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Consistency of gait characteristics as determined from acceleration data collected at different trunk locations

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ABSTRACT

Estimates of gait characteristics may suffer from errors due to discrepancies in accelerometer location. This is particularly problematic for gait measurements in daily life settings, where consistent sensor positioning is difficult to achieve. To address this problem, we equipped 21 healthy adults with tri-axial accelerometers (DynaPort MiniMod, McRoberts) at the mid and lower lumbar spine and anterior superior iliac spine (L2, L5 and ASIS) while continuously walking outdoors back and forth (20 times) over a distance of 20 m, including turns. We compared 35 gait characteristics between sensor locations by absolute agreement intra-class correlations (2, 1; ICC). We repeated these analyses after applying a new method for off-line sensor realignment providing a unique definition of the vertical and, by symmetry optimization, the two horizontal axes. Agreement between L2 and L5 after realignment was excellent ($ICC > 0.9$) for stride time and frequency, speed and their corresponding variability and good ($ICC > 0.7$) for stride regularity, movement intensity, gait symmetry and smoothness and for local dynamic stability. ICC values benefited from sensor realignment. Agreement between ASIS and the lumbar locations was less strong, in particular for gait characteristics like symmetry, smoothness, and local dynamic stability (ICC generally < 0.7). Unfortunately, this lumbar-ASIS agreement did not benefit consistently from sensor realignment. Our findings show that gait characteristics are robust against limited repositioning error of sensors at the lumbar spine, in particular if our off-line realignment is applied. However, larger positioning differences (from lumbar positions to ASIS) yield less consistent estimates and should hence be avoided.

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1. Introduction

Because of their ease of use, low cost and low power requirements, accelerometers have become increasingly popular as a measurement tool for human movement. The trunk is often recommended for sensor placement, based on the assumption that it reflects the body's center of mass movement [1,2]. Accelerometers have been placed at belt [3] or waist height [4], at the hip [5] or at the sternum [6], and at the front [7] or back [8] of the trunk. Do signals obtained from these various anatomical landmarks allow for estimating equivalent characteristics of gait? Thus far, a general mapping between these different sensor placements has not yet been reported. The recorded accelerations may differ in a non-trivial way, e.g., due to relative movement of the sensor locations with trunk deformation, which cannot be compensated for when estimating gait characteristics. Potential differences may also occur if locations differ only by small amounts. This is unfortunate, for instance, when monitoring daily life activities with self-(re-)attachment of sensors so that precise positioning of the sensor cannot be guaranteed. Whenever sensor location affects the estimated gait characteristic, the way subjects wear the sensor may bias scientific results and interpretations. In that case estimates reflect individuals' dressing preferences rather than proper gait characteristics.

Earlier studies investigated validity [9,10] and consistency [11,12] of gait characteristics based on accelerometry, but consistency was typically assessed through measurements at different times or using different sensors and/or estimation methods. Studies particularly addressing effects of sensor location typically focused on activity monitoring and estimates of energy

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consumption [13–15] but hardly on generic gait characteristics. To fill the resulting lacuna we investigated the effect of sensor location on estimates of gait characteristics derived from trunk accelerations. These characteristics included standard gait parameters like gait speed, stride time, stride frequency and their corresponding variability, as well as parameters that are considered informative about fall risk and movement disorders like local dynamic stability, gait symmetry, gait smoothness and various measures of gait variability [16]. The characteristics derived from literature were typically developed and validated for a location in the lumbar region. In our study we tested whether these characteristics can be consistently achieved over a broader range of locations, which can occur in daily life measurements by repeated self-attachment or shifting during sensor use.

We studied (outdoors) over-ground walking over repeated short-distances where we included turns to investigate gait parameters obtained from activities such as in a daily life setting. The consistency of characteristics' estimators was assessed by the absolute agreement between estimates from different locations. Since sensor positioning can affect sensor orientation, we also tested the effect of a new off-line data realignment method.

2. Methods

2.1. Participants

In this study 21 healthy adults (9 males, age 27.7 ± 3.3 years, height 1.75 ± 0.10 m, weight 66 ± 10 kg) participated. All participants provided written informed consent before entering the experiment.

2.2. Protocol

Participants were asked to self-attach three tri-axial acceleration sensors sampling at 100 Hz with a [−6 g, 6 g] range (DynaPort MiniMod, McRoberts, The Hague, NL) fitted on elastic bands to their trunk by closing the elastic bands with Velcro straps in order to fit it secure but still comfortable. They were instructed to place the sensors at the back of the trunk at belt height (the lower lumbar spine, L5), at waist height (on the middle of the lumbar spine, L2) and on the front hip at belt height (the anterior superior iliac spine, ASIS). The effect of selecting the different locations simulates positioning errors that can occur when subjects (repeatedly) self-attach sensors and wear it for longer periods in daily life. The L2 and L5 locations could span a range of (intended) initial positions and effects of unintended shifting of the sensors, and ASIS represents extreme unintended displacement of the sensor. Fitted with the sensors, participants were instructed to walk outdoors on a tarmac surface at their preferred speed continuously twenty times up and down around two markers placed 20 m apart. The experiment had been approved by the ethics committee of the Faculty of Human Movement Sciences, VU University Amsterdam, before it was conducted.

2.3. Data analysis

2.3.1. Realignment

Each session to be analyzed was selected from the start of walking until the end of walking the 40 × 20 m, including all turns, by visual evaluation of the recordings. These data were subjected to further analysis realized in Matlab™ (Mathworks, Natwick, MA, version R2011a). Data were also aligned to a common, body-centered reference frame with axes in the vertical (VT), medio-lateral (ML) and anterior–posterior (AP) directions, to correct for the orientation component of positioning differences. The VT direction was defined as the direction of the average acceleration equivalent to the method proposed by Moe-Nilssen [17]. This method assumes that the average acceleration with respect to the ground is negligible, and the mean acceleration measured must thus oppose gravitation. We extended the method with the estimation of the orthogonal ML and AP directions by maximizing the product of their harmonic ratios (gait symmetry [18]) in the two-dimensional plane perpendicular to the (pre-)determined VT direction (see Appendix A). The realigned data underwent the same analysis as the raw data to evaluate the effect of the realignment.

2.3.2. Gait characteristics

We selected a set of 35 characteristics based on their potential value for determining gait stability and quality. All these characteristics have been shown or are promising to differ between old and young subjects, between patients and controls and/or between fallers and non-fallers (e.g. [16,19]). We determined one estimate for the characteristics per sensor. Data from the start to the end of walking, including all turns, were processed for each estimation.

Gait speed and *speed variability* estimations were based on step lengths using the method proposed by Zijlstra and Hof [3], i.e., as the average speed over the total estimated distance and the standard deviation of speed per stride, respectively. For the estimation of speed variability, the minimum and maximum 10% of stride speeds were excluded.

Movement intensity was estimated for each of the three directions as the signal's standard deviation, which is equivalent

Table 1
Mean (standard deviation) of estimated gait characteristics after sensor realignment.

Sensors	L5	L2	ASIS
Gait speed (m/s)	1.41 (0.15)	1.43 (0.15)	1.43 (0.13)
Speed variability (m/s)	0.06 (0.01)	0.06 (0.01)	0.06 (0.01)
Stride time (s)	1.01 (0.06)	1.01 (0.06)	1.01 (0.06)
Stride time variability (0.01 s)	1.70 (0.43)	1.63 (0.45)	1.63 (0.42)
Stride frequency (Hz)	0.99 (0.05)	0.99 (0.05)	0.99 (0.05)
Stride frequency variability VT	0.14 (0.04)	0.14 (0.04)	0.15 (0.05)
Stride frequency variability ML	0.16 (0.03)	0.16 (0.03)	0.15 (0.03)
Stride frequency variability AP	0.14 (0.04)	0.14 (0.04)	0.15 (0.04)
Stride regularity VT	0.83 (0.06)	0.81 (0.07)	0.84 (0.05)
Stride regularity ML	0.59 (0.14)	0.62 (0.11)	0.60 (0.10)
Stride regularity AP	0.71 (0.07)	0.69 (0.08)	0.73 (0.06)
Movement intensity VT (m/s^2)	3.41 (0.69)	3.42 (0.64)	3.38 (0.59)
Movement intensity ML (m/s^2)	2.02 (0.57)	1.75 (0.40)	1.81 (0.39)
Movement intensity AP (m/s^2)	2.25 (0.45)	2.16 (0.38)	2.41 (0.43)
Low-frequency percentage VT	0.03 (0.01)	0.02 (0.01)	0.02 (0.01)
Low-frequency percentage ML	1.03 (0.98)	2.11 (1.72)	2.54 (2.11)
Low-frequency percentage AP	0.76 (0.48)	1.97 (1.12)	1.41 (0.74)
Gait smoothness VT	0.80 (0.08)	0.83 (0.07)	0.87 (0.06)
Gait smoothness ML	0.09 (0.09)	0.10 (0.12)	0.36 (0.15)
Gait smoothness AP	0.53 (0.08)	0.50 (0.09)	0.53 (0.07)
Gait symmetry VT	4.61 (1.24)	4.97 (0.96)	2.59 (0.68)
Gait symmetry ML	2.98 (0.76)	2.91 (0.61)	2.49 (0.64)
Gait symmetry AP	3.91 (0.79)	3.92 (0.71)	2.42 (0.52)
Local dynamic stability Wolf VT (s^{-1})	0.74 (0.16)	0.80 (0.17)	0.69 (0.14)
Local dynamic stability Wolf ML (s^{-1})	1.20 (0.27)	1.13 (0.21)	1.19 (0.19)
Local dynamic stability Wolf AP (s^{-1})	1.01 (0.19)	1.09 (0.17)	0.95 (0.14)
Local dynamic stability Ros. VT (s^{-1})	0.60 (0.07)	0.64 (0.08)	0.54 (0.06)
Local dynamic stability Ros. ML (s^{-1})	0.55 (0.06)	0.53 (0.07)	0.49 (0.08)
Local dynamic stability Ros. AP (s^{-1})	0.54 (0.05)	0.50 (0.05)	0.52 (0.07)
Local dynamic stability Wolf VT/stride	0.75 (0.17)	0.81 (0.18)	0.70 (0.16)
Local dynamic stability Wolf ML/stride	1.22 (0.30)	1.15 (0.24)	1.21 (0.23)
Local dynamic stability Wolf AP/stride	1.02 (0.21)	1.10 (0.20)	0.96 (0.16)
Local dynamic stability Ros. VT/stride	0.60 (0.08)	0.64 (0.09)	0.55 (0.07)
Local dynamic stability Ros. ML/stride	0.56 (0.07)	0.54 (0.08)	0.50 (0.08)
Local dynamic stability Ros. AP/stride	0.55 (0.07)	0.51 (0.07)	0.52 (0.08)

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