Design and evaluation of a passive dynamic arm support for Robotic Assisted Laparoscopic Surgery

Master Thesis

Pim Schrijvershof

To obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on 25-05-2023

Student number:	4582179
Project duration:	Sept 1, 2022 – March 29, 2023
Supervisor:	Dr. Ir. Ing. T. Horeman
Thesis committee:	Dr. Ir. Ing. T. Horeman
	Prof. Dr. J. Dankelman
	Nicola Leone (surgeon)

Mechanical, Maritime and Materials Engineering (3ME)
Department of BioMechanical Design

TU Delft

Preface

This thesis is the result of seven months of work on a project that I enjoyed a lot. It is the final work of my master BioMechanical Design at the TU Delft, where I try to implement most of the learned knowledge throughout my years in college. The project consisted of a wide range of tasks: Doing background research, following the design process, using milling machines to make parts, designing and 3D-printing sensors, setting up an experimental study with participants, and statistically analyzing results.

First and foremost, I want to thank my wife Esmé Schrijverhof, who has been my support throughout the entire project, also working for the two of us so I could finish my study.

During my bachelor's final project on a wheelchair for paraplegia patients and an internship at Skelex exoskeletons, my interest in devices that support the human body grew, which is why I picked this project after the first conversation with my supervisor Tim Horeman. I want to show my gratitude for the enjoyable cooperation we had during this project, with lots of humor, opportunities, and expertise in the medical field, in which I was new. I learned a lot, and want to thank you for your straightforwardness and dedicated involvement in the project, it suited me very well and it let me know every step of the process where I was standing.

I want to thank Yannick Smits as well, as his knowledge of electrical circuits, Arduino and Matlab saved me a lot of time. I also want to thank him, Eva Schlösser, and Anna Graell Collado for being good company at the lab, it made the long hours much more enjoyable.

I want to thank all the participants who gave their time to help me in the experiments.

And last but not least, I want to thank God for the talents, insights and opportunities he gave me to be able to do this.

I am very pleased with how the project turned out and I hope the arm support can serve as the base for product development in arm supports worldwide for surgeons doing robotic laparoscopy, making their experience more comfortable and improving patient outcomes.

Pim Schrijvershof
March 2023

Abstract

***Background*:** Surgeons performing robotic-assisted laparoscopic surgery experience physical stress and overuse of shoulder muscles due to sub-optimal arm support during surgery. Following background literature research on passive dynamic arm supports, this report presents and evaluates a novel design.
***Objective*:** To present a novel design and prototype of a dynamic arm support for robotic laparoscopic surgery and evaluate the arm support for ergonomics and performance on the AdLab-RS simulation training device.
***Method*:** The prototype was designed using the mechanical engineering design process: Technical requirements, concept creation, concept selection, 3D-design in Solidworks, built of the prototype. A crossover study was performed on participants divided into two groups, all performing a marble sorting task on the AdLab-RS. One group first performed four trials without the arm support, followed by four trials with the arm support, and the other group vice versa. The performance parameters were *time to complete (s)*, *path length (mm)*, and the *number of collisions*. Afterward, the participants filled out a questionnaire on the ergonomic experience regarding both situations, including part of the Nasa TLX questionnaire.
***Results*:** A new arm support was developed and a total of 20 students took part in the study on its evaluation, which led to 160 performed trials on the AdLab-RS. Significant decreases in the subjective comfort parameters mental demand, physical demand, effort and frustration were observed as a result of introducing the novel arm support. Significant decreases in the objective performance parameters path length and the number of collisions were also observed during the tests.
***Conclusion*:** The newly developed dynamic arm support was found to improve comfort and enhance performance through increased stability on the robotic surgery skills simulator AdLab-RS. However, the study's limitations, such as the short trial duration and non-surgeon participants, must be acknowledged when interpreting the results.

Contents

1 Introduction

1.1 Background

Developments in robotic-assisted laparoscopic surgery (RALS) have been made as a means to enable more precise surgical movements and gestures while minimizing the invasiveness and recovery time for patients [1]. RALS, in addition to bringing practical surgical benefits, has brought benefits to the comfort of the surgeon by relieving him of some of the physical stress experienced by traditional laparoscopy, resulting in injuries and overuse of the muscles of the neck, shoulders, and lower back [2]. With RALS, it is possible for surgeons to operate on patients through laparoscopy, while their bodies are in a more comfortable position. A robotic slave device is positioned over the patient with up to 4 arms with instruments that are inserted into the patient's body. At a separate system, the master interface, the surgeon is seated, controlling the robot remotely and more ergonomically. An example of a RALS device is shown in Figure 1, which is the full system of the Da Vinci Si, with the surgery robot and the master interface where the surgeon is seated.

Figure 1: Da Vinci Si system, with on the left the surgery robot above a patient and on the right the master interface where the surgeon is seated, controlling the robot.

Although RALS has improved surgeon comfort by reducing the strain on a surgeon's body during laparoscopic surgery, ergonomic assessments and studies show that there are still ergonomic risks involved in robotic laparoscopy [3] [4] [5]. One potential risk in the current surgical setup involves the armrest of the master device, which typically comprises a fixed leather arm pad positioned in front of the surgeon. In the study of Yang in 2016 [6], researchers found that the arms of surgeons are frequently unsupported during surgery, due to the fixed nature of the armrest. This is caused by the limited range of motion that can be achieved while resting with the elbows on the armrest, prompting surgeons to leave the armrest in order to adjust the position of the instruments with the clutch system of the Da Vinci. This increases muscle activity in the shoulders and trapezius. The fixed leather arm pad is also limited in its ability to provide support beyond the elbow region, resulting in increased biceps fatigue as the surgeon's forearms must be constantly supported. These limitations could compromise the comfort and performance of the surgeon during extended periods of surgery, as one study published 2015 found that surgical performance decreased as gynaecology residents became more fatigued [7].

It would therefore be useful to start developing an improved armrest for RALS systems. This improved armrest should be able to move freely in all directions with the arms of the surgeon during surgery while supporting the full weight of the arms in gravity. The system should have enough range of motion for all movements needed for RALS and should not interfere with the master interface. The new armrest should be tested on a simulator before testing it on real RALS devices. Therefore, the new design will be made for the AdLab-RS, a low-cost RALS simulator developed by Surge-On Medical and the Delft University of Technology. This simulator has proven to be able to improve robotic surgical skills during training on the device [8]. The AdLab-RS differs from the da Vinci Skills Simulator (dVSS) in that it is more mobile and can be used seated as well as in a standing posture. The AdLab-RS also has a different range of motion because it lacks the camera clutches that the Da Vinci has. Therefore, it has a much larger horizontal range motion and prevents the utilization of a stationary armrest.

Prior to this design report, a literature report was made on all passive dynamic arm supports found in the literature. It can be found in Appendix E. It presents 108 different arm support systems with how they work and provides a classification of the different working principles. The report also discusses the most promising working principles for RALS and dives into which systems fit the type of applications within RALS such as suturing and threading. The conclusion was that 4-bar mechanisms with the base as a vertical linkage would be the most useful for horizontal movement applications, and 4-bar mechanisms without the base as a vertical linkage are deemed to be the most useful for vertical movement applications. Therefore, the concepts in this project will be based on the recommendation of a 4-bar mechanism with the base as a vertical linkage, as it fits the horizontal range of motion capabilities needed for the AdLab-RS.

Even though the literature study in Appendix E shows that there are already devices that are able to support the arms of its user and even arm supports made for open surgery, there is no dynamic arm support yet specifically designed for robotic-assisted surgery.

1.2 Problem analysis

1.2.1 Problem statement

Surgeons are experiencing fatigue in their shoulders and arms when performing robotic-assisted laparoscopic surgery at the master interface of such devices, due to the fixed nature of the armrest. Fatigue increases discomfort and can have a significant negative impact on cognitive functioning during surgery, which can lead to mistakes due to a decrease in performance.

1.2.2 Explicit objective

To reduce fatigue and possible errors that may arise during RALS, a dynamic arm support needs to be developed and tested that can be used by surgeons to support their arms when operating the surgery robot from the master interface. To better understand the practice effects, the arm support should be fitted with the necessary sensors and electronics to measure the position of the supported arm of the user. The goal of this project is to design a dynamic arm support for surgeons, which is tracked for its location with sensors, and evaluate it with a study on users performing RALS simulation with and without the designed arm support.

2 Method

The methods used to reach the goal of the project are described in this chapter. First, the problem is translated into a list of technical requirements and performance criteria. Then the design process is discussed for the arm support as well as the sensors. At last, the study design is explained which is used to validate the prototype.

2.1 Technical requirements

1. The device should be able to support the arms of users from 2.8kg - 5.4kg, which is 5.3%[9] of the weight of persons from 54kg - 101kg (average weight women -25% – average weight men +25%)
2. The device should be strong enough that each arm support can bear 11kg without plastic deformation, which is twice the weight of a 101kg person's arm
3. The device should allow the ROM needed for using the AdLab-RS with its full ROM +20% – For the elbow: 20cm in x, 42cm in y, 20cm in z. For the wrist: 31cm in x, 46cm in y, 20cm in z. See Appendix A
4. The arm support should not negatively influence performance on the AdLab-RS for the parameters time, pathlength, and the number of collisions
5. The arm support should be able to be used in a standing posture as well as a seated posture
6. Users should be able to install and remove the arm support within 30 seconds
7. When not used, the arm support should be able to be put in a non-hindering position where the maximum protruding distance from the AdLab-RS case at all sides is 15cm
8. The positions of the points of contact of the arm support with the arms of the user should be measurable (accuracy of 10mm and a step sensitivity of 2mm)
9. Must be safe to use, it should pass a safety inspection by a TU Delft AMA advisor

2.2 Performance Criteria

- Comfort
- Cost of materials
- Complexity - as measured by the number of moving parts
- Smoothness
- Intuitiveness
- Volume
- Durability

2.3 Design Strategy

The design process had multiple phases, as described below. From the technical requirements, sub-problems could be defined of the device, which led to a morphological chart, shown in Appendix A. Three design routes could be taken: the most durable, the least volume, and the most adjustable. This gave three working concepts, which were tested with a Harris profile. The best concept was worked out in full detail and all of its parts were evaluated with FEM simulations in Solidworks before being manufactured into a functional prototype. Part of the engineering was done in parallel with building the prototype, as it was an iterative process. More on the design process can be found in Appendix A. Even though the phases of the design process mentioned above were broadly followed, it was not always in chronicle order, as there was shifting back and forth between steps, and some phases had overlap.

2.4 Sensor calibration

To get accurate readings from the sensors on the position of the arm supports, the sensors had to be calibrated first. This was done by measuring the angles between the links throughout their ranges and noting the sensor value displayed by Arduino at each angle. With MATLAB, this data was fitted to polynomials to be able to determine angles when reading sensor values, as seen in Figure 25. These angles were used in combination with the dimensions of the system to calculate the position of the arm support pad in regard to the steel base on which the arm supports were mounted.

2.5 Study design

As the objective of this project was to design a dynamic arm support that reduces fatigue in RALS without decreasing performance, the research question was stated: "What is the effect of the designed arm support on comfort and performance during tasks on the AdLab-RS?". The hypothesis was that *the dynamic arm support should reduce fatigue by improving comfort while having no significant effect on performance.*

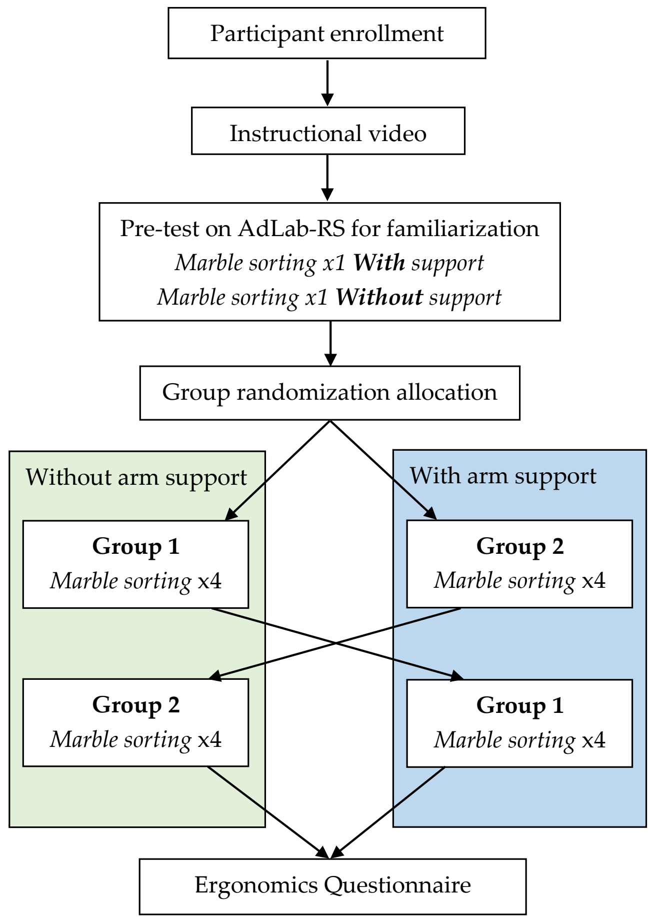


Figure 2: Flowchart of the crossover study design, with equal size of the participant groups

2.5.1 Study protocol

Students at the TU Delft were recruited for voluntary participation in the study. All participants were first shown an instructional video of the task to ensure a baseline of equal information prior to the tests. The participants then did a pre-test on the AdLab-RS to get familiar with the system's inputs and the characteristics of the digital environment. After familiarization, the participants were randomized into two groups for a crossover study. Both groups of participants were instructed to complete one exercise on the AdLab-RS system a total of 8 times. The first group had to do the first four trials without arm support, followed by four trials with arm support. The second group did the first four trials with arm support, followed by four trials without arm support. In the exercise, the participants were asked to sort marbles by their color into matching bowls. They were instructed to sort the green marbles with their left hand and the blue marbles with their right hand to ensure bimanual performance, and alternately left and right, to ensure no differences in strategy. The AdLab-RS system was set up at the Misit lab at 3ME at the Delft University of Technology, see Figure 3. After the tests, the participants were asked to fill out a questionnaire in which they could provide feedback on using the AdLab-RS with and without the arm support system. The questionnaire was mainly concerned with the ergonomics of the system. It contained questions asking for a score scaling from 1 to 20, which are part of the NASA-TLX questionnaire [10], and open questions regarding opinions about their experience. The questionnaire can be found in Appendix D. A schematic representation of the study protocol is shown in Figure 2.

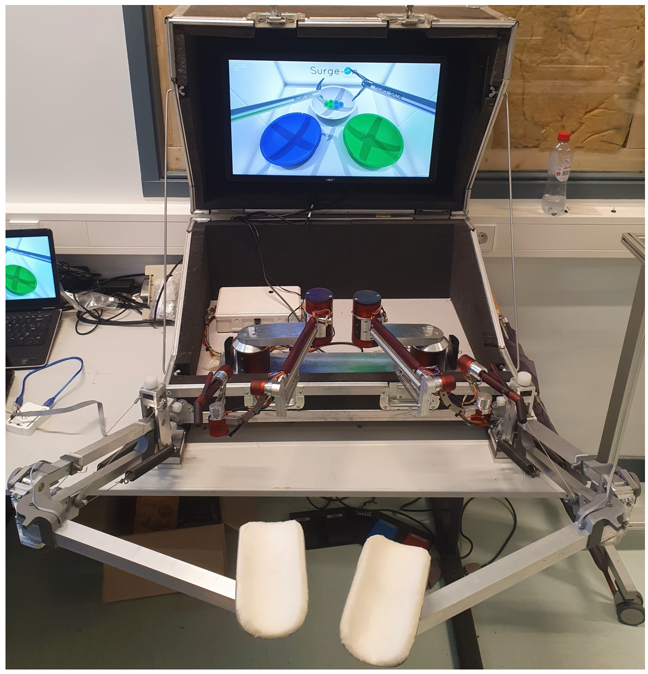


Figure 3: Setup of the experiment. The participants were asked to play a game on the AdLab-RS system where the goal was to sort marbles with laparoscopic instruments. The goal of the experiment was to test comfort and performance differences between playing with and without the novel arm support.

2.5.2 Study parameters

The main performance parameters that were used in this study were: time (s) to complete the task, total instrument path length (mm), and the number of collisions. There was a time limit of 5 minutes for each trial for logistical reasons. Trials exceeding the time limit were marked as "did not finish" and were excluded from the analysis. The subjective parameters used were mental demand, physical demand, effort, frustration, and self-perceived performance. The participants also had to give a score regarding the intuitivity of the arm support, which was solely used for an indication and not for comparisons. For further analysis purposes, data on the position of the arm cups were gathered from the sensors on the arm supports during the trials with arm support. This created six discrete sensor values of the sensors every 0.0254s, ranging from 180 to 850.

2.6 Data analysis & Interpretation

When the data was collected from all participants, it was analyzed with IBM SPSS (version 28.0.1.1 (15), SPSS, Inc., Chicago IL, USA). The normality of the data was tested using the Shapiro-Wilks test. Paired t-tests were used if the data were normally distributed, while the Wilcoxon Signed Rank test was used with non-normally distributed data. The two datasets (with and without support) were compared within each trial to identify differences in performance. Also, the first and last trials of the individual datasets were compared to find learning effects. Differences were determined significant for $p < 0.05$. The data of the questionnaire were analyzed using the same method as the performance data, to spot differences in the experience of participants on the AdLab-RS, with and without the arm support.

3 Results

The results of the project can be divided into two main parts: First, the final design and prototype of the system. Secondly, the results of the study.

3.1 Final design

A render of the final 3D design can be seen in Figure 4. This was made using SolidWorks. The built prototype can be seen in Figure 5. The prototype was tested for all technical requirements except number 4, which was part of the study. In the following subsections, the three main design components are explained.

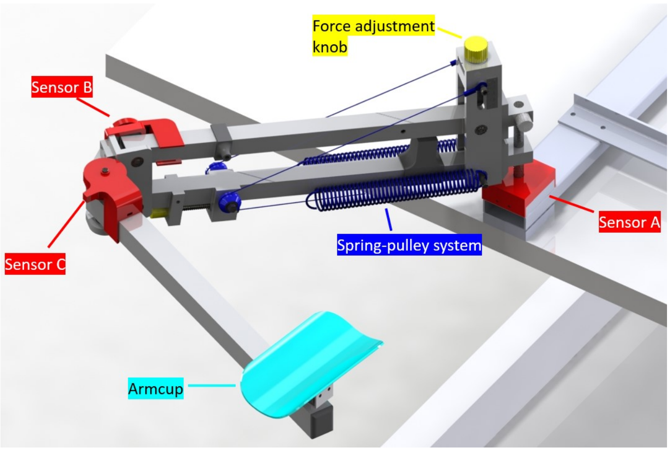


Figure 4: Render of the final Solidworks design; key parts are indicated.

3.1.1 Linkages

The system consists of multiple linkages to provide four degrees of freedom at the arm pad. Rotational joints in the horizontal plane create x and y translation and rotation around the z-axis, while the four-bar mechanism is responsible for translation in z. All the linkages were made of aluminum square rods and the joints consist of ball bearings in combination with solid steel rods. All the custom-made parts at the joints were made from aluminum using a milling machine.

3.1.2 Balancing system

The most important requirement of the design was that it could support the arms of its users throughout the entire range of motion needed to use the AdLab-RS. Through the

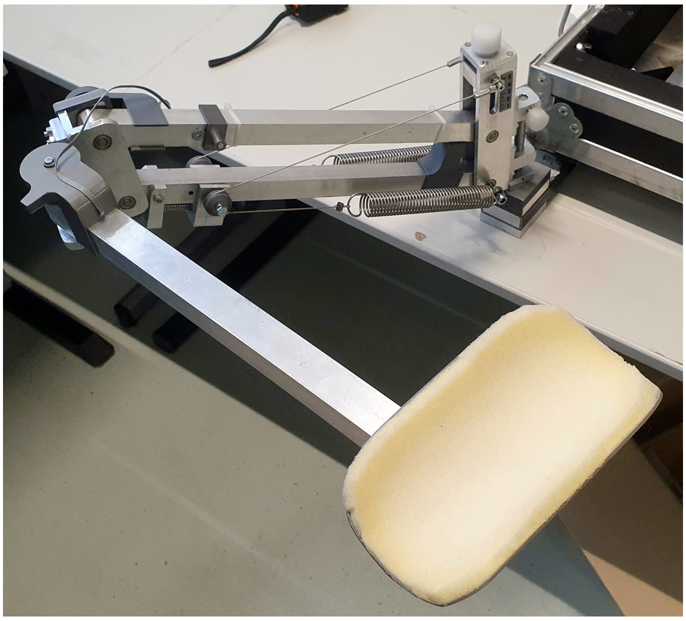


Figure 5: The prototype of which the left arm support is shown. The forearm is rested on the white foam armpad, where it is able to move freely in x,y,z and rotate around z. The support strength is adjustable by rotating the white knob at the base.

concept selection as seen in Appendix A, it was decided that steel springs would be used to reach this goal, as they are the most durable and simple in use. One of the ways to create a system that is balanced throughout its range with springs, is to work with a 'zero-free length spring' design, as found in a paper from Just Herder on balancing mechanisms [11]. It works by combining the increase in strength of the spring with a decreasing effective pulling angle on the bottom rod of the four-bar mechanism, canceling each other out when lowering the support height. This creates a mechanism with a constant support force in the working range instead of a variable support force. The principle used is shown in Figure 6 and the formula to reach this effect is shown below in Equation 1, where m is the mass and g is the acceleration of gravity. The other variables can be seen in Figure 6.

$$mgr_m = rka \tag{1}$$

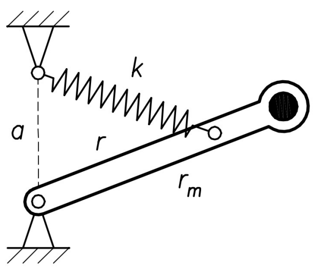


Figure 6: Fundamental principle of the balancing system with a zero-free length spring design [11]. A precondition is that the spring as seen in the figure is made up of extension only.

It is a requirement that the spring depicted in Figure 6 is comprised solely of extension. This outcome was achieved through the utilization of cables and pulleys, which were symmetrically attached. The support force is adjustable by rotating a knob on top of the base of the support, which in turn pulls the attachment point of the cable upwards by a spindle. As the height of the attachment point increases, the moment exerted on the bottom rod increases, which in turn increases the support force.

3.1.3 Sensors

In the final design, there are three sensors per arm, able to measure all translations of the arm pad within the working area. They are placed on the rotational joints of the system, to measure the angle between links. The sensors function by moving a magnet across a hall sensor, which detects the magnetic field strength. This is implemented in two ways. Sensor A and B, as seen in Figure 7 and Figure 8, work by attaching the magnet to one of the links, and attaching the hall sensor to the other link. As the links rotate with respect to one another, the magnet moves along the hall sensor at a distance of 1mm. Sensor C works differently, as it uses a lever that slides on a cam wheel. The magnet is attached to the lever and moves along the hall sensor in the same housing. The camwheel is attached to the other link. The reason for this different working principle is that sensor C must be able to measure a much larger range of angles compared to sensors A and B, which is not possible with the setup used in sensors A and B. All the sensor housings were 3D-printed, and the lever was made from a nylon cable tie. The sensors were powered and read by an Arduino Uno, which was connected to a laptop.

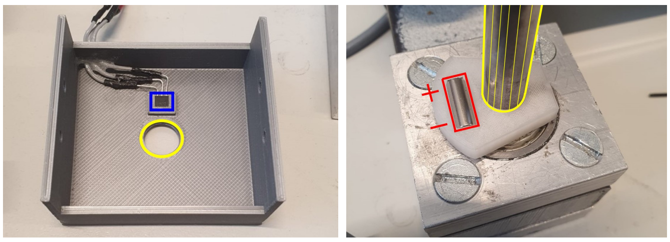


Figure 7: Setup of sensor A. The hall sensor is indicated in blue, the magnet is indicated in red. The left part slides upside down with the yellow hole over the yellow shaft on the right, to ensure that the magnet moves along the hall sensor

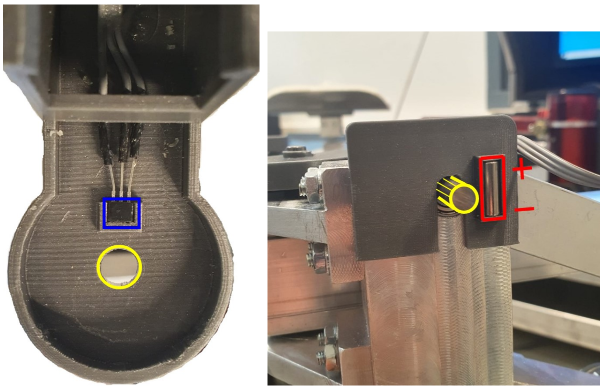


Figure 8: Setup of sensor B. The hall sensor is indicated in blue, the magnet is indicated in red. The left part slides with the yellow hole over the yellow shaft on the right, to ensure that the magnet moves along the hall sensor

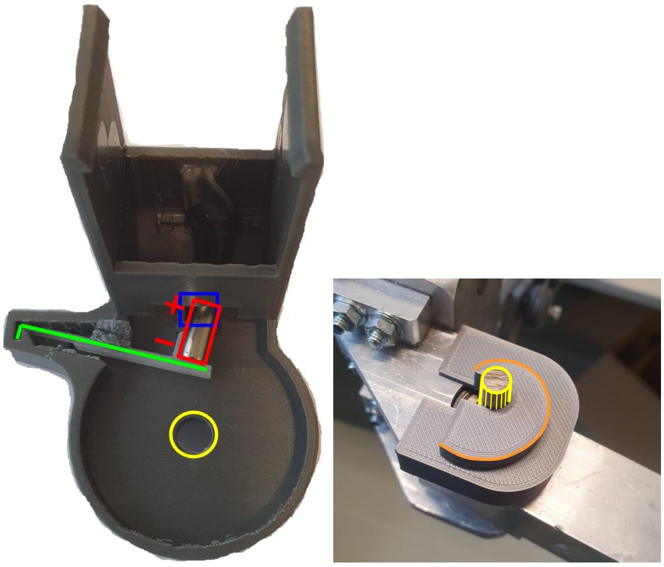


Figure 9: Setup of sensor C. The hall sensor is indicated in blue, the magnet is indicated in red, the lever is indicated in green and the camwheel is indicated in orange. The left part slides with the yellow hole over the yellow shaft on the right to get into position. During use, the lever moves along the camwheel, varying the position of the magnet in relation to the hall sensor.

3.2 Study results

A total of 20 students took part in the study, which led to 160 performed trials on the AdLab-RS. All participants completed the pre-tests and were randomized into two groups of ten participants. In the pre-tests, two participants exceeded the 5-minute time limit. However, no participants exceeded the time limit during the trials and therefore no trials had to be excluded. One participant could not finish the second part of the trials due to external circumstances and therefore had to be excluded from the analysis. The completed trials could not be used because of the paired nature of the study. Thus, a replacing participant was recruited. All participants filled out the questionnaire.

3.2.1 Subjective results

Figure 11 shows boxplots of the results of the questionnaire. Participants found the task in combination with the arm support significantly less mentally and physically demanding, requiring significantly less effort and resulting in less frustration. The perceived performance showed a slight increase, although not significant. The participants also expressed a high score for the intuitiveness of the device.

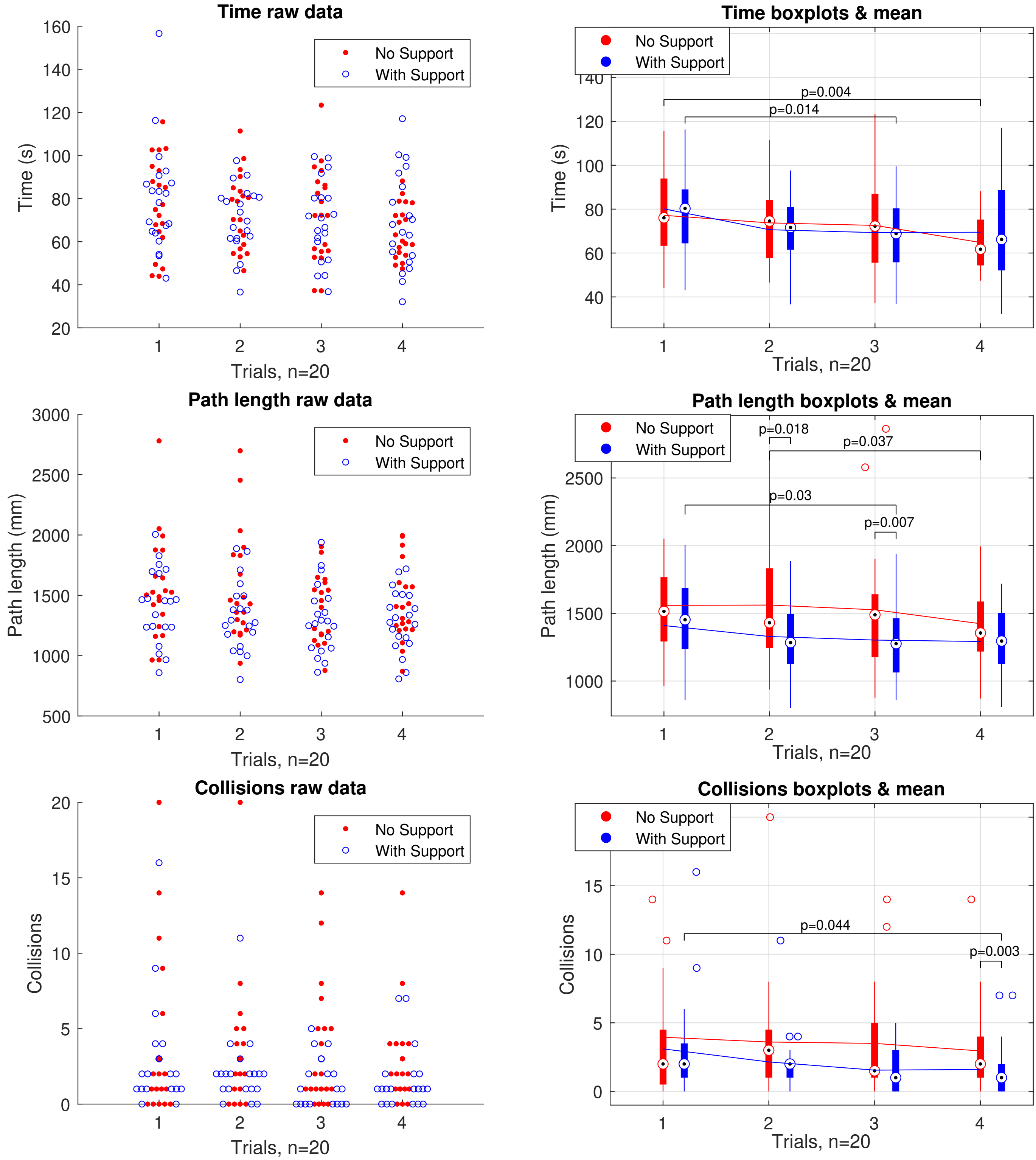


Figure 10: Boxplots per trial of the performance parameters of the task 'marble sorting' on the AdLab-RS with and without the use of the designed arm support. Significant differences are shown and determined by the paired T-test (normally distributed data) and the Wilcoxon Signed Rank test (non-normally distributed data) with $p < 0.05$.

3.2.2 Objective performance results

Figure 10 shows boxplots of the performance parameters time, path length and collisions per trial during the *marble sorting* task on the AdLab-RS, with significant differences shown. Between the first and last trials of the task without arm support it can be seen that the time decreased significantly, as well as between trials 1 and 3 of the task with arm support. This points to a learning curve, which can also be seen in the path length from trials 1 to 3 of the task with arm support and trials 2 to 4 without arm support. The last learning curve can be seen in the collisions figure, where there is a significant decrease in the number of collisions between trials 1 and 4. Within trials 2 and 3, the participants had significantly lower path lengths

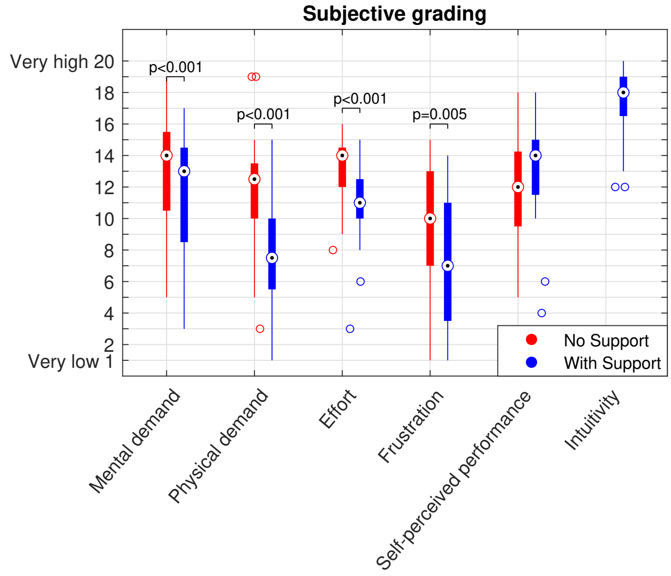


Figure 11: Boxplots of the results of the questionnaire on the experiences of using the AdLab-RS with and without the use of the designed arm support. Significant differences are shown and determined by the paired T-test (normally distributed data) and the Wilcoxon Signed Rank test (non-normally distributed data) with $p < 0.05$.

in the trials with arm support as compared to the trials without arm support. In the last trials, the participants also had significantly fewer collisions with arm support as compared to the trials without arm support. Lastly, in the total statistics, Figure 12, it can be seen that participants, overall, had significantly lower path length and fewer collisions in the tasks with the novel arm support as compared to having no arm support.

3.2.3 Positional analysis of the arm support

Figure 14 provides a visual representation of the movement during all the trials with arm support. Only the first ten participants are shown to prevent cluttering the data. The variability of movement and the main directions are graphically presented as projections of oriented ellipsoids with the principal axes sticking out of the surface. For improved visibility, the ellipsoids are scaled down by a factor of five.

4 Discussion

A novel passive dynamic arm support was designed which is able to balance the arms of users when performing tasks on the AdLab-RS robotic laparoscopic simulator. The results of the performed study show that it increases the perceived comfort in multiple facets during the tasks, while remarkably also increasing the objective performance for the parameters path length and collisions.

4.1 Functional requirements

The functional requirements are shown in Table 1 with a brief discussion on their fulfillment.

4.2 Subjective results

The results of the questionnaire presented to the participants provide insight into the differences in the experiences of using the AdLab-RS with and without the novel-designed arm support. It showed that 18 out of 20 participants preferred working with the arm supports for shorter tasks (5-20min), and all participants preferred the arm support for longer tasks (> 20min), as it decreased fatigue and was less physically and mentally demanding. One of the reasons for an increase in performance could be derived from the answers to the open questions regarding whether there would be added value of the arm support for shorter tasks. Six participants indicated that the arm support provided more stability which led to more precise movements, while 5 respondents attributed a possible increased performance to having more mental energy left for the task because of not having to lift their arms.

4.3 Objective results

From Figure 10 and Figure 12 it can be seen that the performance parameters path length and collisions are significantly lower for the trials with arm support in comparison to the trials without arm support, while the parameter time shows no significant differences. A shorter path length with equal time indicates a decrease in the average speed of the participants on the AdLab-RS. This decreased speed could be the reason for the lower number of collisions as well, as it points to slower, more stable, and more precise movements, effects that multiple participants also stated about their experience with the arm support. Another reason for the shorter path length could be found in observations from the researcher. It appeared that in trials without arm support, participants would bring their non-working arm toward a resting position, where the upper arm is down to the side of the body, in an attempt to decrease the effort of the shoulder in lifting the arm. This positional change from the working position to the resting position and vice versa creates extra path length. Meanwhile, in the trials with arm support, participants held their non-working arm more or less in the same position as the working position, as it could be considered a resting position now due to the arm support. This could have contributed to a decrease in path length of participants for the trials with arm support.

Although some learning curves can be seen in Figure 10, the lack of some can be explained by the crossover nature of the study, as participants were already accustomed to the task when starting trial 1 of the next group of four trials. A practice effect occurred as their newly developed skills are highly transferable to the second set of four trials, preventing the participants from fully developing a learning curve once again.

4.4 Mechanical Design

The prototype worked well and operation was smooth. Most of the feedback from professors, participants, and two surgeons was that it provided a more relaxing experience. However, the mechanical design still has points to

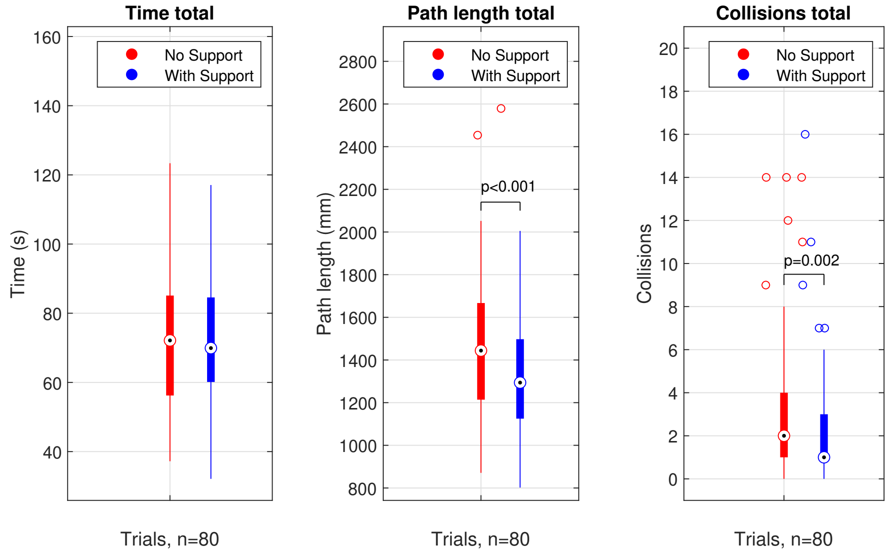


Figure 12: Boxplots of the performance parameters of all trials combined of the task 'marble sorting' on the AdLab-RS with and without the utilization of the designed arm support. Significant differences are shown and determined by the paired T-test (normally distributed data) and the Wilcoxon Signed Rank test (non-normally distributed data) with $p < 0.05$.

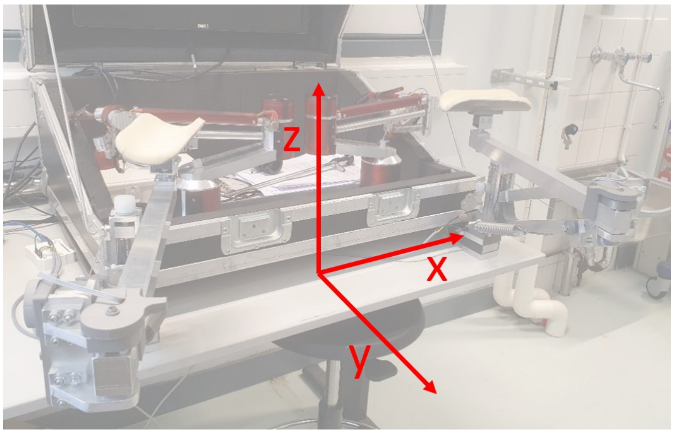


Figure 13: Frame of reference for the coordinate system as shown in Figure 14

discuss. First, most of the parts are custom-made with the use of a milling machine, increasing the cost and time to make the prototype. This could be changed to more standard parts to decrease manufacturing costs.

Moreover, the balancing mechanism did not perfectly balance its support force throughout the range, because of errors made in the calculations concerning the zero-free length spring design. This resulted in an increasing support force when lowering the height of the arm. A design with this feature improved is shown in Figure 17, where a second pulley is added to shorten the distance of the cable from the base attachment to the bottom beam. This distance is important, as it should be equal to the extension of the spring at all times, as a prerequisite for zero-free length springs. The current design does not fulfill this requirement, which is why the system is unable to provide a constant support force. It is questionable though, whether perfectly balancing the system would improve user experience and comfort. One could make the argument that with a perfectly constant support force, the experience will be improved, as the amount of force that the user still has to exert will be lower throughout the range. However, this would make adjusting the arm support to the right support strength more difficult, as it has to be exactly right (the difference between the weight of the user and the support force has to be lower than the friction in the system) to be able to keep the arms of the user floated. A small offset would ensure the user has to exert a constant force either down or up. This won't be the case for the current situation where the arm support is slightly increasing its support force when lowering the arms, as the user will

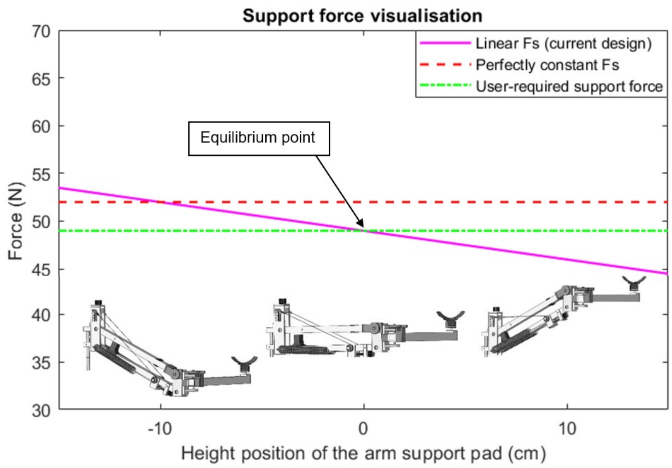


Figure 16: Visual representation of two situations of the support force Fs in the system. It can be seen that an arm support with a linearly decreasing support force always finds an equilibrium point (where the green and purple lines intersect) while other height positions create force differences that have to be overcome. The perfectly constant support force (red) is always parallel to the user-required support force and is therefore difficult to set up, but when done right, requires no effort at all.

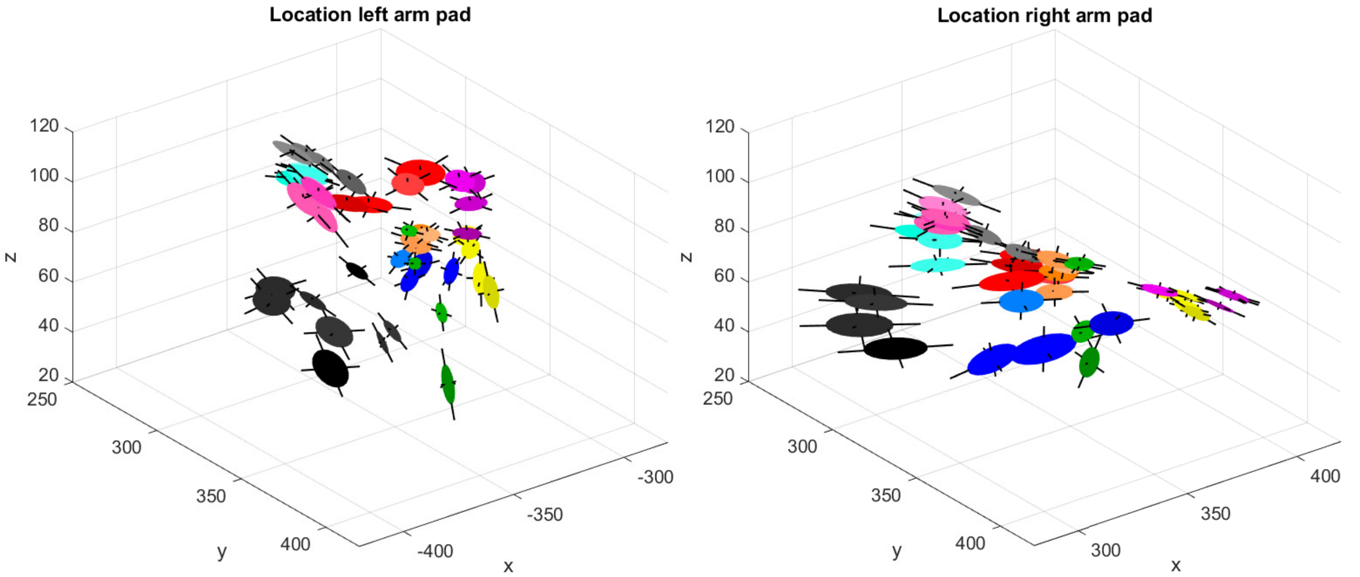


Figure 14: 3D Graphic display of the positional areas of the forearm pads of the participants in trials 1 to 4. Participants are distinguished by color. First trials are shown as the darkest version of a color, last trials are shown in the lightest version of the color

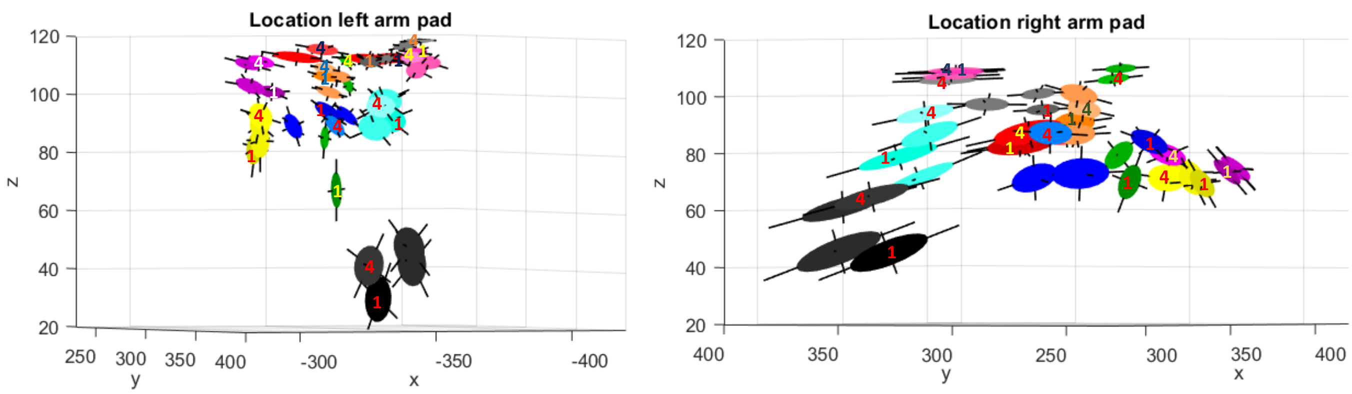


Figure 15: Side view of Figure 14 to see clear height differences in the arm pad movement areas of the participants between trials 1 and trials 4. Left arm pad: 8 out of 10 participants show a higher location of trial 4 as compared to trial 1. Right arm pad: 9 out of 10 participants show a higher location of trial 4 as compared to trial 1.

automatically find an equilibrium point that matches the support force to the weight of their arms. This will make sure that adjusting the support force is much easier, as there is a range of settings that work and guarantees an equilibrium point where the user can rest. The negative to this situation is that other height positions beside the equilibrium height will always require some force, although low in magnitude. This concept is visualized in Figure 16.

As a third comment, the adjustability range of the system's support force was insufficient. To resolve this issue during the experimental phase, the installation of different springs was necessary to accommodate the lighter arms of some female participants. However, the switch-over process was time-consuming. An improved design could have a larger slot to improve the range. Another point of discussion in the current design is the adjustment of the location of the pulley, which turned out to be redundant because its effect is small on the support force of the system and it is only necessary to use when switching springs. If an improved design has a greater adjustment range in the attachment point of the cable, this extra setting becomes excessive.

4.5 Sensor design

The sensor design worked well and produced repeatable readings. All sensors stayed intact during the test phase. However, the design of the sensors could be improved so that they would be easier to calibrate, as the process of calibrating was rather difficult to get right. This has probably taken away from the accuracy of the sensor readings. However, this could be considered less important as the main goal of the positional sensors was to find changes in the area of movement as a result of a learning effect. This is also possible with less accuracy of the sensors, as the differences between readings are much more important than the accuracy of the exact locations. These rely on the repeatability of the sensor readings, or the precision, which was high.

Functional requirement	Discussion
1. The device should be able to support the arms of users from 2.8kg - 5.4kg, which is 5.3%[9] of the weight of persons from 54kg - 101kg (average weight women -25% – average weight men +25%)	The requirement is met, as with one change of springs, the arm support could provide adequate support for most participants. However, one participant had an even lower arm weight than the minimal strength setting supported, requiring a change in springs.
2. The device should be strong enough that each arm support can bear 11kg without plastic deformation, which is twice the weight of a 101kg person's arm	The requirement is met, all parts are designed with a safety factor of 2. After elaborate testing on 20 participants, no parts broke and no parts seemed to be deformed or loosened.
3. The arm support should allow the ROM needed for using the AdLab-RS with its full ROM +20% - For the elbow: 20cm in x, 42cm in y, 20cm in z. For the wrist: 31cm in x, 46cm in y, 20cm in z. See Appendix A.	The requirement is met, as the RoM is sufficient for al operations on the AdLab-RS. In the iterative design process, one of the degrees of freedom was even removed as it caused instability. This was the extra rotation at the arm pad which could tilt the arm up and down.
4. The arm support should not negatively influence performance on the AdLab-RS for the parameters time, pathlength, and the number of collisions	The requirement is met and even exceeded, as the study showed that the performance increased on the parameters pathlength and collisions with the introduction of the arm support. The performance parameter time was unaffected.
5. The arm support should be able to be used in a standing posture as well as a seated posture	The requirement is met, as the arm support is mounted on the frame in which the AdLab-RS is placed. The height of the table is therefore the determining factor for the posture and can be set to any height.
6. Users should be able to install and remove the arm support within 30 seconds	The requirement is met, as the arm support is easily removable and installable within the given time frame.
7. When not used, the arm support should be able to be put in a non-hindering position where the maxi- mum protruding distance from the AdLab-RS case at all sides is 15cm	The requirement is met, as the arm support is designed in a way that it can be folded inwards toward the AdLab-RS. The maximum protrusion in this position from the case is 14cm.
8. The positions of the points of contact of the arm support with the arms of the user should be measurable (accuracy of 10mm and a step sensitivity of 2mm)	The requirement is met, as the sensors are able to measure the position of the arm pad with an accuracy of +/- 3mm and a step sensitivity of +/- 0.1mm.
9. Must be safe to use, it should pass a safety inspection by a TU Delft AMA advisor	The requirement is met, as the device passed inspection by the AMA advisor of BioMechanical Engineering at the TU Delft.

Table 1: The functional requirements with a brief discussion on their fulfillment

4.6 Positional learning effects

When analyzing Figure 14, multiple characteristics can be found. First, it can be seen that the movement areas are grouped, as could be expected. Participants make small adjustments in their posture in the process of learning and trying to improve their performance. However, those positional changes are not drastic, as the participants are still bound to the unchanging dimensions of their body, and most likely to the height of the equilibrium point as explained in Figure 16. However, it appears that the positional variation within those groups as seen in the xy plane is random. These small variations are most likely the result of participants adjusting their posture in between trials, to sit more comfortably or perform better. Interestingly though, it appears that a trend can be seen in the z-axis, as 8 out of 10 participants increased the height of their left arm, and 9 out of 10 participants increased the height of their right arm between the first and last trial with arm support, clearly seen in Figure 15. This can be explained by a development in strategy of the participants. The researcher observed that grabbing the marbles from the top as sort of a crane with a grab is a more efficient way of performing the task than grabbing the marbles from the sides. The researcher also observed that most participants intuitively learn this and moved toward this better strategy during the trials. This can explain the trend of the increasing height of the arm positions of most participants, as the more optimized strategy requires a higher position of the AdLab-RS handles, and thus a higher position of the arm supports for comfort. Another interesting observation is that the size of the ellipsoids in Figure 14 of each participant, and the main directions of variability from the principal axes, appear to stay the same throughout the trials but are different between participants. This indicates that participants keep the same dimensional movement patterns, but express them from different starting locations throughout the trials, due to slightly different postures. When viewing Figure 15, the black, green, and yellow ellipsoids appear significantly lower placed than the remainder of the ellipsoids. However, upon further inspection of the data, no further conclusions can be drawn as a result of, for instance, right- or left-handedness, length

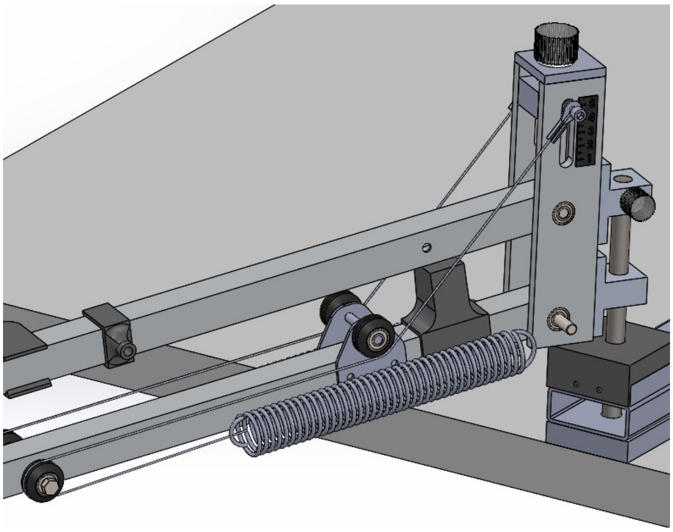


Figure 17: Concept of a new design with an extra pulley to shorten the extension length needed of the spring, creating a zero-free length spring to provide a constant support force

of the participants, or gender. The most likely cause is that these participants set the arm support strength at an insufficient level, causing the arm to find a supporting equilibrium height lower than other participants. The differences in the sizes of the ellipsoids are explained by the performance parameter path length, as the largest ellipsoids coincided with the trials of participants with the most path length. More efficient participants used less path length and also had smaller ellipsoids, likely due to smaller movement patterns.

4.7 Expert opinions

The arm support was subjected to an expert in Robotic laparoscopy. He stated that the arm support would reduce fatigue significantly and provide a more enjoyable experience during procedures. The range of motion was also sufficient, and he stated that if the balancing aspect of the device was perfected, it would improve the experience even more. The expert noted that there would be a learning curve for experienced surgeons, as they would need to get used to having their arms in a different position during tasks as compared to the arm position in the Da Vinci, but this would yield positive results in the long run. A second expert agreed with most of the points, and stated that the novel arm support design could make a significant positive impact on the experience of surgeons in robotic surgery. One notable observation however refers to the position of the arms in the arm support, which, according to the second expert, closely mirrors the high arm position typically employed during laparotomy and laparoscopy procedures, as opposed to the low arm position adopted in RALS devices such as the Da Vinci. He stated that the learning curve of young surgeons for robotic surgery could be reduced as a result of more natural movements that are closer to traditional laparoscopic surgery and in some cases even to open surgery. This is another motivation to further investigate the potential benefits of the arm support not only for existing surgeons but also for surgeon trainees. Another potential benefit mentioned was the increased range of motion of performing robotic surgery without a clutching system. The clutching system decreases the used range of motion of the arms of the surgeon, which is ill-favored compared to a larger range of motion for injury prevention according to a RALS skills training expert. This is in addition to the fact that the clutching system requires a longer learning curve.

4.8 Limitations & recommendations

One of the limitations of the study is that it was only tested with students, not actual practicing surgeons. While this study serves as a good indicator of the design's functionality, it is still uncertain whether the arm support improves the experience of surgeons within the operating room. Further research, incorporating practicing surgeons as participants, is needed to determine the clinical utility and impact of the arm support on surgery outcomes.

The study is also subject to a limitation in that the trial times for the short marble sorting task are not representative of the extended durations of surgical operations that can last for hours. Some participants from the presented study even noted that the short trial times did not sufficiently induce fatigue, thereby limiting their ability to discern differences in comfort levels. This most likely limited differences in performance as well, as a paper by Z. Tsafrir [7] on laparoscopic performance describes that the time to complete tasks increases with increased tiredness. This effect was not found in the current study, where the parameter time showed no differences between groups. To fully investigate the impact of the designed interventions on the total comfort experience of surgeons, trial times should thus be increased in future studies to allow for the onset of fatigue, enhancing the applicability of the findings to real-world surgical scenarios.

Another potential limitation of the present study lies in the credibility of the subjective data, which is susceptible to acquiescence bias when participants respond in a manner that they believe will please the researcher. This effect is relevant as most of the participants were acquaintances or friends of the researcher, as they may have felt a sense of obligation to assist in the study. The possible inflation of supporting statistics should therefore be taken into account when interpreting the subjective results. One could claim that the same situation could have arisen in the objective data where participants could have tried harder in the experiments with the arm support as opposed to the experiments without arm support. However, this effect is limited as the performance metric distance was not known to the participants. Furthermore, the experiments were designed with a challenging level of difficulty to ensure significant effort, further reducing the potential for bias in the objective data.

The last recommendation would be to further develop the system, to automate the procedure of adjusting the support strength to the arm weight of the user with the use of force sensors, as some participants indicated that they found it difficult to find the right setting. This could be achieved by replacing the turning knob on top of the system with a small motor, as seen in Figure 24 in Appendix A.

4.9 Relevance

Although the literature review in Appendix E shows that passively actuated balancing arm supports are not new, this report presents the first one designed specifically for its use in robotic surgery. There are however arm supports designed for other types of surgery, such as the iArmS, seen in Figure 18. This arm support is comparable to the design in this report because of the similar posture that is used. It also balances the arms, but has an extra functionality in that it is able to stop in desired positions through an intelligent operating system within the arm support [12]. The results show that it decreases fatigue and enhances the stability of the surgeon's hand, both outcomes that are also described in the results of this report. A major downside however is the fact that this arm support system is a large standalone device that weighs 97kg, compared to the 2kg of the design in this paper which takes up little space.

Figure 18: iArmS arm support system designed for multiple types of surgery, can be used in a seated as well as a standing posture. The picture on the right shows microscopic neurosurgery with the iArmS, reducing fatigue and increasing stability of the surgeon's hand.

Another arm support study showed higher steadiness of the hand and a shorter surgical path when using a simple forearm support in phonomicrosurgery [13]. This is another result that adds to the credibility of the conclusion that the presented arm support in this report is able to increase the surgeon's stability and decrease the path length of their instruments during surgery.

5 Conclusion

The objective of the project was to design a dynamic arm support for surgeons that can be tracked for its location with sensors and evaluate its efficacy through a comparative study involving users performing robot-assisted laparoscopic surgery simulations with and without the aforementioned designed arm support. A novel passive dynamic arm support was designed and developed that has been shown to increase comfort while also enhancing performance on tasks using the AdLab-RS robotic surgery skills simulator, likely due to increased stability. Despite the limitations imposed by the brief duration of the test trials and the participation of solely non-surgeons in the study, the results nonetheless provide a useful indication of the functionality and effectiveness of the novel-designed arm support for its use in RALS. Going forward, the arm support must be assessed in a clinical setting to examine its utility and effect on surgery outcomes.

References

[1] J. Dwivedi, "Robotic Surgery-A Review on Recent advances in Surgical Robotic Systems." *Florida Conference on Recent Advances in Robotics*, no. January 2012, pp. 1–7, 2012. [Online]. Available: http://www.eng.fau.edu/conf/fcrar/papers/FCRAR{_}2012{_}2{_}1{_}Dwivedi{_}Mahgoub{_}FAU.pdf

[2] T. Dalager, P. T. Jensen, J. R. Eriksen, H. L. Jakobsen, O. Mogensen, and K. Sogaard, "Surgeons' posture and muscle strain during laparoscopic and robotic surgery," *BRITISH JOURNAL OF SURGERY*, vol. 107, no. 6, pp. 756–766, 2020.

[3] N. Hubert, M. Gilles, K. Desbrosses, J. P. Meyer, J. Felblinger, and J. Hubert, "Ergonomic assessment of the surgeon's physical workload during standard and robotic assisted laparoscopic procedures," *INTERNATIONAL JOURNAL OF MEDICAL ROBOTICS AND COMPUTER ASSISTED SURGERY*, vol. 9, no. 2, pp. 142–147, 2013.

[4] E. H. Lawson, M. J. Curet, B. R. Sanchez, R. Schuster, and R. Berguer, "Postural ergonomics during robotic and laparoscopic gastric bypass surgery: a pilot project," *Journal of Robotic Surgery*, vol. 1, no. 1, pp. 61–67, 2007.

[5] T. A. Plerhoples, T. Hernandez-Boussard, and S. M. Wren, "The aching surgeon: a survey of physical discomfort and symptoms following open, laparoscopic, and robotic surgery." *Journal of robotic surgery*, vol. 6, no. 1, pp. 65–72, mar 2012.

[6] E. Rodr, A. P. Kypson, S. C. Moten, L. W. Nifong, and W. R. C. Jr, "A new system for evaluation of armrest use in robotic surgery and validation of a new ergonomic concept," *International Journal*, no. April, pp. 211–215, 2006.

[7] Z. Tsafrir, J. Korianski, B. Almog, A. Many, O. Wiesel, and I. Levin, "Effects of Fatigue on Residents' Performance in Laparoscopy," *Journal of the American College of Surgeons*, vol. 221, no. 2, pp. 564–570.e3, 2015. [Online]. Available: http://dx.doi.org/10.1016/j.jamcollsurg.2015.02.024

[8] S. F. Hardon, A. Kooijmans, R. Horeman, M. van der Elst, A. L. Bloemendaal, and T. Horeman, "Validation of the portable virtual reality training system for robotic surgery (PoLaRS): a randomized controlled trial," *Surgical Endoscopy*, vol. 36, no. 7, pp. 5282–5292, 2022. [Online]. Available: https://doi.org/10.1007/s00464-021-08906-z

[9] S. Plagenhoef, F. Gaynor Evans, and T. Abdelnour, "Anatomical Data for Analyzing Human Motion," *Research Quarterly for Exercise and Sport*, vol. 54, no. 2, pp. 169–178, 1983.

[10] Nasa, "NASA Task Load Index," *Human mental workload*, vol. 1, no. 6, pp. 21–21, 2006. [Online]. Available: http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve{&}db=PubMed{&}dopt=Citation{&}list{_}uids=16243365

[11] J. L. Herder, *Energy-free Systems; Theory, conception and design of statically balanced spring mechanisms Ferrofluid bearings View project Parallel Manipulators View project*, 2001, no. November 2001. [Online]. Available: https://www.researchgate.net/publication/280922819

[12] T. Ogiwara, T. Goto, A. Nagm, and K. Hongo, "Endoscopic endonasal transsphenoidal surgery using the iArmS operation support robot: Initial experience in 43 patients," *Neurosurgical Focus*, vol. 42, no. 5, pp. 1–5, 2017.

[13] T. Chen, A. C. Vamos, S. H. Dailey, Z. Geng, and J. J. Jiang, "A study of phonomicrosurgical arm support postures using a magnetic motion tracking system." *The Laryngoscope*, vol. 126, no. 4, pp. 918–922, apr 2016.

A Appendix - Design Process

A.1 Finding range of motion

In order to quantify technical requirement 3: *The arm support should allow the ROM needed for using the AdLab-RS with its full ROM +20% - For the elbow: 20cm in x, 42cm in y, 20cm in z. For the wrist: 31cm in x, 46cm in y, 20cm in z.* A small test was performed where a camera was placed above a student using the AdLap-RS. The camera footage was analyzed using Kinovea, as seen in Figure 19

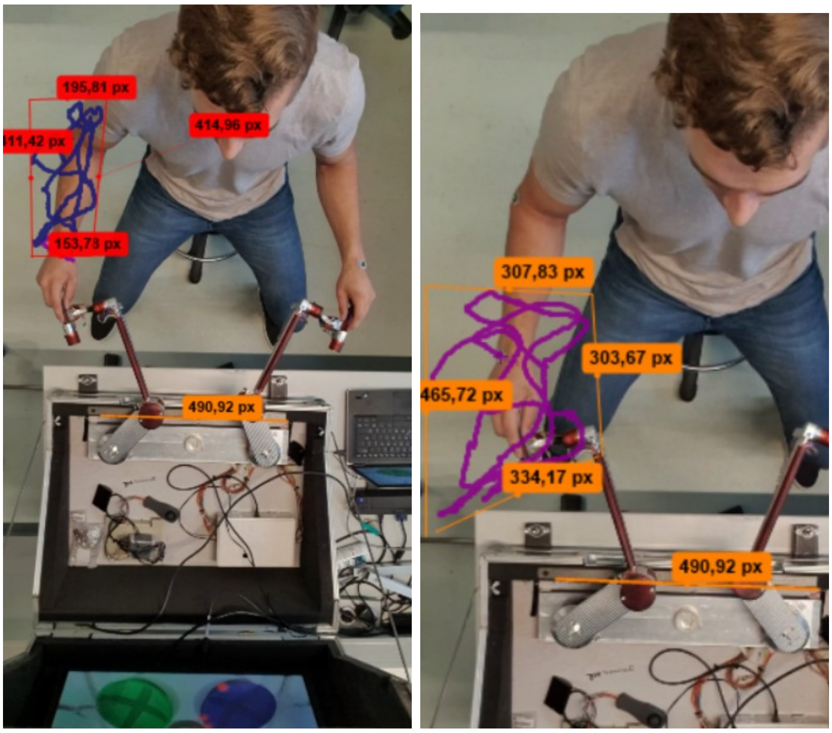


Figure 19: Quantifying range of motion through camera-tracking movements on the AdLap-RS and analyzing the footage through the program Kinovea.

A.2 Morphological chart

The following step was to make a morphological chart of all the partial solutions, seen in Figure 20. The 4 DoF mechanisms were the result of the conclusions of the literature review prior to this report, as seen in Appendix E.

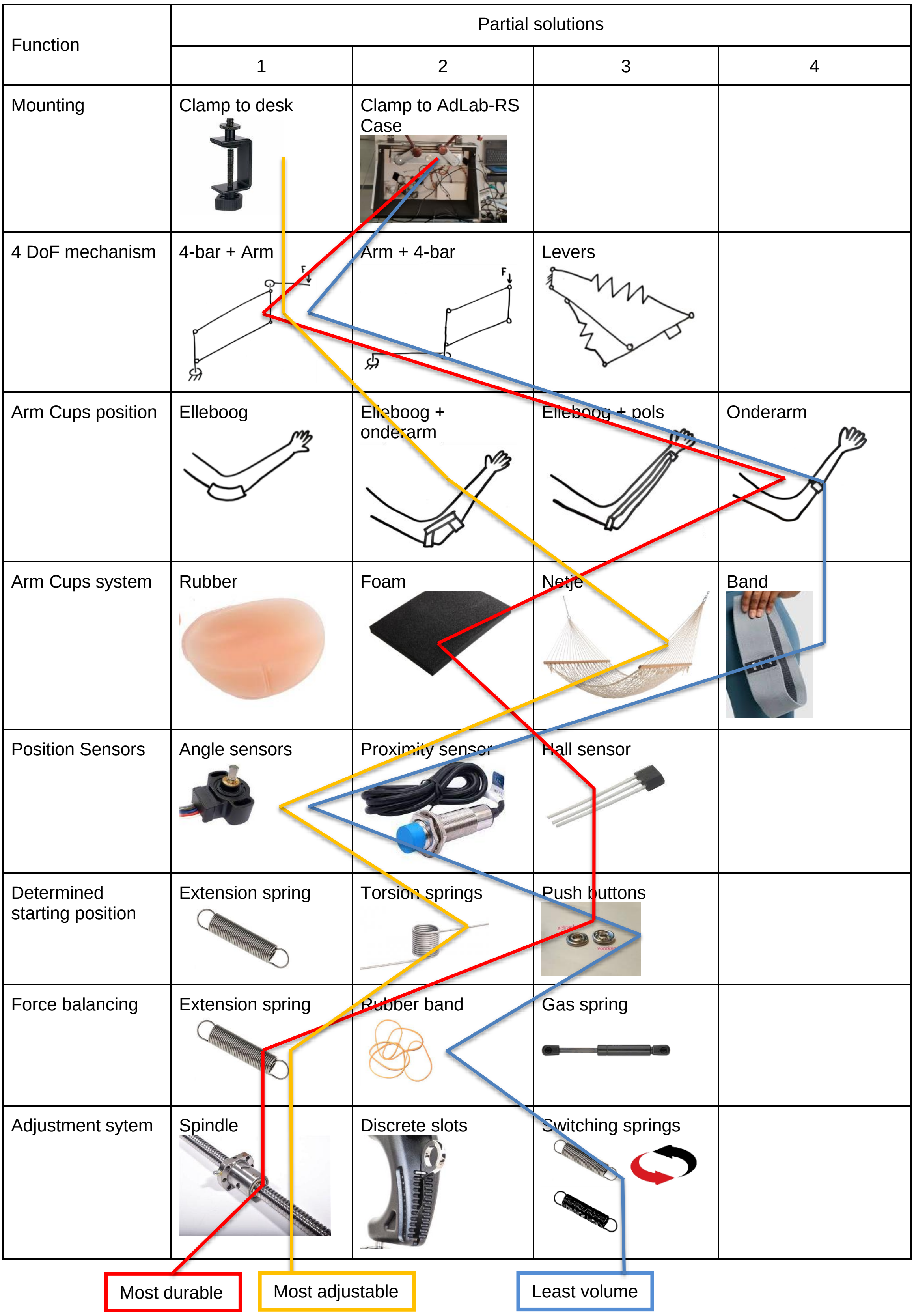


Figure 20: morphological chart

A.3 Concept generation

From the literature review in Appendix E it was clear that two systems were best suited for the application of RALS: 4-bar mechanism with their base as a vertical linkage and 4-bar mechanisms without their base as a vertical linkage. However, in determining the required range of motion for the new design, it was clear that only little vertical RoM was required. Therefore all concepts use the same mechanism principle of the 4-bar mechanism with the base as a vertical linkage, as this is better suited for limited vertical movement and greater horizontal movement. This is explained in the discussion of the literature report in Appendix E.

Therefore the 3 concepts are shown below in Figure 21:

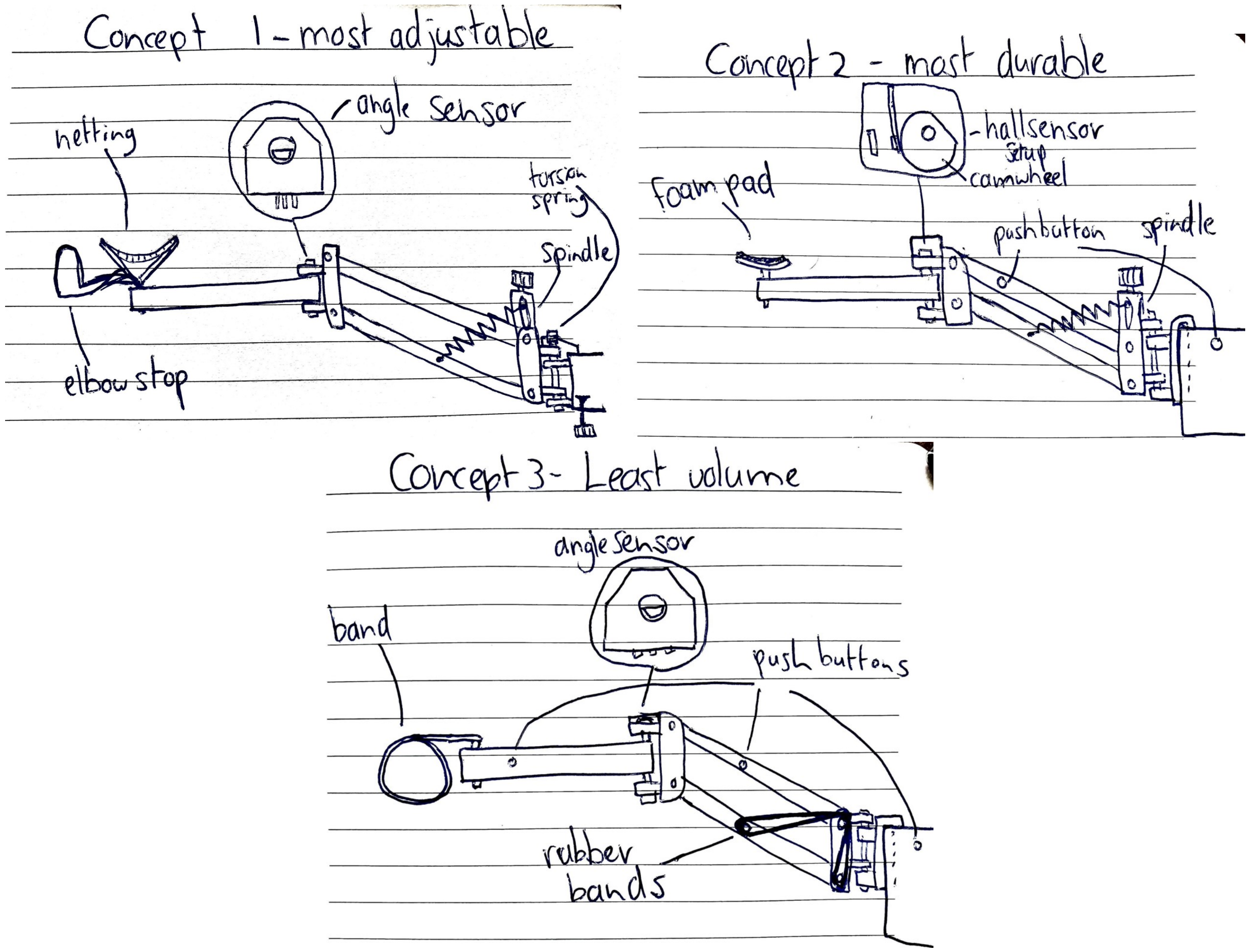


Figure 21: The three concepts

A.4 Concept selection

The criteria used to judge the concepts are the performance criteria:

- Comfort
- Cost of materials
- Complexity - as measured by the number of moving parts
- Smoothness
- Intuitiveness
- Volume
- Durability

	Concept 1					Concept 2					Concept 3			
	--	-	+	++		--	-	+	++		--	-	+	++
Comfort														
Cost of materials														
Complexity														
Smoothness														
Intuitiveness														
Volume														
Durability														

Figure 22: Harris profile for the different concepts

A.5 Design iterations

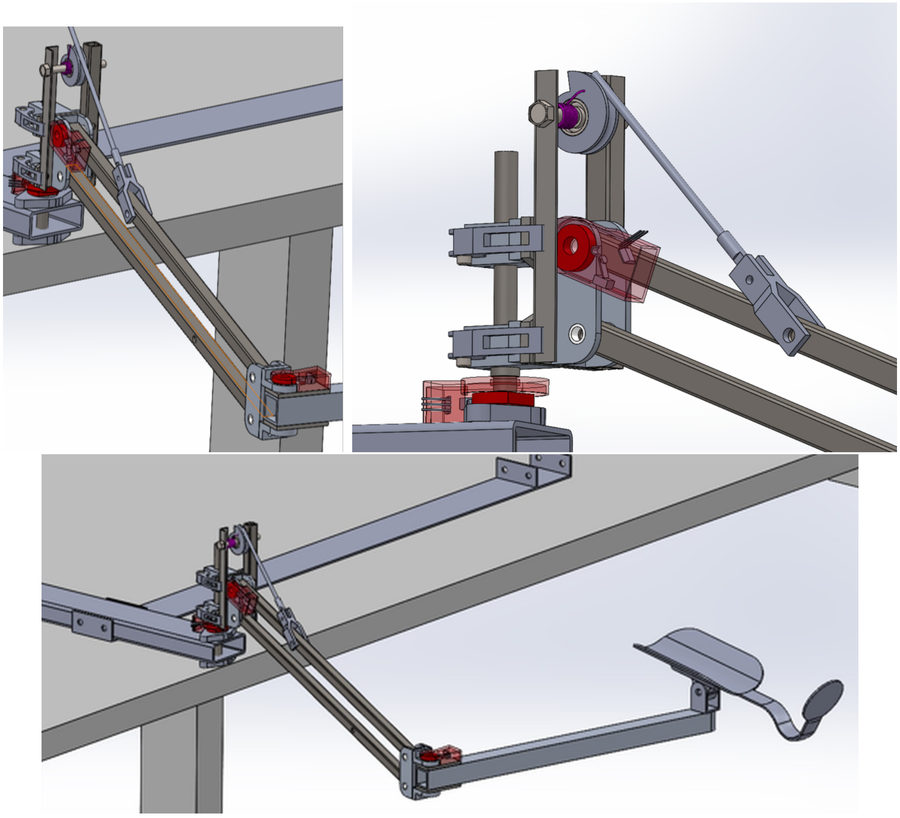


Figure 23: Iteration of the first concept with actuation through a torsional spring attached to a camwheel with a cable, and sensors

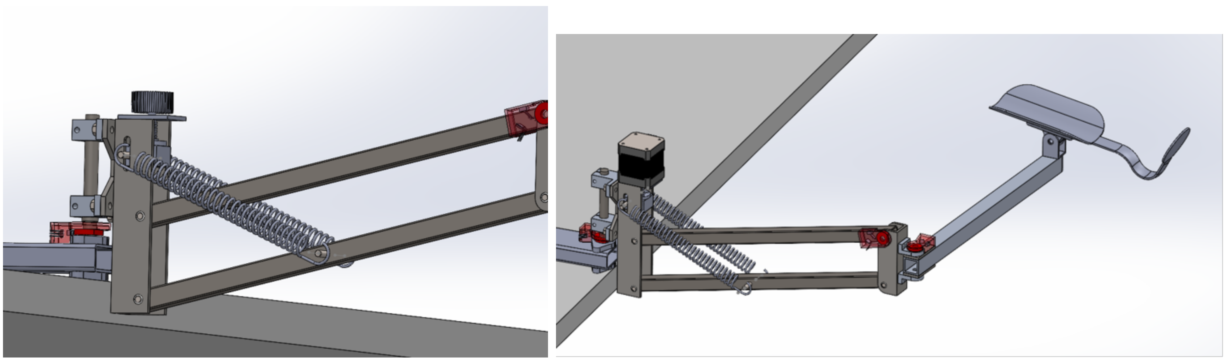


Figure 24: Concept iteration with extension springs. The idea was born to make the adjustment procedure automatic through a stepper motor in combination with pressure sensors. This was however outside of the scope of the project and was therefore discontinued

B Appendix - Calibration of the sensors

Below the graphs of the curve fits can be seen which were used to calibrate the sensors.

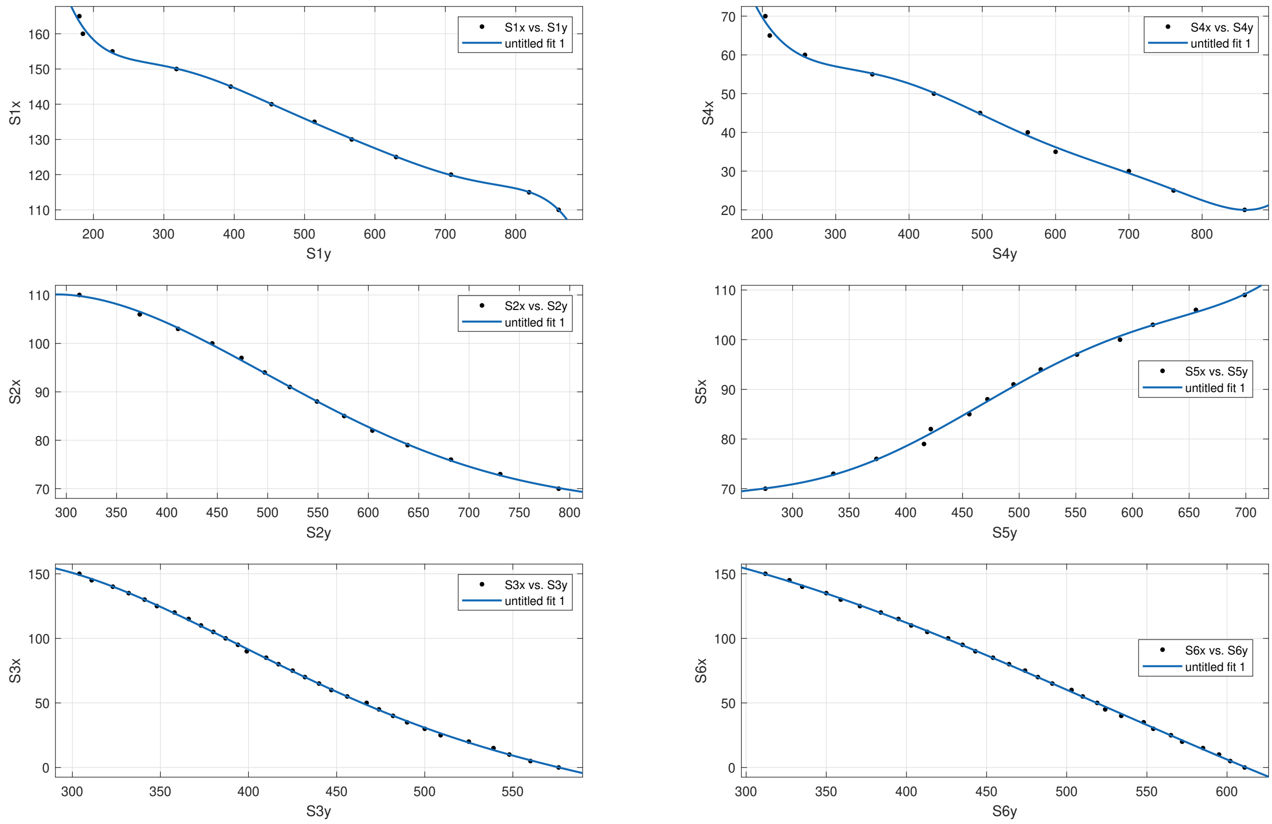


Figure 25: Curve fits of the data of sensors 1-6

C Appendix - Arduino code

```
#define Hall_sensor1 A0
#define Hall_sensor2 A1
#define Hall_sensor3 A2
#define Hall_sensor4 A3
#define Hall_sensor5 A4
#define Hall_sensor6 A5
int Hall_value1;
int Hall_value2;
int Hall_value3;
int Hall_value4;
int Hall_value5;
int Hall_value6;
int xL;
int xR;
int yL;
int yR;
int zL;
int zR;


void setup() {
  // put your setup code here, to run once:
Serial.begin(9600);
}

void loop() {
  // put your main code here, to run repeatedly:
Hall_value1=analogRead(Hall_sensor1);
Hall_value2=analogRead(Hall_sensor2);
Hall_value3=analogRead(Hall_sensor3);
Hall_value4=analogRead(Hall_sensor4);
Hall_value5=analogRead(Hall_sensor5);
Hall_value6=analogRead(Hall_sensor6);


Serial.print(Hall_value1);
Serial.print(",");
Serial.print(Hall_value2);
Serial.print(",");
Serial.print(Hall_value3);
Serial.print(",");
Serial.print(Hall_value4);
Serial.print(",");
Serial.print(Hall_value5);
Serial.print(",");
Serial.println(Hall_value6);
}
```

D Appendix - Participant forms & questionnaire

Study “Experimental Validation of a dynamic arm support”

You are being invited to participate in a research study titled Validation study of a passive dynamic arm support for robotic laparoscopic surgery. This study is being done by Pim Schrijvershof from the TU Delft under the guidance of dr. ir. T. Horeman.

The purpose of this research study is to validate the prototype that is built and to measure changes in arm position in the learning curve of robotic surgery and will take you approximately 10 minutes to complete. The data will be used for a master thesis on the TU Delft and its publication and a paper. We will be asking you to perform a set task in the AdLab-RS robotic laparoscopy simulator for 8 times in a row while your arms are either supported or not supported by an arm support. During these tests, the position of your arms will be measured. Afterwards, we will ask you to fill in a question form on the perceived comfort of the entire activity.

As with any online activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimize any risks by converting the personal data into anonymous data, meaning that all names will be attached to a participant number, which can’t be traced back to the participants. The data will be stored on the project storage of the TU Delft. No sensitive data will be gathered from participants.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions. Within 2 weeks of the experiments your data can still be removed if wished for.

Thank you for taking part!

Pim Schrijvershof

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated __________ , or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves: - taking part in a task on a simulator while my arms are supported - the sensoric tracking of my movements during the task - filling out a questionnaire	☐	☐
4. I understand that I will not be compensated for my participation by financial means	☐	☐
5. I understand that the study will take approximately 15 mins	☐	☐
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
6. I understand that taking part in the study involves the following risks: injuries as a result of failure of the system, personal data such as name and age getting lost. I understand that these will be mitigated by a inspection on the safety of the system and a data protection plan. The experiment can be stopped at any point.	☐	☐
7. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) and associated personally identifiable research data (PIRD) with the potential risk of my identity being revealed.	☐	☐
8. I understand that the following steps will be taken to minimise the threat of a data breach, and protect my identity in the event of such a breach: pseudonymisation, secure data storage.	☐	☐
9. I understand that personal information collected about me that can identify me, such as my name, will not be shared beyond the study team.	☐	☐
10. I understand that the (identifiable) personal data I provide will be destroyed after the publication	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
11. I understand that after the research study the de-identified information I provide will be used for a publication of the thesis of Pim Schrijvershof.	☐	☐
12. I agree that my responses, views or other input can be quoted anonymously in research outputs	☐	☐
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE		

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
13. I give permission for the de-identified research data that I provide to be archived in the TU Delft project storage repository so it can be used for future research and learning.	☐	☐

Signatures

__________________________ _________________________ ________

Name of participant Signature Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

________________________ __________________ ________

Researcher name Signature Date

Study contact details for further information:

Pim Schrijvershof

Questionnaire after taking part in the experiment

participant #___

Name	Date	1^{st} test was with arm support 1^{st} test was without arm support	☐ ☐
Age	Gender	Left handed Right handed	☐ ☐

1. Nasa TLX – For the tests WITH arm support

Mental demand — How mentally demanding was the task?

Very Low | | | | | | | | | | | | | | | | | | | | | Very High

Physical demand — How physically demanding was the task?

Very Low | | | | | | | | | | | | | | | | | | | | | Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect | | | | | | | | | | | | | | | | | | | | | Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low | | | | | | | | | | | | | | | | | | | | | Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed were you?

Very Low | | | | | | | | | | | | | | | | | | | | | Very High

2. Nasa TLX – For the tests WITHOUT arm support

Mental demand

How mentally demanding was the task?

Very Low | Very High

Physical demand

How physically demanding was the task?

Very Low | Very High

Performance

How successful were you in accomplishing what you were asked to do?

Failure | Perfect

Effort

How hard did you have to work to accomplish your level of performance?

Very Low | Very High

Frustration

How insecure, discouraged, irritated, stressed, and annoyed were you?

Very Low | Very High

3. General questions

What can be improved upon the system in total? (The AdLab-RS + Arm support)

Is it more pleasant to work with the arm support or without it?

Do you see the added value of the arm support for shorter tasks? (2-20min)

Do you see the added value of the arm support for longer tasks? (20min – 3 hour)

How intuitive was the use of the arm support?

Very confusing, difficult to setup | Very logical, easy to setup

E Appendix - Literature study

A Classification and Systematic Review of Passive Dynamic Arm Supports by Working Principle

ME51010 Literature Report

Pim Schrijvershof
(4582179)

Delft University of Technology

Mechanical, Maritime and Materials Engineering (3ME)
Department of BioMechanical Design

11-08-2022

Abstract

***Background*:** Surgeons performing robotic assisted laparoscopic surgery experience physical stress and overuse of shoulder muscles due to sub-optimal arm support during surgery. In an attempt to develop an improved arm support system, background research is necessary into the topic of passive dynamic arm supports.
***Objective*:** To present a systematic review of all passive dynamic arm supports found in the literature, classifying them into distinct working principles and presenting the most promising working principles for the applications within robotic assisted laparoscopic surgery.
***Method*:** The PRISMA method was used to conduct the literature review, using three search engines: PubMed, Scopus and WebOfScience. The articles went through an identification phase, screening phase, eligibility phase and the inclusion phase. The arm supports of the included articles were analysed for their working principle and different characteristics.
***Results*:** 68 Papers were included in this report, resulting in 74 unique arm supports. The arm supports could be classified into the following working principles: single pivot point mechanisms (2,6%), single linkage mechanisms (4%), multiple linkage mechanisms (12%), direct pulling cable mechanisms (13,3%), 4-bar mechanisms with the base as a vertical linkage (30,7%), 4-bar mechanisms without the base as a vertical linkage (4%), torsion around shoulder based mechanisms (16%), spring-loaded lever mechanisms (13,3%), leaf spring mechanisms (4%) and mechanisms with multiple springs acting as shoulder muscles (1,3%).
Conclusion It is estimated that 4-bar mechanisms with an added lever, are the most promising mechanisms for the applications within robotic assisted laparoscopic surgery. This report can serve as the first step in developing a new arm support for the robotic master interfaces.

Contents

List of Figures

1 Introduction

Developments into robotic assisted laparoscopic surgery (RALS) were made as a means to relieve surgeons from the physical stress experienced from traditional laparoscopy, resulting in injuries and overuse of neck, shoulder and lower back muscles [14]. With RALS, it is possible for surgeons to operate patients through laparoscopy, while their bodies are in a more comfortable position. A robotic slave device is positioned over the patient with up to 4 arms with instruments that are inserted into the patients body. At a seperate system, the master interface, the surgeon is seated, controlling the robot remotely and more ergonomically. In Figure 1 the full system of the Da Vinci Si is shown, with the surgery robot and the master interface where the surgeon is seated.

Figure 1: Da Vinci Si system, with on the left the surgery robot above a patient and on the right the master interface where the surgeon is seated and controlling the robot.

The master interface consists of a 3D video screen connected to the camera on the robot arm that is inserted into the patients body. There are stereo speakers and a microphone to communicate with the assistants at the patient. During surgery, the surgeon is seated behind the master device while operating the arms of the machine by interacting with two joysticks and four to seven foot pedals. The joysticks have clamps to control clamping or cutting instruments and have up to seven DoF. There are many parameters to control, such as closing/opening the instruments, moving/rotating the instruments and moving/rotating the camera. During these actions, the head of the surgeon is supported by a headrest and the arms are supported by an armrest.

Although RALS was developed as a means to reduce the strain on a surgeons body during laparoscopic surgery, ergonomic studies and assessments show that there are still ergonomic risks involved in robotic laparoscopy. One of these risks is the way the arms of the surgeon are supported by the armrest of the master device, which is usually a stationary leather arm pad in front of the surgeon. In the study of Yang in 2016 [15], researchers found that the arms of surgeons are frequently not supported during surgery, due to the fixed nature of the armrest. Surgeon's arms are frequently off the armrest while they are moving the camera and adjusting positions of the instruments, increasing muscle activity in the shoulders, trapezius and wrists. The main deficits of the armrest are that it is stationary and only supporting at one location. During surgery, there are many actions that require a larger movement pattern of the arms of the surgeon than the armrest is able to support. The armrest is also not a good fit for the arms, as it can only support the arms at a single location. This increases biceps fatigue as the weight of the forearms has to be carried constantly.

	Terms (in title)	AND (in title)	NOT
	Upper extremit*	Orthotic devic*	Effect (title)
OR	Forearm	Orthotic research	Algorithm*
	Arm	Orthotics	Influence (title)
	Arms	Exoskelet*	Control (title)
	Upper limb*	Support	
		Assistive technolog*	
		assistive device*	
		Orthosis	

Table 1: Build of search query, the columns were used with the boolean operator OR between them and the rows with AND and NOT

It would therefore be useful to start developing an improved armrest for RALS systems. This improved armrest should be able to move freely in all directions with the surgeons arms during the surgery, while supporting the full arms in gravity. The system should have enough range of motion for all movements needed for RALS and not interfering with the master interface. Lastly the system needs to be able to be locked in place, so that surgeons can still do the most precise movements with a stable reference point.

To start these developments, background research is necessary to the topic of arm supports, especially dynamic arm supports. Literature reviews towards active arm supports already have been done. Therefore, in this report, a wide range of dynamic passive arm supports are gathered and analyzed. It presents a systematic review on all passive dynamic arm supports found in the literature. It will provide a classification of the different fundamental working principles behind these arm supports and tries to analyse key differences between them. Differences such as range of motion, volume, mounting type and location(s) of support. These factors are also compared to each other to look for relations between them.

The goal is to give an overview of all passive dynamic arm supports, provide a classification based on their working principles and presenting the most promising mechanisms to use when developing an improved armrest for RALS systems.

2 Method

Although the aim of this report was clear, before starting the actual search queries, a pre-study was done on the topic using google scholar, to get more familiar in the field of dynamic arm supports and to maximize the results by finding the proper nomenclature. The search for relevant articles was done using the PRISMA flow diagram, as can be seen in Figure 2. This report is built up from searches in three search engines. Scopus, WebOfScience and PubMed were used. For the report, one search query was used, with inclusion and exclusion criteria. The final search query was the following: ("Upper extremit*"[ti] OR Forearm[ti] OR Arm[ti] OR Arms[ti] OR "Upper limb*"[ti]) AND ("Orthotic devic*[ti]" OR "Orthotic research"[ti] OR Orthotics[ti] OR Exoskelet*[ti] OR Support[ti] OR "Assistive technolog*"[ti] OR "Assistive device*"[ti] OR Orthosis[ti]) AND NOT (Effect[ti] OR Algorithm* OR Influence[ti] OR Control[ti]). It can be seen in a structured manner in Table 1.

This resulted in 2613 records, of which 1029 could be excluded due to being duplicates, leaving us with 1584 original articles. Some of the papers contained relevant sources, from which more articles could be included through chain sampling. After removing the duplicates, the records were screened by their title and abstract. During this screening, articles were excluded if they would not include any type of arm support based from the title. This led to 475 articles to be potentially useful. In the eligibility phase, these articles were downloaded and searched for arm supports. Articles were excluded if they:

- Could not be accessed
- Did not visualize an arm support
- Presented an active arm support
- Were not written in English
- Only included arm supports that did not support the arm in gravity
- Only included arm supports that can not be used while being seated

This led to a total of 68 useful papers for this literature review.
For a structured overview of all the mechanisms found in passive dynamic arm supports, a classification tree was made with the help of Stackexchange. It provides a clear insight into the distinct types of mechanisms found in passive dynamic arm supports, and how many there are in each category. It also shows in which state of development the mechanisms are according to the articles found. The result is seen in Figure 8. For the analysis of different characteristics of the arm supports, a level classification is proposed and used for the range of motion of the devices.

3 Results

The searches resulted in a total of 68 useful papers, which contained 74 unique passive dynamic arm supports. In this chapter, the arm supports are shown with their working principles, classified into distinct categories and judged on multiple characteristics.

3.1 Categories of mechanisms based on rotation only

A few dynamic arm supports were found that only allow rotation without any translation. This is rotation around two axes, so the user has two DoF (Figure 3). It is rarely mentioned in the literature, probably because of its unpractical use: to grab something from down low, the

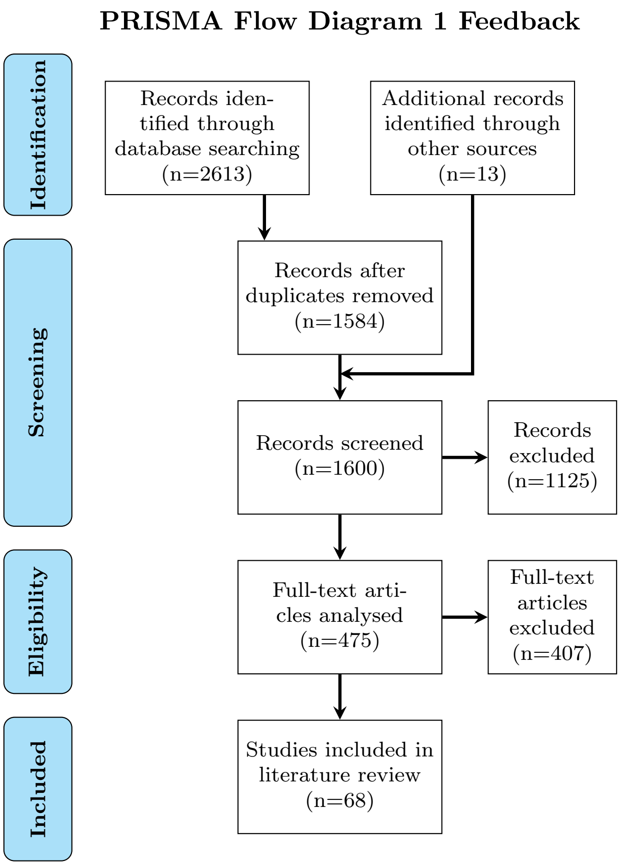


Figure 2: PRISMA flow diagram for systematic literature review (based on [1])

user has to move his elbow very high. Also, this type of arm support lacks a fundamental range of motion for most uses, the translation.

Figure 3: C-Clamp, an arm support rotating around two axes

3.2 Categories of mechanisms that allow xy-translation

This subsection of supports are supports that are based on linkages with rotational joints with the rotational axes parallel to the z-axis. Therefore, they only allow movement in the xy plane, supporting the arm in the z-direction on a fixed height. They consist of

- A single linkage, Figure 4
- Multiple linkages, Figure 5

These type of supports are used in rehabilitation, as well as everyday desk work such as mousing behind a computer. They can be height adjustable as well.

Figure 4: 'Thomas steady arm', a single-linkage xy-plane arm support

Figure 5: The Ergorest, a multi-linkage, height adjustable, xy-plane arm support

3.3 Categories of mechanisms that allow xyz translation

3.3.1 Direct cable pulling mechanisms

Cable pulling mechanisms pull the arm(s) of the user from a vertical cable, leaving the arm in a stable hanging position. The cable is balanced in three ways:

- Mass balanced
- Spring balanced
- User balanced

They are mostly used for people with decreased arm function due to the usually large size and overhead nature of the mechanisms.

Mass balanced
In a mass balanced cable, a lever arm mechanism is made with the weight of the arm on one end and a counterweight on the other end. The counterweight creates a moment around the rotational joint in the middle of the rod, which balances for the moment that is created by the weight of the arm of the user on the other end of the rod. This can be seen in Figure 6.

Spring balanced
In spring balanced mechanisms, the tension on the cable is countered by a spring or a mechanism with springs, an example is seen in Figure 7.

User balanced
User-balanced mechanisms require the user to provide the tension on the cable for lifting the arm. This is done by extending one arm, which lifts the other arm up. Only one arm can be lifted at a time (Figure 8).

Figure 6: The Nitzbon Mobility Arm, a mass-balanced cable pulling mechanism

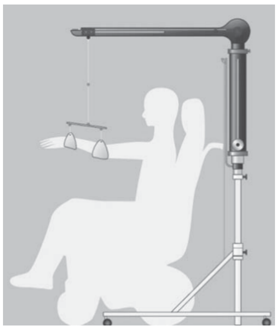


Figure 7: 'The Sling' from Focal Meditech, a spring-balanced cable pulling mechanism [2]

Figure 8: Dynamic triceps driven orthosis (DTDO), where one arm pulls the other arm upwards with a cable

3.3.2 4-bar mechanisms with the base as a vertical linkage

The group 4-bar mechanisms with the base as a vertical linkage is sectioned into the following groups and subgroups:

- Single 4-bar
  - With added lever
- Double 4-bar

They make use of a reference frame, which can be the users body or a wheelchair for one of the links.

Single 4-bar mechanisms

Single 4-bar arm supports use the link parallel to the 'base' link for attaching arm cups or a linkage to the arm cup for extra DoF. The parallel link of the 4-bar usually stays vertical throughout its use, such as in Figure 9

Figure 9: Prototype of an arm support with a 4-bar mechanism with an extra linkage for an added DoF [3]

4-bar with added lever

4-Bar mechanisms with an added lever are typically used for when the system provides support at two locations. This could be the upper- and lower arm, but also the elbow and wrist. The 4-bar part acts as the main support of both the upper and lower arm and provides a stable vertical basis for the lever, as it always stays perpendicular to the ground. An example is seen in Figure 10.

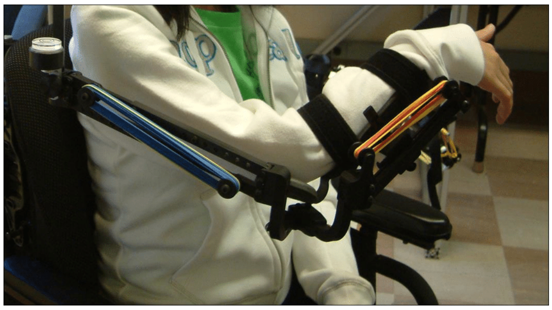


Figure 10: 'The Wrex', an arm support with a mechanism consisting of a 4-bar with an added spring-loaded lever [4]

Double 4-bar mechanisms

Double 4-bar mechanisms have the same characteristics of single ones, but they have the two 4-bars linked to each other by combining one of their vertical links as a rotational joint around the z-axis. This allows significantly more range of motion than single 4-bar mechanisms. An example is seen in Figure 11.

3.3.3 4-bar mechanisms without vertical linkage as a base

This is a seperate group of systems, as the 4-bar mechanism of these arm supports are only supported in one rotational joint, while the previous discussed arm supports have the base acting as the vertical linkage. An example can be seen in Figure 12.

Figure 11: 'Robo-Mate', an exoskeleton arm support using two linked 4-bar mechanisms [5]

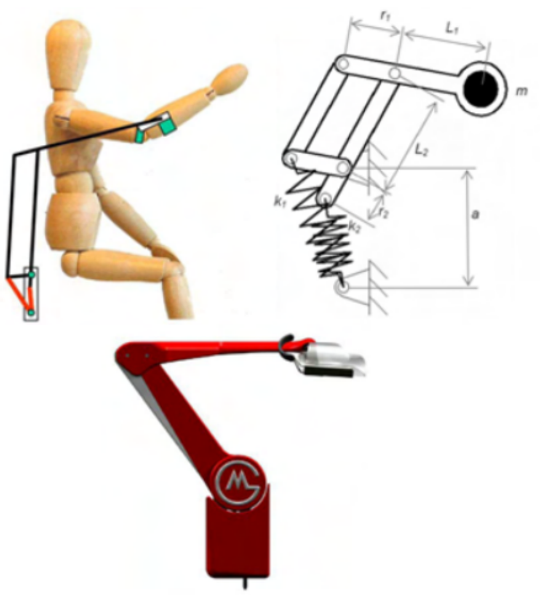


Figure 12: 'ARMON', a 4-bar mechanism arm support without the base as a vertical link [6]

3.3.4 Mechanisms with a single lever with torsion

These type of arm support systems mostly make use of a mechanism inside of a 'black box' around a single joint to generate torsion, such as Figure 13. This joint is usually located at the shoulder of the user. For the instances that the black box is shown in articles, it houses multiple parallel springs in combination with a lever gear, which can be seen in Figure 14, as well as in [16]. 9 Out of 11 of the passive exoskeletons fit into this category. Even though the full working principle inside the black box is not always clear, this category is based on the fact that the torsion is generated around a single joint onto a lever that supports the arm.

3.3.5 Lever mechanisms with extension springs

Spring loaded lever mechanisms are mechanisms where a spring-loaded lever with an arm cup is attached to the arm of the user.

Single lever
Single lever mechanisms have a lever with a rotation point at the shoulder, which is then actuated by an

Figure 13: Examples of arm supports with mechanisms actuated by torsional forces around a single axis of the lever that supports the arm. Left: Exoskeleton 'Levitate' [7], right: 'Dowing' [8]

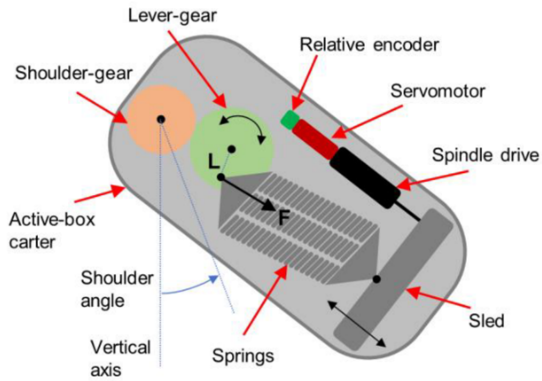


Figure 14: The inside of a black box functioning as a torsional spring. This one has a servomotor for motorized tuning of the torsional force [9]

extension spring or band, such as in Figure 15.

Figure 15: 'Armon Edero', a single lever arm support actuated by an adjustable extension spring [8].

Double lever
Double lever mechanisms use two levers to support the arm in two places, mostly the upper arm and the lower arm. The levers are actuated by extension springs or bands, or strings on pulleys attached to springs. This type of mechanism is heavily dependant on proper dimensioning of the spring attachments to work and can become fairly complicated. It can be seen in Figure 16.

3.3.6 Leaf spring mechanisms

These type of mechanisms differ significantly from each other but use leaf springs as their form of passive

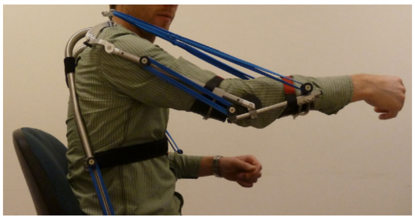


Figure 16: 'A-gear', a double-lever arm support mechanism supporting the arm in two places [10].

actuation. It is an interesting type of mechanism, as leaf springs are able to store energy while still being close to the body and can act in structural ways as well. Skelex [11] uses their leaf springs in an advanced way, combining two tasks: they store energy by bending and function as the main structural component of the exosuit by transferring the weight of the arms into the waist (Figure 17), while other exos need an additional solid piece of metal from the waist to the shoulders for this.

Figure 17: 'Skelex-360', an exosuit with bending beams acting as actuators and structural components. [11].

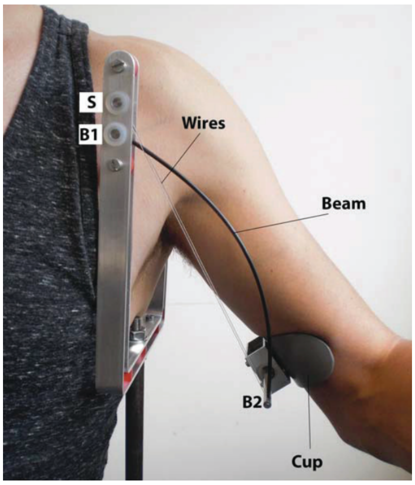


Figure 18: Prototype of an arm support where bending beams function as the passive actuator. The beams support the arm in gravity but also counter rotation of the arm [12].

3.3.7 Multiple springs as shoulder muscles

The last proposed group of systems comes from an exoskeleton that has springs attached between the elbow and the shoulder. As the springs aligned with the direction of the shoulder muscle fibers, it is expected to aid this muscle in lifting the arm and thus reduce strain on the shoulders, mainly in abduction but also some in flexion. Figure 19

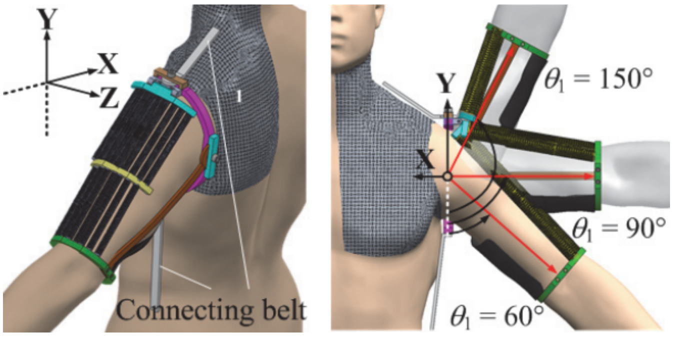


Figure 19: Unique mechanism with springs in the direction of the shoulder muscle [13]

3.4 Proposed Classification tree Figure 20

The arm supports where classified into 3 distinct categories, based upon the movement planes. Allowing rotation only, allowing rotation and xy translation, and supports that allow xyz translation. This was done because the first two categories lack fundamental support for vertical movement patterns of the user. The second stage of the classification was based on the working principles of the arm supports, with each category having its own color for clarity. Some of these categories have subcategories. In the last stage of the classification, the arm supports are assigned to the design phase they were in according to the articles. In these design phase columns, the number of the arm support is seen, with a link to the literature it was found in. The same numbers are used in Appendix A.

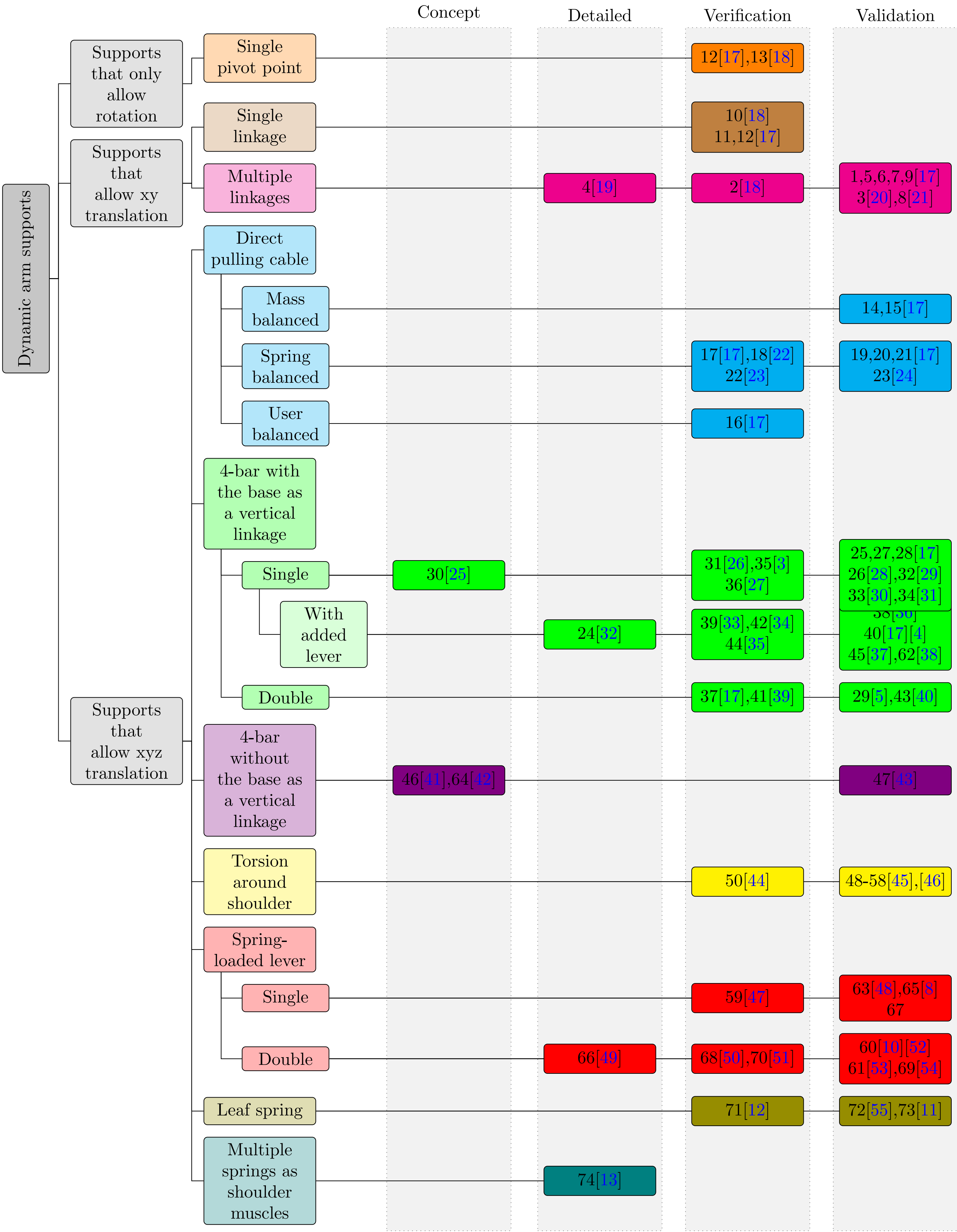


Figure 20: Classification tree of passive dynamic arm supports. Tree diagram was made with codes from Tex Stack Exchange

3.5 Distribution of papers throughout the years

In Figure 21 we can see the amount of included papers per year in a graph. A small number of published papers in the early 2000's can be seen, as well as a sudden spike in 2007. Following 2011, a steady increase is seen which drops back down after 2016. Then 2020 and 2021 both had a substantial amount of papers.

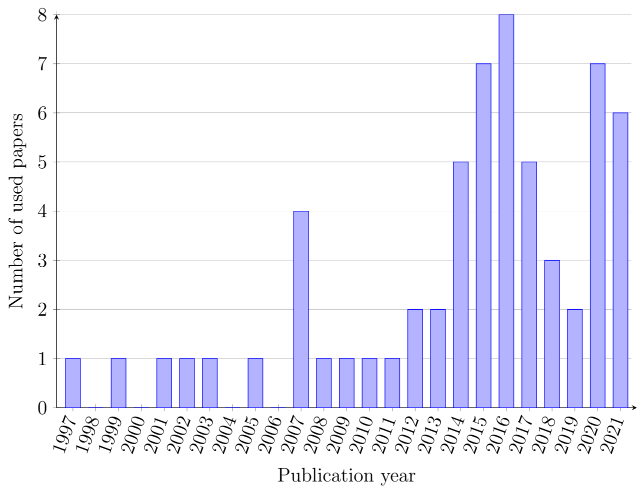


Figure 21: Histogram of the number of used papers each year for this literature review

3.6 Arm supports characteristics

The arm supports were analyzed and rated on multiple characteristics. These were:

- Mounting type
- Location(s) of support
- Volume
- Range of Motion
- Complexity
- Working principle

3.6.1 Mounting type

The mounting type could be analyzed from the pictures shown in the articles. These were the four mounting methods seen:

- Body worn (31,0%)
- Immovable Object (18,9%), such as a table or chair
- Movable object (39,2%), such as a wheelchair
- On a base (10,8%), so a stand designed specifically for the arm support to act as the stable base

3.6.2 Location(s) of support

Most of these could also be seen from the pictures in the articles. Two articles only showed concept drawings where a clear location for the support was not yet determined. The location(s) were:

- Elbow & forearm (25,7%)

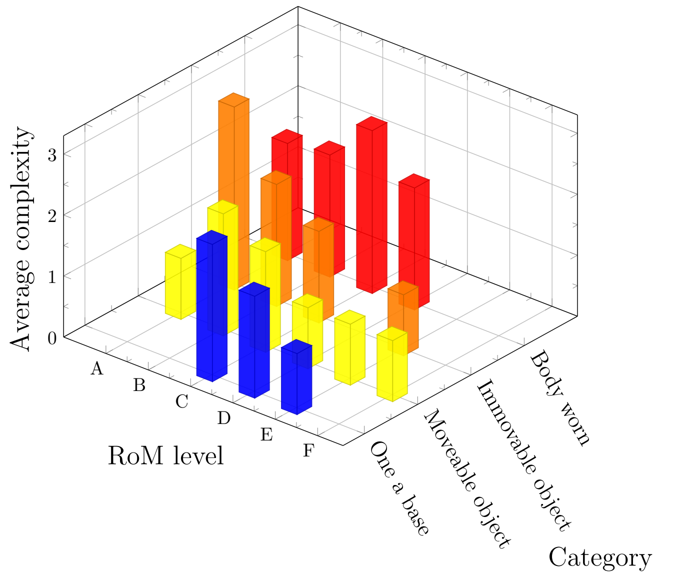


Figure 22: 3D Histogram of the mounting types of arm supports in different range of motion levels with their associated average complexity level.

- Upper arm (23,0%)
- Forearm (24,3%)
- Upper arm & forearm (9,5%)
- Forearm & wrist (5,4%)
- Upper arm & wrist (1,4%)
- Elbow (1,4%)
- Wrist (2.7%)
- Upper arm, forearm & wrist (4,1%)
- Unknown (2,7%)

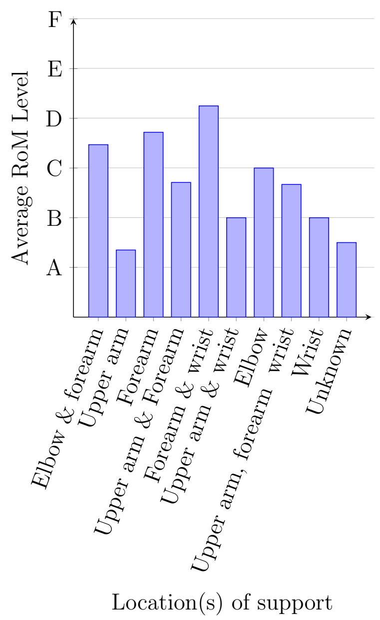
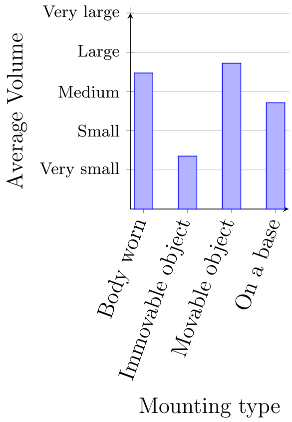


Figure 23: Histogram of the average range of motion level per location(s) of support. RoM levels where given a number score from A=1 to F=6, then combined and their average was calculated.



hfill

Figure 24: Histogram of the Average volume for arm supports with different mounting types

3.6.3 Volume

The volume was judged with a score ranging from very small to very large, relatively to each other. No objective scores were used as this category was more used to compare the arm supports. The levels turned out to be:

- Very small (1,4%)
- Small (25,7%)
- Medium (43,2%)
- Large (25,7%)
- Very large (4,1%)

The "very small" score was given to the arm support with the least volume: an arm support fitted into the clothing of the user, PlaySkinLift. "Very large" was given to the arm support with the most volume: A two meter tall pulling cable mechanism with a base, Freeball. The other scores where based relatively to these.

3.6.4 Proposed level classification of the Range of Motion

For the range of motion, the translation was most important, as all of the arm supports allowed wrist movement and therefore flexion, extension, radial deviation and ulnar deviation. They also all allowed elbow extension and flexion. Thus, the difference between the range of motion was found in the planes where movement was allowed, and the reach within those planes. The amount of translation (small, medium, large) was judged relatively to one another. The information was extracted from making an estimation based on the pictures in the articles and, if necessary, from online videos.

- Level A: All (20,3%)
- Level B: All xy-translation, large z-translation (14,9%) - movements like painting
- Level C: All xy-translation, medium z-translation (40,5%) - movements like bringing a spoon to the mouth
- Level D: Medium xy-translation, small z-translation (6,8%) - movements like writing, petting a cat
- Level E: Medium xy-translation + rotation (14,9%) - movements like using a computer mouse
- Level F: Rotation only (2,7%)

3.6.5 Complexity

There are diverging perspectives in the literature on how to measure the complexity of a certain design. The decision was made to measure complexity based on how much a certain system could be decomposed into smaller systems/parts, as this method is used to assess system difficulty and compare systems [56]. Complexity is therefore judged as follows:

- Low: a maximum of 3 moving parts (47,3%)
- Medium: 4-8 moving parts (36,5%)
- High: 9 or more moving parts (16,2%)

The final overview of all the systems with all their characteristics is shown in Appendix A.
In Figure 25 a 3D-histogram was made to show the connection between the working principles and their associated range of motion level and the number of systems that fit those categories.

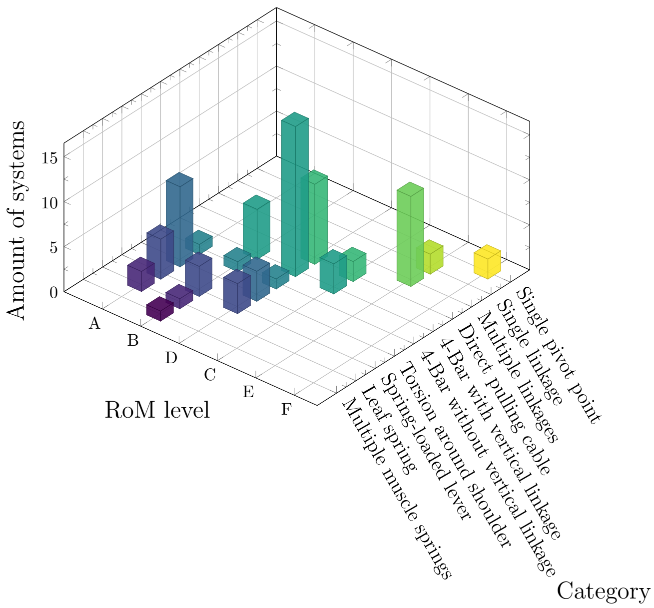


Figure 25: 3D Histogram of the category of systems vs the range of motion and the number of systems that fit the category

4 Discussion

It can be seen from Figure 21 that passive dynamic arm supports have had their trend, publication rate wise, at around 2016 but a new spike of interest can be seen in 2020/2021. Therefore, it can be assumed that this field of study and development is far from done. The results of this literature review, interesting discussion points, the limitations of the report and recommendations will be discussed in this section.

4.1 Classification based upon movement planes

The three main categories in the classification tree are based upon the planes in which the user can is able to move their upper limbs while being supported by the arm support. As stated in the range of motion, all of the arm supports allow all movements of the wrist and elbow, and therefore rotation was not a factor for differentiating the arm supports. What was necessary however, was that for the goal of determining what arm support mechanism would be best for RALS, a number of arm supports missed fundamental movement possibilities. The arm supports should be able to allow translation in all planes, as this is required for the surgeon's input in RALS systems. Arm supports which allow only translation in the xy plane or no translation at all were therefore placed into seperate categories.

4.2 Characteristics of each category

From the analysis of all the arm supports shown in Appendix A, it can be seen that each category has some noticeable characteristics.
Arm supports with a single pivot point consist of low complexity, small volume arm supports.
Arm supports with linkages rotating around z-axes are low in complexity, small in volume, and either support the forearm only, or together with the elbow. They are also mostly mounted on objects such as a table or a wheelchair.
Direct cable pulling mechanisms vary in their complexity, are usually larger in volume and mostly support the elbow and forearm. Their range of motion is mostly in the xy-plane, with small to medium z movement.
4-Bar mechanisms with the base being a vertical link mostly support the elbow & forearm but differ in the other characteristics. This group is also the largest group of all the arm supports, having multiple applications and could be considered the most versatile.
4-Bar mechanisms without the base as a vertical link are both low in complexity, support the elbow & forearm and are mounted onto a movable object.
Mechanisms based on a torsional piece around the shoulder are mostly body-worn exosuits, with the largest range of motion. The location of support is mostly the upper arm but complexity varies significantly. The average volume is medium-large. These are mostly new systems, with one exception from 1990.
Spring loaded single lever mechanisms are usually medium in complexity, medium in volume and have level A and B range of motion 3.6.
Double lever mechanisms always support the arm at two locations, have a medium-high complexity and are medium-large in volume. The RoM is usually level B, so on the larger side.
Leaf spring mechanisms usually have a large range of motion, level A and B. They are body-worn but differ in the other characteristics.
The last group is only one mechanism, which could not fit into the other groups. It is body worn, level E RoM, upper arm supporting, medium in complexity, small in volume and from 2014 in the detailed design phase.

4.3 Complexity and Range of Motion

From Figure 22 it can be seen that there is a link between the average complexity of the different categories and the range of motion levels of these systems. It shows that arm supports with more range of motion are usually more complex systems. This was to be expected, as systems that support more range of motion have to compensate for gravity in more extreme positions, thus require more complex mechanisms for this. Especially when adding in the z-translation, it is seen that the complexity of the systems significantly increases. This added range of motion and complexity usually goes at the cost of an increase in volume.

4.4 Location(s) of support

One thing that is noticed when looking at the location(s) of support of arm supports and other characteristics is that the location(s) of support are very task specific. The main goal of arm supports is to alleviate the muscles involved with performing the specific lifting task of the arm. This is best done by placing the location of support directly under the center of mass (CoM) of the arm combined with the load that is carried by the hand. Therefore, it is seen that supports meant to assist in daily tasks where no load is held in the hands have their location(s) of support either under the elbow, or with an combined upper arm/elbow/forearm support, such as Figure 10 or Figure 12. When supports are more meant to support the user when carrying loads, it is useful that the location of support is more placed forward, such as in Figure 11, as the CoM of the arm and the load is located closer to the wrist. Logically, the more load is carried, the more forward this location of support should be with the shift of the CoM. One could argue that when carrying load, there should always be a location of support at the wrist for dealing with the shear stress as the wrist is carrying the load. In practice however, this is rarely seen as it is close to impossible to support the wrist in all of its DoF without limiting its mobility. A more useful option for carrying heavy loads is removing the support entirely from the arms and attaching it directly to the load, as can be seen in Figure 26. It is also not of interest for the applications within RALS as the wrist is not carrying any load and has to be freely movable anyway. When looking at exoskeletons for upper extremity tasks, it can be seen that most of them provide support on the upper arm, so clearly not at the center of mass one could say. This is because of the application these arm supports are used for, which is overhead lifting and holding tools. In these applications the forearm is held vertically, shifting the CoM far backwards. This way, the location of support is not at the CoM but under it. If these arm supports are used for lifting tasks in front of the body with the forearms horizontal, there is still a significant amount of bicep involvement required. But this type of arm support is much slimmer in terms of size

Figure 26: Exhauss exoskeleton for the stable carry of heavy gimbal videocamera systems

around the arms, and provides more mobility, as can be seen in Figure 23.

4.5 Trends in mounting types

When looking at different mounting types, it can be seen from Figure 22 that different mounting types have different complexities. Arm supports mounted on movable objects are the least complex on average, and body worn arm supports are most complex. In this graph we can also see that systems mounted on movable objects require minimum complexity but tend to be quite high in volume. What is interesting also, is that body worn arm supports have more range of motion than other type of mounting types but at the cost of an increased volume, as can be seen from Figure 24. The more volume, the more the system will likely interfere with the surroundings. However, it can be argued that the bulk of the volume of body worn arm supports is located at the back of the user, which would not be as impractical as volume in the front, when looking at interference with a master interface. Lastly, it can also be seen that arm support systems on a base have the least RoM of the systems.

4.6 Limitations

One of the limitations of this literature report results from the overwhelming number of papers that were found in the database searches. When using all the different terms in the search queries, a total of around 10.000 papers were found, which would have been too much for this literature review. Thus, the decision was made to exclusively search papers that had the search terms in the title, with the exception of the word 'algorithm'. It is possible that because of this, some passive dynamic arm supports were missed in the process, making the list not exhaustive.
Another limitation is the fact that many arm supports that were mentioned in papers could not be found online and so they had to be left out. This limits the completeness of the report, although one could make the argument that an arm support that can not be found, has not proven itself to be thát useful, otherwise it would be well known and findable.

4.7 Most promising mechanisms for robotic laparoscopy

For the application of robotic laparoscopy, it is important to look at the requirements of the yet to be designed system. For robotic laparoscopic surgery, it is important that the device has at least a level D RoM, preferably level C. This rules out arm supports with rotation only or xy translation. Secondly, the RALS environment is tight in space, so support from above with long cables would interfere with the interface of the master devices. Therefore, direct pulling cables are also not a desirable choice. Thirdly, for stabilization and full elevation of the arm, it is preferred that the arm is supported at the forearm, so that the biceps are not strained. This rules out the exosuit mechanisms with torsion around the shoulder, as well as the mechanism with multiple springs replacing the shoulder muscles. Exosuits would be ruled out regardless, as any body-mounted system would be impractical due to having to suit up for several minutes before using it, and the hygiene issues surrounding body-worn systems for multiple users. Leaf spring mechanisms are also ruled out because all the arm supports found in this category are attached to the body instead of to the master interface, which is not preferred. This leaves four types of mechanisms: both 4-bar mechanisms, mounted torsion around shoulder mechanisms and spring-loaded lever mechanisms to be potentially useful in the search for a design for arm support in RALS as discussed in the section 1.

4.8 Which system for which application?

When discussing the best arm support system for robotic assisted laparoscopic surgery, it is important to look at what is required from the systems in certain applications. There are two standardized skill tasks when assessing the performance of trainees on simulators, namely ring transfer and needle passing [57]. A research article about armrest evaluation states that these skills can be assessed with two exercises: thread the rings (TR) and suture sponge (SS) [15]. The simulated exercises are shown in Figure 27. TR is a horizontal running suture exercise where a needle is put through multiple rings in a row. At each ring, the needle has to be transferred from one clamping instrument to the other. This requires clamping, rotating and moving the wrist and the use of both arms at the same time. As the rings are placed quite far from each other and in different directions, the exercise requires a large horizontal range of motion of the forearm. The conclusion of the above mentioned article also states that a stable forearm support is essential in increasing movement accuracy and reducing tremor [15]. It is likely that the 4-bar mechanism with the base as a vertical linkage, with an added lever would be best suited for this type of application for the following reasons:

This 4-bar mechanism type is a system that requires no change in length of the actuating springs when moving across the xy-plane. The full movement can be achieved purely by two rotational joints along the z-axis. This would result in a very stable movement pattern where the surgeon could deviate little from the horizontal plane, while the vertical movement joints could be held in a fixed position. The only other mechanism able of this is the double 4-bar mechanism, which seems the worse option as it is larger in size and heavier. This would interfere much quicker with the master device and the added weight results in a decrease in accuracy due to mass inertia. For adequate rotation of the wrist, it is important that the arms are not supported at the wrist, as this could hinder mobility. Rather the support should be at the forearms.

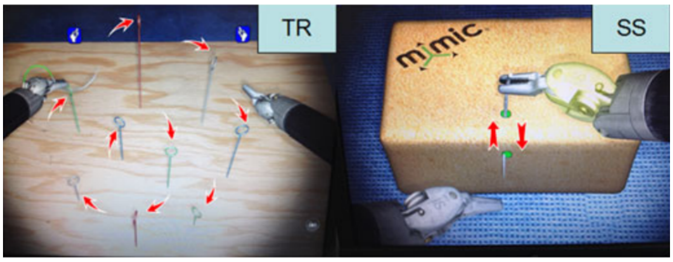


Figure 27: RALS Simulation exercises: Thread the Rings (TR) and Suture Sponge (SS)

SS is an exercise with a lot of wrist movement, where the operator has to put the suturing hook through a sponge at precise locations. This requires more vertical movement of the forearms but not a significant amount of horizontal movement. It requires very precise control of the needle and being able of rotating and translating the the needle with the instrument at the same time. Stability is again important in this exercise, as well as enough vertical range of motion of the system. What we now see is that during these type of exercises, surgeons are often unsupported in vertical movements because the wrist does not have enough RoM to fully grasp the vertical reach needed [15]. Therefore, the surgeons often leave the stationary armrest, something a dynamic arm support could prevent. It would again be best to support the arm at the forearm and not at the wrist, as wrist support could limit wrist mobility. Then a support mechanism such as the ARMON [43], a 4-bar mechanism without the base as a vertical link would be the best suited mechanism for the application. This is because this type of arm support has such a sophisticated support mechanism that the z-support is very precisely balanced, with errors less than 0.5% [6]. This will result in the most stable vertical movement out of all the arm support mechanisms. It also has enough vertical and horizontal range of motion and the wrist is free to rotate and move in any direction. Other systems such as the single levers with torsion or the other 4-bar mechanism would also work but are less precisely balanced, at the advantage of being less complex. But in this field, complexity is not estimated to be an issue due to the large budgets for all systems within the medical robotic field. For both applications, it seems that the second support locations other than at the forearm, should be at the elbow, as it has less contact area with the skin compared to an upper arm support. This will translate to less irritation on the skin because of sweat and heat in long operations. Systems such as Lightarm [23], Armeospring [54] and Freeball [22] seem to double down on range of motion and precise support, leaving volume for what it is. This results in very large arm supports that are high in complexity as well. For the application of rehabilitation, this seems like a viable option as training is in vitro setting and not meant for everyday use, making the downside of volume and complexity not that important. For the application of RALS however, this route seems less of a great option, as volume is a limiting factor in the use of an arm support in combination with the master interface of the RALS systems. Therefore, a system is most suited with a combination of balanced characteristics:

- The system has to have a range of motion level of at least C, so all arm movements within the xy plane and a medium RoM in the z-direction is required.
- The system needs to be mounted onto an object, namely the master interface.
- The system needs to provide support at the elbow and the forearm.
- Complexity is not a limiting factor
- Volume is limited by the master interface of RALS system

If these criteria are met, the system should be optimized for accuracy through precise z-support and smooth movement across all planes, with the least weight possible for mass inertia effects.

4.9 Literature gaps and wealth

From Figure 20, we can see some gaps in the literature. First of all, almost all of the torsion around shoulder mechanisms are validated, and there does not seem to be much research going on in this field. The group 4-bar mechanisms without the base as a vertical linkage has few papers in it, although it seems to be a promising field. Arm supports with single linkages or single pivot points are not well documented, as most are published last century, some going back to 1936 [17]. Leaf spring mechanisms are also a rare group with little research going on. The three papers found also describe a vastly different approach, which means this field still has loads of potential. Lastly, the multiple springs as shoulder muscles group presents only one paper which is in the detailed design phase, although its conclusion shows promising results. When looking at 4-bar mechanisms, we see an abundance of papers, mostly in the verification and validation phase.

4.10 Recommendations

The research presented in this report is aimed towards passive dynamic arm supports, which is not the main

focus of research towards mechanisms of arm supports nowadays. There is much more to be found on active supporting devices as of today. What is still missing, is research towards hybrid systems, which use passive actuation in combination with electrical adjustability. The main advantage of this group of systems is that it offers large power and force while using low powered electrical systems. This way systems can be strong, while still being lightweight and long lasting. In this literature review, only two hybrid systems were found. This could be because of the lack of electrical and robot terms in the search queries but only two papers mentioning hybrids seems to indicate a lack of research to the topic as well. For the topic of the thesis towards an arm support for medical use, it is also necessary to know how a new design would interact with existing master interfaces of RALS systems. Therefore, a literature study towards the diverse types of master interfaces with an analysis of their ergonomics would be useful. Much research has been done towards surgeons' ergonomic experiences of these master devices but an effort to bundle this feedback has not yet been made.
Now that the most promising mechanisms are estimated in this report, and recommendations are given for the best mechanisms per application within the field of RALS, research could be done towards designing a new arm support system purely for RALS systems and a prototype can be made. The list of demands should be worked out with dimensions specifically for the master interfaces and the systems mentioned in this paper can be used to start the design cycle. This is the most logical next step following this literature review.

5 Conclusion

The aim of this literature review was to present an overview and classification of all passive dynamic arm supports found in literature, and present the most useful mechanism for use in RALS.
Using the PRISMA method, the total number of included papers is 68, resulting in 74 unique passive dynamic arm supports.

The review shows that arm supports can be classified into three distinct categories based on movement planes: Rotation only (no movement), xy movement and xyz movement. Further distribution leads to ten different working principles: single pivot point mechanisms, single linkage mechanisms, multiple linkage mechanisms, direct pulling cable mechanisms, 4-bar mechanisms with the base as a vertical linkage, 4-bar mechanisms without the base as a vertical linkage, torsion around shoulder based mechanisms, spring-loaded lever mechanisms, leaf spring mechanisms and mechanisms with multiple springs acting as shoulder muscles.
An analysis of different characteristics of the arm supports shows that there is a correlation between range of motion and complexity, where the more range of motion is available to the arm support, the more complex it is on average. For the applications within robotic assisted laparoscopic surgery, it is estimated that 4-bar mechanisms with an added lever are the most promising, with 4-bar mechanisms with the base as a vertical linkage to be the most useful for horizontal movement applications, and 4-bar mechanisms without the base as a vertical linkage are deemed to be the most useful for vertical movement applications. After meeting the dimensional demands of the RALS interface, the system should be optimized for accuracy through precise z-support and smooth movement across all planes.

Trends in arm support systems can be seen as some systems seem to double down on range of motion and precise support, at the cost of being large in volume and high in complexity as well. These systems are catered towards rehabilitation.

The goals of this literature review, to present a systematic review of all passive dynamic arm supports, providing a classification based on the working principles and to give an idea of the most promising mechanisms for RALS is reached.

Therefore, it is recommended that this literature review is followed up by a design cycle towards a new arm support system purely for RALS interfaces, as this report can serve as the first step in this development.

References

[1] D. Moher, A. Liberati, J. Tetzlaff, D. G. Altman, D. Altman, G. Antes, D. Atkins, V. Barbour, N. Barrowman, J. A. Berlin, J. Clark, M. Clarke, D. Cook, R. D'Amico, J. J. Deeks, P. J. Devereaux, K. Dickersin, M. Egger, E. Ernst, P. C. Gøtzsche, J. Grimshaw, G. Guyatt, J. Higgins, J. P. Ioannidis, J. Kleijnen, T. Lang, N. Magrini, D. McNamee, L. Moja, C. Mulrow, M. Napoli, A. Oxman, B. Pham, D. Rennie, M. Sampson, K. F. Schulz, P. G. Shekelle, D. Tovey, and P. Tugwell, "Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement," *PLoS Medicine*, vol. 6, no. 7, 2009.

[2] L. Heutinck, M. Jansen, D. V. D. Pijl, and I. J. M. D. Groot, "Sling use with virtual gaming duchenne dystrophy," vol. 2, pp. 1–14, 2015.

[3] D. Odell, A. Barr, R. Goldberg, J. Chung, and D. Rempel, "Evaluation of a dynamic arm support for seated and standing tasks: a laboratory study of electromyography and subjective feedback," *ERGONOMICS*, vol. 50, no. 4, pp. 520–535, apr 2007.

[4] A. G. Dunning and J. L. Herder, "A review of assistive devices for arm balancing," in *2013 IEEE 13TH INTERNATIONAL CONFERENCE ON REHABILITATION ROBOTICS (ICORR)*, ser. International Conference on Rehabilitation Robotics ICORR, IEEE; EMB; IEEE Robot \& Automat