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A wearable solution for accurate step detection based on the direct measurement of the inter-foot distance

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ABSTRACT

Accurate step detection is crucial for the estimation of gait spatio-temporal parameters. Although several step detection methods based on the use of inertial measurement units (IMUs) have been successfully proposed, they may not perform adequately when the foot is dragged while walking, when walking aids are used, or when walking at low speed. The aim of this study was to test an original step-detection method, the inter-foot distance step counter (IFOD), based on the direct measurement of the distance between feet. Gait data were recorded using a wearable prototype system (SWING^{2DS}), which integrates an IMU and two time-of-flight distance sensors (DSs). The system was attached to the medial side of the right foot with one DS positioned close to the forefoot (FORE$_{DS}$) and the other close to the rearfoot (REAR$_{DS}$). Sixteen healthy adults were asked to walk over ground for two minutes along a loop, including both rectilinear and curvilinear portions, during two experimental sessions. The accuracy of the IFOD step counter was assessed using a stereo-photogrammetric system as gold standard. The best performance was obtained for REAR$_{DS}$ with an accuracy higher than 99.8% for the instrumented foot step and 88.8% for the non-instrumented foot step during both rectilinear and curvilinear walks. Key features of the IFOD step counter are that it is possible to detect both right and left steps by instrumenting one foot only and that it does not rely on foot impact dynamics. The IFOD step counter can be combined with existing IMU-based methods for increasing step-detection accuracy.

1. Introduction

The accurate detection of steps during gait is crucial for the estimation of gait parameters that are typically analysed in clinical assessments and to measure daily motor activity-related quantities, such as the distance walked, gait speed, and energy expenditure (Lim et al., 2018; Yang and Hsu, 2010). During the last decade, inertial measurement units (IMUs) have been increasingly used to measure human movement both in clinical settings and in free-living conditions (Fong and Chan, 2010; Iosa et al., 2016). IMU-based step detection is obtained by recording accelerations and angular velocities from various body locations and by analysing the signals features using one of several methods proposed in the literature (Aminian et al., 2002; Bertoli et al., 2018; Caldas et al., 2017; Pham et al., 2017; Storm et al., 2016; Trojaniello et al., 2014). However, the performance of IMU-based methods generally deteriorates when highly abnormal gait patterns are analysed, when walking aids are used and when walking at low speed (Motl et al., 2011; Brian et al., 2014; Trojaniello et al., 2015). In this work, we preliminarily tested an original method for bilateral step detection based on the direct measurement of the distance between feet during gait, the inter-foot distance (IFOD) step counter. Gait data were recorded using a single miniaturised prototype system (SWING^{2DS}) attached to the foot, which incorporated two infrared time-of-flight distance sensors (DSs) (STMicroelectronics VL6180X Official Web Page, 2018). The performance of the IFOD step counter was assessed on healthy subjects for two different DS locations on the foot, during two over-ground walking sessions (test and retest).

2. Methods

2.1. System description – SWING^{2DS} system

The SWING^{2DS} includes a magneto-IMU and two DSs (mod. VL6180X, STMicroelectronics, Switzerland (STMicroelectronics

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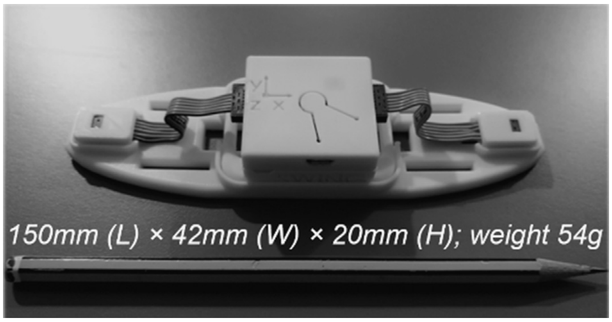

Fig. 1. SWING^{2DS} system embedded on a custom 3D-printed rigid support.

VL6180X Official Web Page, 2018) and represents an upgraded version of the D-MuSe system in terms of hardware performance and number of connectable DSs (Bertuletti et al., 2017). The system was embedded on a custom 3D-printed rigid support (Fig. 1) and attached to the medial side of the right foot with the IMU Z-axis made to coincide with the medio-lateral axis of the foot (Fig. 2a). The DSs were positioned orthogonally to the support and close to the first metatarsophalangeal joint ($FORE_{DS}$) and to the heel ($REAR_{DS}$).

2.2. Step detection method – IFOD step counter

During walking recordings, each DS returned a distance value when the two feet faced each other, hence twice per gait cycle, once during the swing of the instrumented foot (instrumented step, IN-step) and once during the swing of the non-instrumented foot (non-instrumented step, NIN-step). Bilateral step detection was performed by directly counting the number of time intervals characterised by non-zero distance values. Two non-zero distance values were considered to belong to the same time interval, and therefore identified the same step, if the time between the readings was less than 200 ms. This condition was applied to consider the potential multiple-distance readings during the same IN-foot swing (e.g. one distance reading at early-mid swing when the instrumented foot faces the contra-lateral shank and another at late swing when facing the contralateral foot). IN-steps and NIN-steps were discriminated offline by applying a subject-specific threshold on the values of the angular velocity component around the medio-lateral axis (ω_{ML}). Specifically, a non-zero distance time interval characterised by angular velocity higher than the 30% of the maximum ω_{ML} were labelled IN-steps and those that were lower were labelled NIN-steps.

2.3. Experimental data collection

SWING^{2DS} inertial data and DSs data were collected at 100 Hz and 50 Hz (DS maximum frequency) with the full scale of the gyroscope set to ±2000°·s^{-1} and the DS measurement range set to 0–200 mm. For validation purposes, two markers were placed on each foot (markers on the heel and on the first metatarsal head) (Fig. 2). Markers' trajectories were recorded using a nine-camera Vicon Bonita stereo-photogrammetric system (SP) sampling at 100 Hz. SWING^{2DS} and SP systems were software synchronised. The number of actual steps (A-step#) was counted by visually inspecting the heel and toe markers trajectories recorded with the SP. After providing their written informed consent, sixteen healthy adults (age [mean ± sd]: 39 ± 11 y.o.) walked on level ground at a self-selected pace for two minutes along a loop (including both curvilinear and rectilinear portions) during two sessions (test and retest, one week apart). Local ethics committee approval was previously obtained.

2.4. Data processing and accuracy assessment

Rectilinear and curvilinear walking sections were identified and segmented based on the trajectory of the heel marker of the instrumented foot, expressed in the SP coordinate system. For both DS locations ($REAR_{DS}$ and $FORE_{DS}$), the IFOD step counter accuracy was evaluated under the following conditions: (a) type of gait (rectilinear, curvilinear), (b) side (IN-step, NIN-step), and (c) session (test, retest).

As the SWING^{2DS} and SP systems were synchronised, for every experiment it was possible to quantify *(i)* A-step#, *(ii)* the number of missed and extra steps obtained with the IFOD step count, and *(iii)* the accuracy of the IFOD step counter. The latter was computed as the ratio between the IFOD step count (IN-step# and NIN-step#) and the actual number of steps (A-step#). For each condition, the average of the accuracy values across subjects was computed.

3. Results

An example of synchronised time-series of raw $REAR_{DS}$ and $FORE_{DS}$ data and right and left heel markers Z-axis trajectories during a rectilinear walk is reported in Fig. 3.

A total of 5077 steps were analysed: 2763 in the rectilinear portion of the loop (INstep# = 1390 and NIN-step# = 1373) and 2314 in the curvilinear (IN-step# = 1151 and NIN-step# = 1163) portion of the loop. The performance of the IFOD step counter is reported for rectilinear walks in Table 1 and for curvilinear walks in Table 2. For neither DS location the IFOD step counter detected extra steps. The accuracy of $REAR_{DS}$ ($FORE_{DS}$) varied in the range of 96.1–100% (92.0–99.9%) during rectilinear walking and between 88.8% and 100.0% (75.8–100.0%) during curvilinear walking.

4. Discussion

The IFOD step counter detects steps during both straight and curvilinear walks based on direct measurements of the time-variant inter-foot distance. The most effective DS location was the back of the foot ($REAR_{DS}$) which showed, for both rectilinear and curvilinear conditions, an accuracy higher than 99.8% and 88.8% for IN-step and NIN-step detection, respectively. The method's accuracy slightly deteriorated in the $FORE_{DS}$ configuration, and in particular for NIN-step detection during the curvilinear walking (accuracy ≥75.8%). It is worth noting that the lower

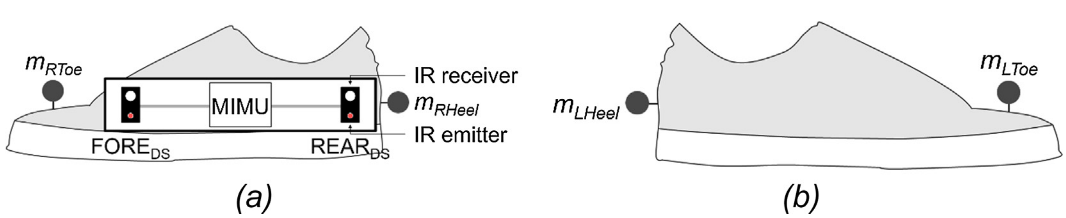

Fig. 2. Experimental setup: (a) right foot with the SWING^{2DS} system (instrumented foot); (b) left foot (non-instrumented foot).

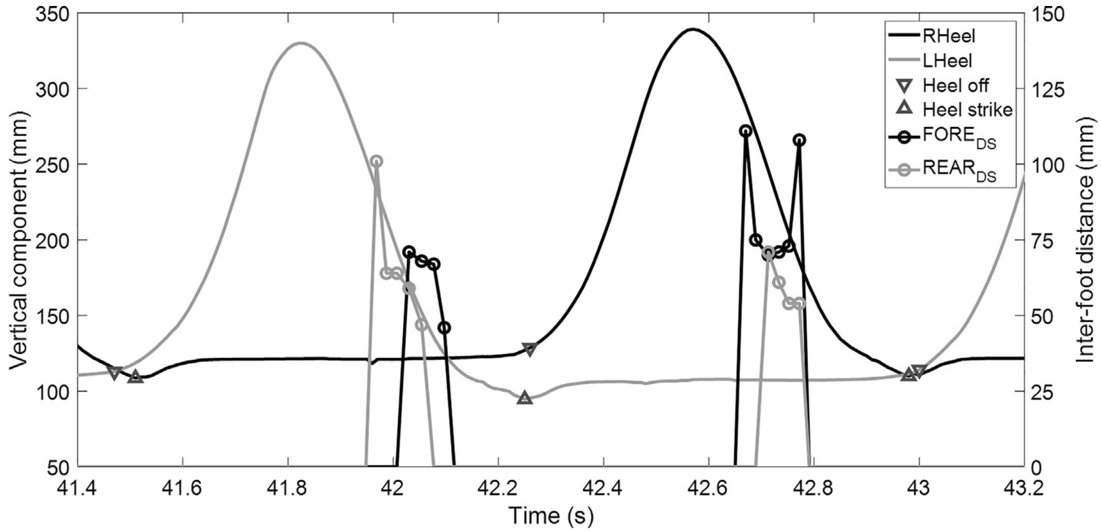

Fig. 3. Synchronised time-series of raw SWING^{2DS} data (REAR$_{DS}$ and FORE$_{DS}$) and vertical component (Z-axis) of right and left heel markers (triangular markers indicate the heel strike and heel off) for the stride of a subject during a rectilinear walk.

Table 1
Performance of the IFOD method for REAR$_{DS}$ and FORE$_{DS}$ locations, instrumented step (IN-step) and non-instrumented step (NIN-step), and test and retest sessions for rectilinear walking portions.

		IN-step				NIN-step			
		A-step [#]	Missed [#]	Extra [#]	Accuracy [%]	A-step [#]	Missed [#]	Extra [#]	Accuracy [%]
REAR$_{DS}$	Test	684	0	0	100.0	687	0	0	100.0
	Retest	706	0	0	100.0	686	27	0	96.1
FORE$_{DS}$	Test	684	1	0	99.9	687	18	0	97.4
	Retest	706	3	0	99.6	686	55	0	92.0

Table 2
Performance of the IFOD method for REAR$_{DS}$ and FORE$_{DS}$ locations, instrumented step (IN-step) and non-instrumented step (NIN-step), and test and retest sessions for curvilinear walking portions.

		IN-step				NIN-step			
		A-step [#]	Missed [#]	Extra [#]	Accuracy [%]	A-step [#]	Missed [#]	Extra [#]	Accuracy [%]
REAR$_{DS}$	Test	575	0	0	100.0	576	6	0	99.0
	Retest	576	1	0	99.8	0	66	0	88.8
FORE$_{DS}$	Test	575	0	0	100.0	576	58	0	89.9
	Retest	576	6	0	99.0	587	142	0	75.8

accuracy observed during retest session was the result of the SWING^{2DS} system being positioned too close to the ground for two of the subjects. In those cases, during the stance of the instrumented foot, the DS did not detect any distance because the subjects raised the non-instrumented foot higher than DSs (Fig. 4a). If those two subjects are excluded from the analysis, the IFOD step counter applied to the REAR$_{DS}$ detected both IN-steps and NIN-steps with a 100% accuracy during both rectilinear and curvilinear walks.

Key features of the IFOD step counter, compared to previously proposed IMU-based methods are that it needs only one foot to be instrumented to detect both left and right steps, and the step detection does not rely on foot-impact dynamics or on angular velocity patterns. Indeed, the IFOD step counter relies exclusively on a single feature of walking: the feet facing each other twice in a gait cycle. For this reason, the IFOD step counter can represent an attractive solution for step detection in subjects walking with severe gait impairments (e.g. hemiparetic subjects dragging a foot) or using walking aids, although its accuracy in populations with gait disorders has not yet been assessed. Conversely, as opposed to IMU-based methods, the IFOD step counter cannot be used to determine initial and final foot contacts, which are used to identify the gait cycle phases. However, as the IFOD step counter and IMU-based methods are based on different sensor technologies, they have complementary features, and could therefore be combined and integrated within a sensor fusion framework, increasing step detection accuracy while reducing the limitations of a single specific technology. Within the experimental setup adopted in this study, potential limitations are that *(i)* a step may be missed when a subject walks with an excessive external foot rotation, causing a distance between feet larger than the maximum distance range of the DSs, *(ii)* a step may be missed when a subject walks with a large foot clearance causing no reflection of the infrared (IR) waves emitted by the DSs, and *(iii)* an extra step may be counted while walking on uneven ground which causes a reflection of the IR waves emitted by the DSs with something between the feet. Therefore, while implementing the IFOD step counter, precautions

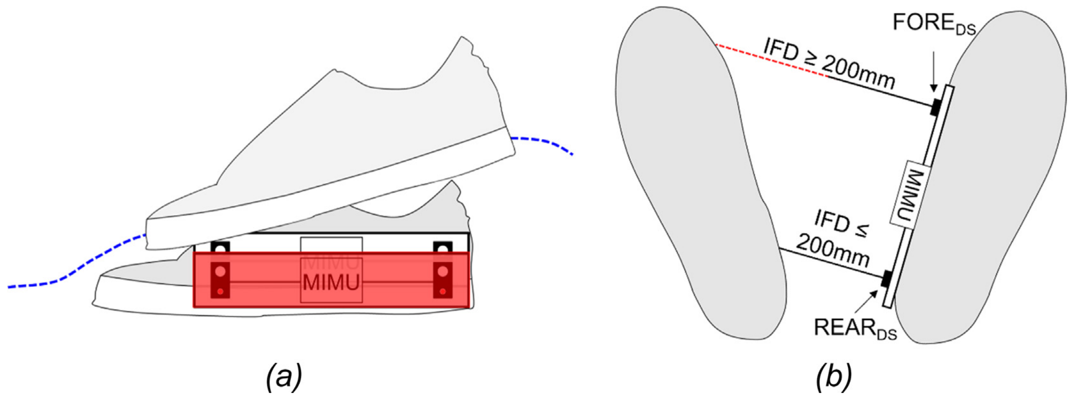

Fig. 4. Potential missed-step scenarios: (a) the distance sensor was positioned too close to the ground and/or a large foot clearance of the contralateral foot during swing; (b) an abnormal foot external rotation during walking and/or an excessively large base of support.

should be taken: the DS should not be positioned too close to the ground and its measurement range should be set high enough to consider excessive external foot rotation (Simic et al., 2013) (Fig. 4). Since an increase of the range of measurement implies both a decrease of the DS sensor resolution and a lower sample frequency (i.e. range 0–200 mm: 1 mm resolution and 50 Hz maximum sample frequency; range 0–400 mm: 2 mm resolution and 33 Hz maximum sample frequency; range 0–600 mm: 3 mm resolution and 25 Hz maximum sample frequency), a trade-off should be pursued. Two potential solutions to increase the method's robustness are *(i)* the design of a support that enables the user to adjust the orientation of the DS to compensate for excessive external foot rotation, and *(ii)* the placement of the DS on the shank to reduce the effect of excessive external foot rotation and artefacts due to uneven terrain.

Conflict of interest statement

None.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2018.12.039.

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