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A novel multi-sensor system for gait assessment in real-world conditions: preliminary results

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***Abstract*— Gait analysis is commonly performed in controlled environments. However, there is a growing interest in methods assessing motor performance in free-living conditions. Inertial measurement units (IMU) constitute a valid solution in the estimation of spatio-temporal gait parameters. However, performance of IMU-based methods is influenced by several factors and their validation in free-living conditions calls for a mobile gold standard as reference.**

To this end, the present study deals with the validation of a wearable multi-sensor system (INDIP) for digital gait assessment in free-living conditions. The INDIP integrates four magneto-inertial units, two distance sensors and two pressure insoles. Since its validation is on-going, preliminary outcomes obtained for two tasks from lab-based acquisitions on one healthy subject are presented and discussed. Results show low percentage errors (always <5%) and hopefully will be confirmed on more subjects and more complex tasks.

***Keywords*— gait analysis, IMU, wearable sensors**

I. INTRODUCTION

A person's mobility is the result of the combination between their motor capacity (what they can do) and their motor performance (what they actually do), with the latter being strongly influenced by daily-life environments and behavioural choices. An accurate assessment of mobility hence calls for complementing a conventional one-time, laboratory assessment with continuous daily-living measures [1]-[4]. In this perspective, the use of a single inertial measurement unit (IMU) represents a low-cost and fully wearable solution to characterize gait in patients with motor impairments [5]. Methods for the estimation of clinically relevant spatio-temporal parameters generally rely on the analysis of signal morphology, the use of biomechanical models and/or machine learning techniques [6], [7]. However, the validity of these methods can be affected by several factors, including IMU location, characteristics, motor impairment severity, measurement environment, presence of obstacles/stairs, number of pauses, etc. Moreover, the use of inertial sensing alone does not allow to estimate some additional but yet important gait parameters such as step width and base of support.

A major obstacle in validating IMU-based methods in real-world conditions is the lack of gold standard measurement systems which allow for long-term monitoring based on minimally intrusive sensors. To respond to the abovementioned requirements, we designed and developed a wearable multi-sensor system (INDIP), which integrates magneto-inertial sensing technologies with infrared time-of-flight sensors and force sensitive resistor pressure insoles [8],[9]. The INDIP system, by exploiting the complementary characteristic of the different sensors and data redundancy, is expected to provide the "best available" reference in out-of-lab gait analysis applications.

The INDIP validation and feasibility assessment entails two different phases: (i) lab-based acquisitions to compare INDIP performance with the stereo-photogrammetric (SP) system (gold standard) (ii) free-living activities acquisitions to evaluate usability and human factors.

In this preliminary study, we focused on the first validation phase by presenting results obtained in two motor tests of different complexity included in lab-based experimental protocol from one healthy subject.

II. MATERIALS AND METHODS

A. *System Description – INDIP System*

The INDIP system includes four magneto-IMU (fs=100 Hz), two plantar pressure insoles (PIs) (16 force resistive sensing elements, fs=100 Hz) and two time-of-flight distance sensors (DSs) (range=0.2 m, fs=50 Hz). 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. Each magneto-IMU includes a 3D accelerometer (full-scale up to ±16 g), a 3D gyroscope (full-scale up to ±2000 °/s) and a 3D magnetometer (full-scale up to ±50 Gauss). Data are processed by an ultra-low-power microcontroller (ARM® 32-bit Cortex®-M4 CPU) and stored in an on-board 128 MB flash storage for up to four hours of data logging. The system allows third-party devices to be synchronized via an external trigger. Multiple INDIP units can be synchronized via a BLE protocol (v. 4.1).

B. *Experimental set-up*

Validation experiments are currently in progress and will include 15 healthy participants recruited at both the University of Sassari (Italy) and the University of Sheffield (UK). The study was performed by following the principles outlined in the Helsinki Declaration. All participants signed the informed consent, approved by the ethics committee of the University of Sassari and Sheffield. For this preliminary study, we presented only the data acquired on a healthy adult female (height 1.70 m, EU shoe size 39). The subject was prepared by positioning the INDIP system and the markers for the SP system as depicted in Fig.1. PIs were inserted in the shoes and feet magneto-IMU where positioned over the instep while lower back magneto-IMU was attached using an elastic belt. Wrist magneto-IMU was positioned on the non-dominant arm. To avoid mutual IR interferences, DSs were positioned asymmetrically (one just above the left ankle and the other about 3 cm higher on the right side), both pointing medially. Both magneto-IMU and DSs were attached using straps. PIs and DSs were connected to the magneto-IMU of the corresponding foot.

A total of 13 markers were used: four markers on the left foot, four markers on the right foot, four markers placed on a rigid cluster used as support for the lower back INDIP and one on the magneto-IMU on the wrist (Fig.1). Of the four markers on each foot, those on the heel and on the second metatarsal head are used in the algorithm, together with the four markers on the rigid cluster. Markers m_{LREF} and m_{RREF} are used to avoid confusion between right and left side in the labelling; m_{INDIP} is for additional checks. Marker trajectories were recorded using a 10-camera motion capture system (Vicon, MX T160, fs = 100 Hz). The SP and the INDIP system were synchronised using the above-mentioned external trigger.

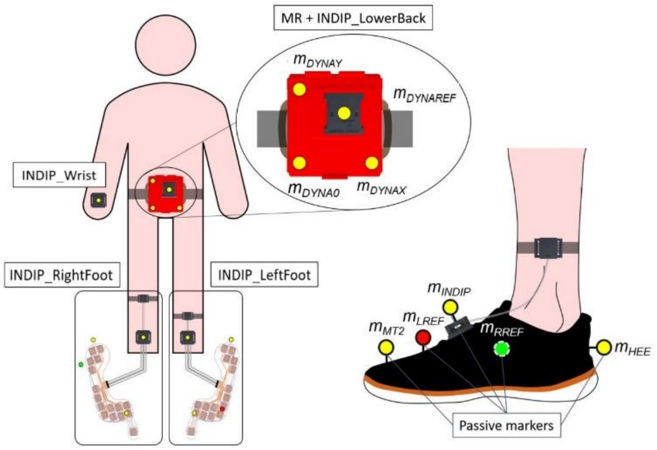

Fig. 1: INDIP system and markers positioning. The INDIP system includes INDIP_Wrist (wrist block), INDIP_RightFoot (right foot block), INDIP_LeftFoot (left foot block), INDIP_LowerBack (lower-back block).

C. Experimental protocol

The lab-based validation included several motor tests with an increasing level of complexity. For sake of brevity, we focused on two paradigmatic motor tests (Fig. 2), described below:

- Rectangle Test: the subject is asked to stand at the starting point and walk along the rectangular path identified with cones doing sharp 90° turnings and stopping at the end line.
- Hallway Test: the subject is asked to stand at the starting point and walk straight to the opposite end of the walkway while making sure of stepping up and down the step (height 20 cm). Once the participant reaches the cross (just after the step), he/she is asked to rest for 10 s before continuing. At the end of the walkway, he/she has to make a sharp U-turn and walk straight back along the walkway. Then, the participant stops at the cross for 10s once again and completes the remaining walkway reaching the end point.

The tasks were executed at comfortable self-selected speed.

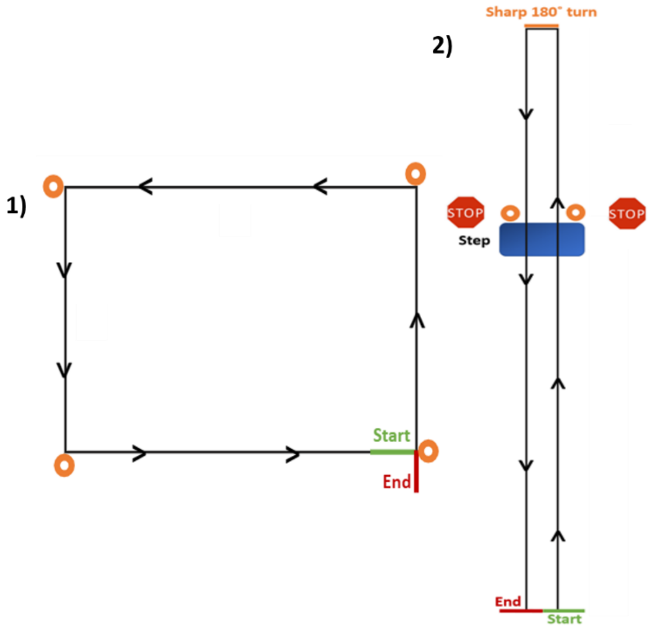

Fig. 2: Representation of the tasks. 1) Rectangle Test; 2) Hallway Test

D. Data processing - INDIP

A preliminary calibration procedure was applied to each sensor according to [10],[11]. Each magneto-IMU underwent to a preliminary static spot check, 30 s long. A pre-processing procedure was applied for data synchronisation. The INDIP-based method exploits the redundancy proper to the multi-sensor platform for the estimation of the spatio-temporal parameters. The implemented algorithm consisted in the following steps:

(i) static/dynamic activity periods recognition is performed to keep only those portions in which there is movement. The subject is "active" if the acceleration of both lower-back and at least one foot is above a certain threshold [12],[13]

(ii) bilateral gait events detection at foot level from PIs signals. The strategy used to find initial contact (IC) and final contact (FC) events considers a sub-group of the PI sensing elements, called *neighbourhood*, looking at signals' morphology [14]. Candidate ICs correspond to rising edges in PI signals, while candidate FCs correspond to falling edges. Rising and falling edges are identified in signal's first derivative using peaks detection [9]. An IC/FC event is defined as the value in the middle of the candidate ICs/FCs obtained for each neighbourhood.

(iii) spatial description at foot level in terms of position and orientation. Starting from feet inertial data, a Madgwick filter is applied to compute orientation for each foot sensor. Then, velocity and displacement are obtained with a direct and reverse integration (DRI) approach [15].

(iv) strides detection and selection based on (ii, iii). Right and left strides are detected starting from the ICs. Selection is performed applying thresholds on some stride relevant parameters, including duration, length and height. At this

TABLE I
RECTANGLE TEST (NUMBER OF WBS = 1)

Parameters	*WB 1*		
	INDIP	*SP*	*e%*
Time location (s)	2.04 to 10.47	2.01 to 10.46	1.5, 0.1
Time duration (s)	8.43	8.45	-0.2
Path length (m)	8.44	8.30	1.7
Gait speed (m/s)	1	0.98	2
Number of strides	13 (7R, 6L)	13 (7R, 6L)	all
Number of turnings	3	3	all

Results obtained for the Rectangle Test

TABLE II
HALLWAY TEST (NUMBER OF WBS = 3)

Parameters	*WB 1*			*WB 2*			*WB 3*		
	INDIP	*SP*	*e%*	*INDIP*	*SP*	*e%*	*INDIP*	*SP*	*e%*
Time location (s)	2.24, 8.33	2.21, 8.35	1.36, -0.24	22.74, 27.9	22.58, 27.9	0.7, 0	42.5, 47.3	42.37, 47.4	0.4, -0.17
Time duration (s)	6.1	6.14	-0.8	5.16	5.33	-3.2	4.8	5	-4
Path length (m)	3.78	3.64	3.8	3.37	3.28	2.7	0.72	0.7	2.9
Gait speed (m/s)	0.62	0.6	3.3	0.65	0.62	4.8	3.45	3.48	-0.86
Number of strides	8 (4R, 4L)	8 (4R, 4L)	all	7 (4R, 3L)	7 (4R, 3L)	all	6 (3R, 3L)	6 (3R, 3L)	all
Number of turnings	0	0	all	1	1	all	0	0	all

Results obtained for the Hallway Test

stage, DSs are used as "stride counters" and give an additional information on the reliability of measure [16].

(v) walking bout (WB) detection and selection based on strides information. Right and left strides are combined to obtain WBs. Only WBs including a minimum of 2 right and 2 left strides are selected for the analysis.

(vi) estimation of spatio-temporal gait parameters for the identified WBs. For every test and each WB, the following information was extracted: time location (start and stop time instants (s)),duration (s), path length (m), gait speed (m/s), number of right and left strides, number of turnings. The accuracy of the INDIP-based method was assessed, for each WB parameter, as the difference between INDIP and SP estimates (obtained from marker-trajectories estimation) in terms of percentage errors.

III. RESULTS

The results obtained with the INDIP-based method and the percentage errors with respect to the gold standard for the Rectangle Test and the Hallway Test are shown in Table I and Table II, respectively.

IV. DISCUSSION

The setup of the validation protocol resulted to be feasible (no unexpected events during the experiment, system crashes, data loss or uncompleted trials) and acceptable for the subject (tasks easy to understand, comfortable technology).

In the Rectangle Test, both the INDIP-based method and the SP system detected a single WB. Extremely small percentage errors were achieved in the estimate of start and stop instants (e%=1.5% for the start, e%=0.1% for the stop), duration (e%= -0.2%), path length (e%= 1.7%) and gait speed (e%= 2.0%); the same number of strides and turnings was obtained with both methods (7R and 6L strides and 3 turnings).

For the Hallway Test, a total of three WBs were detected in both methods. Low percentage errors (<5%) were obtained for all the WBs. In the first WB, errors obtained were: 1.36% and -0.24% respectively for start and stop instant, -0.8% for time duration, 3.8 % for path length, 3.3% for gait speed. The same number of strides and turnings was detected with both INDIP and SP system (4R and 4L strides, no turnings). In the second WB, very low errors were obtained for start (0.7%) and stop (0%) instants, e%= -3.2% for duration, e%=2.7% for path length, e%=4.8% for gait speed. Also, in this case, both systems identified the same number of strides (4R and 3L) and turnings (one U-turn). About the third WB, 3R and 3L strides and no turnings were detected with both INDIP-based and SP-based methods. Percentage errors equal to 0.4% and -0.17% were respectively obtained for start and stop instant. Errors were low also for duration (-4%), path length (2.9%) and gait speed (-0.86%).

Gait initiation and termination phases (first and last step) were excluded by the comparison between the two methods.

It is interesting noting that, when the number of strides within a WB is higher, percentage errors are extremely low. This is what happens, for instance, in the Rectangle Test, were the total number of strides is 7 for the right foot and 6 for the left one. On the other side, when the number of strides is smaller, the difference between the outputs obtained from INDIP and SP is higher. This is expected as the gait speed computed over three strides is obviously highly variable. Despite this, the errors obtained are always below 5%.

The INDIP system is completely wearable, no differences are expected in usability and comfort moving from the lab to real world scenarios. Future algorithm improvements include the estimation of gait events also from feet inertial data to have a more accurate and complete information. Moreover, DS data can be used for the estimation of stride width and base of support. Hopefully, further increasing the INDIP-method robustness, these preliminary encouraging results will be confirmed on more complex motor activities and more subjects.

V. CONCLUSION

A novel multi-sensor wearable system for the identification of WBs and the estimation of spatio-temporal parameters within them has been presented. Preliminary promising results suggest its potential use in prolonged daily-living measures. The same correct number of strides were found by both the INDIP-based and SP-based methods while the WBs where either a single continuous one (i.e. Rectangle Test) or different shorter ones (i.e. Hallway Test). A full validation of the INDIP-based method is on-going where a full experimental protocol with five different motor tasks is performed by 15 healthy subjects.

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