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Surgical Assistance for Instruments' Power Control Based on Navigation and Neuromonitoring

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Abstract—**In order to prevent nerve injuries during ear-nose-throat (ENT) and skull base surgery, the method Navigated Control Functional is presented. Thereby, the power of active instruments is controlled based on position information, provided by a surgical navigation system, and nerve activity information, provided by a neurophysiologic monitoring system. Electrical stimulation is usually required for the extraction of distance information from neurophysiologic signals (e.g., Electromyography (EMG)). However, this article presents an experiment to investigate a possible relationship between EMG signals and the nerve-instrument distance without additional electrical stimulation. The EMG signals and position information were recorded intra-operatively during ear surgery. An off-line statistical analysis with Spearman's rank correlation coefficient was accomplished. The results show that there is occasionally some correlation at a statistically significant level of 5%. They highly depend on time range, the selected threshold value and time window. Moreover, all the observed correlations are positive against an expected negative correlation.**

I. Introduction

During surgical interventions on the temporal bone such as mastoidectomy and tympanoplasty, the facial nerve might be injured mechanically or thermally by a surgical cutting burr (or drill). The common causes of such injuries are: insufficient identification due to distortion caused by diseases or previous surgical interventions [1], the thin bone layer in the tympanic portion of the facial nerve [1], [2], the individual deep mastoidal portion of the facial nerve [1].

In order to minimize the risk of nerve injury, intra-operative EMG-monitoring of the facial nerve is applied [3]-[5]. By means of needle electrodes placed in facial muscles, EMG signals that are triggered by mechanical, electrical, thermal or biochemical stimulation during surgery are recorded and given out to the surgeon/neurophysiologists acoustically or visually. It is frequently not easy for the surgeon to interpret the acoustic signals in certain circumstances (e.g., while milling). Moreover, the delay between correct interpretation of critical acoustic and the actual change in surgical manipulation may exceed one second. This delay could result in nerve injury while cutting with rapid movement.

Other approaches are the applications of medical navigation systems [6], [7] and the Navigated Control® (NC) method [8]. With a navigation system, the surgical instruments or a pointer are visualized on a monitor relative to image data sets (preoperatively recorded). This facilitates the surgeon's orientation in the operation field and the locating of anatomical landmarks. The NC method uses the position information from a navigation system to control the power of an active instrument [8]-[10]. In this way, the instrument can be used as usual by a surgeon and its power will be automatically reduced while approaching a risk structure (e.g., a nerve or a blood vessel). Hence, usage comfort and patient safety can be increased. A disadvantage of medical navigation and NC on the one hand is the limited accuracy due to image quality and registration procedure, which is often dissatisfying for precisely milling on the temporal bone. On the other hand, functional damage to the nerve by heating cannot be prevented while milling.

The possible application of medical robotics for ENT or head surgery [11]-[13] remains a research topic and there has been no use in clinical routine up to now.

In recent years a new concept Navigated Control® Functional (NCF) [14], [15] and the integration of intra-operative EMG data in image data [16], [17] were introduced. The idea of NCF was, that the power of an active instrument is controlled (in fact only reduced) based on the functional neurophysiologic signals (e.g., EMG) from a monitoring system in addition to NC. By means of this redundant design, the risk of nerve injury during tissue removal in surgery may be minimized even more.

In this article, the concept of NCF described in detail in [15], is supplemented again and an experiment for the quantitative analysis of the relationship between intra-operative EMG data and the nerve-instrument distance is presented.

II. Material and Method

A. Concept of Navigated Control Functional

Depending on the usage of the functional neurophysiologic signals (as an example of EMG), the power control via NCF can be generally distinguished in two methods. First, the

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distance between a stimulator (or an instrument) and the nerve fiber is derived from the EMG data for the instrument's power control. Second, typical signal patterns caused by excessive stimulation (mechanical, thermal or electrical) are recognized in order to control instruments. Here, we focus only on the first method. Thereby, the desired instrument power P_{tool} is determined both by NC P_{NC} depending on the relative position (descripted in [15]) and by the distance d_{nerve} deduced from EMG data (as shown in (1), where d_{th} is a user-defined safty limit, u_{EMG} is the actual EMG signal, and I_s is the stimulation current). Only if the deduced d_{nerve} is greater than d_{th} and the distance calculated from navigation information is large enough, the instrument can be activated. Consequently, the main question is, how can distances be derived from the EMG signals. This is based on the relationship between the electrical stimulation threshold and the nerve-stimulator distance. The electrical stimulation threshold is referred to as the minimal stimulation current, which can just elicite a nerve impulse in a nerve. Experimental data from many publications in the field of Neurology indicate a correlation between the stimulation threshold and the nerve-eletrode distance [18]. The distance is derived from the stimulation threshold by using this correlation. In practice the stimulation threshold is not determined at each position, because that requires several stimulations with varying current and is too time-consuming. Therefore, the stimulation is used with a constant current through the instrument on the bone structure in proximity to a nerve. If the distance corresponding to the used current level is achieved, a clear nerve response can be identified by EMG signals. As a result, the instrument will be automatically switched off.

$$p_{tool}\left(d_{nerv}\right) = p_{NC} \cdot \begin{cases} 0 & d_{nerve} \leq d_{th} \\ 1 & d_{nerve} > d_{th} \end{cases} \quad (1)$$

$$with \quad d_{nerv} = f(u_{EMG}, I_s)$$

Another approach could be the direct derivation of the distance from EMG data without additional electrical stimulation. In following sections, this possibility will be investigated by acquiring and analysing intraoperative position and EMG data in an experiment.

B. Purpose and hypothesis of the experiment

The hypothesis can be represented mathematically by (2). The nerve activity U_i, as the sum of the absolute EMG data u_{i-k} within a small time window Δt, depends linearly (simplified) on the nerve-instrument distance d_i:

$$U_i = \sum_{k=0}^{n-1} \left|\lambda \cdot u_{i-k}\right| \approx a + b \cdot d_i \quad (2)$$

a and b are constants ($a > 0$, $b < 0$). d_i is the smallest distance between the burr surface and the nerve ($d_i = d_r - r_f$, where d_r is the relative distance between the nerve surface and the center point of the burr, r_f is the burr radius). Where i is a natural number and n is the number of EMG data in the time window. In addition, λ is defined by (3).

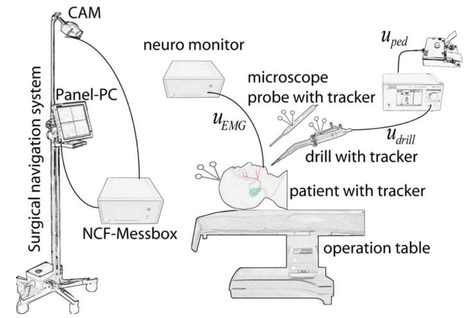

Fig. 1. Schematic illustration of the measurement setup. The main components are a navigation system, a neuromonitoring system and a measurement device NCF-Messbox. The function of NCF-Messbox is scanning data from Stereocamera (CAM), calculating transformations and storing it with a time stamp.

$$\lambda = \begin{cases} 0 & if \quad \left|u_{i-k}\right| < u_s \\ 1 & if \quad \left|u_{i-k}\right| \geq u_s \end{cases} \quad (3)$$

Here, u_s is a selected threshold value, which is used to eliminate the signal noise from the analysis as much as possible.

C. Data acquisition during ear surgery

The Intra-operative data acquisition was accomplished during a revision intervention on ear (cholesteatoma), where EMG Monitoring of facial nerve with the system Nemo (Inomed Medizintechnik GmbH, Emmendingen, Germany) and a navigation system NPU (KARL STORZ GmbH & Co. KG, Tuttlingen, Germany) were used. The standard surgical steps were retained while performing the experiment.

An external measurement device (NCF-Messbox, developed by MIMED) was connected between the Panel PC and the Stereo camera (CAM) (see Fig. 1). The external measurement device is capable of scanning data constantly from the CAM and calculating the transformation ${}^{PT}\mathbf{T}_{TT}$ between the instrument tracker (TT) and the patient tracker (PT) by (4). The calculated ${}^{PT}\mathbf{T}_{TT}$ was stored on a storage medium with a time stamp.

$${}^{PT}\mathbf{T}_{TT} = ({}^{CAM}\mathbf{T}_{PT})^{-1} \cdot {}^{CAM}\mathbf{T}_{TT} \quad (4)$$

Since a quite accurate (better than 1 mm) patient registration without invasive bone screws as landmarks is very difficult to achieve intraoperatively, a reference curve serving as a nerve fiber for subsequent distance calculation was defined by the surgeon. This reference curve was generated through touching some distinctive points (as shown in Fig. 2) along the deep-lying nerve with a microscope-probe (MP) at the end of the surgical preparation. The positions ${}^{PT}\mathbf{p}_{tip}$ of the microscope-probe tip in the coordinate system of the patient tracker were automatically computed by (5) and (6) (Where ${}^{MP}\mathbf{p}_{tip}$ is known from the engineering data of the microscope-probe.) and stored by the NCF-Messbox.

$${}^{PT}\mathbf{T}_{MP} = ({}^{CAM}\mathbf{T}_{PT})^{-1} \cdot {}^{CAM}\mathbf{T}_{MP} = \begin{pmatrix} {}^{PT}\mathbf{R}_{MP} & {}^{PT}\mathbf{t}_{MP} \\ 0 & 1 \end{pmatrix} \quad (5)$$

$${}^{PT}\mathbf{p}_{tip} = {}^{PT}\mathbf{R}_{MP} \cdot {}^{MP}\mathbf{p}_{tip} + {}^{PT}\mathbf{t}_{MP} \quad (6)$$

The EMG signals u_{i-k} were recorded by single channel with

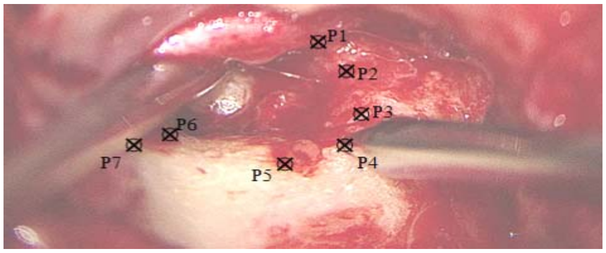

Fig. 2. Definition of a reference curve by seven points (from P1 to P7) in proximity to the facial nerve for simplified calculation of the nerve-instrument distance. The points were touched by the surgeon with a microscope-probe along the deep-lying nerve at the end of bone removal during surgery on the left ear.

two uninsulated needle electrodes which had been parallelly inserted in the muscle Orbicularis Oris around the lips. A reference electrode was placed in chin area. The EMG signals were stored with a sampling frequency of 2 kHz as a matrix **u** in binary format.

In order to determine the time difference between the measured values from the monitoring system and those from NCF-Messbox exactly, the needle electrodes were connected to NCF-Messbox with a special cable at the end of the intervention. Thereafter, the NCF-Messbox sent a pulse signal (one second long pulse duration) activated with the keyboard and stored the starting time of the pulse signal. This pulse signal was detected in the monitoring system and the time shift could be calculated easily.

During the intervention the microscope view was displayed on an external monitor and recorded with a digital camera. The recording was made without interruption and provided additional information for the off-line interpretation.

D. *Off-line data processing after ear surgery*

The nerve activity U_i at the time t_i was calculated by (7) and (8).

$$U_i = \sum_{k=0}^{n-1} \left|\lambda \cdot u_{i-k}\right| = \sum_{k=1}^{i} \left|\lambda \cdot u_k\right| - \sum_{k=1}^{i-n} \left|\lambda \cdot u_k\right| \tag{7}$$

$$u_k = \mathbf{u}(k, N) \tag{8}$$

Here, $\mathbf{u}(k, N)$ is the element (k-th row and N-th column) of the matrix **u**, which contains all the recorded EMG data u_{i-k}.

The shortest distance d_i relative to the reference curve at time $t_{i'}$ (t_i-50 ms$\leq t_{i'} \leq t_i$) was calculated by (10) with the data stored in the navigation system.

$$d_i(t_i) = \min(d_{tcp-Seg_l}) - r_f \tag{10}$$

TABLE I
NUMBER OF LARGER CORRELATION COEFFICIENTS (FIRST NUMBERS) THAN R_0 AND TOTAL CORRELATION COEFFICIENTS (SECOND NUMBERS) UNDER A CERTAIN THRESHOLD AND TIME WINDOW.

	10µV	50µV	100µV
100ms	*3 of 8*	*3 of 8*	*0 of 1**
200ms	*1 of 4*	*1 of 4*	*0 of 1**
500ms	*1 of 2*	*2 of 2*	*0 of 1**

* means that the number of data pairs for calculating correlation coefficient is less than 102.

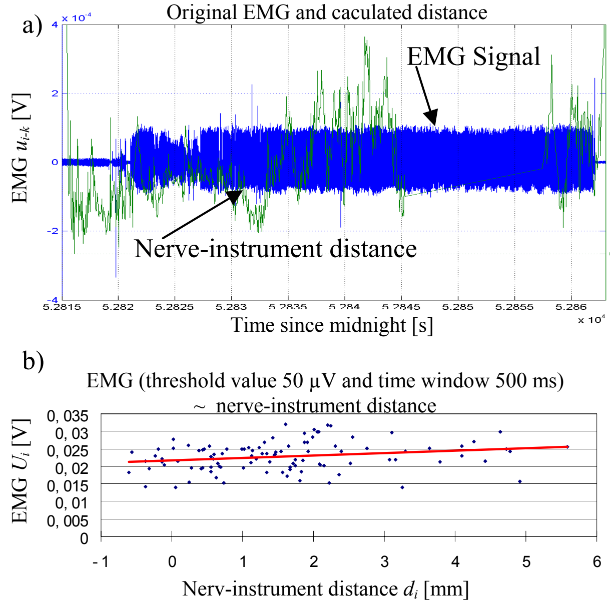

Fig. 3. a). One section of the original EMG signals and the calculated nerve-instrument distances. b). Illustration of the 102 data pairs with a correlation coefficient of 0.249 as an example. The trend line was computed with linear regression.

($d_{tcp-seg_l}$ is the distance between the burr center and a varying line segment seg_l of the reference curve at a given time. With l = 1, 2, 3 ... j-1; j is the number of points on the simplified reference curve)

E. *Statistical analysis of the data*

The Spearman's rank correlation coefficient (2-tailed test) was applied to statistically analyze the data pairs (d_i and U_i). The null hypothesis is: there is no correlation between d_i and U_i. The significance level was chosen as 5%. Then the critical value r_0 for a 5% significance level and a degree of freedom $v = n-2$ (if possible, n = 102) was read from a Spearman's table.

III. RESULTS

The correlation coefficients of the respective 102 pairs of data between d_i and the corresponding U_i were calculated for each threshold value u_s = 10 / 50 / 100 µV and time window Δt = 100 / 200 / 500 ms. The 10 µV threshold value eliminates the ground noise of the monitoring system. The effect of drill contact with temporal bone should be avoided with the 50 µV threshold value. With the 100 µV threshold value, only the large peaks were selected. The selection of time window is the range between 50 ms (defined by the frequency of the stereo camera) and 500 ms (larger windows lead to a higher control latency). The results are shown in Table I. The first numbers represent the numbers of the correlation coefficients, which are greater than r_0. The second numbers are the total numbers of correlation coefficients. Fig. 3a shows an excerpt of the EMG signals and the calculated nerve-instrument distances. For example, 102 data pairs with a correlation coefficient of 0.249 appear in Fig 3b (the trend line was computed via linear regression). This correlation coefficient indicates a positive correlation between the EMG data (with threshold value u_s = 50μV and time window Δt = 500 ms) and the nerve-instrument distance.

IV. Discussion

It was found that there is occasionally some correlation between the EMG data and the distance at statistically significant level of 5%. It highly depends on time range, the choice of the threshold value and time window. Compared to other settings, a correlation occurs more frequently at u_s = 50μV and Δt = 500 ms (2 of 2). Due to the intra-operative necessary visibility of the instrument tracker, the evaluable data pairs were additionally limited at that setting. Hence, it can not be derived that there is some correlation for all the data treated with that setting. Furthermore, all the observed correlations are positive. That means, the EMG signal increases with growing distance. This could probably be explained by the contact pressure, since the bone was ablated at the beginning with larger cutting power (also contact pressure) distant to the nerve fiber. Thereafter, larger vibration energy was transferred to the skull base. The vibration energy and electromagnetic field of the drill motor could cause the higher EMG signals, which are not real nerve activities, but are referred to as artifacts. These effects can possibly be reduced with filtering and better electromagnetic shielding. Moreover, the facial nerve could possibly not be stimulated sufficiently to elicit nerve impulses, as the distance between the instrument tip and the nerve fiber was not close enough. The insufficient stimulation may be the most likely reason, since the EMG signals were rather periodic. Another source of errors could be that the reference curve does not correspond to the real course of the nerve fiber. A more accurate patient registration with bone screws near to operation field would be possible in order to minimize this source of error.

V. Conclusion

In this article, the previously introduced method NCF for the power control of surgical active instruments based on signals from navigation and neuromonitoring was supplemented. In particular, an experiment to investigate the relationship between the intra-operative EMG data and the nerve-instrument distance was presented. With an expected correlation the power control using NCF would be possible even without additional electrical stimulation. The expected correlation could not be determined from the measured data. Instead, a positive correlation was found in some of the data pairs. Whether this correlation is related to the contact pressure, further measurements of contact pressure and distances during surgery are required.

The method NCF for power control using the estimated nerve-instrument distance based on stimulation thresholds seems more promising. The applicability in the clinical practice demands further analysis of experimental and intra-operative data.

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