OpenSim analysis, but it was validated mainly for the lower extremity, and the effect of sensor placement on the same segment remains unclear.

The barbell upright row involves large shoulder elevation and internal rotation and is linked to a risk of subacromial impingement. Its steel barbell, held close to the forearm sensor, adds realistic magnetic disturbance, making the exercise a demanding test case.

Objectives. This study aims to:

1. quantify the accuracy of OpenSense-based upper-extremity kinematics during the upright row against optical motion capture;
2. explore the sensitivity of the error to forearm IMU placement; and
3. derive initial guidelines for IMU use in training settings.

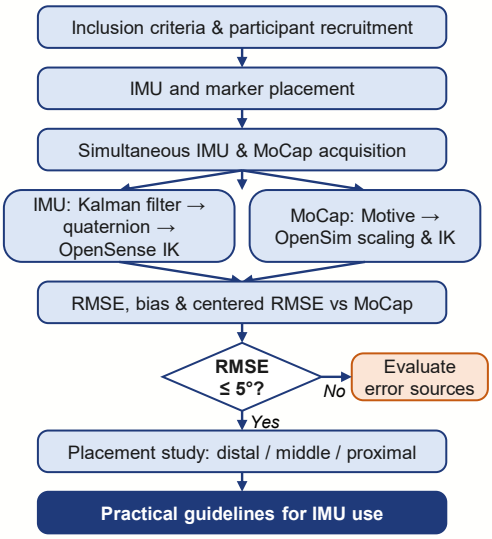
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Research Method

Participants. Ten healthy males (19–25 years, normal BMI, >6 months of resistance training) gave written informed consent.

Instrumentation. Three WitMotion WT901C 9-axis IMUs, each with its own microcontroller, microSD logger, and Li-Po battery, recorded at 10 Hz on the sternum, lateral distal humerus, and dorsal distal forearm. An eight-camera OptiTrack system with a Helen Hayes–based marker set provided the reference.

Protocol. After a static calibration pose, participants performed the barbell upright row (normal grip, 70% 1RM, one set), lifting until the upper arm reached shoulder level.

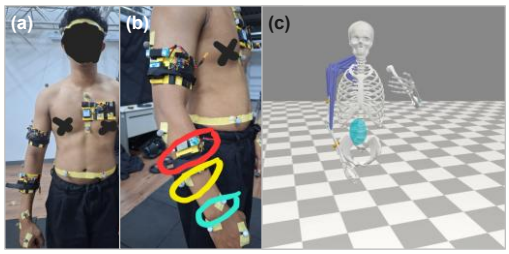


Picture 1. Research flow.

Processing. IMU orientations were corrected with a Kalman filter, converted to quaternions, and processed in OpenSense (sensor calibration and IMU inverse kinematics) with the Rajagopal model. Marker data were labeled in Motive, then scaled and solved with inverse kinematics in OpenSim using the same model.

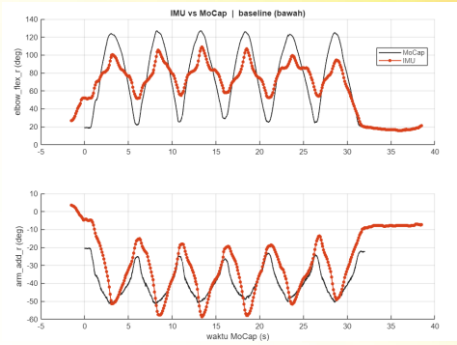
Analysis. Elbow flexion and shoulder adduction were compared over the movement window using RMSE, bias (mean IMU − MoCap), and centered RMSE (bias removed). The accuracy criterion was RMSE ≤ 5°.

Placement study. In two participants, the forearm IMU was moved to distal, middle, and proximal locations (Picture 2b), with recalibration at each location.



Picture 2. (a) IMU and marker setup; (b) forearm IMU locations: proximal (red), middle (yellow), distal (cyan); (c) OpenSense model.

Discussion & Result

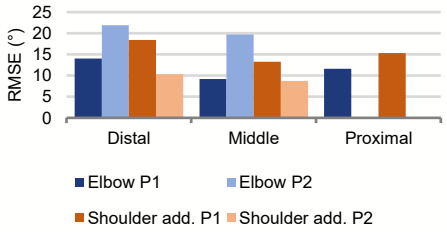


Picture 3. IMU (red) vs MoCap (black) for participant P2, distal (baseline) placement.

Overall accuracy. No condition met the 5° criterion: RMSE was 9.2–21.9° for elbow flexion and 8.7–18.4° for shoulder adduction (Picture 4).

Error structure. The IMU underestimated elbow ROM (≈55° vs ≈100° in P2), an amplitude rather than offset error. Shoulder adduction showed a calibration-dependent offset (−2.7 to 15.8°) on top of a stable waveform error (centered RMSE 8.1–10.1°), suggesting crosstalk from sensor-to-segment misalignment.

Timing and magnetic effects. At 10 Hz, a one-sample (0.1 s) lag alone adds ≈4.4° of elbow RMSE. The steel barbell distorted 9-axis orientation, whereas 6-axis mode drifted in heading.



Picture 4. RMSE by forearm IMU location (P2 proximal excluded: synchronization error).

Placement. The middle location gave the lowest RMSE in both participants, consistent with a trade-off between magnetic disturbance near the barbell (distal) and soft-tissue artifact over the forearm muscles (proximal). With n = 2, this finding is preliminary.

Conclusion

The low-cost IMU–OpenSense setup did not yet reach the 5° accuracy needed to monitor the upright row. Initial recommendations:

1. place the forearm IMU at mid-forearm, away from the barbell;
2. match the model's default pose to the actual calibration posture;
3. increase the IMU rate and use a shared synchronization trigger;
4. prefer relative measures (e.g., ROM change) over absolute angles.

Future work will complete the full cohort and add shoulder flexion and rotation.