How Wrong Can You Be? A Sensitivity Analysis of Kalman Filter Skeletal Kinematics Estimates to Imperfections in Inertial Measurement Unit Calibration

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Summary

Out-of-laboratory motion capture has exploded in recent years due to the increased popularity of inertial measurement units (IMUs) and their ability to capture kinematic data in unconstrained environments. Kalman filters are often used in conjunction with IMUs to estimate body motion such as joint angles and segment centre of gravity kinematics. Kalman filters rely on accurate physical representations of the IMU relative to the body, which is typically achieved through calibration. However, calibration is not a perfect process, leading to imperfections in the relative representation of the IMU with respect to the body. Here, we conducted a Monte Carlo sensitivity analysis to assess how these imperfections affect Kalman filter estimates.

Introduction

IMUs are a popular sensor to measure biomechanics outside of the lab. IMUs directly measure linear accelerations and angular velocities and rely on Kalman filters to relate IMU measures to useable kinematic metrics such as joint angles. The Kalman filters require precise calibration that determine the position and orientation of IMUs relative to the body. Similarly, as many IMU-based motion capture systems rely on multiple IMUs, the separate IMUs must be time synchronized. However, calibration and time synchronization are vulnerable to imperfections, and we wanted to understand how this may influence Kalman filter estimates.

Methods

We previously established a Kalman filter to predict segment linear accelerations and angular velocities during impacts using multiple noisy IMUs affected by dynamic soft tissue artifacts [1]. To explore how this filter is affected by imperfect IMU calibration and time synchronization, we first generated representative half-sine (0.018s period) impact signals in the linear acceleration only (LO, 60m/s^2 peak), angular acceleration only (AO, 150 rad/s^2 peak), and linear and angular acceleration combined (C) conditions for the centre of gravity of a rigid segment.

We then generated IMU data using rigid body dynamics for three IMUs placed 10cm relative to the rigid segment centre of gravity in the three translation dimensions with added random calibration and time synchronization imperfections. We applied random translation ±2cm, rotation ±5deg, and time shift ±5ms imperfections independently (Ind.) to explore their individual effects on the Kalman filter results. We also applied the imperfections simultaneously (Sim.) to better represent real-world use. We used the Kalman filter to estimate the rigid segment centre of gravity kinematics relying on an assumed 10cm translation and no relative rotation for each IMU, and computed the root mean square error normalized by the peak rigid segment centre of gravity measure (nRMSE). We performed 10,000 iterations for each condition (impact kinematics and imperfection) with imperfections randomly sampled in each iteration.

Results and Discussion

Imperfections in the time-synchronization were most correlated with nRMSE in the linear acceleration, while imperfections in sensor rotation were most correlated with nRMSE in the angular velocity (**Figure 1a**). Translation imperfections were least correlated with nRMSE overall, indicating the Kalman filter was robust to translational imperfections**.** This indicates that the Kalman filter is least sensitive to imperfections in IMU translation. The effect of time synchronization is clearly seen in its effect on the linear acceleration nRMSE, where the nRMSE at 10ms maximum IMU time difference is over four times the nRMSE at 2ms maximum IMU time difference (**Figure 1b**).

Conclusions

This work shows the sensitivity of the Kalman filter to calibration and time-synchronization imperfections. This will inform what calibration methods are required to achieve precise calibration and bound the expected estimation error.

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References

[1] Kuo C. (2018) *J. Biomech. Eng.*, **140**

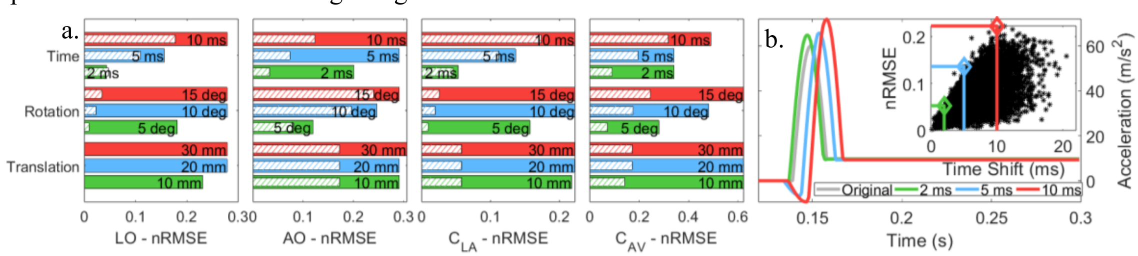

Figure 1: (a) Monte Carlo results for "Sim." trial with all signal types. Hatching indicates "Ind." trial results. (b) Vertical axis accelerations before and after imperfections are applied for the combined (C) condition.