# Accurate Estimation of The Kinematics Using An IMU-Based Motion Capture System

HUman Rehabilitation Group
TEXAS A&M UNIVERSITY

Wyatt Hahn, Tyler Marr, Moein Nazifi, and Pilwon Hur Ph.D.

{wyatt_hahn, marres, moeinnazifi, pilwonhur}@tamu.edu

UNDERGRADUATE RESEARCH SCHOLAR

## Introduction

- Optical motion capture systems (MCSs) have many drawbacks
    - Require large space inside laboratory
    - Very expensive
    - Missing data points when markers hidden from camera
    - Time consuming post-processing of data
- Inertial measurement unit (IMU) based MCSs offer appealing alternative with minor reduction in accuracy
    - Operable anywhere
    - Cheaper
    - No missing data points
    - Faster and easier post-processing
- **Objective:** Create an IMU-based MCS that can be used to replace an optical MCS, and compare the data of the systems by simultaneous gathering of data in order to determine accuracy.

**Figure 1**: Delsys Trigno IMU sensors used for motion capture system

## Design Method

***Position Estimation Algorithm***

- IMU sensors used include 3-axis gyroscope, accelerometer, and magnetometer as well as EMG readings (not used in this study)
- Data is gathered at 60 Hz using Microsoft C# and then is immediately filtered via a third-order low pass filter with a 5 Hz cutoff frequency [1]
- At each data point a new orientation is calculated in two ways:
    1. **Via gyroscope readings:** The system takes readings of the angular velocity from the gyroscope and performs trapezoidal integration to find the absolute rotation angle in quaternion form and then applies this rotation to the orientation of the previous time step
    2. **Via accelerometer and magnetometer readings:** Static readings are taken of the initial magnetometer and accelerometer readings and a right-handed orientation matrix is created from the gravitational vector ($\vec{G}$), cross product of $\vec{G}$ and the magnetic field vector ($\vec{M}$), and the cross product $\vec{G} \times (\vec{G} \times \vec{M})$. At each reading, an orientation matrix is formed in the same manner, and the originally-oriented vector is rotated by the rotation from the new orientation to the old
- An average is calculated between the two orientations produced based on various magnitudes: for increasing values of gyroscope and accelerometer readings the average is weighted heavier to the gyroscopic orientation, unless the gyrscope value exceeds the sensor range (250 deg/s)
- Rotations are performed on vectors assuming an initial x-direction (in the local coordinate system)
- Vectors are rotated to their orientaion in the global coordinates and plotted end-to-end from the pelvis "joint"
- The entire model is shifted upwards such that the lowest joint position is in contact with the ground plane at all times to avoid negative values
- The system calculates and saves all joint angles and positions at each reading and exports all of this data in a spreadsheet after data collection is stopped

## Experimental Methods

***Optical MCS***

The optical motion capture (Qualisys Oqus, Göteborg, Sweden) used 30 markers (as denoted by the blue circles in Figure 2) on the bony landmarks of the body to collect the full-body kinematics at 100Hz. The markers were placed bilaterally on toe tip, heel, medial/lateral malleolus, medial/lateral condyle of tibia, trochanter, ASIS, PSIS, acromion, medial/lateral humeral epicondyle, and ulnar/radial styloid process, plus unilateral C7 and T10 markers

***IMU Based MCS***

The motion capture system developed in this study comprises 16 wireless IMU sensors (Delsys Trigno, Natick, MA) (pictured in Figure 1) bilaterally attached to major upper and lower extremity links (as denoted by the red rectangles in Figure 2) as follows: Back of the shoulders (scapula), upper arms, forearms, back of the hands, thighs, shanks, feet, and unilateral at lumbar (L3), and sternum

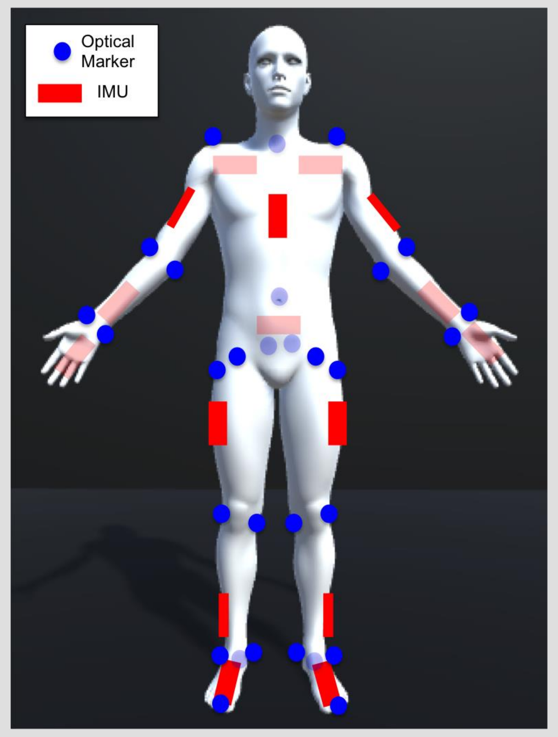


**Figure 2**: IMU and optical marker positions

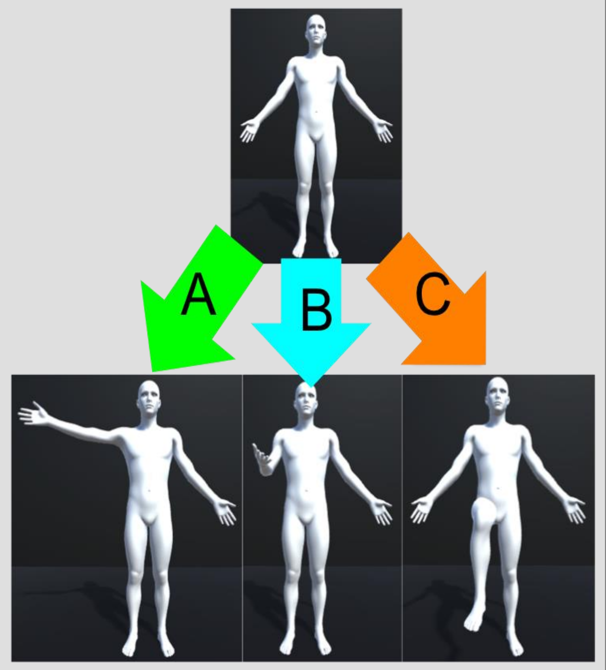


**Figure 3**: The tasks performed by the subject

***Experimental Procedure***

- To test the accuracy of the IMU-based MCS, kinematic data was simultaneously collected using both devices
- Both devices were first calibrated and then attached as depicted in Figure 2
- One recruited subject performed three tasks starting from reference anatomic position (Fig. 3)
    A. Ten bilateral shoulder abduction/adductions (90°)
    B. Ten bilateral elbow flexion/extension (90°)
    C. Ten hip flexion/extensions (90°, right limb first then left limb)
- Prior to and following each task the subject performed a clap so that the data from both systems could be synched for analysis

***Post Processing of Data***

- The data from the optical MCS took approximately 5 minutes per trial of post processing in order to estimate marker positions for when the camera could not see a marker
- The data from the IMU based MCS was filtered (4$^{th}$ order zero-lag Butterworth, cutoff 1Hz) using MATLAB [2].
- Optical motion capture data was processed offline using MATLAB and the corresponding joint angles were calculated using custom codes
- The data was then synched based off of elbow and shoulder joint angle peaks that occurred when the subject clapped
- The IMU data was then shifted so that the mean value of both data sets were the same (this is necessary because of the assumption of exact initial starting position)
- Finally, the RMS error and the Pearson's correlation coefficients ($r$) were calculated to determine the accuracy of the IMU-based motion capture system

## Results and Discussion

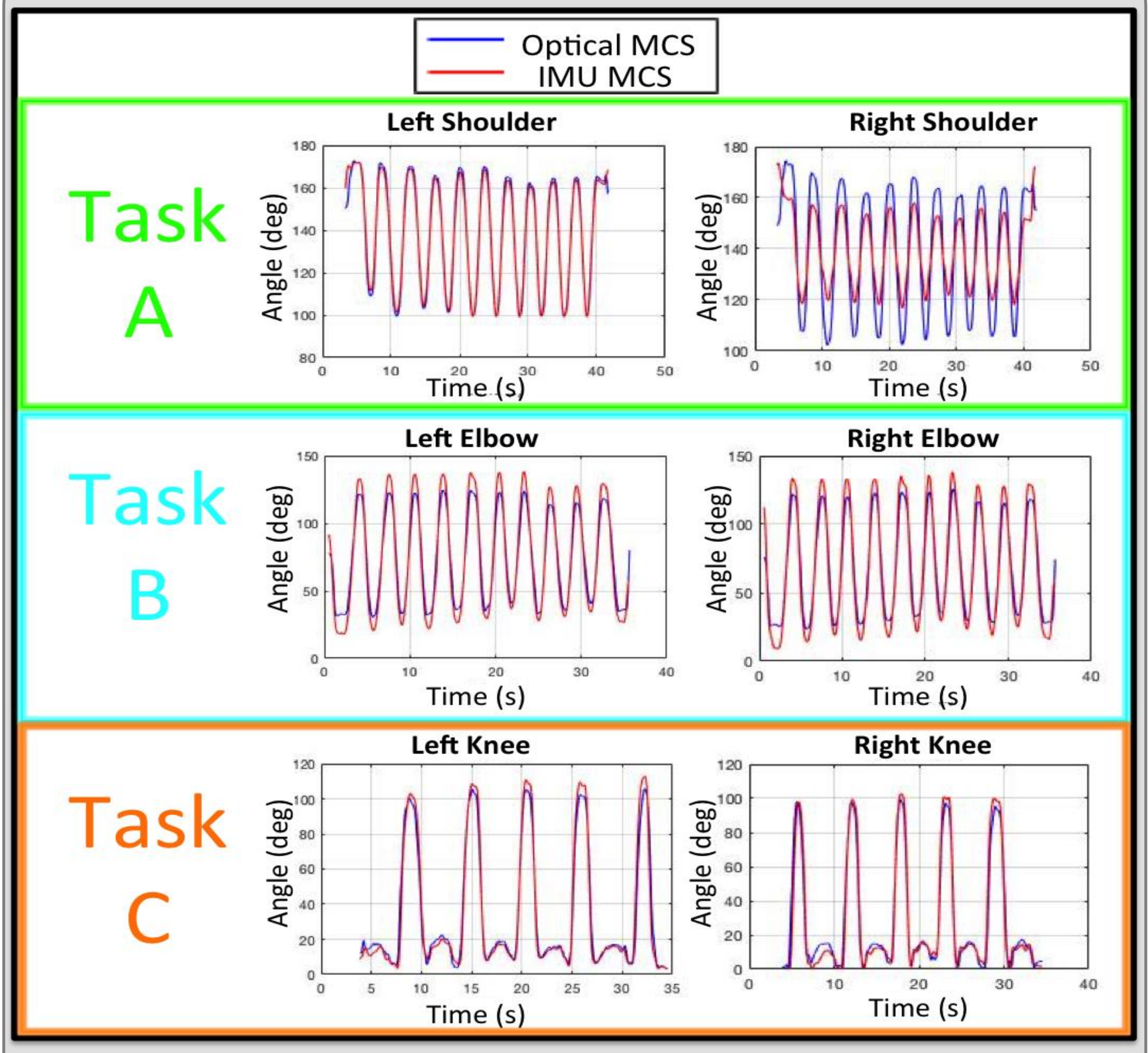


**Figure 4**: Comparison of angle vs. time for both MCSs

- Results of the primary joints in each motion show that the IMU-based MCS was able to closely follow the optical MCS

**Table 1.** Root mean square errors (RMSE) in degrees and correlation values

| Task | Left Shoulder | | Right Shoulder | |
|---|---|---|---|---|
| A | RMSE | Correlation | RMSE | Correlation |
| | 2.56 | 0.99 | 10.73 | 0.95 |
| | Left Elbow | | Right Elbow | |
| B | RMSE | Correlation | RMSE | Correlation |
| | 8.55 | 0.99 | 9.00 | 0.99 |
| | Left Knee | | Right Knee | |
| C | RMSE | Correlation | RMSE | Correlation |
| | 5.58 | 0.99 | 5.93 | 0.99 |

- A statistical analysis of these results for both the right and left side reveals Pearson's correlations of 0.99 for all joints except for the right shoulder, which still maintained a correlation of 0.95
- All of these correlations are very strong and indicate the joint angles are following the same path over time
- The statistical analysis also revealed RMS errors of each joint under 10° except in the case of the right shoulder which is slightly above 10°
- All of the ranges of the joint angles are approximately 100°, therefore these RMS values are relatively small
- The reason for the deviations of the right shoulder angle is believed to come from one of two reasons:
    - Calibration error of the magnetometer
    - Misplacement of the IMU on the arm
- Other non-essential joints for each test showed lower correlation due to noticeable noise a very low ranges, in some cases <1°
- Other sources of error could be due to the following:
    - Inappropriate filtering (e.g., too low cutoff frequency)
    - Misalignment of local coordinate systems between the optical MCS and the IMU-based MCS

## Conclusions

- The system developed in this study uses IMU sensors to capture human kinematics
- The preliminary test involving shoulder abduction, elbow flexion, and hip flexion revealed strong correlations and minimal RMSE values
- The largest deviation was found in the right shoulder angle measurements but still showed a strong correlation and a relatively low RMSE value
    – ***System Benefits***
        - Usable anywhere with wall-outlet access
        - Easier to set-up and more cost-effective than optical MCSs
        - Little post-processing required for joint angles
    – ***System Drawbacks***
        - Full-calibration required at each new location (approx. 15 minutes)
        - Model is fixed to one horizontal location
        - Assumes exact initial starting position
- There are many known potential sources of error that need to be, and can be minimized
- Overall, these results substantiate feasibility of usage of IMU-based MCSs

## Future Works

- Refinement of filtering process
- Implementation of principal component analysis (PCA)
    - PCA can be used alongside predetermined motions, such as task A in this experiment, in order to better calibrate the MCS
- Closer examination of more complex motor tasks including walking and other movements of the entire body
- Increased user-friendliness of software
- Upon completion of all experimentation the codes will be made open-source for public use and individual customization

## References

[1] Pavol MJ, *Journal of Gerontology: Medical Sciences* **59**, 2004.
[2] Parijat P, *Annals of Biomedical Engineering* **40**, 2012.

## Acknowledgements

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