

Objective Skill Analysis and Assessment of Neurosurgery by using the Waseda Bioinstrumentation System WB-3 – Pilot tests –

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Abstract— 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 advanced surgery. In other fields several training methods and metrics have been proposed, both to improve the surgeon's abilities and also to assess her/his skills. For neurosurgery, however, the extremely small movements and sizes involved have prevented until now the development of similar methodologies and systems. In this paper we present the development of an ultra-miniaturized Inertial Measurement Unit and its application for the evaluation of the performance in a simple pick and place scenario. This analysis is a preliminary yet fundamental step to realize a better training/evaluation system for neurosurgeons, and to objectively evaluate and understand how the neurosurgery is performed.

I. INTRODUCTION

In recent years, more and more technologies have entered the operating theater. By using cameras or microscopes and miniaturized tools, surgeons are allowed to operate in smaller spaces, thus obtain better results in terms of reduction of the tissue damaged. While these new technologies have many advantages and benefits for patients, such as less pain and scarring, lower probability of critical hemorrhage, speed recovery, and reduced incidence of post-surgical complications, they often require surgeons to undergo long and difficult training [1]. One of the paramount issues in this training is the objective evaluation of surgical skill. Historically, the performance of surgeons has been assessed subjectively by senior surgical staff in both training and operating environments. However, with the advancements of surgery and neurosurgery, it is fundamental to establish efficient training exercises to enhance the dexterity of surgeons and to define objective metrics for assessing their experience and performance.

Among the different challenges posed by neurosurgery, one of the most critical aspects is the objective evaluation of the surgical gesture. In other fields, such as laparoscopy for example, several metrics [2-5], and procedures [6-8] have already been proposed and employed to characterize different phases of surgical movements in laparoscopy, with interesting results. The extremely small movements and sizes involved in neurosurgery, however, have prevented until now the development of similar methodologies and systems. One possibility for the realization of compact measurement systems is offered by MEMS (Micro-Electro-Mechanical Systems) technology, which is becoming widely popular in sensors for measuring motion, acceleration, and inclination, offering multiple-axis response with high resolution and low power consumption in a single package. However, current prototypes such as WB-2 [9] or commercial systems (xSens MTx, InterSense InertiaCube3, and so on) are still too big and too heavy for the application in neurosurgery.

Our aim, therefore, is to develop evaluation tools and to define a set of parameters that allow us to characterize the neurosurgeon's movements during a surgical procedure, in order to see how surgeons of different expertise acts during the operation, and to evaluate the improvement of performance after training. These analyses and modeling, in turn, represent a significant step towards the automatization and the robotic assistance of the surgical gesture. The data collected, moreover, provide an important baseline for design specification and performance evaluation of microsurgical devices. In this paper we present the development of an ultra-miniaturized Inertial Measurement Unit, named WB-3, and its application for the evaluation of the performance of neurosurgeons in a simple pick and place scenario.

II. MATERIALS AND METHODS

A. Bipolar Forceps

During neurosurgery, one of the most commonly used instruments is the bipolar forceps (Fig. 1). The main characteristics of the system we used in our experiments are summarized in TABLE I. A connector made by acrylonitrile butadiene styrene (ABS) polymer in rapid prototyping for housing WB3 is placed at the proximal end of the bipolar forceps. Our IMU's extremely reduced weight and size allows it to be mounted on the bipolar forceps, and to be used during normal tasks without disturbing the surgeon's performance.

The Skill Evaluation System (SES) used for this preliminary experiment is shown in Fig. 2. SES is composed by 5 main parts:

- 1) The Test bed, made by ABS, simulates the most common operating space. Current version has a size of 60x40x60mm.
- 2) The Support Base (SB) is an aluminium base of 100x100mm with housing for the test bed made by ABS. SB's purpose is to hold the main unit stable.
- 3) The Surgical Field (SF, size 50x19mm) simulates the aperture in the human skull. The surgeon accesses the Object Area and the Target Area from here.
- 4) The Object Area (OA) is a replaceable soft surface made by Hitohada skin-like gel RTV-2K#1406 Hardness 0 (EXSEAL Corp., Tokyo, Japan), on which the targets are placed for the experiment. Three different types of OAs, each with 5 small targets randomly placed on it, were prepared to simulate the typical objects that are handled during neurosurgery (Fig. 3): BIG: 3.2x1.6x0.4mm; MEDIUM: 2.0x1.2x0.3mm; SMALL: 1.0x0.5x0.2mm. Five target areas for each type were prepared in advance to simplify the experimental procedure.
- 5) The targets picked up from the OA are put in the Target Area (size 10x30mm). To facilitate the release of the object, a putty-like adhesive is placed at the bottom of this area.

The experimental setup is shown in Fig. 4. The microscope is a MITAKA MRI (Mitaka Kohki Co., Ltd, Tokyo, Japan).

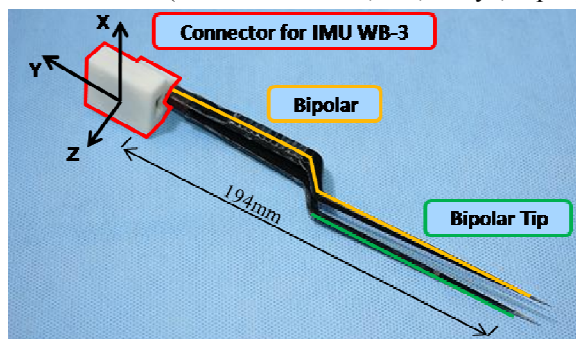


Fig. 1: The Bipolar forceps tool used in the experiments. X, Y, and Z axis are indicated.

TABLE I
Main characteristics of the Bipolar Cutting Tool.

Bipolar Cutting Tool	
Total Length	194 mm
Tip Length	100 mm
Weight	34.0 g

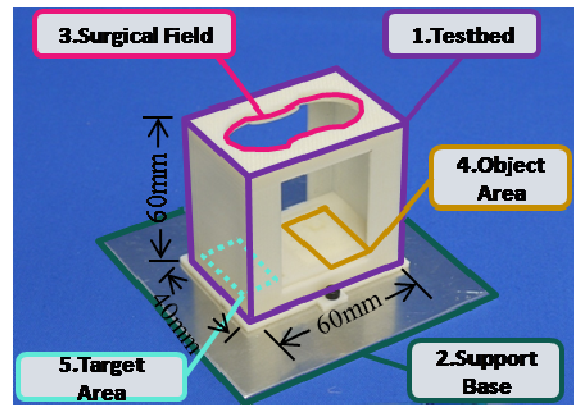


Fig. 2: Training system.

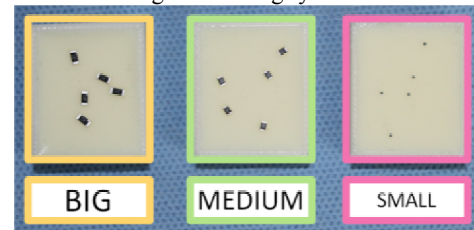


Fig. 3: The 3 types of object areas, each with 5 targets randomly disposed on them.

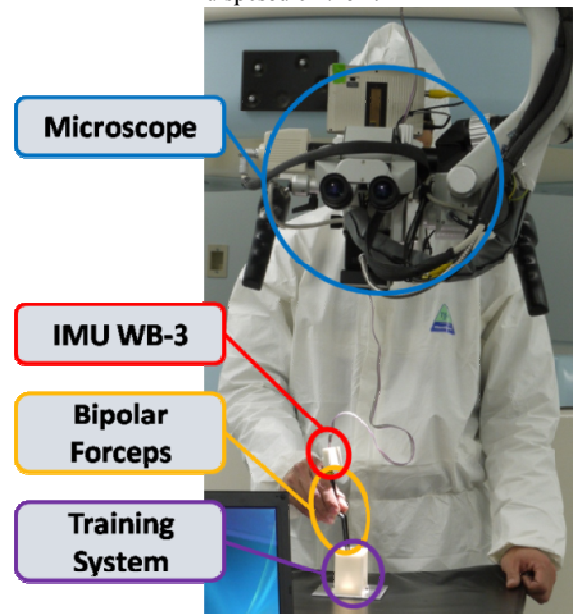


Fig. 4: Overview of the experimental setup.

B. Inertial Module Unit IMU WB3

Our group recently developed a new IMU very compact and lightweight (size 20x20mm and weight 2.9g). A picture of the new IMU is shown in Fig. 5 (left) side by side with the previous version (right) [9]. The IMU is composed by the following sensors: 3-axis Accelerometer LIS3LV02DL; 2-axis gyroscope IDG300; 1-axis gyroscope LSIY300AL. The IMU also includes a 3-axis Magnetometer HMC5843; however the data of this sensor have not been analyzed for this paper, and therefore its description is omitted. IMU's characteristics are summarized in TABLE II.

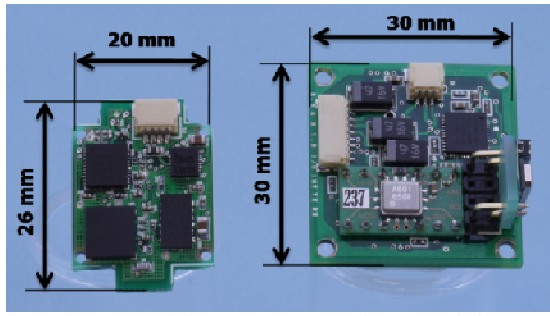


Fig. 5: Inertial Measurement Unit WB-3 (left), side by side with WB-2 (right).

TABLE II
Main characteristics of the sensors in WB3.

	LIS3LV02DL	IDG300	LSIY300AL
Range	$\pm 2G$	$\pm 500\text{deg/s}$	$\pm 300\text{deg/s}$
Sensitivity	12 \pm 1bit	12 \pm 1bit	12 \pm 1bit
Bandwidth	40 Hz	140 Hz	88 Hz
Sample Rate	160 Hz	500 Hz	500 Hz
Linearity (FS)	$\pm 2\%$	<1%	$\pm 0.8\%$
Noise level	0.0051 m/s ²	0.35 Deg/s	0.26 Deg/s

The LIS3LV02DL (STMicroelectronics) is a 3-axis accelerometer, whose small size (4.4x7.5x1mm) and high performance characteristics are fully compatible with the strict requirements of neurosurgery. The resolution with a Full-scale $\pm 2G$ and Bandwidth of 160Hz is 2mG, with noise level of about 0.005m/sec², less than one bit. The LISY300AL (STMicroelectronics) is a miniaturized 7.0x7.0x1.9mm z-axis gyro sensor. Its full-scale is $\pm 300\text{Deg/s}$ with a Bandwidth of 88Hz and a sensibility of 3.3mV/Deg/s. In order to measure 3-axes angular velocities, we also used a bi-axial gyro IDG300 (InvenSense). The IDG300 size is 6.0x6.0x1.5mm, the measurement range is $\pm 500\text{Deg/s}$ and the sensitivity is 2.0mV/Deg/s. Unlike all other prototypes and commercial IMUs available today, this mixed configuration allows our IMU to obtain all the 3 axis of the gyros in one planar layer.

Our IMU also contains a STMicroelectronics 32 bit microcontroller STM32 Cortex for embedded signal elaboration and data exchange. The communication with the module is performed using a CAN BUS at 1Mb/s, directly connected with a PC.

C. Experimental protocol

Thirteen non-medical subjects (Average age 27.5 years, age range 22-39, all male, all right handed) and 1 professional neurosurgeon (age 40) kindly agreed to participate to the experiments after providing informed consent. Among the non-medical subjects, only 1 had some experience with neurosurgical tools, and 1 had some experience with laparoscopy; all the other subjects were totally novice.

The experimental setup is shown in Fig. 2. The subject looks through the microscope at the evaluation system. The experiments consist in picking all the objects in the object area, one by one, and releasing them in the target area. In total there

were 15 target areas (3 sizes x 5 repetitions), and they were replaced by following the order BIG \rightarrow MEDIUM \rightarrow SMALL, repeated 5 times.

D. Data saving and pre-processing

Acceleration data were sampled at $F_{ACC}=160\text{Hz}$, gyro data at $F_{GYRO}=500\text{Hz}$. Data were acquired on the pc for real-time display, and saved for storage and offline analysis. The raw data were trimmed to remove dead-time at the beginning and at the end of the trial due to the manual start/stop as follows:

The beginning of the trial is defined as the first sample when $|a_y| > 9.1\text{m/s}^2$; the end of the trial is defined as the first sample from the end of the data log when $|a_y| > 9.1\text{m/s}^2$. Y is the long axis of the bipolar cutting tool as defined in Fig. 1. Acceleration components and angular speed components were then filtered and smoothed by using a 10th order bandpass IIR Butterworth filter with cutoff frequencies $f_{c1} = 0.05\text{Hz}$, $f_{c2} = 8\text{Hz}$ (accelerometers), $f_{c1} = 0.05\text{Hz}$, $f_{c2} = 2\text{Hz}$ (rate gyros) to remove bias and to remove physiological tremor [10, 11]. In this way only the data due to the voluntary movement of the instrument were analyzed. Furthermore, the filtering proposed reduce the effect of noise in the band outside the human movements (<15-20Hz) improving the SNR (Signal-to-Noise Ratio).

III. EXPERIMENTAL EVALUATION

The following sections present the details about the experimental evaluation. In particular, the following variables were calculated and analyzed: Execution Time T_{task} ; Acceleration Module $|a|$; Angular Speed Module $|\omega|$. The Fast Fourier Transformation (fft) for $|a|$ was calculated with $\text{FFTsize} = 8192$ samples obtaining a frequency resolution $f_{res(acc)} = f_{ACC}/\text{FFTsize} = 160/8192 = 0.0195\text{Hz}$. The fft for $|\omega|$ was calculated with frequency resolution $f_{res(gyro)} = f_{gyro}/\text{FFTsize} = 0.061\text{Hz}$. The Power Spectral Density (PSD) was estimated in both the cases with the following formula $(\text{fft} \cdot \text{conj}(\text{fft}))/\text{FFTsize}$. The frequency range chosen for the evaluation was 0.2–8Hz for $\text{fft}(|a|)$, and 0.2-2Hz for $\text{fft}(|\omega|)$, to take into account only the voluntary movements. Several other parameters such as Jerk Module $|\dot{a}|$, Angular Acceleration Module $|\dot{\omega}|$, and so on, were also calculated; however, their analysis is not included in this paper due to space limitations. In the following figures (norm.) indicates that the data have been normalized to the average corresponding data of the surgeon (subject #14) for an easier visual comparison of the scales. The averaging value is always indicated. Surgeon's data are always displayed with dark gray bars, while non-medical subjects' data are displayed in light grey.

A. Execution Time

The surgeon, as expected, proved to be usually faster and showed high constancy in the execution time (lower $\text{var}(T_{task})$) of the different tasks than all the novices (Fig. 6). In addition, it can be noticed that both BIG (Fig. 7A) and MEDIUM targets (Fig. 7B) showed a fast learning effect for the novices, with the execution time stabilizing after the 3rd trial; however,

these learning effect could not be seen for the SMALL target (Fig. 7C).

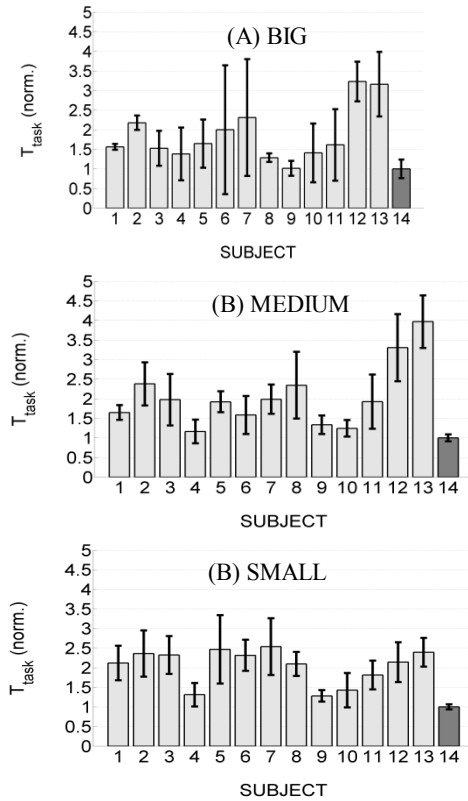


Fig. 6: Execution time for the (A) BIG, (B) MEDIUM and (C) SMALL targets, averaged on the 5 trials for each subject. Normalization values are 11.7, 11.8 and 16.2s respectively.

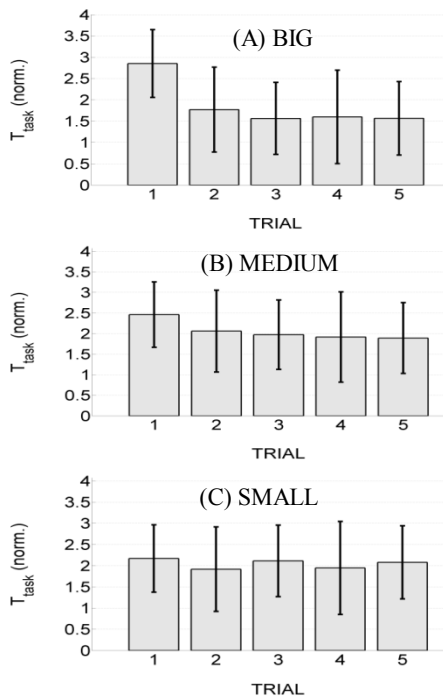


Fig. 7: Execution time for the (A) BIG, (B) MEDIUM and (C) SMALL objects averaged on all novice subjects for each trial. Normalization values are the same as in Fig. 6.

B. Analysis of the acceleration

As can be seen in Fig. 8, the average PSD clearly identifies the experienced neurosurgeon respectively from the other subjects. Subject #2 and Subject #9 performs in a similar way as the surgeon regarding this parameter. The spectral edge frequencies $SEF_{75\%}$ and $SEF_{95\%}$, and the Spectral Centroid SC ($SEF_{50\%}$) were also calculated. Their analysis, however, would require a longer discussion and therefore it is left for a successive paper.

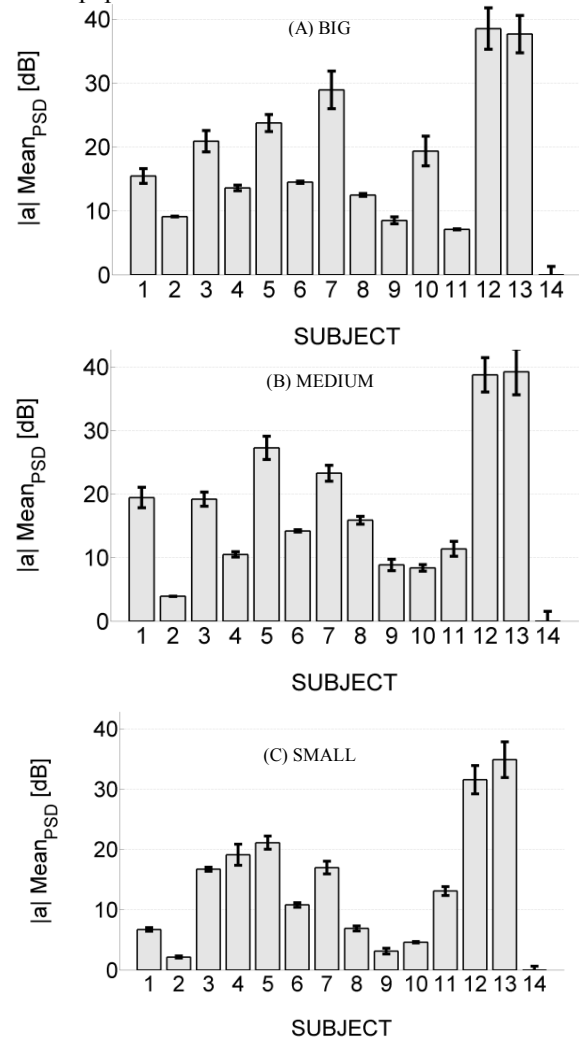


Fig. 8: Mean power of the acceleration in decibel for the (A) BIG, (B) MEDIUM and for the (C) SMALL targets, averaged on the 5 trials for each subject.

Another parameter which discriminates between the surgeon and the novices is the Cumulative Distribution Function (CDF) of the acceleration $|a|$ calculated as $CDF(|a|) = P(X \leq |a|)$ evaluated for $X = 95\%$ ($CDF_{95\%}$). For the BIG objects (Fig. 10A) the neurosurgeon outperforms all the novices; the data about the MEDIUM target shows similar trends. Things are different for the SMALL target, when several novices have similar or lower $CDF_{95\%}(|a|)$ than the neurosurgeon. These however are due to a much higher T_{task} for the novices.

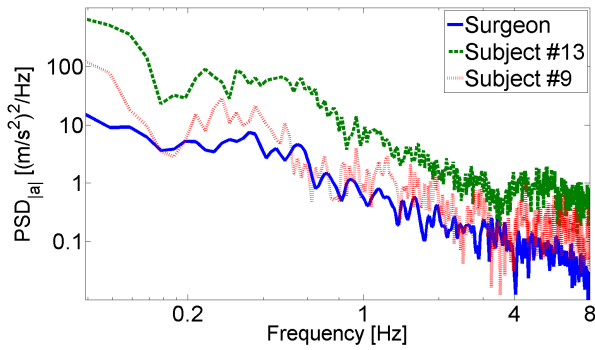


Fig. 9: Power Spectrum Density (PSD) of the $|a|$ for the subject #13, subject #9 and the surgeon (MEDIUM objects).

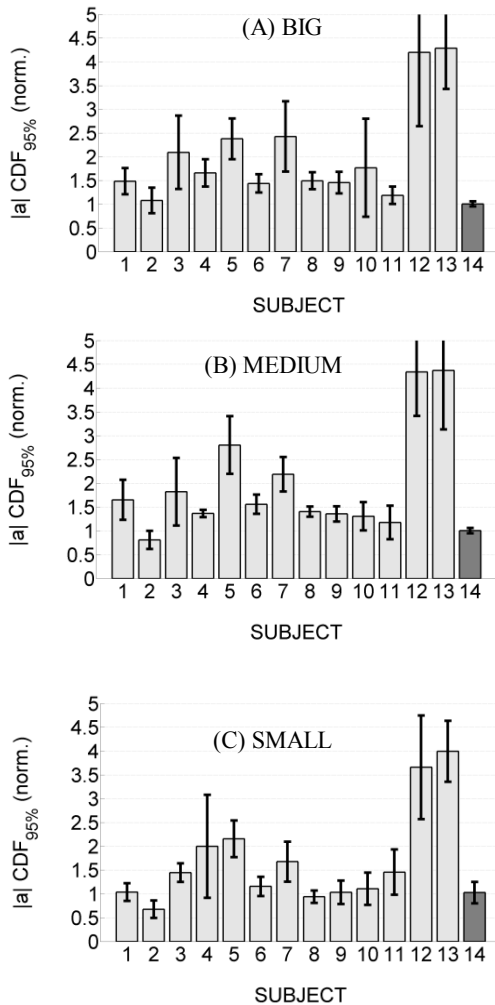


Fig. 10: Cumulative Distribution Function (CDF) of the acceleration $|a|$ for the (A) BIG, (B) MEDIUM and (C) SMALL objects. Normalization values are 1.10, 1.14 and 1.37 m/s^2 .

In Fig. 9 are showed the $PSD_{|a|}$ for the Surgeon, the subject #9 (medium experience with neurosurgical tools) and the subject #13 (no experience). The scale of the frequency is logarithmic in order to emphasize the low frequencies. Interesting consideration can be done analyzing two different frequency ranges.

The surgeon uses clearly lower $PSD_{|a|}$ than the other subjects in the frequency range 0.2-2Hz that covers the voluntary movements for the main task (pick and place of the objects). The frequency range 2-4Hz represents the voluntary movements for the corrections during the task. Also in this case the surgeon performs the task with the $PSD_{|a|}$ significantly lower than the other subjects.

C. Rate Gyro

Among the different parameters, the Cumulative Distribution Function (CDF) of the angular speed $CDF(\omega) = P(X \leq \omega)$ evaluated for $X = 95\%$ ($CDF_{95\%}$) shows some difference between the surgeon and the novices (Fig. 10). In particular, the surgeon's $CDF_{95\%}$ is usually lower than the other subjects; more important, it shows a very limited variance, thus signifying high regularity in the exercises (Fig. 11).

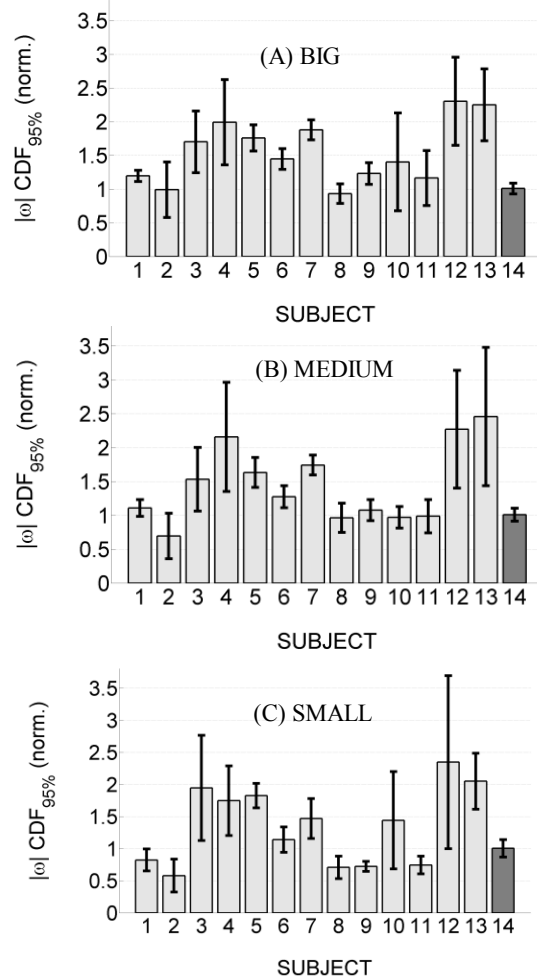


Fig. 11: Cumulative distribution function (CDF) of the angular speed $|\omega|$ for the (A) BIG, (B) MEDIUM and (C) SMALL objects. Normalization values are 16.6, 17 and 19.3 Deg/s .

In Fig. 12 are showed the $PSD_{|\omega|}$ for the same subjects of the previous analysis on the $PSD_{|a|}$ (Surgeon, Subject #9 and Subject #13). The $PSD_{|\omega|}$ for Subject #13 has two peaks: the first one at lower frequency (0.3Hz); the other one is at higher frequency (1.3Hz). The low frequency peak is due to the main

movement of the task (pick and place of the object) while the other is the results of the frequently movement corrections. The Subject #9 (medium experience with neurosurgical tools) has a $PSD_{|\omega|}$ very close to the surgeon but the peak is at lower frequency. This result showing that, even though the subject #9 performs the task with smooth movements, he is slower than the expert surgeon.

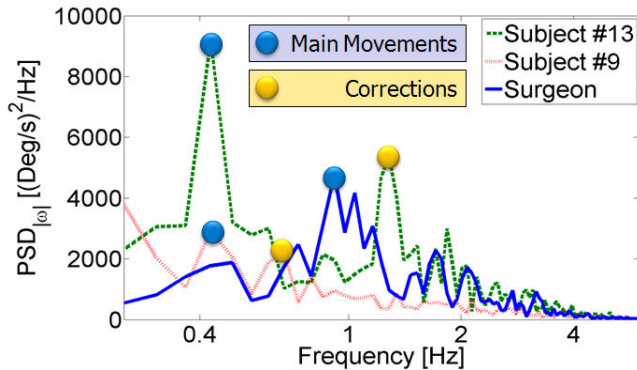


Fig. 12: Power Spectrum Density (PSD) of the $|\omega|$ for the subject #13, subject #9 and the surgeon (MEDIUM objects).

IV. CONCLUSIONS

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 enhance the dexterity of neurosurgeons. The extremely small movements and sizes involved in neurosurgery, however, have prevented until now the development of such methodologies and systems.

In this paper we presented the development of an ultra-miniaturized Inertial Measurement Unit named WB3 suitable for applications in neurosurgery due to its very low size and weight, and its high performance. We evaluated the WB3 in a simple pick and place test bed with a group of non-medical novices and one professional neurosurgeon. The preliminary results proved that several parameters extracted from the IMU's data. the PSD and the CDF of both acceleration and angular speed 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.

Overall, this work shows that a substantial set of parameters is necessary to investigate and analyze the performance of surgeons. Currently, work is still in progress, and our future commitment in this field is to continue to analyze the performance of surgeons in more complex procedures and with other sensor systems.

ACKNOWLEDGMENT

This research has been conducted at Humanoid Robotics Institute, in collaboration with the G-COE Global Robot Academia and S-COE ASMeW. Waseda University, Partial

support was also provided by the ASMeW Priority Research C Grant #11, by the JSPS Grant-in-aid for Scientific Research #19700389 and by Waseda University Grant for Special Research Projects (No. 266740). This research has been supported by JSPS Postdoctoral Fellowship Program for Foreigner Researcher FY2008. Partial contribution has also been received by the G-COE Global Robot Academia Program in Japan, and by the Advancement of University Education Project of Chinese government. The authors would like to express their thanks to the Italian Ministry of Foreign Affairs, General Directorate for Cultural Promotion and Cooperation, for its support to RoboCasa. The authors would also like to express their gratitude to Okino Industries LTD, STMicroelectronics, Japan ROBOTECH LTD, SolidWorks Corp, Dyden, for their support to the research.

Eventually, the authors would like to thank the neurosurgeon and the volunteers who kindly accepted to take part to the experiment.

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