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研究課題名（和文）　着用型人間計測システムの開発と生理指標および動作の解析

研究課題名（英文）
Development of the wearable motion capture system WB

研究代表者
ゼッカ　マッシミリアーノ（ZECCA Massimiliano）
早稲田大学・理工学術院・准教授
研究者番号：30434377

研究成果の概要（和文）：
このプロジェクトの主な成果は Inertial Measurement Unit(IMU) WB-4 の開発したことである．IMU は加速度センサ，ジャイロセンサ，および地磁気センサから構成されており，寸法は 20x17[mm]，質量は 2.0[g]で現在のところ，世界最小で最も性能が優れている．
このプロジェクトで IMU は，以前開発した WB-2 や WB-3 と共に，以下のような様々なアプリケーションに適用された．あ）腹腔鏡検査：動作計測とスキル評価．い）神経外科：動作計測．う）咀嚼：咀嚼パターンと食物判別の分析．え）歩行分析：健常者と身体障害者の動作計測とスキル評価．われわれが提案している手法の有効性は，多数の学会誌掲載や受賞，および実験の実績によって裏づけされており，様々なアプリケーションで成功を収めた．

研究成果の概要（英文）：The main result of this project is the development of the Inertial Measurement Unit (IMU) WB-4, which integrates 3D accelerometer, gyroscope, and magnetometer in a 20x17mm board (2.0 grams weight) – at present the smallest and most performing IMU in the world. During the project this IMU and the previous prototypes was applied in a vast range of applications, such as: performance measurement and assessment for laparoscopy skill analysis, both on the surgeons and on the tools; performance measurement and assessment for neurosurgery; mastication analysis; gait analysis for healthy and disabled persons. All the applications were successful as testified by the published literature and the relative awards, thus validating the proposed approach.

交付決定額

（金額単位：円）

	直接経費	間接経費	合　計
2007 年度	1,300,000	390,000	1,690,000
2008 年度	1,100,000	330,000	1,430,000
2009 年度	900,000	270,000	1,170,000
総　計	3,300,000	990,000	4,290,000

研究分野：総合領域
科研費の分科・細目：人間医工学
キーワード：生体情報・計測，人間・ロボットインタラクション，医療路簿ティクス，リハビリテーション，ヒューマン・マシン・インターフェース，モーションキャプチャ，慣性測定ユニット，センシング

１．研究開始当初の背景

In recent years there has been an ever increasing amount of research and development of technologies and methods to improve the quality and the performance of medicine. The introduction of robotic technologies in the clinical practice can improve existing clinical procedures as well as provide innovative approaches to current clinical problems. A fundamental task for the development of these technologies is a better understanding of the performance of human being in clinical and surgical applications, clarifying not simply what a skilled (or healthy) person does better than a novice (or patient), but also how.

Among the different technologies currently available, motion capture usually provides an effective solution for analyzing human motion. Motion capture can obtain motion data from the human performers, track their key points/joints movement, and translate them into a digital model. With this digital model it is possible to analyze in details the performance under investigation. The most commonly used technologies for motion capture are:

- camera-based motion capture system;
- magnetic-based motion capture system;
- inertial-sensor-based motion capture system.

However:

- camera-based systems are very expensive and they can be used only in a calibrated room; the markers they need are heavy and bulky; moreover, markers need to be always in sight with the cameras, which is not always possible;
- magnetic-based systems have magnetic distortion problem; moreover position data are acquired at relatively low frequency, thus limiting the precision of the analysis;
- current inertial-sensor-based systems are too big for most practical applications in surgery and clinical practice.

None of the current systems fits the requirements of motion capture for applications such as Minimally Invasive Surgery (MIS), neurosurgery, gait analysis, rehabilitation, and so on.

２．研究の目的

The goal of my research, therefore, is to develop a portable Bioinstrumentation System that can objectively measure human's full body motion.

I also aim at developing evaluation tools and to define sets of parameters that allow the characterization of the human's movements, in order to see how different people acts during the selected tasks, and to evaluate their improvements of performance after training.

３．研究の方法

The main component of this project is the Inertial Measurement Unit, which allows capturing the motion of the persons and/or the objects it is attached to.

During these three years several prototypes were built and tested in different applications, such as performance measurement and assessment for laparoscopy skill analysis, both on the surgeons and on the tools, performance measurement and assessment for neurosurgery, mastication analysis, gait analysis for healthy and disabled persons, and so no.

The methodology used in each experiment is briefly presented in the next sections. For the detailed methodology and the obtained results please refer to the published literature.

４．研究成果

4.1 Inertial Measurement Units

During this project, several miniaturized inertial measurement units were developed, based on from the original WB-2 (Fig. 1). This sensor was used mostly during the first and second year of the project for the initial testing and evaluations. Although it showed very good performance, it was still too big and difficult to use; more important, it was not suitable for a wearable system.

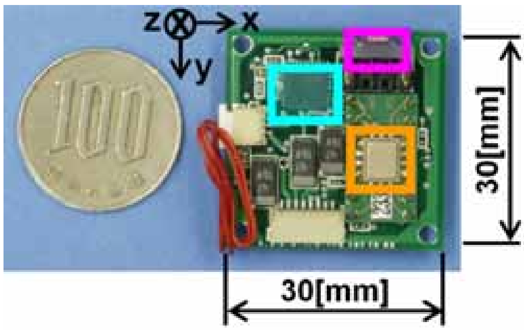

Fig. 1: Inertial Measurement Unit WB-2R (2007~2008)

Therefore during the second year I developed a new ultra-miniaturized Inertial Measurement Unit, named WB-3 (Fig. 2), which is very compact and lightweight (size 20x20 [mm] and weight 2.9 [g]).

Thanks to its extremely reduced dimensions it can be attached to human body with less physical restriction (for comparison, a commercial system with the same characteristics would be 8 times bigger); it can also be easily attached to objects and tools without effecting their overall weight and balance.

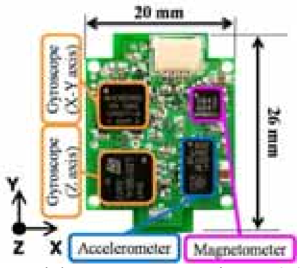

Fig. 2: Inertial Measurement Unit WB-3 (2009)

The WB-3 IMU is composed by the following sensors: 3-axis Accelerometer LIS3LV02DL; 2-axis gyroscope IDG300; 1-axis gyroscope LSIY300AL; 3-axis Magnetometer HMC5843. The IMU contains also a 32 bit microcontroller STM32 Cortex (STMicroelectronics) for embedded signal elaboration. The communication between PC and IMU is performed using CAN BUS at 1 Mb/s. See Table 1 for the details of the sensors. Fig. 3 presents the block diagram of WB-3.

Table 1: WB-3 IMU characteristics

	LIS3LV02DL	IDG300	LISY300AL	HMC5843
Axis	3 axis	2 axis	1 axis	3 axis
Range	±2 G	±500 deg/s	±300 deg/s	±4Gauss
Sensitivity	12±1bit	12±1bit	12±1bit	12 ± 1bit
Bandwidth	40 Hz	140 Hz	88 Hz	50 Hz
Sample Rate	100 Hz	100 Hz	100 Hz	100Hz
Linearity (FS)	±2%	<1%	±0.8%	±0.1%
Noise level	< 1 bit	< 1 bit	<2 bit	< 1 bit

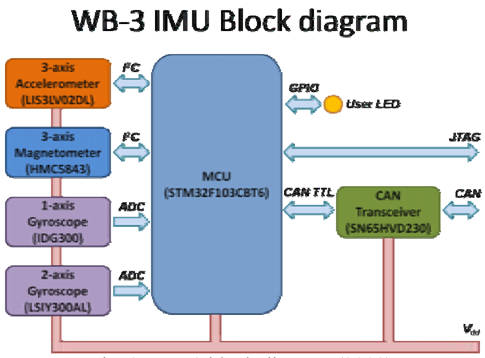

Fig. 3: WB-3 block diagram (2009)

The WB-3 wearable bioinstrumentation system was developed by using 20 Inertial Measurement Units (Fig. 4). The weight of whole system (including cables, suit, and battery) is about 1.1kg (less than 40% of the similar system realized with WB-2R). The WB-3 portable bioinstrumentation system is capable of measuring the motion of human's arms, legs, head and body. Thanks to the CAN bus interface, moreover, it can be easily expanded to integrate the data coming from other sensors.

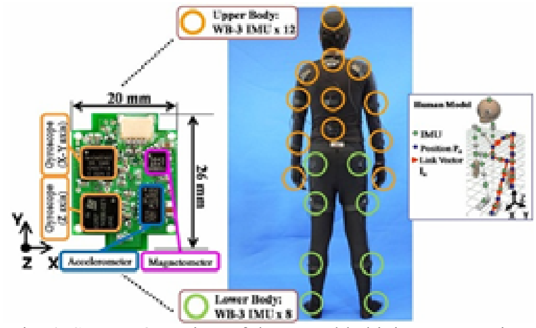

Fig. 4: System Overview of the wearable bioinstrumentation system WB-3 (2009)

All the applications of WB-3 were successful (for the details see the following sections and the published literature); however the experimental results and the questionnaires with the users pointed out the need for a more compact sensing unit, together with the wireless capability.

Therefore in 2009 I also developed a new IMU, named WB-4 (Fig. 5). WB-4 integrates the following components in a 20x16mm board (2.0 grams weight): 16 bit 3 Axis accelerometer LYS331DLH; 12 bit 3-axis Gyroscope LYPR540LH; 12 bit 3-axis Magnetometer HMC5843; STM32F103CB 32bit microcontroller for embedded signal elaboration and data exchange (see Fig. 6 for the detailed block diagram). Table 2 presents a comparison of WB-4 with the previous IMUs. WB-4 is 39% smaller than WB-3 and 31% lighter.

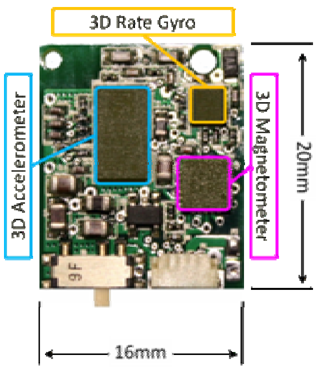

Fig. 5: Inertial Measurement Unit WB-4

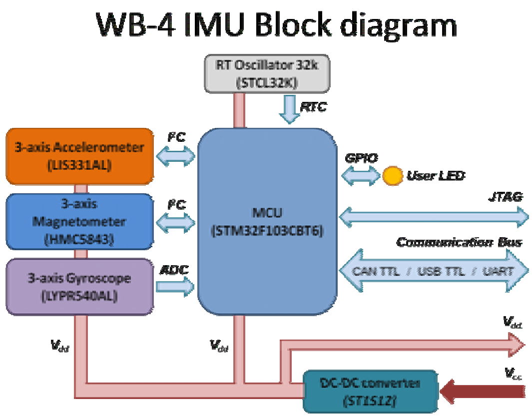

Fig. 6: WB-4 block diagram (2010)

Table 2: Comparison of the dimensions of the three IMUs used in the project.

System	WB-2R (2008)	WB-3 (2009)	WB-4 (2010)
Size	30x30	26x20 (-43%)	20x16 (-39%)
Weight	6.7	2.9 (-57%)	2.0 (-31%)

A complete wireless solution can be obtained by adding the commercial Bluetooth communication board ZEAL-C01 and the Li-Ion battery KAIO 501717 (80 mAh). The resulting system is enclosed in a case of 20x17x7mm, and weights about 6.0 grams (this is about 10 times smaller than any other commercially available system). WB-4 can reach 100Hz continuous data exchange up to 10 meters and with autonomy up to 1 hour.

4.2 WB for Laparoscopic Surgery

The research for laparoscopic is focused on assessing the abilities of surgeons by measuring their movements during laparoscopic training. This study is very important to evaluate the effectiveness of laparoscopic training systems; moreover, the objective evaluation results and expert's suggestions allow the development of better training/evaluation systems for young surgeons.

Main objective of this application is to define a set of parameters that allow us to characterize surgeon's movements during a surgical procedure, in order to see how surgeons of different expertise rank act during the operation in relation to these movement parameters, and to evaluate the improvement of performance after training.

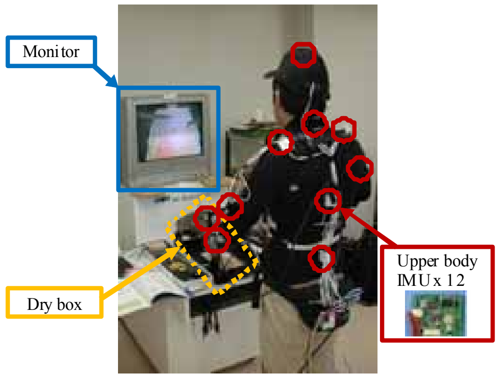

Fig. 7: Experimental setup with WB-3

In this preliminary experiment I used the wearable bioinstrumentation system WB-2R as a tool to assess the performance of novice during laparoscopic. The advantage of the proposed system is that – unlike all the other measurement systems currently used in laparoscopy training – it could be used as a measurement/validation tool not only during simulations but also during real surgery.

I collected the movements of the upper body from the novice subject during a basic C-loop suture, to verify the effectiveness of the training course.

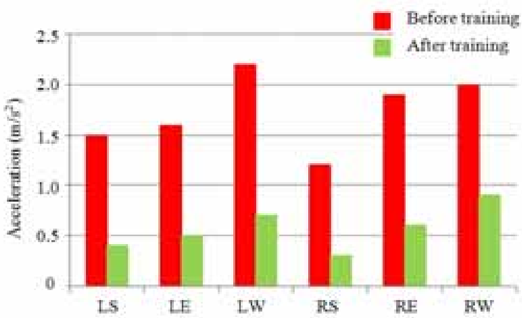

Fig. 8: Standard deviation of acceleration before and after training

The analysis of mean and standard deviation of acceleration value, 95% acceleration cumulated distribution, path length based on the movements of subject’s arms and execution time, although preliminary, the overall results are in line with the ones obtained with other - more expensive and more cumbersome - systems, thus confirming the validity of the proposed approach.

These preliminary results are a clear step towards the development of a training system for an objective evaluation of the surgeon’s performance in particular during MIS. These results could also be extended to develop instruments and methodologies for a functional/ergonomic evaluation of surgical instruments.

Fig. 9: Experimental setup with WB-3

I also used WB-3 for other experiments in collaboration with the University of Kyushu (Fig. 9). The results are not yet available at the time of preparation of this report, though.

4.2 WB for Neurosurgery

With the diffusion of more and more advanced tools and technologies in the operating room, it is fundamental to establish more efficient training exercises and to define objective metrics to objectively evaluate the dexterity of neurosurgeons. The extremely small movements and sizes involved in neurosurgery (working field is usually 280-370 [mm2] x h5-10[cm], target size 0.2-1.5[mm]) have prevented until now the development of similar methodologies and systems.

The extremely reduced weight and size of WB-3 IMU allow it to be mounted on the bipolar forceps of neurosurgery, and to be used during normal tasks without disturbing surgeon's performance. As a preliminary experimental setup (Fig. 10), I applied WB-3 IMU to a bipolar forceps (Fig. 11), the most commonly used instrument in neurosurgery, and I used the skill evaluation system (Fig. 12) to analyze the movements of neurosurgeons in a simple pick and place scenario.

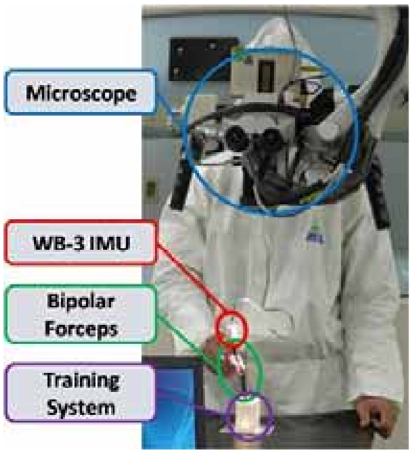

Fig. 10: Overview of experiment setup for neurosurgery

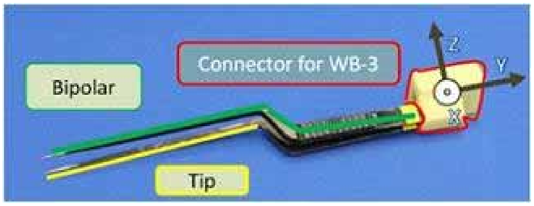

Fig. 11: Bipolar forceps with WB-3 IMU

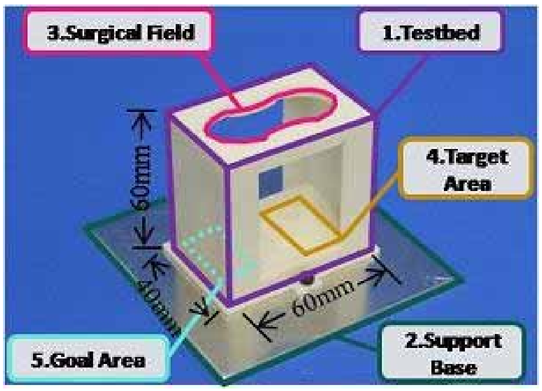

Fig. 12: Skill evaluation system

The preliminary results (Fig. 13 and Fig. 14) proved that several parameters extracted from the IMU's data (and in particular the mean Power Spectral Density $PSD_{|a|}$ and the Cumulative Distribution Function $CDF95\%$ of both acceleration $|a|$ and angular speed $|\omega|$) allow a clear distinction between a professional neurosurgeon and a group of novices; moreover, these data also could show which non-medical subject performs similarly to the surgeon, and how, thus validating the approach proposed in this pilot study.

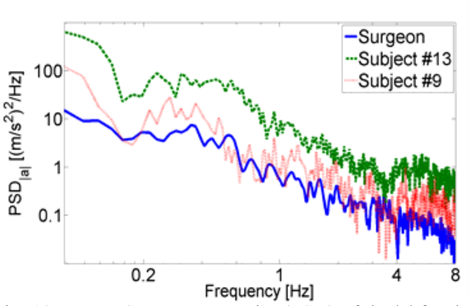

Fig. 13: Power Spectrum Density (PSD) of the |a| for the subject #13, subject #9 and the surgeon (MEDIUM objects).

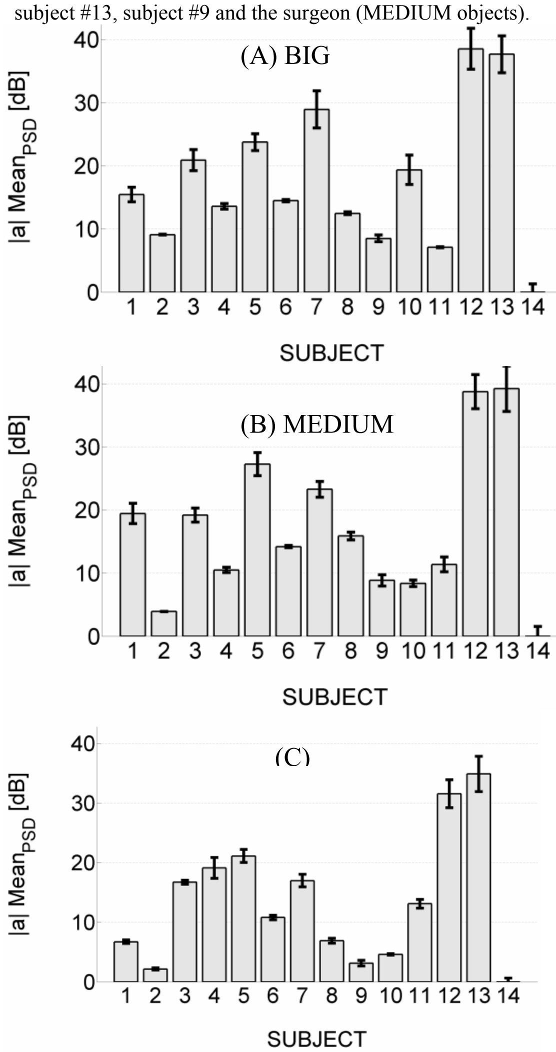

Fig. 14: Mean power of the acceleration in decibel for the (A) BIG, (B) MEDIUM and for the (C) SMALL targets, averaged on the 5 trials for each subject.

4.5 Mastication Analysis

Many types of jaw tracking devices have been developed for the analysis of functional jaw movement, but most of them are still not handy. To improve the handiness of the jaw movement analysis devices, I propose a jaw-tracking prototype by using WB-3 IMU, in order to overcome the limitations of the existing devices and improve the handiness of tools for jaw movement analysis

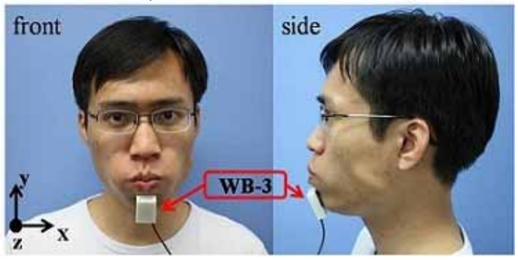

Fig. 15: Mastication experimental setup with WB-3

The IMU was attached to mandible during normal tests without physical restriction to the subjects. The preliminary results of jaw movement analysis during free chewing with three types of food of different shapes and hardness are evaluated. A group of 9 healthy subjects aged from 21 to 36 years old kindly participated in the experiment.

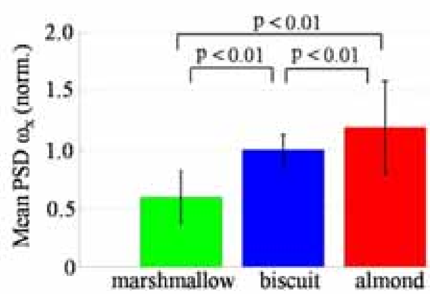

Fig. 16: Normalized Power Spectrum Density (PSD) of the x-axis angular speed ωx for 3 different foods, averaged on all subjects' trials for each food

The parameters of chewing time, chewing frequency, power spectrum density of jaw's angular speed and acceleration, cumulative distribution function of jaw's acceleration, and mouth opening angle are presented. The experimental results clearly show that the subjects used less chewing time, less chewing frequency, less acceleration cumulative distribution and energy to eat soft food; higher values were found in the case of hard food; and there was no significant difference in mouth opening angle while eating these three foods.

The jaw movement analysis prototype using IMU WB-3 was proved to be a valid and handy method for jaw movement and pattern analysis which may be used clinically as an assistant system for dental therapy.

4.4 Gait Analysis

In our elderly-dominated society, there is considerable expectation for a growing need for home, medical, and nursing care services to assist this aging society, both from the physical and psychological points of view. Among these services, special importance has the rehabilitation process and specifically the clinical assessments of motor abilities. The current rehabilitation process, however, lacks of objectiveness.

I proposed to objectively measure and assess the physical and physiological effects of the rehabilitation therapy by using WB-3 system, both in the hospital/rehabilitation center and at home, and by integrating the analysis of human motion into the analysis of physiological indexes.

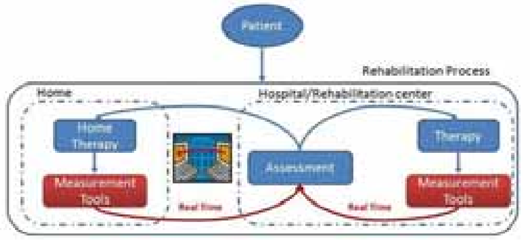

Fig. 17: Concept for rehabilitation by using the WB motion capture system

In this study, focusing on the training process of handicapped gait, we simulated the process with imitation handicapped gait with hemiplegic para-experienced orthosis. From the view point of stability of the motion the simulated gait during the training process is similar to the real training [1]. As validation experiments, I tested the WB-3 system for gait analysis in two separate setups, as outlined below.

The first one Fig. 18 with 20 healthy subjects 7 WB-3 IMU (3 for each leg and one on the back) was performed inside a Vicon room to compare the results of the analysis using conventional systems(Vicon and Force plates) and the inertial measurement unit WB-3.

During the experiments each subject performed normal straight walking (about 5 meters) and the straight walking using the Manabi-tai hemiplegic simulator for five times each. The data were acquired from both the systems at 100Hz synchronous.


Fig. 18: Concept for rehabilitation by using the WB motion capture system

In the second experiment (Fig. 19), three healthy subjects were asked to perform a walking on the snow. Objective of the experiment was to compare the walking style on the snow of healthy subjects with hemiplegic subjects, and the effect of the application of an orthosis on the gait stabilization for hemiplegic patients in case of slipping surfaces like the snow.


Healthy subject | Healthy subject with hemiplegia simulator | Orthosis for gait correction

Fig. 19: Concept for rehabilitation by using the WB motion capture system

A path with artificial snow (thickness 4 cm, length 3 meters) was prepared for the experiment. The subjects performed three different kind of walking for five times; the first one, free walking, the second one with a hemiplegic simulator (blocking the right knee joint) and the last one with the orthosis on the foot.

It is extremely important to notice that this particular type of experiment cannot be done with other motion capture system such as Vicon (which is currently considered the state of the art in motion capture) because of the reflective characteristics of the snow; the markers inside the Vicon room cannot be distinguished from the snow, thus making the motion reconstruction impossible.

For both the above experiments, the experimental data are still being elaborated, and were not ready at the time of preparation of this report.

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

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○取得状況（計１件）

ZMP inc., (6F Sumitomo Fudosan Koishikawa Bldg., 5-41-10, Koishikawa, Bunkyo-ku, Tokyo Japan) acquired from the proposer the rights for the commercialization of 9-axis wireless motion sensor e-nuvo IMU-Z, which is based on the design of the “WB-3 (Waseda Bioinstrumentation system No.3)”.

〔その他〕
ホームページ等
日本語:
http://www.takanishi.mech.waseda.ac.jp/top/research/wb/wb-3/index_j.htm
English:
http://www.takanishi.mech.waseda.ac.jp/top/research/wb/wb-3/index.htm

６．研究組織

(1)研究代表者

ゼッカ　マッシミリアーノ（ZECCA Massimiliano）
早稲田大学・理工学術院・准教授
研究者番号：30434377