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A Wearable Inertial Sensors-based Framework for Complete Gait Analysis

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I. MOTIVATION AND GOALS

Gait analysis is often used as a measure of function in terms of daily life. It has been proposed as an additional way to analyse patients to overcome the subjectivity of self-reported scores. In particular, the attention during the gait analysis is mainly focused on monitoring knee outcomes, as knee malfuncionalities represent the most diffused cause for gait abnormalities. At present, gait analysis in actual medical practice is mostly done by visual observation, but this protocol has been shown to not be adequate for accurate assessment. As the technology of 3D-motion analysis has advanced hugely in recent years, quantitative gait analysis of kinetic or kinematic data is proposed to be a useful clinical tool. Camera-based 3D motion analysis systems can provide accurate results. However, it presents serious feasibility issues including high costs, complexity and long procedure, and is inconvenient for regular clinical use. Additionally, traditional gait analysis provides an untrue representation of gait due to the Hawthorne Effect. A potential solution to the problems associated with lab-based gait analysis is the emerging area of wireless inertial sensors, which have been shown to be capable of measuring human body orientation, postures etc. As well as having the potential to monitor gait and movement in everyday life, the small size and low-cost make them an ideal tool for human motion analysis, providing a potentially more accurate analysis of a patient's gait. These sensors have indeed already been used in the monitoring of joint kinematics and kinetics of the lower limbs [1-5]. Such approaches generally focus on only one of the two main aspects (joint angles or spatio-temporal parameters) producing an incomplete picture of a patient's condition. To the best of authors' knowledge, only [6] considers both aspects; however, the proposed solution can be cumbersome, as adopting up to 7 wireless sensors, and constrained to a "10 m Walking Test". The goal of this work is, therefore, to implement a wireless inertial system, requiring only 4 sensors (2 on the thighs, 2 on the shins), for evaluating

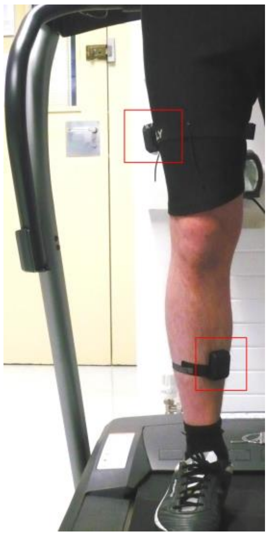

Fig. 1. WIMUs placement on lower limbs

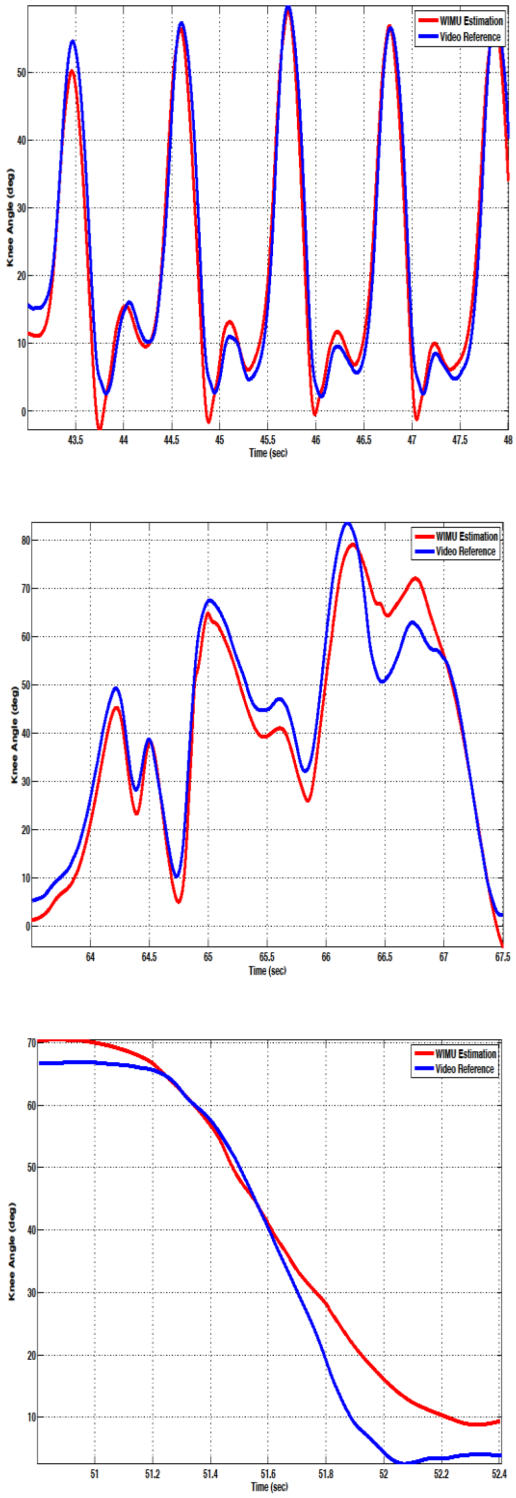

Fig. 2. Knee angles from WIMUs (red line) and camera (blue) for one subject performing walking test at 1.11 m/s (top), drop test (centre) and STS test (bottom).

bilateral gait considering both joint angles and spatio-temporal variables simultaneously for a number of test. The clinical aim is to understand the evolution of gait (i.e. during rehabilitation) and to identify gait abnormalities. A framework, consisting of several algorithms for all the mentioned aspects and for a wide set of test, has been implemented and tested in a lab-environment. Medical feedback derived from these algorithms can be analyzed by clinicians to study the overall patients' gait condition. The obtained results are promising and demonstrate the suitability of the realized system.

II. METHODS

For the calculation of the knee joint angle [1-3], two wireless inertial sensors are attached to the thigh and shank segments. The two sensor frames are aligned vertically and horizontally according to [1] and, then, the orientation for both body segments is individually estimated by using a quaternion-based complementary filter [7] (differently tuned depending on the test executed). The flexion/extension angle is, finally, calculated by multiplying the amplitude of the rotation by the component of the rotation axis perpendicular to the sagittal plane, where these two variables are provided by the conversion of the thigh-shank sensor frames differential orientation, into the angle-axis representation. As per spatio-temporal parameters, temporal events, such as toe-offs, heel-strikes, and flat-foot (e.g. the instants where the foot approaches the zero velocity condition at mid-stance) are obtained by analyzing shin's angular rate along the sagittal plane. Stride time (ST) is easily estimated by measuring the time between two consecutive toe-offs, while cadence is the reciprocal of ST. Stride length (SL) is, instead, calculated with two different approaches for comparison. In the first one, a complete dual-segments gait model [4] is solved geometrically using the measured angular rates and the lengths of subjects' thighs and shanks. In the second approach [5], SL is obtained from the direct integration of the accelerometer and gyroscope signals gathered on the shanks. Finally, stride speed (SS) is calculated by multiplying cadence and SL.

III. RESULTS AND DISCUSSION

A novel complete wearable gait system is proposed. The employed system is constituted of four Rev4 Tyndall Wireless Inertial Measurement Units (WIMUs) attached to the thighs and the shanks of the subject (Fig. 1). The WIMUs consist of a 3D accelerometer and a 3D gyroscope (@ 250 Hz) and transmit the data to a PC via the 802.11 protocol. Acceleration signal is smoothed via a first-order low-pass Butterwoth filter with 1.25 Hz cut-off frequency, while angular rate signal is not filtered. The framework algorithms are implemented in Matlab, and have been adopted with a wide set of test for the complete analysis of patients' gait:

1. Walking Test: the subject walks on a treadmill at different speeds (joint angles and spatio-temporal parameters both estimated).

2. 30 cm Drop Test: the subject drops from a box landing on both feet (joint angles measured).

3. Sit-to-Stand (STS): the subject performs three STS repetitions without any arm support (joint angles measured).

As for spatio-temporal feature, results are summarized in Table I. ST decreases when the speed rises, as expected, and SL estimated with both methods is similar. Consistently, it occurs also when estimating SS, although the second method presents a reduced mean error but higher variability. Such effect is mainly due to the shank's zero-velocity assumption when it is in a vertical position during the mid-stance, resulting in a speed underestimation. However, compared to the first method, the second algorithm requires less sensors on-body and no anthropometric information. Finally, the average Root Mean Squared Error (RMSE) for both techniques is comparable (0.11 m/s for [4], and 0.15 m/s for [5]), while the mean relative error is -8.7 ± 5.7% for the first method, -6.7 ± 7.1% for the second one, and -5.2 ± 8.1% for the algorithm in [6] which considers a technique similar to [5] that takes into account shoe-worn inertial sensors. Knee joint angles are instead validated by using a high speed camera Basler (@ 100 Hz) and a comparison between the two technologies is illustrated in Fig. 2. Results are summarized in Table II and show good repeatability

Actual SS (m/s)	0.97	1.11	1.66
ST (sec)	1.19 ± 0.03	1.07 ± 0.01	0.91 ± 0.01
SL (m) – [4]	1.02 ± 0.02	1.03 ± 0.02	1.48 ± 0.025
SL (m) – [5]	1.05 ± 0.11	1.04 ± 0.11	1.53 ± 0.15
SS (m/s) – [4]	0.87 ± 0.02	0.96 ± 0.02	1.62 ± 0.025
SS (m/s) – [5]	0.9 ± 0.1	0.96 ± 0.07	1.67 ± 0.16

Table I. Spatio-temporal parameters estimation

	Mean error ± st_dev (deg)	Pearson's r	RMSE (deg)
Walking (0.97 m/s)	2.28 ± 2.2	0.992	3.16
Walking (1.11 m/s)	-0.89 ± 3.91	0.978	4.01
Walking (1.66 m/s)	-1.85 ± 4.18	0.969	4.56
Drop Test	4.92 ± 7.11	0.968	9.6
STS Test	5.41 ± 5.65	0.972	7.81

Table II. Knee joint angles estimation

and accuracy, especially during the walking test (mean RMSE equal to 3.91 deg, while in the same conditions in [6] is 5 deg), even though the error is slightly larger in the drop/STS test due to the higher dynamism involved. Pearson's r is between 0.97-0.99 (similarly to [6]), highlighting an almost total correlation between WIMUs and video reference.

IV. CONCLUSIONS

This work presents a wearable inertial sensors-based framework for the implementation of a complete bilateral gait analysis. The system provides an accurate picture of patients' gait by estimating both spatio-temporal feature and joint angles for a wide set of test, minimizing the number of sensors adopted. Overall results present good repeatability and the accuracy is comparable with the state-of-the-art [1-6]. Future work will consider the test of the proposed framework on a wider population, and will involve both healthy and gait-afflicted patients in a clinical setting. The system, once fully tested, will be used by clinicians as a platform for the knee function assessment during rehabilitation (such as, following knee arthroplasty or anterior cruciate ligament injury).

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