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Conceptualization of Virtual Reality Experiments for Optimized Sinus Surgery Planning and Execution

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ABSTRACT

Technology development allows the design and standardization of manual work in human activities which are yet to be observed, especially those of low-volume discrete production, such as in ear, nose and throat (ENT) surgery, particularly endoscopic sinus surgery (ESS). The paper considers the possibilities of developing an approach that would be useful for specific ESS manual work analysis and design and its automation in a future. The consideration includes, beside other aspects, initial steps, such as the traditional work motion capture by camera and experiments by Leap Motion Controller, Perception Neuron 2.0 and Emotiv Epoc+.

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1. Introduction

Contemporary research in the field of technology and production is focused on the intensive development of highly automated – so called intelligent and autonomous devices and systems, for smaller (discretized) production volumes (of products and business – production activities of their realization). This development implies a need to create a new knowledge and change – re-evaluate and upgrade of existing knowledge: project approaches and content related to product, process, and system design, as well as a need to include traditional non-engineering areas such as biology and medicine (neuroscience, anatomy, psychiatry). Regarding products, especially, it is interesting to consider the performance of processes in which deformable objects and sculpture surfaces appear in different industries. Consideration of advanced sensorics and virtual reality (VR) involves the analysis of manual processes [1], as yet the most widespread, and as a basis for better understanding and optimization (stabilization) as well as standardization ("normization") of manual processes [2], thus enabling development of mechatronic devices for automatic process execution.

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Advanced sensors and VR have increasing importance in a variety of applications, so they require an appropriate place in engineering process design activities. Their undeniable potential is still not sufficiently utilized in a multitude of work processes that are still predominantly performed manually, partly because of still insufficient development of these technologies, and partly because of insufficient knowledge on the processes in which they should be implemented. So, much research on the nature of manual work processes is yet to be done.

ESS is a minimally invasive sinus surgery technique developed in the late 1960s and 1970s for the treatment of chronic rhinosinusitis [6] [7]. This technique was refined and popularized by Stammberger and Kennedy [8] [9]. ESS has replaced the way sinus surgery is performed i.e., open surgical techniques involving external access, skin incisions, and visible scars, and nowadays is a standard surgical technique used in the treatment of almost all conditions of the nose, sinuses and skull base. Some specificities of ESS include: very complex surgical anatomy, particularly in revision surgery; many important and vital surrounding structures that can potentially lead to serious or even potentially life-threatening complications; a one-handed surgical technique that involves working in a small space and volume; specific hand movements, with many forearm rotations. There is a necessity for additional studies and useful tools to delineate best practices specific to ESS and optimize surgical outcomes.

1.1 Manual work analysis

An intent to make some work more efficiently is a constant task in all human activities, despite the kind and origin of those activities – medical and non-medical, engineering and non-engineering, more or less technical, just to superficially mention a few.

Fast development of technology allows ever-growing materialization and objectivization (digitalization) of all kinds of human work -- physical and mental. That means that human activities become a matter of strict systematic technical approach.

Human physical work and its optimization is always in the focus of interest, especially since the first stage of industrial maturity in Taylor's time, more than 100 years ago, since then did the ideas of training and standardized work to improve productivity become very relevant [10]. Afterwards, Gilbreth concluded [11] that human motions can be put down to 17 fundamental motions, a conclusion he came to by analyzing film shots. Unlike Taylor who merely focused on reducing process times, Gilbreth wanted to make the process more efficient by reducing the number of motions involved, thus improving the workers' well-being. [12]

As a result of these early researches, so-called predetermined motion time systems (PMTS) were developed, such as the Methods-Time Measurement (MTM) system [13]. These systems allow the analysis and planning of human work, that in turn gives an opportunity for realization of efficient workplaces, optimized regarding execution times, ergonomics and to achieve required product quality. In the case of already existing (and stabilized) workplaces, the use of the MTM method is based on filming the work performed by qualified workers, and the subsequent analysis. There are numerous MTM system variants [14] that correspond to production quantities (volumes): as the quantities are larger, the applied variant of the MTM system deals with finer and finer body movements. In fact, MTM appears as some kind of old-fashioned and traditional virtual reality, nowadays embedded in software tools.

The application of a particular MTM system variant as well as work planning itself, implies the costs that should be covered by the price of the product. Traditionally, processes (activities) with small quantities rely on manual work that is not particularly in-depth analyzed. In these processes people tend to be independent in their work and their full control over their own work planning and performance is assumed. At the same time, the execution time is only generally known, and cost of their work is not considered as such of larger importance to be interesting for overall profit intention. Also, in past times, there was no technology and tools to adequately track and analyze complex human skills involving body movements. So, there are many human physical activities that are still inadequately analyzed nowadays, assuming main role of human performer whose skills are even not entirely known yet. However, modern biometrics technology allows overcoming the depicted state.

A possibility to analyze and measure human work is of great importance for standardization, which implies the identification of the best work method, and the possibility to have more reliable data for various levels of enterprise, institutional, social and individual planning (nudging in social credit systems). In that way, also, a basis for the design of new mechatronic devices (tools, jigs and fixtures) is established, allowing the increase in mechanization and automation levels. Additionally, having the nature of analyzed particular tasks revealed and explained, the further progress needs not to be entirely based on human work and anatomy and their limitations, but also allows seeking of inspiration in physical problem-solving methods of other living beings (multiphysics [15] [16] and biomimetics/biomimicry).

1.2 Aim of the research

The proposed research aims to capture manual work processes in the specific circumstances of deformable, flexible and biological work objects, such as assembly, dismantling and other activities related to industrial products (for example, cables and wiring), but also for minimally invasive ENT surgery [3] such as ESS. By choosing ESS, the proposed research appears especially challenging as the anatomy of the paranasal sinuses and the skull base are considered to be among the most complex anatomies of the human body, with great morphological differences among individuals [4]. By motion capturing or recording, the necessary data would be collected (motion trajectory [5], force, brain activation area...) to gain new insight into the nature of the process. This will serve to objectively contemplate (standardization, ergonomic) human work in many areas that have so far been unobserved. It will also provide valuable information to automate manual processes i.e., the development of mechatronic devices and tools that include advanced sensorics (force and torque sensors, vision systems and other) and work environments (e.g. completely new design and exploitation capabilities; machine teamwork and man-machine collaboration).

2. State of the art

The mentioned predetermined motion time systems exist today in engineering software (CAD/CAE/CAM; Product Life-cycle Management) such as CATIA (that incorporates previously stand-alone DELMIA [17]), allowing integrated product design and process and system planning.

Beyond the area of manufacturing and production, motion capture (mocap or mo-cap) and tracking is of great interest in many other fields such as sport [18], medicine and art, and till now many systems have been developed and used. For example, Avezedo-Coste et al. [19] have designed a complete setup and methodology to assess and track the movement of medical personnel present in operating rooms by using motion tracking and sensors. After initial simulations without patients, the system was tested in real conditions during two pilot surgical procedures with an experienced surgical team. The team members were then interviewed to identify possible issues and give input regarding future improvements. It was considered non-disruptive to the normal flow of surgical procedures and did not present any risk for the patients. Furthermore, research [20] has been done to compare the efficiency of laparoscopic maneuvers in operating personnel with varying degrees of experience (from low levels to very experienced surgeons) using motion-capture technology, noting differences among them.

In the automotive industry motion capture technology is frequently used for virtual assembly scenarios such as virtual training, maintenance and virtual process verification tasks [21], which results in production-oriented product optimizations, ergonomics, time planning or process verification. An example of this is walk path analysis in assembly plant layouts [2] where real walk paths can be compared with planned ones, with such a feedback loop serving for further improvements.

Robotic and robot-assisted surgical systems are a rapidly developing field. For instance, da Vinci Xi robot [22] is used for ENT surgery i.e. for its training [23], where a simulation course was organized for post-graduate medical students to gain vital experience in ENT surgeries, with no risk of hurting a human being. The researches [24] [25] relate to robotic nasal swab collecting for COVID-19 evidence sampling. The Autonomous Nasal Swab Collecting Robot [24] helps reduce staff-patient contact with highly infectious diseases. The robot automatically recognizes the patient's facial structure and the accurate nostrils location.

Xing et al. [25] have presented an automated mobile laboratory for fast deployment in response to disease outbreaks, equipped with a robot for specimen collecting, such as PCR testing. The laboratory was set up in a modified van and features a 6-axis robot with built-in artificial vision for specimen collecting. Such a system can be deployed to virus-outbreak locations where it can collect and analyze up to 150 samples in eight hours, with the safety of the medical personnel ensured.

Motion capture and analysis can be done in many ways, for example:

- Traditional way, comprising motion recording by video camera, and subsequent analysis by MTM.
- Motion recording by video camera, while markers are attached to moving bodies. With this system, analysis is done almost instantly [5] [26].

- Marker-less motion recording by the video camera. Multi-Depth-Camera based motion tracking systems are used for production planning [21], such as in previously mentioned automotive production planning environments [5]. Specifically, in most cases players in sporting fields or surgeons in medical environments do not wear any markers or marker-less motion capture hardware, yet such data can still be analyzed afterwards.
- Computerized video tracking systems, with which data can be analyzed at any later time. Sophisticated semi-automated systems have been developed, however still only for the highest level of professional football. [18]
- GPS-based technologies for tracking analysis [27]. While they show good results for tracking large movements in vast areas [28] and they are widely used for those instances, these technologies are limited in their precision for differentiating fine movements, and as such of little use for fine movement analysis.
- Special motion capture devices, such as Leap Motion Controller [1] (Figure 1.) and Perception Neuron 2.0 (Figure 2.)
- ProCapture/ProAnalyst [30] and Cortex [31] systems and software.

Leap Motion Controller (LMC) is a compact, portable and low-cost motion capture system that does not use markers and is progressively used to replace marker-based motion capture systems, especially in clinical environments. It is used for tracking elbow, wrist and finger joints positions, and as such could be used for surgery training. In that sense, research [32] has been done to show the use of LMCs in training for laparoscopic surgery. Further proving its worth in medicine, LMCs were also used to investigate hand tremor, a common movement disorder that is often attributed to Parkinson's disease [33]. Ganguly et al. [34] have compared LMC to the standard motion capture techniques. Integration of CAD systems and LMC has been already successfully achieved [35].

Figure 3. shows a part of a motion capturing session [36] using Perception Neuron 2.0 in Axis Neuron software. With the one-handed mode with nine connected sensors, it is possible to monitor the movement of the hand in the area of the upper arm, forearm and each finger on the hand separately. In the experiment, the index finger of the left hand was bent 12 times in 25 seconds. Diagram in Figure 3. shows only part of the experiment: three repetitions of bending (in degrees) lasting six seconds.

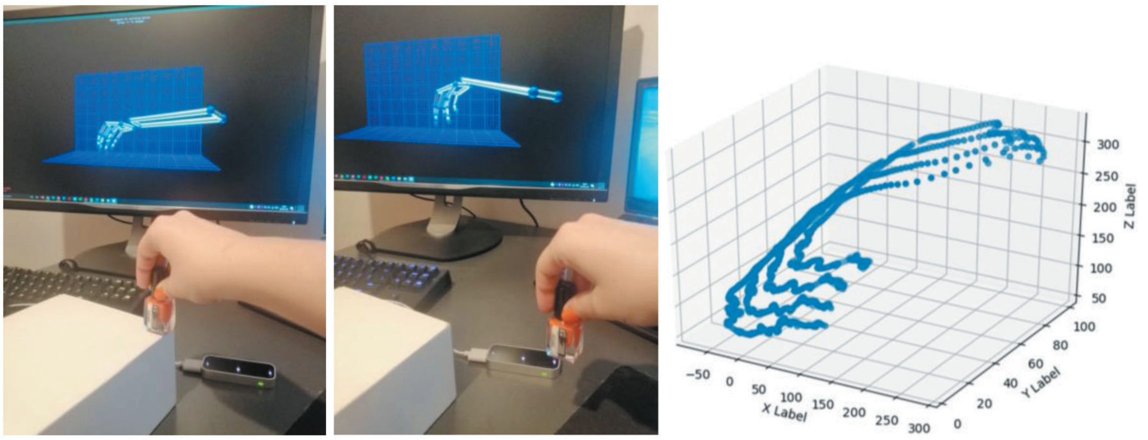

Figure 1. Grasping an object by hand (left) and moving the object by hand (middle) in the interaction space of Leap Motion Controller; right: fingertip points tracking acquired, mm [26]

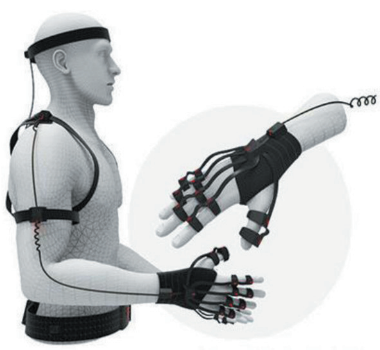

Figure 2. Perception Neuron 2.0 [29]

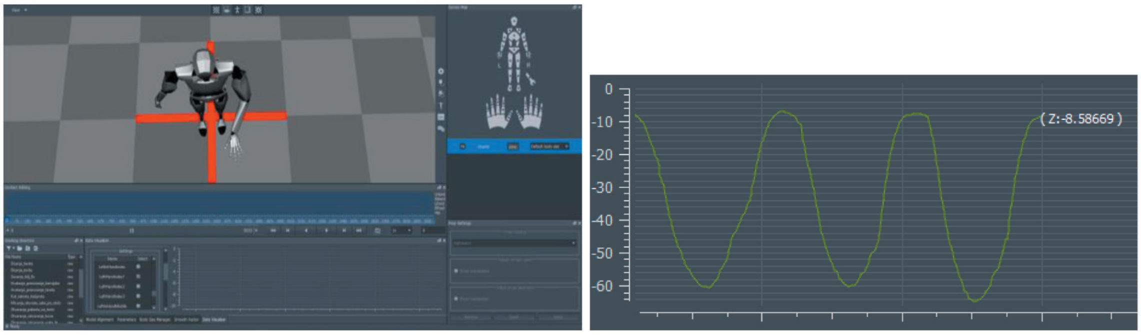

Figure 3. Motion capturing session using Perception Neuron 2.0 [36]

3. Approach, apparatus and planned experiments

In this paper, an effort will be made to consider and to design experiments that could be suitable to present a basis for further work that would eventually lead toward application in ESS, contributing to optimization and automation of work of surgeons and thus reduce the process time and the surgical complication rate (particularly important in EES surgery, as the operation zone is closely surrounded by the brain and orbit eyes). The research is multidisciplinary and as such intended for readers of differing background, some terms can get intertwined. A reader with a medical background might look at the patient's nose as a matter of anatomy, whilst an engineer would look at it as a "workpiece" geometry. Subsequently, whilst a person with medical background would refer to an instrument, an engineer would call it a tool.

The first task is a choice of a specific surgery process to be analyzed and potentially improved including the development of ideas for mechanization and automation. Opening of the frontal sinus and reduction of the inferior nasal turbinates are the chosen surgical processes for further consideration. Both these surgeries consist of highly precise hand motions, each requiring a specific evaluation.

The opening of the frontal sinus is a complicated procedure, offering less possibility for standardization due to the varying conditions of the sinuses among the patients.

The reduction of the inferior nasal turbinates is a simpler procedure, possibly even lasting as little as a few minutes in patients with a standard nose anatomy/geometry. It is a surgery in which the inferior nasal turbinates are reduced in size, in order to greatly enhance the patients breathing by improving the nasal airflow. As such, it represents a more feasible option to standardize a procedure, although it must be noted that different techniques for this surgery exist.

Both procedures are performed during the same operation shown in Figure 4. (the difference in lighting conditions during the stages of surgery can be seen).

A surgeon's work usually occurs two-handedly during the operation: the surgeon uses a rigid endoscope in one hand and a cutting or different instrument/tool in another. The individual endoscope has a predefined view angle, so changing of endoscopes may be expected during the operation. If the surgeon needs to investigate or inspect during surgery, she/he will use the endoscope single-handedly (differing from the pre-operative investigation or check-up, as described above).

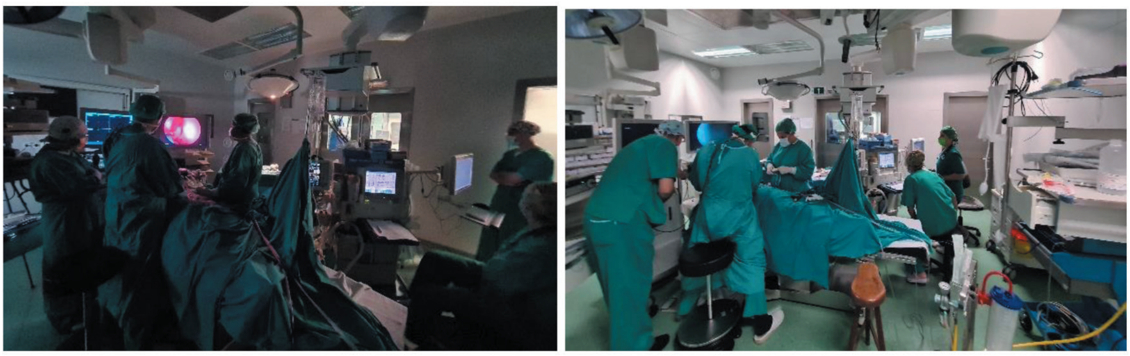

Figure 4. Left: the main, endoscopic stage of the surgery; right: the final, non-endoscopic stage

During the surgery, a variety of instruments/tools has been used in the different phases of the surgeon's work (Figure 5.).

Living beings bring about solving of specific challenges, such as the problem of variable geometry. For example, when a surgeon successfully removes a tumor from the brain, she/he must consider the fact that with time, due to gravity, the brain tissue (as well as other soft tissue) might expand into that empty area, filling the void. Also, if mucosa is swollen during inspection or scanning, the state at that given moment may not be the same as during the operation. That being said, from an engineering point of view ("technically"), neglecting the specific biological/human "work piece" and necessary ethics (that is unavoidable in further phases of work), basically a product with appropriate technology process should be observed, which includes:

(1) product, comprising data on: geometry and other features; possibilities of data acquisition and representation (data sources) and CAD modelling; production quantities and costs. This includes preoperative CT and/or MRI scan, which is later used for image-guidance navigation system [38].

(2) "product design" -- pre-operation analysis. Among other considerations (anamnesis), here a surgeon uses the endoscope for investigation of the condition of the patient's sinuses (usually using two hands).

(3) present (existing) technological process:
- process content and flow, divided into phases and operations
- sequences of phases and operations
- materials
- tools [39] [40], jigs and fixtures (endoscopes [41] and other devices and equipment)
- motions (movements) and specific functions (such as cutting and measuring)
- motion and specific function parameters (forces [42] and torques; distances [43]; cutting speeds and depths etc.)
- execution times and the number of personnel
- lighting and other relevant conditions.

Technological process includes the navigation which helps the surgeon to know her/his operating zone, reducing the risk of complications in the surgery [44] [45]. The navigation (Figure 6.) is based on a CT scan of the patient's

Figure 5. The movement of the surgeon's hands with tools during the reduction of the inferior nasal turbinates (1-4) and the opening of the sphenoidal sinus (5-8), shown with the time progression of the surgery: 1 -- cotton pledges are removed after 5-10 minutes with Hartmann forceps, 2 -- nasal lavage, 3 -- outfracture of the lower inferior turbinate with a freer elevator, 4 -- aspirator pump, 5 -- 8 Kerrison rongeur, an instrument [37] specifically designed for cutting and removing small pieces of bone during surgery

Figure 6. The Fusion navigation system, used in the preparation stage, before the operation

head. In the beginning of the operation, the navigation system is calibrated by dragging the probe across the relevant head geometry thus establishing the connection between the real geometry and scanned images.

If the calibration is successful, the navigation is ready to use, and will be shown on the screen in three different planes: the coronal, axial, and sagittal. However, a surgeon must never fully rely on the navigation due to possible deviations, as mentioned to some extent previously. The surgeon should periodically check the accuracy of navigation by identifying the three-dimensional position of the pointing tool tip inside the patient. Too extensive following of the navigation would result in long operating times.

The navigation system used in the observed operation(s) is the Medtronic Fusion ENT navigation system [46]. The navigation shows the location of the tip of the tool, represented by a green dot when the connection with the tool is stable, or with a red dot if the connection is lost. It can also show the angle of view of the endoscope (represented by a cone shape).

(4) identification of surgery process contents that could be appropriate for improvement (mechanization/automation) -- ideally, those that are not present in practice nor technical solutions are developed for them.

An analysis of the present technological process is required here. Regarding the process time, it has been observed that considerable idle time during EES surgeries is present due to necessary auxiliary operations. Such operations are nasal irrigation, change of instruments (powered instrumentation -- microdebrider, surgical drills, ultracision harmonic scalpel, cautery) and endoscope, and the insertion and subsequent removal of nasal tampons. Regarding the surgical procedure specifically, the steps of the reduction of the inferior nasal turbinates are as follows:

- insertion of the nasal tampon (cotton pledgets soaked in vasoconstrictor), used to get more room during the procedure, and to minimize the future bleeding
- once the tampon is removed, the surgeon enters the nasal area and removes the desired part of the turbinate (both mucosal and bony if necessary)
- in turbinate reduction microdebrider can be used, and for hemostasis electrocoagulation.

In the early stage of the research, it is more important however to establish as robust as possible process plan that will minimize risks by more detailed and precise process parameters such as calculating the angles of access and approach. This relates to the off and on-line planning of an optimal path for ESS surgery. The mentioned issue is tackled in [47][48].

(5) development and proposal of improved surgery process and system based on optimized layout (distances -- movements) and forces/torques (the use of force/torque sensors) in integrated on-line (real time), VR and CAD environments [49] [50]

(6) the last stage of the research: development and proposal of advanced, preferably automated, surgery process and system with equipment specification.

In the first stage of the research, images of the scanned object (CT and/or MRI scan) can be treated by some DICOM Viewer software that „has the capability to open and display studies obtained from different imaging modalities“ [51]. Further, images can be converted into CAD geometry (conversion of DICOM format to STEP format) by 3-D Slicer [52].

The existing process may be captured in several ways:

(1) traditional way: motion recording by video camera, and subsequent analysis by MTM „by hand on paper“ and by CAD software simulation
(2) by LMC and Perception Neuron 2.0 (PC) -- both devices are for motion capture tasks of particular interest here due to their low-cost
(3) Emotiv Epoc+ Brainware (EEB) [53] [54] [55].

In terms of simplicity and effectiveness, the first possibility appears as the more appropriate and realistic at first glance, so LMC and PC could be more suitable for usage in off-line experiments and analysis. However, LMC applicability of on-line motion capturing still must be evaluated, taking into account possible limiting aspects such as: LMC (static or/and dynamic) positioning (table mount or head mount), conditions of sterility, and, of importance for all involved equipment, with no disturbance to the surgeon and her/his activities. At the moment, just because of the possible disturbance to the surgeon, PC is considered of limited applicability (light conditions are not relevant since the device works with infrared light).

EEB could be used to capture and analyze surgeon′s mental signals and facial expressions related to motions. A simple example for a ground to use this device is the connection of an object's geometry and symmetricity (angles α and β of symmetry [56]) with the necessary work (energy) of its handling, shown in Figure 9.

To set a basis for capturing the surgeon's work in future research, a connection between EEB and LM was established by performing a "peg in hole" experiment, with the results shown in Figures 8. through 10. The experiment gives a connection between the precise hand motions (provided by LM) and the mental work (provided by EEB). The subject was given several tasks, varying in their difficulty, in order to examine the values of the different metrics of mental work. The metrics measured are [57]:

- Engagement (En), experienced as alertness and the conscious direction of attention towards task-relevant stimuli. It measures the level of immersion in the moment and it is a mixture of attention and concentration. It contrasts with boredom.
- Excitement (Ex), the awareness or feeling of physiological arousal with a positive value. It is characterized by activation in the sympathetic nervous system which results in a range of physiological responses including pupil dilation, eye widening, sweat gland stimulation, heart rate and muscle tension increases
- Focus (Fo), being a measure of fixed attention to one specific task. Focus measures the depth

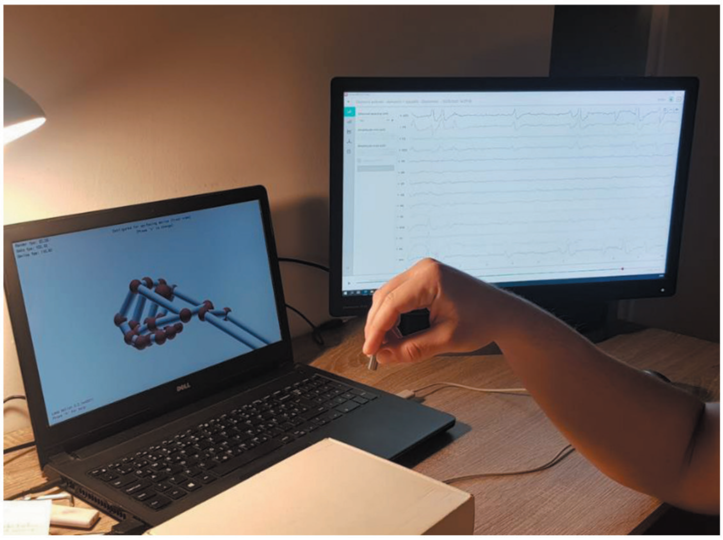

Figure 7. The work environment in connecting LMC (left: screen while capturing the motion) and EEB (right: screen with captured signals from the brain) [55]

of attention as well as the frequency that attention switches between tasks. A high level of task switching is an indication of poor focus and distraction.

- Interest (In), the degree of attraction or aversion to the current stimuli, environment or activity
- Relaxation (Re), measure of an ability to switch off and recover from intense concentration
- Stress (St), a measure of comfort with the current challenge. High stress can result from an inability to complete a difficult task, feeling overwhelmed and fearing negative consequences for failing to satisfy the task requirements.

The result is an established connection between hand motions and mental work, which presents a novel (to the best of our knowledge) and attainable principle of complete manual work capture. It stands as a basis for capturing the surgeon's work (both hand motions and mental) in future research. Furthermore, it might prove interesting to achieve additional integration with contents such as collaborative and cognitive robotics [58], transaction analysis [59] and theory of motivation [60], having in mind ever increasing ethics issues [61] [62].

4. Conclusion

The possibility to analyze and measure human body movements is always of great importance for work but also for everyday life. Technology development, particularly in biometrics, results in new, more complex tools and higher levels of materialization that cover and create more and more realities, that are offered for the involvement of human consciousness (eros), immersed in digital multi-twinning. This allows the design and standardization of manual work in human activities which are yet to be observed, especially those of low scale (small production volume, single-unit production), such as ESS surgery. Therefore, the paper considers the development of an approach that will be useful for specific ESS manual work design and its subsequent automation.

The consideration includes, beside other aspects, initial steps, among which the collecting of the data that describe and quantify the ESS surgery is crucial and comprising the traditional motion capture by camera and off-line experiments by contemporary devices such as Leap Motion Controller, Perception Neuron 2.0 and Emotiv Epoc+. The results expected in the near future could prove valuable initially in the training of new generations of ESS surgeons.

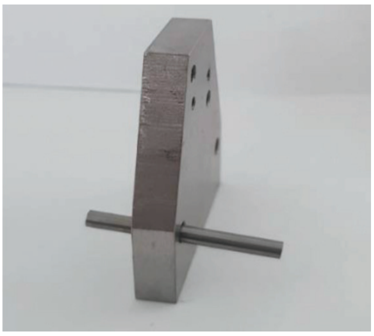

Figure 8. The manual task to be performed: orientating the pin and inserting it into the hole [55]

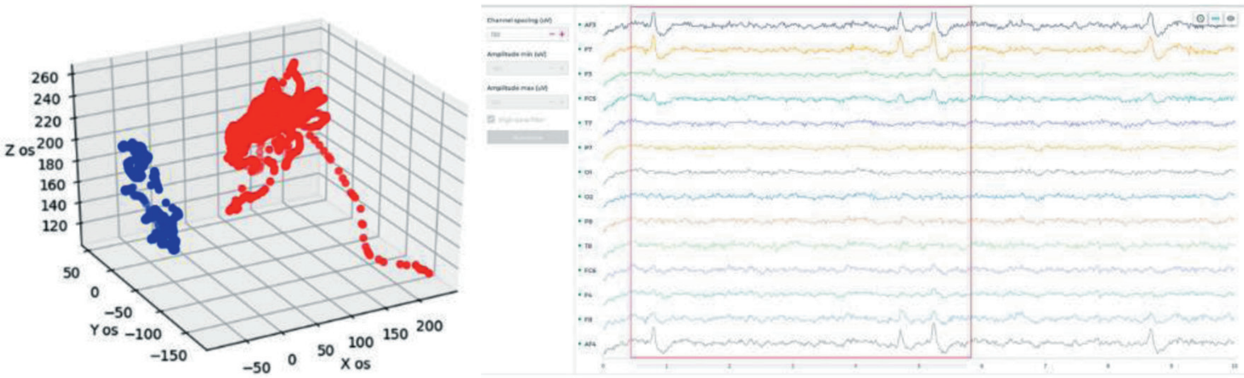

Figure 9. The raw data as a direct output of: LMC, mm -- left, showing the hand movement; EEB -- right, giving the brainwaves from different sensors placed on the subject [55]

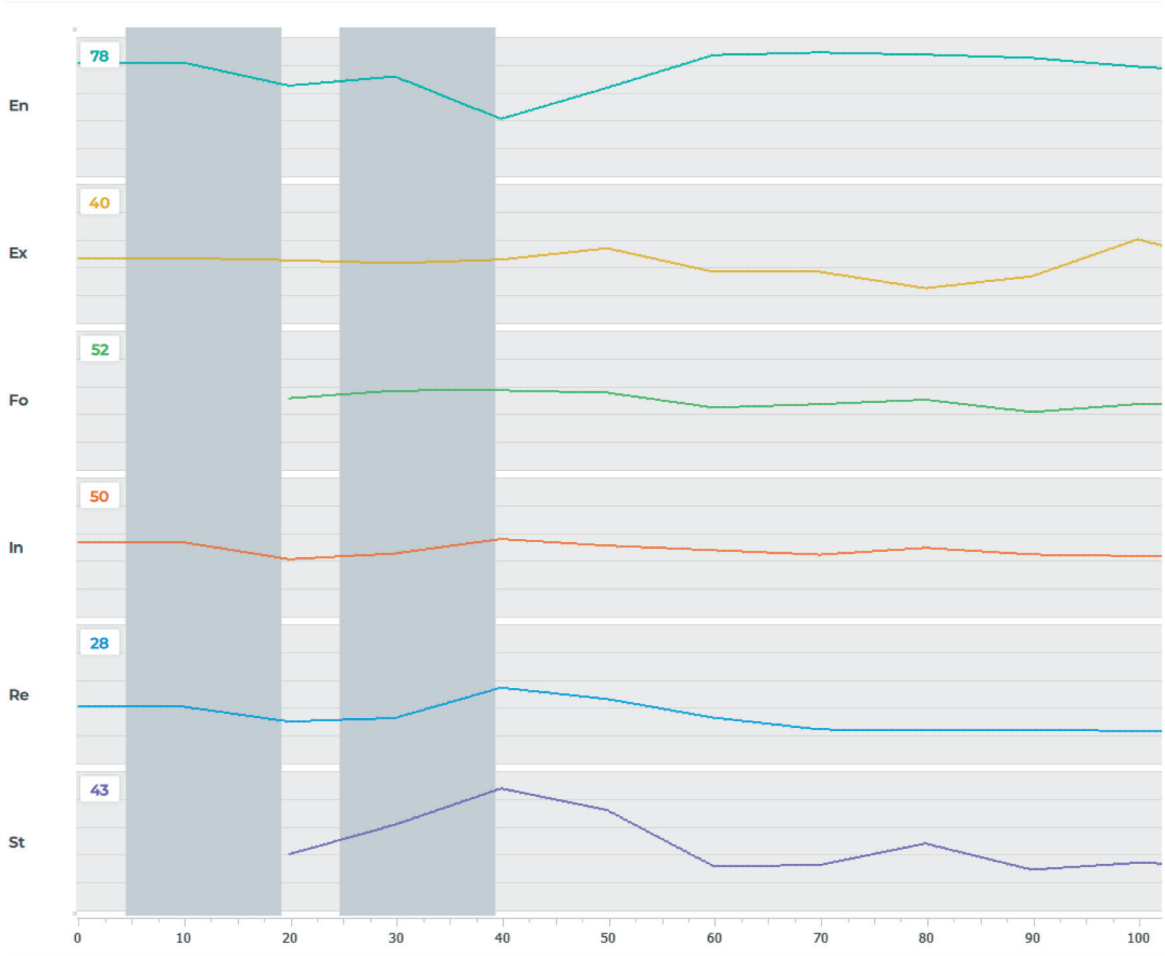

Figure 10. The six different metrics in EEB whilst performing the task (abscissa: milliseconds) [55]

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