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Inter-leg distance measurement as a tool for accurate step counting in patients with multiple sclerosis

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Abstract— Step detection is commonly performed using wearable inertial devices. However, methods based on the extraction of signals features may deteriorate their accuracy when applied to very slow walkers with abnormal gait patterns. The aim of this study is to test and validate an innovative step counter method (DiSC) based on the direct measurement of inter-leg distance. Data were recorded using an innovative wearable system which integrates a magneto-inertial unit and multiple distance sensors (DSs) attached to the shank. The method allowed for the detection of both left and right steps using a single device and was validated on thirteen people affected by multiple sclerosis (0 < EDSS < 6.5) while performing a six-minute walking test. Two different measurement ranges for the distance sensor were tested (DS_{200}: 0–200 mm; DS_{400}: 0–400 mm). Accuracy was evaluated by comparing the estimates of the DiSC method against video recordings used as gold standard. Preliminary results showed a good accuracy in detecting steps with half the errors in detecting the step of the instrumented side compared to the non-instrumented (mean absolute percentage error 2.4% vs 4.8% for DS_{200}; mean absolute percentage error 2% vs 5.4% for DS_{400}). When averaging errors across patients, over and under estimation errors were compensated, and very high accuracy was achieved ($E_{\%}$<1.2% for DS_{200}; $E_{\%}$<0.7% for DS_{400}). DS_{400} is the suggested configuration for patients walking with a large base of support.

I. Introduction

Multiple sclerosis (MS) is a chronic and progressive immune mediated neurological disorder of the central nervous system which causes conduction delays and blockage of electrical potentials along the central neuronal pathways. Although people with MS have a life expectancy similar to that of the general population, they suffer from multiple symptoms including spasticity, weakness, tremor, fatigue, cognitive disabilities and difficulties in performing daily activities. About 40% of people with MS have difficulty in walking and 50% requires walking assistive aids within 15 years of diagnosis [1, 2].

The most commonly used clinical scale to monitor the progress of a patient with MS is the expanded disability status scale (EDSS). The EDSS ranges from 0 (normal) to 10 (death due to MS). Scores from 0 to 2.5 refer to people with MS who have mild disability, 3 to 5 refer to people with moderate disability, but can still walk at least 100 meters without aids, while scores above 5 refer to people with MS who require an aid to walk (severe disability) [3].

Clinical scales are often accompanied by clinical motor tests such as the six-minute walking test (6MWT), which provide quantitative information about subject motor capacity. Recently, the 6MWT has been better characterised with wearable inertial sensors (IMU) thus providing a finer and quantitative description of a subject's gait. The effectiveness of IMU based analysis has already been extensively proven [4]. However, IMU-based methods may not be effective in detecting steps when gait patterns are highly abnormal (e.g. low speed walks, foot-dragging walks, and use of walking aids) [5]. In such cases, alternative technological solutions are required to overcome the intrinsic limitations associated with the IMU-based methods. In this respect, time-of-flight distance sensor (DS) represents a promising technology for human movement analysis applications due to its small size (~ 15 mm^3), sampling frequency up to 50 Hz, measurement range up to 600 mm and spatial resolution down to 1 mm [6].

The aim of this study is to test and validate an innovative method for step detection in people with MS (normal to severe disability) while performing a 6MWT. The method, referred to as DiSC (distance sensor step counter), is based on the use of a single wearable system (SWING), which integrates a magneto-IMU and a DS, and allows the detection of both right and left steps. The DiSC method was applied in a previous study [7] on gait data recorded on healthy adults during two different experimental sessions.

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II. Material and Methods

A. System description – SWING system

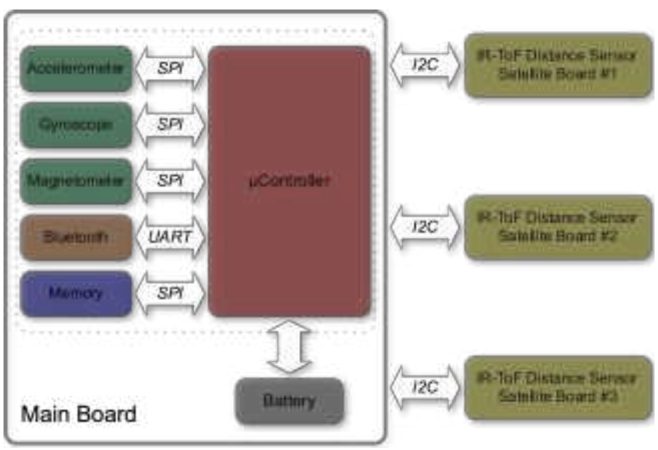
The SWING wearable multi-sensor system, developed at the Bioengineering Laboratory of the University of Sassari [8], integrates a triaxial accelerometer (full-scale range of ±2 / ±4 / ±8 / ±16 g), a triaxial gyroscope (±125 / ±250 / ±500 / ±1000 / ±2000 degree·s^{-1}), a triaxial magnetometer (±2 / ±4 / ±8 / ±12 gauss) and up to three time-of-flight distance sensors (mod. VL6180X, STMicroelectronics, Switzerland [6]). Each DS provides distance readings by estimating the time that an electromagnetic wave (i.e. infrared ray) takes to travel a distance or, more properly, by measuring the phase shift between the emitted and the reflected signals. Magneto-inertial measurements can be sampled at a maximum frequency of 200 Hz, while the maximum sampling frequency for DSs readings is 50 Hz. A summary of the specifications of the time-of-flight DS is reported in Table I.

TABLE I. Specifications of the VL6180X time-of-flight distance sensor [6].

Range (mm)	Resolution (mm)	Sampling frequency (Hz)
0–200	1	Up to 50
0–400	2	Up to 33
0–600	3	Up to 25

A Bluetooth module and a 128 Mbit flash non-volatile memory were integrated into the system to enable stream and log modes, respectively. Fig. 1 shows the block diagram of the SWING system.

Figure 1. Block diagram of the SWING system.



B. Participants

The recruitment of participants and data collection took place at the Royal Hallamshire Hospital, Sheffield, UK. The study was conducted according to the declaration of Helsinki and received ethical approval from the North of Scotland ethics committee.

The inclusion criteria for the participation in the study were: i) diagnosis of MS based on the McDonald's criteria (revised in 2017) [9], ii) age > 18 years, iii) cognitive ability to give informed consent, and iv) ability to walk for six minutes without rest. Thirteen participants were recruited after obtaining an informed consent. The severity of MS was measured using the EDSS [2]. Participants' demographic and clinical characteristics are shown in Table II.

TABLE II. Demographic and clinical characteristics of patients.

Characteristics	
Age (years)	42 ± 12
Sex (women:men)	5 : 8
Height (m)	1.74 ± 0.10
Weight (kg)	75 ± 20
MS type (n, %)	
RRMS	11 / 13 (85%)
SPMS	2 / 13 (15%)
MS duration (months)	133 ± 107
EDSS	5 ± 2

Note: All data are presented as mean ± SD unless otherwise noted; RRMS = relapsing-remitting multiple sclerosis; SPMS = secondary-progressive multiple sclerosis.

C. Equipment and protocol

To identify the most appropriate DS measurement range, the SWING system was used in the two-DSs configuration ($SWING^{2DS}$) with two different full scales (DS_{200}: 0–200 mm; DS_{400}: 0–400 mm). The $SWING^{2DS}$ system was attached to the medial side of the right shank by means of a custom made support and two elastic straps (Fig. 2). Recordings started with participants in the standing position for about 5 s with their heels aligned to the start line. Participants were asked to complete a 6MWT while walking in a corridor along a closed loop (including 10 m straight and turn portions) (Fig. 3). Two video cameras (60 frames per second) were placed one at each turn of the loop and used as reference system.

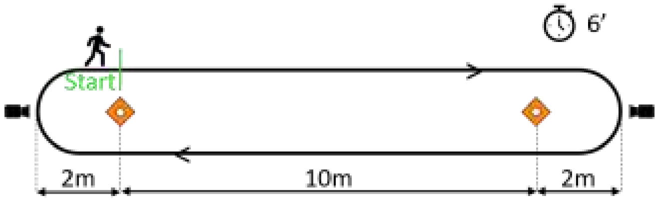
D. Data analysis

The current version of the DiSC method is based only on the data recorded by a gyroscope and a DS and consisted of two phases: 1) the detection of right and left steps, and 2) the identification of instrumented and non-instrumented steps (IN-step/NIN-step).

Bilateral step detection was performed using distance data provided from each DS by counting the number of distinct non-zero distance values intervals. Distance readings were

Figure 2. A patient with multiple sclerosis wearing the $SWING^{2DS}$ system positioned above the right medial malleoluswith the DSs pointing to the contralateral leg.

Figure 3. A schematic view of the six-minute walking test performed by a patient with multiple sclerosis.



considered to belong to the same step when separated by a time interval below 200 ms, to account for accidental multiple-distance readings during the same IN/NIN-step (early-mid swing and late swing phases).

The distinction between IN-step and NIN-step was performed offline. First, the medio-lateral component of the angular velocity (ω_{ML}) was pre-processed by removing the offset during the initial standing position. Subsequently, the signal was low-pass filtered (cut-off frequency of 5 Hz) for reducing high frequency noise. The first IN-step was identified as the first non-zero distance data interval with a ω_{ML} value larger than a threshold ε_1 (computed as the 30% of the mean value of ω_{ML} peaks over the trial). Six minutes of data starting from the instant of time of the initial value of the first IN-step were considered. To distinguish between IN-steps and NIN-steps, for each non-zero distance values interval (Δt), the local maximum of ω_{ML} was compared with a threshold ε_2 (calculated as the 20% of the mean value of ω_{ML} peaks over the trial). Steps were labelled as IN-step when the maximum ω_{ML} value in the non-zero distance values interval was above ε_2, and as NIN-step when the latter value was below ε_2. An example of the DiSC method application on a patient with an abnormal gait and severe disability (EDSS = 6) is depicted in Fig. 4. The actual number of steps was visually determined by an operator from video recordings for both instrumented and non-instrumented legs (A-IN-step and A-NIN-step). The accuracy of the DiSC method was assessed as the difference between the number of steps estimated using the DiSC method (IN-step and NIN-step, step#) and the number of steps obtained by the reference system (A-step#). Error, percentage error, absolute error and absolute percentage error were computed for each participant as follows:

$$e = step\# - A\text{-}step\# \quad (1)$$

$$e_{\%} = (step\# - A\text{-}step\#) / A\text{-}step\# \cdot 100 \quad (2)$$

$$mae = |step\# - A\text{-}step\#| \quad (3)$$

$$mae_{\%} = |step\# - A\text{-}step\#| / A\text{-}step\# \cdot 100 \quad (4)$$

The grand mean and standard deviation values of the latter indices were computed across participants (E ± SD, MAE ± SD, and $MAE_{\%}$ ± SD). Difference plots (Bland–Altman) were used to assess the agreement between the measures and evaluate bias between the scores of the two DSs configurations.

III. RESULTS

Among the total of 6,876 steps, 3,436 were IN-steps and 3,440 were NIN-steps. The overall performances of the DiSC method for both DSs configurations are shown in TABLE III.

TABLE III. THE DISC METHOD PERFORMANCE ACROSS PATIENTS FOR EACH DS CONFIGURATION (DS_{200} VS DS_{400}) AND INSTRUMENTED/NON-INSTRUMENTED LEG.

	IN-Step		NIN-Step	
	DS_{200}	DS_{400}	DS_{200}	DS_{400}
A-step ± SD (#steps)	264 ± 68		265 ± 67	
step ± SD (#steps)	263 ± 63	265 ± 65	259 ± 62	264 ± 67
E ± SD (#steps)	-1 ± 8	0 ± 7	-6 ± 18	0 ± 19
$E_{\%}$ ± SD (%)	0.2 ± 4.2	0.6 ± 3.2	1.2 ±8.5	0.7 ±12
MAE ± SD (#steps)	5 ± 6	4 ± 5	11 ± 16	9 ± 16
MAE% ± SD (%)	2.4 ± 3.4	2 ± 2.5	4.8 ± 7	5.4 ± 10.7

Figure 4. Example of the DiSC method application for both DSs configurations on a patient who showed an abnormal gait and a severe disability (EDSS = 6). DS_{400} detected 641 out of 641 steps, while DS_{200} missed 58 steps (583 out of 641).

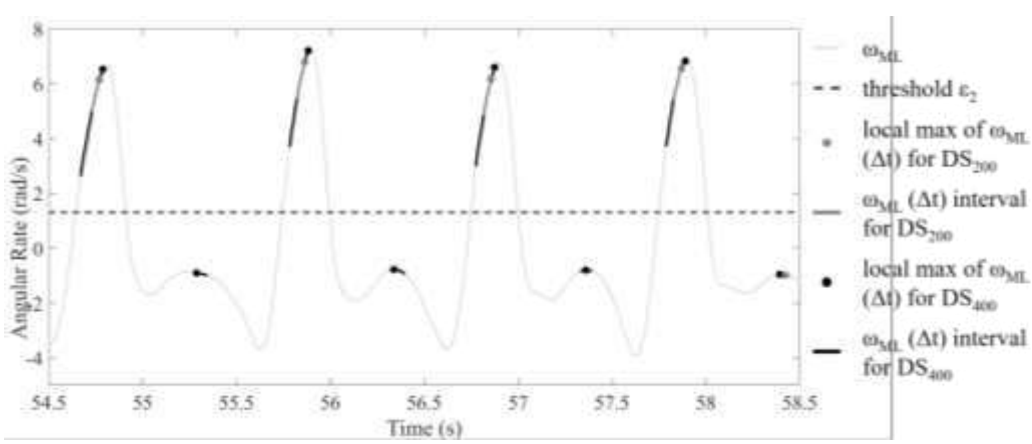


Fig. 5 shows the percentage errors $e_{\%}$ for DS_{200} and DS_{400} configurations for each participant sorted by EDSS. In addition, for both DSs configurations, the difference plots for IN-step and NIN-step detection are reported in Fig. 6.

Figure 5. Percentage errors ($e_{\%}$) for DS_{200} and DS_{400} are reported for each patient. Patients have been sorted by EDSS (from normal to severe). *Patients walking with a cane on the contralateral side.

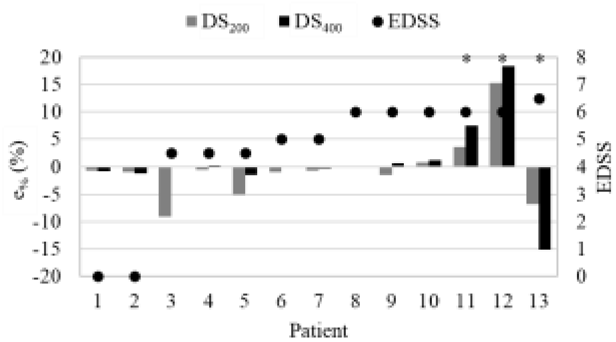
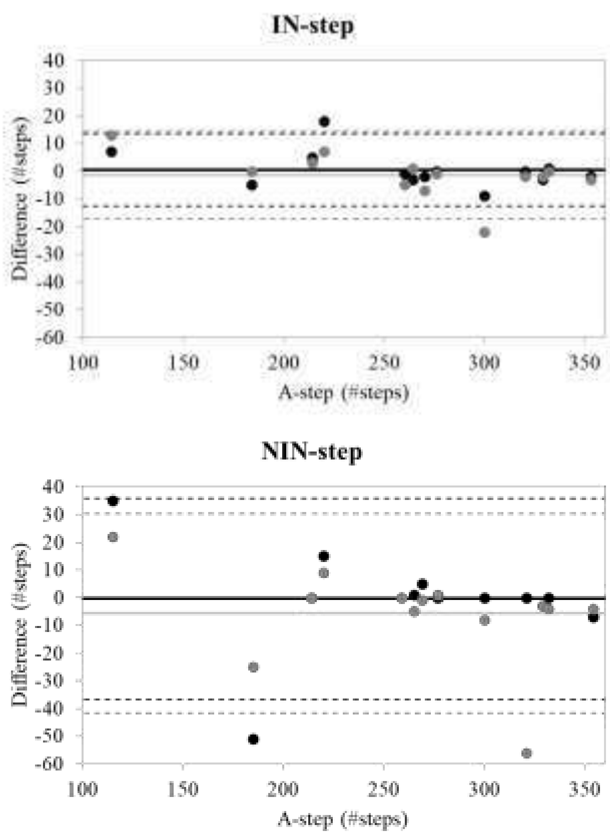


Figure 6. Difference (Bland–Altman) plots for IN-step and NIN-step between DiSC method and reference system. Limits of agreement (±1.96 SD) are, respectively, 16, 13, 36, 36 steps. Bias are, respectively, -1.4, 0.5, -5.7, -0.4 steps. DS_{200} in green and DS_{400} in blue.



IV. DISCUSSION

Regardless the DS range used, the DiSC method showed good accuracy in detecting steps showing half the errors for IN-steps compared to NIN-steps ($MAE_{\%,200}$: 2.4% vs 4.8%; $MAE_{\%,400}$: 2% vs 5.4%). When averaging errors across patients, as reported in previous studies [10–13], over and under estimated errors were compensated. Indeed, extremely small mean percentage errors for both scale ranges were achieved ($E_{\%}$<1.2% for DS_{200}; $E_{\%}$<0.7% for DS_{400}). In general, the performance of DS_{200} and DS_{400} were similar, although for patients walking with a large inter-leg distance the DS_{200} underestimated the number of steps (Fig. 4). In light of this consideration, the use of DS_{400} is preferable to DS_{200} since while false positive steps can be reduced by improving the specificity of the algorithm, missed steps cannot be recovered. It is important to consider that in two of three patients walking with a cane on the contralateral side (EDSS = 6), the number of steps was overestimated by 35 and 16 steps for DS_{200} and 42 and 33 steps for DS_{400} due to false distance readings. This suggests paying particular attention in applying the DiSC method to patients using walking aids (patients with * in Fig. 5). When comparing the results of the present study with those obtained on healthy subjects [7], a slight worsening of the performance is observed ($MAE_{\%}$ in the range of 2–5.4% vs 0%) probably due to large inter-leg distances (larger than DS measurement range) and the use of walking aids. Several studies in the literature have discussed the validity of activity monitors/pedometers in step counts across different sensor positions (e.g. wrist, waist, ankle, foot, etc.), tasks (e.g. walking, ascending/descending stairs, running), conditions (e.g. laboratory-setting, free-living) and populations (e.g. healthy, unhealthy) with accuracy in the range of 88-100% [10–20]. In a recent study, Sandroff and colleagues [13] compared the accuracy of two commercial IMU-based systems (StepWatch™ and ActiGraph attached to the shank and waist, respectively) on 63 subjects with MS during 6MWTs at slow, comfortable and fast walking speeds. Accuracy was expressed as the percentage of the actual number of steps taken by direct observation during each of the 6MWT. The best performance was obtained with the StepWatch™ with an accuracy in the range of 95.7–101.8%, versus 87.3–100.4% with the ActiGraph. Interestingly, the performance of both step counters worsened when analysing patients with severe disabilities (EDSS in the range of 6–6.5) walking at slow speed. Another commercial IMU-based system (MoveMonitor), positioned on the lower back, was tested and validated by Storm and colleagues [20]. Fourteen patients with MS (from moderate to severe disability) were recorded while walking in a laboratory setting performing four 15 m straight walks and a one minute walk (including straight walk, turn, and walking in spirals) at comfortable speed. For all the participants with moderate disability (EDSS = 5.0), walking speed above 1.0 m/s, $E_{\%}$ resulted below 4%. Interestingly, the device accuracy decreased with increasing EDSS with an $E_{\%}$ larger than 20% for five participants with severe disability (EDSS = 6.5) walking at a slower speed (< 0.6 m/s). On the contrary, the DiSC method accuracy is expected to improve when analysing slow walkers with no aids since the number of distance readings increases when decreasing the gait speed. This hypothesis however requires to be tested in further studies including a larger and more heterogeneous subject group.

V. Conclusion

The present study tested and validated a novel step counter (DiSC method), based on the measurement of the inter-leg distance, on people affected by MS (moderate to severe disability). The DiSC method showed promising results in terms of accuracy for both tested DS configurations (recommended distance sensor measurement range: 0–400 mm). To improve the overall method accuracy the integration of distance and magneto-inertial data in a sensor fusion algorithm, including also accelerations and local magnetic field information, will be explored in further studies, where the validation will also be performed on larger number of patients.

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