

# Stride-by-Stride Walking Speed Estimation Using Inverted Pendulum Model

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## SUMMARY

In this study we investigated the feasibility of walking speed estimation using a shank-mounted inertial measurement unit (IMU), and proposed a stride-by-stride walking speed estimation method. By taking advantage of the inverted pendulum model of walking, we identified a new way to segment a walking sequence into gait cycles. Within each gait cycle, this method integrated the transformed accelerations to calculate the stride length, and walking speed. Human walking experimental results demonstrated that the proposed method could accurately estimate the walking speeds under different slopes.

## INTRODUCTION

Gait speed is a well-accepted indicator of gait performance and self-perceived physical function, and is positively related to independence. Traditionally, gait speed has been measured in a clinic using a stopwatch and tape measure with a lower accuracy, or in a gait laboratory using a motion analysis system with a higher accuracy. Generally, the above-mentioned approaches are relatively immobile and require some post-processing of the measurements, which restrict them to use in a laboratory. Recent efforts have focused on the development of ambulatory gait speed estimation methods using miniaturized accelerometers and gyroscopes [1-3]. Most of these approaches estimated the stride length indirectly by first computing an intermediate kinematic parameter from sensor measurements and, then relating the stride length to the intermediate parameter using a gait model. An alternative is to double integrate the associated horizontal and vertical accelerations directly. However, it is difficult to integrate acceleration data. This is for two reasons. First, double integration requires known initial conditions which generally is unavailable. Secondly, the acceleration and angular velocity signals are usually noisy and spiky during walking. Thus, continuous integration of these signals may introduce large accumulation error to the estimation results.

The inverted pendulum model, accurately predicting the exchange pattern of kinetic and gravitational potential energy during walking [4] (Fig.1), provided insights for segmenting a walking sequence into gait cycles.

## METHODS

To estimate stride-by-stride walking speed, we first resolved the measured acceleration signals into component accelerations in the world coordinate, and then double integrated the accelerations to obtain the travel distance. However, the long-term integration will accumulate any

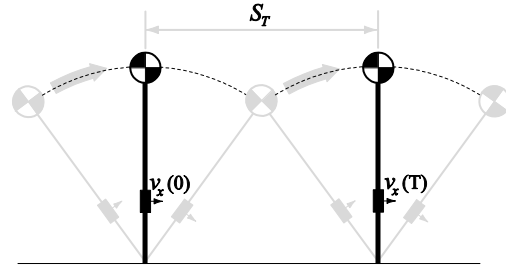


Figure 1: Inverted pendulum walking model.

error in the measurements. Therefore, we need to segment a walking sequence into gait cycles. In the inverted pendulum model, the stance limb rotates around the ankle joint at the mid-stance shank vertical events where the angular velocity reaches its minimum with a value close to zero (Fig. 2). This property allowed us to identify gait cycles and acquire the integration initial values for double integration.

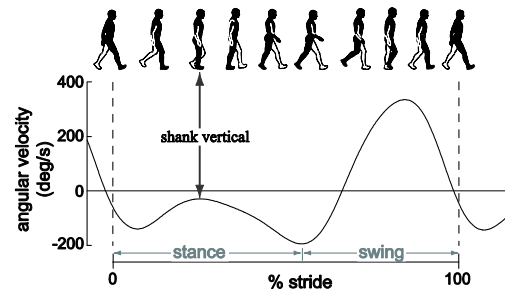


Figure 2: Filtered shank angular velocity in a gait cycle

## RESULTS AND DISCUSSION

Data was collected from eight subjects walking at treadmill speeds of 0.8-1.8 m/s under 0%,  $\pm 5\%$ ,  $\pm 10\%$  inclinations. Results indicated the method estimated the walking speed with relatively high accuracy (about 5% error). There was no significant difference in speed estimation error as a function of speed during 0%,  $\pm 5\%$  slope walking ( $P > 0.05$ ).

The proposed method has the potential to estimate the stride length and speed of dynamic walkers. Additionally, IMU measurements may assist analyzing the dynamic walker behavior to achieve a better design.

## REFERENCES

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