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# Evaluation of the Performances of Two Wearable Systems for Gait Analysis: A Pilot Study

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## Abstract:

**Introduction:** Wearable sensor systems to perform human motion analysis are receiving increasing attention in different application fields. Among wearable sensors, inertial sensors have promising features. However, before they can be employed routinely in clinical applications, it is important to evaluate their reliability. Gait analysis was performed on one male volunteer: data were simultaneously collected with H-Gait System, based on magnetic and inertial measurement sensor units system, and with STEP32, a commercial electromechanical system already used in clinics.

Spatio temporal parameters and joint kinematics in the sagittal plane obtained with H-Gait and STEP32 are compared. The MIMUs system provides a reliable estimation of spatio-temporal parameters, and acceptable hip and knee kinematic curves, while ankle joint measurements must be improved to be clinically useful.

**Keywords:** Gait analysis, Joint kinematics, MIMUs, Electrogoniometers, Wearable sensors, Spatio-temporal parameters, Gait parameters

## INTRODUCTION

Human motion analysis interests different fields of application: movies industry, medicine, sports, video surveillance, military use, manufacturing processes, just to name a few. This increasing interest towards human motion analysis has led to a continuous evolution of the methods used to detect it, although the solution adopted has to be strongly linked to the requirements of the specific application [1-3]. In particular clinical motion capture and motion analysis are used to collect quantitative information about the mechanics of the musculo-skeletal system during the execution of motor tasks. The final goal is to obtain a quantification of the way an individual executes a motor activity and the changes that may occur.

Results can be used for diagnoses, pre-surgical or pre-therapy decision making, but also to better monitor the progress obtained during rehabilitative treatment [3]. Since changes in the movement patterns might be subtle, high accuracy and repeatability are needed. Moreover, the used techniques should not be invasive or intrusive in order to not alter natural patterns of movements.

Optical motion capture, which is still very much relevant today, was introduced since the 80's. It is a traditional solution where passive reflective markers are placed in

correspondence of the joints and segments of the body, and calibrated cameras are arranged to create a capture volume in which passive markers can be tracked to calculate 3-dimensional positions of joints and body segments during movement. However, optical methods present various drawbacks among which the cost of the system, the time consuming post-processing phase, and the fact that the analysis has to be limited to a laboratory setting [4]. Moreover optical motion capture is not easily applicable to the study of daily-life activities, rehabilitation sessions [5], especially in outdoor and in non-traditional environments [6].

In the framework of human motion analysis, gait analysis is the systematic measurement and description of quantities that characterize the normal and pathological function of human locomotion [7]. It is used in the clinical field to evaluate quantitatively human walking patterns and quantify disabilities [8]. When analyzing human locomotion, it is important that the subject has the possibility to walk uninterruptedly, in an unconstrained setting for several gait cycles [1, 2, 9]. The increasing interest towards clinical gait analysis and more generally human motion [10, 11] has led to a continuous evolution of the methods used to carry out this examination. Some recently introduced techniques allow the kinematic analysis of the motion considering point tracking of some features of a body, without requiring the presence of markers [12-14], however these techniques were developed for space missions and their application to motion analysis has still to be developed.

In order to overcome the drawbacks intrinsic to optical motion capture techniques, in the past decade, alternative gait analysis methods using different techniques were studied. Wearable sensors seem to be a promising technique, since they allow for measuring and recording gait in natural condition for the patient. Many different types of wearable systems were developed [15]. Among them, electromechanical systems, based on electro-goniometers and foot-switches, present high accuracy in the measurement of joint angles in the sagittal plane, and have been widely used in clinics [16, 17]

A more recent solution is represented by wearable magnetic and inertial sensors [18, 19]. Inertial sensors have been successfully used for different tasks, including detection of falls [20], remote observation of elderly people [21], rehabilitation [22], and evaluation of gait symmetry in clinics [23], 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 motion analysis [24],

especially if coupled with the estimation of the CoM and CoP, based on the segmental method and the 3D scanning of the human body [25]. The main advantage offered by inertial sensors is the possibility to monitor the subject during daily activities, referring not only to gait. As a matter of fact, their characteristics (low cost and small size) make these sensors easily integrated into common objects used daily. In this context, measurements collected with MIMUs are sufficiently precise and accurate to give the users a proper feedback. An entirely different issue is the employment of inertial sensors in clinical gait analysis: in this framework measurements accuracy and repeatability are overt requirements, since subtle changes may indicate a different motor strategy. As a matter of fact, magnetic and inertial measurement sensor units (MIMUs) do not directly measure positions or ground reaction forces, but, typically, accelerations (accelerometers), angular velocities (gyroscopes), magnetic field (magnetometers) of the body segments they are attached to. Therefore, translating the collected data into meaningful kinematic ones, for helping patient diagnosis, has been the challenge in the field of biomechanics. In fact, additional and smart signal processing algorithms, providing useful information for a clinical analysis of gait, are required.

In a number of studies, video cameras are used as a reference to evaluate the inertial sensor performances [26, 27]; but, in general, stereo-photogrammetric systems have a low accuracy when compared to electromechanical systems (i.e. electrogoniometers). This is due to the fact that stereo-photogrammetric systems provide a derived measure (through a reconstruction of the 3D body model) instead that a direct measure of joint kinematic angles in a specific body plane (e.g. sagittal plane).

The final goal is to promote the use of MIMUs for gait analysis for portable systems, with the actual clinical high standards (i.e. high accuracy and repeatability). The aim of this work is to give a contribution toward this final goal. In the paper, results of a pilot study comparing the gait measurements obtained by means of H-Gait, a system based on MIMUs [18] with the one obtained with a commercial electromechanical system (STEP32, <http://www.medicaltec.it/STEP32.html>), which is more

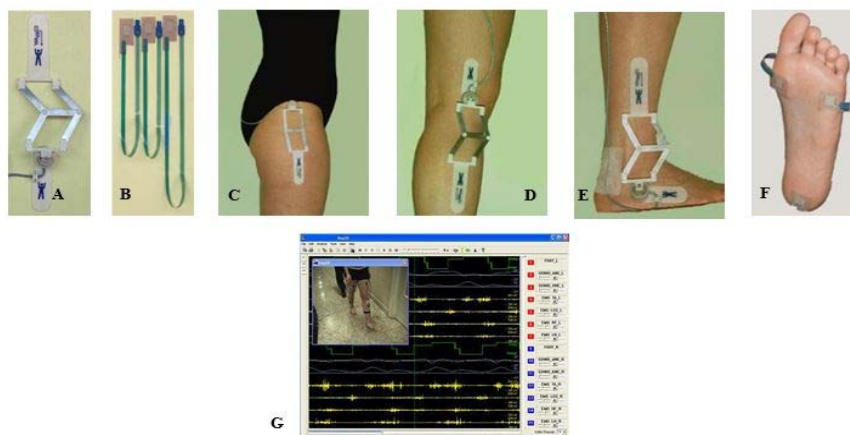
accurate respect to optoelectronic stereo-photogrammetry [28-30]. Since the final aim is to investigate the suitability of H-Gait as a clinical instrument for gait evaluations, a comparison of walking events, spatio-temporal parameters and joint kinematics in the sagittal plane obtained with the two systems (H-Gait and STEP32) is performed. The pilot study is essential to validate the use of H-gait since the mentioned clinical gait variables are not directly measured by the MIMUs system, but they are a consequence of preliminary calibration and data post-processing.

## MATERIALS AND METHODS

To assess the soundness of the MIMUs system for clinical use, a comparison of the results obtained with STEP32 has been performed considering gait spatio-temporal parameters and joint kinematics of the hip, knee and ankle, in the sagittal plane. From a clinical point of view, the most relevant plane is the sagittal one: where the main range of motion of the different joints occurs and gait pattern changes are more evident.

### STEP32 system

Recently the STEP32 system has been successfully used in clinical gait analysis [29, 16, 17]. The system allows for a direct measure of 1) gait events [28] and 2) joint kinematics in the sagittal plane. The joint flexion-extension angles are measured by means of electrogoniometers (Fig. 1A), while the timing of foot floor contact events is performed by means of electrical switches (Fig. 1B). In particular, on each side, electrogoniometers are placed in correspondence of hip (Fig. 1C), knee (Fig. 1D) and ankle (Fig. 1E) joints. Three foot-switches are placed under each sole (Fig. 1F), beneath the back portion of the heel, and the first and fifth metatarsal heads. Due to their structure based on articulated parallelograms, STEP32 goniometers do not require a very precise alignment of the potentiometer shaft with the instantaneous center of rotation of the joint. The system allows obtaining repeatability higher than 0.5 degrees and an accuracy of about 1 degree.

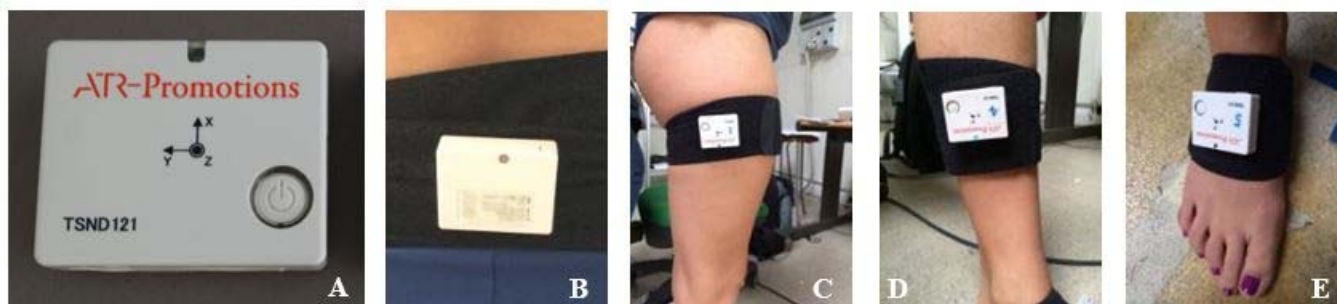


**Fig. 1:** STEP32 system sensors: A. electrogoniometers and B. switches. Electrogoniometers positioned over C. hip, D. knee and E. ankle joint to measure flexion-extension angles in the sagittal plane; F. foot-switches positioned under the back portion of the heel and under the first and fifth metatarsal heads to measure gait phases. The system includes a G. video recording synchronized with gait signals.

**H-Gait: MIMUs system**

A wearable sensor gait analysis system called H-Gait (Development Code, Laboratory of Biomechanical Design, Hokkaido University, Sapporo, Japan) was used [18]. The system relies on seven MIMUs, TSDN121, ATR Promotions (Fig. 2A), fixed to the lower limbs of the subject on pelvis (Fig. 2B), thighs (Fig. 2C), shanks (Fig. 2D), and feet (Fig. 2E). Each sensor unit (Fig. 2A) 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, consistent with the application. 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.



**Fig. 2:** H-Gait system: **A.** MIMUs (TSDN121, ATR Promotions) fixed to the lower limbs of the subject on **B.** pelvis, **C.** thighs, **D.** shanks and **E.** feet.

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 are transferred wirelessly (Bluetooth ver.2.0 + EDR) to a laptop computer or can be recorded in a local data storage (512 Mbyte). All the MIMUs characteristics are summarized in Table 1

**Table 1:** Specification of MIMUs ATR Promotions TSDN121

CPU	RX621
Operating time	About 6 hours
Dimensions	37mm(W) × 46mm(H) × 12mm(D)
Weight	22 g
Transmission protocol	Bluetooth Ver2.0 + EDR Class2
Memory	512Mb (about 5.8 hours with 100Hz sampling frequency)
Wireline connection	USB serial communication
Accelerometer and angular velocity sensor	InvenSense MPU-6050 Sampling: Up to 1000Hz (1 ~ 255msec period ) Acceleration range : ± 2G / ± 4G / ± 8G / ± 16G Angular velocity range : ± 250dps / ± 500dps / ± 1000dps / ± 2000dps
Geomagnetic sensor	Aichi Steel AMI306 Sampling: Up to 100Hz (10msec ~ 255msec period ) Detection range : ± 1200μT
Barometric pressure sensor	Freescale MPL3115A2 Sampling: Up to 25Hz (40 ~ 2550msec period ) Detection range : 500 ~ 1100hPa

### Experimental protocol

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

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

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

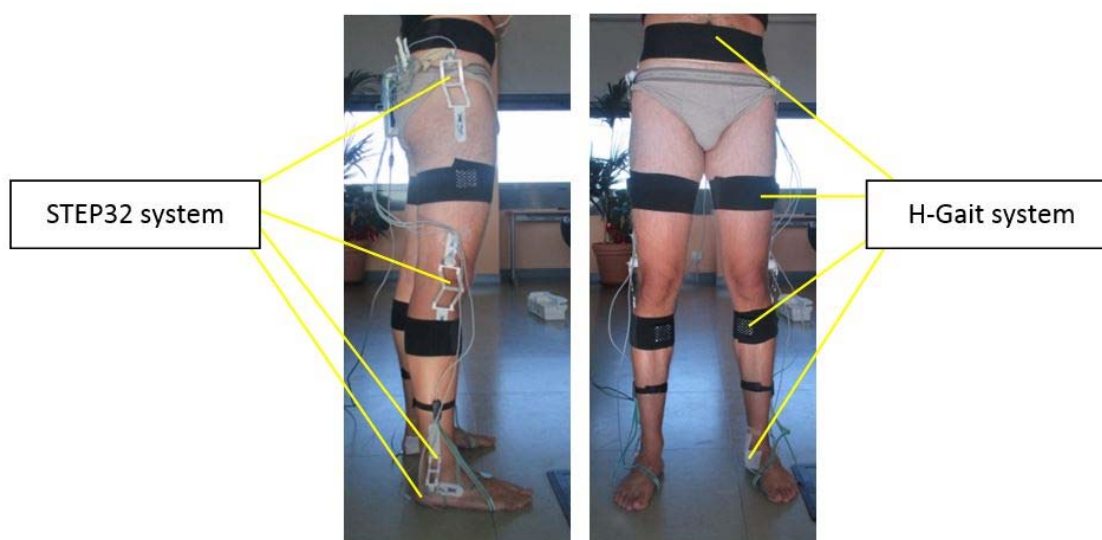
A specific sequence was defined to optimize the subject's preparation and to avoid problems in the positioning of the sensors of each system.

For the calibration of the MIMUs system, firstly, 10 reflective markers were placed, bilaterally, in specific anatomical landmarks: greater trochanter, lateral epicondyle of femur, medial epicondyle of femur, lateral malleus, and medial malleolus. Three digital images were taken from the front,

right side and left side of the subject, for the calibration procedure [18]. 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.

Then electro-goniometric sensors are placed in correspondence of hip, knee and ankle joints, on each leg and finally foot-switches are fixed under each sole (see Fig. 3).



**Fig. 3** STEP32 and H-gait sensors mounted together on the subject. The electro-goniometers can be clearly spotted on the left photo, while MIMUs of the H-Gait system, whose position is pointed out in the right photo, are covered by the black elastic bands.

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 [31]

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.

### Signal processing and data analysis

The MIMUs signals recorded during level walking were fused through a Kalman filter 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

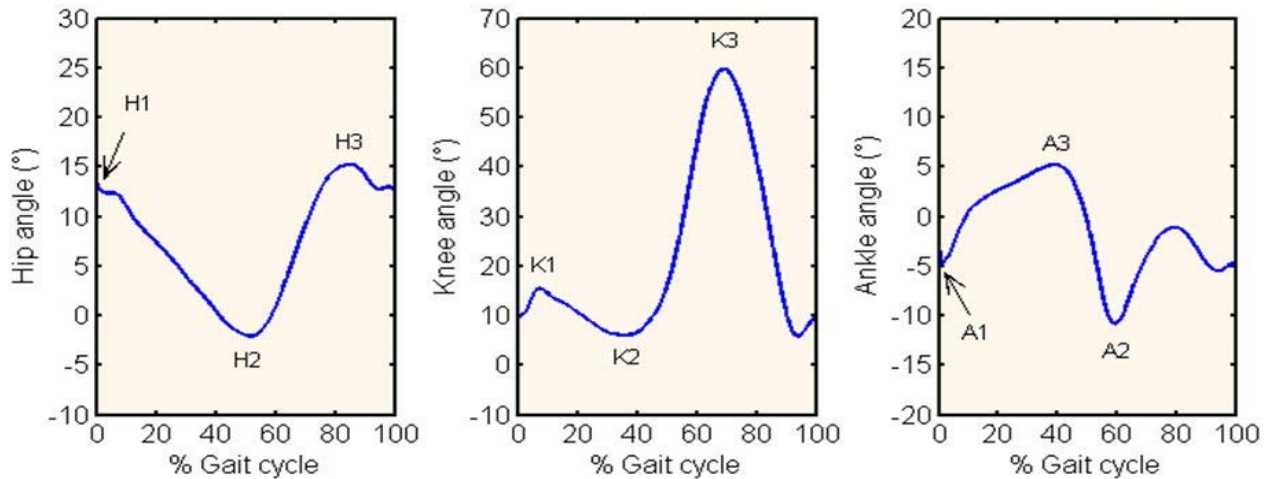
frame of each sensor to the anatomical frame of each body segment [18]. Custom Matlab<sup>®</sup> routines were used to evaluate hip, knee and ankle joint angles and to produce a 3-dimensional wire frame animation during the gait. Thanks to angular velocity recorded by the sensors placed on the shank 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. During one stride, the two negative peaks of pitch angular velocity of shank are known to robustly estimate HS and TO. Those peaks were detected and used to split gait trials into separate gait cycles and define limited time windows for further robust detection of the kinematic features.

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 [7]. Joint kinematics was compared between the two systems, using the curve parametrization outlined in Fig. 4,

similarly to what was proposed in [32]. H1, K1, and A1 are the joint angles at initial heel contact for hip, knee and ankle, respectively. For hip, H2 and H3 indicate the minimum and maximum joint flexion-extension angles, respectively. For knee, K2 and K3 indicate 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 ankle, A2 indicates the maximum plantar-flexion, and A3 the maximum dorsiflexion. These parameters are considered crucial from a clinical point of view.



**Fig. 4:** Hip-, knee- and ankle-joint kinematic curves in the sagittal plane. For each curve, the three main parameters, corresponding to maximum/minimum of flexion are labelled: hip (H1, H2, H3), knee (K1, K2, K3), ankle (A1, A2, A3).

**RESULTS**

Results between STEP32 and H-Gait systems are compared for spatio-temporal parameters and joint kinematics at hip, knee and ankle, bilaterally. Totally for the pilot test 288 steps were analyzed.

**Spatio-temporal parameters**

Spatio-temporal gait parameters were evaluated both with the H-Gait and STEP32 systems. Cadence is the number of strides the subject carries out per minute. Stride time is a temporal parameter that describes the period of time from foot contact to the following foot contact by the same foot (i.e. the time taken for the foot to do a full gait cycle), Stance is the percentage of the gait cycle between initial contact HS and terminal contact TO of the same foot, Swing is the percentage of the gait cycle between TO and following FO. Finally, double support is the percentage of the gait cycle where both feet are in contact with the ground. Table 2 reports spatio-temporal gait parameters evaluated with the H-Gait and STEP32 systems. The values reported are the average ( $\pm$  standard deviation) over three gait sessions. Left and right sides were also averaged.

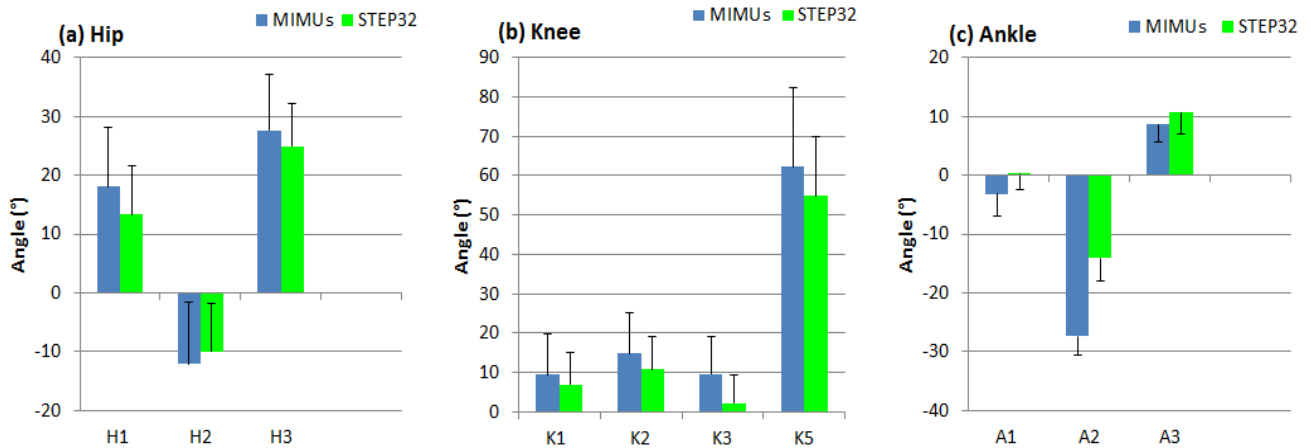
**Joint kinematics**

In the following, we compare the joint kinematics obtained by the two systems. Fig. 5 depicts the joints flexion-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. 6 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.

**Table 2:** Spatio-temporal parameters.

Gait parameters	H-gait	STEP32
Cadence (cycles/min)	51.5 $\pm$ 1.8	51.9 $\pm$ 1.2
Stride time (s)	1.2 $\pm$ 0.1	1.2 $\pm$ 0.03
Stance (% GC)	58.2 $\pm$ 1.5	53.8 $\pm$ 1.4
Swing (% GC)	41.8 $\pm$ 1.5	46.2 $\pm$ 1.4
Double support (% GC)	8.9 $\pm$ 2.1	7.8 $\pm$ 2.3



**Fig.6:** Comparison of the kinematic parameters obtained by the two systems (MIMUs and STEP32) for (a) hip, (b) knee and (c) ankle joints. Average values and standard deviations are represented.

## DISCUSSION

- For what concerns the spatio-temporal parameters obtained with the two systems, a very good agreement was found for cadence and stride time, and a good one for stance, swing, and double support, especially considering that in STEP32 the spatio-temporal parameters are directly measured by the foot switches that record gait events, while in H-Gait system they are indirectly calculated by means of key points in the trends of shanks accelerations. Differences were lower than 5% of the gait cycle. However, this discrepancy is most probably due to the different estimation of toe-off with STEP32; as a matter of fact, the metatarsal contact with floor, and not the big-toe contact is measured with STEP32. From the spatio-temporal parameters reported in Table 2, other global and local gait parameters, which are usually taken into account in the clinical context, can be evaluated.
- Considering gait kinematics, also in this case STEP32 system directly measures the functional joint angles, while with the H-Gait system they are indirectly measured and they are the results of the combination of calibration, accelerometer measurements accuracy, and algorithm pertinence to filter and remove drifts. For what concerns the joint kinematics, the STEP32 system shows a better repeatability among the different recorded gait cycles than the H-Gait system (see Fig. 5). While the hip and knee flexion-extension curves are similar for the two systems, a higher discrepancy may be noticed for the ankle joint kinematics. In this case, the H-Gait system shows higher curve dispersion (see lowermost left plot of Fig. 5). This is probably due to fact that foot sensors are affected by the vibrations arising during gait. This finding may be due to the fact that: 1) the sensor distal position is more influenced by vibrations due to the foot-floor contact; 2) the sensor positioning on the foot dorsum is critical because it may move during gait due to the fixing bands or due to soft tissue artefact (motion of the MIMUs with respect to the bone due to interposed tissues); 3) minimal errors in the initial calibration influence considerably joint kinematics: this is even more evident for the ankle joint,

since it is the last in the kinematic chain to be reconstructed and hence it is affected by the sum of the errors arising in determining the local sensors reference frames; 4) even small distortions of the magnetic field may influence the accuracy of the MIMU orientation and the accuracy of collected data and consequently post processing results (the magnetometer of the MIMUs mounted on the feet is more sensible to a magnetic field created by metallic structures laying beneath the floor, due to proximity).

- Considering the kinematic joint angles in the sagittal plane, overall, a good correlation of the curves was found between the systems. However, from the clinical gait analysis perspective, it is important to evaluate the reliability of specific kinematic parameters extracted from these curves, rather than just verifying that the two systems provide similar trends. For this reason a total of 10 kinematic parameters (3 for the hip, 4 for the knee and 3 for the ankle) were compared between H-gait and STEP32. We found that the differences between the systems are clinically acceptable for the hip and knee joints; on the contrary they are critical for the maximum ankle plantar-flexion (A2 parameter). This can be explained by the above mentioned issues related to foot sensors and in any case ankle results must be enhanced.

## CONCLUSIONS

In clinical gait analysis and, more in general, in out-of-the-lab motion analysis, the H-Gait system represents a potentially valid alternative to traditional optoelectronic systems. In this paper the results obtained from a single case pilot study are reported. Although results do not allow assessing the applicability of H-Gait system for clinical usage, they are valuable for protocol fine tuning and to highlight the weaknesses of the system. Moreover, the outcomes of the pilot study justify the effort toward a more extended campaign, considering both a larger number of subjects and subjects with gait disorders. As a matter of fact H-Gait system does not reach the same accuracy of the gold standard STEP32, it

allows a statistical gait analysis with a reliable estimation of spatio-temporal parameters. It also provides an acceptable estimation of hip and knee kinematics. On the other hand, ankle joint measurements have to be improved to be clinically applicable. Before extending this pilot experiment to a larger subject population, it would be important to revise the sensors' position on the foot, in order to minimize errors on the ankle kinematics.

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