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Workspace and Kinematic Modeling and Analysis of Semi-Robotic Laparoscopic Surgery

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WORKSPACE AND KINEMATIC MODELING AND ANALYSIS OF SEMI-ROBOTIC LAPAROSCOPIC SURGERY

By

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Abstract

Laparoscopic Surgery has been revolutionized by the world of Surgical Robotics. Robot-Assisted Surgeries have been proven to have many advantages over the fundamental, traditional "by-hand" procedures previously conducted, and still currently being done for certain operations. Robot-assisted surgery may offer benefits to patients through the use of minimally invasive techniques, which may result in reduced blood loss, reduced blood transfusion, fewer complications, reduced postoperative pain, shorter hospital stays, and reduced recovery times (Ho et al., 2011). Studies have proven that robotic surgery may lead to patients recovering faster depending on the timeframe and the type of procedure (Tang et al., 2018). These benefits provide the highest quality care for the patient that can be provided. Robotic-assisted surgical platforms may overcome many of the shortcomings of laparoscopy while preserving the patient benefits (Boggess, 2007). Laparoscopic Surgery provides many benefits over open surgery as well and including the Robotic Surgical Assist allows for further/amplified benefits for the parties involved. The idea is to minimize the need for lengthy patient recovery time, discomfort, and complications caused by the procedure itself. The pain, discomfort, and disability, or other morbidities as a result of surgery is more frequently due to trauma involved in gaining access to the area to perform the intended procedure rather than from the procedure itself (Mack, 2001). Regulating certain areas of the procedure, such as required incision size, allows the patient a smoother recovery.

With laparoscopic surgery, it limits risks and complications as a minimally invasive approach but, with robot-assisted laparoscopic surgery, it is even more as such. Currently, there seems to be a struggle in the field of medicine between how best to improve the surgical robots in comparison

to how to better optimize, or create, smaller surgical devices to assist in surgeries. A factor that was found to be lacking in the field of medicine was the definition of actions done during surgical procedures. While used widely from a medical standpoint, from an operational standpoint it is not common practice to question the mathematical symbolization of the movements and actions done during surgery. The goal of this research is to determine, analyze, evaluate, and simplify the parameters that are present during Laparoscopic Surgery. These parameters will be compared between traditional surgery and robot-assisted surgery. The robot-assisted condition will be established using the Semi-Robotic Laparoscopic Surgery Support System developed by a University of Central Florida Senior Design Team finalized in the academic semester of Spring 2020. This system utilizes the aspects and features of a surgical robot while maintaining a small form factor and cheap production and purchasing price. Ultimately, this will allow for further evaluation of technologies exploiting the developed surgical robot for research in semi-autonomous control, and safety mechanisms in the context of robotic surgery. It is important to note that this technology is developed as a kinematic guide for laparoscopic surgery. This guiding assist is similar to the features incorporated in robot-assisted laparoscopic surgery which is what allows us to use this surgical assist device to represent the robot-assisted condition.

This technology optimizes the condition of conventional laparoscopic surgery by introducing a braking mechanism into the standard procedure without requiring the major application of the full surgical systems. Through the utilization of this guiding system, this research has established and compared the kinematic and workspace parameters for robot-assisted laparoscopic surgery when the system is equipped vs. when it is equipped and activated; creating two different conditions of Workspace Controlled Laparoscopic Surgery and Kinematically Constrained Laparoscopic

Surgery. It was deemed necessary to accomplish an understanding of both domains as well as in comparison to traditional laparoscopic surgical practices in order to engage the argument from a holistic point of view.

Throughout this research, it was determined that, when evaluating traditional Laparoscopic Surgery, there are a series of parameters that are present when discussing the workspace of the human abdomen and the kinematics of the trocar, surgical tool, and camera placed into that workspace. Between these parameters, a variety of similarities was discovered using geometric rules and algebraic functional relationships within the kinematics. Upon equipping the Semi-Robotic Laparoscopic Surgery Support System to the procedure, certain parameters get "zeroed out" due to the fixed nature of the device from one abdominal insertion point to the next. While most parameters may maintain the same behaviors upon the installation of the technology, the majority of these same parameters get "zeroed out" when the technology is activated.

The overall purpose and intent of this research is to define, evaluate, and compare various surgical parameters associated with the practice of laparoscopic surgery while running a comparison between the effectiveness of traditional surgery against robot-assisted surgery that can be made from a new perspective by evaluating the differences in their respective parameters. Results which will be discussed include: specific parameter definitions and labeling, how these parameters benefit the medical field, direct parameter comparison between the evaluated conditions of traditional surgery and robot-assisted surgery (represented by kinematic guiding technology and comparing when the device is applied, Workspace Controlled condition, versus when the braking system is activated, Kinematically Constrained condition), and how these different surgical techniques modify the conditions of surgery for the surgeon and the patient.

Dedication

To the work done by the UCF 2020 Senior Design Team on the Semi-Robotic Laparoscopic Surgery Support System and to the advancement medical field in surgical assist devices and robotic technology.

Acknowledgements

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1 Introduction

1.1 Overall Background

Even with all the advantages associated with Robot Assisted Surgery, there are size constraints and high expenses associated with acquiring and maintaining robotic surgical equipment for minimally invasive surgery (Grande et al., 2013). A suitably sized operating theatre can reduce operation duration and the risk of de-sterilization which is a common reason for hospitals to opt-out of purchasing such technologies due to not having the appropriate size operating environment to accommodate for it (Randell et al., 2019). Therefore, research has been, and continues to be, done for the development of the Semi-Robotic Laparoscopic Surgery Support System. This device would work in tandem with the Trocars used in the laparoscopic procedures to provide the functionality and benefits that come with having a surgical robot without the limitations of pricing and size constraints associated with the device.

Hand-held robots have the advantages of being compact and easily integrated into the normal surgical workflow since there is typically little or no setup time and also have a significantly reduced cost to healthcare providers as they do not necessitate the complex, multi degree-of-freedom linkages that grounded robots require (Payne & Yang, 2014). Such a device and similar technologies could allow for lower budget hospitals to afford to have the advantages of a robot assisted surgery, or close to it, without the burden of being unable to afford the product due to the high price-tag associated with it to benefit their patients at the most that can be offered by the facility.

In particular, the armed forces and their medical divisions would benefit greatly from such a device. Being on active duty and requiring to conduct surgeries generally indicates that the soldier would need to be able to be up and ready in a timely fashion. Since its implementation, the frequency of Robot-Assisted Surgery use has increased at a faster rate in the Department of Defense than in the civilian world (Grasso et al., 2019). For many procedures, the "invasiveness" involved has been dramatically reduced resulting in superior outcomes manifested as improved survival, fewer complications, and quicker return to functional health and productive life which is important out in the field because it would ensure that the soldiers recover in a quicker time than they would with the traditional procedures which generally require larger incision sizes leading to longer recovery and, due to the conditions they would be facing, a very high chance of infection (Mack, 2001). Being that most of the equipment would need to abide by certain size constraints because they would be unable to transport the entire robot, this smaller product would be more suitable for transport in situations where it would be impossible to accommodate the full scale surgical robot.

Rural Hospitals would also benefit from these features for they may not have the suitable funding or the space to accommodate for the purchase of the full-scale surgical robots on the market. These types of hospitals can only accommodate a small number of patients at a time due to their limited size and availability of resources at the facilities. Having access to surgical tools/devices that can provide such hospitals with the functions of the robot that they cannot acquire would allow for them to better the experience of their patients. Thus, practicing rural surgeons have several barriers to keeping up with advancing technology (Gruber et al., 2015). While these may be lower volume facilities, the level of patient care should always be targeted to be the highest that can be provided but, with the price-tags associated with the surgical robots, these hospitals would be unable to provide the benefits that come from these devices to their patients. This is the premise of which this product is being researched; a small form factor with high portability and an affordable price-tag providing similar functionality as the upscale surgical robots currently on the market.

1.2 Conventional Procedure

Laparoscopic Surgery is also known as Minimally Invasive Surgery (MIS). This is a type of procedure where minor incisions are made in order to input the surgical tools, along with a camera system for guidance, to conduct the procedure. There are many appreciated benefits of MIS compared to traditional open approaches (Vitiello et al., 2013). A common benefit is being able to avoid large incisions which, while may be more difficult to access the surgical field, provides the patient with a much easier recovery post-operation. Generally, these procedures are designed that the surgeon would make an incision near the targeted location for surgery and insert the surgical tools in the incision and guide it internally to necessary location. This is very different than open surgeries for those would require a large, wide incision allowing the surgeon to operate while directly looking at the surgical field rather than viewing and conducting the operation on the screen.

Since the introduction of laparoscopic colectomy, improved short-term surgical results have been noted in the literature (Chen et al., 2011). An example of this is, when doing an open surgery over a Laparoscopic Surgery, the Surgeon would be dealing with more blood loss due to the size of the incision required to conduct such procedures which raises the chance of post-op complications, such as infection, ultimately leading to a more painful and lengthy hospital stay after the procedure.

Laparoscopic Surgery also allows for an ease of conducting the procedure as a whole. The surgeon has the ability to avoid creating the large incisions which shortens the length of the surgery versus open surgery significantly. It also reduces, or even eliminates, the requirement for reconstruction of the incision which may take multiple procedures depending on the size of the incision, any trauma caused prior to or during the procedure, or any complications post-op leading to the need for additional procedures to correct the problem. Overall, laparoscopic surgery benefits patients through the decreased length of stay, decreased blood loss, decreased pain, quicker return to work, and improved cosmetic result through smaller incisions (Mattei, 2007).

Some of these concerns about open surgery are issues that have even come to attention about Laparoscopic Surgery itself which is why efforts have shifted to reducing the invasiveness of laparoscopic surgery, resulting in the invention of single-incision laparoscopic surgery (Chen et al., 2011). This method would allow to minimize the risk of complications even with Laparoscopic Surgery which already reduces risk over open surgery and benefits the patient in their recovery. The idea of the procedure is to provide the patient with the highest quality care that can be provided by the hospital, the medical professional, and the medical field and this is why medical ethics deal with the principles that guide behavior and decisions that concern patients in the clinical field so that decisions can be regulated to ensure that they are made with the best interest of the patient in mind (Cardenas, 2020).

1.3 Robotic Procedure

Laparoscopic Surgery has been growing over decades and continues to grow in present day. Whether that be through further development of certain procedures or improving the quality of life for the patience by better understanding post-op conditions from procedures done laparoscopically. Laparoscopic Surgery has evolved tremendously through the introduction of robotic technology into the field of medicine. Surgical robots were developed to facilitate minimally invasive surgery (laparoscopy) and to assist surgeons performing surgical procedures that would otherwise not be possible with traditional open or laparoscopic techniques (Ho et al., 2011). Robot Assisted Surgeries have been shown to have higher success rate and ease on the patient and surgeon over traditional surgeries both laparoscopic and open procedures. Due to these benefits, Robot-Assisted Minimally Invasive Surgery (RAMIS) was believed to be feasible, safe and the surgical procedure of the future (Khairy et al., 2005).

Current marketed Surgical Robots include the Laparoscopic tools used in traditional surgery but integrated into the robotic assist. The most widely marketed and studied surgical robot is the da Vinci Surgical System (Ho et al., 2011). This system brings forth various instruments which provide EndoWrist Technology for ease in the OR as well as advanced instruments and technology that bring vision, energy, and innovation to the OR (*Intuitive Surgical*, n.d.). Instruments that come with the system include Force Bipolar with DualGrip, which enhances the grip strength of the surgeon, and First Entry Accessories for smooth, single-site entry into the surgical site. The wristed laparoscopic instruments used in robotic surgery provide seven degrees of freedom which may allow for more precise dissection with increased magnification and visibility (Bruns et al., 2015).

Da Vinci's wide range of available technologies provide accessibility to various features such as different forms of stapling equipment for reconstruction, energy, or heating, products for sealing, and visual devices for guidance through the procedure. These tools are all controlled by the Da Vinci system through a single incision which takes Laparoscopic Surgery to a different level.

When dealing with a robotic assist such as the Da Vinci System, the operating room would include the patient cart, the surgeon console, and the vision cart. While this may take up a lot of space in the OR, many operating rooms have integrated their equipment as ceiling units for mobility and to save space in the OR.

The Da Vinci Surgical System does not only improve the quality of surgery through the devices available to conduct the procedure but also the comfort and ease for the surgeon who is doing the operation. Surgeons may benefit through improved ergonomics (for example, three-dimensional visualization and freedom, and intuitiveness of movement-enabled eye-hand coordination that may be lost in laparoscopic surgery), potentially resulting in better surgical performance (Ho et al., 2011). Having a surgeon console allows for the medical professional to remain seated while conducting the procedure which reduces the issue of fatigue and potentially even exhaustion. Even though the surgeon would be staring into a screen in order to do the operation, they would be doing this seating in the console using it to move the robotic system to do the surgery while being able to adjust the console in multiple ways to help get a good fit for the height and reach of the surgeon (*Intuitive Surgical*, n.d.). Additionally, such procedures are also beneficial for the surgeon. Autonomous surgery allows faster and more precise execution, and reduction of the surgeon's burden (Yip & Das, 2017).

Surgical Robotics are also available for the quality of surgery for the patient but the convenience and comfort of the medical professionals as well for the ease provided to them also can take effect on the patient. The Surgical Console allows for the surgeon to have total control of the wristed instrument on each of four arms, and can customize settings at the console while being able to see the surgical field in 3DHD and benefit from built-in innovation, such as tremor filtration (*Intuitive Surgical*, n.d.).

These systems can also hold the position of the surgical tool if the surgeon releases their grip (Payne & Yang, 2014). This is put in place for the safety of the patient should the surgeon need to respond to an emergency and be forced to let go of the tools or even if the surgeon's grip simply slips, it is available for safety precautions and even ease of the surgeon should they need to let go due to cramp or fatigue. This feature is a significant advancement over conventional surgery for it allows the surgeon to simply freeze the procedure if need be. This is not currently possible using standard surgical tools for, even moving an inch in the wrong direction, trauma can be caused to the patient during the surgery.

Even though these features are specific to the Da Vinci Surgical System, it shows the benefits that come from having a robotic surgical assist in the operating room and these advancements in medicine how Surgical Robots improve the process of the laparoscopic procedure for both the patient and the surgeon. Current applications of robotics include surgical assistance, dexterity enhancement, systems networking and image-guided therapy (Mack, 2001). As the medical field continues to advance, we are shown that Laparoscopic Surgery, as well as surgery as a whole, has grown greatly through the introduction of Surgical Robotics and Medical Devices in the operating room and have significantly benefitted the patients who have procedures with these technologies readily available.

1.4 Limitations

Provided the many advantages that come with conducting Robot Assisted Surgery, it is not a perfected system which means that it shall come with limitations, issues, or questions that need to be addressed and hopefully researched for a solution. Robot-assisted surgery is associated with high capital and operating costs with purchasing the device as well as properly maintaining it throughout its time of usage (Ho et al., 2011). This confirms that robot-assisted surgery indeed leads to increased costs that are not balanced by augmented patient value, i.e. robot-assisted surgery cannot be regarded as cost efficient (Sjövall & Persson, 2016). Basic surgical equipment would be exponentially cheaper than purchasing the robotic system which makes the system unsuitable for certain medical facilities and hospitals. Robotic surgery has higher costs than open and laparoscopic procedures and this is due to the high costs of purchasing and maintaining a robot, increased operative time, and costs of disposable surgical supplies (Geller & Matthews, 2013). Despite the growth demonstrated in both the civilian and military sectors, Robot-Assisted Surgery is still viewed as a relatively young, in-development surgical approach that requires high resource expenditure and the championing of a steep learning curve for it to be effective (Grasso et al., 2019).

This learning curve leads to separate training which is associated with additional costs for the surgeons needing to go to facilities such as the AdventHealth Nicholson Center for Surgical Training and get training on how to properly use the surgical assists for their operations. The practice of Robot-Assisted Minimally Invasive Surgery (RAMIS) requires extensive skills from the human surgeons due to the special input device control, such as moving the surgical instruments, use of buttons, knobs, foot pedals and so (Elek & Haidegger, 2019). Aside from cost, it is also very time consuming. The training alone can take a long time off the surgeon's hands which they have other responsibilities and emergencies to tend to as well. The majority of robot-assisted surgical trainings lack of clinical modular training that consists of progressive, proficiency-based training through surgical steps with increasing levels of complexity (Puliatti et al., 2020). Additionally, it has been found that Robotic Assists, such as the Da Vinci Robot, can actually lengthen the time of procedures. This brings about further issues such as fatigue of the surgeon and the time that the patient is under anesthesia.

Robotic Surgical Assists, while being extremely advanced, despite these successes, progress in this field is limited by an unresolved problem: the lack of haptic (force and tactile) feedback to the user (Okamura, 2004). This is problematic for the surgeon must operate solely through sight due to the lack of feeling when working from the console. Even though devices like the Da Vinci System provide signals and warnings for the surgeon on the console screen regarding pressure produced by the device, it cannot compete with actual, physical feeling when conducting the procedure. In order to incorporate this level of haptic feedback, it requires the integration of haptic sensors into the instruments used by surgical robots, as well as methods for displaying haptic information to the human operator (Okamura, 2004).

Many procedures have successfully been conducted with a Robot Assist but it does not mean that this is not a major issue that needs to be addressed and researched. The Surgical Systems available on the market come across a common issue which is size constraints. Not all hospitals have the space availability for the magnitude of the Surgical Robots available which is unfortunate for those facilities would be unable to take advantage of Robot Assisted Surgery for their patients. Additionally, these size restrictions interfere with facilities associated with the Military for they would be unable to transport a device of this size. These constraints make it difficult for the advantages of Surgical Robots to be utilized by the majority of the medical field which is unfortunate for they can largely benefit the patients who may need them or even simply to better the experience of the patient through their procedures. This leads to only hospitals with the particular facilities to accommodate for these robots to be able to utilize them, and, when they do come in possession of them, robotic surgery ends up replacing conventional laparoscopic approaches for procedures that may not be complex enough to warrant the consideration of an advanced, expensive, and unproven minimally invasive platform (Sheetz et al., 2020).

1.5 Innovation and Approach

The role of the current generation of surgical robots is to assist rather than replace the operating surgeon (Davies, 2000). The Semi-Robotic Laparoscopic Surgical Support System has been designed with this purpose by optimizing the practice of laparoscopic surgery through the implementation of the benefits of robot-assisted surgery without the high costs and requirements associated with purchasing an entire surgical system. Through an easily accessible 3-arm flexible design, the device is mounted on the abdomen of the patient and is connected to each of the abdominal entry points for the surgery. The structure of the device utilizes insertion plates where the trocar is placed through to feed the surgical tools into the abdomen. Attached to these disks are actuators which are connected to a smaller braking disk mechanism which halts all movement of the trocar, and, by association, the surgical tool.

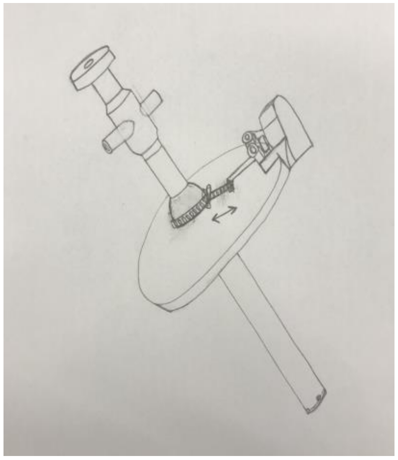

Figure 3: Trocar Braking System Sketch

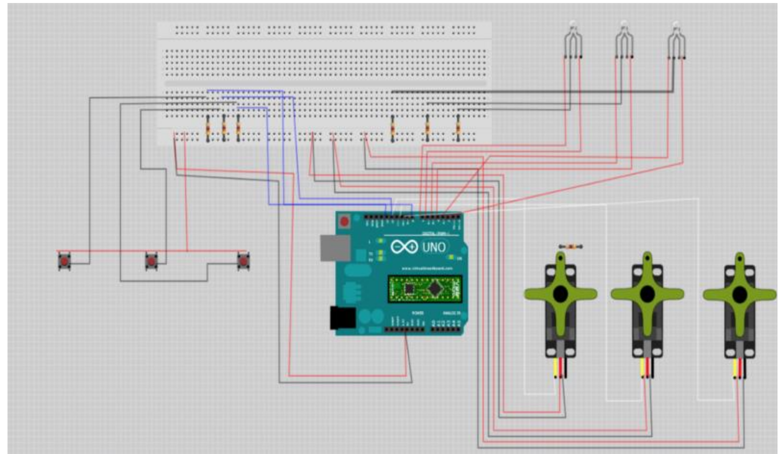

Figure 4: Brake Pedal Circuitry and User Interface

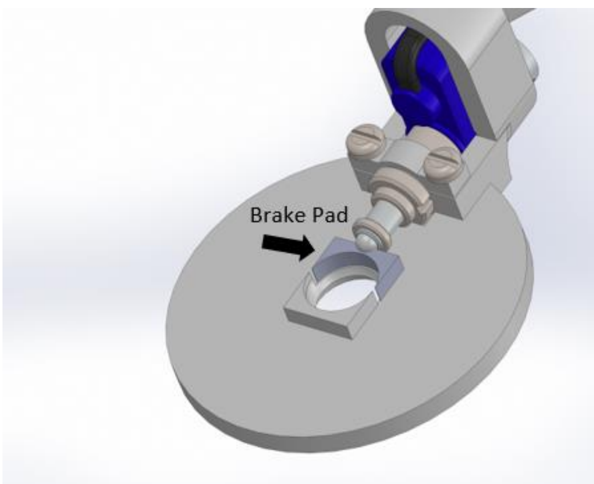

Figure 1: Trocar Braking System

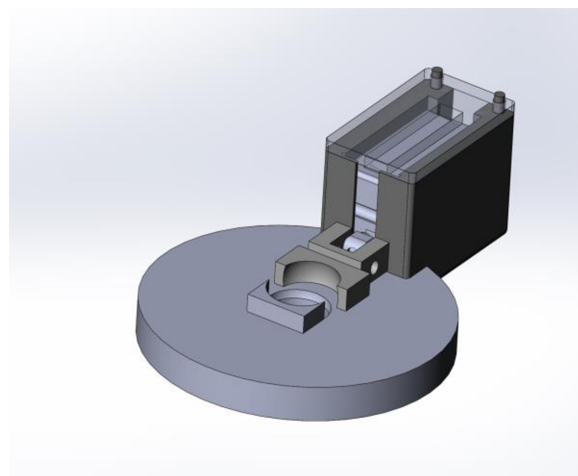

Figure 2: Motor Housing and Braking Disk

Figure 1, *Figure 2*, and *Figure 3* depict the trocar braking system design. This design is compiled of a brake pad, disk body, and a motor/actuator that activates upon the surgeon pressing the pedal on the surgical floor. This braking system stops, or "freezes," the trocar in its live position in order for the surgeon to be able to release grip of the surgical tool without fear of injuring the patient. This braking system functions so that, when the surgeon presses on the brake pedal, whose circuitry and surgical pedal user interface displayed in *Figure 4*, the motor, shown in *Figure 2* to reside in the motor housing, would activate and the actuator would push the brake pad across the braking disk and against the body of the trocar, imobilizing it until the surgeon chooses to deactivate the system. Similar to how the braking system of a car would function, the user would apply force to the brake pedal and in return the braking system will apply the force of a brake pad against the object in question, in this case, a trocar. The applied force must be greater than the natural movement of the trocar in order to keep it frozen in its current position. The disk body of the system allows for extra support on the patient's abdomen and additional surface area to increase the stability of the trocar during its frozen state. Upon deactivation by the surgeon, the motor/actuator would reverse the brake pad and release the trocar from its frozen state, able to be moved as necessary with the full degrees of motion as conventional laparoscopic surgery.

As shown in *Figure 1*, *Figure 2*, and *Figure 3* above, the Trocar Braking System utilizes a brake pad in order to freeze the positioning of the trocar. This is done by the actuator causing the pad to press against the body of the trocar, ultimately causing it to be frozen in its live position and allows

Figure 5: 8-Slot Trocar Design

Figure 5 shows the design utilized for the trocars in conjunction with the aspects of the Semi-Robotic Laparoscopic Surgery Support System braking mechanism. This 8-slot design features a rounded bulb center which allows for the brake pad to apply compressive pressure against the trocar while also applying the pressure on the tool that would be inside the trocar. This bulb-like body feature sits on the brake disk shown in *Figure 1*, *Figure 2*, and *Figure 3* while the cylindrical body of the trocar is fed through the hole in the disk in order to make entry access for the surgical tool into the abdomen (workspace). This bulb is structured with slits in it to allow for compression of the bulb against the surgical tool inside the trocar. When the brake pad is pressed against the bulb upon the surgeon's activation of the brake pedal, the bulb is then compressed inward which allows the slits to close and the force to be applied against the tool inside as well. Upon the bulb being enclosed against the tool, the tool will be in suspended animation and the surgeon can then release grip from the surgical equipment.

the surgeon to release grip of the tool and trocar for whatever further action is deemed necessary by the doctor conducting the procedure. The brake pedal system in *Figure 4* is used to activate the mechanism, causing the pad to press against a bulb like structure designed in the center of the cylindrical body of the trocar, displayed in *Figure 5*. This allows for a concentrated region where pressure can be applied against the trocar wall and compression against the tool would occur, suspending both the trocar and tool. The action of the brake pad acting on the trocar wall must also be analyzed for risk of deformation. The pressure of the pad against the trocar leads to the main points of contact to be at higher risk of deforming than the rest of the trocar, as displayed in *Figure 6*. This analysis had been done on a segment of the trocar, shown in *Figure 7,* to indicate that the technology uses a force pressing against the trocar to stop the possible motion of that trocar.

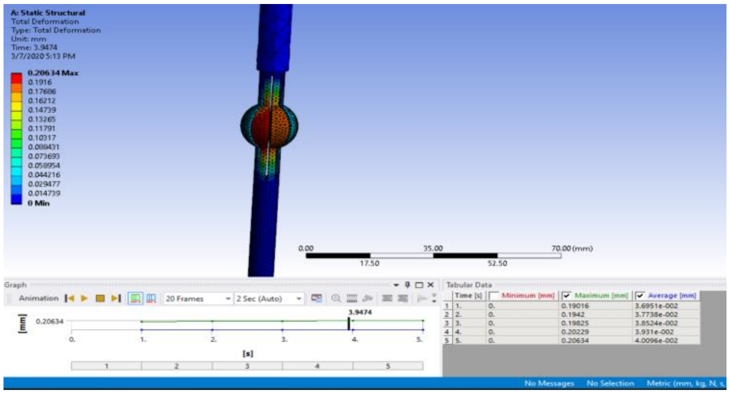

Figure 6: Total Deformation Plot

Figure 7: Segment of Trocar for Ansys Analysis

Figure 6 displays the deformation of the trocar body during brake and the segmented piece of the trocar design used to conduct the Ansys deformation plot analysis is shown in *Figure 7.* When the braking system is applied, as expected, the highest point of deformation, or risk of deformation, is at the point where the brake pad is pressed against the trocar body in order to make it freeze in its live state. This deformation plot shows that the pressure against the trocar where there is the highest load distributes outwards from that point and the load begins to fade away the farther the analysis it from the main location of pressure. The trocar is designed with a central bulb which is used to allow for the applied pressure to place the force against the trocar body as well as the tool inside the trocar which allows for the freezing action to take place. This is as expected being that the brake occurs due to the pressure at that point and the force applied on the trocar body. This information is also beneficial in discussing the force necessary to be applied against the trocar to prevent any movement or premature release of the braking system. Determining the highest load applied on the point of highest deformation allows for the calculations to take place regarding what force is required to prevent movement but at the same time not deform/damage the trocar making it ineffective or problematic during the procedure. Too little force would allow for unwanted movement from the trocar but too high of a force would risk damaging the trocar during surgery which could also affect the tool inside this trocar (depending on how much the trocar has been deformed/damaged. This analysis determines a safe force application being that there was a goal of 0.2mm deformation to be reached which was achieved as shown by the data displayed in *Figure 6.* This also helps to explain how the braking mechanism functions; it shows that the force of the brake pad is applied against the bulb of the trocar and pressing against it at the highest point of deformation detected. Ultimately, this would lead to compression of the bulb and pressure against the tool that is fed through the trocar, and, therefore, the tool also receives this applied force from the brake pad.

The final design of the Semi-Robotic Laparoscopic Surgery Support System is shown in *Figure 8* which fully depicts the design of the device being used to establish the Robot-Assisted condition of this research. While technology is not necessarily “robotic” due to its unmotorized nature, its design incorporates major benefits of actual robot-assisted surgery which is what allows for this kinematic guiding technology to be used as a representative for the robot-assisted condition. Correspondingly, while the type of surgery being conducted with the implementation of this technology is more of a “kinematically guided” laparoscopic procedure rather than a “robot” one, the benefits and practices that are accessible through the use of this device allow for this style of kinematically guided surgical procedures to be representative of the robot-assisted condition in this research.

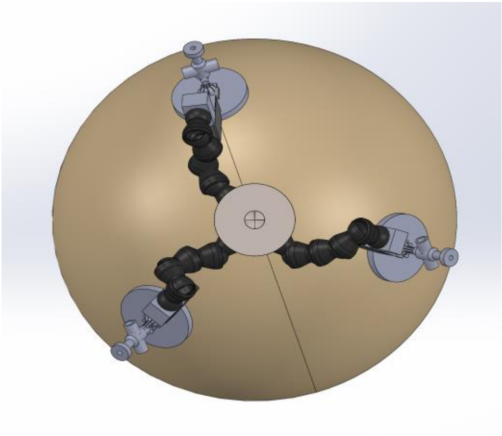

Figure 9: System Placement Model

Figure 10: Endo Trainer Surgical Simulation Setup

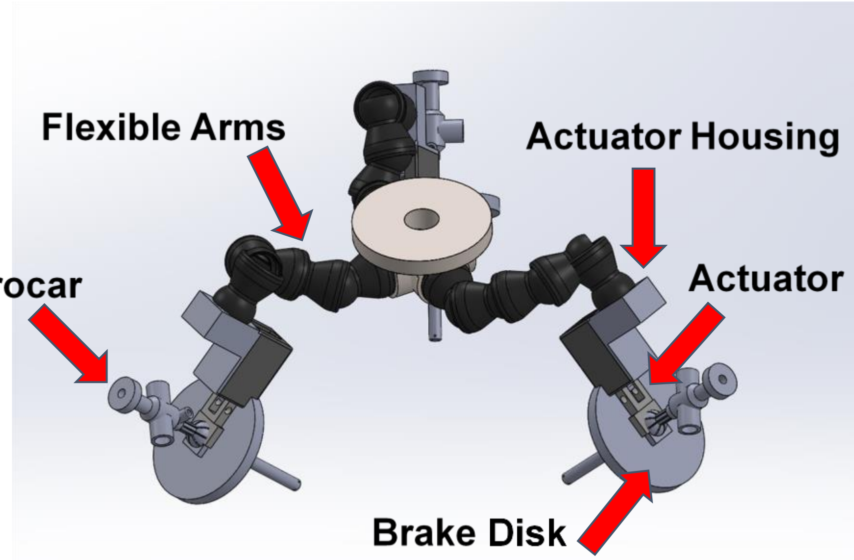

Figure 8: Semi-Robotic Laparoscopic Surgery Support System Final Design

In *Figure 8*, the Semi-Robotic Laparoscopic Surgery Support System Final Design is shown. This CAD Design indicates the components that make up the system and provides a visualization to the figures mentioned in prior sections. The trocar would be placed within the insertion point through a disk, this disk would provide a body for the braking system for the surgeon to use as necessary, as referred to in *Figure 1*, *Figure 2*, and *Figure 3*. When the surgeon chooses to activate the braking system, they would have a brake pedal under the surgical table that they can access by pressing it down with their foot; this brake pedal can be seen in *Figure 4* and *Figure 10* showing the tri-pedal design and wiring to the system. Upon activation, the brake pad is mobilized by an actuator attached to the insertion disk. The brake pad would then press against the bulb, as shown in *Figure 5*, on the trocar design and compress it against the surgical tool being fed through the trocar. This would freeze the trocar and tool in place forcing all movements to be grounded in order for the surgeon to be able to release grip from the surgical tool and adjust their focus to whatever is necessary next in the procedure without the additional requirement of stabilizing the tool manually. The arms of the system are flexible in order to position the plates and trocars as necessary for the surgery. These arms are what allow the trocar insertion plates to be placed on the abdomen at a fixed angle, as shown in *Figure 9* and *Figure 10*. Prior to the use of this system, these plates remained on the abdomen but had varying movement due to nothing holding them in place such as one of the functions of this system. The flexible arms of the system meet at the center in order to be coordinated and positioned from a main point. This all-in-one positioning system allows for the entry points of the surgery to remain within a single coordinate system rather than having three different floating systems as in Conventional Laparoscopic Surgery. The system has three plate sections implemented into it and this schematic shows to have three trocars in the system but the analyzed situation in this study is to use two of the insertion plates utilized for the trocars and tools and the remaining third insertion plate for the camera to be inserted into the abdomen and display the workspace on the screen for the surgeon.

Through the application of this technology, there are parameters for the workspace and system that become necessary to consider. The primary plan is to determine the accuracy of these provided parameters and measurements through analysis of the laparoscopic procedure and current surgical tools and equipment measurements. Per determination of these measurements, the viability of the provided parameters will be dictated, and further development of the device will be in order should there need to be updates to the equipment parameters based on this information. Updated parameters for a new/next version of the system will be set in place as well as new designs for the system using the updated information that is determined by this research.

The methods and sequence intended for this research begin with the premise of identifying the parameters needed to develop a device. This is to be done in order to determine specific lengths and angles for the system design to further develop the device. Modeling and analysis will be used to better understand the procedure and the intervention system which will allow for evaluating and using optimized numbers for the next version of the device to update it with more accurate dimensions.

Modeling this research is parted into two forms: Workplace Modeling and Tool Kinematics Modeling. Workplace Modeling will be developed by researching laparoscopic procedure dimensions of the patient per inflation of the abdomen at preparation for the procedure as well as throughout the surgery. This will help determine space provided in the abdomen for surgical tool insertion and motion. Once the information on the procedure has been addressed, a model of the procedure would be designed for analysis of parameters to dictate a range of motion constraint that the device would need to accommodate for and the values that need to be considered for the measurements and dimensions as associated with the human patient.

The Tool Kinematics Modeling process is similar to that of the previous steps but directed towards the surgical equipment. Research on product dimensions of laparoscopic tools and consideration of size constraints regarding the device itself would need to be addressed as well as how it would be involved in the procedure. Determining the angles and motion parameters of the tools inserted into the abdomen are essential in designing the product for certain limitations would need to be put in place to accommodate for accessibility of the surgical field from the device as determined previously by the Workspace Modeling. Modeling the tools for would allow for defining such parameters through analysis of the design.

Analyzing the findings would then be to evaluate workspace and kinematic measurements found and dictate the viability of implementing such parameters to other systems. There would need to be comparison of the determined parameters with the measurements previously decided for the current intervention Semi-Robotic Laparoscopic Surgical Support System design and model to dictate the accuracy of the current measurements that had already been used. Upon deciding on the measurements that are believed to be the appropriate constraints for the device, further optimization to the design would need to be provided using new measurements and the accuracy of these measurements would need to be tested in order to implement them into developing a new and improved device.

2 Methods

2.1 Task and Parameter Identification

Every action that a surgeon, or surgical assist, makes in the operating room on a patient can be defined by a vector, coordinate, value, etc. In laparoscopic surgery, the procedure commonly consists of a trocar and its insertion, the tools to be used in the procedure, and a camera that relays over the field of view (FOV) to the surgeon on a nearby screen. Each of these components and the movements that they are affected by can be defined by various parameters. These parameters have been split into "types" regarding the nature of that parameter (coordinate, cartesian, polar, rotational, and other parameters). The types of component groups are as they sound; coordinate parameters are used to dictate workspace dimensions to normalize the positive orientations and values of various locations in the inflated patient abdomen, cartesian parameters indicate the translational motion of the component, polar parameters indicate the angles that define the motion of the parameters, rotational parameters are used to establish movements of turning that the component can experience when the surgeon rotates their wrist on the arm of the component, and other parameters to be defined are miscellaneous dictations such as the camera's FOV which contains definable dimensions that can greatly affect the surgeon's ability to conduct the surgical procedure.

These parameters have been addressed for each of the major working components during laparoscopic surgery: Workspace, Trocar, Tool, and Camera. While "Workspace" is not a physical component in the procedure, it is being considered a component as it is a necessity to the procedure and is used to compare potential differences between conventional and robot-assisted laparoscopic surgery. For the robot-assisted aspect, the Interventional Robotics Laboratory's Semi-Robotic Laparoscopic Surgery Support System will be used. This evaluation process has been done on Conventional, Workspace Controlled, and Kinematically Constrained surgical conditions. The Workspace Controlled and Kinematically Constrained conditions are different stages of the "robot-assisted" circumstance represented by the surgical guiding system being used when the system is simply being "equipped" or "applied" in the surgical procedure and when the braking system is "activated" by the surgeon. This allows for experimentation on this new device in order to determine how it would affect the convenience, safety, cost-effectiveness, and ease of operation of the procedure. Due to the flexible nature of Laparoscopic Surgery, the location of the surgeon and the camera may vary. The surgeon and camera can either be on the same side, facing the abdomen from the same point of view (POV), or the surgeon and camera are on opposite sides and the camera is facing him. Depending on the orientation of the camera and the locations of the surgeon, the workspace positive directional axes may change in accordance to the positioning of the origin. However, this should not affect the determined kinematic parameters in this study and the adjustments to the workspace parameters are limited. What is being considered the 'standard' location for both the surgeon and the camera in all of these evaluations through the research is when the two are positioned with having the same direction and POV.

2.1.1 Conventional Laparoscopic Surgery

In defining and evaluating Conventional Laparoscopic Surgery parameters, standard practices of the surgical procedure are narrowed down to the use of two independent trocars and tool combinations and a camera within the abdomen of the patient. Using this information, the parameters have been established for each component within independent coordinate systems.

2.1.1.1 Workspace Parameters

For Laparoscopic Surgery, the abdomen of the patient must be inflated in order to provide room for the surgeon to conduct the operation. This creates a three-dimensional workspace for the procedure. The standards of three-dimensional axes are commonly known as being the x-, y-, and z-axis. This set of labeling, albeit standard in mathematics, is not implemented in the standard directions. When determining what point to make the origin, it was established that it should either be either at the very top or very bottom of the inflated abdomen while being directly in line with the camera lens upon insertion. It was determined that, unless the camera is to be inserted into the absolute center of the abdomen, which is impractical and unlikely, that there would not be a way to put the origin in line with the camera while avoiding any presence of negative values in the workspace. Should the origin be located above the camera in an attempt to be at the belly-side of the patient, it would be on the curve of the inflated abdomen which would require all values above that origin to be dictated as negatives (provided the z-direction would be assumed with positive orientation when pointing down into the abdomen). In an effort to avoid these complications, it was determined that the best location for the origin to be dictated is at the abdomen floor below the camera lens upon insertion. This would indicate that the z-direction would be positively orientated when pointing up through the abdomen. This allows for all depth values to remain positive regardless the positioning of the component or point being analyzed.

Table 1: Workspace Parameters (Conventional Laparoscopy)

Workspace Parameters		
Type	**Symbol**	**Definition**
Coordinate	x	x-direction across abdomen floor
	y	y-direction across abdomen floor
	z	z-direction above abdomen floor (height/depth of abdomen)

What remains in the coordinate plane parameters of the workspace would be the x- and y-axis. These axes make up the basic two-dimensional plane with the z-axis incorporating depth to establish a three-dimensional domain, as defined in *Table 1* above. Based on the determination that the origin will be located against the abdomen floor under the camera, it is expected that the starting points of the x and y axial directions will be from that same point as well. What needed to be established from these axes is the direction that they would be pointing. In order to continue incorporating a methodology of avoiding the necessity of using negative values, the directions of the x- and y- axis must coordinate with the POV of the camera. Being that the camera and surgeon share the same POV, the axes would be creating a positive two-dimensional x-y plane following the same orientation as that POV.

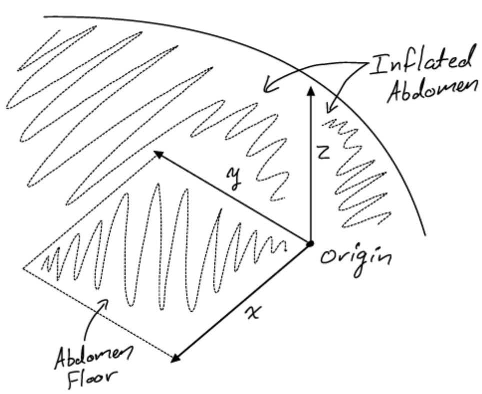

Figure 11: Workspace Parameters (Conventional)

The workspace is determined from the perspective of the surgeon. Assuming that the surgeon is conducting the procedure from the right of the inflated abdomen in the figure, the abdomen floor is dictated by the x-y-plane as shown. The depth of the abdomen is dictated by the z-axis but the origin of where the axes meet is located at the abdomen floor in order to orient the parameters in a positive workspace and avoiding negative coordinates.

While this orientation does not fully encompass the entire inflated abdomen, it essentially analyzes what could be considered as the entire relevant section of the abdomen. This is due to the fact that the workspace is defined as the area in which the surgeon conducts the surgical procedure. While the abdomen is that location, it is not the entire abdomen that is being worked on. In-fact, the surgeon only conducts the procedure in the areas which reside in the FOV of the camera. This indicates that the region of the abdomen that is posterior to the camera can be considered negligible in this analysis. This allows for the workspace parameters to maintain positive orientations at all times being that, in order to reach negative depth, the surgery would need to cross the "abdomen floor" which is impossible being that his would be the back of the patient. Addressing this same concept on the x-y plane, the only times where a negative positioning would be found with respect to these axes would be when the point in question resides behind the camera which has been determined to be considered a negligible location in regard to the directional and …36+66location decisions of how these parameters should function and be defined.

2.1.1.2 Trocar Parameters

The one of the first steps to conducting a laparoscopic surgery is inserting a trocar. When inserting a trocar, there is commonly some form of plate or wedge that is used to help stabilize the trocar at the insertion point. In Conventional Laparoscopic Surgery, this wedge is reasonably stable but not perfectly frozen in place. There is likely to be some slight shifting at the plate point from right to left as the surgeon moves during surgery. There is also a potential shift inwards depending on how hard the surgeon pushes the device against the patient. These shifts are necessary to determine due to the fact that, when it comes to conducting a surgery, every motion, regardless how minor, needs to be accounted for to ensure the patient's safety. This shift has been labeled using the standard x, y, and z dictation, however, the orientations of each axis are wildly different from the primary x-, y-, and z-axis of the workspace. It was found that using the same directional components when determining the shift on the insertion point would create extensive negatives in regard to the depth and be much more complicated to determine in regard to the x-y plane. If the z-directional shift would be dictated by the positive orientation being upwards, there would be many more negatives being determined than positives due to the nature of how surgeries are done. It is expected that the surgeon may push inwards, even slightly (possibly subconsciously or unintentionally), when doing a procedure significantly more than they would be pulling outwards. Due to this, it was determined that the best way to establish the insertion point shift in the z-direction would be to positively orient this axis downwards into the abdomen. In regard to ease of incorporating these parameters into the situation, it was found that having the axis positioned similar to the workspace parameters, but on top of the abdomen, would be overly complicated when used to determine the insertion point shift. This brought about the new orientations for the x- and y-axis. It was established that the easiest way to determine this shift would be to make the y-axis parallel with the midline of the patient and the x-axis to be perpendicular to it. This would make it simple to determine how shifts in the insertion shift can affect the procedure. Due to the changes in orientation, the insertion point shift has been labeled x_{PT}, y_{PT}, and z_{PT} to differentiate it from the original workspace parameters labeling.

Table 2: Trocar Parameters (Conventional Laparoscopy)

Trocar Parameters		
Type	**Symbol**	**Definition**
Cartesian	x_{PT}	Trocar Insertion Point Shift in the x-direction
	y_{PT}	Trocar Insertion Point Shift in the y-direction
	z_{PT}	Trocar Insertion Point Shift in the vertical direction
	d_T	Trocar Tip Linear Travel Distance
	a_T	Trocar Tip Arch Travel Distance
Polar	θ_{PT}	Trocar Plate (Pivoting) Angle
	θ_T	Trocar Travel Angle
	θ'_T	Trocar Tip Travel Angle
Rotation	M_T	Trocar Rotation
	M'_T	Trocar Tip Rotation

The discussed insertion point shifts are considered to be cartesian parameters. There has also been found that a polar parameter establishing shift is present in Conventional Laparoscopic surgery. Being that the patient's abdomen is round due to it being inflated, the surface that the plate is placed on is only making contact with small portions. Since the abdomen is not flat, the plate will inevitably pivot on the insertion point. This pivoting, however slight, is still necessary to be considered when conducting a surgery due to the requirement for high precision when conducting a procedure. The pivoting motion of the plate can be defined by the angle in which is created when the pivot occurs. The angle is labeled by θ_{PT} to indicate that it is the angle of the Trocar Plate. This angle can be calculated between the positioning of the plate and the tangent of the point in which the plate is located for insertion. Upon determining the tangent line and the position that the plate is angled at (during any point in pivoting) this angle can then be calculated.

Being that the Trocar is not fixed in the insertion point, it has the ability to tilt and turn which allows the surgeon to conduct the actions necessary for the procedure. These motions are produced by the surgeon's movements and actions during the procedure. The parameters of the portion of the trocar outside of the abdomen is designated by different labeling than the other parts of that component. For the Trocar Travel Angle produced by comparing the trocar in the current position being analyzed to its original position, the labeling θ_T is representative of that generated angle. This is created when the surgeon moves the trocar (or the tool which could also affect this positioning – additional information about this phenomenon can be referenced in the following section) in order to conduct a procedural action. This movement of the trocar causes for it to be repositioned which ultimately generates an angle of motion from the original position to the new one. Similar to this, the trocar also has a rotational component which is also directly affected by the surgeon's actions. The rotation of the trocar is represented by M_T which is dependent on how the surgeon rotates, or turns, their wrists in order to adjust the components during the procedure.

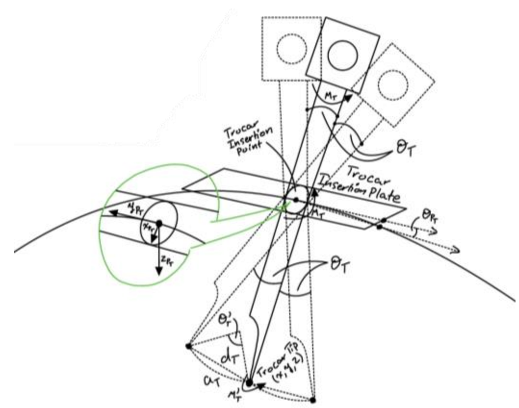

Figure 12: Trocar Parameters (Conventional)

The trocar parameters are a mix of Cartesian, Polar, and Rotational aspects, as seen in *Figure 12* above. The trocar enters the body on an insertion plate. This plate is not fixed on the skin and therefore has a pivoting angle of θ_{PT}. At this entry point, the plate has slight potential shifting. This directional shifting has been denoted by the terms x_{PT}, y_{PT}, and z_{PT} where the x and y terms are representative of the horizontal plane and the z term is representative of the vertical direction which is positive in the down orientation to represent the skin as the origin and pressing onto it is positive. When the surgeon inserts and operates the trocar, the movement of the body of the trocar creates a reciprocated movement for the trocar tip. This tip movement is established by an arch travel distance labeled a_T. This is calculated using the linear distance traveled by the tip and the angle of which the movement occurs, labeled d_T and θ_T, respectively. The arch angle is denoted as θ'_T which can be determined geometrically through the use of the rules of similar angles which equates θ_T and θ'_T. The trocar also has the ability to rotate clockwise and counterclockwise as the surgeon sees fit. This rotational component of the body is labeled M_T. When the surgeon rotates the body of the trocar by hand, the tip or the trocar will also rotate in relation to it. The rotation of the trocar tip is labeled as M'_T and, through the law of superposition, can be determined that M_T and M'_T are equal.

There are trocar parameters that occur inside the abdomen as well. These parameters vary from cartesian, to polar, and even rotational. From a cartesian standpoint, the trocar tip goes through translation ever time any adjustment, movement, or repositioning takes place. Every movement that takes place would produce an arch travel distance which has been defined as a_T. This arch distance can be calculated from the angle which occurs from the movement of the tip from one position to another. This angle is represented by θ'_T. Along with the angle, the linear travel distance, d_T, would also be required in order to determine the value of the arch. Using the Trocar Tip Arch Travel Distance equation, the value of the arch can be found which will allow for a quantifiable representation of the distance that the trocar moved. The trocar can also rotate inside of the patient's abdomen just as it would outside. This rotational parameter is represented by M'_T.

Equations:

Equation 1: Trocar Tip Arch Travel Distance (Conventional Laparoscopy)

$$a_T = \frac{d_T}{2} * \theta'_T$$

Equation 2: Trocar Travel Angle Function Relationship with Trocar Tip Arch Distance, Linear Distance, and Tip Travel Angle (Conventional Laparoscopy)

$$F(\theta_T) = f(a_T, d_T, \theta'_T)$$

Equation 3: Trocar Rotation Function Relationship with Trocar Tip Rotation (Conventional Laparoscopy)

$$F(M_T) = f(M'_T)$$

As expected, what happens to the trocar on the outside of the abdomen also affects what happens on the inside of the abdomen. This is due to the fact that anything the surgeon does outside of the abdomen will reflect over into actions taking place inside the abdomen. These actions are represented by the relationship equation between the Trocar Travel Angle and Arch Distance, Linear Distance, and Tip Travel Angle as well as the relationship equation between the rotation of the Trocar and Trocar Tip. These functions are intended to display how the result of the Trocar Travel Angle and Trocar Rotation (which are the parameters that occur outside of the patient's abdomen) affect the result of the Tip Travel Angle and Linear Distance, and as a result, the Tip Arch Travel Distance (which occurs inside of the patient's abdomen) and how the Trocar Rotation affects the result of the Trocar Tip Rotation (which also occurs inside of the patient's abdomen). These functions equate and explain how the quantitative output of the parameters beyond the workspace affect those that take place within the workspace.

2.1.1.3 Tool Parameters

The Tool Parameters behave very similarly to those of the Trocar, some even behave exactly the same. Initially, when inserting a tool through a trocar, the tool and trocar, unless manufactured in conjunction with one another, are not perfectly modeled to fit each other without gap. It is expected that, when a tool is used through a trocar during laparoscopic surgery, it is likely that this tool will have minor free areas of movement between the wall of the tool body and the wall of the trocar body. This spacing could present a chance for potential motion to occur at the insertion point of the trocar for the tool. This is highly related to the slight present shifting at the trocar insertion point into the patient's abdomen. This shift is modeled by x_L, y_L, and z_L, similar to x_{PT}, y_{PT}, and z_{PT} for the trocar shift. Additionally, the orientation of each of these shift parameters is directed the same as those of the trocar shift. This is done to mitigate complications that arise from having too many varying orientations and attempting to have a functional, uniform basis to go off of for all parameters indicating aspects of insertion shift where the y-direction is oriented parallel to the patient's midline, the x-direction is perpendicular to that, and the z-direction is oriented downward into the patient's abdomen.

Table 3: Tool Parameters (Conventional Laparoscopy)

Tool Parameters		
Type	**Symbol**	**Definition**
Cartesian	x_L	Tool Insertion Point Shift in the x-direction
	y_L	Tool Insertion Point Shift in the y-direction
	z_L	Tool Insertion Point Shift in the vertical direction
	d_L	Tool Tip Linear Travel Distance
	a_L	Tool Tip Arch Travel Distance
Polar	θ_L	Tool Travel Angle
	θ'_L	Tool Tip Travel Angle
Rotation	M_L	Tool Rotation
	M'_L	Tool Tip Rotation

For the remainder of the components, d_L, a_L, θ_L, θ'_L, M_L, and M'_L all behave the same way it has been deemed that the components d_T, a_T, θ_T, θ'_T, M_T, and M'_T behave for the trocar. These parameters still affect one another, as represented by the function relationship equations below. The arch distance equation for this component is the same as well just adjusted to account for the tool rather than the trocar. The coordinates of the surgical tool tip within the workspace are used to indicate the location of the tool in regard to depth and positioning. Through this, depth becomes apparent since the surgeon's positioning of the tool's depth will cause the coordinates to change.

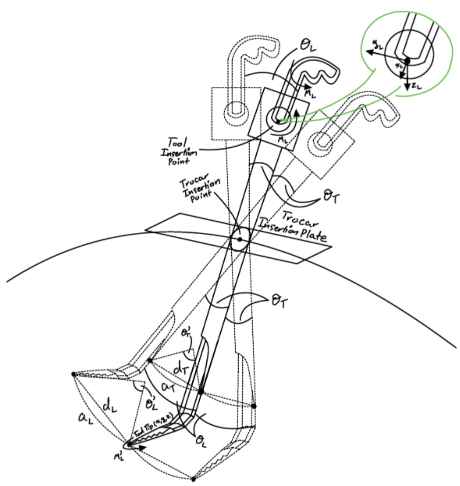

Figure 13: Tool Parameters (Conventional)

The tool parameters are a mix of Cartesian, Polar, and Rotational aspects, as seen in *Figure 13* to the left. The tool enters the body through the trocar. This tool is not fixed on the trocar and therefore has slight potential shifting. This directional shifting behaves similarly to that of the insertion point shifting of the trocar to the skin and has been denoted by the terms x_L, y_L, and z_L where the x and y terms are representative of the horizontal plane and the z term is representative of the vertical direction which is positive in the down orientation to represent the tool entry point into the trocar as the origin and pressing down through the trocar into the abdomen is positive. When the surgeon inserts and operates the tool, the movement of the handle of the tool creates a reciprocated movement for the tool tip. The tip coordinates are also used to indicate the depth of the surgical tool. Depending on how the surgeon proceeds through the operation, it is possible that the tool be inserted deeper than the original placement or pulled out to establish less depth in the abdomen. These x-, y-, and z-based coordinate parameters are used to establish the tool tip's location within the workspace while also indicating the surgical tool's depth during the procedure. This tip movement is established by an arch travel distance labeled a_L. This is calculated using the linear distance traveled by the tip and the angle of which the movement occurs, labeled d_L and θ_L, respectively. The arch angle is denoted as θ'_L which can be determined geometrically through the use of the rules of similar angles which equates θ_T and θ'_T with each other and then equates θ_L and θ'_L. Additionally through similar angles, θ_T and θ_L are equal (and relatively θ'_T and θ'_L) which allows for θ_L and θ'_L to be determined by the quantities of θ_T and θ'_T. Due to this equated association between the θ terms for the tool and trocar, it is shown that the tip arch travel distance for the tool, a_L, is equal to the trocar tip arch travel angle, a_T, based on the laws of translation and how each term relates to each other for the d and θ components of the tool and trocar. The tool also has the ability to rotate clockwise and counterclockwise as the surgeon sees fit. This rotational component of the handle and body of the tool is labeled M_L. When the surgeon rotates the handle of the tool, the tip or the tool will also rotate in relation to it. The rotation of the tool tip is labeled as M'_L and, through the law of superposition, can be determined that M_L and M'_L are equal. Additionally, through the law of superposition and geometric laws of translation, it was determined that M_L and M'_L are also equal to M_T and M'_T determined by the trocar parameters.

Where the Tool Parameters includes an additional steppingstone over the Trocar Parameters is actually in the relation between the Tool and Trocar. When addressing the Trocar Parameters on their own, there is no way to see how they affect any other aspects of the surgery other than the relation between one trocar parameter to another. When establishing a combined view of the Trocar and the Tool Parameters, it is possible to see the additional relationship present between the two. This relationship is a functional relationship between the outputs of parameters d_L, a_L, θ_L, θ'_L, M_L, and M'_L in relation to the outputs of components d_T, a_T, θ_T, θ'_T, M_T, and M'_T. This allows for there to be an understanding of how the tool and the trocar affect one another. The surgeon can choose to move the tool in order to reposition the tip to another location in the abdomen, this same movement would take place on the trocar as well. Being that the trocar is used to drive the tool into the abdomen and use it during surgery, motions that affect the tool can also affect the trocar.

Equations:

Equation 4: Tool Tip Arch Travel Distance

$$a_L = \frac{d_L}{2} * \theta'_L$$

Equation 5: Tool Travel Angle Function Relationship with Tool Tip Arch Distance, Linear Distance, and Tip Travel Angle

$$F(\theta_L) = f(a_L, d_L, \theta'_L)$$

Equation 6: Tool Rotation Function Relationship with Tool Tip Rotation

$$F(\mathrm{M}_L) = f(\mathrm{M}'_L)$$

Equation 7: Tool Parameters Function Relationship with Trocar Parameters

$$f(a_L, d_L, \theta'_L, \theta_L, \mathrm{M}_L, \mathrm{M}'_L) = f(a_T, d_T, \theta'_T, \theta_T, \mathrm{M}_T, \mathrm{M}'_T)$$

2.1.1.4 Camera Parameters

When addressing the parameters of the camera, it is important to note a few key similarities. These parameters, for the most part, are the same as some parameter that has already been addressed, whether it comes from the Trocar Parameters or the Tool Parameters and is tailored to the camera. Starting with the insertion point at the abdomen, just as the Trocar, the Camera component has an insertion plate just the same. As addressed prior, it is essential to have this aspect of the component insertion in order to optimize the stability of the component. In the same nature as the trocar component, the Camera component could experience some shifting taking place at the insertion point for the same potential spacing reasoning as was for the trocar shift. This set of parameters is modeled by x_{PC}, y_{PC}, and z_{PC}, in conjunction with parameters x_{PT}, y_{PT}, and z_{PT} of the Trocar. Acting in the same manner, the parameters are analyzed the same way and oriented under the same directional system. The plate scenario of the camera continues to equate to that of the trocar when the Plate Angle is addressed. As like the trocar, this angle changes upon location of the plate in comparison to the tangent line generated by the location on the abdomen where the insertion point lies. The difference between this tangent line and the location of the camera insertion plate is used to develop and calculate the Plate Angle which can be in pivoting or fixed depending on whether or not any variation occurs and if the angle is to change.

Table 4: Camera Parameters (Conventional Laparoscopy)

Camera Parameters		
Type	**Symbol**	**Definition**
Cartesian	x_{PC}	Camera Insertion Point Shift in the x-direction
	y_{PC}	Camera Insertion Point Shift in the y-direction
	z_{PC}	Camera Insertion Point Shift in the vertical direction
	d_C	Camera Lens Linear Travel Distance
	a_C	Camera Lens Arch Travel Distance
Polar	θ_{PC}	Camera Plate (Pivoting) Angle
	θ_C	Camera Arm Travel Angle
	θ'_C	Camera Lens Tip Travel Angle
Rotation	M_C	Camera Arm Rotation
	M'_C	Camera Center Point (Lens) Rotation
Other	C_U	Upper Boundary Camera FOV
	C_L	Left Boundary Camera FOV
	C_D	Lower Boundary Camera FOV
	C_R	Right Boundary Camera FOV

The Camera component continues to be related to the Trocar and Tool components. While the Camera Parameters are individual of the Trocar or Tool Parameters, they still behave in the same manner as the others do. The Camera parameters d_C, a_C, and θ'_C are dependent on θ_C where the Camera Arm Angle, which is created by the motion of the camera arm outside of the abdomen operated by the surgical assist, outputs quantitative measurements that affect the functional output of the Linear Distance, Arch Distance, and Camera Tip/Lens Travel Angle. Similarly, the rotational relationship with M_C and M'_C is a functional relationship between the outputs of parameter M'_L. This allows for there to be an understanding of how the Camera component parameters correlates with the Trocar and Tool component Parameters, even though they are not associated with one another directly nor do they have any effect on each other in Conventional Laparoscopic Surgery.

The camera parameters are a mix of Cartesian, Polar, Rotational, and Field of View aspects, as seen in *Figure 14* to the right. The camera behaves similar to, but individually from, the trocar. It enters the body on an insertion plate. This plate is not fixed on the skin and therefore has a pivoting angle of θ_{PC}. At this entry point, the plate has slight potential shifting. This directional shifting has been denoted by the terms x_{PC}, y_{PC}, and z_{PC} where the x and y terms are representative of the horizontal plane and the z term is representative of the vertical direction which is positive in the down orientation to represent the skin as the origin and pressing onto it is positive. When the surgical assist inserts and operates the trocar, the movement of the body of the camera arm creates a reciprocated movement for the camera lens. This camera lens movement is established by an arch travel distance labeled a_C. This is calculated using the linear distance traveled by the lens and the angle of which the movement occurs, labeled d_C and θ_C, respectively. The arch angle is denoted as θ'_C which can be determined geometrically through the use of the rules of similar angles which equates θ_C and θ'_C. The camera also has the ability to rotate clockwise and counterclockwise as the surgeon needs. This rotational component of the body is labeled M_C. When the surgical assist rotates the camera arm by hand, the camera lens will also rotate in relation to it. The rotation of the camera lens is labeled as M'_C and, through the law of superposition, can be determined that M_C and M'_C are equal. Where the camera parameters differ from the trocar parameters is that the camera has a field of view of which will be displayed on a screen for the viewing of the surgeon. This field of view is denoted by the 4 edges of the camera view C_U, C_L, C_D, and C_R labels for the boundaries of the top, left, bottom, and right edges of the view, respectively.

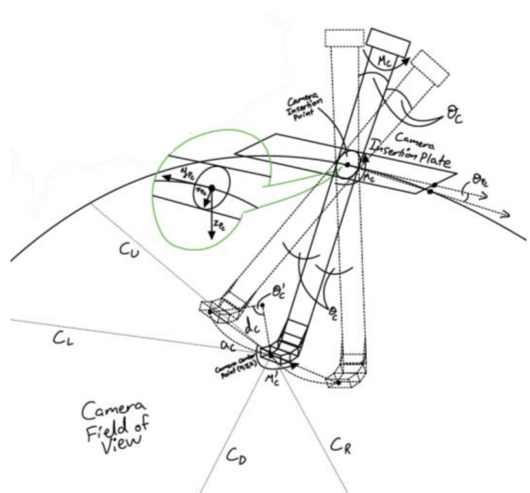

Figure 14: Camera Parameters (Conventional)

Equations:

Equation 8: Camera Lens Arch Travel Distance (Conventional Laparoscopy)

$$a_C = \frac{d_C}{2} * \theta'_C$$

Equation 9: Camera Travel Angle Function Relationship with Camera Lens Arch Distance, Linear Distance, and Tip Travel Angle (Conventional Laparoscopy)

$$F(\theta_C) = f(a_C, d_C, \theta'_C)$$

Equation 10: Camera Rotation Function Relationship with Camera Tip Rotation (Conventional Laparoscopy)

$$F(\mathrm{M}_C) = f(\mathrm{M}'_C)$$

Where the Camera Parameters become unique from all the other component parameters is regarding the FOV. None of the components have this aspect other than the Camera. Due to the nature of how a camera functions, the FOV would encompass all of the workspace viewable in front of the camera. This FOV can be defined by four boarders of the view on the screen. Each of these viewable edges has been defined by a dimension from the camera lens and through the workspace to indicate the FOV. These dimensions are defined by C_U, C_L, C_D, and C_R to represent the Up/Top, Left, Down/Bottom, and Right dimensions of the FOV. These FOV parameters would then translate into the view on the screen that the surgeon would use to conduct the laparoscopic surgery

2.1.2 Robot-Assisted Laparoscopic Surgery

As discussed in prior sections, the Robot-Assisted Laparoscopic Surgery condition is represented by the Semi-Robotic Laparoscopic Surgery Support System. This guiding system allows for us to establish two different circumstances for this condition: Workspace Controlled and Kinematically Constrained.

2.1.2.1 Workspace Controlled – Applied System

In the following sections, an evaluation of the parameters will take place under the condition of the Semi-Robotic Laparoscopic Surgery Support System being equipped but inactive during a laparoscopic surgical procedure. The application of the system produces "controlled" parameters and, therefore, this "applied" condition is being analyzed individually from when the system is activated.

2.1.2.1.1 Workspace Parameters

The analysis of this assisted surgery will take the original parameters that has been discussed for the Conventional Laparoscopic Surgery and restrict certain parameters to zero. Be that as it may, the Workspace Parameters would likely not be affected by this. The abdomen of the patient must still be inflated in order to provide room for the surgeon to conduct the operation. The Workspace Parameters would likely behave similar for this Workspace Controlled condition as it would for Conventional Laparoscopic Surgery. However, prior to analysis of these parameter, there is hesitation to use the same parameter labeling as for conventional surgery due to the currently unknown changes that may occur when the system is applied. Due to this, for these parameters, the labeling of x'- and y'-axis are used to depict the abdomen floor of the patient and the z'-axis

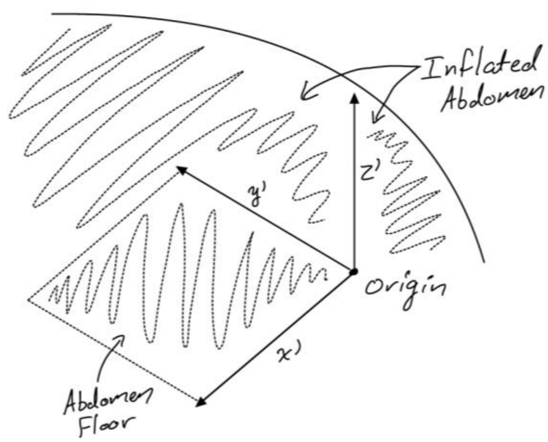

Figure 15: Workspace Parameters (Controlled)

The workspace is determined from the perspective of the surgeon. Assuming that the surgeon, as per the *Figure 11* and similar to the workspace in *Figure 15* above, is on the right of the inflated abdomen, the abdomen floor is dictated by the x'-y'-plane as shown. The depth of the abdomen is dictated by the z'-axis but the origin of where the axes meet is located at the abdomen floor in order to orient the parameters in a positive workspace and avoiding negative coordinates.

is used to establish depth but from a positive orientation starting from the abdomen floor and leading up to the abdomen wall (the belly-side of the patient). This creates a similar three-dimensional workspace labeling of x'-, y'-, and z'-axis together establishing a procedural workspace. Just as for Conventional Laparoscopic Surgery, the orientation in this situation does not fully incorporate the entire abdomen. However, it still takes into account the essential locations which are visible by the camera component since the camera is what ultimately defines the workspace. The areas outside the camera's FOV (the regions behind the camera) can still be considered negligible in this analysis just as it did in the Conventional Laparoscopic Surgery Workspace Parameters analysis.

Table 5: Workspace Parameters (Workspace Controlled – Applied System)

Workspace Parameters		
Type	**Symbol**	**Definition**
Coordinate	x'	x-direction across abdomen floor
	y'	y-direction across abdomen floor
	z'	z-direction above abdomen floor (height/depth of abdomen)

2.1.2.1.2 Trocar Parameters

For this form of guided surgery, when the braking system is deactivated but installed, as per the conditions of evaluating the Workspace Controlled circumstance, onto the patient's abdomen such that the trocars are fed through the disks for usage, the Trocar parameters should be the same as they would be for Conventional Laparoscopic Surgery where the surgical assist device would not be incorporated at all. The only factor where a parameter my vary from this situation from the conventional model would be for the Trocar Insertion Plate Angle. Due to the nature of the application of this guiding technology, even without the braking system being activated, this angle would no longer be considered a pivoting angle for the system would freeze the insertion plates on the abdomen at a fixed position and restrict any movement to take place. This would indicate that, should the position in which the plate is fixed at be different from the position of the tangent line, there will be a quantified value for the plate angle. If this plate is located in the same location as the tangent line, the angle would be equal to zero. In any case, the angle would not change throughout the guided surgical procedure, differing greatly from Conventional Laparoscopic Surgery where the plate is pivoting and the angle could be completely different depending on when the analysis takes place and what actions are being done by the surgeon. This is primarily due to the fact that the conventional procedure consists of three floating coordinate planes at each insertion due to their variable nature, but, when the Semi-Robotic Laparoscopic Surgery Support System is applied, turning this procedure into a guided one, the free-hand variables that are unable to be regulated no-longer exist and become fixed at the originally set positions that they were placed in at the start of the procedure.

Table 6: Trocar Parameters (Workspace Controlled – Applied System)

Trocar Parameters		
Type	**Symbol**	**Definition**
Cartesian	d_T	Trocar Tip Linear Travel Distance
	a_T	Trocar Tip Arch Travel Distance
Polar	θ_{PT}	Trocar Plate (Fixed) Angle
	θ_T	Trocar Travel Angle
	θ'_T	Trocar Tip Travel Angle
Rotation	M_T	Trocar Rotation
	M'_T	Trocar Tip Rotation

It is necessary to note how the Semi-Robotic Surgery Support System would connect all the components to one another through a single central module. This is what allows for a single coordinate system rather than each component running on its own floating coordinate plane. While all these components are still individually controlled, their positioning is frozen in accordance to one another as per the central module of the system. This fixing of the plates with each other will allow the surgeon to have better control over their range of motion. Should they attempt to reach a portion of the abdomen that requires the plate to not shift, this would become increasingly risky for the

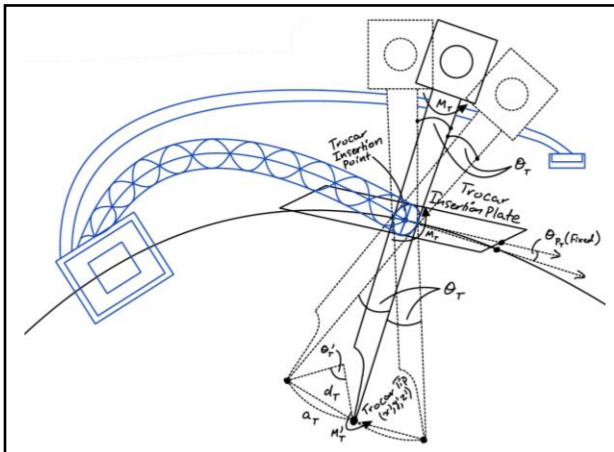

Figure 16: Trocar Parameters (Controlled)

The trocar parameters depicted in *Figure 16* are the same as those from *Figure 12* for parameters d_T, a_T, θ_T, θ'_T, M_T, and M'_T. With the attachment of the Semi-Robot Laparoscopic Surgery Support System, even when the braking system is deactivated, the θ_{PT} is now fixed on the skin at an angle rather than pivoting and varying on the skin as per the surgeon's usage. The same equations are used for the conditions displayed in this figure as in *Figure 12*.

shifting may cause the surgeon to go too far, or even – in opposite perspective – not close enough, which could lead to complications during the surgery. Having control over all the insertions and mitigating any range of error or variation in the positioning can help increase the accuracy, precision, and safety of the actions in the procedure due to the limiting of variables.

2.1.2.1.3 Tool Parameters

Table 7: Tool Parameters (Workspace Controlled – Applied System)

Tool Parameters		
Type	**Symbol**	**Definition**
Cartesian	x'_L	Tool Insertion Point Shift in the x-direction
	y'_L	Tool Insertion Point Shift in the y-direction
	z'_L	Tool Insertion Point Shift in the vertical direction
	d_L	Tool Tip Linear Travel Distance
	a_L	Tool Tip Arch Travel Distance
Polar	θ_L	Tool Travel Angle
	θ'_L	Tool Tip Travel Angle
Rotation	M_L	Tool Rotation
	M'_L	Tool Tip Rotation

For the Tool Parameters in this analysis (still considering that the device braking system is still deactivated), the parameters for this component are still the same as they would be for the analysis for Conventional Laparoscopic Surgery. During the Workspace Controlled condition, the system has no effect on the Tool Parameters. According to this, the parameters d_L, a_L, θ_L, θ'_L, M_L, and M'_L for this analysis would be the same as the parameters d_L, a_L, θ_L, θ'_L, M_L, and M'_L for the conventional analysis and the functional outputs of these parameters would also be in relation to the outputs of components d_T, a_T, θ_T, θ'_T, M_T, and M'_T for the Trocar Parameters.

The tool parameters depicted in *Figure 17* are the same as those from *Figure 13* for parameters d_L, a_L, θ_L, θ'_L, M_L, and M'_L. With the attachment of the Semi-Robot Laparoscopic Surgery Support System, even when the braking system is deactivated and analyzed under the Workspace Controlled condition, the parameters for the tool do not change. The same equations are used for the conditions displayed in this figure as in *Figure 13*. Additionally, just as explained in *Figure 13*, the coordinates of the tool tip may behave independently from the trocar. While there are many instances where these parameters will behave in association to one another, should the surgeon choose to adjust the depth of the surgical tool the coordinates of the tool tip will change independently from the trocar which would, under these circumstances, would not change. This indicates, just as previously mentioned under the conventional condition, how the tool and trocar coordinate parameters behave in relationship to one another under certain circumstances and how the other situations where they are independent is what allows for the depth of the surgical tool to come into consideration and how this particular mechanic of the tool is completely independent from the rest of the parameters (this is ultimately defined not as its own parameter but rather under the conditions of the coordinate parameters of the tool tip in comparison to the coordinate

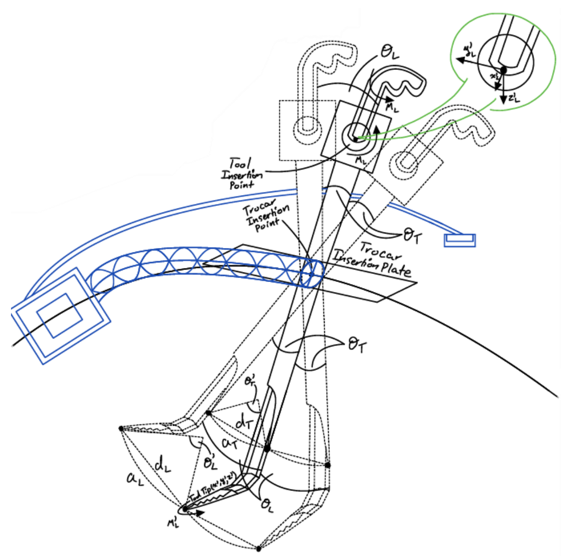

Figure 17: Tool Parameters (Controlled)

While the braking system remains deactivated under this condition, this analysis can be treated just as a conventional analysis. It also holds true that the coordinates of the tool tip will remain under the same conditions as under the conventional laparoscopic surgery constraint. As explained in prior sections, these coordinates will continue to describe the positioning of the tool regarding its 2D placement as well as its depth associated with the surgeon's direction of the tool. This continues to establish the understanding that the tool tip coordinates, while they can be associated with the trocar tip coordinates and their variation, may be presented to have different quantitative properties than the trocar coordinates due to the factor of depth.

2.1.2.1.4 Camera Parameters

Similar to the analysis for the Trocar Parameters under the Workspace Controlled condition, the Camera Parameters would fall under the same evaluation; they should be the same throughout just as they would be for the conventional analysis. Where the parameters differ in the Workspace Controlled analysis from the conventional analysis is just like it differs for the Trocar Parameters; in this case the Camera Insertion Plate Angle is the parameter in question. This angle will remain fixed on the patient's abdomen. It is important to note that the quantifiability of this angle is evaluated exactly as the Trocar Insertion Plate Angle is as it is still in reference to the tangent line of the insertion point location on the abdomen and does not vary throughout the procedure. Just like the Trocar Plate Angle, the angle would not change throughout the surgical procedure.

Table 8: Camera Parameters (Workspace Controlled – Applied System)

Camera Parameters		
Type	**Symbol**	**Definition**
Cartesian	d_C	Camera Lens Linear Travel Distance
	a_C	Camera Lens Arch Travel Distance
Polar	θ_{PC}	Trocar Plate (Pivoting) Angle
	θ_C	Camera Arm Travel Angle
	θ'_C	Camera Lens Tip Travel Angle
Rotation	M_C	Camera Arm Rotation
	M'_C	Camera Center Point (Lens) Rotation
Other	C_U	Upper Boundary Camera FOV
	C_L	Left Boundary Camera FOV
	C_D	Lower Boundary Camera FOV
	C_R	Right Boundary Camera FOV

For the remaining Camera Parameters in this form of assisted surgery, the parameters for this component are still the same as they would be for the analysis for Conventional Laparoscopic Surgery. During the Workspace Controlled condition when the system is applied, the device has no effect on the remaining Camera Parameters. According to this, the parameters d_C, a_C, θ_C, θ'_C, M_C, and M'_C for this analysis would be the same as the parameters d_C, a_C, θ_C, θ'_C, M_C, and M'_C for the conventional analysis. Additionally, the other parameters being analyzed on the Camera regarding the FOV would remain unaffected as well. These parameters are simply aspects of the camera component that are present due to the nature of the component itself rather than the circumstances of the procedure or its methods. Therefore, The Workspace Controlled condition parameters can be treated just as a Conventional Surgery condition and its analysis.

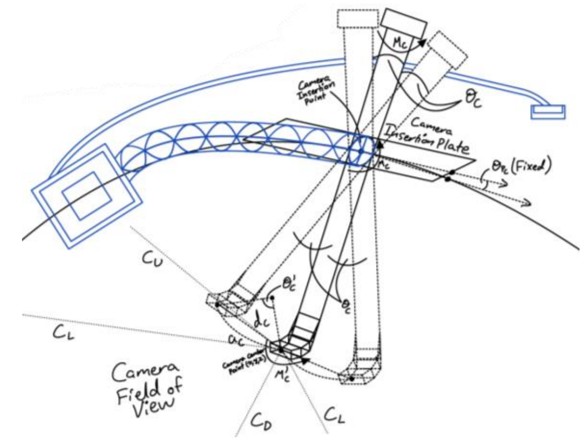

Figure 18: Camera Parameters (Controlled)

The camera parameters depicted in *Figure 18* are the same as those from *Figure 14* for parameters d_C, a_C, θ_C, θ'_C, M_C, and M'_T. With the attachment of the Semi-Robot Laparoscopic Surgery Support System, even when the braking system is deactivated, the θ_{PT} is now fixed on the skin at an angle rather than pivoting and varying on the skin as per the surgeon's usage. The same equations are used for the conditions displayed in this figure as in *Figure 14*.

2.1.2.2 Kinematically Constrained – Activated System

Similar to the previous sections, the following parameter evaluations will take place under the condition where the Semi-Robotic Laparoscopic Surgery Support System is still equipped. However, in these evaluations, the braking system of the device will be considered activated during the procedure which develops a "kinematically constrained" condition for evaluating the parameters.

2.1.2.2.1 Workspace Parameters

Table 9: Workspace Parameters (Kinematically Constrained – Activated System)

Workspace Parameters		
Type	**Symbol**	**Definition**
Coordinate	x'	x-direction across abdomen floor
	y'	y-direction across abdomen floor
	z'	z-direction above abdomen floor (height/depth of abdomen)

Now an analysis on the workspace takes place for the Kinematically Constrained condition where the Semi-Robotic Laparoscopic Surgery Support System is activated; this circumstance is being defined as being Kinematically Constrained. This will restrict the majority of the parameters to zero for they will be frozen due to the fixed braking mechanism. However, the Workspace Parameters continue to remain unaffected by this. The abdomen of the patient must still be inflated in order to provide room for the surgeon to conduct the operation. The Workspace Parameters would behave the same for this guided laparoscopic surgery whether or not the system is activated as well as it would for Conventional Laparoscopic Surgery. For these parameters, the x'- and y'-axis continue to indicate the abdomen floor of the patient and the z'-axis is used to establish depth but from a

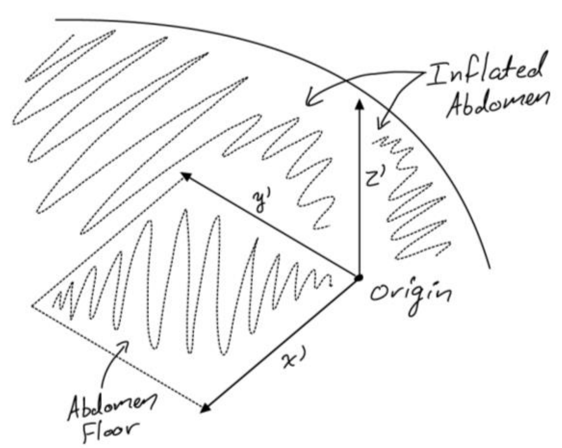

Figure 19: Workspace Parameters (Constrained)

The Robot Assisted workspace parameters when the braking system is activated maintains the same x', y', and z' workspace components as for when the system is applied but the braking mechanism is deactivated.

positive orientation starting from the abdomen floor and leading up to the abdomen wall (the belly-side of the patient).

2.1.2.2.2 Trocar Parameters

Table 10: Trocar Parameters (Kinematically Constrained – Activated System)

Trocar Parameters		
Type	**Symbol**	**Definition**
Polar	θ_{PT}	Trocar Plate (Fixed) Angle

When the braking system is activated on the trocar, all the components get zeroed out except for the Trocar Plate Angle. This angle may have a value but it will remain fixed throughout the entire time that the system is activated. This braking system is meant to freeze the component in place and prevent any movement from taking place. According to this the only parameters that remain relevant when the braking system is activated other than the fixed plate angle is the coordinates of the Trocar Tip in accordance to the Workspace Parameters.

Each component goes go zero when this baking system is activated except for the Trocar Plate Angle being that this aspect can have a quantitative value but shall not change. This would remain as a fixed angle when comparing the fixed position of the Trocar Plate with the tangent line relative to the insertion point. This

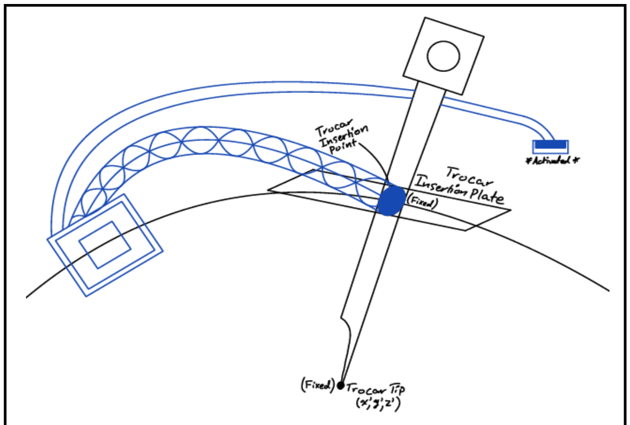

Figure 20: Trocar Parameters (Constrained)

When the braking system is activated, as displayed in *Figure 20*, the only parameters that remain for the aspects associated with the trocar are the Robot Assisted workspace parameters as determined in *Figure 15* and *Figure 19*.

measurement can be equal to zero if the position of the plate is on the tangent line; hence, no angle would be present. Using the relations provided in the Trocar Tip Travel Angle (Kinematically Constrained – Activated System), Trocar Travel Angle Function Relationship (Kinematically Constrained – Activated System), and Trocar Rotation Function Relationship (Kinematically Constrained – Activated System) equations, the fixed components are shown to go to zero upon activation of the braking system.

Equations:

Equation 11: Trocar Tip Travel Angle (Kinematically Constrained – Activated System)

$$a_T = \frac{d_T}{2} * \theta'_T = 0$$

Equation 12: Trocar Travel Angle Function Relationship with Trocar Tip Arch Distance, Linear Distance, and Tip Travel Angle (Kinematically Constrained – Activated System)

$$F(\theta_T) = f(a_T, d_T, \theta'_T) = 0$$

Equation 13: Trocar Rotation Function Relationship with Trocar Tip Rotation (Kinematically Constrained – Activated System)

$$F(\mathrm{M}_T) = f(\mathrm{M}'_T) = 0$$

2.1.2.2.3 Tool Parameters

When the braking system is activated on the trocar, all the Tool Parameters go to zero just as they would for the trocar. Being that the braking force is applied directly on the Trocar, the tool parameters will work in conjunction with those of the trocar. According to this the only parameters that remain relevant for the Tool Parameters when the braking system is activated is the coordinates of the Tool Tip in accordance to the Workspace Parameters.

Each component goes go zero when this baking system is activated. Using the relations provided in the Tool Tip Arch Travel Distance (Kinematically Constrained – Activated System), Tool Travel Angle Function Relationship (Kinematically Constrained – Activated System), Tool Parameters Function Relationship (Kinematically Constrained – Activated System), and Tool Rotation Function Relationship (Kinematically Constrained – Activated System) equations, the fixed components are shown to go to zero upon activation of the braking system.

It is necessary to account for the difference between the relevant workspace parameters against the specific tool parameters that become zero. The reason for these workspace parameters to remain relevant even with the activated braking system is due to the fact that they do not become zero but rather are frozen in their positioning. Under these conditions, unlike the prior circumstances of the deactivated system under the Workspace Controlled condition and the Conventional procedure, the tool tip coordinates and the trocar coordinates now become fully associated with one another. Being that neither of these components can move freely under the activated system constraint, they now behave as a single entity which eliminates the prior concept of the adjustable depth of the surgical tool moving independently from the trocar.

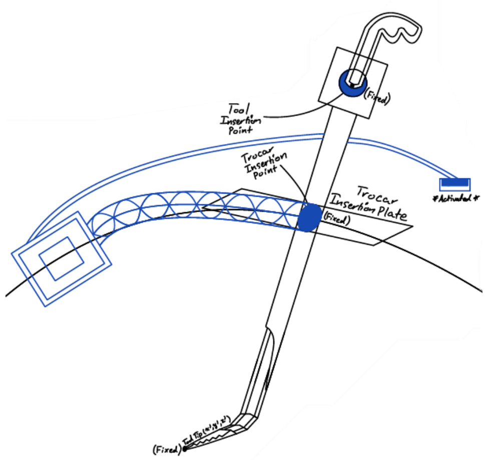

Figure 21: Tool Parameters (Constrained)

When the braking system is activated, as displayed in *Figure 21*, the only parameters that remain for the aspects associated with the trocar are the Robot Assisted workspace parameters as determined in *Figure 15* and *Figure 19*.

Equations:

Equation 14: Tool Tip Arch Travel Distance (Kinematically Constrained – Activated System)

$$a_L = \frac{d_L}{2} * \theta'_L = 0$$

Equation 15: Tool Travel Angle Function Relationship with Tool Tip Arch Distance, Linear Distance, and Tip Travel Angle (Kinematically Constrained – Activated System)

$$F(\theta_L) = f(a_L, d_L, \theta'_L) = 0$$

Equation 16: Tool Parameters Function Relationship with Trocar Parameters (Kinematically Constrained – Activated System)

$$f(a_L, d_L, \theta'_L, \theta_L) = f(a_T, d_T, \theta'_T, \theta_T) = 0$$

Equation 17: Tool Rotation Function Relationship with Tool Tip Rotation (Kinematically Constrained – Activated System)

$$F(\mathrm{M}_L) = f(\mathrm{M}'_L) = 0$$

2.1.2.2.4 Camera Parameters

Table 11: Camera Parameters (Kinematically Constrained – Activated System)

Camera Parameters		
Type	**Symbol**	**Definition**
Polar	θ_{PC}	Camera Plate (Fixed) Angle
Other	C_U	Upper Boundary Camera FOV
	C_L	Left Boundary Camera FOV
	C_D	Lower Boundary Camera FOV
	C_R	Right Boundary Camera FOV

When the braking system is activated on the camera, all the parameters go to zero except for the Camera Plate Angle just as they would for the trocar. This angle may have a value but it will remain fixed throughout the entire time that the system is activated. Being that the braking force is applied directly on the camera arm, the only parameters that remain relevant for the Camera Parameters when the braking system is activated other than the fixed plate angle is the coordinates of the Camera Tip/Lens in accordance to the Workspace Parameters.

Each component goes go zero when this baking system is activated except for the Camera Plate Angle being that this aspect can have a quantitative value but shall not change. This would remain as a fixed angle when comparing the fixed position of the Camera Plate with the tangent line relative to the insertion point. This measurement can be equal to zero if the position of the plate is on the tangent line; hence, no angle would be present. Using the relations provided in the Camera Lens Arch Travel Distance (Kinematically Constrained – Activated System), Camera Travel Angle Function Relationship (Kinematically Constrained – Activated System), and Camera Rotation Function Relationship (Kinematically Constrained – Activated System) equations, the fixed components are shown to go to zero upon activation of the braking system.

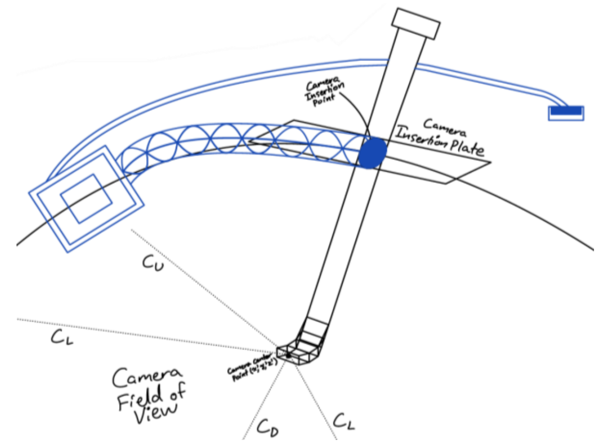

Figure 22: Camera Parameters (Constrained)

When the braking system is activated, as displayed in *Figure 22*, the parameters that remain for the aspects associated with the tool are the Robot Assisted workspace parameters as determined in *Figure 15* and *Figure 19*, and the FOV parameters for this is unaffected by the activation of a braking system.

Equations:

Equation 18: Camera Lens Arch Travel Distance (Kinematically Constrained – Activated System)

$$a_C = \frac{d_C}{2} * \theta'_C = 0$$

Equation 19: Camera Travel Angle Function Relationship with Camera Lens Arch Distance, Linear Distance, and Tip Travel Angle (Kinematically Constrained – Activated System)

$$F(\theta_C) = f(a_C, d_C, \theta'_C) = 0$$

Equation 20: Camera Rotation Function Relationship with Camera Tip Rotation (Kinematically Constrained – Activated System)

$$F(\mathrm{M}_C) = f(\mathrm{M}'_C) = 0$$

3 Results

3.1 Pre-Reevaluation

Upon determining the parameters in the above sections per each particular condition, this information has been collected and placed side by side for each specific set of parameters in order to gain a clearer understanding of the information for the workspace, trocar, tool, and camera parameters from one condition to the next.

3.1.1 Workspace Parameter Comparison

It has been established that, through the various analysis between Robot-Assisted Laparoscopic Surgery (using as the guiding system technology representative of the Workspace Controlled and Kinematically Constrained conditions, involving an activated and deactivated braking system, respectively), and Conventional Laparoscopic Surgery, that the Workspace Parameters would remain the same from one scenario to the next and would not vary in any aspect.

Table 12: Workspace Parameters (Compared)

Workspace Parameters				
Type	**Conventional**	**Workspace Controlled**	**Kinematically Constrained**	**Comparison**
Coordinate	x	x'	x'	All Equal
	y	y'	y'	All Equal
	z	z'	z'	All Equal

3.1.2 Trocar Parameter Comparison

It was found that the Trocar Plate Insertion Point Angle will remain the same throughout any of the analyses provided that the case is under the circumstance of being fixed. This can still be incorporated in Conventional Laparoscopic Surgery but the scenario would not be "fixed" necessarily but rather be the same if that quantitative value for the angle had not changed from one calculation to the next. While this is a hypothetical situation being that the conventional analysis would have the plate pivoting and therefore varying in angle, there is a possibility where the plate would not move which would be related to the fixed scenarios when using the guided laparoscopic technology. All other parameters were found to remain present during the Workspace Controlled case except for the cartesian parameters used to indicate trocar insertion point shifting. When analyzing the Kinematically Constrained condition, all components would go to zero except for the insertion plate angle which would be fixed (unless the fixed value is already 0 due to it being in line with the tangent line in that specific scenario) and the Workspace Parameters which become relevant for the trocar when indicating the Trocar Tip's coordinate locations in the workspace.

Table 13: Trocar Parameters (Compared)

Trocar Parameters				
Type	**Conventional**	**Workspace Controlled**	**Kinematically Constrained**	**Comparison**
Cartesian	x_{PT}	0	0	Different
	y_{PT}	0	0	Different
	z_{PT}	0	0	Different
	d_T	d_T	0	Equal (Controlled) Different (Constrained)
	a_T	a_T	0	Equal (Controlled) Different (Constrained)
Polar	θ_{PT}	θ_{PT} (Fixed)	θ_{PT} (Fixed)	All Equal (When Fixed) Different (When Pivoting)
	θ_T	θ_T	0	Equal (Controlled) Different (Constrained)
	θ'_T	θ'_T	0	Equal (Controlled) Different (Constrained)
Rotation	M_T	M_T	0	Equal (Controlled) Different (Constrained)
	M'_T	M'_T	0	Equal (Controlled) Different (Constrained)

3.1.3 Tool Parameter Comparison

All Tool Parameters were found to go to zero during the Kinematically Constrained analysis. This indicates that the only parameters that become relevant for the tool when the braking system is activated are the Workspace Parameters when indicating the Tool Tip's coordinate locations in the workspace. All of the tool parameters remain present when comparing the Workspace Controlled case with the conventional procedure instead.

Table 14: Tool Parameters (Compared)

Tool Parameters				
Type	**Conventional**	**Workspace Controlled**	**Kinematically Constrained**	**Comparison**
Cartesian	x_L	x'_L	0	Different
	y_L	y'_L	0	Different
	z_L	z'_L	0	Different
	d_L	d_L	0	Equal (Controlled) Different (Constrained)
	a_L	a_L	0	Equal (Controlled) Different (Constrained)
Polar	θ_L	θ_L	0	Equal (Controlled) Different (Constrained)
	θ'_L	θ'_L	0	Equal (Controlled) Different (Constrained)
Rotation	M_L	M_L	0	Equal (Controlled) Different (Constrained)
	M'_L	M'_L	0	Equal (Controlled) Different (Constrained)

3.1.4 Camera Parameter Comparison

It was found that the Camera Plate Insertion Point Angle will remain the same throughout any of the analyses and can still be incorporated in Conventional Laparoscopic Surgery but would not be "fixed." All other parameters were found to remain present during the Workspace Controlled case except for the cartesian parameters used to indicate camera insertion point shifting. For the

Kinematically Constrained case, all components would go to zero except for the insertion plate angle which would be fixed (unless the fixed value is already 0 due to it being in line with the tangent line in that specific scenario), the Workspace Parameters which become relevant for the trocar when indicating the Trocar Tip's coordinate locations in the workspace, and the FOV parameters as they are associated with the camera itself and are independent of the braking system.

Table 15: Camera Parameters (Compared)

Camera Parameters				
Type	**Conventional**	**Workspace Controlled**	**Kinematically Constrained**	**Comparison**
Cartesian	x_{PC}	0	0	Different
	y_{PC}	0	0	Different
	z_{PC}	0	0	Different
	d_C	d_C	0	Equal (Controlled) Different (Constrained)
	a_C	a_C	0	Equal (Controlled) Different (Constrained)
Polar	θ_{PC}	θ_{PC} (Fixed)	θ_{PC} (Fixed)	All Equal (When Fixed) Different (When Pivoting)
	θ_C	θ_C	0	Equal (Controlled) Different (Constrained)
	θ'_C	θ'_C	0	Equal (Controlled) Different (Constrained)
Rotation	M_C	M_C	0	Equal (Controlled) Different (Constrained)
	M'_C	M'_C	0	Equal (Controlled) Different (Constrained)
Other	C_U	C_U	C_U	All Equal
	C_L	C_L	C_L	All Equal
	C_D	C_D	C_D	All Equal
	C_R	C_R	C_R	All Equal

3.1.5 Comparison Overview

When evaluating each of the conditions side by side, the similarities become clear from one condition to the next. It is also visible that certain cartesian, polar, rotational, and other coordinates maintain relevance and equivalency across multiple situations, or all for some. This information has been collected and compiled all together into a Venn Diagram as shown in *Figure 23*. This compilation of the data allows for an easy breakdown of the information to show between which conditions certain parameters are related.

It was determined that most of the defined parameters revert to 0 when the braking system becomes activated under the Kinematically Constrained condition. This is viewable by the lack of available parameters related between the activated braking system condition and the other conditions (Conventional and Workspace Controlled) that have been analyzed. From this, it can be understood that the only parameters that hold up under all conditions are the workspace coordinate parameters and the camera field of view (FOV) parameters. The only other parameters that appear to be non-zero when the braking system is active are the trocar and camera plate angle (when fixed) which hold true for both robot-assisted conditions. This condition can also be considered to hold true for the conventional condition however this is only the case if the plates exhibit a pivoting capability and are not limited under a fixed constraint.

All other parameters are either exclusively present in the conventional condition or they exhibit a relationship between the Workspace Controlled case and Conventional Surgery conditions but are not non-zero in the Kinematically Constrained condition.

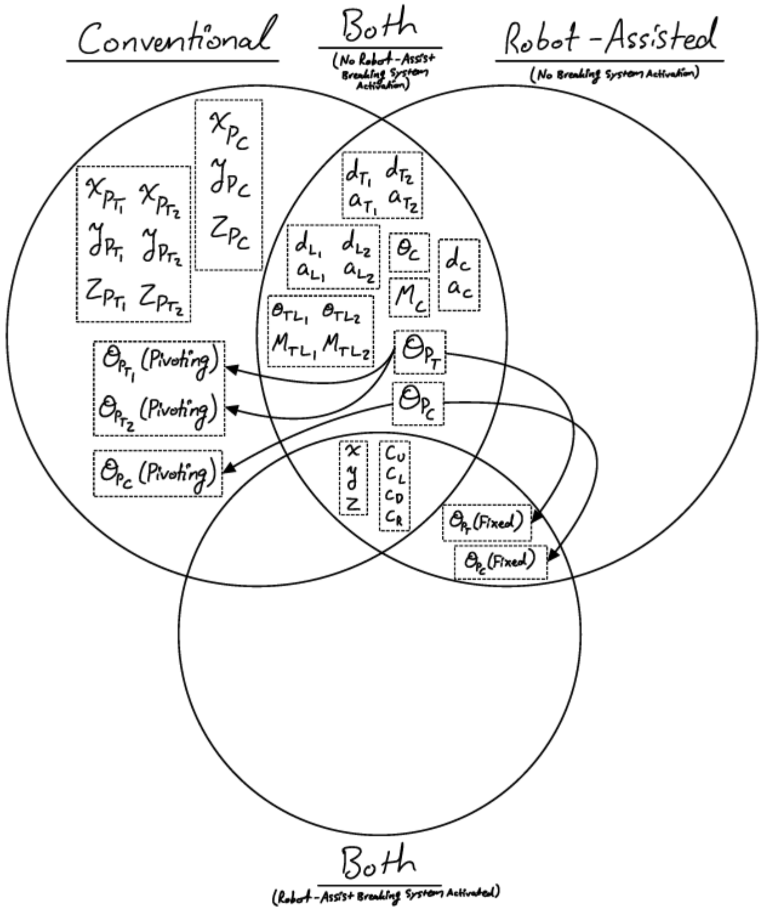

Figure 23: Parameters Comparison

The information compiled in *Figure 23* is a summarized diagram of the parameters and when they are incorporated. This Ven Diagram comparison is sectioned into Conventional Laparoscopic Surgery, Robot-Assisted (No Braking System Activated) – which represents the Workspace Controlled condition, and Robot-Assisted (Braking System Activated) – which represents the Kinematically Constrained condition. This figure lists the parameters θ_{TL} and M_{TL}. These parameters are used in order to associate θ_T, θ'_T, θ_L, and θ'_L, and M_T, M'_T, M_L, and M'_L. Being that these θ and M parameters are all equal to one another (regarding like terms) they can be replaced by θ_{TL} and M_{TL} in order to incorporate all the terms in a single symbolization. Workspace parameters have also been adjusted to indicate only x, y, and z since the workspaces of the Conventional Laparoscopic Surgery and the Robot Assisted Surgery (both when activated and deactivated) conditions are all the same so they have been denoted with simplified variables down to all x-, y-, and z-axis notations. Additionally, it is necessary to not that each Trocar and Tool acts individually from the other, and the same goes for the Camera component. This is the reasoning for the subscripting of 1 and 2 for the terms that differ from one component to the next. The θ_{PT} and θ_{PC} parameters can be associated with both the Conventional Parameters separately and the relation between all 3 cases addressed. When considering the Conventional θ_{PT} and θ_{PC} parameters, these components are variable, or "pivoting" which is exclusive to Conventional Laparoscopic Surgery. When considering the association between the Conventional, Workspace Controlled, and Kinematically Constrained conditions, the θ_{PT} and θ_{PC} parameters are fixed at a single quantitative value which is uniform across all three scenarios for Laparoscopic Surgery. While Conventional Surgery is not necessarily fixed, the idea of the term "fixed" is to identify a single quantity that the plat remains at, should this quantity remain constant during the surgery it is still considered "fixed" as it would if the Semi-Robotic Laparoscopic Surgery Support System were to be implemented (regardless whether the braking system is activated or not). It has also been determined that the parameters x'_L, y'_L, and z'_L representing the tool variation shift within the trocar has been deemed minute and insignificant so they are not included in the final parameters for the tools. These values would be so small that they can be deemed as negligible for the purposes of determining operation parameters during laparoscopic surgery.

3.2 Post-Reevaluation

Once the parameters have been established, the relationships between all the parameters that have been discussed began to be connected to each other. Initially, the Workspace Parameters were simple to create an association between them being that, while the labeling had been different from one analysis to the next, each of the Workspace Parameters were the same in every case and representative of the exact same concepts. Due to this, it was adjusted that all Workspace Parameters be reestablished using the standard convention of the x-, y-, and z-axis.

Table 16: Workspace Parameters (Reestablished)

Workspace Parameters (Reestablished)					
Type	**Conventional**	**Workspace Controlled**	**Kinematically Constrained**	**Comparison**
Coordinate	x	x	x	All Equal
	y	y	y	All Equal
	z	z	z	All Equal

Using the functional relationships established in prior sections, it was realized that the Trocar and Tool Angle and Rotation parameters were always equal to one another. Using geometric rules of similar angles to discern, it was determined that the Trocar and Tool Angles were equal to one another. It was also determined that the rotational aspect of these components was also equal. Due to this, it was adjusted that the Tool and Trocar Angle and Rotation parameters be merged and reestablished using the conventions of θ_{TL} and M_{TL}. For the Tool Insertion Point, the potential shifting that may be present at that location was evaluated as being extremely minimal. Being that it is very minute of a variation in the procedure, it has been deemed to be negligible. Due to this, it was adjusted that the Tool Insertion Point Shift values would be reestablished to always equal zero and the parameter would be removed from consideration during any of the analysis cases.

Table 17: Trocar Parameters (Reestablished)

Trocar Parameters (Reestablished)				
Type	**Conventional**	**Workspace Controlled**	**Kinematically Constrained**	**Comparison**
Cartesian	x_{PT}	0	0	Different
	y_{PT}	0	0	Different
	z_{PT}	0	0	Different
	d_T	d_T	0	Equal (Controlled) Different (Constrained)
	a_T	a_T	0	Equal (Controlled) Different (Constrained)
Polar	θ_{PT}	θ_{PT} (Fixed)	θ_{PT} (Fixed)	All Equal (When Fixed) Different (When Pivoting)
	θ_{TL}	θ_{TL}	0	Equal (Controlled) Different (Constrained)
Rotation	M_{TL}	M_{TL}	0	Equal (Controlled) Different (Constrained)

Table 18: Tool Parameters (Reestablished)

Tool Parameters (Reestablished)				
Type	**Conventional**	**Workspace Controlled**	**Kinematically Constrained**	**Comparison**
Cartesian	d_L	d_L	0	Equal (Controlled) Different (Constrained)
	a_L	a_L	0	Equal (Controlled) Different (Constrained)
Polar	θ_{TL}	θ_{TL}	0	Equal (Controlled) Different (Constrained)
Rotation	M_{TL}	M_{TL}	0	Equal (Controlled) Different (Constrained)

Finally, these same rules and evaluations were used to establish that the Camera Angle and Camera Lens Travel Angle are equal along with the Camera Arm Rotation and Camera Lens Rotation also being equal. Due to this, it was adjusted that the Camera and Camera Lens Angle and the Camera and Camera Lens Rotation parameters be reestablished using the conventions of θ_C and M_C.

Table 19: Camera Parameters (Reestablished)

Camera Parameters (Reestablished)				
Type	**Conventional**	**Workspace Controlled**	**Kinematically Constrained**	**Comparison**
Cartesian	x_{PC}	0	0	Different
	y_{PC}	0	0	Different
	z_{PC}	0	0	Different
	d_C	d_C	0	Equal (Controlled) Different (Constrained)
	a_C	a_C	0	Equal (Controlled) Different (Constrained)
Polar	θ_{PC}	θ_{PC} (Fixed)	θ_{PC} (Fixed)	All Equal (When Fixed) Different (When Pivoting)
	θ_C	θ_C	0	Equal (Controlled) Different (Constrained)
Rotation	M_C	M_C	0	Equal (Controlled) Different (Constrained)
Other	C_U	C_U	C_U	All Equal
	C_L	C_L	C_L	All Equal
	C_D	C_D	C_D	All Equal
	C_R	C_R	C_R	All Equal

Equations:

Equation 21: Workspace Relationship

$$x, y, z = x', y', z'$$

Equation 22: Trocar and Tool Angle Relationship

$$\theta_T, \theta'_T = \theta_L, \theta'_L = \theta_{TL}$$

Equation 23: Trocar and Tool Rotation Relationship

$$M_T, M'_T = M_L, M'_L = M_{TL}$$

Equation 24: Camera and Camera Lens Angle Relationship

$$\theta_C = \theta'_C$$

Equation 25: Camera and Camera Lens Rotation Relationship

$$M_C = M'_C$$

Equation 26: Tool Insertion Point Shift Negligibility Representation

$$x_L, y_L, z_L = x'_L, y'_L, z'_L = 0$$

3.3 The Final Product

After the re-evaluation measures of the study, some parameters were redefined, others remained the same, and a few were determined to be negligible. These simplifications to the data allow us to clarify the parameter labeling into a more generalized structure. This establishes a more coherent and simplistic standard of identifying these parameters which will enhance its use in the field of medicine. In the tables below, the parameters have been set side-by-side per each condition with the newly adjusted labeling/definitions for these parameters that have been determined:

Table 20: Final Simplification of Workspace Parameters

Workspace Parameters				
Type	**Conventional**	**Workspace Controlled**	**Kinematically Constrained**	**Definitions**
Coordinate	x	x	x	x-direction across abdomen floor
	y	y	y	y-direction across abdomen floor
	z	z	z	z-direction above abdomen floor (height/depth of abdomen)

Table 21: Final Simplification of Trocar Parameters

Trocar Parameters				
Type	**Conventional**	**Workspace Controlled**	**Kinematically Constrained**	**Definitions**
Cartesian	x_{PT}	0	0	Trocar Insertion Point Shift in the x-direction
	y_{PT}	0	0	Trocar Insertion Point Shift in the y-direction
	z_{PT}	0	0	Trocar Insertion Point Shift in the Vertical direction
	d_T	d_T	0	Trocar Tip Linear Travel Distance
	a_T	a_T	0	Trocar Tip Arch Travel Distance
Polar	θ_{PT}	θ_{PT} (Fixed)	θ_{PT} (Fixed)	Trocar Plate Angle
	θ_{TL}	θ_{TL}	0	Trocar and Tool Travel Angle
Rotation	M_{TL}	M_{TL}	0	Trocar and Tool Rotation

Table 22: Final Simplification of Tool Parameters

Tool Parameters				
Type	**Conventional**	**Workspace Controlled**	**Kinematically Constrained**	**Definitions**
Cartesian	d_L	d_L	0	Tool Tip Linear Travel Distance
	a_L	a_L	0	Tool Tip Arch Travel Distance
Polar	θ_{TL}	θ_{TL}	0	Trocar and Tool Travel Angle
Rotation	M_{TL}	M_{TL}	0	Trocar and Tool Rotation

Table 23: Final Simplification of Camera Parameters

Camera Parameters				
Type	**Conventional**	**Workspace Controlled**	**Kinematically Constrained**	**Definitions**
Cartesian	x_{PC}	0	0	Camera Insertion Point Shift in the x-direction
	y_{PC}	0	0	Camera Insertion Point Shift in the y-direction
	z_{PC}	0	0	Camera Insertion Point Shift in the vertical direction
	d_C	d_C	0	Camera Lens Linear Travel Distance
	a_C	a_C	0	Camera Lens Arch Travel Distance
Polar	θ_{PC}	θ_{PC} (Fixed)	θ_{PC} (Fixed)	Camera Plate Angle
	θ_C	θ_C	0	Camera Travel Angle
Rotation	M_C	M_C	0	Camera Rotation
Other	C_U	C_U	C_U	Upper Boundary Camera FOV
	C_L	C_L	C_L	Left Boundary Camera FOV
	C_D	C_D	C_D	Lower Boundary Camera FOV
	C_R	C_R	C_R	Right Boundary Camera FOV

When comparing these final tables with the prior ones above, it can be coordinated that the simplified parameters, the θ and M terms, have adjusted definitions for their labeling. The insertion plate parameters, θ_{PT}, and θ_{PC}, have been adjusted to simply state that this is the plate parameter rather than specifying whether it is for a pivoting condition or a fixed one. This would require knowledge of the facts outlined in this research about how the traditional surgery condition comes with more free-variables which ultimately explains why the plate parameters are considered as "pivoting" and the conditions utilizing the guiding-system technology, which control these free-variables (the amount of control depends on whether or not the braking system is activated by the surgeon), considers a "fixed" plate in the surgical environment. While this terminology does affect the quantitative properties of the parameters, it was deemed unnecessary to explicitly include them in the overall labeling of the parameter. Based on this, the parameters associated with the insertion plates have been generalized to just state the type of plate (i.e., Trocar Plate Angle, Camera Plate Angle).

Similarly, the travel angle parameters have been adjusted as well. Prior to the evaluation which re-established the parameters, the travel angles were split into two components: the component travel angle (i.e., Trocar Travel Angle, Tool Travel Angle, Camera Travel Angle) and the component tip or lens travel angle. As shown in the Post-Reevaluation section, it was found that, by using *Equation 22: Trocar and Tool Angle Relationship* and *Equation 24: Camera and Camera Lens Angle Relationship*, we can condense down the parameters into combined entities. This worked slightly different between the Trocar and Tool and the Camera components because the Trocar and Tool had their travel angles combined all together while the camera had its travel angles combined separately. This is due to the fact that the Trocar and Tool work as a single entity for the majority of the surgery while the Camera is an individual entity from the others. This information has entertained the idea that these same, priorly individual, parameters, should have their definitions condensed down just as their labeling has been. Due to this, the parameter terminology has been changed to encompass all effective travel angles between the components by using

“Trocar and Tool Travel Angle” and “Camera Travel Angle” as the simplified definition for these terms.

For the rotational parameters, there occurs the same process as that of the polar parameters. As shown in the tables above for the Trocar, Tool, and Camera, the rotation, representative by label M, was initially split into two separate parametric labels and then condensed into a single entity for the Trocar and Tool and for the Camera. These single labels have been renamed with the generalized terminology of “Trocar and Tool Rotation” and “Camera Rotation” which takes into account the entire rotation as a whole being that all sectioned rotations that were previously evaluated turned out to be equal.

This simplification process, while not necessarily heavily extensive, allows for the unnecessary redundancies in labeling to be avoided and for a coherent, understandable definition to be provided for each parameter that has been deemed essential for consideration when conducting a surgical procedure.

4 Discussion

Throughout the studies done in this research and the comparison that took place, it was determined that the parameters were able to be simplified into related terminology. The parameters ended up being narrowed down to specific, universal labels that remain consistent from one condition to the next. This labeling contained, essentially, only variation on the subscripts T, L, and C used to indicate the Trocar, Tool, and Camera, respectively. This provides a coherent means of understanding what the parameters are and what each is defined as while avoiding extensive, complex labeling for the parameters across each laparoscopic case condition being compared.

While the scope of this research remains within the walls of a conceptual study, this should not be gauged as a hinderance to further research to be done on a more quantitative basis. There was an intention to utilize the Semi-Robotic Surgery Support System and laparoscopic surgery simulation technologies to develop a greater quantitative understanding of the values that these parameters symbolize. For instance, a potential leg for future research is to establish the maximum reachable points within the workspace that certain surgical tools can achieve. This information is not necessarily considered in common practice since a surgeon can simply reach for a desired location with their tool and whether they can or cannot reach it is then realized during that moment. However, while this may be considered as 'second hand' for the surgeon, it is necessary to establish an understanding of the actual limitations of the tools being used in the operation within the scope of the workspace. When it comes to surgery, those few seconds that a surgeon might attempt to reach a bleed, organ, artery, etc. with their tool and discover that they cannot reach it could mean life or death for a patient. Due to this, it is in fact essential to determine what these maximum reachable coordinates are in the workspace and for surgeons then to become aware of such limitations so that they can respond accordingly if it becomes necessary.

Another area in which this research can be furthered is more directly regarding the braking system itself. Should research be done on the force being applied by the braking system in a more detailed manner, the actual force needed to manually dislodge from the braking system would also become apparent. While this research did not venture into defining the parameters of components beyond the threshold of the workspace and standard surgical equipment, it is believed that such a parameter would be labeled with a force parameter, F, and would be beneficial to gain a better understand of whether the force is large enough that, should the surgeon accidentally move or slip, it would maintain the fixed position, or if it is more minimal to the point where a moderate adjustment of the wrist could be cause for concern. It is obvious that surgery is meticulous and surgeons are cautious when doing their jobs, however there can be differences in how careful a surgeon is required to be depending on the nature of the surgery. Due to this, it is believed to be beneficial if the structural integrity of the braking force technology in the device is researched and the nature of its usage in the surgical environment is evaluated.

This research had encountered some interference during the work due to the global viral pandemic of the Coronavirus during the year of 2020 through the start of 2021, and ongoing. The COVID - 19 Pandemic posed an issue when all facilities were subject to closure to limit the spread of the virus. It was necessary, for the progression of this research, to go to the University of Central Florida campus in order to utilize the Interventional Robotics Laboratory for use of the laparoscopic simulation technology. However, the pandemic did not permit such access and this halted that portion of the study tremendously. In order to professionally and ethically take the safety and health of everyone involved into careful consideration, it was deemed necessary for this section of the research to be postponed until the COVID-19 pandemic subsides. Evidently, the pandemic had not been controlled in a timely fashion for this research and the resulting consequence is that this had to be omitted from the scope of the current work. While, under these circumstances, this research was not able to include the quantitative evaluation of the determined parameters, the parametric definitions and condition evaluations of this research have been structured so that future researchers can utilize real world laparoscopy, or simulation technologies, in order to add the numerical values or ranges to these parameters to further benefit the laparoscopic surgical process. Additionally, allowing for these values to be determined opens the door for extensive comparison between traditional laparoscopic surgery and robot-assisted laparoscopic surgery through this new scope. Current comparisons are based on price, surgery lead time, and the patient experience. Taking into account the numerical differences between traditional surgery and robot-assisted surgery is an effective way to limit outlier interferences in the evaluation between the two conditions.

The desired outcome from this research is for a standard to be set for the definition of surgical parameters in laparoscopic procedures. It is obvious common practice for a surgeon to conduct a surgery while having an understanding of the procedure that they are about to conduct. Ideally, that same surgeon would now be able to have knowledge over what the actions being done in these procedures are being defined as from a kinematic and functional point of view. It may be obvious that, for example, if the surgeon rotates the arm of the surgical tool, the tip of the tool will move in conjunction to the motion done by the surgeon, however it is also necessary to define this relationship; it is not a coincidence but rather a functional relationship between the handle of the tool and the tip. This relationship, just as the other parameters defined through this research, are intended to define the fundamental standards and conceptual foundation of the aspects, tasks, and surgical decisions taking place during laparoscopic surgery whether it is under conventional or robot-assisted conditions.

What makes this research unique is that is has never truly been addressed before. Some prior studies have focused on how to optimize laparoscopic surgical workspace by changes in intra-abdominal pressure, level of muscle relaxation or body position (Nervil et al., 2017). While these work evaluate the properties of the surgical workspace, it does not evaluate the particular parameters that make up that workspace; it is more based on the medical factors that establish and affect the workspace. One work that could be considered relatively close to the scope of this research is that done by Francesco Cursi, George P. Mylonas, and Petar Kormushev in *Adaptive Kinematic Modelling for Multiobjective Control of a Redundant Surgical Robotic Tool*. In their research, they evaluated the kinematics of Micro-IGES, a surgical robotic tool, composed of a rigid shaft (27 cm) and a flexible section (54 mm at zero configuration) (Cursi et al., 2020). Their research related heavily to the work done here due to the kinematic modeling taking place regarding the degrees of freedom of the Micro-IGES where they had evaluated Roll, Elbow joints, Wrist Pitch, and Wrist Yaw. Throughout their work, the analysis of cartesian conditions takes place and the approach employs Feedforward Artificial Neural Networks (ANN) for building the kinematic model (Cursi et al., 2020). Even though some of the work they have done in their research bares a similarity to the work done here, their work still remains heavily unique due to the targets and structure of the research. In the research done by Cursi et al., the target was to present an approach to effectively model a surgical robotic system and use the learned model to perform a tumor resection task autonomously (Cursi et al., 2020). This research differs from Cursi et al., however, because the goal of this research is not implementing a process to analyze a learned model but rather to define the parameters of which these established kinematic medical models use somewhat automatically. Cursi et al. also utilizes a very specific robot for their kinematic analysis in order for them to best address a *Redundant Surgical Robotic Tool*, whereas, in this research, the robot is also specifically selected to identify the robot-assisted condition but the parameters established are intended to be generalized and are not entirely independent to that particular surgical technology. It was acknowledged and understood that the Semi-Robotic Laparoscopic Surgery Support System is not explicitly "robotic" since it is unmotorized and is purposed more as a "guiding system" for laparoscopic surgical procedures instead of being a "robotic-assist." However, it is necessary to consider that, while the braking system aspect of this technology is a very new among the majority of surgical tools, the functions of this technology are applicable to the concept of "robot-assisted surgery" since it is representative of a small, unmotorized version of the current surgical robots on the market being that the braking system feature is not uncommon to the full-scale surgical robots, such as the Da Vinci Surgical System. This is being done without the additional implications of utilizing the large, expensive marketed robots, which is one of the goals of this study. These factors allow for this research to be advantageously applicable to the robot-assisted condition when compared to the work done on parameter analysis by Cursi. et al. This relation is what makes the Semi-Robotic Laparoscopic Surgery Support System a valid representative device for the robot-assisted condition differing from the Micro-IGES used in the Cursi et al. research which is particularly specific as a device which results in consequently specific kinematic modeling in the research. While their choice of technology to analyze is in fact a robotic surgical tool whereas the Semi-Robotic Laparoscopic Surgery Support System is more of a guiding system, the parametric analysis and functions of the Micro-IGES are limited to the particular degrees of freedom that were discussed in their research. While Cursi et al. has done well at establishing the kinematic modeling in their approach and share a related focus for future work for implementing the proposed method on a real surgical procedures, this research remains unique from theirs in that it establishes parameters intended to be universally applicable over laparoscopic surgery and, ideally, can be applied to a widespread of surgical technologies on varying scales as per the choice of technology being used in the studies.

Ultimately, this research also indicates a comparison between the state of traditional laparoscopic surgery against the robot-assisted condition represented by the Semi-Robotic Laparoscopic Surgery Support System developed primarily by the University of Central Florida Senior Design Team between Summer 2019 and Spring 2020. These parameters comparisons show how the majority of the defined parameters get grounded to zero upon the activation of the surgical device. This indicates that these parameters are no longer variable contrary to what had been viewed in the traditional/conventional laparoscopic surgery condition. When evaluated, this explains how the system is not only structured for convenience for the surgeon to be able to let go of the tools but also as a major benefit to the level of safety in the procedure. The overarching purpose of surgery is to help the patient, and all parties involved, under the most ideal conditions that can be produced at that time. A hospital can now choose between spending money on the high price tag of the marketed surgical robots or a robot-assist device that implements the major benefits of the latter option rather than being locked into either spending a significant amount of money or ending up with nothing. This research indicates how the simple applying a surgical assist device can already bring about benefits to the surgical environment by limiting variability in the insertion plate angles and pivoting. Beyond this comes more benefits when the braking technology is activated since the guiding system suspends all movement from the external portion of the components to all involvement inside the workspace. Since the surgeon can activate and deactivate this system at will, the concept of safety increases tremendously with the application of this technology and indicates that the use of robot-assisted procedural practices is more favorable that the traditional process while being cheaper than the use of the full surgical robot. This allows for there to be a viable and competent competitor to the Surgical Robot that does not fall inferior in benefits when comparing options to the conventional surgery.

Analyzing even further, it is likely that the use of the Semi-Robotic Laparoscopic Surgery Support System would be considered to be more favorable than the current options for Robot-Assisted Laparoscopic Surgery. This is due to the fact that the Semi-Robotic Laparoscopic Surgery Support System is cheaper, requires less or no training, and does not involve a space constraint because of its small form factor when compared to the marketed surgical robots; for example, the Da Vinci Surgical System. Further research using these parameters may be necessary to more directly evaluate the comparison between current surgical robots and the Semi-Robotic Laparoscopic Surgery Support System, however, according to the finding in this research, it is hypothesized that the quantitative outcomes for that parametric comparison would be highly related from one condition to the next and would therefore confirm that this surgical-assist device is a more favorable purchase and implementation into the surgical process over the current surgical robots on the market.

While it is understood that this is a specifically identified robot-assisted condition as it is represented by a specific device, this does not diminish from the outreaching capabilities of this research nor does it limit the applicability of these parameters to other surgical devices and technologies. In order to evaluate specific details of a procedure such as the parameters in effect, there must be a specific situation representative of the robot-assisted condition. This does not carry over to the traditional condition as severely due to the nearly universal nature of the traditional procedure. The robot-assisted condition does not have an entirely general basis and, therefore, it is necessary to name a certain technology as the icon of the case when analyzing it. Additionally, the scope of this research was not to particularly define the Semi-Robotic Laparoscopic Surgery Support System in full but rather to define, evaluate, and compare the related parameters between the traditional condition and the robot-assisted condition.

As per these evaluations, the determined parameters labels, what they represent, the relationships from one parameter to the next, and their comparisons across each condition, the data determined in this research can still hold true for other technologies and continuing research to be done. Future researchers should apply this work to additional conditions to further determine what options present best for the patients and surgeon as the medical field opens more to technological use.

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