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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

35 energy expenditure [7] [16]. During the last decade, inertial measurement units
36 (IMUs) have been increasingly used to measure human movement both in clinical
37 settings and in free-living conditions [5] [6]. IMU-based step detection is obtained by
38 recording accelerations and angular velocities from various body locations and by
39 analysing the signals features using one of several methods proposed in the
40 literature [1] [2] [4] [9] [13] [14]. However, the performance of IMU-based methods
41 generally deteriorates when highly abnormal gait patterns are analysed, when
42 walking aids are used and when walking at low speed [8] [10] [15]. In this work, we
43 preliminarily tested an original method for bilateral step detection based on the direct
44 measurement of the distance between feet during gait, the inter-foot distance (IFOD)
45 step counter. Gait data were recorded using a single miniaturised prototype system
46 (SWING^{2DS}) attached to the foot, which incorporated two infrared time-of-flight
47 distance sensors (DSs) [12]. The performance of the IFOD step counter was
48 assessed on healthy subjects for two different DS locations on the foot, during two
49 over-ground walking sessions (test and retest).

50

51 **2. METHODS**

52 *2.1 System description - SWING^{2DS} system*

53 The SWING^{2DS} includes a magneto-IMU and two DSs (mod. VL6180X,
54 STMicroelectronics, Switzerland [12]) and represents an upgraded version of the D-
55 MuSe system in terms of hardware performance and number of connectable DSs [3].
56 The system was embedded on a custom 3D-printed rigid support (Fig. 1) and
57 attached to the medial side of the right foot with the IMU Z-axis made to coincide
58 with the medio-lateral axis of the foot (Fig. 2a). The DSs were positioned
59 orthogonally to the support and close to the first metatarsophalangeal joint (FORE_{DS})
60 and to the heel (REAR_{DS}).

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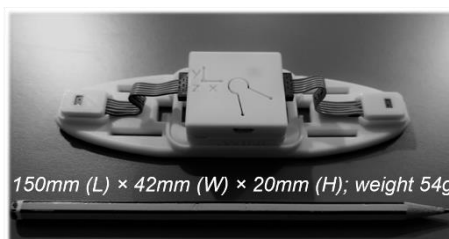


Fig. 1: SWING^{2DS} system embedded on a custom 3D-printed rigid support.

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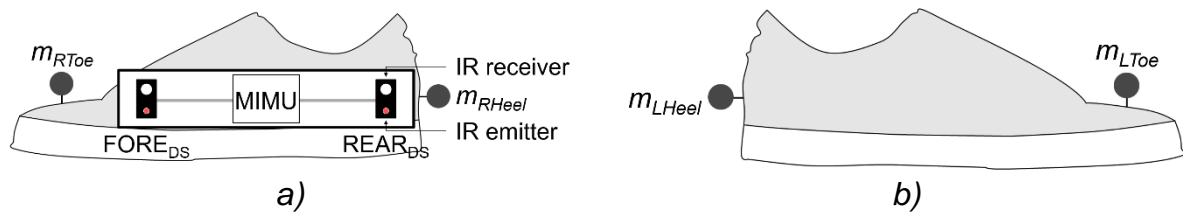


Fig. 2: Experimental setup: a) right foot with the SWING^{2DS} system (instrumented foot); b) left foot (non-instrumented foot).

63

64 2.2 Step detection method - IFOD step counter

65 During walking recordings, each DS returned a distance value when the two feet
66 faced each other, hence twice per gait cycle, once during the swing of the
67 instrumented foot (instrumented step, IN-step) and once during the swing of the
68 non-instrumented foot (non-instrumented step, NIN-step). Bilateral step detection was
69 performed by directly counting the number of time intervals characterised by non-
70 zero distance values. Two non-zero distance values were considered to belong to
71 the same time interval, and therefore identified the same step, if the time between
72 the readings was less than 200ms. This condition was applied to consider the
73 potential multiple-distance readings during the same IN-foot swing (e.g. one distance
74 reading at early-mid swing when the instrumented foot faces the contra-lateral shank
75 and another at late swing when facing the contralateral foot). IN-steps and NIN-steps
76 were discriminated offline by applying a subject-specific threshold on the values of
77 the angular velocity component around the medio-lateral axis (ω_{ML}). Specifically, a
78 non-zero distance time interval characterised by angular velocity higher than the
79 30% of the maximum ω_{ML} were labelled IN-steps and those that were lower were
80 labelled NIN-steps.

81

82 2.3 Experimental data collection

83 SWING^{2DS} inertial data and DSs data were collected at 100Hz and 50Hz (DS
84 maximum frequency) with the full scale of the gyroscope set to $\pm 2000^\circ \cdot s^{-1}$ and the
85 DS measurement range set to 0–200mm. For validation purposes, two markers were
86 placed on each foot (markers on the heel and on the first metatarsal head) (Fig. 2).
87 Markers' trajectories were recorded using a nine-camera Vicon Bonita stereo-
88 photogrammetric system (SP) sampling at 100Hz. SWING^{2DS} and SP systems were
89 software synchronised. The number of actual steps (A-step#) was counted by
90 visually inspecting the heel and toe markers trajectories recorded with the SP. After

91 providing their written informed consent, sixteen healthy adults (age [mean \pm sd]:
92 39 ± 11 y.o.) walked on level ground at a self-selected pace for two minutes along a
93 loop (including both curvilinear and rectilinear portions) during two sessions (test and
94 retest, one week apart). Local ethics committee approval was previously obtained.

95

96 2.4 Data processing and accuracy assessment

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

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

108

109 RESULTS

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

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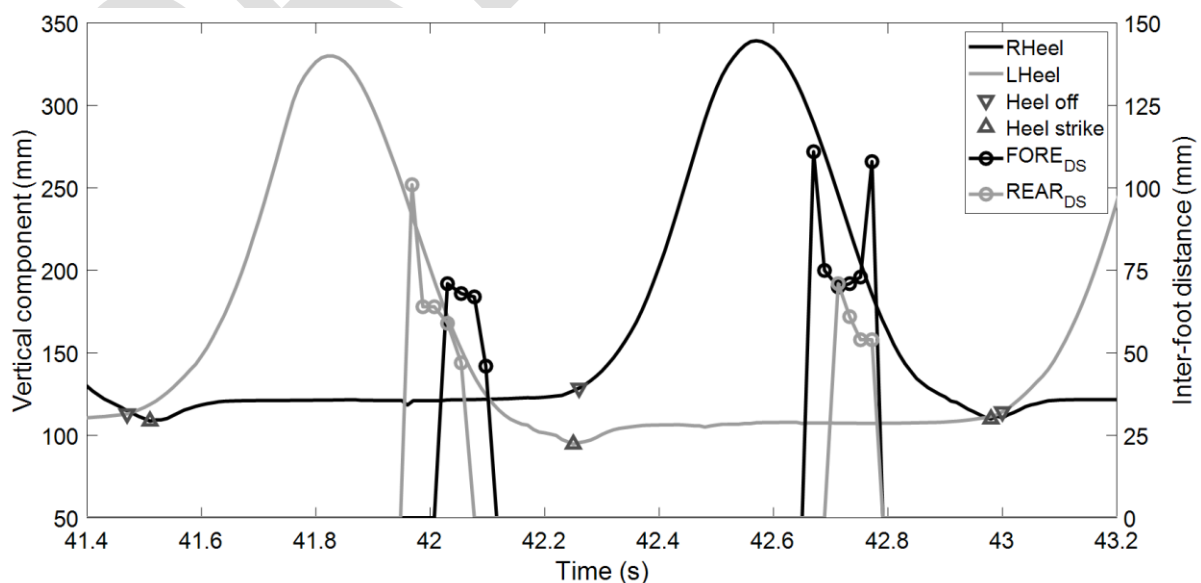


Fig. 3: Synchronised time-series of raw SWING^{2DS} data (REAR_{DS} and FORE_{DS}) and vertical component (Z-axis) of right and left heel markers (triangular markers indicate the heel strike and heel off) for the stride of a subject during a rectilinear walk.

113

114 A total of 5,077 steps were analysed: 2,763 in the rectilinear portion of the loop
 115 (INstep#=1,390 and NIN-step#=1,373) and 2,314 in the curvilinear (IN-step#=1,151
 116 and NIN-step#=1,163) portion of the loop. The performance of the IFOD step counter
 117 is reported for rectilinear walks in Table 1 and for curvilinear walks in Table 2. For
 118 neither DS location the IFOD step counter detected extra steps. The accuracy of
 119 REAR_{DS} (FORE_{DS}) varied in the range of 96.1–100% (92.0–99.9%) during rectilinear
 120 walking and between 88.8–100.0% (75.8–100.0%) during curvilinear walking.

121

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 |

122

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 | 587 | 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 |

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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 $\geq 75.8\%$). It is worth noting that the lower 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.

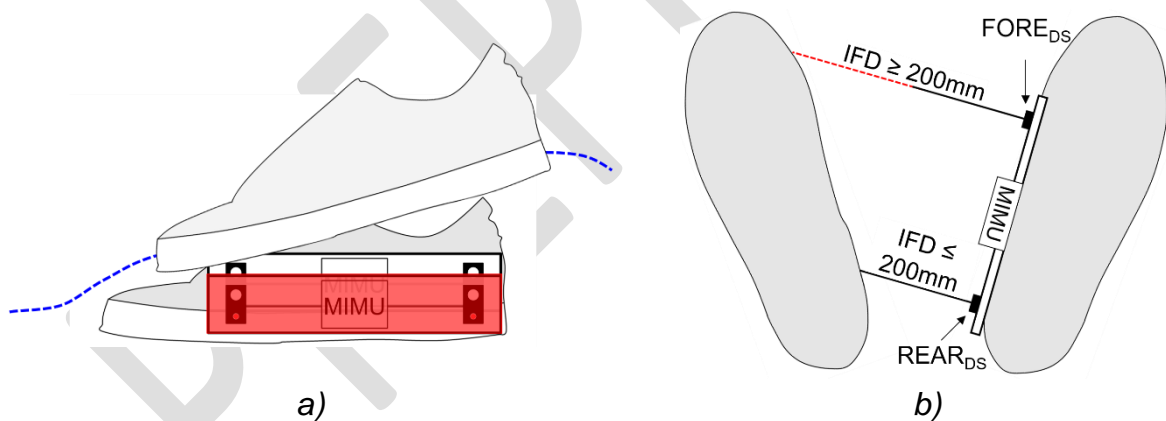


Fig. 4: Potential missed-step scenarios: a) the distance sensor was positioned too close to the ground and/or a large foot clearance of the contralateral foot during swing; b) an abnormal foot external rotation during walking and/or an excessively large base of support.

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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

145 single feature of walking: the feet facing each other twice in a gait cycle. For this
146 reason, the IFOD step counter can represent an attractive solution for step detection
147 in subjects walking with severe gait impairments (e.g. hemiparetic subjects dragging
148 a foot) or using walking aids, although its accuracy in populations with gait disorders
149 has not yet been assessed. Conversely, as opposed to IMU-based methods, the
150 IFOD step counter cannot be used to determine initial and final foot contacts, which
151 are used to identify the gait cycle phases. However, as the IFOD step counter and
152 IMU-based methods are based on different sensor technologies, they have
153 complementary features, and could therefore be combined and integrated within a
154 sensor fusion framework, increasing step detection accuracy while reducing the
155 limitations of a single specific technology. Within the experimental setup adopted in
156 this study, potential limitations are that (i) a step may be missed when a subject
157 walks with an excessive external foot rotation, causing a distance between feet
158 larger than the maximum distance range of the DSs, (ii) a step may be missed when
159 a subject walks with a large foot clearance causing no reflection of the infrared (IR)
160 waves emitted by the DSs, and (iii) an extra step may be counted while walking on
161 uneven ground which causes a reflection of the IR waves emitted by the DSs with
162 something between the feet. Therefore, while implementing the IFOD step counter,
163 precautions should be taken: the DS should not be positioned too close to the
164 ground and its measurement range should be set high enough to consider excessive
165 external foot rotation [11] (Fig. 4). Since an increase of the range of measurement
166 implies both a decrease of the DS sensor resolution and a lower sample frequency
167 (i.e. range 0–200mm: 1mm resolution and 50Hz maximum sample frequency; range
168 0–400mm: 2mm resolution and 33Hz maximum sample frequency; range 0–600mm:
169 3mm resolution and 25Hz maximum sample frequency), a trade-off should be
170 pursued. Two potential solutions to increase the method's robustness are (i) the
171 design of a support that enables the user to adjust the orientation of the DS to
172 compensate for excessive external foot rotation, and (ii) the placement of the DS on
173 the shank to reduce the effect of excessive external foot rotation and artefacts due to
174 uneven terrain.

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