Real-time Open Source Kinematic Estimation with Wearable IMUs

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MOTIVATION

Aging Population and Rehabilitation Challenges

The global aging population increases healthcare demand, especially in rehabilitation. Traditional hospital-based rehab is inconvenient and time - consuming. Home - based rehab is a promising alternative, but real - time kinematic monitoring is difficult.

Significance of Human Kinematics Analysis

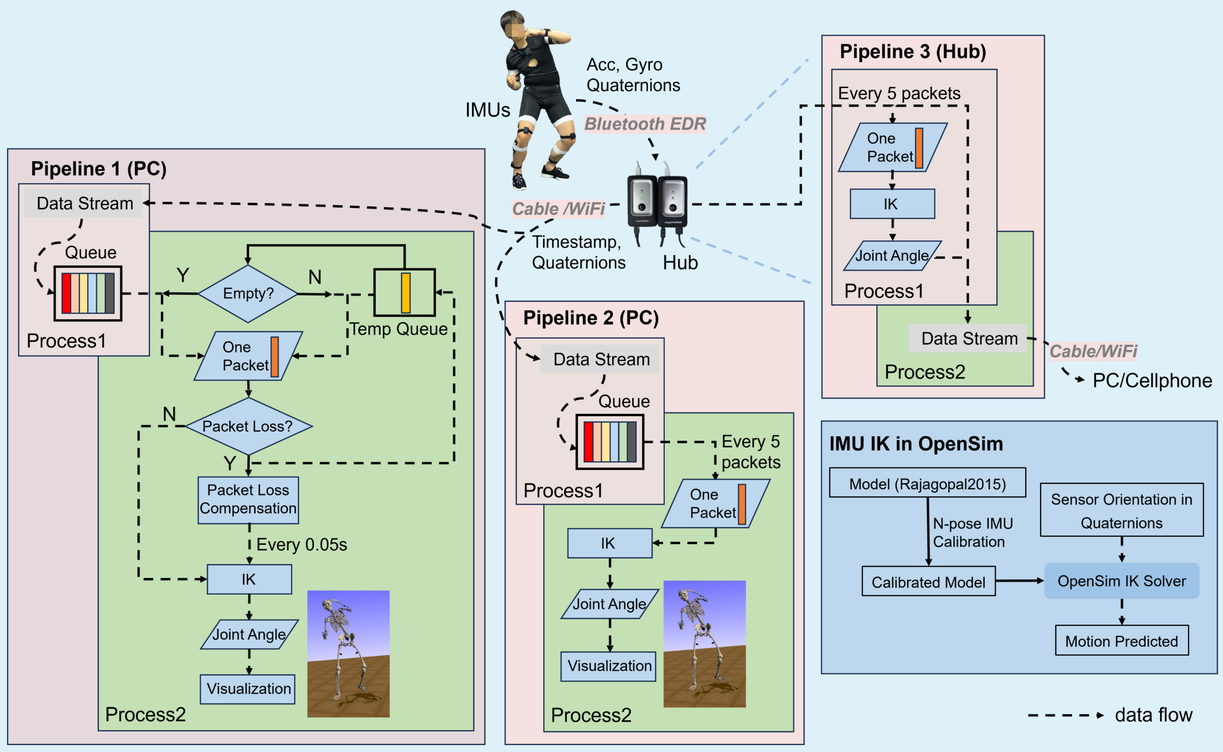
Essential in fields like human - computer interaction, ergonomics, and biomechanics. Crucial for diagnosing and studying diseases, especially useful for rehabilitation assessment of patients with musculoskeletal or neurological disorders.

Limitations of Optical Motion Capture (OMC) and Advantages of IMUs

OMC is the gold standard in biomechanics but is expensive, space - limited, and requires professional operation. Wearable IMUs are lightweight, portable, and affordable, suitable for home - based rehabilitation.

METHODS

Real-Time Kinematics Estimation Pipelines

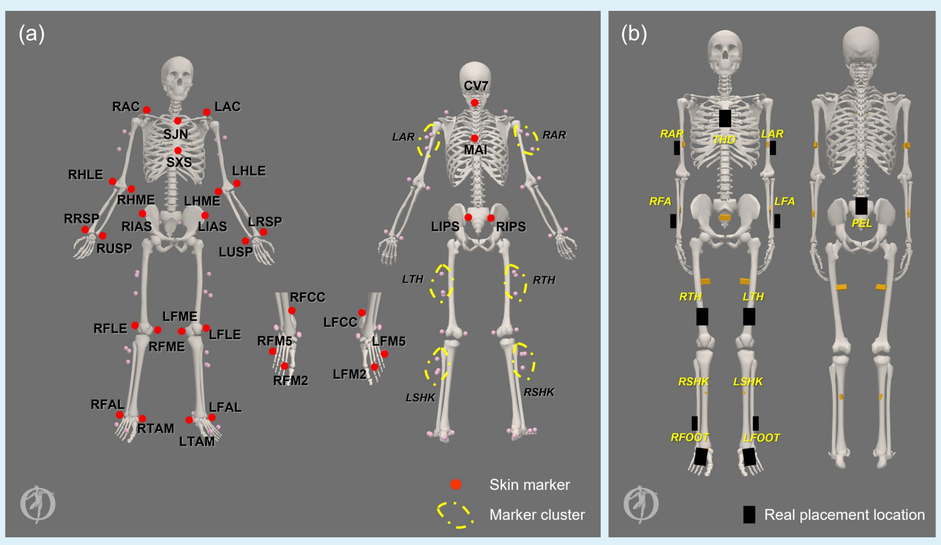


- **Pipeline 1 (PC with Packet Loss Compensation)**: IMU data goes to the hub then PC. Two - step process on PC: data at 100 Hz in buffer, IK at 20 Hz with packet loss fix. Visualizes movement.
- **Pipeline 2 (PC without Packet Loss Compensation)**: Data flow like Pipeline 1. IK on PC every 5 packages (20 Hz), but no packet loss fix, may have frequency issues.
- **Pipeline 3 (Hub without Packet Loss Compensation)**: Hub processes IMU data directly using OpenSim. Computes and outputs angles at 20 Hz.

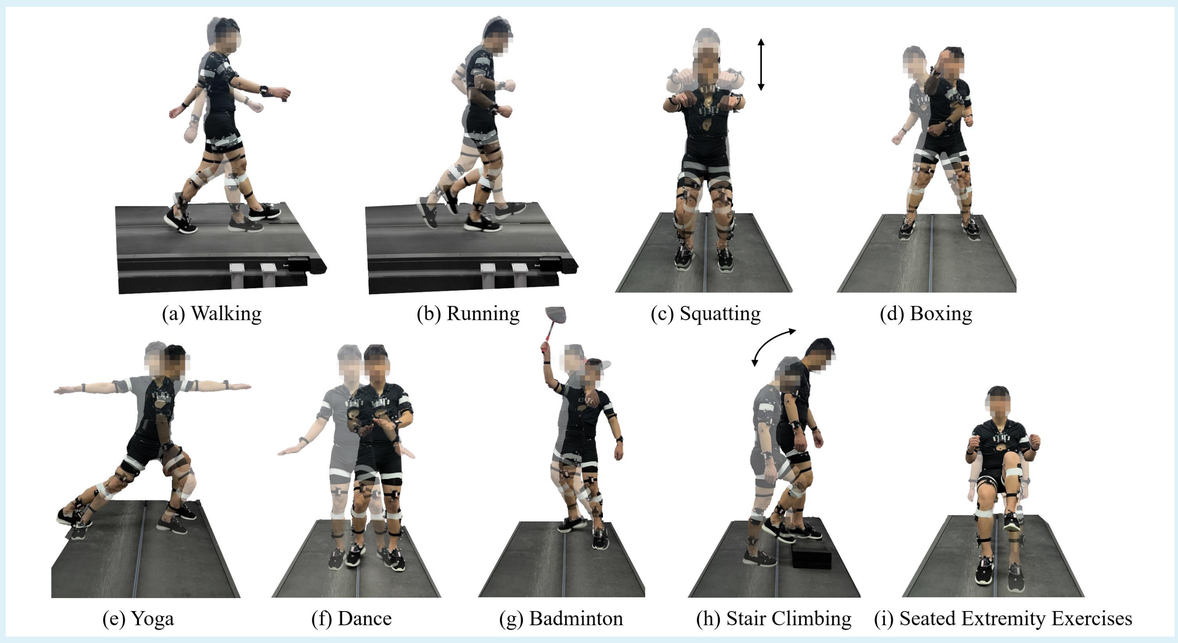
Each pipeline uses the **OpenSim IMU IK Tool** with a model calibrated through the N-pose at the experiment's start to estimate human kinematics using quaternions.

Experiment Protocol

- **Subjects**: Seven healthy male volunteers with no relevant disorders.
- **Marker placement**: 32 markers on anatomical landmarks. 8 clusters with 3 markers on each on segments.
- **IMU placement**: 12 IMUs (SageMotion, Kalispell, MT, USA) on segments.
- **Experimental procedure**: For each trial, the subject performs a N-pose for calibration and one of nine activities.



(a) Marker placement on anatomical landmarks and marker clusters placement on segments. (b) IMU placement calibration on N-pose model.



9 Activities

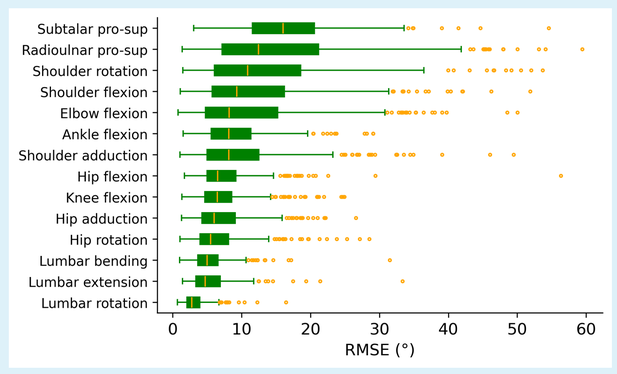
Data Processing

- **Ground Truth Kinematics:** OMC data is processed to get ground truth joint angles.
- **Offline and Online Predicted Kinematics:** Offline data at 100 Hz and online data at 20 Hz are processed with OpenSim's IMU IK tool.

RESULTS & DISCUSSION

Kinematics Estimation Accuracy

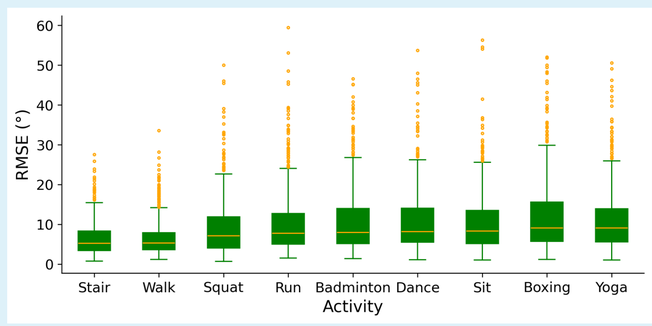
- Overall median RMSE compared to OMC was 7.4 deg. Walking and stair climbing had the highest accuracy (median RMSE 5.3 deg), and the most accurate joint angle was lumbar rotation (median RMSE 2.7 deg).
- Median RMSE between real - time and offline estimation was 0.2 deg.



Human body kinematics estimation RMSEs across different joint angle types

Delay Time and IK Computation Time

- Average time delay was 31.7 ms.
- Different computing methods and devices showed varied delay and IK computation times.



Human body kinematics estimation RMSEs across all activities

Error Analysis

- **IMU Orientation Estimation**: Sensor drift caused errors, as seen in badminton trials.
- **Calibration Offset**: Variances in calibration offsets were significant for certain joint angles due to marker placement, N - pose non - standardization, and skeletal differences.
- **IK Computation Error**: Subtalar angle prediction was least accurate. Upper body joint angles were poorly estimated due to model limitations and skin motion artifacts.

Advancements and Limitations

Our approach was tested on more activities and enabled fully portable kinematic estimations compared to previous studies. It showed potential for enhancing rehabilitation assessment and treatment through rapid evaluation and real - time biofeedback. However, it cannot replace optoelectronic systems in clinical practice as RMSE didn't meet medical standards.

ACKNOWLEDGEMENTS

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