LONG-TERM MEASUREMENT OF FOOT PLACEMENT AND ITS VARIABILITY DURING WALKING

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## SUMMARY

Foot placement and its variability can serve as indicators of mobility and walking ability as a function of age, injury, and disease. Inertial measurement units (IMU) can potentially quantify these parameters without need for laboratory-based motion capture equipment, and for relatively long bouts of walking or during daily living. One limitation is that integration of data from inertial sensors is sensitive to drift, referring to accumulation of errors from noisy data. Another is that inertial sensors can track motion of only a single foot, and not the distance to the other foot. This limits the measurable quantities to stride parameters (sequential footfalls of the same foot), rather than the more commonly measured step parameters (one foot relative to the other). Here we quantify the accuracy of stride measurements derived from inertial sensors over relatively long distances. We also analyze the relationship between step parameters and stride parameters in healthy subjects. In particular, we focus on foot placement variability, which has been identified as a measure of mobility in the elderly. We show that overground stride variability measured with inertial sensors can be accurate to within a few percent. Moreover, stride variability is correlated with step variability, indicating that it may be similarly useful as a measure of walking function. This may allow gait measurement to occur over unlimited distances and more naturally than with laboratory data collection.

## INTRODUCTION

Foot placement parameters such as step distances and variabilities are used to quantify gait in the context of fall risk, development, and various disorders [1]. Gait is normally measured using laboratory based equipment such as gait mats and motion capture systems. These systems have limited capture volume and are seldom used outside of the laboratory. Advances in inertial sensors offer the possibility to measure human motions using unobtrusive foot-mounted sensors during ordinary daily life. Drift correction algorithms can be used to calculate the trajectory of a foot-mounted inertial sensor in space [2]. This may allow for the quantification of gait parameters such as stride length, and the variabilities of stride length and width. It is unknown how well such methods perform over long overground bouts of walking [3]. It is also unknown whether these stride parameters correspond with step parameters that have previously been quantified in the literature. We therefore quantified the accuracy of stride parameters as estimated by IMUs, and tested their correspondence to step parameters measured by traditional means.

## METHODS

To quantify stride and step parameters for overground walking, we measured the gait of 9 healthy young adults. Subjects walked the length of a straight hallway (about 93 steps per trial), with inertial sensors affixed to their feet. As a reference, we also performed motion capture with a mobile system mounted on a cart, which was instrumented with optical wheel encoders and a vertical-axis gyroscope for dead-reckoning localization (figure 1) [3]. The mobile motion capture system was pushed behind the subject and used to track the feet. The inertial sensors were used to calculate the positions of the feet, using drift correction algorithms [2,3]. To determine whether stride parameters have similar discriminatory power to step parameters the subjects performed trials with eyes open and with eyes closed. To quantify the agreement between step and stride parameters, we tested the correlation between stride and step width (RMS) values for each condition, using motion capture estimates.

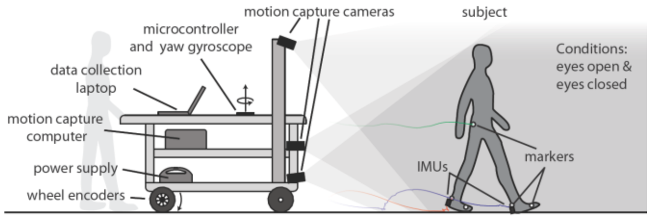


**Figure 1**: Experimental setup. Subjects walked IMUs and optical markers on their feet, followed by an optical motion capture system mounted on a position-tracking cart.

## RESULTS AND DISCUSSION

The IMU and the motion capture system estimated stride mean parameters within 1% and variabilities within 4%, except for stride duration variability. (We attribute the exception to poor motion capture estimates of stride duration rather than IMU errors). Statistical differences between eyes open and eyes closed conditions were found for stride width RMS and stride length RMS, using both motion capture and the IMUs (figure 2). The correlations between stride width RMS and step width RMS are 0.89 (eyes open) and 0.90 (eyes closed) (figure 3).

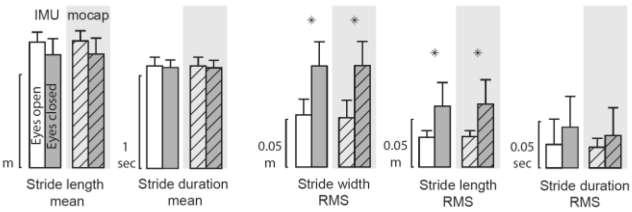


**Figure 2**: Comparison of conditions using IMU *vs* motion capture, for all subjects ($N$ = 9) and conditions. IMU-data are numerically very similar to motion capture data, and reveal the same statistical differences.

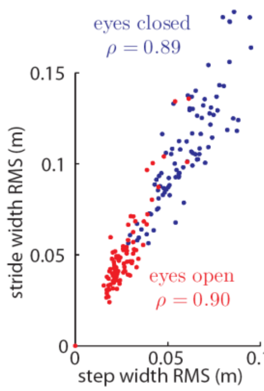


**Figure 3**: Correlations between step and stride width RMS for each walking trial, all subjects and conditions. Results computed from motion capture data.

The correlations between step and stride variabilities, although not reliably close to unity, indicate reliable correlation (all p values less than $3*10^{-35}$) (figure 3). Therefore we expect stride width RMS to be useful as a proxy for how step width RMS changes with varying walking conditions.

One limitation of inertial sensors is that average step width, measurable with motion capture and gait mats, cannot be directly measured from foot-mounted inertial sensors alone. However, in cases where general foot placement variability is considered important, IMUs are a convenient way to capture long walks in laboratory settings, or natural everyday walking that is otherwise unavailable. One illustrative example is a clinical walking test of step placement variability, using a gait mat which allows only a few consecutive steps (figure 4). The confidence intervals around a stride parameter RMS estimate for steady walking become smaller with the number of steps in the walk. Inertial sensors allow an unlimited capture volume of overground walking, yielding increased statistical confidence. In addition, a gait mat does not capture the turning segments of the walking at the ends of the mat, whereas an inertial sensor can. Although not the focus of this work, IMUs also allow limited localization of a subject in natural environments, such as hallways and stairs (figure 5).

## CONCLUSIONS

We found that IMUs can estimate mean stride parameters and stride variabilities well, within a few percent motion capture estimates. We found that step and stride parameters correlate well with each other, because each stride foot placement is a sum of two step foot placements. This suggests that stride parameters measured with IMUs may correspond well with step parameters, which have been much studied in the literature but are difficult to record outside of the laboratory.

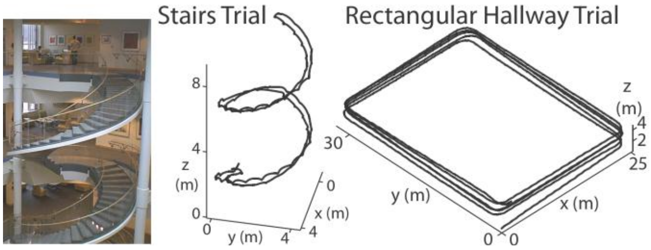


**Figure 5**: Examples of foot placement localization with IMUs in everyday environments. Shown are trajectories of foot motion for walking in a 110m hallway circuit 5 times (top), and walking up and down a spiral staircase (bottom).

## ACKNOWLEDGEMENTS

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## REFERENCES

1. Bauby, C. and Kuo, A. Active control of lateral balance in human walking. *Journal of Biomechanics*, **33(11)**:1433–1440, 2000.
2. Ojeda L and Borenstein J,. Non-gps navigation for security personnel and first responders. *The Journal of Navigation*, **60(03)**:391–407, 2007.
3. Rebula et al., Measurement of Foot Placement and Its Variability with Inertial Sensors, *Gait and Posture*, submitted

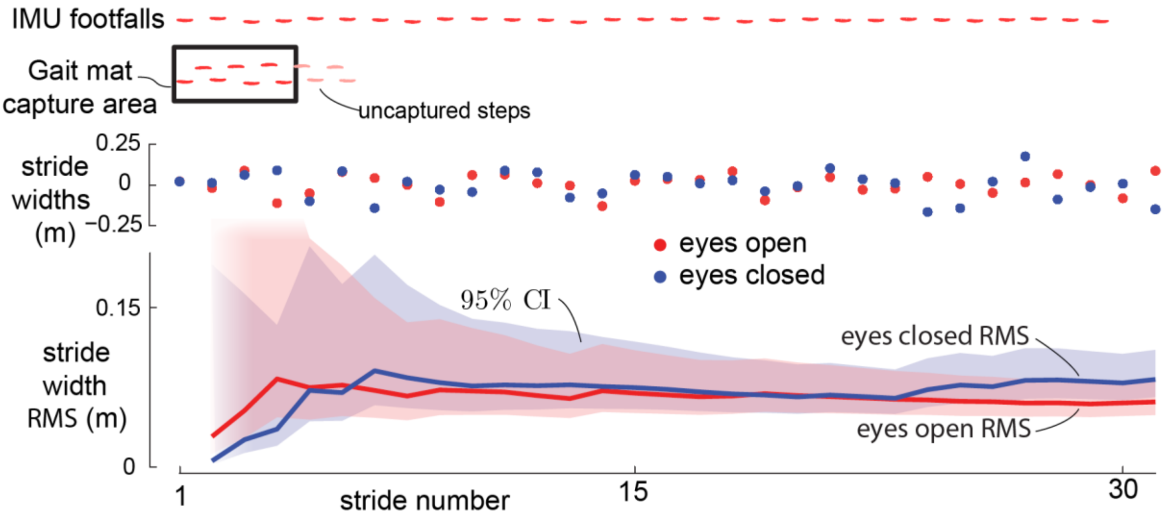


**Figure 4:** Statistical analysis of gait variability. Top: Right footfalls for a single eyes open walking trial (IMU data, with a representation of the data measured by a force sensitive mat). Center: Stride widths for an eyes open and eyes closed trial. Bottom: RMS estimates and confidence intervals are shown as a function of the number of strides in each trial. More steps provide tighter bounds on the variability estimates, increasing statistical confidence when distinguishing between different walking conditions.