Wearable sensors for gait analysis

Comparison between a MIMUs system and a gold standard electromechanical system

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***Abstract*—Systems based on inertial sensors are increasingly used in motion analysis due to their low cost, portability and wearability. However, since accuracy is crucial in clinical gait analysis, it is important to assess it in new systems. The aim of this study is to compare the performances of a magnetic and inertial sensors system (MIMUs) to a gold standard, the electromechanical system STEP32. Results shows that spatio-temporal parameters are accurately estimated by the MIMUs system. Joint kinematics does not reach the accuracy of the STEP32 system. In fact, although MIMUs measurements on the knee and hip joints are clinically acceptable, they are not yet reliable for the ankle joint.**

Keywords—gait analysis; gait parameters; IMUs; joint kinematics; spatio-temporal parameters.

I. INTRODUCTION

Gait analysis is the systematic measurement and description of quantities that characterize human locomotion. It is used in the clinical field to evaluate quantitatively human walking patterns and quantify disabilities [1,2]. The increasing interest towards clinical gait analysis [3] and more generally human motion has led to a continuous evolution of the methods used to carry out this examination. Traditionally, gait analysis is performed using optical systems in which cameras and markers are used to calculate 3-dimensional positions of the body segments during gait. However, optical methods present some drawbacks: considerable work space is needed, analysis has to be limited to a laboratory setting and it is difficult to apply it in daily life or outdoor and in non-traditional environments [4-5].

To overcome these problems, wearable systems were developed. Among them, electromechanical systems, based on electro-goniometers and foot-switches, present high accuracy in the measurement of joint angles in the sagittal plane. A more recently used method is represented by wearable magnetic and inertial sensors [6-7].

Inertial sensors have been successfully used for different tasks, including detection of falls [8], remote observation of elderly people [9], rehabilitation [10], evaluation of gait symmetry in clinics [11], ergonomics, sport science, virtual reality and computer games.

Their small size, weight, low cost and the possibility to use them in a wide range of environments make these systems an interesting solution for human motion analysis. However, some concerns have been raised about the accuracy of magnetic and inertial measurement sensor units (MIMUs).

In a number of studies, video cameras are used as a reference for comparison with inertial sensor data [12-13]. In general, stereo-photogrammetric systems have a low accuracy when compared to electromechanical systems (i.e. electro-goniometers) [5].

The work presented here is a pilot study with the aim to compare the gait measurements obtained by means of a commercial electromechanical system (STEP32,

Fig. 1. Lateral and posterior views of the subject.

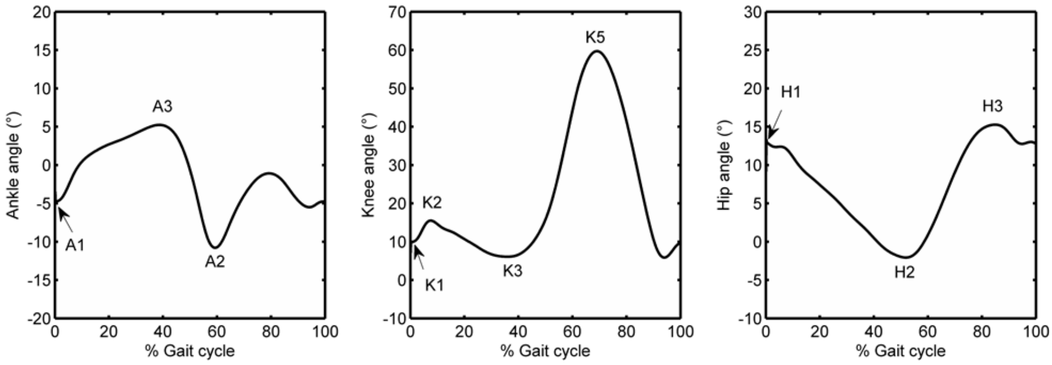

Fig. 2. Parameterization of joint kinematic curves: (a) ankle, (b) knee, (c) hip.

http://www.medicaltec.it/STEP32.html), assumed as a gold standard [14-19], and an experimental one, based on MIMUs [6].

II. Materials and Methods

A. MIMUs System

Seven sensor units (TSDN121, ATR Promotions) were fixed to the lower limbs of the subject. Each sensor unit consists of a tri-axial accelerometer, a gyroscope and a magnetometer (size: 37 mm × 46 mm × 12 mm, weight: 22 g). The accelerometers and the gyro sensors are incorporated in a MEMS (InvenSense MPU-6050). It is possible to choose a measurement range for each component. For the accelerometer, full scale values are ±2 g, ±4 g, ±8g, ±16 g with accuracies of 0.06 mg, 0.12 mg, 0.24 mg, 0.48 mg, respectively. For the gyroscope, full scale values are ±250 dps, ±500 dps, ±1000 dps, ±2000 dps, with accuracies of 0.008 dps, 0.015 dps, 0.030 dps, 0.061 dps, respectively. The sampling rate can vary between 1 Hz and 1000 Hz. The geo-magnetic sensor was produced by AICHI STEEL (AMI306) and it allowed a measurement range of ±1200 µT with accuracy of 0.3 µT and maximum sampling rate equal to 100 Hz. Measured data could be transferred wirelessly (Bluetooth ver.2.0 + EDR) to a laptop computer or could be recorded in a local data storage (512 Mbyte).

B. STEP32 System

In the last decade the STEP32 system has been successfully used in clinical gait analysis [14-19]. The system allows for a direct measure of 1) gait events [18] and 2) joint kinematics in the sagittal plane [14]. It is based on foot-switches, timing foot-floor contact events, and electro-goniometers, measuring joint flexo-extension angles during gait. In particular, three foot-switches are placed under each sole, beneath the back portion of the heels, and in correspondence of the first and fifth metatarsal heads. Three electro-goniometers are placed in correspondence of ankle, knee and hip joints, in each leg. Due to their structure, based on articulated parallelograms, STEP32 goniometers do not require the alignment of the potentiometer shaft with the instantaneous center of rotation of the joint. They allow obtaining an accuracy of about 1 degree and a repeatability higher than 0.5 degrees.

C. Protocol

Experiments were conducted indoor on an healthy volunteer with no history of physical disabilities or injuries.

A frontal camera synchronized with STEP32 system was positioned in order to record the entire trial.

Measurement range of the inertial sensor were set to ±4 G for the accelerometer and ±500 dps for the gyroscope and a sampling rate of 100 Hz was chosen for both. STEP32 system used a sampling rate frequency equal to 2 kHz.

A specific sequence has been defined to optimize the subject's preparation and to avoid problems in the positioning of the sensors of each system.

Firstly, 10 reflective markers used only for the calibration phase were placed, bilaterally, in specific anatomical landmarks: greater trochanter, lateral epicondyle of femur, medial epicondyle of femur, lateral malleus, medial malleolus. Three digital images were taken from the front, right side and left side of the subject, for the calibration procedure [6]. Measurements of pelvis breadth, iliospinale height, tibiale height and sphyrion height were taken to create a wire frame model and calculate joint angles.

Markers were then removed and foot-switches were positioned. Elastic bands and Velcro were used to fix the inertial sensors on the seven predefined positions, in the following order: 2 on the dorsum of feet, 2 on the shanks in correspondence of the anterior side of the tibia bone, 2 on the thighs above the center of quadriceps and 1 on the pelvis in the posterior center point between the left and right iliac crest. Sensor positions were chosen in order to minimize motion artifacts.

Finally, the electro-goniometric sensor were placed in correspondence of ankle, knee and hip joints, on each leg.

Before performing the test, the subject was asked to assume the sitting position for the MIMUs calibration procedure that allows, along with the standing position, to determine the rotation matrix between the sensor coordinate system and the global coordinate system [20].

Afterwards, the subject was requested to start the experimental trial consisting of: 1) standing still for the IMUs calibration procedure and to set zeroes of the STEP32 system, 2) performing an initial flexion of the hips to synchronize the two systems; 3) walking back and forth 6 times on a 12-m straight path. The subject stopped in the standing position for about 2 seconds after every direction change. Three gait trials were performed.

D. Signal Processing and Data Analysis

The MIMUs signals recorded during level walking were fused through a Kalman filter [21] designed to calculate the orientation of each sensor by the three Euler angles. By means of roto-translation matrices it is then possible to move from the local frame of each sensor to the anatomical frame of each body segment [6],[21]. Custom Matlab® routines were used to evaluate ankle, knee and hip joint angles and to produce a 3-dimensional wire frame animation during the gait. Thanks to angular velocity recorded by the sensors placed on the shank and to the toe trajectory calculated during the exam, it was possible to evaluate the spatio-temporal parameters by the identification of the heel contact (HC) and the toe off (TO) instants.

Proprietary software routines of the STEP32 system were used to post-process the data collected during the gait analysis session.

The following spatio-temporal parameters were estimated with both systems: cadence, stride time, stance, swing and double support [1]. Joint kinematics was compared between the two systems, using the curve parametrization outlined in Fig. 2, similarly to what was proposed in [22]. A1, K1, and H1 are the joint angles at initial heel contact for ankle, knee and hip, respectively. For ankle, A2 indicates the maximum plantar-flexion, and A3 the maximum dorsiflexion. For knee, K2 and K3 indicates the maximum and the minimum joint angles during stance (approximately within 60% of the gait cycle) and K5 indicates the (absolute) maximum knee flexion. For hip, H2 and H3 indicates the minimum and maximum joint flexo-

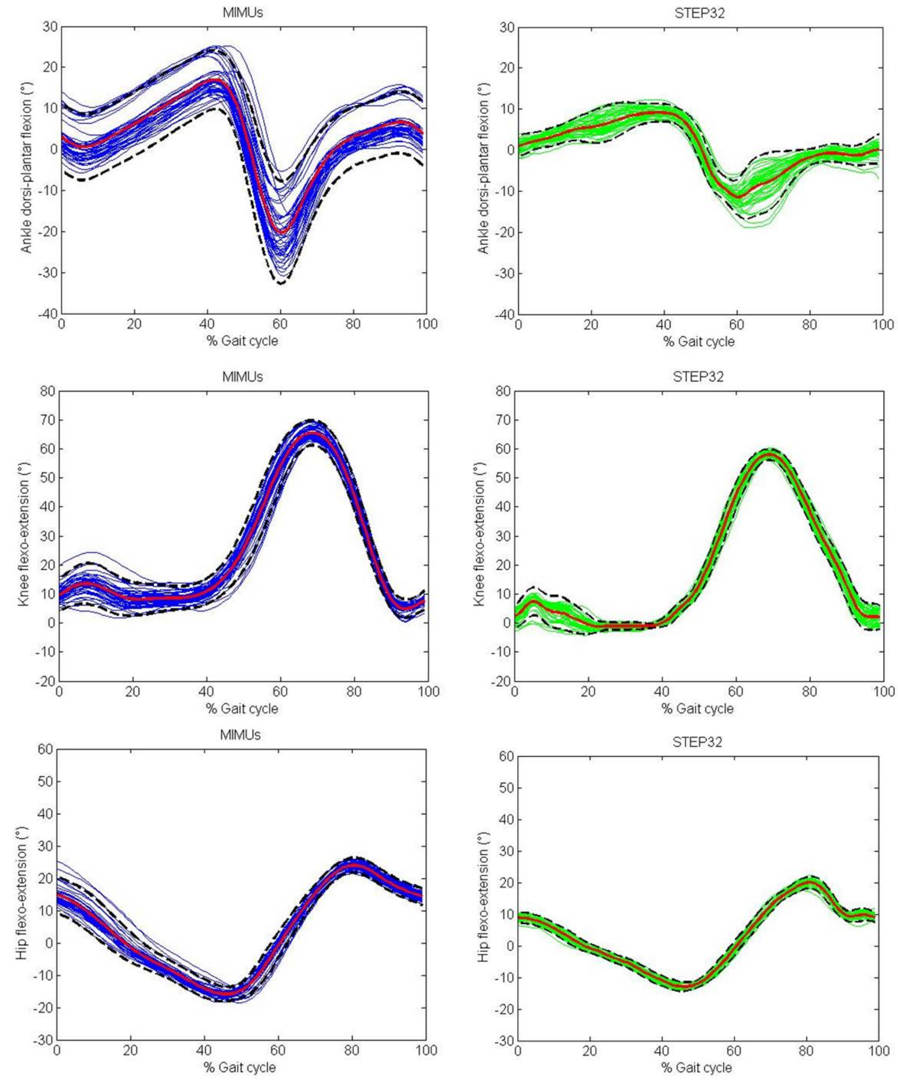

Fig. 3. Comparison between MIMUs and STEP32 systems: joint angles of the gait cycles collected in a single trial (right leg). Single gait cycles (blue line for MIMUs and green line for STEP32), average (red line) and standard deviation (black dashed lines) of the curves are represented.

extension angles, respectively.

III. Results

A. Spatio-temporal parameters

Table I reports spatio-temporal gait parameters evaluated with the MIMUs and STEP32 systems. The values reported are the average over three gait sessions. Left and right sides were also averaged.

TABLE I. Spatio-Temporal Parameters

Gait parameters	Gait analysis system	
	MIMUs system	***STEP32***
Cadence (cycles/min)	51,5 ± 1,8[a]	51,9
Stride time (s)	1,2 ± 0,1	1,2 ± 0,03
Stance (% GC[b])	58,2 ± 1,5	53,8 ± 1,4
Swing (% GC)	41,8 ± 1,5	46,2 ± 1,4
Double support (% GC)	8,9 ± 2,1	7,8 ± 2,3

a. *Mean ± Standard Deviation*

b. *GC: Gait Cycle*

B. Joint kinematics

In the following, we compare the joint kinematics obtained with the two systems MIMUs and STEP32. Fig. 3 depicts the joints flexo-extension angles of right leg referred to a single trial. All the gait cycles collected during the trial are represented, along with the average and standard deviation of the curves. Fig. 4 compares the joint kinematic parameters obtained with the two systems. The values reported are the average over three gait sessions. Left and right sides were also averaged.

IV. Discussion and Conclusion

Comparing the spatio-temporal parameters obtained with MIMUs and STEP32 we found a very good agreement for cadence and stride time, and a good one for stance, swing, and double support, with differences lower than 5% of the gait cycle. This small discrepancy is probably due to the different estimation of toe-off with STEP32, since foot-switches take into account the metatarsal contact with floor, and not big toe contact [15].

For what concerns the joint kinematics, the STEP32 system shows a better repeatability among the different recorded gait cycles than the MIMUs (see Fig. 3). While the knee and hip flexo-extension curves are comparable between the systems, a higher discrepancy may be noticed for the ankle joint. In this case, the MIMUs system shows a higher curve dispersion (see uppermost left plot of Fig. 3). This is probably due to fact that foot sensors are affected by the vibrations that arise during gait. This may be explained by the fact that: 1) the sensor positioning on the foot dorsum is critical because it tended to move during gait (probably because of the fixing bands), 2) the sensor distal position is more influenced by vibrations due to the foot-floor contact. Furthermore, the ankle joint is the last in the kinematic chain to be reconstructed and, hence, it is affected by the sum of

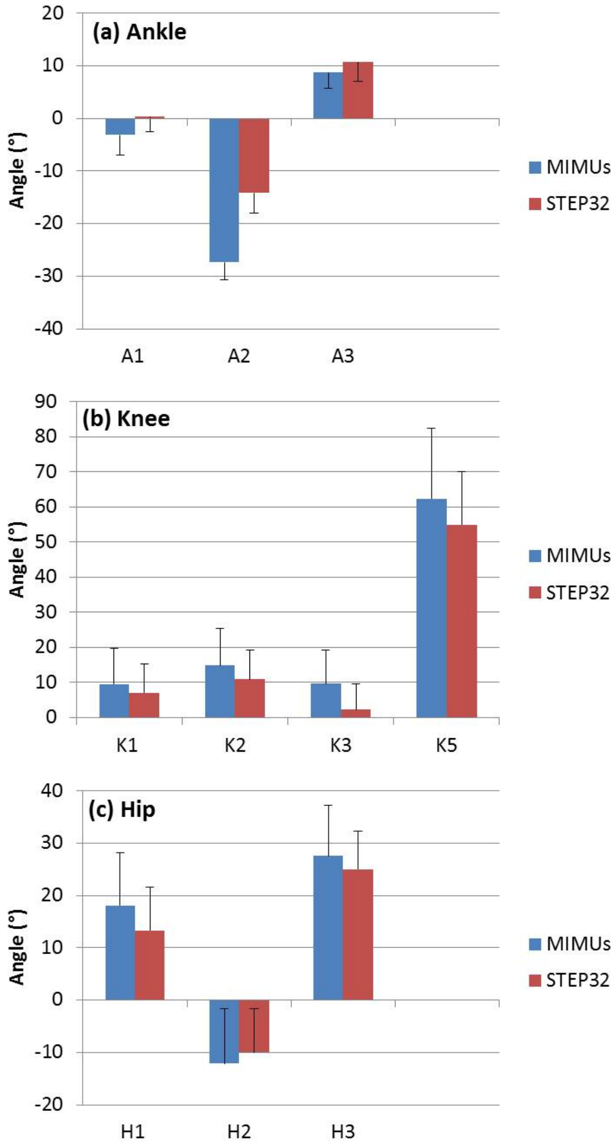

Fig. 4. Comparison between MIMUs and STEP32 systems: kinematic parameters for (a) ankle, (b) knee, (c) hip. Average values and standard deviations are represented.

the errors arising in determining the local sensors reference frames.

Considering the kinematic parameters, the differences between the systems are clinically acceptable for the knee and hip joints, while are critical for the maximum ankle plantar-flexion (A2 parameter). This can be explained by the above mentioned issues related to foot sensors.

In conclusion, the MIMUs system represents a potentially valid alternative to traditional optoelectronic systems, especially in out-of-the-lab environments. Although it does not reach the same accuracy of the gold standard STEP32, it allows a reliable estimation of spatio-temporal parameters. It also provides an acceptable estimation of knee and hip kinematics, while ankle joint measurements must be improved to be clinically useful.

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