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A wearable system for the measurement of the inter-foot distance during gait

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Abstract **– Inter-foot distance (IFD) is an important indicator of gait stability. The IFD evaluation in outdoor conditions is still an open issue. The aim of this work was to develop and evaluate a wearable system integrating an infrared range sensor (IRR) and an inertial measurement unit (IMU), for the IFD estimation during mid-stance and mid-swing. First, the IRR sensor output was characterized and calibrated. Second, precision and accuracy were assessed in static conditions using a target object. Third, data were acquired on a subject during various lower limb movements and compared to a gold standard to evaluate the IRR-IMU dynamic performance. Mean error during the IRR accuracy tests revealed a mean error of 2.7 mm. During walking the error was about 5 mm (up to 10 mm for gait with wide steps). In conclusion, the tests performed seems to support the feasibility of the IRR-IMU use for the estimation of the IFD during specific gait phases.**

I. INTRODUCTION

Inter-foot distance (IFD) is defined as the projection along the medio-lateral direction of the distance between corresponding points of the feet. During gait, it is informative of the feet motion coordination and relative position, gait symmetry and the base of support. It is considered an indicator of the stability of gait throughout the gait cycle [1]. Its value at heel strike coincides with the step width (SW). SW ranges from 50 to 170 mm in normal subjects and increases up to 200 mm in subjects with limited balance [2,3]. It is used in clinical gait analysis to evaluate the stability of gait and risk of falls. In fact, its variability has been associated to the risk of falling in older adults [4,5] and it has been identified as a more meaningful descriptor of locomotion control than step length and step time variability [6].

SW is commonly measured in laboratory settings with instrumented treadmills and instrumented gait mats [6,7]. Conversely, to measure the entire IFD pattern during the gait cycle (including SW), conventional marker based motion capture systems [1] or LIDAR laser range sensors [8] have been proposed.

However, IFD or SW measurements obtained in laboratory settings may not represent the subject specific gait characteristics in real life. Few studies proposed the measurement of IFD using wearable technologies such as ultrasounds (US) and infrared light (IR), often by integrating the measurement units into the shoes [9-12]. In both cases, transmitter(s) and receiver(s) are attached to different shoes. US based systems were not validated and were found to be bulky and obtrusive [9,10]. IR based systems proposed in the literature included a micro camera and a panel with LEDs and were integrated with inertial measurement units (IMUs) [11,12]. In the latter study, the authors used the IR based measurements to correct the inter-shoes position error to properly estimate the 3D trajectories of the two feet [12]. Although the technology employed provided promising results, the sensor unit size was relatively large with consequences on walking patterns [12].

Infrared range sensors (IRR) integrated with IMUs may represent a valid alternative to the above-mentioned technologies. IRR sensors employ the single point optical triangulation principle for measuring the distance from a target object and are competitive in terms of response time, resolution, beam width, power consumption and size. Unfortunately, IRR sensors are characterized by a non linear output [13] (more precise at smaller distances from the target object), and cannot measure distances smaller than 20-40 mm. However, since SW reference values range between 70 and 90 mm [14,15], such limitation does not affect their potential use in gait analysis applications.

The aim of this preliminary work was to evaluate the feasibility and applicability of the use of IRR sensor technology for the IFD estimation in the two time instances of the gait cycle in which the IFD is minimum (in mid-stance and mid-swing). To this purpose an IRR sensor was integrated to IMUs placed on the subject shoes, laying the foundations for the estimation of the entire IFD pattern within the gait cycle and therefore of

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the SW. The IRR sensor output was characterized and its accuracy and precision evaluated in static conditions. Data acquired during human lower limbs movements, including gait, were compared to a gold standard to evaluate the accuracy of the IRR-IMU system in dynamic conditions.

II. MATERIALS AND METHODS

An IRR sensor (mod. GP2Y0A41SK0F, Sharp Corp, Japan) with a measuring range of 40 to 300 mm and a short measuring cycle (16.5 ms) was used. The IRR sensor works with IR radiation (λ = 870nm ± 70 nm) and returns a voltage as the target object reflects back the beam transmitted by the transceiver [13]. The output analog voltage is dependent on the transceiver-target distance. The IRR sensor was connected through an analog expansion board (Shimmer™ AnEx board, Shimmer sensing, Ireland) (Fig.1) to a pre-calibrated IMU (Shimmer™ 2r) featuring a three-axial accelerometer and a three-axial gyroscope. The analog output voltage of the IRR and the IMU signals are measured simultaneously. Recorded data (sampling frequency: 204.8 Hz) were transmitted via Bluetooth™ to a nearby computer and then analyzed.

A. IR sensor characterization

To estimate and characterize the noise affecting the IRR sensor output, several tests with the IRR sensor placed at various distances from a white target object were performed. For each distance, the distribution of about 2000 consecutive samples was evaluated. Descriptive statistics (mean, mode, median, standard deviation) was computed for each distance to characterize the samples distribution.

i. IR sensor calibration

According to the IRR sensor datasheet [13], a solid white box was used as target object during the calibration [16]. IRR data were collected within the full sensor measurement range and used to determine the calibration function.

ii. Accuracy and precision

The target object used for calibrating the IRR sensor was also used to test the accuracy of the IRR sensor estimates at nine different distances. Error, absolute error and percentage error values were computed for each distance and then averaged. The measurement precision was expressed as the 95% confidence interval of the measured samples distribution.

B. Human movement acquisition session

i. Experimental setup

Data from a healthy subject (male, 49 y.o., height: 1.87 m) were acquired. A single IMU was attached on the dorsal region of each foot. The IRR sensor was positioned on the right shoe and connected to the IMU placed on the same shoe whereas a target object (a white flat cardboard of 100 mm x 120 mm) was firmly attached to the left shoe. Both the IRR sensor and the target object were placed just below the medial malleolus (Fig. 2).

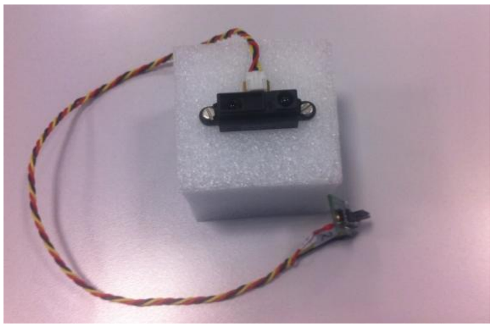

Fig. 1. The IR range sensor wired connected to the analog expansion board

The trajectories of three retro-reflective markers placed on each foot (toe, heel and over the IMU) were recorded with a five-camera stereo-photogrammetric (SP) system (Vicon T20, 128 frames/s, λ = 870nm) and used as reference data. Two additional markers were attached to the IRR sensor case and in the middle of the target object to calibrate their position with respect to the feet markers [17] and were then removed.

ii. Analysis of the interferences with the SP system

Static tests were performed with the subject standing in the upright posture with the feet parallel at a distance of about 150 mm inside the SP calibration volume. Before acquiring data, levels of strobe intensity and visibility thresholds of the cameras were set to limit interferences with the IRR sensor. Tests were performed first disabling the cameras (test1), then enabling the cameras (test2). For both tests, the distribution of 4000 samples acquired by the IRR sensor was examined. To characterize the samples distribution, descriptive statistics (mean, mode, median, standard deviation) was computed.

iii. Movement data acquisition

The following acquisitions were performed:
1) subject standing with parallel feet at shoulder width (*ST*);
2) subject standing while swinging the left leg (target object leg) back and forth, while the right leg (IRR sensor leg) was on the ground (*SWl*);
3) subject standing while swinging the right leg (IRR sensor leg) back and forth, while the left leg (target object leg) was on the ground (*SWr*);
4) slow gait with narrow steps (*sGn*);
5) comfortable speed gait with narrow steps (*cGn*);
6) slow gait with wide steps (*sGw*).

Data were acquired for about 30 seconds in all conditions.

Fig. 2. IR range sensor on the right foot, white cardboard facing it on the left foot, IMUs on the dorsal aspect of the feet and toe and IMU markers

iv. Inter-feet distance estimation

In the *ST* condition the IFD values were obtained by simply averaging the readings obtained from the IRR sensor.

When a lower limb swings while the other stands (*SWl* and *SWr*), the minimum IFD was supposed to occur at the timing of maximum absolute values of the IMU angular velocity signals along the medio-lateral direction of the swinging limb. Therefore, only the IRR readings occurring at those timings were used to estimate IFD values.

In walking (*sGn*, *cGn* and *sGw*) left and right legs swing repetitively alternating their swing phase while the opposite leg is in contact with the ground. Therefore, one limb swings in front of the other twice in the gait cycle (i.e. middle swing and middle stance) and at those times the distance between feet (i.e. the euclidean distance between the medial malleoli) is minimum. Hence, we hypothesized that, in each gait cycle, the minimum values of the IRR sensor readings in proximity of the mid-swing and mid-stance could reliably estimate the IFD values. Time intervals of trusted swing and trusted stance were identified from the IMU angular velocity signals for each foot [18]. Trusted swing was identified by isolating the time interval during which the gyroscope signal along the medio-lateral direction exceeded the 60% of its cycle maximum value. The trusted swing interval of a lower limb was made to coincide with a trusted stance time interval of the opposite lower limb. The minimum distance within those intervals as detected by the IRR sensor was assumed as the measurement of the IFD value.

v. Data analysis

The IFD values were computed with both IRR-IMU system and the SP system which was used as gold standard. Errors, absolute errors and percentage errors of the IFD values estimates were computed for each swing/step and then averaged for each test (mean absolute errors, MAE and mean percentage absolute errors, MAE%).

III. RESULTS

A. IR sensor characterization

i. IR sensor calibration

Analog to Digital Converter (ADC) and IRR sensor voltage (V) outputs for the tested static distances were normally distributed and therefore their mean values and standard deviation were associated to the actual distances (Table 1). The resulting calibration curve is a quasi-inverse function of the distance (D) (Eq.1):

$$D = 125.59\ V^{-1.117} \quad (1)$$

$$R^2 = 0.9989 \quad (2)$$

ii. Accuracy and precision

The nine imposed and measured distances are reported in Table 2. Accuracy of the measurement was expressed in terms of error, absolute error and percentage error, while the precision of the measurement was computed as the 95% confidence interval (Fig. 3). Mean error (±*sd*), mean absolute error and mean absolute percentage error over the nine measurements were respectively 2.7 mm (±4.8 mm), 4.3 mm and 2%.

B. Human movement acquisition session

i. Analysis of the interferences with the SP system

Differences between the measured distance samples distributions with and without SP cameras interference were negligible.

Table 1. Calibration look up table (actual distances, values of 12 bit Analog to Digital Converter (ADC) and associated voltages)

actual distance [mm]	ADC value mean (*sd*)	voltage mean (*sd*) [V]
40	3659 (4)	2.681 (0.003)
50	3063 (5)	2.244 (0.004)
60	2659 (7)	1.948 (0.005)
70	2334 (5)	1.710 (0.004)
80	2075 (5)	1.520 (0.004)
90	1874 (7)	1.373 (0.005)
100	1685 (5)	1.234 (0.004)
120	1452 (5)	1.064 (0.004)
140	1264 (9)	0.926 (0.006)
160	1108 (5)	0.812 (0.003)
180	969 (7)	0.710 (0.005)
200	888 (5)	0.651 (0.003)
250	728 (5)	0.533 (0.003)
300	621 (6)	0.455 (0.004)

ii. Inter-feet distance estimation

Twelve IFD values (two times for each swing cycle) were evaluated for the *SWl* and *SWr* conditions. Two gait cycles were evaluated for the *sGn*, *cGn* and *sGw* conditions and two IFD values were computed for each gait cycle. The mean error (±*sd*), the MAE and MAE% for all tests, are reported in Table 3.

IV. DISCUSSION

The results presented in this paper are a preliminary step for the development of a wearable IRR-IMU system for measuring gait parameters typically used in clinical applications. The bench tests allowed to characterize the IRR sensor. The IRR sensor was calibrated between 40 and 300 mm using a function closely related to the inverse of the output voltage (the IRR calibration range includes the expected operating range for IFD estimates during walking). Consequently, the sensor sensitivity was higher for lower distances. During the test with the target object accuracy errors up to 8.5 mm (3% of the actual distance), with an average of 2.7 mm, were observed.

Due to the non linear sensor sensitivity and a constant signal to noise ratio values, the measurements of higher distances (between 250 and 300 mm) suffered of lower precision (Fig. 3).

The tests performed after fine tuning the amount of IR light emitted by the SP cameras and their visibility thresholds showed that it was possible to avoid the effects of the SP system IR emissions on the IRR sensor readings.

The errors affecting the IRR sensor readings while the subject was standing were about 5 mm (i.e. 4% of the measured distance). The IRR sensor measurement error was lower during the leg swing trials since the absolute distance between the feet was lower. As expected, no differences were noticed between the errors generated when the target object was made to swing and when the IR sensor was made to move.

During walking, the error was again about 5 mm, but

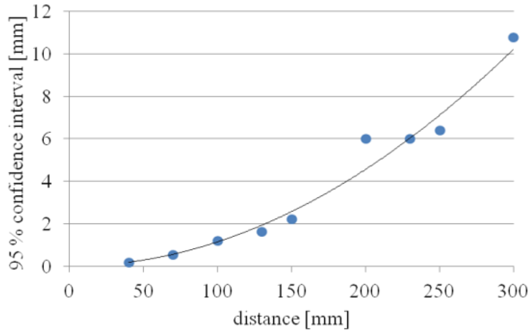

Fig. 3. Values of 95% confidence interval of the measured samples distribution reported for the nine measured distance for the IR sensor output values characterization.

Table 2. Accuracy and precision of the IR sensor measured distance compared to actual values (error, absolute error, percentage error and 95% of confidence interval)

actual distance [mm]	measured distance [mm]	error [mm]	absolute error [mm]	% error	95% confidence interval [mm]
40	40.4	0.4	0.4	1%	0.2
70	67.9	-2.1	2.1	-3%	0.6
100	97.9	-2.1	2.1	-2%	1.2
130	127.0	-3.0	3.0	-2%	1.6
150	150.7	0.7	0.7	0%	2.2
200	205.8	5.8	5.8	3%	6.0
230	238.4	8.4	8.4	4%	6.0
250	257.5	7.5	7.5	3%	6.4
300	308.5	8.5	8.5	3%	10.8

with IFD values lower than those recorded when the subject was standing. The reason why during gait the MAE doubles with respect to the leg swing trials could be related to the ankle motion and standing foot deformation which are limited during the swing trials. Finally, as expected, when gait was performed with a wide base of support (large IFD values) the error reached 10 mm, which was however only 5% in terms of MAE%.

V. CONCLUSIONS

In conclusion, the preliminary tests performed appear to support that the IRR based measurements of the IFD during gait can be used for clinical evaluation with an approximate range of validity of 5-10 mm.

The determination of the IFD values associated with the recordings of the IMUs located on the feet (or ankles) can be exploited to compensate for sensor noise and drift and thus improving the determination of the 3D feet trajectories during gait. Moreover, the combination of inertial data and information regarding the IFD during midstance and midswing (twice in a gait cycle) might open new possibilities for the development of algorithms for the estimation of the entire IFD pattern during the gait cycle (therefore including the SW).

Table 3. Mean (sd), mean absolute error (MAE) and mean percentage absolute error (MAE%) of the IFD values for the five test conditions.

Test	error: mean (*sd*) [mm]	MAE [mm]	MAE %
ST	-5.5 (n.a.)	5.5	4%
SWl	0.5 (*4.6*)	2.7	5%
SWr	-2.3 (*2.4*)	2.7	5%
sGn	1.1 (*6.6*)	5.3	8%
cGn	3.1 (*6.6*)	5.8	8%
sGw	2.1 (*12.8*)	10.1	5%

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