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Use of an ultra-miniaturized IMU-based motion capture system for objective evaluation and assessment of walking skills

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***Abstract*— The increasing age of the world population is posing new challenges to our society, such as how to keep this aging population healthy and active despite of the age. In recent years, there has been a lot of interest for gait analysis for rehabilitation purposes as well as for performance assessment of this aging population. While current systems work well, they still have several limitations. Cost, need for specialized personnel, need to be used in a research center, and sporadic measurement prevent these systems from being widely used.**

The authors propose the use of extremely miniaturized, portable measurement systems, which can be worn by the users during their everyday life, and can monitor their gait over a long timespan. This paper presents the preliminary experiments with such a system.

Keywords- Inertial Sensor, Walking pattern, Gait Rehabilitation, Gait Phase Detection

I. Introduction

In 2012 UNFPA, United Nations Population Fund, reported that the world's population surpassed 7 billion [1], a milestone that is both a challenge and an opportunity. According to global demographics, at the end of 2012, 1 in 10 people was over 60 years old; by 2020 the ratio will be 1 in 7 (surpassing the one billion milestone) and by 2050 will reach 1 in 5, finally outnumbering the number of children aged 0-14. By that year the countries with more than 30% of the population over 60 years will be at least sixty, with the number of centenaries increasing globally from the actual 316,600 to the projected 3,2 millions [2].

The greater longevity projected for all regions means that many countries will be confronting the challenge of ageing populations and how to keep them healthy and active despite of the age.

In recent years, there is a lot of interest for gait analysis, in particular for rehabilitation purposes as well as for performance assessment of the aging population. Some researches [3] showed that gait disturbances, such as a slowing of walking pace or a more variable stride, could indicate a decline in cognitive function, and not simply be due to the increasing age. Difficulties with walking are not inevitable consequences of aging. They are, however, common and relevant problems among older adults. Research shows that people with walking difficulties not only have an increased risk of falling, but may also have an increased risk developing memory disorders and dementia. The standard techniques for the gait rehabilitation are still based on visual observations from the physicians, with repeated manual timing measurements with a stopwatch [4]. Unfortunately, these techniques have several main limitations: 1. They are very expensive, because of the high cost of equipment and human resource; 2. It is difficult to find specialized people with the required experience; 3. They can be used only in appropriate care centers; 4. Single time point analysis of walking might overestimate walking abilities [5]. Some rehabilitation centers have started to use more sophisticated equipment to help an objective measurement analysis and to help the personnel increase their skill, especially using optical systems based on cameras and reflective markers [6]. The results are very promising and many researchers are concentrating to develop complex biomechanical models with the help of optical systems [3]. Indeed, not many rehabilitation centers have the budget and the skilled people to manage such systems.

One solution could be the possibility to monitor persons at home or during their normal daily life. It may provide a much more accurate reflection of walking speed and may be more sensitive at detecting motor changes associated with future cognitive decline. Additionally, this continuous monitoring could give us a very early alert on the appearance of some indicator of diseases such as Parkinson's disease or Alzheimer Disease.

A. Objective of this paper

In this work, the authors propose a system that can provide a fast and objective walking assessment using a new measurement system, named WB-4R, composed of Inertial Measurement Units (IMUs). The WB-4R can be used for the gait analysis in rehabilitation centers or at home because it is compact and relatively maintenance-free. It means that the therapists can enhance their productivity and the patients will

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have the advantage to be assessed everywhere. Furthermore, it will be shown that the system is able to reconstruct the gait phases with high accuracy.

In particular, in this paper the authors present their preliminary results for the realization of such a system. Section II presents the materials and methods for the experiments. Section III presents the preliminary results of the comparison with a standard marker-based motion capture system (Sec. III.A) and the preliminary results of walking measurement (Sec. III.B).

II. Materials and Methods

This section presents the details of the proposed IMU-based measurement system, as well as the protocols for the two proposed experiments. These experiments were carried out at the Rehabilitation Center of Tokyo Women's Medical University, Tokyo, Japan, under the supervision of professional rehabilitators. The experiments were approved by the ethical committees of both Universities.

A. WB-4R ultraminiaturized inertial measurement unit

The WB-4R ultraminiaturized Inertial Measurement Unit [8] allows measuring the lower limbs movements during walking activity. The WB-4R is very compact and lightweight (size 20 x 20mm and weight 2.9 g), and is composed of a 3-axis accelerometer, a 3-axis gyroscope and a 3-axis magnetometer (see Fig.1). The sensors' characteristics are summarized in

TABLE I.

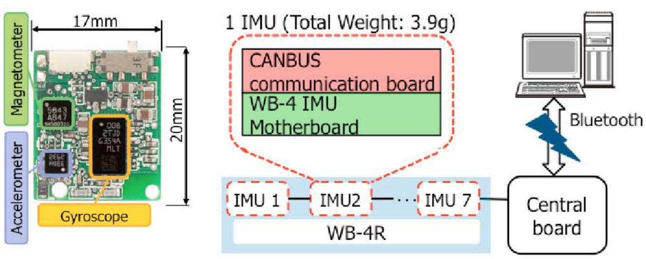


Fig. 1. WB-4R inertial measurement unit (left) and lower body motion measurement system (right)

TABLE I
Main characteristics of the sensors in WB-4R IMU

	LIS331DLH	LYPR540AH	HMC5843
Category	Accelerometer	Gyroscope	Magnetometer
Axis	3-axis	3-axis	3-axis
Range	±8 [*G*]	±1600 [deg/s]	±4 [Gauss]
Resolution	3.9[m*G*/digit]	0.8[mV/dps]	12 [bit]
Bandwidth	500[Hz]	140 [Hz]	50 [Hz]

The IMUs acquire data at a sample rate of 200Hz and communicate with the central board via CAN BUS at 1Mb/s. More details about the IMU hardware and performance are available in [9] and [10]. It is also important to notice that the core components of this IMU are the same that could be found in any of the current smartphones (such as Apple iPhone 4S or later, Samsung Galaxy S2 or later, and so on); therefore, the authors believe that this research can be easily transferred into current commercial products for a more invisible monitoring.

Seven IMUs were connected through CAN bus to a Central board placed on the back of the subject; a Bluetooth connection ensured a continuous data communication with a standard personal computer (Fig. 1, right). Total weight of the measurement system (including IMUs, central board, cables, support bands, and batteries), is 224.3 g. The kinematic model of the lower limb is shown in Fig. 2.

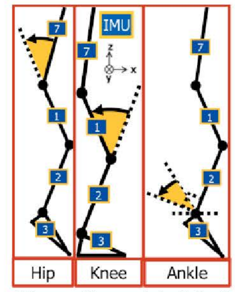


Fig. 2. Kinematic model of the lower limb.

B. Experiment I: experimental setup

Objective of the first experiment was to confirm the validity of the proposed WB-4R system as motion capture device. For this purpose, the authors compared the results of WB-4R measurements with the results obtained with the Optical systemLotus3D MA-3000 (Anima corp., Japan), one of the optical motion capture system commonly used in rehabilitation centers for this kind of analysis.

The treadmill used for the experiments was the TR33 by SportsArt [11]. A camera was placed close to the treadmill allowing the physician to visually observe the walking pattern of the subject. The motion capture system used 6 IR cameras with a frame rate of 100 [Hz], placed closely around the treadmill to ensure a working space big enough to contain the whole movement. 17 markers (8 on the right side, 8 on the left, one on the back) were placed with the help of a professional rehabilitator, as shown in Fig. 3 (left).

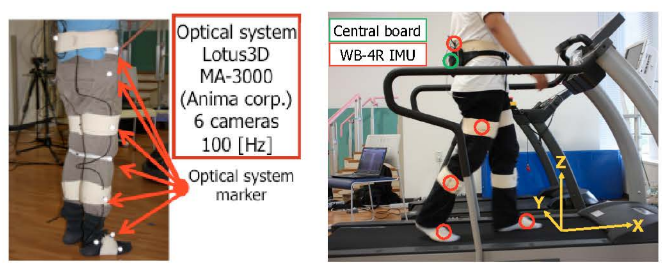


Fig. 3. Placement of the IR Markers for experiment I (left) and of the 7 WB-4R IMUs (right).

The WB-4R IMUs were placed on the subject as shown in Fig. 3 (right): pelvis, right and left upper leg, right and left lower leg, right and left forefoot. Each IMU was positioned roughly on the middle between the hip, knee, and ankle joints. One subject (33yo, male, healthy) kindly agreed to perform the experiment after the initial explanation. The experiment consisted of 3 repetitions of 1 minute normal walking at 4km/h on the treadmill.

B. Experiment II: experimental setup

Objective of this second experiment was to compare the walking parameters of healthy subjects with the ones of disabled subjects during indoor walking. With the exception of the IR markers, which were not used in this case, the experimental setup is the same as in Experiment I. The inclination of the treadmill (horizontal) and the initial toe direction (parallel feet) were identical in all trials to provide the same experimental conditions for all subjects.

Ten healthy subjects (age: 29.3±5.03, all male) kindly agreed to participate to the experiments. Each subject performed 6 repetitions of 2 different trials: 1. Free, normal walking (self-selected speed); 2. Simulated disabled walking. Disabled walking (hemiparesis) was simulated with the use of an orthosis to lock the right ankle, a sling, to keep the right arm in place, and a cane, to support the person during walking (Fig. 4). Each subject was given instruction of how to walk with the cane, and did some free trials to better understand how walk before the actual experiment.

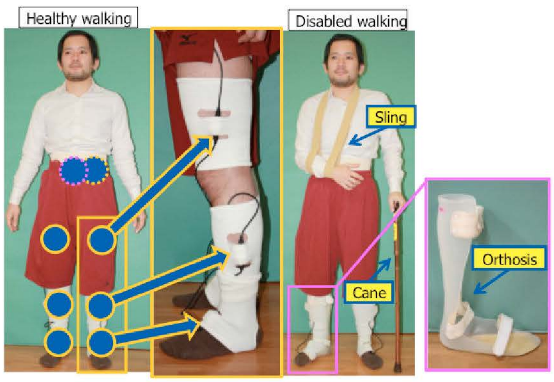


Fig. 4. Experimental setup for Experiment II.

III. Experimental Results

A. Results of Experiment I

The results of experiment I are shown in Fig. 5. As can be seen, the reconstructed joint angles are equivalent to the ones reconstructed with the optical system, therefore proving the possibility to use WB-4R as a valid alternative to the conventional motion capture systems. As widely known, optical systems can be only be used in limited, previously setup working space. In our case, the working space was limited to the treadmill center. Placing the cameras far apart can increase the working space; this however decreases the resolution of the reconstructed marker position. Moreover, optical systems suffer from the presence of IR component of daylight, which must be masked during the experiments (Fig. 6). In addition, the authors noticed that one of the markers was occluded by the support bar of the treadmill during the experiment, thus corrupting the whole data (Fig. 7 left). Eventually, one of the marker briefly disappeared, during the experiment (Fig. 7 right).

It is important to notice that the proposed IMU-based measurement system does not suffer from the above problems, thus giving a much higher flexibility for the assessment of the walking skills in unstructured environment.

B. Results of Experiment II

The detailed reconstruction of the lower limb movements during normal walking and simulated hemiparesis walking is presented in Fig. 8 for one of the subjects (Blue: normal walking; Red: simulated disabled walking). The results from the other subjects are similar.

While the curves for normal walking are more or less similar for both left and right leg, they are completely different – as expected, of course – in case of simulated disabled walking.

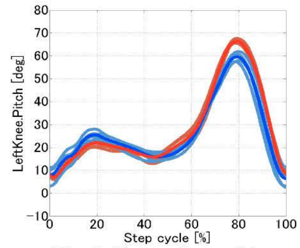


Fig. 5. Comparison of the reconstructed knee angle on the sagittal plane. Red: optical system; Blue: WB system.

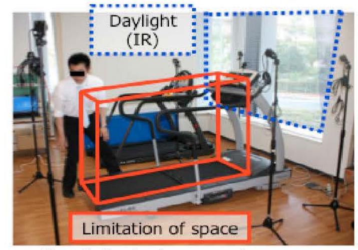


Fig. 6. Optical systems have a limited working space. In addition, they suffer from the presence of IR component of daylight.

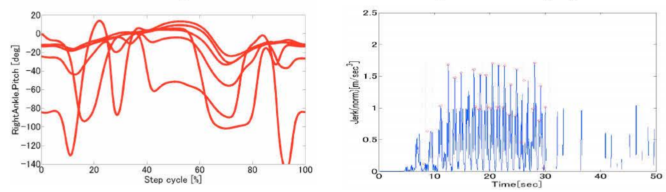


Fig. 7. (left) Corrupted data due to a marker not correctly fixed in the ankle; (right) Data loss due to marker occlusion (from 30 sec on).

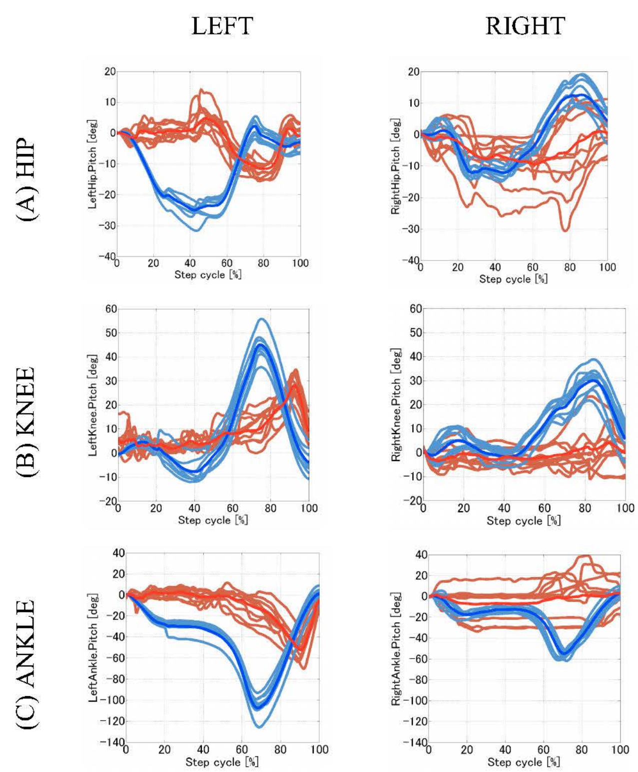
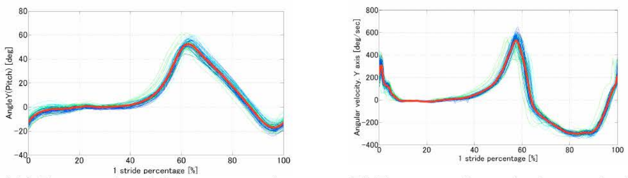


Fig. 8. Detailed reconstruction of the lower limb movements during normal walking and simulated hemiparesis walking. Blue: normal walking; Red: simulated disabled walking

As additional information, the authors calculated also the angular speed for these joints. An example is shown in Fig. 9 for the ankle joint analyzed in the sagittal plane. The combination of these two figures leads to. The normal walking cycle clearly shows two main peaks, one at the initial contact of the foot with the ground, and the other one right before the toe off. Of course, these parameters are dependent on each subject physical dimensions and walking speed/style. In case of disabled walking, instead, the above double-peaked loop changes its shape for the disabled limb.

This kind of analysis can shows different walking patterns for healthy subjects as well. For example, in Fig. 11 it can be seen that subject one has very similar curves for both left and right feet (top row); subject 2, however, shows a different walking pattern at all walking speeds, thus indicating that his walking style his not perfectly balanced. Walking speeds are 2km/h (disabled, pink), 3km/h (blue), 4km/h (green), 5km/h (red).



(A) Foot angle with respect to the floor, sagittal plane. (B) Foot angular velocity, sagittal plane

Fig. 9. Conventional gait analysis

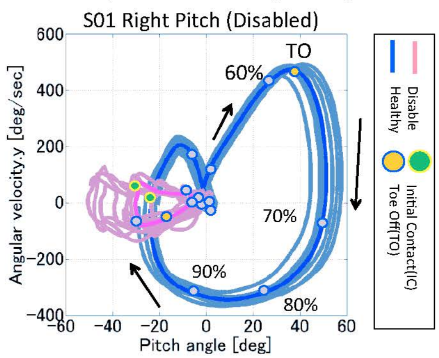
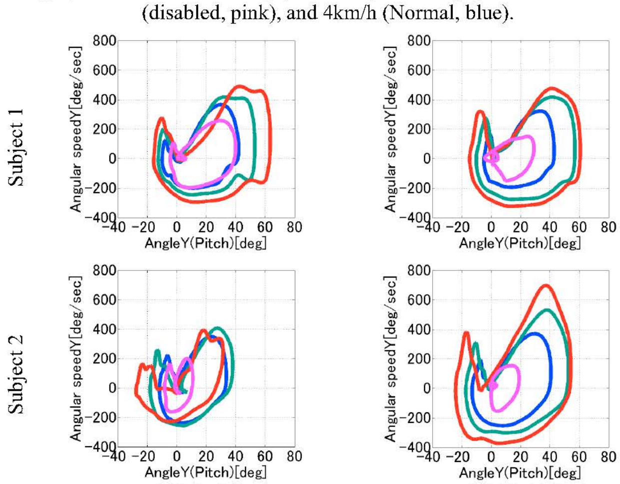


Fig. 10. Comparison of the combined foot angle – foot angular velocity graph in case of a disability (simulated). Walking speeds are 2km/h (disabled, pink), and 4km/h (Normal, blue).



(A) Left foot (B) Right foot

Fig. 11. Combined foot angle – foot angular velocity graph in case of a disability (simulated). Walking speeds are 2km/h (disabled, pink), 3km/h (blue), 4km/h (green), 5km/h (red).

IV. Discussion and Conclusions

For the clinical assessment of patient, it is necessary to identify appropriate parameters that can measure the significant feature values of movement for objectively evaluating the patient's gait. The authors performed the experiments with healthy subjects, and the data show that using IMUs it is possible to obtain several significant parameters that might be useful in classifying the human gait. While the current system works well in an indoor setup, the authors must try it outdoor as well. The final goal is to develop a measurement system that can be used by everybody at home or during his or her normal daily life.

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