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3D handheld laser scanner based approach for automatic identification and localization of EEG sensors

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Abstract—**This paper describes and assesses for the first time the use of a handheld 3D laser scanner for scalp EEG sensor localization and co-registration with magnetic resonance images. Study on five subjects showed that the scanner had an equivalent accuracy, a better repeatability, and was faster than the reference electromagnetic digitizer. According to electrical source imaging, somatosensory evoked potentials experiments validated its ability to give precise sensor localization. With our automatic labeling method, the data provided by the scanner could be directly introduced in the source localization studies.**

I. Introduction

The strength of electrical source imaging relies on co-registration of high resolution electroencephalography data (HR-EEG) and magnetic resonance images (MRI). The precision of surface electrodes localization is one of the parameters which influence the accuracy of source localizations [1]. According to the literature, precision of less than five millimeters is necessary for dense arrays of electrodes and source inversion algorithms [2]. Three steps are currently needed to obtain EEG sensors localizations: (i) digitizing the EEG sensors positions, (ii) labeling them and (iii) adjust the resulting labeled 3D positions on the MRI and so on the headmodel. Several approaches (reviewed in [3] and [4]) have been proposed to locate EEG sensors: manual methods, electromagnetic or ultrasonic digitization, photogrammetry. The labeling of the EEG sensors is then obtained with acquisition of the coordinates in a given order, specific software (for photogrammetry, digitization …), or a combinatorial optimization based algorithm [5]. For co-registration of the EEG data with the MRI volume, the common way employs a fiducial landmark (e.g. nasion, left and right ears) to define a reference frame. More sophisticated methods can use 3D geometrical moments [6] or anatomical similarities [7]. Another approach, which combines the three steps described above, is the use of MR compatible and localizable EEG sensors with an automatic method named ALLES [8]. The drawback of this technique is that specific EEG-MRI sensors are necessary and so ALLES method cannot be applied with standard EEG caps. At last, resolution, accuracy, and robustness to disturbances are the main qualities required for a registration system but the user friendliness, the time needed to acquire sensors locations and the degree of automation of the procedure are also important to take into account.

In this paper we focused on the acquisition and labeling of EEG sensors included in a cap using a 3D laser scanner. To validate this new utilization of a scanner, a metrological comparative study with an electromagnetic digitizer which is currently the most used system, and somatosensory evoked potentials experiments were presented.

II. The localization devices

A. The 3D laser scanner

To obtain the position of the EEG sensors, we proposed to use a handheld 3D laser scanner. This new generation of scanner is now utilized for inspection, reverse engineering, digitization of models, interactive visualization, and, also, human body scanning for orthesis or biometry. However, this kind of device was never used for EEG electrodes localization. The handiness, announced acquisition speed and accuracy of such a system prompted us to compare it with the electromagnetic digitizer *Fastrak* (Polhemus) mainly employed for that purpose. Thus, we used an auto-referenced scanner *Handyscan 3D*, type *EXAscan*, with the dedicated software *VxScan* (Creaform). This apparatus establishes spatial reference with a resolution of 0.05 mm. It is composed of a class II laser diode that projects a crosshair over the surface to digitize and of two synchronized cameras that capture the image of projections (Fig. 1). As the relative position of these three elements is calibrated, a triangulation-based algorithm allows obtaining the coordinates of the points that set the crosshair [9]. By fixing reflective targets as positioning features on the object, one can simultaneously measure the 3D surface geometry and estimate a model of positioning features for tracking. Thus, this scanner does not need any positioning device to integrate 3D measurements in a global coordinate system while it is moving [10].

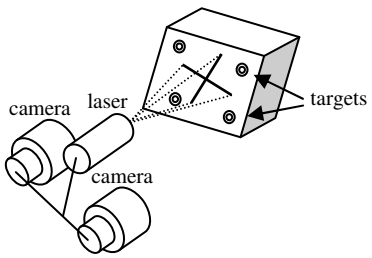

Fig. 1. Handheld 3D laser scanner principle. At least four reflective target positions need to be recognized by the scanner at all time.

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B. The electromagnetic digitizer

The *Fastrack* system is a 3D apparatus which uses a magnetic field to localize EEG electrodes. This system has a transmitter device that produces the electromagnetic field, and constitutes as well a geographical reference for the positioning and orientations of the receivers. To carry the measurements, three receivers are placed on the head of the patient. This allows free motion of the head during the digitization process. Then a pen shaped device with a receiver coil assembly built inside, called a Stylus, is used to digitize the electrode position. In order to localize EEG sensor in the fiducial system, this electromagnetic digitizer need to digitize the position of the nasion and the pre-auricular points. This technique is actually the reference method to localize EEG electrodes.

III. Overview of the Study with Human Subjects

Five healthy volunteers were included in this study (median age: 30 years old, one woman, four men). Informed consent was obtained from each subject. Depending on the cranial perimeter of the subject, two sizes of cap (large and medium, Electro-Cap International) with sixty-four Ag/AgCL sensors included according to the ten/ten international system were used.

To evaluate the metrological and operating mode differences, we acquired with the two devices twice the positions of the EEG electrodes and the fiducial landmarks (nasion and pre-auriculars) for each subject. For each device, all the measurements were made by the same trained operator. Then, for validation purpose we also analyzed the accuracy of the modeled sources obtained with the scanner. Somatosensory evoked potentials (SEP) were studied for several stimulation sites (right and left median and tibial nerves).

IV. 3D Points Acquisition with the Scanner

A. Experimental setup

Before scanning, adhesive reflective targets were placed onto the electrodes and a hole in their centre was made to introduce conductive gel. These targets have the same diameter than the electrode supports and they resist to washing. Three targets were also placed on the fiducial landmarks. Thanks to the "scan features" acquisition mode of the scanner, it was possible to only obtain the "positioning model", that is the 3D position of the centre of all the targets. The scanning was realized manually by an operator who turned around the head with the scanner.The average time to collect the sixty-eight positions was equal to 53 s (minimum: 31 s, maximum: 1.14 min). This short time must be compared to a mean of 7.95 min reported in [11] for the acquisition of sixty-seven points with the electromagnetic digitizer. We also scanned the subject's forehead and nasal surface to co-register the EEG sensors with the anatomical head model defined with the MRI volume. Fig. 2 shows an example of such a shape. To assure a correct scanning, we placed two targets on the cheeks and four on the nose. The scanning average time for the headshape was equal to 2.06 min (minimum: 58 s, maximum: 3.36 min) and the average number of 3D points was equal to 5 263 for a standard resolution (1.95 mm).

B. Data processing

After acquisition, the first step was to control the result with the *VxScan* software. Indeed, the positioning model loses sometimes its shape during the acquisition, creating one or several target artefacts due to traction on the ribbon cable of the EEG cap when moving it for scanning underneath. Among the 747 targets acquired during 10 sequences, only seven target artefacts were present. Moreover, the obtained artefacts were easily detected (they were clearly inside or outside the head) and removed as well as the six targets of the face. For the scanned shape, it was necessary to remove useless parts (pieces of cap ...) with a graphical tool of the software. Then, the coordinates of the 3D points (targets and face) were recorded in two separate files for further processing with *Matlab* as follows.

The second step was completely automated and was partially based on previous work [8]. First, the three points of the fiducial landmarks were identified and labeled (a convex hull made up of triangles was determined with all the 3D points representing the targets; the triangle with the largest surface area links the three searched points). These three points were used to define a new coordinate system for the other 3D points (sensors and face) whose origin was the intersection of a perpendicular line from the nasion and the inter-pre-auricular line. Next, we identified and labeled the temporo-basal sensor points: FT9, FT10, P9 and P10 (they were the vertices of two triangles of a new convex hull, without the three landmark points, with a special position in the coordinate system). Then, the remaining sensor points were projected on a plane where the outer ring forms an ellipsoid. It was thus easy to identify and label the points of the outer ring and, next, the other points taking into account the coordinates of the points on the plane. At the end, we obtained a file usable by the *ASA* software for visualisation and source localizations (Fig. 2).

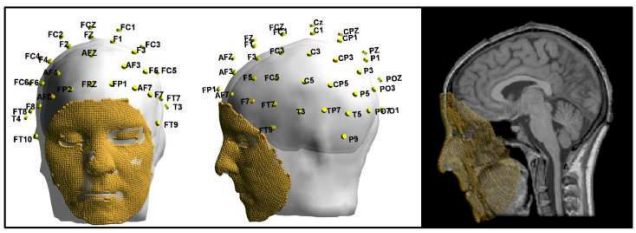

Fig. 2. Co-registration of the headmodel defined with the MRI volume and the headshape with the sixty-four sensors obtained with the 3D laser scanner. At the right, headshape and sensors were surimposed onto the MRI volume. The high resolution headshape allows accurate co-registration with the MRI and so with the headmodel.

V. METROLOGICAL RESULTS

A. Accuracy evaluation

Using the two devices and a numerical caliper, we measured thirteen inter-electrodes distances on the anterior right quarter of the scalp: along the anterior-posterior midline (FPz-AFz, FPz-Fz, FPz-FCz, FPz-Cz), along the right-left pre-auricular axis (T8-C6, T8-C4, T8-C2, T8-Cz) and along the temporal circumference (FPz-FP2, FPz-AF8, FPz-F8, FPz-FT8, FPz-T8).

Then, we computed the differences, two by two, between the 130 distances (thirteen distances for ten groups of measurements) obtained for each measurement method. The hypothesis of normality was satisfied for these three differences (Lilliefors test) whose mean and standard deviation are given Table I. Next, a linear model was determined between the three sets of data (Table II): the R^2 coefficient was equal to 0.999 for the three models. These results showed that the two devices had similar performances: the electromagnetic digitizer seemed a little bit more accurate but the scanner seemed more precise.

TABLE I
MEAN AND STANDARD DEVIATION OF DISTANCE DIFFERENCES BETWEEN MEASUREMENT METHODS

Distance Differences	Mean (mm)	Std. Dev. (mm)
Scanner distance - Caliper distance	1.34	0.76
Electromagnetic digitizer dist. - Caliper dist.	-0.49	1.16
Scanner dist. - Electromagnetic digitizer dist.	1.83	1.16

TABLE II
LINEAR REGRESSION RESULTS BETWEEN MEASUREMENT METHODS

$y = f(x) = p_1 x + p_2$	p_1	p_2	RMSE
Scanner dist. = f(Caliper dist.)	1.001	1.295	0.759
Elect. digit. dist. = f(Caliper dist.)	0.980	1.205	0.892
Elect. digit. dist. = f(Scanner dist.)	0.979	-0.048	0.871

RMSE: Root Mean Squared Error

B. Repeatability evaluation

To evaluate the test-retest reliability of the two devices, we computed, for each subject and each device the average distance between the two repeated measures of the sixty-five electrodes. The mean results obtained with the five subjects showed that the measures of the scanner were more repeatable than those of the electromagnetic digitizer (Table III).

TABLE III
MEAN AND STANDARD DEVIATION OF AVERAGE DISTANCE BETWEEN TWO ACQUISITIONS OF THE SAME POSITIONS

Device	Mean (mm)	Std. Dev. (mm)
Scanner	1.21	0.58
Electromagnetic Digitizer	2.92	1.06

VI. SOMATOSENSORY EVOKED POTENTIALS EXPERIMENTS

We further validated the precise sensor localizations, by studying its influence on electrical source localizations of SEPs. High resolution evoked potentials data were referenced to Fpz. The signal was recorded at 1 kHz sampling rate using *LTM64 Headbox* (Micromed). During sessions, the subjects were relaxed and their eyes were closed. The patients were placed in a sound attenuated and electrically shielded room. Impedances were all below 5 kΩ. SEPs were evoked by bipolar transcutaneous electrical stimulation applied on the skin over the left and right median and tibial nerves. Monophasic square-wave electrical pulses of 0.1 ms were delivered with stimulus intensity able to produce a clear but tolerable and reproducible muscle twitch. Stimulation rate was 3 Hz and we average at least 500 trials for each SEP. All latencies were considered as normal. For each subject, electrical source localizations (*ASA software*, ANT) were performed on the N20 peak of the median nerve SEP and on the P39 peak of the tibial nerve SEP. A time window of analysis of 5 to 8 ms was chosen for each potential. Equivalent current dipole (ECD) and LORETA source models were used for electrical source localizations. For median nerve SEPs, maximum negative amplitudes were recorded on the controlateral central, centro-parietal and parietal electrodes of the stimulated limb. For tibial nerve SEPs maximum negative amplitudes were recorded on the inter-hemispheric central, centro-parietal and parietal electrodes with an ipsilateral predominance of the stimulated limb. As described in Table IV, source localizations were found in the lateral post-central gyrus for median nerve SEPs (only one patient presented left lateral pre-central gyrus for right median nerve SEP). For tibial nerve SPEs all source localizations were located in the medial part of the post-central gyrus and the supplementary motor area. In our study, source localizations were mainly localized in the post-central gyrus as described in the literature [12], [13].

TABLE IV
ELECTRICAL SOURCE LOCALIZATIONS OF THE MEDIAN AND TIBIAL NERVES SEPS USING ECD AND LORETA MODELS

Stimulation site	ECD source localization	BA	GOF
Right median nerve	Left lateral PostC gyrus (4/5)	1, 2, 3	88.2
Left median nerve	Right lateral PostC gyrus (5/5)	1, 2, 3	92.2
Right tibial nerve	Left medial PostC gyrus (5/5)	1, 2, 3	85.9
Left tibial nerve	Right medial PostC gyrus (4/5)	1, 2, 3	91.1

Stimulation site	LORETA source localization	BA
R. median n.	Left lateral PostC gyrus (4/5)	1, 2, 3
L. median n.	Right lateral PostC gyrus (5/5)	1, 2, 3
R. tibial ner.	Left medial PostC gyrus and SMA (5/5)	1, 2, 3 & 4
L. tibial ner.	Right medial PostC gyrus and SMA (4/5)	1, 2, 3 & 4

BA: Brodmann area, GOF: goodness of fit (%), PostC: post-central, SMA: supplementary motor area

Source models (distributed source models and ECD) gave reproducible source localizations in our population. Goodness of fit of ECD during the time window of analysis was ranged from 88.2 to 92.2%. Results of electrical source localizations for one subject are illustrated Fig. 3.

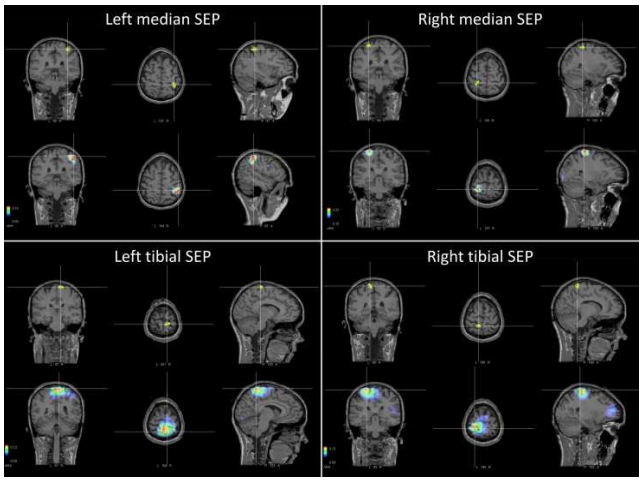

Fig. 3. Electrical source localizations of median and tibial nerves SEP using ECD (upper) and LORETA (downer) source models. Results show contro-lateral post-central localization of the stimulated limb. Median nerve SEPs localizations were in the lateral part of the post-central gyrus whereas tibial nerve SEPs localizations were in the medial part of the post-central gyrus.

SEPs were generated from a spatially limited cortical area consistent with the well-known somatosensory area within the post-central gyrus. As demonstrated in [1], inaccurate localization of EEG sensors (mean displacement of 5 mm) induces source localization error of 5 mm. Since we did not observed mislocalized SEP generators, we can then conclude that 3D laser scanner gave precise sensor localizations.

VII. Discussion and Conclusion

This study showed that the 3D laser scanner could be used for the localization of EEG sensors with an equivalent accuracy (from a metrological and clinical point of view) and a better repeatability than the electromagnetic digitizer. This last point could be explained by the fact that the positioning system of the scanner depends on the whole set of reference targets and not on three points coordinates like the electromagnetic digitizer. The usability and the fast digitization time of the scanner allowed employing it for a clinical use in a standard medical environment (no special room, no special light). Associated with the automatic labeling method previously developed, it yielded directly available data for source localization software without risk of false labeling due to human error.

The scanner allowed also obtaining a high resolution scan of the headshape very useful to validate the co-registration in the MRI volume. In future works, we intend to develop a fully automatic co-registration procedure using this headshape.

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References

[1] Y. Wang and J. Gotman, "The influence of electrode location errors on EEG dipole source localization with a realistic head model," *Clinical Neurophysiology*, vol. 112, pp. 1777-1780, 2001.

[2] B. Brinkmann, T. O'Brien, A. Dresner, T. Lagerlund, W.A. Sharbrough, and R. Robb, "Scalp-recorded EEG localization in MRI volume data," *Brain Topography*, vol. 10, pp. 245-253, 1998.

[3] L. Koessler, L. Maillard, A. Benhadid, J.P. Vignal, M. Braun, and H. Vespignani, "Spatial localization of EEG electrodes," *Neurophysiologie Clinique/Clin. Neurophysiol.*, vol. 37, pp. 97–102, 2007.

[4] U. Baysal, and G. Sengül, "Single camera photogrammetry system for EEG electrode identification and localization," *Annals of Biomedical Engineering*, vol. 38, pp. 1539–1547, 2010. .

[5] M. Péchaud, R. Keriven, T. Papadopoulo, and J.M. Badier, "Automatic labeling of EEG electrodes using combinatorial optimization," in *Proc. 29th Int. Conf. of the IEEE Engineering in Medicine and Biology Soc.*, Lyon, 2007, pp. 4398-4401.

[6] D. Kozinska, F. Carducci, and K. Nowinski, "Automatic alignment of EEG/MEG and MRI data sets," *Clinical Neurophysiology*, vol. 112, pp. 1553-1561, 2001.

[7] Z. Spiclin, S. W. Warfield, B. Likar, and F. Pernus, "Registration of MRI and EEG based on internal and external anatomical similarities," in Proc. *11th Int. Conf. Med. Image Computing Computer-Assisted Intervention*, Pt 1, pp. 762-770, 2008.

[8] L. Koessler, A. Benhadid, L. Maillard, J.P. Vignal, J. Felblinger, H. Vespignani, and M. Braun, "Automatic localization and labeling of EEG sensors (ALLES) in MRI volume," *NeuroImage*, vol. 41, pp. 914–923, 2008.

[9] P. Hébert, "A self-referenced hand-held range sensor," in *Proc. 3rd IEEE Int. Conf. on 3-D Digital Imaging and Modeling*, Québec City, 2001, pp. 5-12.

[10] P. Hébert, E. Saint-Pierre, and D. Tubic, "Auto-referenced system and apparatus for three-dimensional scanning," U.S. Patent 2008/0201101 A1, Aug. 21, 2008.

[11] J. Le, M. Lu, E. Pellouchoud, and A. Gevins, "A rapid method for determining standard 10/10 electrode positions for high resolution EEG studies," *Electroencephalography and clinical Neurophysiology*, vol. 106, pp. 554–558, 1998.

[12] M. Valeriani, D. Restuccia, V. Di Lazzaro, C. Barba, D. Le Pera, and P. Tonali, "Dipolar generators of the early scalp somatosensory evoked potentials to tibial nerve stimulation in human subjects," *Neuroscience Letters*, vol. 238, pp. 49-52, 1997.

[13] M. Valeriani, D. Restuccia, V. Di Lazzaro, D. Le Pera, C. Barba, P. Tonali, and F. Mauguiere, "Dipolar sources of the early scalp somatosensory evoked potentials to upper limb stimulation. Effect of increasing stimulus rates," *Experimental Brain Research*, vol. 120, pp. 306-15, 1998.