Stride count and frequency measured with a wrist-worn inertial sensor

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Abstract - This study proposes three simple approaches to estimate the stride count and frequency during walking and running using an inertial measurement system on the wrist. The approaches were based on a time-domain, frequency-domain and autocorrelation analysis, respectively. They were compared and validated against a reference on walks and runs of 16 participants in different conditions (different speeds, over ground and on treadmill). Results showed that the three methods provided an accurate and precise measure of the stride count and frequency: the median stride count error was 1 stride with a 90% confidence interval of 4 strides and the stride frequency presented a median error of 0.03 strides/min with a 90% confidence interval lower than 1.5 strides/min for all three methods. The approach, based on a wrist-worn inertial sensor, offers an effective and simple way to quantify the strides of healthy subjects in various conditions.

Keywords - pedometer; stride count; stride frequency; inertial sensor; gait analysis; wrist

1. Introduction

The analysis of human locomotion has received a lot of attention in the past decades. Temporal parameters related to the cyclic movement of locomotion, i.e. stride count and frequency, are useful for daily activity monitoring, disease assessment or sport science. To this end, body-worn inertial sensors provide an efficient measurement system as they are easy to use and have an unlimited capture volume. They were used in many studies which focused on the measurement of lower limbs and trunk movements for gait analysis. Several approaches were proposed to extract the stride count or frequency: event detection based on foot measurement [1-3], event detection, pendulum model or pattern matching from trunk data [4], frequency analysis [5] or autocorrelation analysis [6]. Although these methods provide an efficient way to quantify the stride frequency or number of performed strides, they still require a dedicated system and fixation to be attached on the foot (shoe dependent) or on the trunk (not very ergonomic). An interesting alternative is the use of a wrist-worn sensor which can be easily attached with a strap or integrated in a watch. Only a few studies used inertial sensors at the wrist or hand level to analyze gait [7, 8] and they reported errors up to 30% on the stride count. Moreover, during gait, arms can perform movement independent of locomotion. Thus, there are still open questions regarding the validity and robustness of current wrist-worn pedometers. The objective of this study was to implement different methods for determining the stride count and frequency based on a wrist-worn sensor. The accuracy and sensitivity of each method was compared to a reference system for different walking and running conditions.

2. Material and Methods

Measurements

Sixteen healthy participants (age between 21 and 30 with a mean of 26 years, eight men and eight women) were enrolled in the study, which was approved by the local Ethics committee. The participants were asked to perform different locomotion tasks on treadmill and over ground as described in Table 1. The self-selected walking and running speeds were evaluated in field conditions, during which the subject received the instruction to walk or run a given distance at their preferred speed. The measurement system was composed of inertial modules including a tri-axial accelerometer and gyroscope (Physilog®, GaitUp, CH) sampled at 200 Hz. One module was placed on each wrist, at the same position as one would wear a watch. Additionally, one module was placed on each foot as a reference for gait analysis using the algorithm proposed and validated by Mariani et al. [2].

Stride Detection and Frequency Estimation

The movements of each wrist were analyzed in order to extract the stride frequency and the number of strides for each trial. First, the locomotion periods were identified from the measurements using a threshold-based method: when the variance of the acceleration norm over a 1s period was larger than an empirically fixed threshold, the period was considered as a locomotion time. Then, three simple methods exploiting the cyclic behavior of arm swing during locomotion to extract the stride frequency were compared: time-domain, frequency-domain and autocorrelation analysis.

- The time-domain method was based on event detection. Principal component analysis was used to extract the principal axis of arm rotation during gait. It was hypothesized that each stride starts at a local maximum of the angular velocity around this axis of rotation. The stride frequency was defined as the inverse of the average duration between two successive strides and was expressed in strides/min.
- The frequency-domain approach used the spectrum of the acceleration norm. It was hypothesized that the dominant frequency of this spectrum corresponds to the stride frequency. To maximize frequency resolution, the spectrum was estimated by an autoregressive model instead of using a conventional Fourier transform.
- The autocorrelation-based approach was used to assess the periodicity of the acceleration norm. It was hypothesized that the duration between the peaks of the autocorrelation corresponds to the inverse of the stride frequency.

For both frequency-domain and autocorrelation methods, the number of strides was calculated as the locomotion duration divided by the estimated stride frequency. The reference stride count and frequency were given by the analysis of the feet inertial signals using the gait analysis algorithm of Mariani et al. [2].

Statistical Analysis

For each of the three methods, the estimated stride count and frequency was compared to the reference values. The differences over all trials were reported by the median value and the 90% confidence interval, i.e. the range between the 5th and 95th percentiles. ANOVA was used to investigate if the condition, participant or arm side (right and left) had an effect on the errors. The significance level was set to p=0.05.

3. Results

Data of 111 trials (16 participants, 7 conditions per participant, one outdoor running recording had to be cancelled due to heavy rainfall) were collected for both arm sides and analyzed, for a total of over 23’000 strides. All conditions were successfully analyzed with the three methods. The reference stride frequency was between 44 and 81 strides/min for walking and between 71 and 97 strides/min for running (Table 1). The number of strides per trial varied from 17 for free over ground walking to 186 for treadmill trials.

For the estimation of the stride frequency, all three methods performed similarly with a median error lower than 0.04 strides/min and a 90% confidence interval of lower than 1.5 stride/min (Table 2). The side (left and right) had no effect on the error and the participant only had an effect on the error for the autocorrelation method. The condition had a significant influence on the error for the time-domain and autocorrelation methods. The error on the estimated stride frequency did not depend on the measured value, i.e. the error is in the same range at low, medium and high frequencies (Fig. 1).

The stride counters performed similarly, with a median error in stride count of 1 stride. For 90% of the recorded trials, the error in the stride count is at most four strides, regardless of the trial type (Table 3). The absolute stride count error over all conditions seems to be consistent between methods. All methods have a higher overestimate of the stride counts for running than for walking (Fig. 2). For all three methods, the condition and the participant presented both a significant effect on the error, whereas the effect of arm side was not significant.

Table 1. Description of the measurement conditions and of the characteristics of the collected data by the reference system placed on the foot

Condition	**Description**	**Imposed speed**	**Frequency,** strides/min (mean ± std)	**Stride count** (mean ± std)
Walk – free	30 m over ground	Self-selected	57.3 ± 3.9	20.8 ± 1.7
Walk – slow	2 min treadmill	Self-selected - 1km/h	52.7 ± 4.0	110.7 ± 11.2
Walk – medium	2 min treadmill	Self-selected	58.3 ± 6.9	122.5 ± 15.5
Walk – fast	2 min treadmill	Self-selected + 1km/h	60.9 ± 3.6	127.2 ± 17.2
Run – free	100 m over ground	Self-selected	82.6 ± 6.1	40.8 ± 4.0
Run – medium	2 min treadmill	Self-selected	77.5 ± 4.3	150.9 ± 23.4
Run – fast	2 min treadmill	Self-selected + 1km/h	78.6 ± 4.6	158.7 ± 8.9

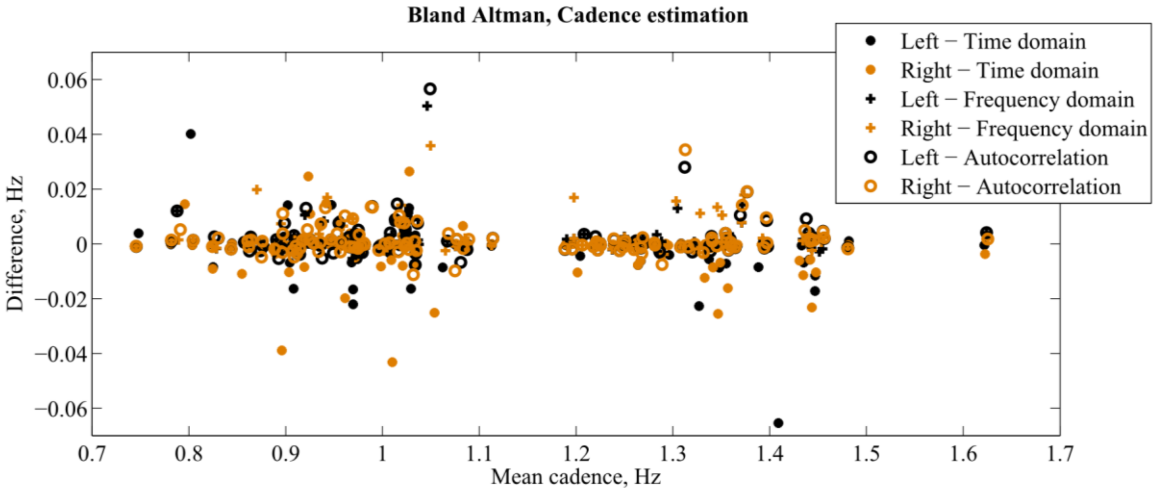

Figure 1. Bland Altman plot for the stride frequency estimation of the three methods, compared to the reference system. One outlier for the left side, frequency domain method, with an error of -0.125Hz has been omitted in the figure.

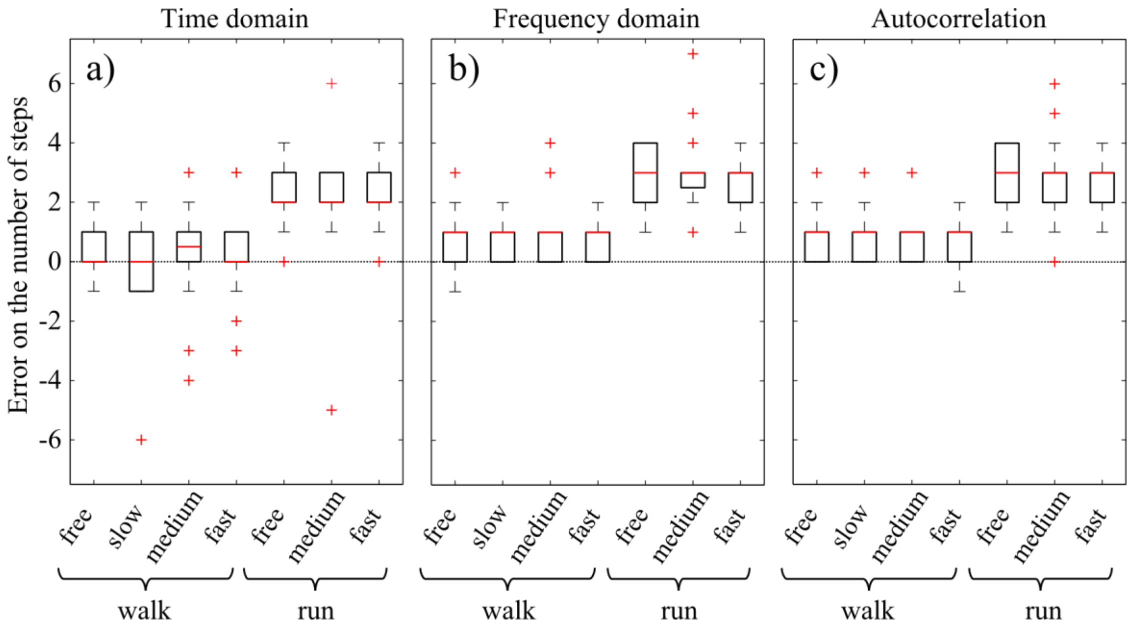

Figure 2. Boxplot of the error of the stride count according to the conditions for the three methods: a) time-domain analysis; b) frequency-domain analysis; c) autocorrelation

Table 2. Median and 90% confidence interval of the error on the stride frequency for the three methods, with the level of significance of the effects (condition, participant, side) on the error (n.s. = non-significant)

Method	**Stride frequency error,** strides/min	**ANOVA effects**		
	Median [90% CI]	***condition***	***participant***	***side***
Time domain	-0.02 [-0.99; 0.50]	< 0.001	n.s.	n.s.
Frequency domain	0.04 [-0.15; 0.74]	n.s.	n.s.	n.s.
Autocorrelation-based	0.02 [-0.21; 0.79]	< 0.001	0.03	n.s.

Table 3. Median and 90% confidence interval of the error of the stride count for the three methods, with the level of significance of the effects (condition, participant, side) on the error (n.s. = non-significant).

Method	**Stride count error**	**ANOVA effects**		
	Median [90% CI]	***condition***	***participant***	***side***
Time domain	1 [-1; 3]	< 0.001	0.007	n.s.
Frequency domain	1 [0; 4]	< 0.001	< 0.001	n.s.
Autocorrelation-based	1 [0; 4]	< 0.001	< 0.001	n.s.

4. Discussion

All three methods were able to accurately and precisely estimate the stride count and frequency for all conditions and participants. The stride frequency estimation error is independent from the measurement period as long as the gait speed is constant and has a sufficient duration. However, not all methods perform equally well for different conditions. The frequency-domain and autocorrelation analysis are more robust than the time-domain analysis. Arm swing breaks or artifacts due to voluntary arm movements are not affecting the stride frequency estimation as the entire measurement duration is averaged in the frequency domain and dominant frequency or main signal periodicity is not influenced by those additional movements. Compared to a previous study using a method based on frequency-domain analysis of accelerometer signals [8] that reported relative mean errors of the stride frequency estimated from arm and hand sensors in the order of 2%, with deviations of up to 35%, our algorithm performs better. However, it has to be emphasized that this previous work, in contrast to our project, allowed a variable sampling rate and used low quality inertial sensors (smartphones).

On the other hand, both the frequency-domain and autocorrelation methods do not directly detect each stride. Therefore, especially for very short walking durations of a few seconds, those methods may prove to be unreliable and give a wrong estimate of the stride count. In the current study, the error on the stride count did not depend on the walking duration. However, only locomotion durations between 20 seconds and 2 minutes were analyzed. The performance of the methods was not analyzed for very short locomotion durations or long durations with varying stride frequency. Additionally, the time-domain method is the only method which allows cutting the inertial signals into cycles for a further inter- or intra-cycle analysis of the locomotion.

In conclusion, the presented methods provide accurate and reliable measurement of the stride count and frequency for a wrist-mounted sensor. Depending on the application, either method can be implemented in order to obtain an optimal result. A reliable wrist-worn system further allows long term ubiquitous monitoring of the walking/running stride count and frequency for daily activity monitoring.

5. Acknowledgment

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