Modeling Soft Tissue in IMU Kalman Filters Improves Measurement Accuracy

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Summary

Soft tissue is excited into oscillation during impacts, which produce dynamic soft tissue artifact (dSTA) measurement errors in data collected from skin-mounted inertial measurement units (IMUs). Our previous work has established Kalman filtering with multiple redundant IMUs is an effective method to reduce the effect of dSTAs and improve measurement accuracy [1]. Our original rigid body Kalman filter treated dSTA measurement errors as random noise, but we have previously shown that these dSTAs exhibit behaviors indicating the underlying soft tissue can be modeled as a spring-mass-damper system [2]. This work introduces a soft tissue Kalman filter incorporating soft tissue material models to reduce median peak vertical acceleration error from 60.8% for single IMUs to -5.8% in the presence of dSTAs.

Introduction

Bipedal locomotion is a crucial part of everyday life for all humans. The introduction of wearable IMUs has allowed us to measure these movements in everyday environments. However, each step produces a small foot strike impact, exciting soft tissue into oscillation. These dSTAs affect measurements from IMUs mounted over the soft tissue. As a result, IMU measures are not representative of segment skeletal motion at the foot strike impact. Traditional low-pass filtering (<20Hz cut-off) is not ideal for removing dSTAs, as foot strike impacts can contain high-frequency content (up to 50 Hz) [2,3]. Instead, a Kalman filter with multiple IMUs is proposed to obtain more accurate estimates of skeletal motion.

Methods

To develop and test our Kalman filter, we performed a series of simulated foot strike impacts using a soft tissue phantom approximating the shank. This allowed us to obtain direct measurements of an underlying skeleton surrogate while also reproducing *in vivo* dSTAs [2]. The soft tissue phantom was created using silicone rubber (Ecoflex 00-30, Smooth-On) cast around a rigid surrogate bone (total weight 3.3kg). We placed three IMUs (ICM-20649) on the soft tissue surrogate (anterior, posterior, and transversely) and one on the surrogate bone serving as the ground truth. The IMUs captured triaxial linear accelerations (±30g) and triaxial angular velocities (±4000°/s) at 1000Hz during 30 simulated impacts induced by 5cm vertical drops of the phantom.

We ran data from the three IMUs mounted on the soft tissue surrogate through a rigid body Kalman filter relating IMU measures using linearized rigid body dynamics [1]. dSTAs in this model were represented as a source of Gaussian white noise. To better capture the dSTAs, we further expanded the rigid body Kalman filter with spring-mass-damper soft tissue representations connecting the IMUs to the rigid body shank – termed the soft tissue Kalman filter. We assessed the rigid body and soft tissue Kalman filter estimates against the IMU mounted on the skeleton surrogate by finding the peak vertical acceleration percent error. We performed a sign test to determine if the median peak vertical acceleration percent error over the 30 impacts was significantly different from 0%.

Results and Discussion

The soft tissue Kalman filter provided a better estimate of ground truth peak kinematics compared to the rigid body Kalman filter (median peak vertical acceleration percent error of -5.8%, p=0.005 vs. 13.7%, p=5.8e-8 respectively). They both improve median peak vertical acceleration percent error over individual IMUs (60.8%). The sample impact (**Figure 1**) demonstrates individual IMUs overestimated peak vertical accelerations and exhibited post-impact oscillations from the dSTAs. The rigid body Kalman filter contains some post-impact oscillations while the soft tissue Kalman filter further reduces the oscillations due to the better representation of the underlying dSTAs with the spring-mass-damper representation. However, the soft tissue Kalman filter also has a phase lag, which is likely due to the behaviour of the spring-mass-damper as a first-order delay. Future work will address this with a Kalman smoother.

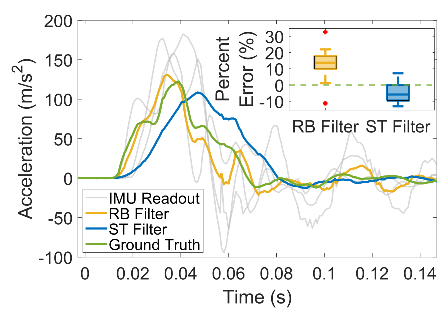

Figure 1: Example skeletal vertical acceleration estimates using the rigid body (RB) and soft tissue (ST) Kalman filters. Inset compares peak vertical acceleration percent errors over 30 impacts.

Conclusions

This work shows that Kalman filters can effectively reduce IMU measurement errors from dSTAs to better estimate skeletal motion during impacts such as foot strikes. Furthermore, better representing the dSTAs with a more biofidelic soft tissue material model in the soft tissue Kalman filter further improves accuracy of the estimates.

Acknowledgements

This work is funded by an NSERC Discovery Grant and CFI JELF Grant for C.K. as well as a Mitacs Accelerate partnered with Lululemon and UBC Affiliated Fellowship funding G.B.

References

[1] Kuo C. (2018) *J. Biomech. Eng.,* **140**
[2] Rong R. (2024) *IEEE Trans. Biomed. Eng.,* **71**(11)
[3] Shorten M.R.. (1992) *Int. J. Sport Biomech.* **8**:288-30