# Gait Analysis Using Shoe-worn Inertial Sensors: How is Foot Clearance Related to Walking Speed?

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## ABSTRACT
Spatiotemporal gait analysis with body worn inertial sensors improves diagnosis in clinical practice. Most of the gait performance measures are affected by walking speed. However, it has not been investigated that how much information foot clearance parameters share with the key parameters of gait performance domains. Using shoe-worn inertial sensors and previously validated algorithm we measured spatiotemporal as well as clearance gait parameters in a cohort of able-bodied adults over the age of 65 (N=879). Principal components analysis showed that variability of foot clearance parameters contribute to the main variability in gait data. Moreover, only weak to moderate correlation of gait speed and stride length with some clearance parameters has been observed. We recommend the assessment of clearance parameters during gait analysis in addition to parameters such as gait speed, bearing in mind the importance of foot clearance measures in obstacle negotiation, slipping and tripping related falls.

### Author Keywords
Gait speed; elderly; foot clearance; inertial sensor; data fusion; variability.

### ACM Classification Keywords
J.3 Computer Applications: [Medical information systems]

## INTRODUCTION
Gait analysis aims to provide a systematic procedure for measurement and characterization of those parameters that describe human locomotion [1]. The ambulatory nature of gait necessitates a motion analysis system that can capture both variability and occurrence of rare events in walking. Contrary to traditional motion analysis systems, the capture volume of wearable inertial sensors is not limited and does not require controlled condition either [2]. These features along with the low cost are the main incentives for the extensive application of inertial sensors in the study of different forms of human locomotion [3, 4, 5, 6].

In a study by Verghese et al., three domains have been introduced to characterize gait performance in elderly persons [7]; The "Rhythm" domain that is best represented by cadence, swing time and stance time. The "Pace" domain that is best represented by gait speed and stride length. Finally, is the "Variability" domain best represented by stride length variability. Another class of studies advocates the walking speed as a general indicator that reflects functional and physiological changes in the health state and aids to predict falls [8, 9, 10]. This category of studies suggests that walking speed has significant influence on most of the objective gait performance measures in older adults. Nevertheless, in gait performance characterization, the swing foot trajectory as a source of information has been overlooked. Foot clearance parameters characterize the heel and toe trajectory during swing phase of the gait [11]. The obstacle negotiation and fall occurrence due to slipping and tripping in older adults can be explained based on foot clearance parameters [12], [13].

The aim of the presented study is to investigate how much information foot clearance parameters share with the key parameters of gait performance domains. To this end, we measured spatiotemporal as well as clearance gait parameters in a cohort of able-bodied adults over the age of 65 [14]. The assessment of these parameters was achieved using shoe-worn inertial sensors and corresponding previously validated algorithms [11, 15, 16, 17]. In the following paragraphs we briefly explain the algorithm to extract foot clearance parameters using shoe-worn inertial sensors. Next, we use principal component analysis (PCA) to examine the variability that the "Clearance" domain contributes to gait variability. Moreover, the correlation of clearance with other gait parameters allows evaluating the significance of "Clearance" domain in gait analysis.


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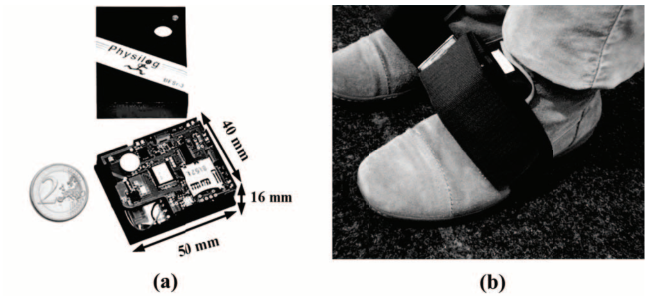


**Figure 1. (a) A Physilog III sensor (dimensions: 50 mm × 40 mm × 16 mm, weight: 36 g). (b) Sensor attachment to the shoe with the elastic strap.**

## MATERIALS AND METHODS

### Data Acquisition and Calibration

A Physilog® III (Gait Up, Lausanne, Switzerland) was used in this study. Physilog® is an inertial sensor including a tri-axial accelerometer (MMA7341LT, range ±3 g, Freescale, Austin, TX, USA), a tri-axial gyroscope (ADXRS, range ±600 °/s, Analog Devices, Norwood, MA, USA), a battery (3.7 V, 595 mAh), a memory unit and a microcontroller acquiring data at 200 Hz (Figure 1a). The sensor was fixed on the upper part of the shoe with an elastic strap as shown in Figure 1b. The sensor frame was aligned with the foot's walking frame during each walking trial in line with [11] in order to be sure that the measurement was not affected by the sensor location on the foot. According to participants, the sensor weight and its fixation on the shoe did not lead to any unusual experience during the walking tests.

### Participants and Measurement Protocol

In this study 879 (513 female) community-dwelling people of age 73 to 78, included in the Lausanne cohort Lc65+, participated. Gait parameters were recorded during the 2011 follow-up examination. The demographics of the participants were reported in Table 1. We assessed the spatiotemporal and clearance gait parameters during a 20 m walking trial in a corridor at a self-selected pace. For each participant on average 26 ± 5 steps have been captured.

### Estimation of Gait Spatiotemporal Parameters

Each gait cycle was defined based on detecting two successive heel-strike instants. A rule-based event detection on the foot kinematic signals (explained in [15]) was used to extract temporal parameters including gait cycle time ($\Delta T_{GC}$), cadence ($\Delta f$), swing duration ($\Delta T_{Swing}$), double support duration ($\Delta T_{DS}$).

The orientation of the shoe-worn inertial sensor was represented by a rotation matrix *R(t)* relative to the global frame (GF) of measurement. The rotation matrix was updated at each time frame by strap-down based integration of angular velocity [18, 19]. The foot sensor's position in 3D was then calculated by double integration of acceleration and trajectory drift compensation using a p-chip interpolation function [16].

| Participant | Age (Year) | Mass (Kg) | Height (cm) |
|---|---|---|---|
| Female | 75.0±1.4 | 67.9±12.7 | 159.3±6.0 |
| Male | 74.9±1.3 | 82.4±11.9 | 171.9±6.9 |

**Table 1: Demographics of the participants in the study.**

Spatial gait descriptors including velocity (V), stride length (SL) and swing width (SW) were then calculated. Figure 2 depicts the flow of data for extraction of the spatiotemporal and clearance parameters.

### Estimation of Heel and Toe Clearance Parameters

The clearance parameters show the extremes of the heel and toe elevation from the ground during the swing phase. One should note that $P_{GF}^{k}(t)$ in Figure 2 is an estimate of the IMU trajectory. In order to calculate the heel and toe trajectories with regard to IMU placement on the shoe, we adopted the 2D kinematic model proposed in [11]. Suppose $\theta_{HS}$ be the pitch angle at heel strike after applying linear drift compensation between two successive foot-flat periods [11]. Moreover, suppose $P_{GF}^{k}(t)$ the vertical component of the foot trajectory at instant $t$ of the $k^{th}$ cycle. By defining the sensor distance with regard to the heel and toe as three unknowns $a$, $b$, $c$ (see Figure 2), the vertical trajectory of the sensor $P_{S}^{k}(t)$:

$$P_{S}^{k}(t) = P_{GF}^{k}(t) + b \tag{1}$$

Accordingly vertical trajectory of the toe $P_{Toe}^{k}(t)$ and heel $P_{Heel}^{k}(t)$ are given by:

$$P_{Toe}^{k}(t) = P_{GF}^{k}(t) - b.\cos\left(\theta_Y(t)\right) + c.\sin\left(\theta_Y(t)\right) \tag{2}$$

$$P_{Heel}^{k}(t) = P_{GF}^{k}(t) - b.\cos\left(\theta_Y(t)\right) - a.\sin\left(\theta_Y(t)\right) \tag{3}$$

Knowing the shoe size of the participant, the foot trajectory is constrained by Equation 4:

$$\begin{cases} a + c = Shoe\,Size \\ P_{Toe}^{k}(toe\_off) = 0 \\ P_{Heel}^{k}(heel\_strike) = 0 \end{cases} \tag{4}$$

At each cycle, from the instant when toe strikes the ground until the toe-off: $P_{Toe}^{k}(t) = 0$. Similarly, from heel-strike until the time when heel is lifted from the ground: $P_{Heel}^{k}(t) = 0$. Applying these two constraints over all cycles data, a least square solution was used to estimate $a$, $b$ and $c$ and then the 2D trajectory of the toe and heel were corrected. Thereafter, at each cycle the following clearance parameters were calculated: heel strike pitch angle ($\theta_{HS}$), maximum heel clearance (MaxHC), minimum toe clearance

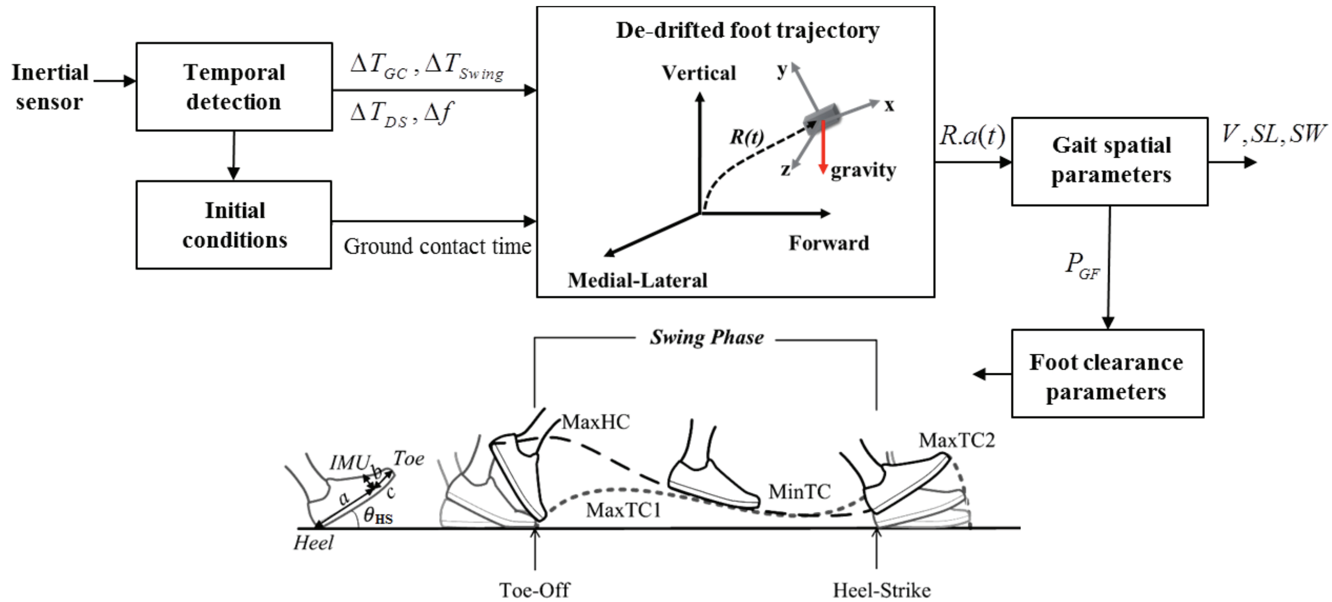


**Figure 2: Different steps of the gait analysis algorithm for extraction of spatiotemporal and clearance parameters using a shoe-worn inertial sensor. The heel (black line) and toe (light gray line) trajectories during swing phase and corresponding clearance parameters were also illustrated.**

(MinTC), first and second maxima of toe clearance trajectory (MaxTC1, MaxTC2).

These parameters have been illustrated in Figure 2. Technical validation of the abovementioned algorithm against Vicon motion capture has been previously addressed in [11].

### Gait Parameters Analysis

We calculated the average, standard deviation (SD) and coefficient of variation (CV) of the participant's trial for each of aforementioned parameters. The correlation of the spatiotemporal and foot clearance parameters was calculated to investigate common information between parameters ($\alpha$=0.05). Principal components analysis (on the CV value of gait spatiotemporal and clearance parameters) was used to investigate which parameters contribute most to gait data variability in older persons. Parameters with coefficient of 0.3 or higher were interpreted as being significant contributors to principal components (PC).

## RESULTS

The correlations between the average values of spatiotemporal and clearance parameters are shown in Table 2. Only $\theta_{HS}$ and MaxTC2 are significantly correlated with speed.

Four PCs contributed to 89.3% of gait data variability. The parameters that best represent each of these PCs are shown in Figure 3. The first two principal components contribute to 68.8% of variability of the data and all parameters above the threshold belong to the "Clearance" domain i.e. MaxTC1, MaxTC2 and $\theta_{HS}$ (Figure 3, left panel). The next two components that contribute to 20.5% variability of the data are temporal parameters i.e. $\Delta T_{GC}$, $\Delta T_{Swing}$, $\Delta T_{DS}$ and $\Delta f$ (Figure 3, right panel).

## DISCUSSION

An interesting finding of this study is the relation of gait speed and clearance parameters. Gait speed is considered as a reliable measure in geriatric assessment in clinical settings which correlates with functional ability and balance confidence [7, 20, 21]. Table 2 shows that most of clearance parameters (MaxHC, MinTC, MaxTC1) has no significant correlation with gait speed. Besides, gait speed is only significantly (but moderately) correlated to

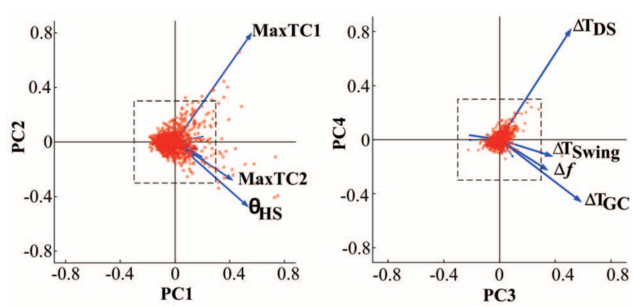


**Figure 3: Contribution of extracted parameters to variability of gait data (CV of parameters has been shown). Parameters with coefficient of 0.3 or higher (outside dotted square) were interpreted as being significant contributors to principal components.**

| | | Foot Clearance Parameters | | | | |
|---|---|---|---|---|---|---|
| | | $\theta_{HS}$ | MaxHC | MinTC | MaxTC1 | MaxTC2 |
| Temporal Parameters | $\Delta T_{GC}$ | 0.05 | 0.13 | 0.09 | 0.17 | 0.06 |
| | $\Delta f$ | 0.03 | 0.17 | 0.10 | 0.21 | 0.08 |
| | $\Delta T_{Swing}$ | 0.24 | 0.46 | 0.02 | 0.46 | 0.26 |
| | $\Delta T_{DS}$ | 0.28 | 0.48 | 0.01 | 0.43 | 0.32 |
| Spatial Parameters | V | 0.61* | 0.48 | 0.12 | 0.13 | 0.54* |
| | SL | 0.72* | 0.68* | 0.09 | 0.30 | 0.70* |
| | SW | 0.16 | 0.16 | 0.01 | 0.05 | 0.11 |

**Table 2: Correlation values between spatiotemporal and clearance parameters. * indicates significant correlations ( *$p<0.001$*) between spatiotemporal and clearance parameters.**

$\theta_{HS}$ and MaxTC2. Consequently, assessment of foot clearance parameters could bring new information for analysis of gait performance in a linear sense. Of note in Table 2 is that the correlation trend between SL and clearance parameters is similar to that between V and clearance parameters. This observation can be explained based on the strong linear relation between V and SL.

This study shed a new light on the main domain of variability in the gait data by considering a large cohort of community-dwelling elderly people. It has been previously suggested that the gait variability examination offers a complementary way of quantifying locomotion [22]. In [23], using electronic walkway (GAITRite®), gait cycle variability has been characterized by variability in $\Delta T_{GC}$, $\Delta T_{Swing}$, SL, SW and V. In the present study, by taking into account the foot clearance parameters, we provided new evidence that the variability in clearance parameters is more than three times higher than variability in spatiotemporal gait parameters (Figure 3). It is well-known that the gait variability changes with aging and disease [24]. Clearance parameters are associated with obstacle negotiation strategy [13], and thus assessment of foot clearance variability could be advantageous as a mean of monitoring the effects of rehabilitation and therapeutic interventions in older adults.

## CONCLUSION

Using shoe-worn inertial sensors, we realized that variability of foot clearance metrics contribute to the main variability of gait data that was not accounted for in previous studies [7, 23]. Moreover, only weak to moderate correlation of V (also SL) with some clearance parameters has been observed. Bearing in mind the association of MaxHC, MaxTC1 and MaxTC2 in obstacle negotiation, as well as $\theta_{HS}$ and MinTC in slipping and tripping related falls, assessment of clearance parameters during gait analysis is recommended to get further insight about the evolution of gait in elderly persons. Besides, characterization of the difference in clearance parameters between young people and older adults could be explicative of age-related gait pattern alteration in clinical research.

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