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## Study on Dexterity of Surgical Robotic Tools in a Highly Immersive Concept

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*Intelligence is the ability to adapt to change.*  
**Stephen Hawking**

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# Abstract

Robotic minimally invasive surgery (RAMIS) has proven to have noticeable benefits for the patients, making it a favorable approach for a wide range of surgeries and overcoming many of MIS issues like surgeon's poor vision and difficult control of the instrument's motion. To date, many efforts have been made to improve the dexterity of the slave manipulators to enable surgeons to perform more complex tasks. However, the advantages of a highly dexterous instrument may be offset by its complexity and a loss in tele-operation control with a more difficult coordination between the surgeon and the robot. The right balance between higher dexterity and intuitive control needs yet to be defined. In this study, a dexterous, anthropomorphic master has been deployed to assess and compare the efficiency of simulated anthropomorphic surgical instruments in an immersive surgical concept. A virtual surgical training task has been built using a software for graphics applications (Unity), consisting of picking up colored objects and placing them in color-correspondent boxes, placed behind tubular obstacles, which posed additional difficulty. Different tools were tested including shafts with a wrist joint or with a wrist and elbow joints, together with a standard DaVinci Grasper or a 3-fingered anthropomorphic tool. The motion of the tools were controlled using a IMUs sensors and virtual reality gloves. As in real RAMIS, we used a clutch to lock the motion of the tools and avoid uncomfortable arm poses. For a full visual immersion in 3D, we utilized an HTC Vive VR headset. For each trial the time needed to complete the task, number of collisions with the obstacles, kinematic data from the motion tracking and EMG signals from the forearm were recorded. Standard usability and workload assessment questionnaires were filled in by the participants. The study was conducted with 10 lay users with no experience in surgery and 3 trained surgeons. The results showed that a tool with an elbow joint could help to avoid obstacles better in more than 70% of cases but required more physical and mental effort. Standard workload assessment questionnaires also revealed the user perception of putting more effort in picking up the objects with the DaVinci grasper. The system was perceived differently from the trained surgeons, familiar with the DaVinci surgical system. Even with an initial struggle, most of the users could quickly adapt to the system. In fact, the best performance (90% of users) was achieved when using the wristed or elbowed tool for the second time, despite the order of the tasks.





# Sommario

La chirurgia mini-invasiva ha dimostrato di avere evidenti benefici per i pazienti, rendendola un approccio favorevole per un ampio numero di operazioni. Tuttavia, i potenziali vantaggi sono ostacolati dalla diminuita visione del chirurgo e dalla difficoltà nel controllare il movimento degli strumenti. L'avvento di sistemi robotici di assistenza alla chirurgia mini-invasiva hanno marcato un passo decisivo nella sua evoluzione, superando molte delle sue limitazioni e portando a tempi di operazione ridotti, compensazione dell'effetto fulcro e migliore destrezza. Ad oggi, molti sforzi sono stati fatti per migliorare la destrezza degli strumenti e permettere al chirurgo operazioni più complesse. Spesso, però, i vantaggi di uno strumento chirurgico altamente articolato possono essere messi in secondo piano dalla sua complessità ed una conseguente perdita di controllo, con maggiore difficoltà di coordinamento tra mani e strumento. Il giusto bilancio tra destrezza e controllo intuitivo non è stato ancora ben definito.

In questo studio, un sistema di controllo antropomorfo, agile e adattabile è stato utilizzato per controllare e testare strumenti chirurgici simulati in un concept altamente immersivo, per valutare e comparare la destrezza di tali strumenti, assieme alla intuitività del controllo stesso. Per testare ciò, è stato costruito un ambiente virtuale che rispecchia le simulazioni di formazione per i chirurghi, utilizzando un software per la programmazione di giochi e applicazioni grafiche (Unity). Gli strumenti testati includono: un'asta rigida con un'articolazione al polso e uno strumento più articolato con sia un'articolazione a polso che una a gomito. Entrambe le aste articolate sono state testate con uno strumento DaVinci per l'afferraggio e uno strumento antropomorfo con 3 dita articolate. Il movimento degli strumenti all'interno della simulazione è controllato usando Xsens (Xsens Technologies), con sensori IMU posizionati sulle braccia dell'utilizzatore per tracciarne il movimento. L'apertura e chiusura degli afferraggi (sia Davinci che quello a 3 dita), sono controllate grazie a due guanti Manus VR. Come in un sistema chirurgico reale (DaVinci robot, Intuitive Surgical Inc.), è stato utilizzato un pedale per bloccare il movimento degli strumenti ed evitare malposizionamenti della parte superiore del corpo e delle braccia. Per una totale immersività, è stato utilizzato un visore per la realtà virtuale HTC Vive. È stata progettata una particolare simulazione che prevede l'afferraggio di cubi colorati e il loro posizionamento su di una piattaforma del colore corrispondente, utilizzando il braccio destro o sin-

istro. Le piattaforme sono posizionate dietro ad ostacoli tubulari, che aggiungono un'ulteriore difficoltà nel manovrare gli strumenti. Ai partecipanti è richiesto di completare la simulazione utilizzando le combinazioni di strumenti corrispondenti: articolazione a polso con afferraggio Davinci o a 3 dita (W\_DV e W\_3F) oppure articolazione a polso e articolazione a gomito con afferraggio Davinci o a 3 dita (E\_DV e E\_3F), in ordine casuale. Per ogni simulazione, il tempo necessario a completarla e il numero di collisioni con gli ostacoli è stato misurato, assieme a dati cinematici dai sensori IMU e ad una registrazione di segnali elettromiografici (EMG) dall'avambraccio. Dopo ciascuna simulazione è stato chiesto ai partecipanti di compilare dei questionari standard per la valutazione del carico lavorativo e dell'utilizzabilità del sistema, oltre ad un questionario per ottenere opinioni generali sulla simulazione. SUS è stato scelto per valutare l'usabilità, NASA TLX per valutare il carico fisico e mentale. Lo studio è stato condotto su 10 partecipanti senza alcuna esperienza in campo chirurgico e da 3 clinici esperti nell'uso del DaVinci all'ospedale di SouthMead, in Bristol.

I risultati hanno dimostrato che l'approccio al completamento della simulazione è differente per ogni utente. Il confronto del movimento utilizzando gli strumenti articolati proposti ha mostrato che uno strumento più complesso (con un'articolazione a gomito) ha permesso di evitare meglio gli ostacoli nel 70% dei casi. Tuttavia, tale articolazione è stata valutata come più naturale solo da 4/10 utenti, perchè più simili al braccio umano. Per gli altri, la preferenza è stata per uno strumento più semplice. L'analisi dei segnali EMG ha rivelato un'aspettato aumento di attività, in termini di ampiezza del segnale, per strumenti più complessi.

I questionari hanno riportato un maggiore sforzo nell'utilizzo dell'afferraggio DaVinci per raccogliere gli oggetti, mentre per quanto riguarda l'asta, il 60% dei partecipanti ha ritenuto meno laborioso l'utilizzo di uno strumento più semplice, anziché di uno con entrambe le articolazioni. Il sistema è stato percepito differentemente dai chirurghi, poiché abituati ad un diverso sistema per la chirurgia robotica (DaVinci). Malgrado ciò, si è visto che, nonostante la difficoltà iniziale, la maggior parte dei partecipanti si è adattata velocemente al sistema. È infatti vero che la miglior performance per il 90% dei casi è stata raggiunta la seconda volta nell'utilizzo di una tipologia di articolazione, nonostante l'ordine delle simulazioni fosse casuale. Ciò significa che un allenamento è essenziale per padroneggiare questa tipologia di sistema, ma il tempo richiesto per farlo può essere notevolmente ridotto.

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# Chapter 1

## Background and State of the Art

### 1.1 Minimally Invasive Surgery

Minimally invasive surgery (MIS) and its noticeable benefits for the patient in term of recovery make it at date the mainstream approach to a wide range of surgeries. Open surgery has always been strictly invasive with a big impact on various systems, from cardiovascular to respiratory, to immune, causing high stress and pain for the patient, a long time for recovery and also a higher risk of infections [5]. This leads to a less efficient recovery for the patient, both physical and psychological and that's why MIS was born and improved starting from 20th century. Opposite to open surgery, MIS does not require long incisions, but just small ones to create a hole and allow an instrument to enter the surgery site through a trocar; additional holes are cut to insert lights and cameras and assist the surgeon with the vision of the field. It is well known that MIS brings a lot of benefits to the patients: first of all the small cuts prevents excessive bleeding and guarantees a safer and more sterile access, reducing the risk of infections. Furthermore, the small cuts cause less pain and leave smaller scars with consequently shortened recovery times in hospital and in general a better physical and psychological recovery [5, 6].

There are different kinds of MIS, to treat different diseases, including colon, rectal, throat, endovascular, gynecologic, urologic and many other kind of surgery [7].

According to the anatomical area of the surgery and the type of endoscope used they can be grouped in:

- Colonoscopy, for procedures inside the colon
- Thoracoscopic surgery, for procedures inside the chest
- Head and Neck MIS [8]
- Laparoscopic surgery, for surgeries inside the belly

In a typical MIS surgery, such as laparoscopic surgery, a cut is done to make a tube pass and inflate the surgical area with carbon dioxide gas in order to have the space to operate. The same cut is used to insert the laparoscope and then additional holes are cut to insert other instruments necessary to the operation [9]. More techniques have been developed in order to minimize the number and size of transcutaneous access: Single Incision Laparoscopic Surgery (SILS) and Natural Orifice Transluminal Endoscopic Surgery (NOTES) are the ones who got more attention in recent years. The first one requires just one cut through which both endoscope and instruments are inserted. NOTES, on the other hand, uses natural orifices to insert the endoscopes [10, 11], resulting in the absence of transcutaneous incisions. Multiple NOTES procedures have been performed successfully in humans, including transvaginal cholecystectomy [12, 13]. The main advantage of SILS and NOTES procedures is that they are less invasive and will also lead to minimal or no post-procedural pain while improving cost-effectiveness and patient safety.

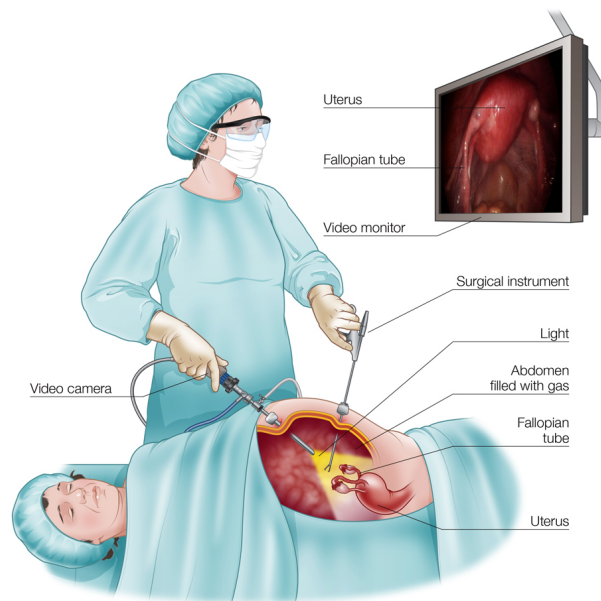


Figure 1.1: Standard Laparoscopy for surgery on the uterus. Picture taken from RANZCOG website, 2020/03/13 [1]

Even though the benefits for the patient have been established, MIS brings some challenges to the operator concerning vision, dexterity and ergonomics. The vision of the surgical field is hidden behind the keyhole access and the surgeons need an endoscope with a camera to see inside the patient, watching the images through a screen. That means they must adapt to a 2-D image of a 3-D environment. Since it is impossible for the surgeon to use his hands on the surgery site, he has to use long shafted tools and move them through the holes cut in the

patient. This brings a loss in dexterity, of the haptic feedback, a more difficult manipulation and complications such as the “fulcrum effect”, which is when the tool endpoints move in the opposite direction to the surgeon’s hands due to the pivot point, making it a non-intuitive motion [14]. In SILS and NOTES the access is even more constrained, the space to maneuver the tools is reduced and it gets more difficult to teleoperate.

Robotic Assisted Surgery has marked a step into evolution of MIS overcoming many of its issues. Robotic surgical platforms have been available since the late 1990s, supporting the surgeons and bringing sundry advantages [5]. The robot takes the place of the surgeon in holding the tools, while the clinician controls the robot through a tele-operation system. This implies the elimination of fulcrum effect and other limitations of the human arm as the physical tremors or muscular fatigue; it also allows to scale movements improving motion. Robotic surgical platforms increase dexterity and partially restore hand-eye coordination, with an improved vision and ergonomic position. This made surgery that were unfeasible previously, now possible [15]. The most known platform is the DaVinci surgical system, developed by the American company “Intuitive Surgical” and approved by the FDA in the 2000. It is used for different kind of surgeries in urology, gynaecology and thoracoscopy. Other surgical platforms are commercially available and used for specific surgeries; some examples are Sensei X, for cardiac catheter insertions, Senhance, for laparoscopy and gynecology, ViaCath system, for NOTES [16]

There are still few disadvantages of these systems that have to be taken into account. First of all they have a high cost and the lack of haptic feedback is still present. Furthermore, the surgeon has to adapt to a new technology and requires a period of training to learn to use the system. Further improvements can be made on dexterity, control and vision.

## 1.2 Dexterity

### 1.2.1 Definition of Dexterity

To understand why it is needed to enhance dexterity in a surgical MIS it has to be clear what dexterity means for a robot. The concept of dexterity is widely mentioned in literature as:

- “The capability of changing the position and orientation of the manipulated object from a given reference configuration to a different one, arbitrarily chosen with the hand workspace” [17]
- ”The kinematic extent over which a manipulator can reach all orientations” [18]

- "The process of manipulating an object from one grasp configuration to another" [19]

Generally speaking, dexterity is the capability to perform a manipulation task with a wide range of possible configurations. The previous definitions, however, constraints dexterity to fingered manipulators while not considering the dexterity of the arm of the manipulator. If we differentiate between hand and arm dexterity then we can assume that for the hand, dexterity is more related to manipulate objects in different ways, while for the arm it is about the possible orientations in which it can bring the end-effector and the point that it can reach [20]. The dexterity of a robotic arm depends on its kinematic structure, its location in space, the relative location of the objects and on environmental restrictions. According to this concept, one can increase the dexterity of the robot by adding kinematic redundancy to the arm or complexity to the hand. How much dexterity is needed for a robot it depends on the specific application.

In designing a robot manipulator, dexterity plays a major role in defining the system kinematic properties and performance. Depending on the purpose of the manipulator, optimizing dexterity may be one approach for its mechanical design; this leads to the quantification of dexterity through the definition of performance indices used to characterize it:

- *Workspace*

The reachable workspace is the volume the manipulator end effector can reach, while the dexterous workspace is the subset of all the positions its end-effector can reach with any orientation. The workspaces depend on a number of factors including the dimensions of the arm. The reachable and dexterous workspace can be computed offline, which make it possible to understand the robot dexterous behavior only based on the kinematic structure. A more dexterous arm is defined by a wider workspace and knowing the configuration of the workspace helps to understand which are the areas for the most effective manipulation. To compute the exact workspace of a robot may sometimes be challenging, because of the high computational cost for a high number of the end effector poses especially in the case of redundant robots.

- *Manipulability*

It represents the capability of the tip of the manipulator to move in space from a specific configuration and is a value of the distance from a singular configuration. A singularity is a point of the workspace in which the Jacobian matrix loses its rank and the end effector loses one or more degrees of freedom, leading to unwanted robot motions, such as blocking or sudden reconfigurations which should be avoided. It is computed as

$$\mu = \sqrt{\det(J^T(q)J(q))} \quad (1.1)$$

where  $J$  is the Jacobian Matrix of the robot. A higher index is desired in order to have a higher dexterity.

- *Condition Number*

The condition number of the Jacobian matrix, similarly to the manipulability, is an index used to measure how close the robot is to a singularity. It is defined as

$$k = \|J^{-1}\| \|J\| \quad (1.2)$$

with  $J$  the Jacobian Matrix and  $\|\cdot\|$  its norm. It represents the ratio between the maximum and minimum singular value of the matrix. However, the use of this index is limited to those manipulators for which  $J$  matrix entries have all the same units, otherwise it would be dimensionally inconsistent. This is not possible for manipulators that have both translational and rotational movements in the Cartesian space. Even though some solutions to overcome this problem and obtain a homogeneous Jacobian matrix have been researched (), still it does not act as a fully reliable dexterity index.

- *Dexterity Index*

Another index has been proposed by Tanio Tanev and Bogdan Stoyanov [21]. It is a measure of a manipulator to achieve different orientations for each point within the workspace. Since the orientation of the end effector of the manipulator can be given as a rotation of three angles (Roll, Pitch and Yaw), for a singular point of the workspace one can vary these three angles, solve the inverse kinematic problem to find the corresponding joint configuration, verify the joint limits, then compute the maximum range for each angle as

$$dx = \frac{\Delta\gamma}{2\pi} \quad (1.3)$$

$$dy = \frac{\Delta\beta}{2\pi} \quad (1.4)$$

$$dz = \frac{\Delta\alpha}{2\pi} \quad (1.5)$$

where alpha beta and gamma are the roll, pitch and yaw angles. The dexterity index is computed as

$$D = \frac{1}{3}(dx + dy + dz) \quad (1.6)$$

This index is useful to show that a point in the workspace can be reached from different configurations, which is desirable because this is the synonym of higher dexterity.

### 1.2.2 Dexterity in Surgery

It is clear that, in robotic assisted surgery, distal dexterity of surgical tools is necessary to enable complex operations such as suturing, cutting or grasping and increasing the reachability. Since the surgeon has to move the surgical tools through the trocar on the patient, he loses the dexterity of the tool shaft. A more dexterous tool can recover that loss or even exceed it.

The tools used for standard MIS are rigid shafts with a functional tip, such as a grasper or a cutter. The rigidity of the tools prevents from performing articulated movements and the surgeon has to account for the fulcrum effect, which reverse the position of the tooltip relative to the hand. He can manoeuvre a standard rigid laparoscopic instrument with 4 degrees of freedom (DOFs) by longitudinally sliding the rigid tool into the trocar, pivoting around the fulcrum and open/close the tooltip. In this case the level of manoeuvrability is limited by a poor manipulability and the reduced workspace. Recently, a new generation of tools have been developed to increase the dexterity of these tools. The enhancement is obtained by adding a wrist joint at the tooltip, so it can adjust to different orientation; the solutions vary from pinned wrist joints to curved ones [22]. Since the complexity of the tool has increased, the handle of the tools on the master side needs to be modified to allow the surgeon to control the orientation of the tooltip. Then, the enhanced flexibility might be hampered by the increased complexity of the control, as discussed by Martinec et al.[23]

Further improvements in tools dexterity are found in robotic assisted surgery. In robotic systems, the tool is held by the robotic arm and the surgeon controls them with a teleoperation system resulting in the possibility to add more degrees of freedom to the tool. Robotic surgical systems such as DaVinci commonly use graspers provided with a 3-axis joint wrist able to mimic the motion freedom of the human wrist; it allows surgeons to perform more dexterous tasks, like suturing, that are otherwise impossible with the rigid laparoscopic tools [24]. Despite the immense progress made using rigid instruments with dexterous wrists, the continued demand for dexterity motivated development of more articulated tools that can be used for less invasive surgeries such as SILS or NOTES. The addition of an elbow joint helps to secure surgical triangulation and positioning of the tools in SILS [25, 26].

The number of DOF can be further enhanced to reach even more articulated and flexible tools [27, 28]. Soft robots are designed to have a continuously deformable structure made of soft, shrinkable and extensible materials. They have the advantage of performing complex manipulations of objects in a confined environment by allowing curvilinear trajectories. In the case of an endoscope, high dexterity may translate into multiple points of view of the surgical site, thus providing the surgeon with more information about the target site. Examples are the ViaCath system, designed for Endoluminal Robotic Surgery, with a flexible shaft that provides a total of 7 Degrees of Freedom within the visual field of the scope [2] or the



DaVinci single incision surgical platform, equipped with both straight and flexible cannulae and designed for SIS [29]. A number of other research platforms for flexible access surgery have been developed, including the Highly Articulated Robotic Probes (HARP) [30], the Multitasking Platform [31] and 2-module soft endoscopes [32] and others for surgeries to be performed in particularly constrained areas such as the throat [33]. Snake-like robots overcome some limitations of NOTES and SIS such as the lack of dexterity in confined spaces.

The dexterity of the instrument can be enhanced in many different ways, meeting the needs of specific surgeries. More flexible tools are able to reach more remote sites, avoiding organs or vessels and improving safety as well as enabling more complex tasks.

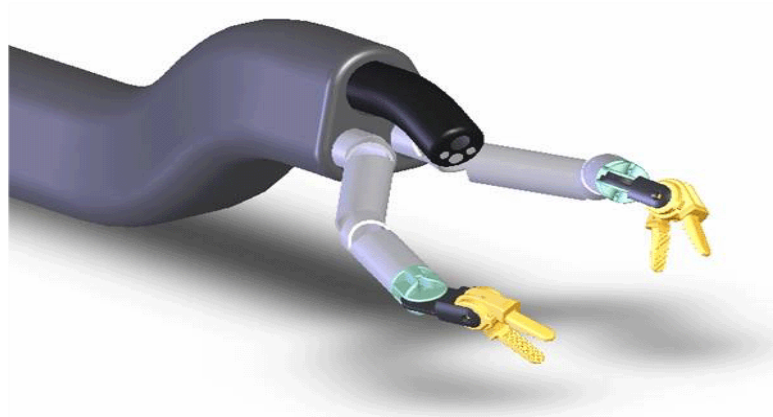


Figure 1.2: Robotic endoluminal surgical system developed for NOTES. It uses an articulated overtube to introduce a flexible endoscope and two highly articulated instruments into the patient. Picture from [2]

### 1.3 Control

The main drawback on dexterity is the complexity of telecontrol. The more the tool is articulated, the more complex is to control its motion and the orientation of each of the links. Besides robot design, there are fundamental challenges in terms of human-robot interaction, sensing and high-level telemanipulation control. Robotic surgical systems partially restore the maneuverability of the tools, that was drastically reduced with standard laparoscopic tools. Robotic systems such as DaVinci allow the surgeons to operate the tools through an immersive teleoperator console, with high quality stereoscopic vision and a control system for the wrist that restore the degrees of freedom of the hand lost in conventional laparoscopy; in addition a number of pedals is used to constraint or engage tool's motions [4]. However, when it comes to more articulated robots, the motion control is not so direct and intuitive. Often, to control the orientation of an highly articulated soft

robot, a joystick or more complex controller is needed, to meet the high number of DOFs of the arm as in [32]. Consequently, the need for long surgical training and an increased workload while performing surgery. Even though some effort to gain an intuitive control of complex devices has been made by [34, 35], still the difficulty in teleoperation is an impediment to the development of effective and easily usable dexterous systems.



(a) *Davinci console*



(b) *DaVinci handle*

Figure 1.3: Example of the console used to control the DaVinci Surgical System. Pictures from [3](a) and [4](b)

### 1.3.1 Anthropomorphic Control

Examples of anthropomorphic control of robotic arms can be found in literature. In the work of Hussein et al. [36] the human arm motion is mapped with the one of a five-axis articulated robot arm using a Kinect sensor as input device. Another example is the study of Su et al. [37], in which they use a Deep Neural Network approach to optimize the mapping between the human arm and a LWR4+ KUKA robotic arm, after capturing human motion with a Kinect sensor. Other researches adopted the same approach using wearable IMU sensors commercially available (Xsens products) [38, 39]. The advantages of a natural interface are an intuitive control of the robot pose, reduction of training times, dexterity comparable to the human arm and enhanced human-robot interaction. These projects were not developed specifically for surgeries, but for different branches of industry and research. However, the idea of using natural motion of human body to control human-like robotic arms can be valid in surgical fields, too. It might avoid spending a lot of time for training the surgeons, since a natural and more intuitive interface is used and they could restore the arms and hands dexterity in operations. The research project SMARTsurg [40] is an European project led

by the Bristol Robotics Laboratory, in which this study was conducted. Its vision is to enable more complex minimally invasive surgical operations by developing a novel robotic platform reducing cognitive load and gain greater dexterity with an anthropomorphic teleoperation system. The objective is to develop dexterous anthropomorphic tools, a wearable multi-sensor master operator to control them, composed of a hand exoskeleton with haptic feedback and haptic manipulators as Haption Virtuose 6D. For a more immersive experience wearable smart glasses will be used for augmented reality guidance of the surgeon based and dynamic active constraints, restricting the instruments to safe regions.

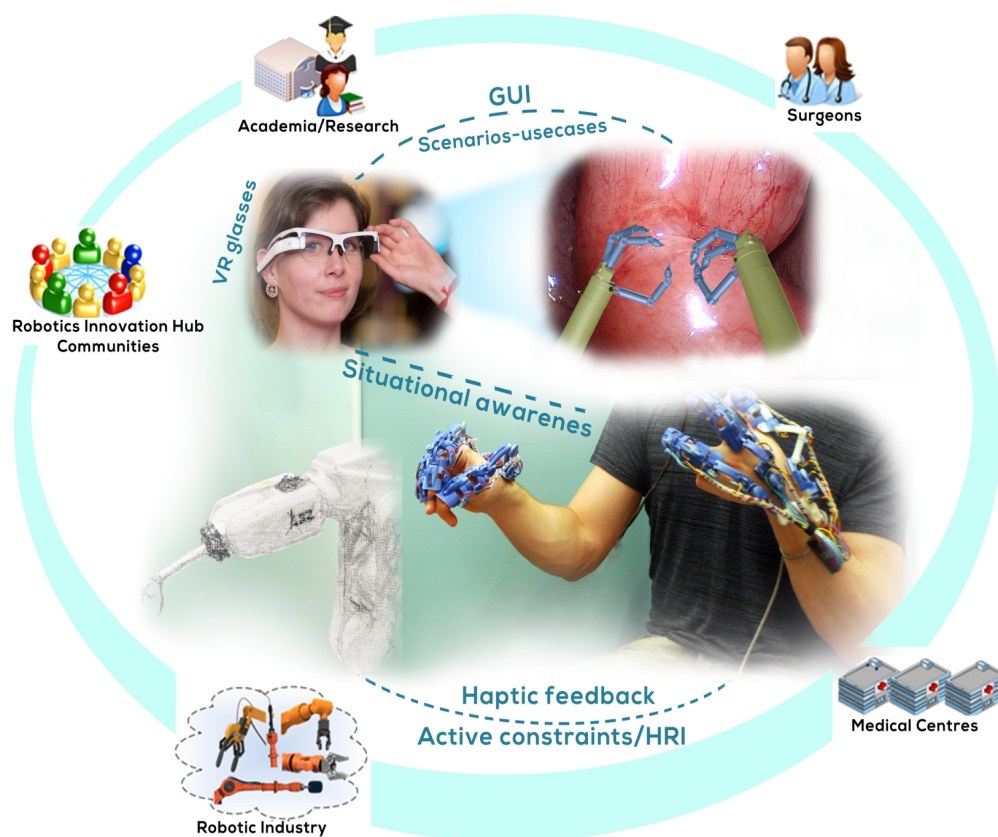


Figure 1.4: SMARTSurg EU project to develop a wearable robotic system for minimally invasive surgery. Picture from SMARTSurg website, 2020/03/13



# Chapter 2

## Motivation and Approach

The enhancement of dexterity in RAMIS could improve the performance of the surgeon and allow more complex operations, more accurately and more safely. But as previously discussed the advantages of a highly dexterous instrument might be offset by its complexity and a loss in operation control with a more difficult coordination between the surgeon and the robot. The prospect of a natural anthropomorphic control might overcome this impairment and reduce mental and physical workload. The right balance between higher dexterity and intuitive control has yet to be defined. A better understanding of the requirements in terms of surgical dexterity and manipulability associated with natural, immersive maneuverability, might help the development of advanced systems for performing RAMIS, to design adaptable tools, lessening the overall complexity of robotic systems. The possible results of such application would be decreased MIS procedure time, shortened training time, enhanced accuracy, safety and diminished system costs.

The purpose of this work is to study the advantages and limits of an intuitive, anthropomorphic tele-operation system in a surgical scenario and investigate the efficacy of tools with more degrees of freedom, which are mapped to the anthropomorphic master. The objectives are to compare the performance, physical and cognitive effort controlling different tools with the proposed system. To achieve this aim, a dexterous, adaptable, anthropomorphic master is implemented using a set of wearable sensors and deployed to control and test simulated anthropomorphic surgical instruments in an immersive, virtual surgical training concept. The instruments used in the simulation feature different number of joints on the shaft and different graspers. The performance and usability of the system in completing the tasks together with the perceived workload and muscular activity are evaluated for the purpose of this research. In the following chapters it will be presented how the system has been implemented, and also how a preliminary evaluation test has been designed, with the results and their analyses.

The process toward the development of the test includes the following steps:

- Design dexterous anthropomorphic tools to be tested (section: 3.2)
- Understand and implement the tele-operation, with human arm and hand tele-controlling the surgical tool and end effector (section: 3.3)
- Develop a suitable task to retrieve data of interest (section: 3.4)
- Perform trials on a small population of users (section: 3.5)
- Analyze data and feedback from the trials (section: 4)

The results obtained from this study want to assess the feasibility of a more intuitive master control, compared to the current robotic surgical systems and point out the limits of instruments dexterity. The analysis of the collected data is used to verify whether an increased dexterity of the tools is offset by a loss in tele-operation control using the proposed system, affecting performance (sections 4.1.2 and 4.2.2), perceived workload (sections 4.1.3 and 4.2.3) or muscular activity (section 4.1.5)

# Chapter 3

## Materials and Methods

The main purpose of this project is to compare the dexterity of surgical tools using a highly immersive tele-operation system. To do so, a virtual reality simulation of a surgical training task has been designed and implemented. Virtual Reality (VR) facilitates an iterative and fast testing of the proposed system without the need to build physical highly dexterous tools in a real surgical system, since they can be designed virtually. VR simulations are already used in robotic surgery training; by using virtual reality, surgeons can develop their skills and pass their basic learning curve before operating on patients [41].

The requirement for VR prototyping is to be kinematically close to a real surgical system. That means that the tools behave as they are inserted inside a patient, through the trocars. In robotic surgery a clutching mechanism is used to lock the motion of the tools, to improve tool control, to keep a comfortable arm pose and to increase safety. A similar clutch system is used in this work.

In this chapter, the equipment and the methods used to implement the task are detailed.

### 3.1 Hardware and Software

#### Unity

Unity is the software chosen to implement the surgical VR system. It is a cross-platform game engine for real-time development; released in 2005, it is used to create 3D, 2D, VR and AR visualizations for Games, Auto, Transportation, Film and Animation. The editor is supported on Windows and macOS, with a version available for Linux; the engine itself supports building games for more than 25 different platforms. The engine offers a primary scripting API in C# as well as a drag and drop functionality. The improved usability and intuitivity of the editor, make Unity an appropriate choice for the development of this project. Example of more complex surgical simulations made with this game engine can be found in literature [42].

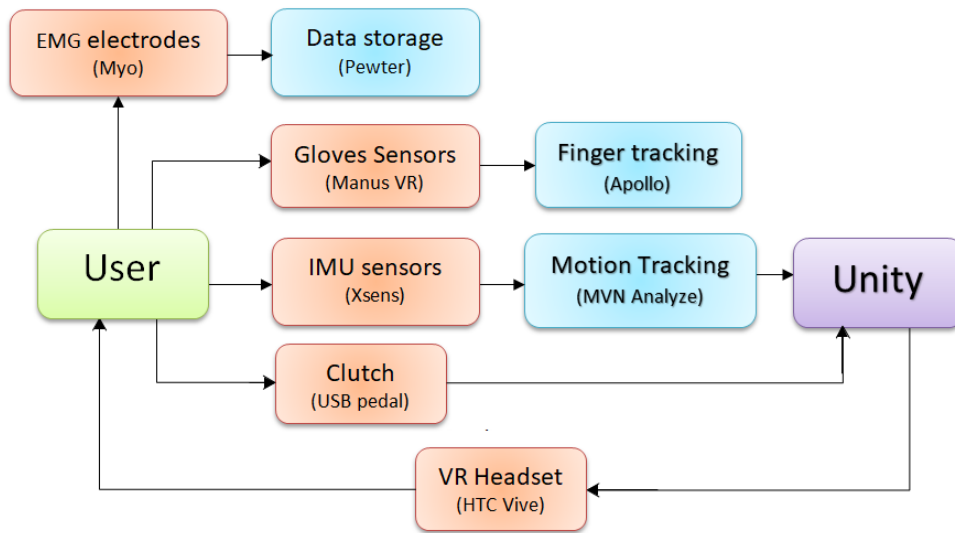


Figure 3.1: Hardware and software I/O hierarchy

## Blender

Blender is a free open-source 3D computer graphics toolset used for the creations of 3D models, 3D applications, visual effects, animations, art and games. It was used to create some of the models for the simulations, such as the surgical tools and some components of the tasks; the created models are imported into Unity as FBX files.

## HTC Vive

To create a highly immersive experience performing the simulation, a HTC Vive kit has been used. Developed by HTC and Valve, it includes a VR headset and two Base Stations, needed to define the working area. The headset uses room scale tracking, allowing the user to see and move in 3D space, ensuring highly immersive vision of the applications.

Steam VR is the software tool used to manage and experience VR with different possible hardwares, including HTC Vive. Valve provide a Unity plugin to interface SteamVR with the game engine; developers can handle input from VR headset and controllers and the game camera output can be seen from the headset.

## Xsense

For the recording of the body kinematic to be used as a control system in the simulation, an Xsens MVN Link set has been used. The standard MVN system consists of a combination of hardware and software, developed for 3D motion capture with a wide range of applications, from animation and film-making to kine-



matic analysis for robotics and medicine [43] [44]. The products are based upon miniature MEMS inertial sensor technology; in particular the motion trackers of MVN Link (MTx) integrates 3D rate gyroscopes measuring angular velocities 3D linear accelerometers measuring accelerations including gravitational acceleration, 3D magnetometers measuring the (earth) magnetic field, and a barometer to enable measurement of atmospheric pressure. Two types of motion trackers are integrated in the suit, the MTx, and MTx-STR. These are identical on the inside but have different connectors. 17 sensors are provided for the full body tracking, plus extra sensors that can be used as probes. However, for this application, only 11 are used for upper body tracking. A Body Pack (BP), powered by a single rechargeable battery pack, interconnects multiple strings of MTx's and retrieves their data ensuring exactly synchronized samples. The collected data is transmitted by an optimized 2.4 or 5.0 GHz spread spectrum wireless link to the Access Point connected to the PC via Ethernet cable.

MVN Analyze is the software, which can be used for real-time viewing and recording as well as off-line playback, analyzing and editing of previously recorded sessions. Both real time recording and playbacks from MVN Analyze can be streamed to different computers and softwares, among the others Unity, thanks to the MVN Unity plugin.

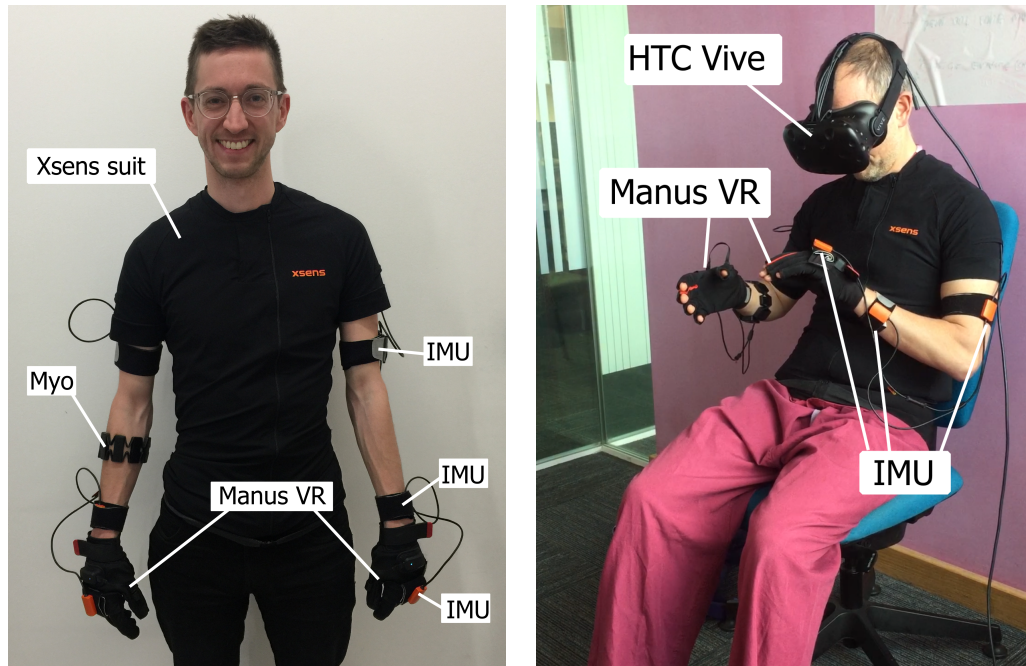
### Manus VR

Manus VR is a commercial product released in 2016, which consists in a pair of sensorized gloves, created as input devices for virtual reality applications. Each finger contains two sensors that track its movement with an accuracy of +/- 3 degrees. In addition, the thumb has a separate IMU sensor to measure its rotation. Each glove contains a gyroscope, accelerometer and magnetometer to measure the orientation of the hand with an accuracy of +/- 3 degrees. The hand tracking is sampled at 200 Hz using the proprietary software Apollo, which features a dashboard for 3D hand viewing and quick calibrations, as well as sensors settings. With Apollo it is possible to stream hand and finger tracking with a number of other systems including HTC Vive and Xsens. In addition, using Apollo with plugins allow to track the movements in development software like Unity, Unreal Engine or Motion Builder.

### Myo

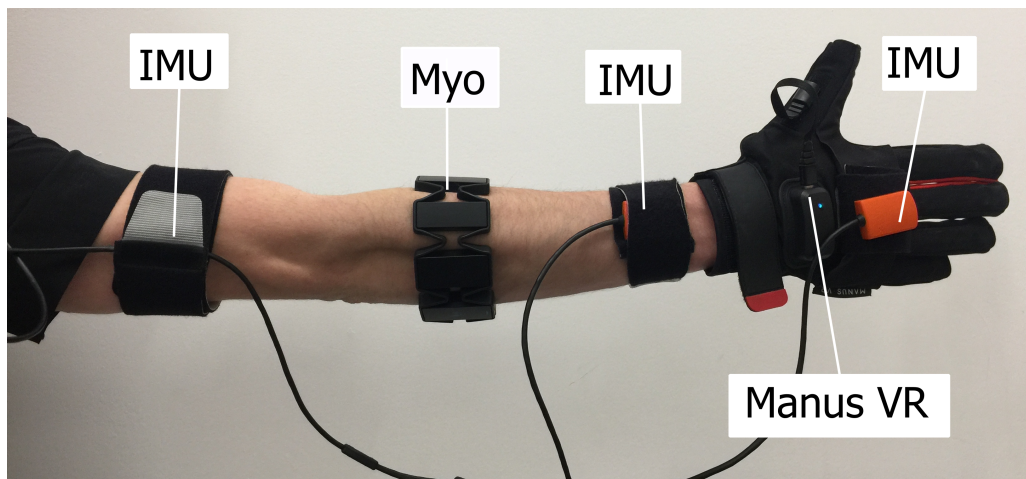
To assess the muscular activity of users during the trials, a Myo armband was used. The Myo gesture control armband, developed by Thalmic Labs, reads the muscle activity with 8 different EMG sensors placed around the forearm and gives touch-free control of technology with hand gestures and motion. It was developed with open APIs and free SDK to build solutions for home automation, drones, computer games, virtual reality, and more [45]. A tool named Pewter was

used in order to acquire data from Myo. Pewter is an open-source project that was originally developed for data acquisition and analysis of raw data from Myo Armband for a project called SigVoiced [46]. The EMG from each one of the 8 electrodes is stored in a Json file and can be processed afterward.



(a) User wearing the Xsens suit and the Myo armband on the right forearm

(b) User wearing all the hardware while performing the trial



(c) Detail of the sensors placed on the arm. Xsens IMUs, Myo armband and Manus VR glove

Figure 3.2: Hardware setup

## 3.2 Tool Design

For this study, dexterous tools were designed with the intention to find the meeting point between dexterity and intuitive control. As explained before, many options are suitable to increase dexterity, but often are associated with a higher complexity. Thinking about intuitiveness and dexterity leads almost naturally to think about the human arm. The human upper limbs permit highly dexterous movements and if the same can be obtained by a robotic arm, then the dexterity loss in MIS, due to the closed surgical field, might be regained and the control of the instruments would be as easy as moving the hands. Anthropomorphism appears as a natural solution to this problem, even though its applicability might be constrained by the limits of robotic surgery.

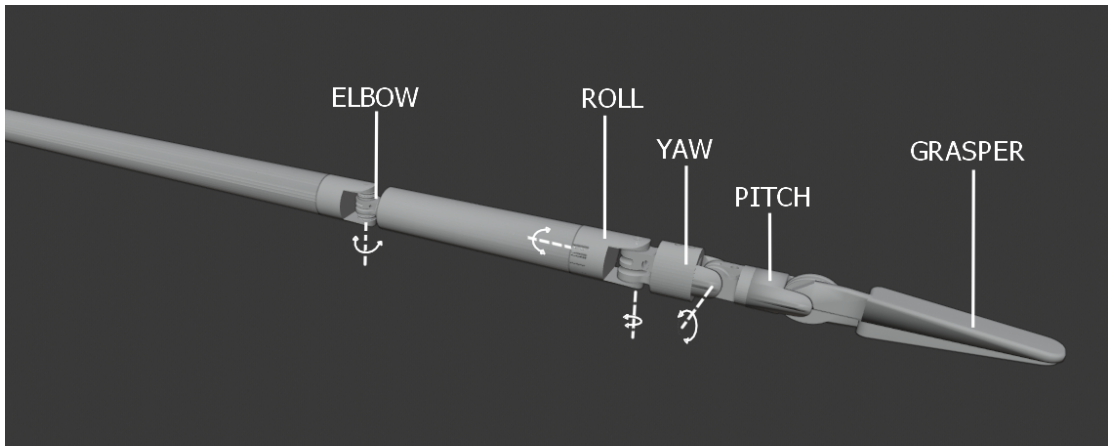


Figure 3.3: Tool featuring a wrist joint, an elbow joint and a standard DaVinci grasper

### 3.2.1 Wrist joint

An example of this concept can be found in the DaVinci surgical tools equipped with the EndoWrist technology, designed to provide surgeons with natural dexterity while operating. They are modeled after the human wrist, mimicking the mobility of the wrist joint and they offer even a greater range of motion than human hands. The efficacy of these tools is the reason why they were chosen as starting point in this study. Therefore, the first tool category that is analyzed is provided with a wrist with 6 degrees of freedom (DOF); the wrist joint is composed of two separate sections, each one of them is able to rotate around one axis. The wristed Yaw and Pitch motions are equivalent of wrist movement of abduction/adduction and flexion/extension respectively. The rotation of the wrist is given by the shaft which can rotate around its longitudinal axis. A simple model has been created using the Matlab Robotic Toolbox to understand better

the dexterity in terms of workspace and manipulability. To decrease the computational workload needed to compute the workspace, the model shows the tool as completely inserted in the patient, with a length of 30 cm, not considering the translational DOF that allow the tool to move forward and backward. The trocar, through which the tool is inserted, is then modeled as a 3 DOF joint which allows Yaw, Pitch and Roll movements. The range of motion of the wrist is defined by the limits of the joints. The human wrist can have 75 degrees flexion, 70 degrees extension, 20 degrees abduction and 20 degrees adduction [47]. The tool's wrist is designed to have a greater range of motion with up to 90 degrees flexion and extension and 45 degrees of abduction and adduction. The reachable workspace and the manipulability values at each point of the workspace are plotted in Figure 3.4(a) and 3.5(a).

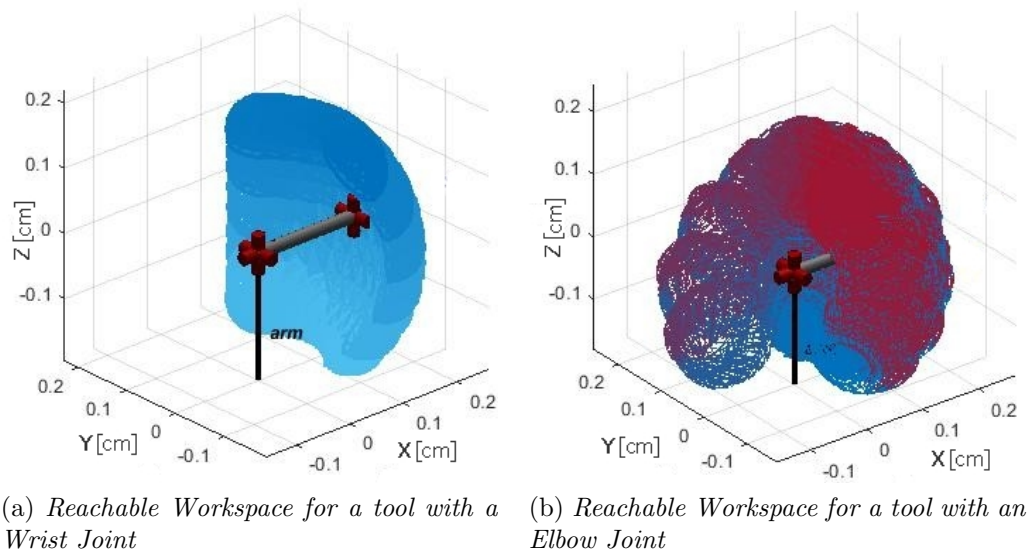
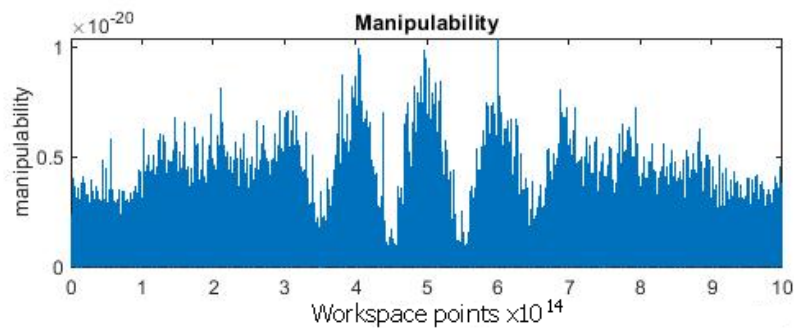


Figure 3.4: Reachable workspace obtained from the model of the tools in Matlab

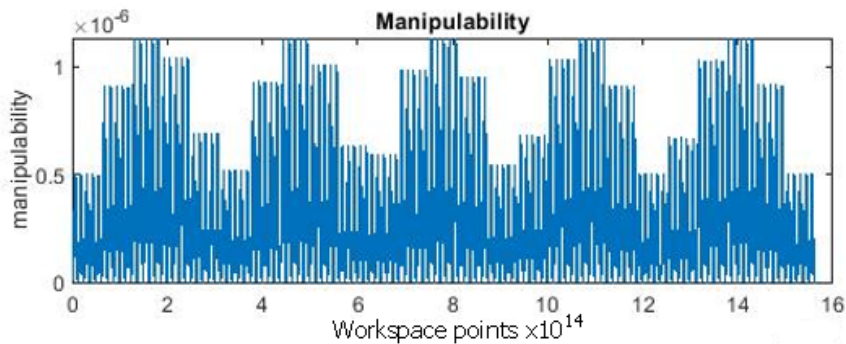
### 3.2.2 Elbow Joint

To further increase the dexterity, a second category of tools was designed with an additional joint thought of as an elbow joint, to get closer to the anatomy of the human arm. Examples of this kind of dexterous tools are seen in the work of Hwnag et al. [26] and Singh et al. [25]; for SILS applications, an additional joint is helpful to secure surgical triangulation and positioning of the tools. A bendable shaft ensure a wider reachable workspace and a greater number of possible orientations, which might be helpful in particularly narrow surgical operations as SILS or NOTES. The tools presented here are provided both with a wrist joint and with the additional elbow joint placed at 3,75 cm from the instrument tip,

considering a 40 cm long shaft, which can be inserted in the patient up to 30cm. This choice was made upon the work of Defne Ege Ozan (Appendix E.1), which demonstrates that the maximum number of points is reached at this point for an instrument with an elbow joint. The wrist joint placed at the tooltip has an additional component which allow the rotation of the wrist (Roll), not anymore coincident with the rotation of the shaft up the elbow joint. The ROM of the wrist remains the same, and the elbow joint has a range of 140 degrees in flexion. As before, a model has been implemented in Matlab and the workspace and manipulability are plotted in Figure 3.4(b) and 3.5(b). The number of reachable points is greater for this tool and the manipulability mean value is higher.



(a) *Manipulability for a tool with a Wrist Joint*



(b) *Manipulability for a tool with an Elbow Joint*

Figure 3.5: Manipulability Values, as defined before, obtained from the model of the tools in Matlab

### 3.2.3 Graspers

For each one of the aforementioned tools category, two different tooltips were taken in account: a DaVinci standard grasper and a Three Fingered tool. The first are forceps used as a grasper tool with the DaVinci system; the length of each side of the grasper is 2.8 cm. The second one is a newly kind of grasper

which is being developed within the SMARTSurg project. It is an anthropomorphic tool made of three articulated digits, each one of them with two DOF. The first phalanx of each digit is 24.64 cm long and the tip of each digit is 19.84 cm long. The tool is designed to have a powerful grasp and permit more dexterous manipulations, but its efficacy might not be comparable to a simpler grasper in simple pick and drop task, as shown in a preliminary study [48].

In this work, no real physics models are implemented for grasping physical interactions. The aim is not to compare the efficacy of the different tools in grasping, but to compare the kinematics of the hand and workload in controlling the tools.

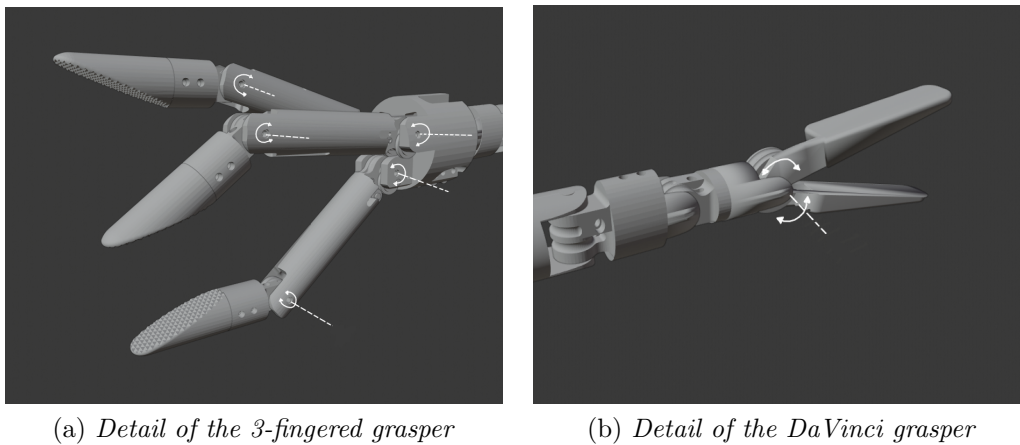


Figure 3.6: Graspers

### 3.3 Motion Tracking

For motion tracking, the Xsens hardware and Manus VR gloves were used. The Xsense sensors were set in the upper body configuration, without placing any sensor on the legs. The user is dressed in the suit, which embed sensors to track shoulders, sternum and pelvis. Three more IMUs are placed on each arm to track the upper arm, forearm and hand. On each hand the user wears one Manus VR glove used to track the motion of fingers. It is possible through the Xsense software, to set the gloves as an extension of the suit, for fingers tracking. After a quick calibration, it is possible to visualize the motion tracking trough MVN Analyze. To calibrate the sensors, the users are required to stand with the arm along sides for few seconds and then to make few step forward; the data collected are used by MVN Analyze to perform the calibration and match the motion of the body to the one of a virtual avatar moving in 3D space. Each segment of the avatar is coupled with one IMU, the fingers with the Manus VR gloves. Through MVN Analyze it is possible to stream the avatar in any Unity application at runtime, so

that in the latter it is possible to see the avatar matching the user's motion in real time. In Unity, each part of the avatar is a `GameObject`, which is a component defined by position and orientation in space and it is hierarchically organized in a parent-child system. It is possible to know position and orientation of each component relative to the virtual world space and even relative to the parent transform. A number of C# scripts were written to measure the parameters needed to drive the tools and obtain the desired behavior.

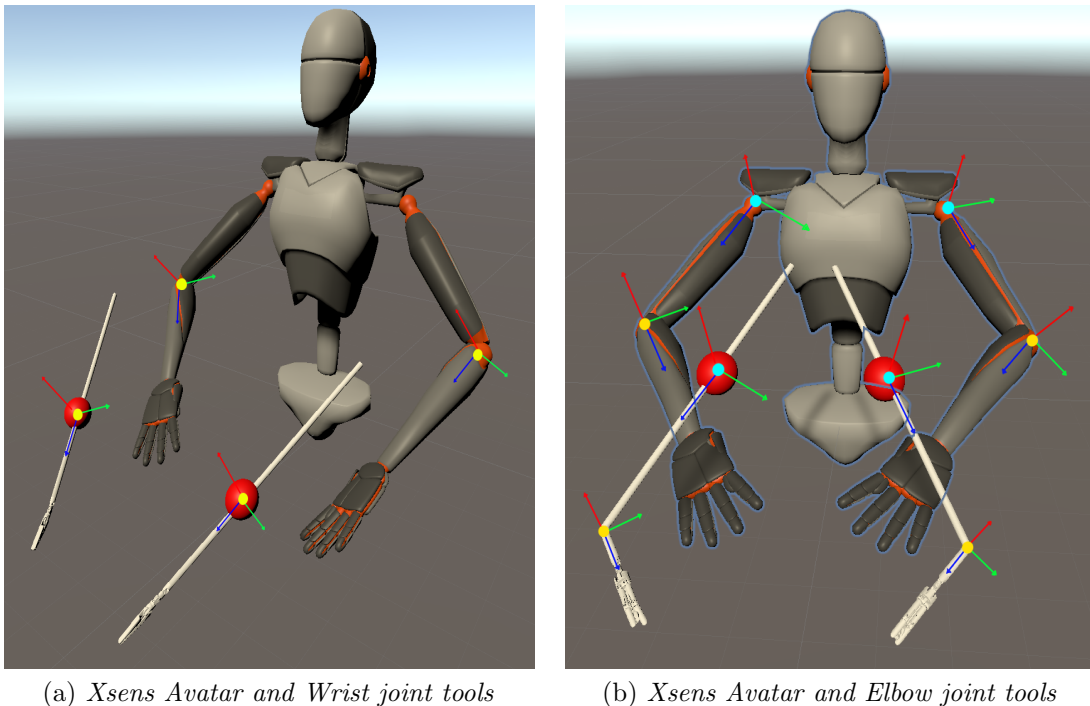


Figure 3.7: In figure the Xsens avatar are shown, together with the virtual surgical tools. The red spheres represent the pivot point, around which the tool is able to rotate. The avatar pose pairs exactly the one of the user; the orientation of the tools is driven by the rotation of the arms.

### 3.3.1 Tool Shaft Motion Tracking

The tools are constrained to pass through the trocar, it can only move forward and backward and rotate around the fulcrum. In the case of a tool with only a wrist joint and a rigid shaft, the motion is controlled by the user forearm; in the second case, with the addition of an elbow joint, the shaft corresponds to the user upper arm. The orientation of the tool is then driven by the orientation of the respective segment of the arm in space. The fulcrum point around which the shaft rotates is updated at each frame to match always the same entrance point,

represented by the red ball in figure 3.7.

The translation of the tooltip is obtained by computing at each frame the difference between the forearm/upper arm position at the current frame and at the previous one, only in the forward direction relative to its local space.

The process at each frame is the following:

$$D_{\text{glob}} = d'[x', y', z'] - d[x, y, z] \quad (3.1)$$

$$D_{\text{loc}} = [T] * D_{\text{glob}} \quad (3.2)$$

$$dx = D_{\text{loc},x} \quad (3.3)$$

Where  $d'$  and  $d$  define the position in space at the actual frame and at the previous one,  $D_{\text{loc}}$  and  $D_{\text{glob}}$  are the same vector in the local reference frame and in the global reference frame and  $T$  is the transform matrix between the two. Finally  $dx$  is the vector component which represents the forward movement.

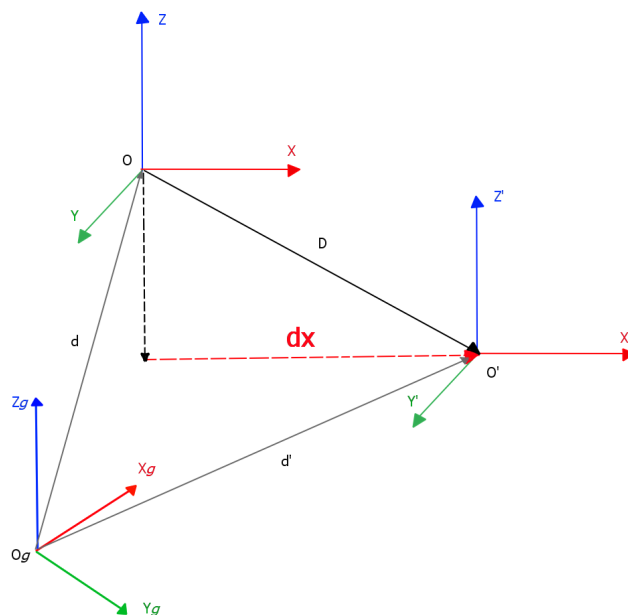


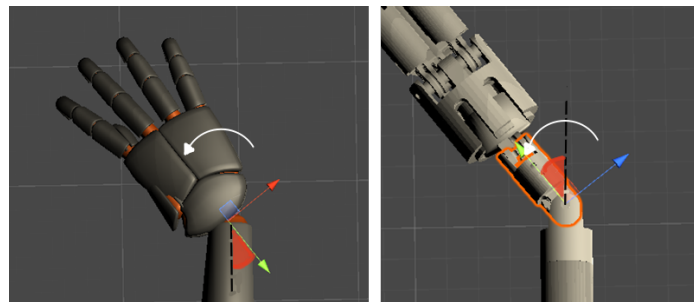
Figure 3.8: Computation of the translation  $dx$  in the forward direction of the arm reference frame ( $x$  axis) in one frame.  $O$  and  $O'$  are the reference frame of the arm at the previous and actual frame.  $Og$  is the global reference frame.



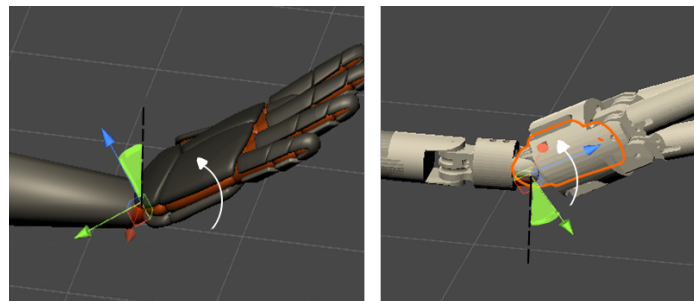
### 3.3.2 Joint Motion Tracking

The motion of each joint of the tool is driven by one possible movement of the user's arm joint as follows (Figure 3.9 and 3.10):

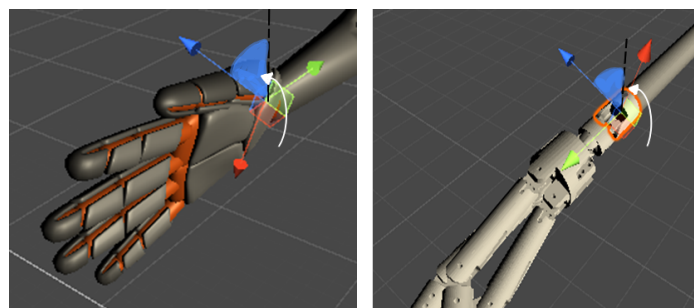
- The tool Pitch segment is moved by the flexion/extension of the wrist.
- The tool Yaw segment is moved by the adduction/abduction of the wrist.
- The tool Roll segment is moved by the rotation of the wrist.
- The tool Elbow segment is moved by the flexion/extension of the elbow



(a) *Abduction of the wrist and of the tool Yaw segment*



(b) *Extension of the wrist and of the tool Roll segment*



(c) *Rotation of the wrist and of the tool Roll segment*

Figure 3.9: Wrist movements

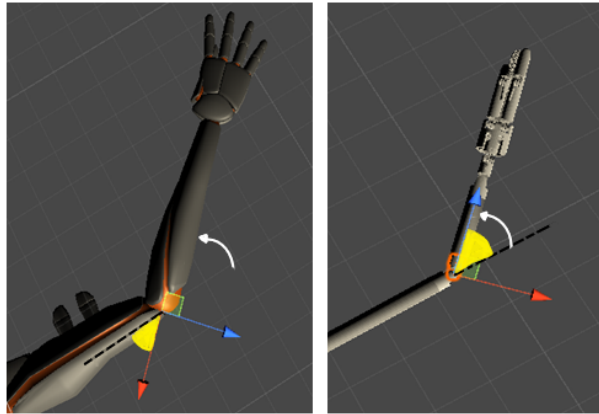


Figure 3.10: Flexion of the elbow and of the tool elbow

When the user performs any movement with the arm, the corresponding part of the tools has to move accordingly. In order to do so, it is necessary to know the joint angles at each frame and the tools have to move consequently to the registered arm motion. The joint angle necessary to rotate the various parts of the tools are obtained by measuring the angle between each joint reference frame (J) and a specific customized reference frames (R). Each reference frame (R) keep the same position of the joint frame (J) and the same rotation around all the axis except one, the one that has to be measured. Since the reference frame behave exactly as the joint except for the rotation around one axis, the rotation around that axis can be measured as the offset between the joint frame (J) and the reference one (R). To further explain, the following example of the flexion movement of the wrist is proposed:

- in Figure 3.11 (a) the reference frame of the wrist joint (J) is shown. in Figure 3.11 (b), the custom reference frame (R) is shown. The position of the second one is coincident with the position of the first one.
- The z axis of R is always directed as the inverse of the x axis of J. Then, R copies the abduction/adduction and rotation movement of J, represented by a rotation around the z and y axis of the joint reference frame (J), respectively.
- When the wrist rotates around its x axis, the reference does not move. It is then possible to measure the angle between the z axis of J and the x axis of R, which is the flexion/extension angle of the wrist, in Figure 3.11 (c).
- The Pitch segment of the tool's wrist is then rotated of the exact same angle. With the same procedure, it is possible to measure the angles for abduction/adduction and rotation of the wrist, as well as the flexion/extension of the elbow.

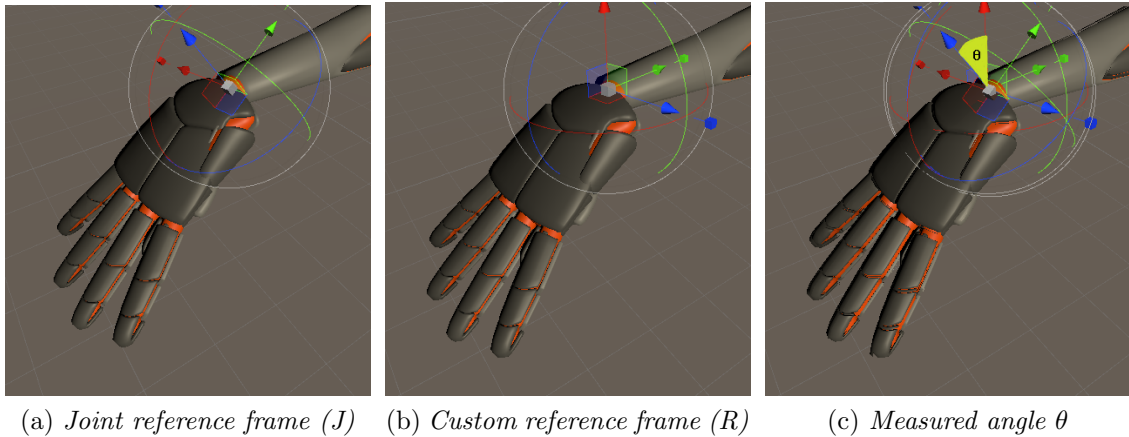


Figure 3.11: X (red), Y (green) and Z (blue) axis of the wrist and reference.  $\theta$  is the flexion angle measured between the wrist ( $J$ ) and the reference frame ( $R$ )

### 3.3.3 Finger Motion Tracking

For the fingers a slightly different approach has been used. The movement recorded by the Manus VR sensors is only of flexion and extension of the first two phalanges of each finger, therefore the fingers of the virtual avatar can only bend in one plane, while no adduction, abduction or rotation is permitted. Thus, it is easier to read the bending angle of each phalanx as the orientation of the above relative to the Parent Object, which is the preceding segment. The same orientation is then applied to the related component on the tool grasper, relative to the Parent Object. The calibration of the fingers is automatically managed by the Apollo software and an offset has been manually calibrated via script to obtain the wanted angles on the tools. Joint limits were applied not to overextend the graspers. As a result, the user can easily open and close the grasper simply opening and closing the fingers.

For the DaVinci grasper:

- The orientation of the upper side of the grasper relative to the base is coupled with the orientation of the proximal phalange of the thumb relative to the metacarpus.
- The orientation of the lower side of the grasper relative to the base is coupled with the orientation of the proximal phalange of the index relative to the metacarpus.

For the three-fingered grasper:

- The orientation of the first phalange of one of the upper tool's fingers relative to the base is coupled with the orientation of the proximal phalange of the index relative to the metacarpus.
- The orientation of the first phalange of one of the upper tool's fingers relative to the base is coupled with the orientation of the proximal phalange of the middle finger relative to the metacarpus.
- The orientation of the first phalange of the lower tool's finger relative to the base is coupled with the orientation of the proximal phalange of the thumb relative to the metacarpus.
- The orientation of the second phalange of one of the upper tool's fingers relative to the first phalange is coupled with the orientation of the middle phalange of the index relative to the proximal phalange.
- The orientation of the second phalange of one of the upper tool's fingers relative to the first phalange is coupled with the orientation of the middle phalange of the middle finger relative to the proximal phalange.
- The orientation of the second phalange of the lower tool's fingers relative to the first phalange is coupled with the orientation of the middle phalange of the thumb relative to the proximal phalange.

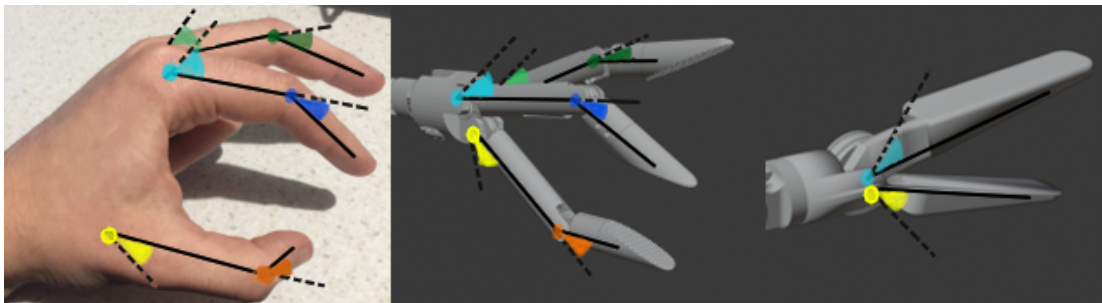


Figure 3.12: Fingers mapping between hand and 3-fingers tool, achieved thanks to the Manus VR glove. The calibration of the glove is carried out by the Apollo software, then the measured angles are calibrated manually through a script

### 3.3.4 Clutch

The clutch is a digital input that allows the user to lock and unlock the tool's motion at any time. A clutching system is commonly used in surgical robotic systems as the DaVinci, to better control cameras and tools. When active, the

clutch temporarily disconnects the robotic arm guidance from the console so that the controllers can be repositioned to allow for additional movement along the previous axis [49].

The clutch is needed:

- For safety reasons, it is possible to stop the system and avoid damages or complications.
- To extend the range of motion. For example, if there is need to reach a further point with the tool, but the controller has already reached its maximum range, then it is possible to clutch, reset the position of the master and then move again.
- To avoid uncomfortable position. Since the DOF of the tools are less than the DOF of the arm, the motion is not always perfectly matching, and this might lead to inconvenient arm poses to complete the task. The user can stop the tools, get comfortable and then resume the movement.
- To control the tools better with smaller motion steps, increasing accuracy.

The use of the clutch can simplify the control of the slave manipulator and avoid limitations related to physical boundaries. However, it is also known that an extensive use of the clutch can introduce a visual-perceptual mismatch, between the mental perception of the pose of the arm and what the eyes see as the actual pose of the tool, enhanced by the lack of any other kind of feedback.

For this simulation the clutch was created using a USB pedal connected to the computer as an input device. The press of the pedal is registered as an input from a keyboard. Few scripts manage the clutch of translations and rotations of every component of the tool.

When the input is received, the pose of the tool is locked and saved. Every angle of the arms' joints is then normally computed as explained before, but instead of being used for the tools motion, these values are stored as offset values. When the clutch is released, the new angle given to the tools is increased or decreased by the offset angle and the tools start moving again from its previous position.

## 3.4 Task Design

For the aim of this project, the simulation is not meant to strictly replicate a surgical operation, but primarily stress the dexterity of the system in reaching and manipulating objects. However, a reference to a real case scenario can lead to more appreciable results. The task was inspired by typical training exercises for RAMIS systems, which are used to develop knowledge and skills of surgeons in a safe virtual environment. Virtual reality training has been extensively used in surgical training systems like dV-Trainer and DaVinci Skills Simulator, which feature a

high immersivity level and provide almost equal training capacities compared with the real robotic system [41]. This novel approach to surgical training has been validated as a training and assessment tool and has been shown to improve a surgeon's performance in the operating room [50]. Sundry different single-handed or bi-manual tasks can be implemented in these training systems including Peg transfer, suturing, bimanual carrying, needle passing, path following and many specific real surgery simulations.

The task for this project was designed with the help of a surgeon, expert in the use of DaVinci Surgical System, keeping in mind the objective of the trials to test dexterity and intuitiveness. Moreover, the task did not have to be too complex or difficult, since the test are also carried on a group of lay users with no previous experience of robotic tele-operation surgery. The choice fell upon a single-handed pick, carry and drop task. It was decided to implement a grasping task to allow the comparison of different grasper. The decision of a single-handed carrying task was made after few trials with more complex manipulation tasks, such as the bi-manual passing of an object through rings behind the obstacles. Since this last kind of task has a greater level of complexity, it required an higher effort to complete the task, leading to excessively long trials and struggle for the user. With a simpler movement, such as the single-handed carrying, the user can focus on the movements of one arm at a time, which requires less workload when compared to bi-manual tasks but still the dexterity of the instruments is essential in trying to reach the targets beyond the obstacles.

The virtual environment (Figure 3.13) includes the following components:

- A cavity, inside which the simulation take place that can be taken as the pelvic cavity or any other workspace that can be seen through the endoscope in a laparoscopy surgery.
- A group of obstacles, that can depict tissue or vessels to avoid during the surgery.
- 4 platforms are placed behind the obstacles, 2 of them colored in green and 2 of them in blue.
- 4 cubes, referred as targets, which can be grasped and moved around.
- 2 robotic tools, with the entrance point fixed at half of the height of the cavity and just behind the point of view of the user.

For each task, the user sees one cube and one platform of the same color at a time. The user has to pick up the cube with the corresponding hand (green indicates the left arm and blue the right one) and place it on the platform, trying not to touch the obstacles. When the cube is in position, it disappears together with the platform and a new one appears in another place, randomly. There are 4 transfers to carry out to complete the task.

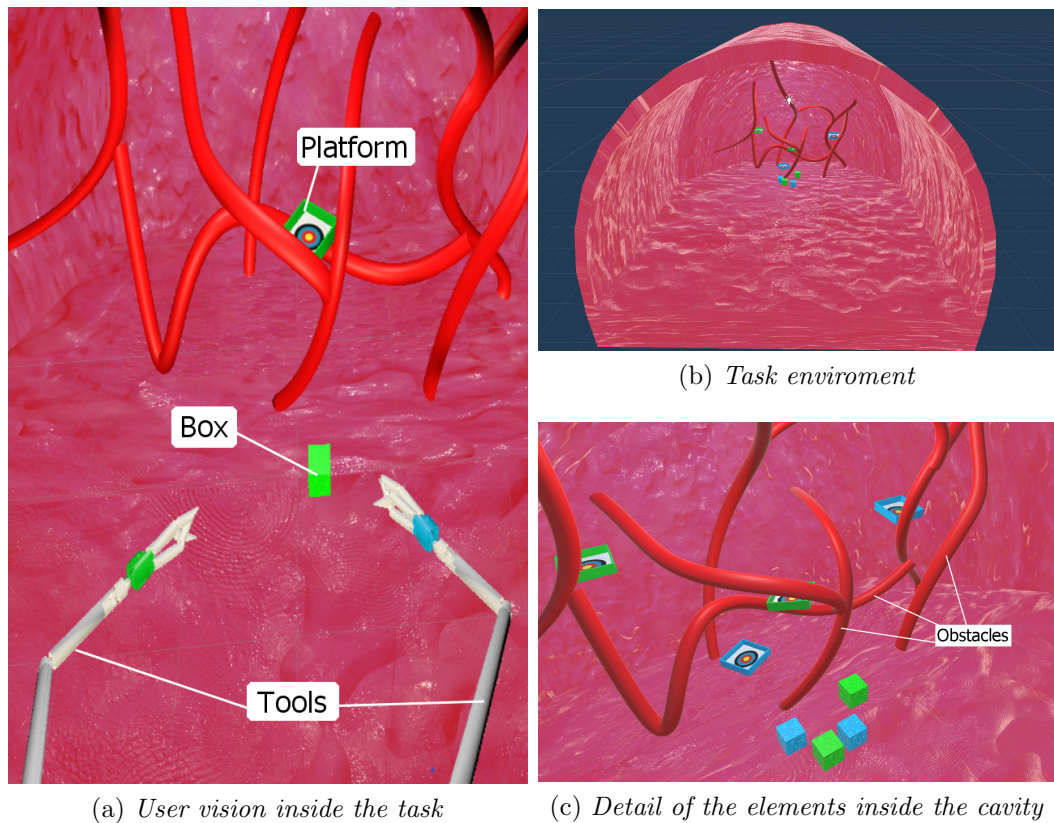


Figure 3.13: View of the task and of its elements

### 3.4.1 Grasping and Collisions

Every object in the scene is provided with a collider that can detect collisions and interact physically according to the Unity built-in Physics Engine, which provides components that handle the physical simulation. The boxes are affected by gravity and collide with any element in the scene. The physical interaction between the boxes and the tooltips was reduced, to avoid unwanted collisions which continue after the object is grabbed and only increase the grasping difficulty. The grasping is managed by a script: once the box is touched by the two sides of the DaVinci grasper or at least 2 fingers of the three fingers tool, it is set as “picked-up” by a script and become kinematic, meaning that it is not affected by colliders anymore and it can be moved. In the same way, if the grasper opens, the box returns a rigid body and is dropped. Since there is no haptic feedbacks or constraint on the users’ arm, the repulsive forces that arise from the collisions once the tool bumps into an obstacle generate motions and interactions that are very different from the ones mentally perceived by the arm and it results in unwanted divergencies, imbalance and loss in control. For this reason, physical interactions were reduced also between the tools and the obstacles or the walls of the cavity. However, the collisions are correctly registered and stored.

### 3.5 Experimental Protocol

The tests were conducted with 2 groups. The first one was composed of 10 lay users, with no previous experience on robotic surgery. The second group was composed of 3 clinicians from the South Mead Hospital in Bristol, 1 surgeon and 2 surgeon assistants, all of them experts in the use of the DaVinci Surgical System. It was important to have the tests on both groups to investigate the response of non-trained users to the system and retrieve a comparison with existing systems from trained surgeons.

For the first group of 10 users the executed protocol was the following:

1. The user is instructed on the procedure of the trial and asked to read and sign a Consent Form to participate in the study.
2. The user wears the Myo armband, the Xsens sensors and the Manus VR gloves.
3. A brief maximum contraction of the forearm is registered with Myo for later data normalization.
4. The Xsense sensors are calibrated on the user. After the calibration the user can look at the virtual avatar to see if the calibration is successful. If not, the calibration is repeated.
5. The user seats on a chair and is given the VR headset and the pedal.
6. Before each task there is a “training room”, a simplified version of the task itself in which the user can understand the system and get confident with the new tool. No data are recorded at this stage.
7. The user completes 4 different tasks, one for each different combination of articulated grasp and grasper. The tasks are given in random order, which was previously randomly determined from Random.org, which is a website to generate random number or series based upon atmospheric noise.
8. After each task the user is asked to fill the NASA TLX form.
9. At the end of the trial, the user is asked to fill the SUS form and the User Form.

The second set of tests was taken at the Southmead Hospital in Bristol on 3 clinicians. The protocol of the tests was the same of the other group, with the only difference that only 2 tasks were taken by each user. The combination of tasks was different for each trial and every surgeon had the possibility to try all different shaft and tools. No EMG signal was retrieved in this group, due to the low number of users.

The ethics approval for this study was obtained from the University of the West of England.



## 3.6 Analyzed Data

Different data sets were retrieved from different sensors and software and from a group of questionnaires:

### Performance

As an indicator of the performance of users, the time needed to complete the task was measured with a script in Unity, together with the number of times a collision is registered between the tools and the obstacles. The mean values of time and collision among all users were compared for different tools and the single performance of each user was analyzed as explained in detail in section 4.1.2. These data were used to understand if a difference in performance is related to changes in tools.

### Kinematic Quantities

With Xsens MVN Analyze it is possible to record a session and extract kinematic quantities for every segment and joint of the avatar at every frame, up to 240 fps. The collected data include segment position, orientation, velocities, accelerations and different conventions of joint angles. The linear velocity [m/s], linear acceleration [ $m/s^2$ ], angular velocity [rad/s] and angular acceleration [ $rad/s^2$ ] of the arms were considered in this study, to observe if there is a difference in motion velocity while changing the tools. While position and orientation of the arms are highly subjective and depends on various factors, the velocity is a parameter that easily distinguish motion, if compared on the same subjects between different tasks. The aim is to see if users tends to move faster using some tools instead of others, showing whether there is greater ease of movements or higher confidence in controlling the system.

### Muscle Activity Recording

EMG signals were recorded during the trials for the whole duration of each task. These signals were then processed and analyzed to evaluate if the system produces muscular fatigue and how different tools can affect it. The EMG signals were firstly sampled to 1000Hz, then filtered between 20Hz and 450Hz. After this was performed a Short-Time Fourier Transform (STFT) leading to calculate the Power Spectrum Density (PSD) that is needed for finding the features in analysis in this study such as Root Mean Square, defined as the square root of the average power of the EMG signal for a given period of time. (equation 3.4), Mean Frequency, calculated as the sum of product of the EMG power spectrum (P) and the frequency (f) divided by the total sum of the power spectrum (equation 3.5) and Median Frequency, which is a frequency at which the EMG power spectrum is divided into two regions with equal amplitude (equation 3.6) [51]. The followed

procedure is based upon the work of Mendes (Appendix E.2) who performed a comparison between DaVinci and SMARTSurg system in producing fatigue. These parameters are commonly used as EMG features to characterize both muscular activity and fatigue for stationary contractions as they relate to the amplitude and frequency of muscle activation [52, 53]. For this study, potential differences in muscular activity from one task to another have been examined. The armband was placed on the user's forearm, so the activity of the main flexors and pronators of the hand and fingers was measured.

$$x_{\text{rms}} = \sqrt{\frac{1}{T_1 - T_2} \int_{T_1}^{T_2} [f(t)]^2 dt}. \quad (3.4)$$

$$MNF = \frac{\sum_{j=1}^M f_j P_j}{\sum_{j=1}^M P_j} \quad (3.5)$$

$$\sum_{j=1}^{MDF} P_j = \sum_{j=MDF}^M P_j = \frac{1}{2} \sum_{j=1}^M P_j \quad (3.6)$$

$f_j$  is the frequency value of EMG power spectrum at the frequency bin  $j$ ,  $P_j$  is the EMG power spectrum at the frequency bin  $j$ , and  $M$  is the length of frequency bin.

## NASA TLX

NASA task load index (NASA TLX) [54] is a tool for measuring and conducting a subjective mental workload assessment. It allows to determine the workload of a participant while they are performing a task. It rates performance across six dimensions to determine an overall workload rating. The six dimensions are as follows:

1. Mental demand: how much thinking, deciding, or calculating was required to perform the task.
2. Physical demand: the amount and intensity of physical activity required to complete the task.
3. Temporal demand: the amount of time pressure involved in completing the task.
4. Effort: how hard does the participant have to work to maintain their level of performance?
5. Performance: the level of success in completing the task.

6. Frustration level: how insecure, discouraged, or secure or content the participant felt during the task.

Each subscale is presented to the participants after the experimental trial. They are asked to rate their score on an interval scale ranging from low (1) to high (20). The TLX also employs a paired comparisons procedure. This involves presenting 15 pairwise combinations to the participants and asking them to select the scale from each pair that has the most effect on the workload during the task under analysis.

### System Usability Scale

SUS is a widely used ten item Likert attitude test presented in [55] that gives a score in the range 1-100, where 100 is the maximum value, representing the usability of a system, based on the users' reviews. The user has to indicate a value in the range 1-5 for each item, where 1 stands for a strong disagreement and 5 stands for a strong agreement; mid values are shades ranging between the extremes. The score is computed as follows:

$$SUS_{score} = 2.5 \sum_{i=0}^4 [(5 - q_{2i}) + (q_{2i+1} - 1)] + (5 - q_{10}) \quad (3.7)$$

where  $q_i$  is the  $i$ -th question (or item). As can be seen in the formula, odd items carry a positive value with them, while even ones give a negative opinion on some aspects. The questionnaire was embedded in a Google Form, together with the user form.

### User Form

A customized survey was designed to retrieve personal feedbacks about the general usage of the system, opinions and preferences. It was implemented in Google Forms, to be easily readable and usable and permit a quick results analysis. The form can be visualized in Appendix BOH and includes questions about the immersivity of the systems, preferences on the tools, perceived physical or mental fatigue and general thinking.



# Chapter 4

## Results

In this chapter the results obtained with the aforementioned methods are presented, divided by group and data category. Part of the data are plotted in the appendix as reported below. To clarify, for brevity I used acronyms in this section and in the plots to refer to the different tools. The tools provided with just a wrist joint are referred to as W, the ones that include also the elbow joint are referred to as E. To indicate the two different grasper I used the abbreviation DV for the standard DaVinci grasper and 3F for the 3-fingered tool. Thus for instance the task in which the user controls a tool with an elbow joint and a DaVinci grasper is written as E.DV. The 4 tools combination tested are, therefore, E.DV, E.3F, W.DV and W.3F.

### 4.1 First User Group

#### 4.1.1 User Form

The general feedback and preferences from the users are collected in the Appendix A. The system achieved a good degree of immersion, with a medium-high feeling of control of the tools related to the intuitiveness of pairing anthropomorphic tools with the arms (figures:A.1,A.2). A higher grade of intuitiveness seems to be reached by the tools provided only with a wrist joint (WJ), since everyone could use them without excessive effort. However, the same cannot be said for more complex tools with the additional elbow joint (EJ). For the latter, the increased complexity was perceived at the beginning for most users, resulting in an initial difficulty to move the elbow, but for few users the elbow joint was more “arm-similar” and therefore more intuitive and natural to use than the WJ. Half of the user group found easier to use the EJ tools and 4 out of 10 confirmed to prefer this one over the simpler WJ tools (A.4,A.9). For the rest of the users, the limitations of the tools were perceived more and affected more the control, resulting in the preference of a simpler tool. Tools limitation refers to the DOF diminished by the constraint at the entrance point of the tool, the trocar, which

act as a pivot point and prevents some translation, and to the use of the clutch. The clutching system is useful to control the motion better but, when activated, creates an offset angle between the orientation of the tools in VR and the orientation of the arms. This is even more evident using a complex tool (EJ), since the number of DOF is higher and therefore there is a greater number of possible different offsets in orientations; there is often a considerable effort in understanding how to get the intended motion. For the same reasons, some users found physically trying to complete the performance, than perceiving the mental effort. Regarding the use of different graspers, no significant difference was observed. Half of the group expressed preference for the three fingered tool (3F) over the DaVinci grasper (DV), mainly because the 3F tool seemed to be more accurate and made it easier to pick up the targets, although maybe not necessary for this specific task. 4 out of 5 of the other users did not express any preference (A.3, A.9)

Other feedback came from speaking individually with each user. All of them agreed that at the first attempt the system seemed really difficult to control, even more with EJ tools; nevertheless, during the trial they got more confident and managed to find a way to master it. Since the order of the task is randomized, there is not a proper learning curve, but every user felt an improvement and asserted that the performance could be improved considerably with some more training. The training is needed in almost all the cases. Suggestions to improve the system included also the implementation of haptic feedback and an adaptable sensitivity of tools motion.

### 4.1.2 Performance

For each task, the time needed to complete it and the number of collisions between the tools and the obstacles were measured. The results are summarized in Figure 4.1. The Figure shows the distribution of time (left) and collision (right) performances, grouped for each of the 4 tasks.

#### Time Performance

It can be seen in the boxplots that there is not a combination of shaft and grasper that prevails among the others. The average time measured for each task (considering a trimmed mean at 20%, not to include the outliers) is of 141.5 sec for the tool with EJ and 3F, 156.2 sec for the EJ with DV, 124.9 sec for WJ with 3F and 166.2 sec for WJ with DV. If we look at the performance of tools with the same grasper but compare different number of joints (for example E\_3F and W\_3F), the results are comparable.

If we compare different grasper on the same tools, the average time seems to be lower using three-fingered tools. A statistical test has been performed to assess statistical difference between groups; the Friedmann test has been chosen. It is

the non-parametric alternative to the one-way ANOVA, used to assess whether there is significant difference between 3 or more groups. As expected, the test gave a negative result, with a high pvalue of 0.5164, meaning that there is no difference related to the use of different tools.

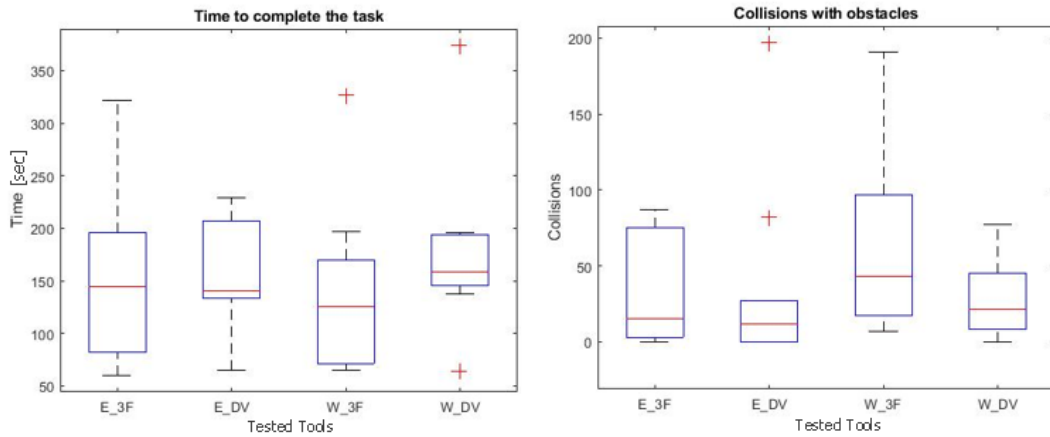


Figure 4.1: On the left the time [sec] recorded for each task among all the participant. On the right the number of collisions recorded between the tools and the obstacles.

### Collision Performance

From the boxplot it can be seen that high and low numbers of collisions have been achieved in every task. As before, the average for each group, which is 29 for E\_3F, 19.25 for E\_DV, 52.75 for W\_3F and 25.125 for the W\_DV, seems only to suggest that EJ tools has lower values of collisions, if we consider the same grasper. The DaVinci grasper has lower values, if we compare the same shaft. Again, the Friedmann test is performed and this time a lower p-value of 0.0792 is obtained. The value is low, but not enough to assess statistical difference; a further post hoc test, in this case a Dunn test, to assess statistical difference between paired groups, has confirmed the same result, being unable to reject the null hypothesis of no statistical difference.

In both graphs it is evident that the dispersion of data is high, in fact the standard deviations of each group range from 22.9 to 80 for the Time boxplots and from 10.24 to 60.16 for the Collisions boxplot. Such a wide distribution of value tells us that the mean cannot be considered a reliable value to represent the data. Further analysis is needed to understand and compare better the data.

### Single Performance Analysis

Looking at the single trial of each user and comparing the performances between the tasks, the results plotted in Appendix B were obtained. Each plot shows the time and collisions for each task for one single user. Looking at the plots, it can be counted that the lowest time for one user trial has been achieved 3 times with the E\_3F, 3 times with the W\_3F, 2 times with E\_DV and 2 times with the W\_DV. The best performance in terms of collision for one user trial has been achieved 5 times with the E\_3F, 5 times with E\_DV, 3 times with W\_DV and 0 times with W\_3F (considering that some users made their lowest score more than one time with different tools). The same logic is applied to the worst performance: for time it is achieved 5 times with the W\_DV, 2 with W\_3F, 1 with E\_DV and 2 with E\_3F. For collisions, 1 with W\_DV, 2 with E\_DV, 5 with W\_3F and 2 with E\_3F. Results are summarized in Figure 4.2 and 4.3.

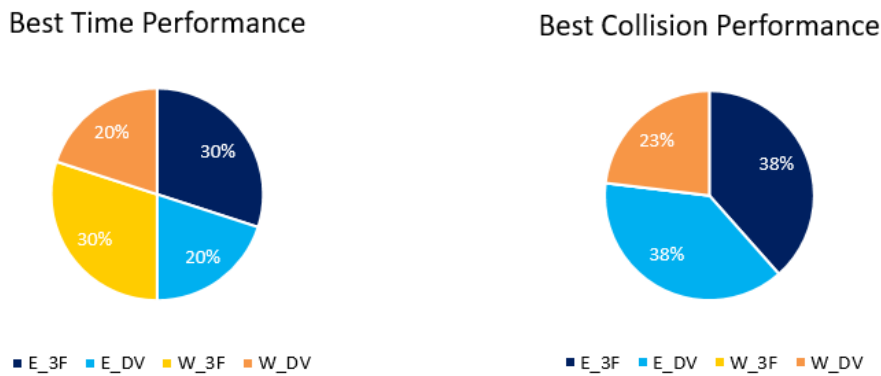


Figure 4.2: The plot shows for each tool, how many users achieved their best performance.

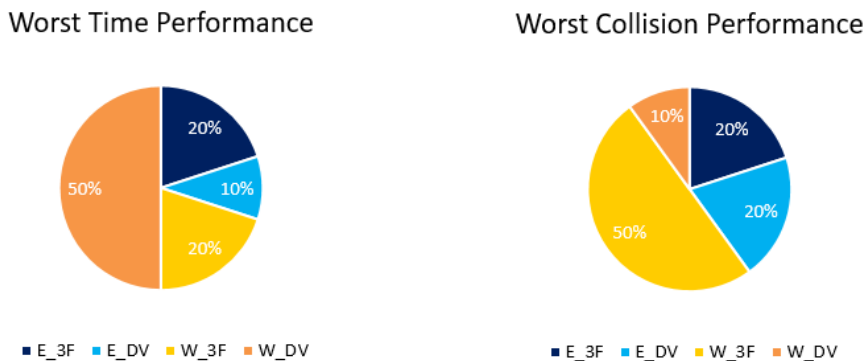


Figure 4.3: The plot shows for each tool, how many users achieved their worst performance.



From this analysis, it appears that the worst performance both in terms of time and the number of collisions was achieved with the use of a WJ tool. The best performance in terms of time, seems not to be related to the change in tools, but to other factors, like adaptation to one tool or errors during the task performance. Nevertheless, looking at the number of collisions, it is clear that in the majority of cases, using an EJ tool leads to a better performance. Even if more difficult to coordinate, a higher number of joints seems to help in avoiding better the obstacles. A difference in performance can be seen also between the two graspers. It seems that while using DaVinci graspers the users hit less obstacles than while using a three fingered tool, but it took more time to perform with a DaVinci than with the 3F.

Another interesting result is obtained by looking at the order of the tasks performed by each user. As previously stated, the order is randomized and different for each user; by ordering the results of each user by the order they performed the tasks, the results still seems to be random, meaning there is not a proper learning curve, with very few exceptions. However, it is interesting to see the difference in performance between the first time and second time the user control one kind of shaft (WJ or EJ). While the average improvement from the first and second usage of a WJ tool is around 0, both for time and collisions, an important improvement is perceived between the first and second usage of an EJ tool. The 80% of users lowered the time needed to complete the task with an EJ, with an average of 55.59 seconds less. The 90% percent scored the same or lower number of collisions, with an average of 77.5 less collisions.

More generally, it is true that the best performance of the user, whether with WJ or EJ tools, is achieved on the second time he uses that kind of articulated shaft, 8/10 times for time and 9/10 for collisions.

### 4.1.3 Questionnaires

#### SUS

The results from the Standard Usability Scale are reported in Appendix C. As reported, there are 2 low scores under 40, 3 high scores above 80 and the rest ranges from 50 to 65. The average score is 61 on a maximum of 100. The result underlines that the system is in average usable even by lay users, but it requires improvements to enhance intuitiveness, as it is quite hard to master at first use and users need to be trained. The score cannot be said to be better or worse than others, since there are no scores for similar systems to compare.

The score relative to each question of the questionnaire is also reported and the mean scores can be computed as reported in the following table [4.1]. The score ranges from 1 (totally disagree), to 5 (“totally agree”).

Questions Q4 and Q10 are referred to the what is needed to use the system and they show that some training and assistance might be needed before performance.

Question	score
Q1: "I think I would like to use this system frequently"	3.4
Q2: "I found this system unnecessary complex"	2.5
Q3: "I thought this system was easy to use"	3.3
Q4: "I think that I would need assistance to be able to use this system"	2.4
Q5: "I found the various functions of this system were well integrated"	3.6
Q6: "I thought there was too much inconsistency in this system"	2.5
Q7: "I would imagine that most people would learn to use this system very quickly"	3.8
Q8: "I found this system very cumbersome or awkward to use"	2.6
Q9: "I felt very confident using this system"	3.2
Q10: "I needed to learn a lot of things before I could get going with this system"	2.9

Table 4.1: SUS single question average scores for the first group

Question Q8 underline once again that users felt like they were adapting quickly to the system. Q3, Q5, Q6 shows that the system seemed quite well implemented, even if some adjustments are needed. Q3 and Q9, instead, tell us that users did not feel completely confident using the system and found it not so easy to use. Finally, question Q8 shows that even wearing a quite high number of sensors and the VR headset, it was not felt too much by the users.

## NASA TLX

The results plotted in figure 4.4 shows once again, the distribution of the score is quite wide, with average values of 51.03, 63.03, 55.77 and 57.53 respectively and standard deviations that range from 10.88 to 22.16. No statistical difference can be found between groups, since the Friedmann test gives a p-value of 0.2518. For this reason, similarly to the performance analysis, the scores of each user have been analyzed; the plots can be found in Appendix C. From the single user analysis, it emerges that the lowest score was registered with a W\_3F, W\_DV, and E\_3F 3 times each, 2 times with the E\_DV. The highest workloads were perceived with an E\_DV for 5 users, W\_3F for 3 users and for 1 W\_DV, as shown in figure . The highest workloads were perceived equally with EJ or WJ tools and this reflects exactly what emerged from the User Questionnaire: for those who found the EJ tools more natural to use the workload was accordingly lower; for those who

found the EJ tools too complex the perceived workload with those tools was much greater. The lowest workload scored for each user match the expressed preference in 90% of cases. It appears also that in average a higher workload is associated to a tool provided with a DaVinci grasper rather than a three-fingered tool. As in previous section, the first and second performance for each kind of shaft (WJ and EJ) were compared. It is true that the second performance has a lower score only in the 60% of cases, meaning that the workload is not only related to the adaption to the motion, but also to the change in grasper and possible other factors.

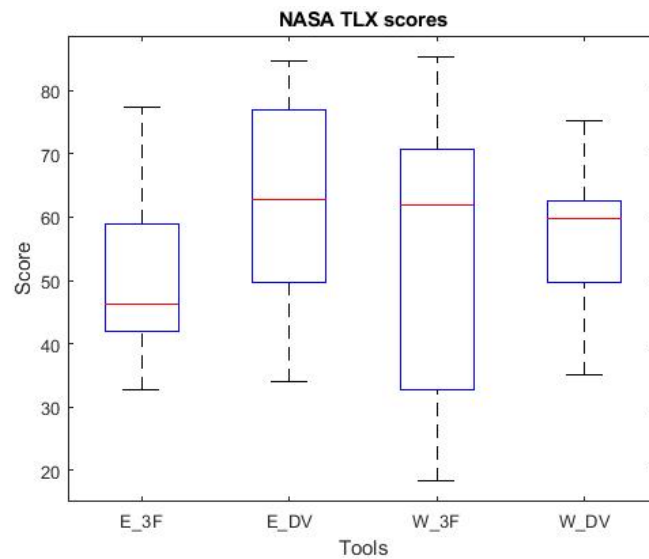


Figure 4.4: Average NASA TLX score for each task

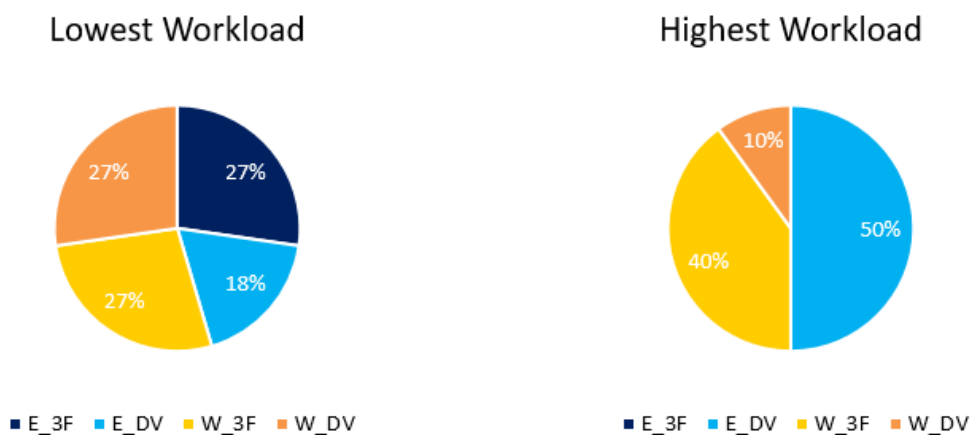


Figure 4.5: Number of users that perceived the lowest and highest workload for each task.

#### 4.1.4 Kinematic Data

Kinematic data were retrieved from Xsens IMUs sensors through MVN Analyze. For each user all the 4 tasks were recorded and the data analyzed include linear and angular velocity and acceleration. The results are plotted in Appendix D. As expected, it can be easily seen from the plots that the average values of velocities and accelerations are slightly higher for the shoulder and upper arm of instruments with an elbow joint, because of the system design.

It is also true that these values differ only by few units ( $cm/s$  for velocity,  $cm/s^2$  for acceleration,  $rad/s$  for angular velocity or  $rad/s^2$  for angular acceleration) between tools with the same shaft but different grasper. In fact, it was expected that the motion of the arm is not influenced by a different tool tip.

Dissimilarities are more noticeable between different levels of tools complexity and differences are more evident on left arms than on right arms. While for the right arm the values of velocities and accelerations seem comparable, a slightly wider gap can be seen on left arms where the tools with an elbow joint find higher values for every segment on all parameters compared with the others. It has to be considered, then, that 9 out of 10 participants were right-handed. This explains the difference in speeds and lower accelerations, since users might feel less confident using the left arm. However, the same differentiation is absent using a tool equipped with an elbow joint, where the values are comparable or even greater than the correspondent on the right arm. These differences, though, are quite small. To see if it is statistically significant, the Friedman test has been executed for each articulation and for each measure among the different tools. The p-values, showed a statistical difference ( $< 0.05$  or values close to 0.05) more often on comparison between tools on the left arms, highlighting what can be seen from the plots: using a tool with an elbow joint brings to higher velocity and acceleration values on the left arm for right handed users, compared to a simpler WJ.

#### 4.1.5 EMG Data

The muscular activity of the dominant forearm was measured with the Myo armband. The RMS, Median Frequency and Mean Frequency mean values for each electrode of the Myo and for each task have been reported in the following tables.[4.2][4.3][4.4] The main difference stands out looking at the first column of the RMS values, which correspond to the task completed with a tool equipped of elbow joint and three-fingered grasper. To further investigate if the difference is consistent, firstly, the Friedman test was executed. The statistical test showed a p value of 0.000961 for the RMS, meaning there is a difference between the tasks with 95% of confidence interval. Multiple Wilcoxon pairwise tests were performed to compare each column and, as expected, the obtained p-values were 0.0207, 0.0148 and 0.0379 respectively for comparison between the first and the other

three columns. Since all the values are  $< 0.05$  the difference is statistically consistent. This result was expected, since the E\_3F tool is the one with the greatest level of complexity, featuring both an highly articulated shaft and fingers and this is reflected by an higher muscular effort to control the behavior of the instrument. However, it will be incorrect to consider this result meaningful, because of the high standard deviation values of the RMS measurements, that make the mean less meaningful. To confirm the outcome, a greater number of participants is required. The same statistical tests were performed on Mean and Median frequency, too. No substantial difference was found for these parameters.

Electrode	E_3F	E_DV	W_3F	W_DV
1	22.10	10.27	9.340	9.54
2	15.47	6.61	5.63	11.10
3	48.41	26.83	33.17	37.55
4	48.58	29.80	35.58	33.26
5	124.49	18.64	12.92	23.15
6	38.26	13.76	13.05	12.80
7	53.37	30.29	27.13	34.44
8	18.82	13.37	6.79	13.22

Table 4.2: RMS mean values [mV] for each one of the 8 electrodes of Myo

Electrode	E_3F	E_DV	W_3F	W_DV
1	60.26	59.37	60.78	60.64
2	61.64	60.72	61.11	60.33
3	61.96	62.01	62.42	62.41
4	62.47	61.35	62.83	62.02
5	62.70	61.26	63.09	63.49
6	62.48	61.54	61.61	62.81
7	60.83	60.24	60.19	60.08
8	59.77	58.69	60.88	60.66

Table 4.3: MNF mean values [Hz] for each one of the 8 electrodes of Myo

Electrode	E_3F	E_DV	W_3F	W_DV
1	53.66	52.84	55.15	54.95
2	55.94	55.00	55.75	54.34
3	56.18	57.00	58.24	57.46
4	57.45	56.34	58.85	57.73
5	57.55	56.16	59.25	59.27
6	56.88	56.37	56.52	58.11
7	54.21	54.03	54.22	53.81
8	52.92	52.32	55.53	55.24

Table 4.4: MDF mean values [Hz] for each one of the 8 electrodes of Myo

## 4.2 Second User Group

These results include the tests with 3 clinicians: 1 male surgeon and 2 female surgeons assistants, all of them trained in the use of the DaVinci surgical system. The tests featured only 2 tasks out of 4, chosen to have every clinician to try different articulations and graspers and in different order.

### 4.2.1 User Form

From the user form results, which can be seen in Appendix A, the system resulted highly immersive, but with a lower level of control, compared to the feedback from the other group (figures: A.10, A.11 ) All the users agreed on the three-fingered tool as the best grasper between the two possibilities, because they felt it was easier to use to pick up the objects even though they asserted is a tool that might have few applications in a real surgery (A.12). Regarding the difficulty, 2 users found the wristed shaft to be simpler to use, also because more similar to the ones they are used to (A.13).

No particular physical or mental fatigue was perceived during the tests (A.14, A.15), but 2 of them agreed on the need of more training before using the system, to perform better (A.16).

Most of all it was interesting to get a feedback and a comparison from professionals, accustomed to maneuver robotic systems in real surgeries. The idea of a more natural control was well received, and they confirmed the need of less training time on this kind of master. However, huge differences were found on the clutching system. On the DaVinci Surgical System, many clutches allow the surgeons to move differently tools, shafts and cameras. Differently, on this system there is

only one clutch that lock both position and orientation of every part of the tools. Furthermore, the camera is just controlled by the head motion in the 3D space and it is not possible to clutch its position and move it manually. Since they are trained on a different master, it took some time to understand the new control system, resulting in a lower perceived intuitiveness compared to the other group of lay users. The impossibility to clutch the camera and motion differences were at first an obstacle to the attainment of the desired motion. Nevertheless, they all managed to adapt to the new system and complete the tasks.

### 4.2.2 Performance

User performance are resumed in Figure 4.6 and 4.7. Users 1 and 3 used the same tools, but in different orders; user 2 completed the tasks with the other 2 tools. The registered values are in the same range of the ones obtained with the other group, except for one outlier (a high number of collisions for the first user, with W\_DV). For users 2 and 3 the performances were not too dissimilar passing from one tool to another, with range of values close to each other, both for time and collisions. For the first user, the high time and collisions number registered with the W\_DV is related to his first performance, showing an initial struggle to adapt to the new system, which was greatly overcome on the second task with E\_3F. For this group of user, the number of trials is fair small to identify strong differences between tools and the similarities between performances on a same user suggest that the outcome is more related to the individual adaptivity to the master manipulator than to difference in tools.

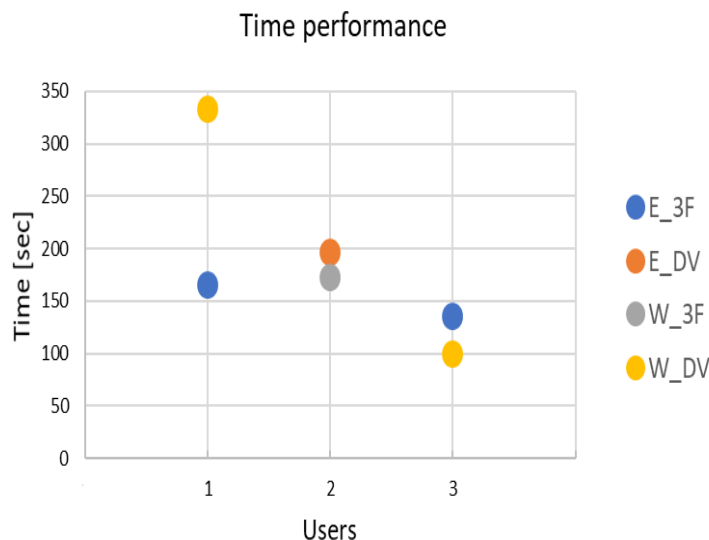


Figure 4.6: Surgeons Time Performance. Each point represents one single task.

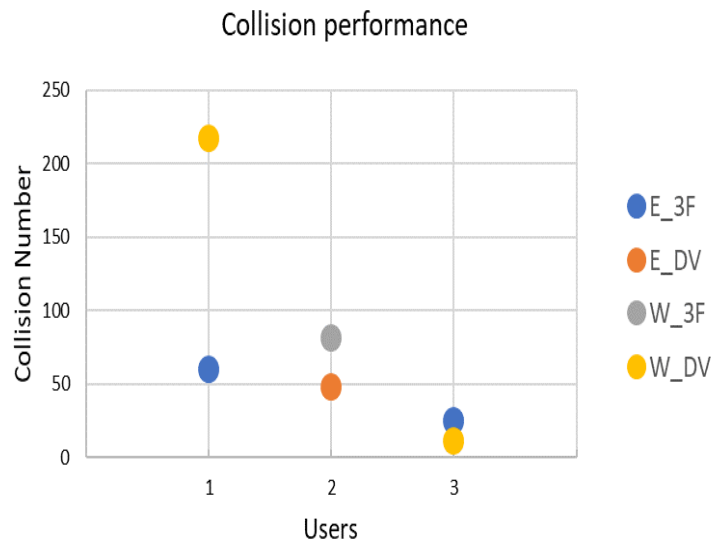


Figure 4.7: Surgeons Collision Performance. Each point represents one single task.

### 4.2.3 Questionnaires

The 3 users scored respectively 50, 57.5 and 62.5 on the SUS usability questionnaire with a mean value of 56.67. The scores are in range with the other users' group, with a slightly lower mean value. The individual answers' mean values are reported below [4.5].

From the analysis of the answers it appears that differently from the other group, they found the system to be a little more complex (Q2 and Q4), but the first question (Q1) scored a higher value, showing appreciation for the new master concept. The other questions' score is close to the first group, highlighting once again a quick adaptability to the system (Q7 and Q10) and the moderate usability which leaves room for improvements.

As shown in figure, NASA TLX outcome revealed moderately higher score for tools with an elbow joint, pointing out a higher physical and mental effort compared to a less articulated tool. As mentioned in the previous paragraph, the three fingered tool was perceived as easier to use and its score was the lowest among the wristed tools, which were felt as less mental demanding.

### 4.2.4 Kinematic Data

The same procedure of extraction and analysis of velocities and accelerations values of the segments of the upper limbs was followed for the second group and the results are plotted in the Appendix D. The data are more homogeneous compared



to the first group, with only few differences detected between 3F tools and DV tools for angular velocities and accelerations for the right hand.

The main difference was observed between the two user groups: the average values of linear velocity and linear and angular acceleration are greater for the surgeons. The average increment ranges up to  $3.07 \text{ cm/s}$  for velocities,  $48,99 \text{ cm/s}^2$  for accelerations,  $0.1 \text{ rad/s}$  and  $6.79 \text{ rad/s}^2$  for angular velocities and accelerations. While using a system like the DaVinci, the movements are scaled, so that the tool moves slower than the arm and the surgeon needs to extensively use the clutch and make faster and wider movements in order to obtain the desired motion. This is reflected on the higher velocities and accelerations registered with this system.

Question	score
Q1: "I think I would like to use this system frequently"	4
Q2: "I found this system unnecessary complex"	3.67
Q3: "I thought this system was easy to use"	3.3
Q4: "I think that I would need assistance to be able to use this system"	3.67
Q5: "I found the various functions of this system were well integrated"	4.33
Q6: "I thought there was too much inconsistency in this system"	2.66
Q7: "I would imagine that most people would learn to use this system very quickly"	3.67
Q8: "I found this system very cumbersome or awkward to use"	3
Q9: "I felt very confident using this system"	3
Q10: "I needed to learn a lot of things before I could get going with this system"	3

Table 4.5: SUS single question average scores for the second group



# Conclusions

The progress of Robotic Assisted Minimally Invasive Surgery have undeniably led to improved performances for surgeons and significant advantages for patient recovery. Still, the need to overcome the dexterity and maneuverability limitations, drove the research to the development of highly dexterous tools. Nevertheless, the enhanced dexterity implies higher complexity on the master side, diminishing intuitiveness and fluency of control.

The purpose of this work was to assess the feasibility of an intuitive, anthropomorphic, immersive tele-operation concept and investigate the dexterity limits of tools with this kind of master manipulator. A virtual reality task, inspired by standard virtual surgical training, has been designed and developed to compare multiple anthropomorphic, dexterous instruments with different levels of complexity. To control them, a set of sensors are placed on the users' upper body and fingers to track their motion, allowing them to use arms and hands as a controller. The immersivity is furthermore enhanced by the vision through a VR headset. 10 lay users and 3 trained surgeons participated in the study; their performance and response to the system has been measured and analyzed from different points of view.

The results indicate that users adapted to the system differently. The comparison of performances using the proposed articulated tools showed that a more dexterous one, with an added elbow joint, could help to achieve a better performance. On the other hand, the increased complexity was often an obstacle to an intuitive control, leading to higher efforts in motion for half of the user group and to preference of the simpler tool for 6 out 10 users. Nevertheless, for the others the EJ felt more natural and consequently more intuitive. It can be said, then, that the preference of the tool depends on the approach of the single user, but while all of them could use the WJ tools, only a few could use the EJ better. Differently, for clinicians, the performance was strongly influenced by the habit on a different robotic system, mostly by a diversity of the clutch, but the intuitivity of the movements was perceived likewise.

The kinematic control of the two graspers was compared, too. The difference is not greatly perceived among the users, but the 3-fingered tool seemed to have a better feeling of stability for clinicians, for this particular task, while the DaVinci grasper is related to higher effort in picking up the objects and also the need of a

higher amount of time to complete the transfers, even though this might lead to more accurate movements.

Further analysis of kinematic quantities highlighted the higher velocity and acceleration of the shoulders and upper arm using an instrument with an elbow joint, since the upper part of the arms is more involved in the control of the tools' pose. Moreover, the muscular activity registered on the forerarm increased accordingly to the complexity of the tool.

The whole system shows a good level of transparency, but less intuitiveness due to some limiting elements related to surgery, such as the constrained motion of tools and the use of clutch. However, the lack of intuitiveness could be quickly overcome as all users reported increased confidence in using the system after the completion of the first task. In fact, after an initial struggle, the performances resulted to be improved subsequently few tasks, even if their order was randomized. The difficulties related to its structure might be overcome by training; this result indicates that an application of this concept to real surgical systems could significantly diminish training times for surgeons.

This preliminary study highlighted the advantages and limitations of using anthropomorphic control to manipulate dexterous tools. Different improvements can be applied to the system, to obtain a better kinematic and tele-operation control. Realistic forces and haptic feedbacks can be added and improve immersivity and performance. A larger number of participants, primarily surgeons, is needed to get more statistically consistent results. As a future prospect, the development of the concept, accordingly to the demands of clinicians, could be useful to test it on more realistic simulations as well as on actual robotic systems and provide more insight into the usability and learning curve on surgical scenarios.

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# Appendix A

## User Forms

### A.1 Group 1

How immersive was your experience? (Considering awareness of surroundings, motion control, vision, etc.)

10 responses

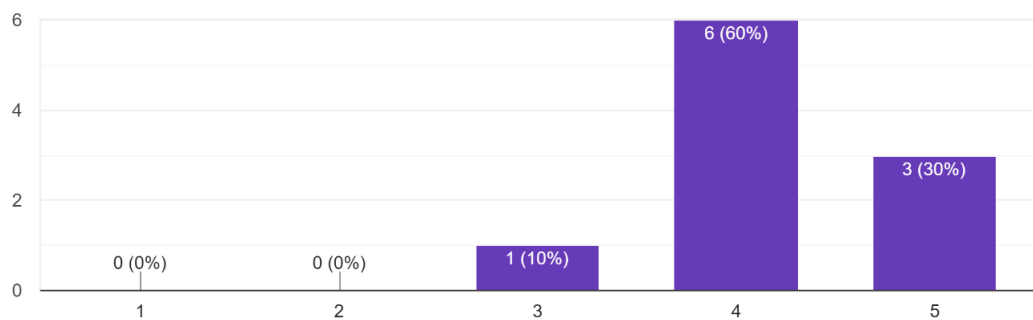


Figure A.1: Question 1

How much did you feel in control of the tools?  
10 responses

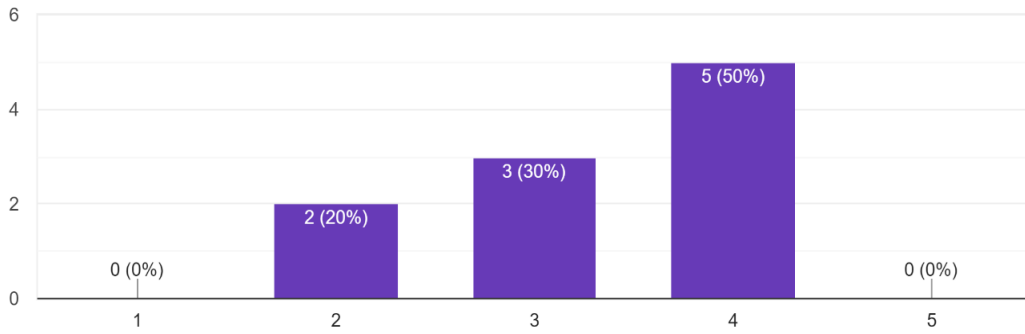


Figure A.2: Question 2

To pick up the objects, did you find more difficult to use the pinch or the three fingered tool?  
10 responses

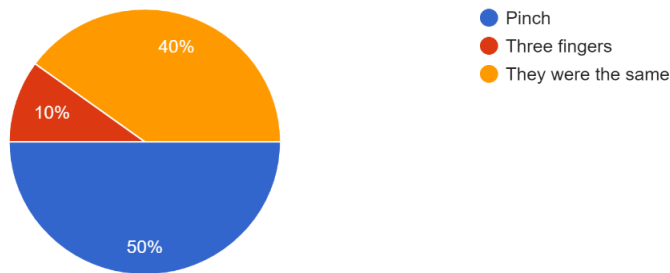


Figure A.3: Question 3

Which tools did you find more difficult to move?  
10 responses

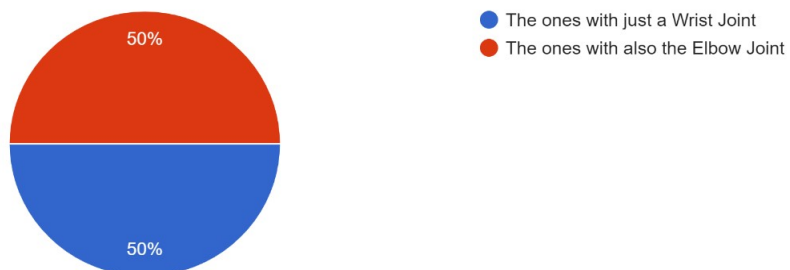


Figure A.4: Question 4

Did you feel mentally tired after the trial?  
10 responses

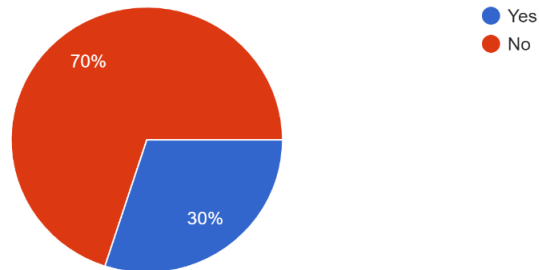


Figure A.5: Question 5

Did you feel physically tired after the trial?  
10 responses

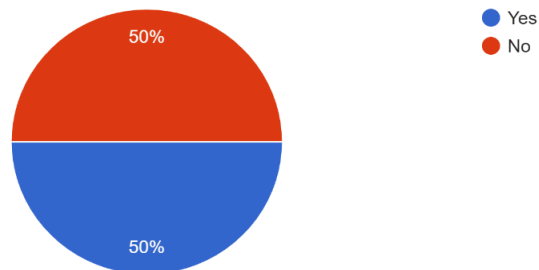


Figure A.6: Question 6

Do you think this system requires training before being used?  
10 responses

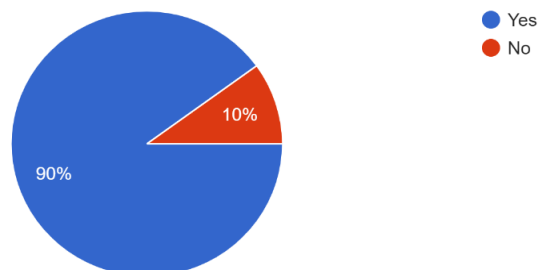


Figure A.7: Question 7

Would you perform a surgery using this system?  
10 responses

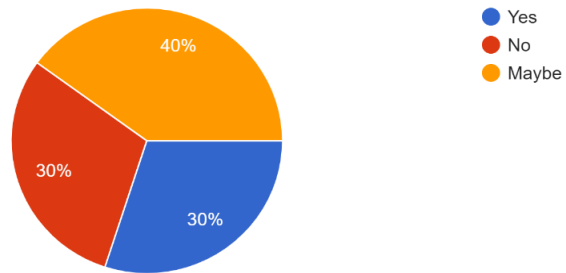


Figure A.8: Question 8

Which one, among all the tools, did you prefer and why?

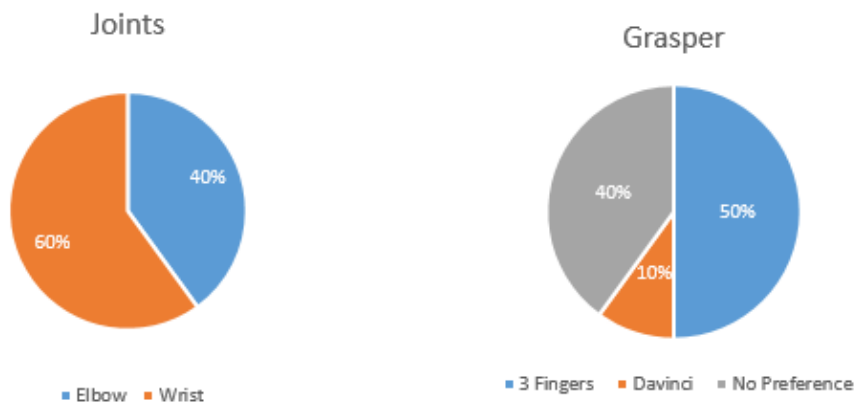


Figure A.9: Question 9

## A.2 Group 2

How immersive was your experience? (Considering awareness of surroundings, motion control, vision, etc.)

3 responses

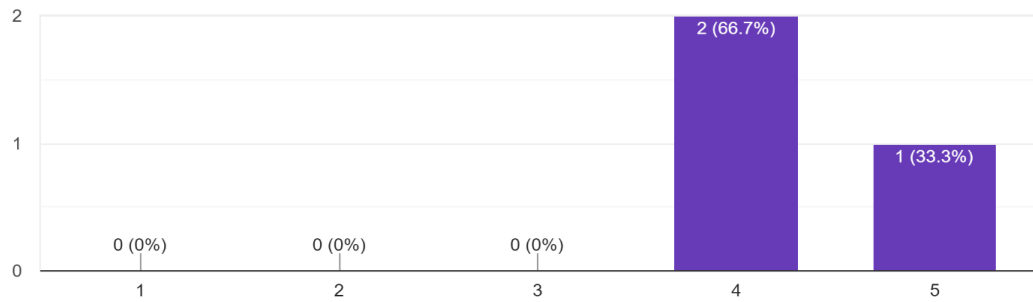


Figure A.10: Question 1

How much did you feel in control of the tools?

3 responses

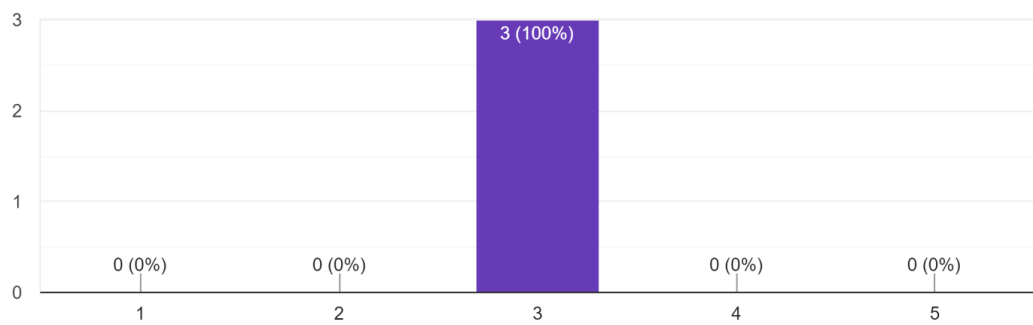


Figure A.11: Question 2

To pick up the objects, did you find more difficult to use the pinch or the three fingered tool?  
3 responses



Figure A.12: Question 3

Which tools did you find more difficult to move?  
3 responses

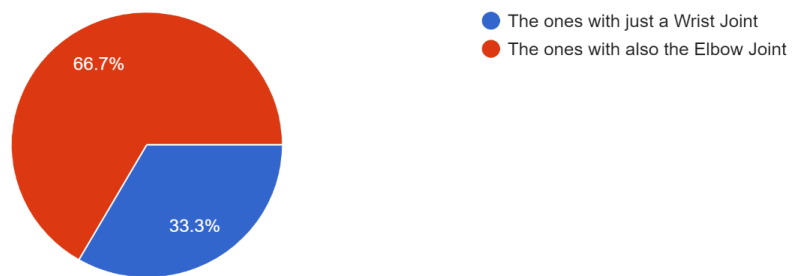


Figure A.13: Question 4

Did you feel physically tired after the trial?  
3 responses

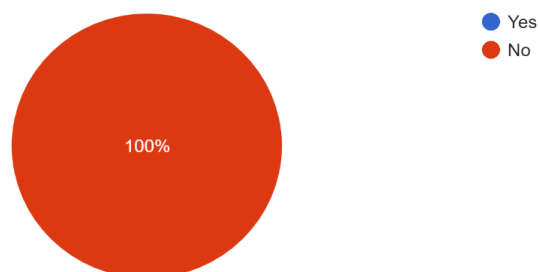


Figure A.14: Question 5



Did you feel mentally tired after the trial?  
3 responses

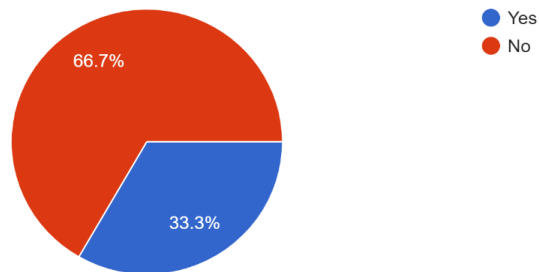


Figure A.15: Question 6

Do you think this system requires training before being used?  
3 responses

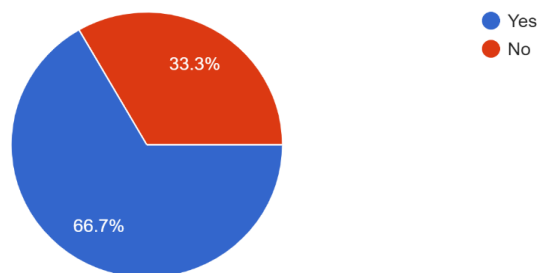


Figure A.16: Question 7

Would you perform a surgery using this system?  
3 responses

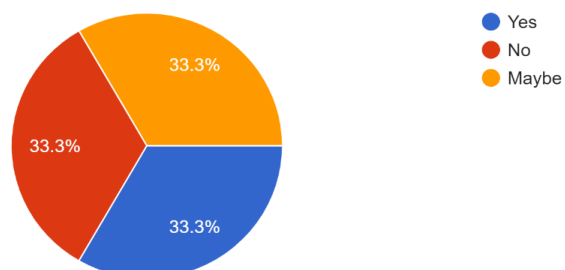


Figure A.17: Question 8



# Appendix B

## First Group Performance

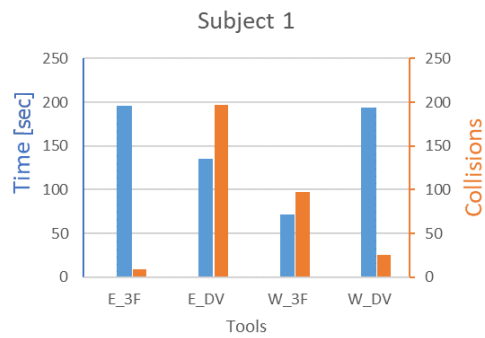


Figure B.1: User 1 Performance

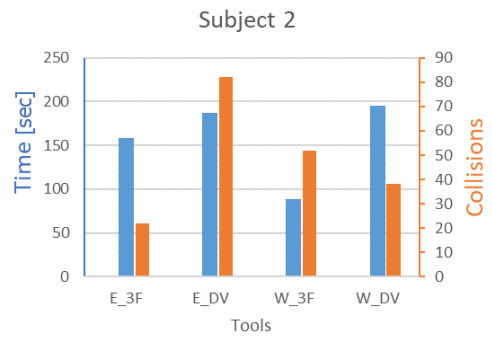


Figure B.2: User 2 Performance

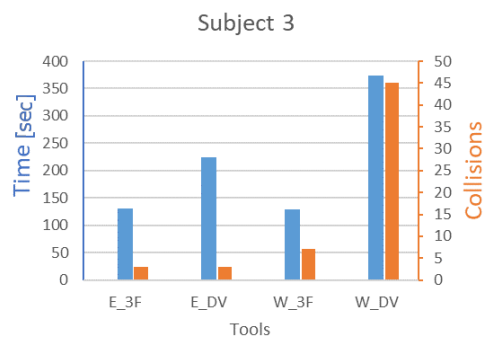


Figure B.3: User 3 Performance

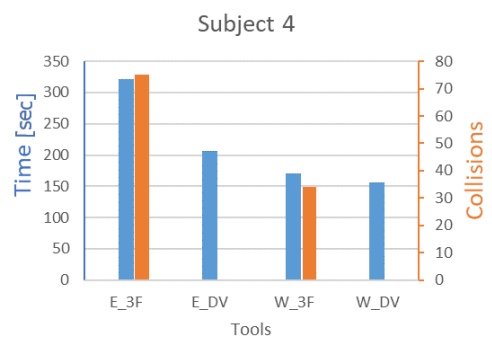


Figure B.4: User 4 Performance

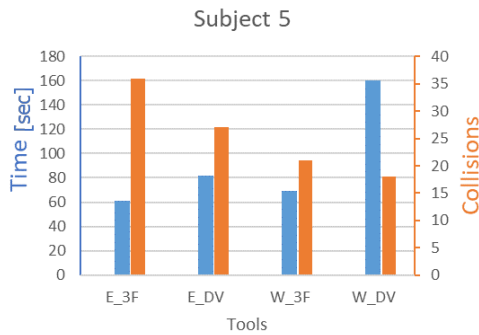


Figure B.5: User 5 Performance

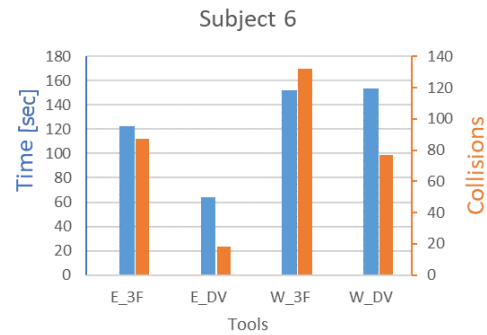


Figure B.6: User 6 Performance

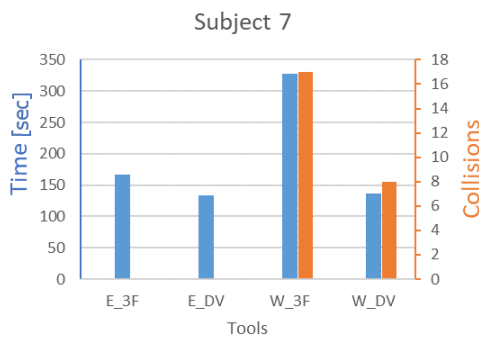


Figure B.7: User 7 Performance

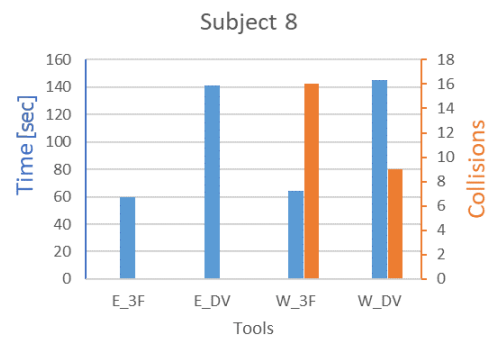


Figure B.8: User 8 Performance

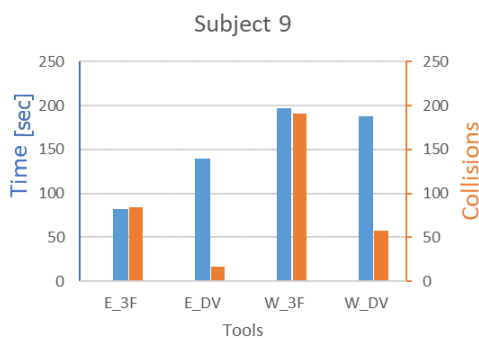


Figure B.9: User 9 Performance

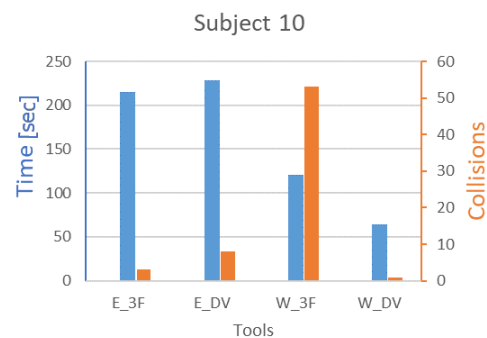


Figure B.10: User 10 Performance

# Appendix C

## Questionnaires

### C.1 SUS

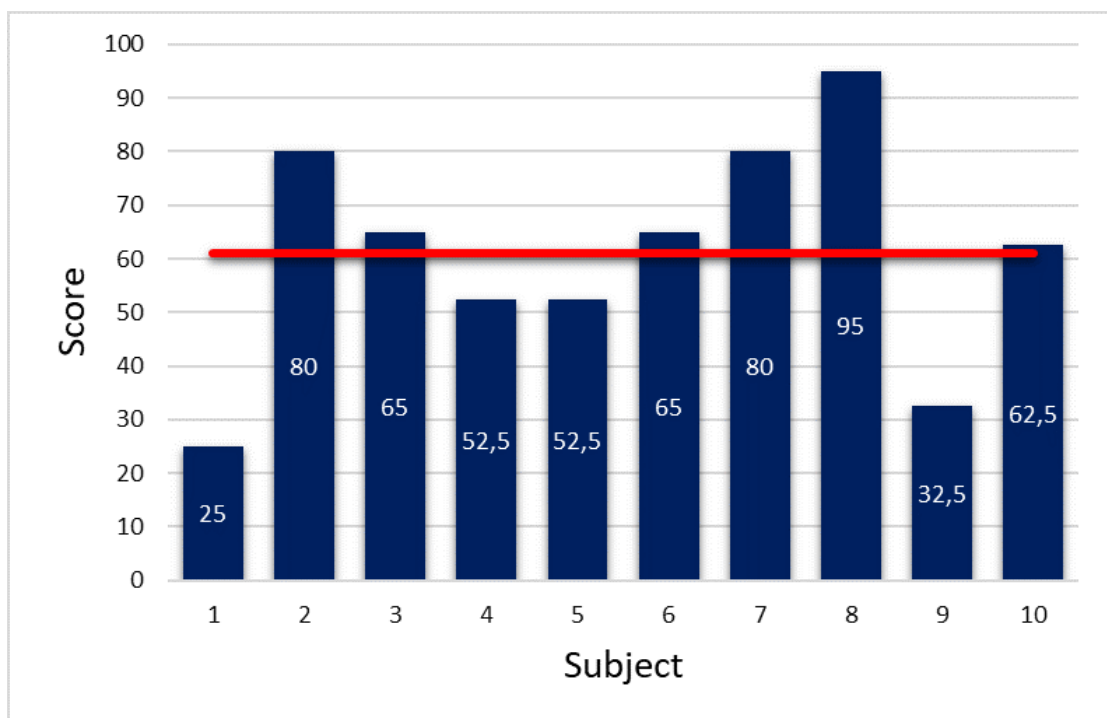


Figure C.1: Average SUS scores

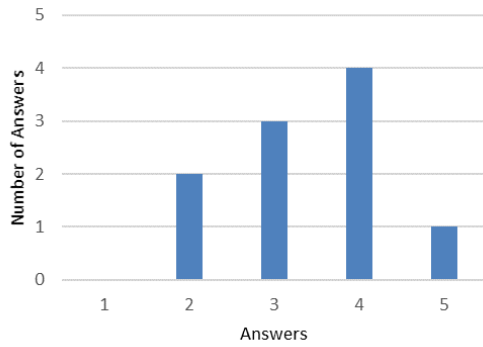


Figure C.2: Q1: "I think I would like to use this system frequently"

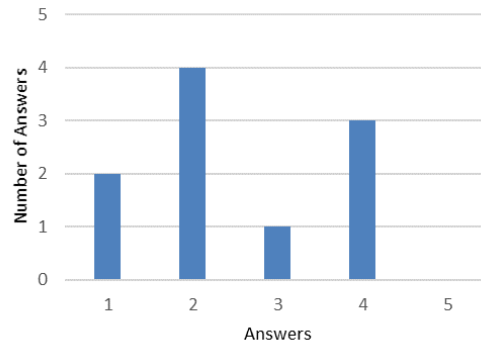


Figure C.3: Q2: "I found this system unnecessarily complex"

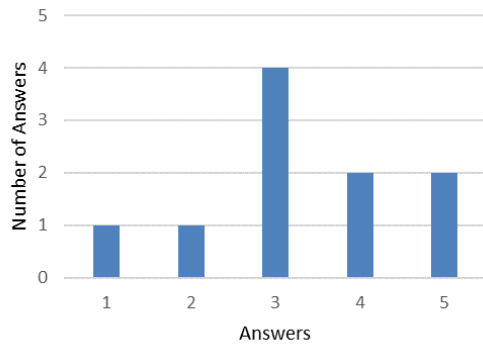


Figure C.4: Q3: "I thought this system was easy to use"

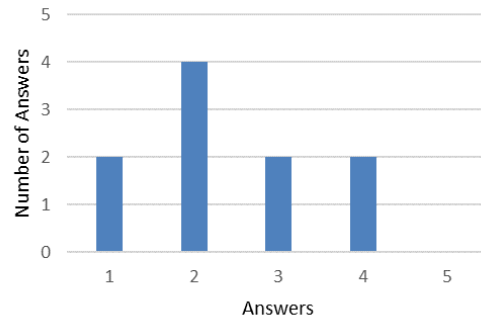


Figure C.5: Q4: "I think that I would need assistance to be able to use this system"

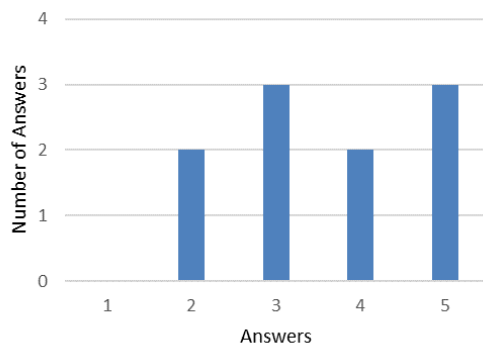


Figure C.6: Q5: "I found the various functions of this system were well integrated"

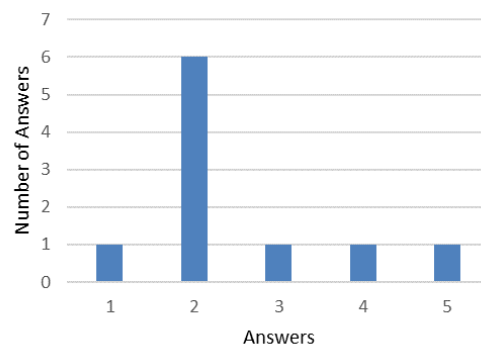


Figure C.7: Q6: "I thought there was too much inconsistency in this system"

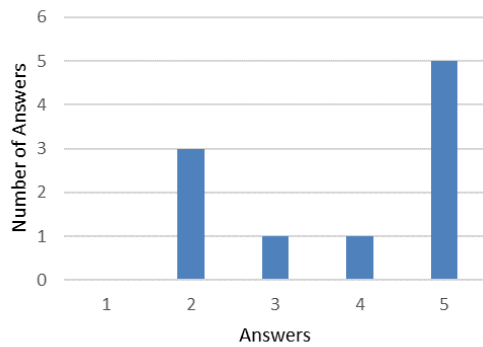


Figure C.8: Q7: "I would imagine that most people would learn to use this system very quickly"

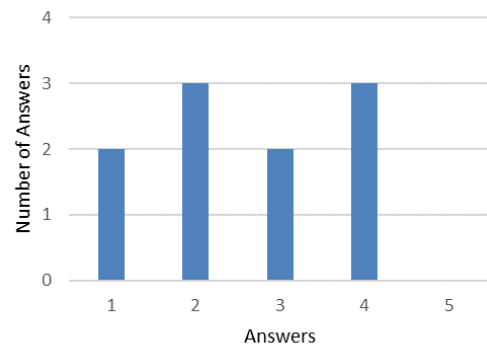


Figure C.9: Q8: "I found this system very cumbersome or awkward to use"

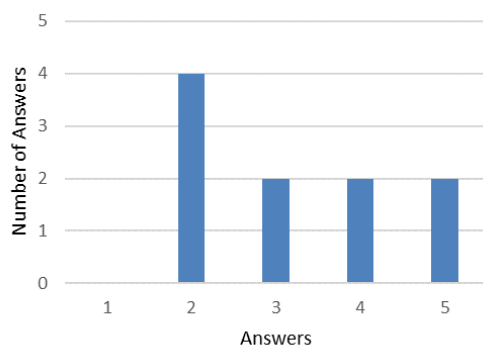


Figure C.10: Q9: "I felt very confident using this system"

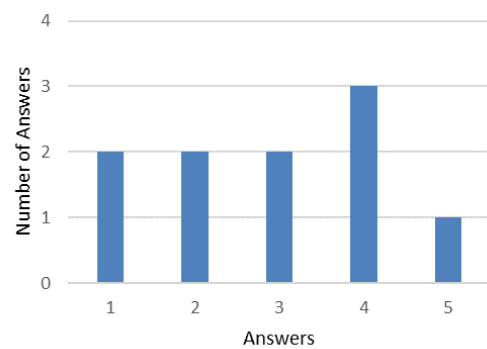


Figure C.11: Q10: "I needed to learn a lot of things before I could get going with this system"

## C.2 NASA TLX

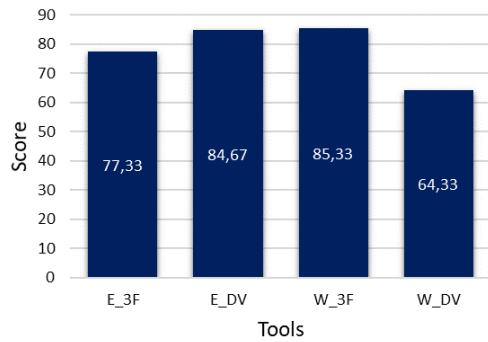


Figure C.12: User 1 NASA TLX score

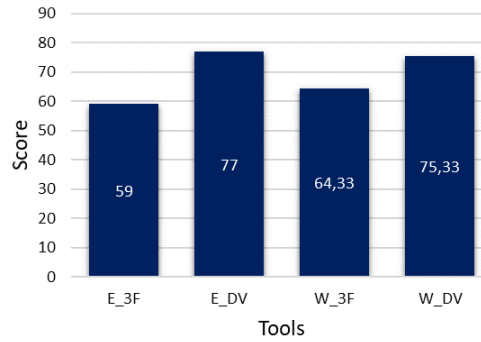


Figure C.13: User 2 NASA TLX score

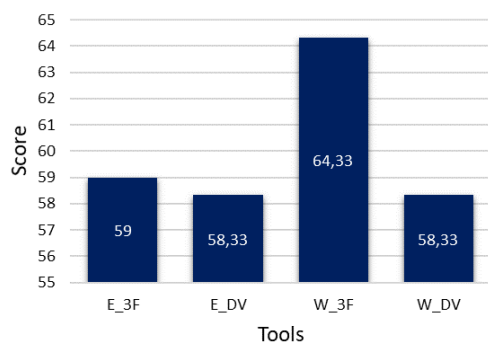


Figure C.14: User 3 NASA TLX score

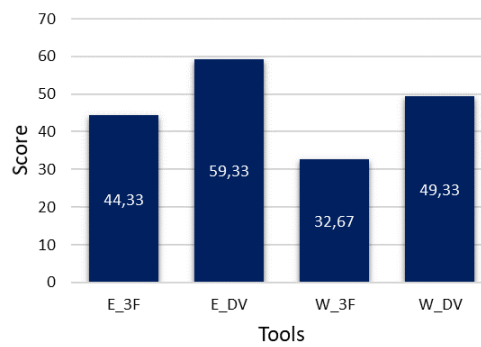


Figure C.15: User 4 NASA TLX score



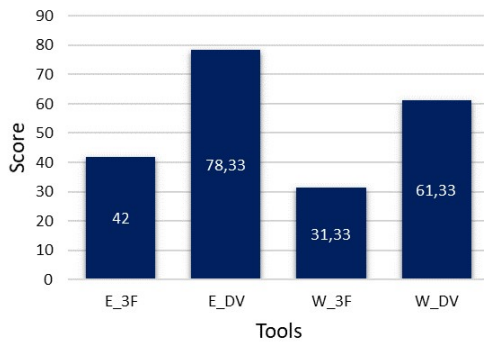


Figure C.16: User 5 NASA TLX score

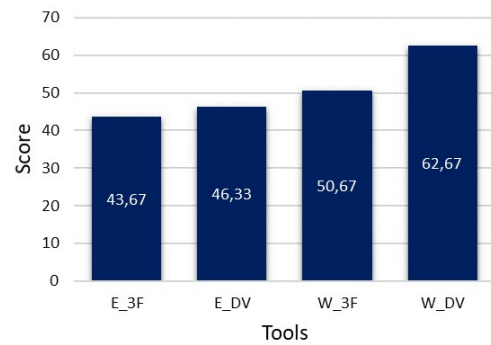


Figure C.17: User 6 NASA TLX score

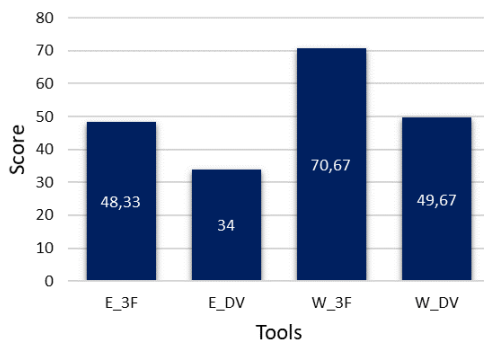


Figure C.18: User 7 NASA TLX score

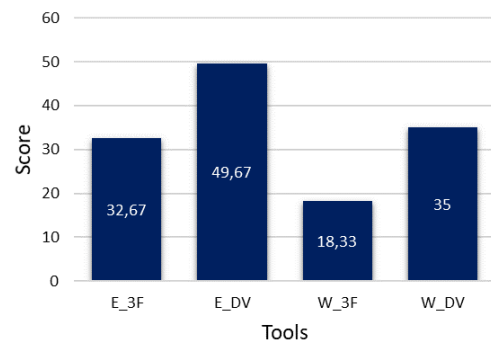


Figure C.19: User 8 NASA TLX score

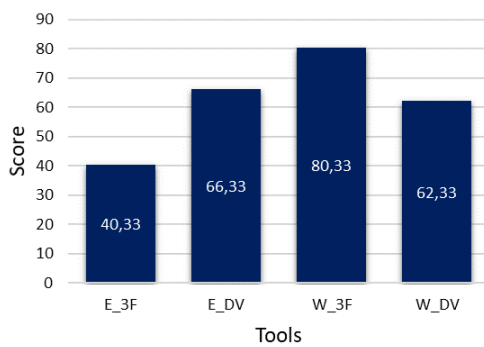


Figure C.20: User 9 NASA TLX score

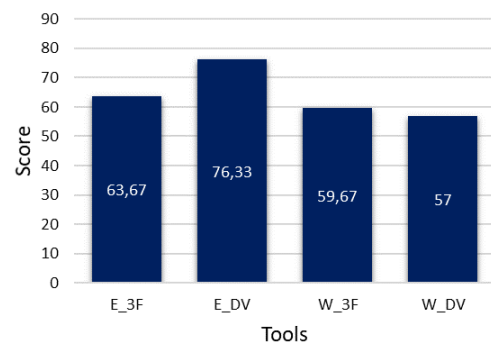


Figure C.21: User 10 NASA TLX score



# Appendix D

## Kinematic

### D.1 Group 1

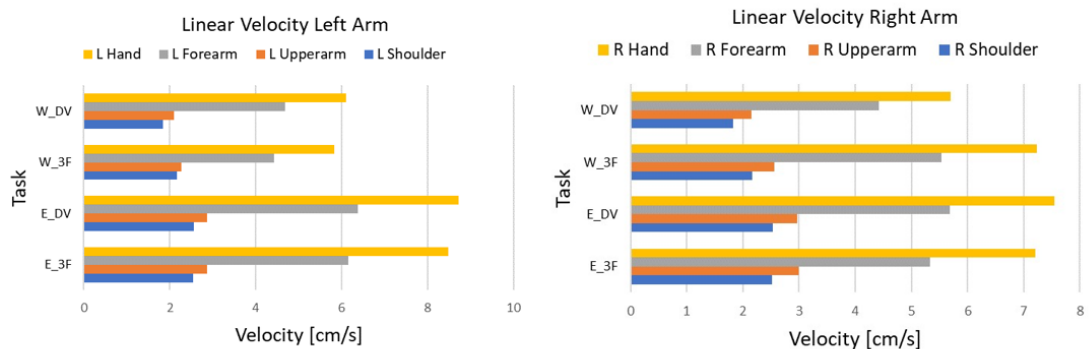


Figure D.1: Average Linear Velocity [cm/s]

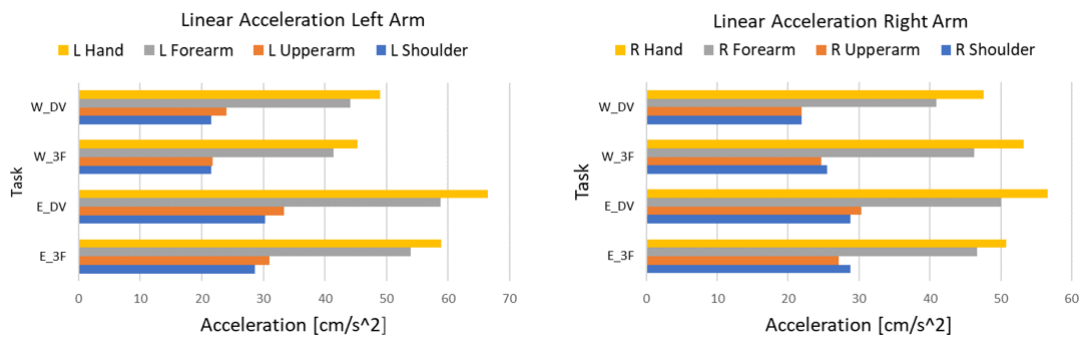
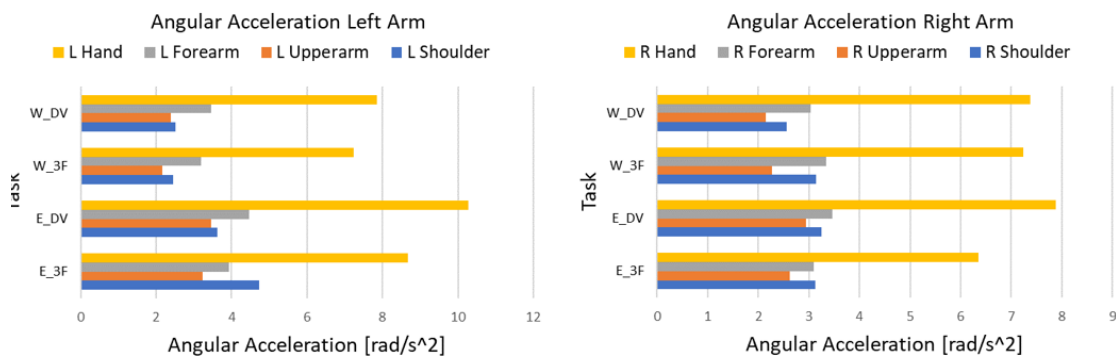


Figure D.2: Average Linear Acceleration [cm/s<sup>2</sup>]



Figure D.3: Average Angular Velocity [rad/s]

Figure D.4: Average Angular Acceleration [rad/s<sup>2</sup>]

## D.2 Group 2



Figure D.5: Average Linear Velocity [cm/s]



Figure D.6: Average Linear Acceleration [cm/s<sup>2</sup>]

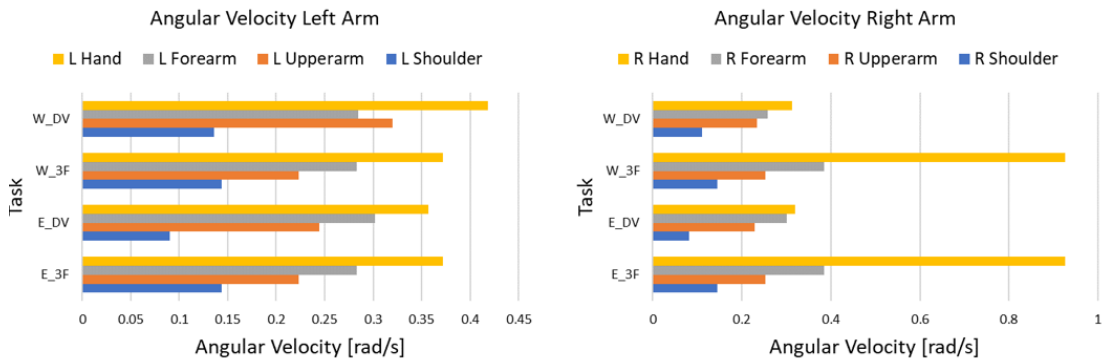
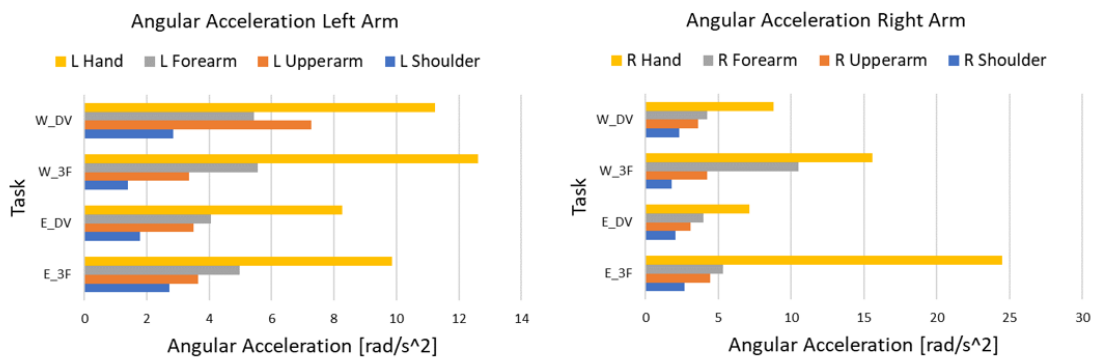


Figure D.7: Average Angular Velocity [rad/s]

Figure D.8: Average Angular Acceleration [rad/s<sup>2</sup>]

# Appendix E

## Other studies

In this appendix is reported a summary (abstract and results) of two internship studies conducted at the Bristol Robotics Laboratory, which are not public documents.

### E.1 Investigation of an Elbow Joint to Existing Surgery Tool

Defne Ege Ozan, 7/09/2018

#### E.1.1 Abstract

In this project, I explore the addition of an elbow joint to the existing surgery tool. I investigate whether this addition will improve the dexterity of the surgery robot and if so, where the joint should be placed so that the dexterity is maximised. The performance of the robot is evaluated on how effectively it operates in the desired workspace, which is the pelvic or abdominal cavity where the surgeries take place. Basically, in my simulations, I test each point in the geometric model that I have created to represent the surgical area, check if that point can be reached by the surgery tool, and determine which version of the tool returns the maximum number of points reached. I started out the project by developing a 4-DOF surgery tool including the elbow joint. Then, I compared the performance of this tool with a 2-DOF surgery tool (a degree of freedom becomes redundant without the presence of an elbow or a gripper at the end), which I modelled as the existing one used in Da Vinci. Also, I used simple workspace models, such as cylindrical, to represent the surgical area. During the progress meeting I held with Prof. Dogramadzi and Dr. Tzemanaki, certain improvements to the work came into discussion. First of all, my surgery tool models at that time missed a degree of freedom that the existing Da Vinci tools have. This degree of freedom turns out, however, to be vital since it provides the tool with a spherical wrist joint

and enables operation in 3D space. So, I did my forward and inverse kinematics computations again according to this new model. Another improvement is related with surgical planning. In surgeries, the tool is not inserted perpendicular or parallel to the abdominopelvic cavity, but rather with an angle so that it can reach more space. Thus, I made the changing of the incision point and angle of the surgery tool possible in the simulations. It has also been suggested that it should be checked whether the surgery tool remains within the boundaries of the abdominopelvic cavity model at all times while reaching a point. I also implemented this suggestion in my simulations.

### E.1.2 Results

In this project, I investigated the advantage of adding an elbow joint, thus adding one more degree of freedom, to the existing surgery tools. I derived the kinematics of the existing and proposed robotic surgery tool and created a simple geometrical model of the abdominopelvic cavity to represent the surgical area. When surgery tools with and without elbow joint are compared, it is shown that more points can be reached with the elbow joint. In addition, there are multiple orientations possible for those points, which increases the dexterity. These orientations can enable the surgeon to perform operations more easily and smoothly without having to put their hands in forced, unnatural positions, while also allowing them to reach behind the organs inside the body. An elbow joint placed 3.75 cm from the tip provides the maximum number of points reached, when the total length of the part of the surgery tool inserted in the abdomen is assumed to be 20 cm. However, it should be noted that the surgery tool without elbow joint can also be sufficient depending on where exactly the prostate is located and how the surgery is conducted, since it is shown that the surgery tool can reach the lower part of the pelvis even without an elbow joint. The performance of the surgery tools are also assessed in the presence of an organ. It is shown that with an elbow joint, the tool can reach beneath the organ. Although, the computation yielded that more points can be reached without the elbow joints, this is an error related with the nature of the code, since the code for the tool with the elbow joint iterates over orientation angles to be fed in the inverse kinematics calculation (5 DOF problem), whereas the code for the tool without the elbow joint does not need orientations (3 DOF problem). It is self-evident that the 5 DOF tool can reach any point the 3 DOF tool can reach. For further research, another organ can be introduced, for example to represent the bladder, the performance of the tool can be tested in this new environment. Also, the pelvis model can be improved for a more accurate and realistic result.



## E.2 Fatigue Evaluation on Surgical Robotic Systems

Nuno Miguel Patrício Mendes

### E.2.1 Abstract

The experimental trials took place at the Southmead Hospital Bristol and at the Bristol Robotics Lab using the da Vinci surgical system and the SMARTSurg system, respectively. Myo (EMG armband) and EMOTAI (EEG headband) were attached to the participants for acquisition of data in real time during their performance for further analysis. This project aims to evaluate and compare mental and muscular effort of surgeons during some surgical training tasks using different surgical robotics systems, in particular, da Vinci surgical system and SMARTSurg system. Five surgeons with different level of experience with da Vinci surgical system were submitted to a simple sequence of surgical tasks. With the recording devices attached, the participants were asked to, using the simulator built in the da Vinci system, perform five different tasks: Sea spikes, ring and rail, pick and place, interrupted suturing and sponge suturing. Some of these tasks were repeated a few times ensuring that by the end of the trial all the participants spent, at least, 20 minutes doing it. In a second group, most of the participants were volunteers that had no background experience with surgical robots besides only one of the participants being a surgeon with experience in this type of systems. Using the simulator created for the SMARTSurg system, the participants were able to do some basic tasks as pick and place and ring and rail. Because of the early stage of the simulator and interferences between the devices used to record biosignals and the devices for the simulator, only one try was performed per each participant

### E.2.2 Results

During the experiments, EMG and EEG were performed to evaluate muscular and mental fatigue. The results for each type of signal are presented and discussed separately in order to determine the presence of fatigue in each area.

Firstly, to verify that both surgical systems were producing fatigue, the first and last minute of acquisition were extracted from the data and compared between each other. This comparison was made using three features: Root Mean Square (RMS), Mean Frequency (MNF) and Median Frequency (MDF). According to surgeons' feedback after completing the trial at the da Vinci system, some of them felt muscular fatigue. When comparing their answers with the results, it is possible to see that only the frequency dependent features are able to follow their feedback. In fact, the only feature capable of identifying values significantly different between the beginning and end of the trial is the Median Frequency (when

using a significance level of 5%). Thus, it would be obvious to use the same feature to compare how much fatigue both systems create on surgeons, considering that both systems create fatigue on them. The problem is that SMARTsurg results do not point out the presence of fatigue in the surgeons, which may lead to the conclusions that this system is better because it does not create fatigue. In fact, that is an incorrect conclusion. The fact that none of the feature have been able to detect fatigue using the SMARTsurg system is because the trial was short on time (around 5 minutes) when comparing with 20 minutes long (at least) trials from da Vinci. When visually comparing how median frequency changes over time in both systems, it is possible to notice that the linear fit have a negative slope across all the electrodes for da Vinci system while for SMARTsurg system the slope is nearly zero or increasing over time. The next step for this analysis should be comparing the slopes from the tendency line for each feature and, with that, determine which system produces more fatigue along the surgeons. However, because the results show that was not possible to measure fatigue in the SMARTsurg system, this analysis does not make sense.

For the analysis of mental fatigue, only the theta power will be considered. The results from the Mann-Whitney test show that neither of the systems produced fatigue on the participants (p-value above the significant level of 5%) and because of that it is not possible to evaluate which system causes more fatigue. Besides that, even if there was any fatigue, the standard deviation for the mean values show that trying to conclude something from these results would be meaningless due the high deviation registered. On other note, there is not a clear pattern, that allow to conclude that theta power increased or decreased across all the subject in both systems. This should be explained because it is hard to ensure the same position for the electrodes across all the participants and make sure that the contact between skin and electrodes is the same for all of them. Finally, the trials for the SMARTsurg system were too short on time to allow to detect any fatigue. Although, and regarding the da Vinci surgical system, when comparing surgeons' feedback with graphical results, there is a pattern that shows off. Surgeons 1, 3 and 4 reported to feel some mental fatigue and observing is noticeable that the theta power increases in that participants.

Although the main objective for this study was not accomplished, there are important conclusions to get from it. First, it was proved that using wearable devices as method to evaluate fatigue is a good solution because provides freedom of movements to surgeons to do surgical tasks. Second, and as suggested by some literature, regarding EMG analysis, the median frequency came up as the best feature in order to evaluate fatigue over time. For EEG analysis, more tests are needed in order to ensure that the increase of theta power really mean an increase of fatigue over time and the results shown in three of the participants were not only coincidence. Regarding the SMARTsurg system, there is a need of improving the simulator developed so the trials could be long enough to detect some fatigue in the participants. Finally, for future work, the same participants should be submitted

to trials in both systems taking approximately the same time in the trials in order to be possible evaluate fatigue across all the participants but also for each one of them individually. In other hand, should be possible to do a calibration to the EMOTAI EEG acquisition system (as occurs with MYO) in order to ensure little deviations and more constant values across all the participants. Thus, this study was important to define some guidelines that could be implemented in future studies of fatigue across surgeons using different robotic surgical systems in order to improve this industry, making it more ergonomic for surgeons.

