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Critical Review of "Kinematic design considerations for minimally invasive surgical robots"

This paper provides a detailed overview of the design considerations for minimally invasive surgery (MIS) robots, discusses the remote center-of-motion (RCM) mechanism, classifies MIS robots based on their RCM mechanisms, and compares eight different RCM mechanisms. Eight design goals are outlined that focus on preserving confidence of safety, a high level of accuracy, natural ergonomics, and surgical dexterity. The following kinematic considerations are also discussed: motion representation, pivoting motion, decoupling actions, workspace determination, isotropy, backdrivability, and redundancy. Based on a review of the literature and systems developed for robotically-assisted minimally invasive surgery, this paper aims to formulate the common kinematic design goals, design requirements, and design preferences for general MIS robots and determine the current limitations and open problems in terms of kinematic design for MIS robotic manipulators.

For all laparoscopic surgeries, the movement of the tool within the patient's body is constrained by the entry port, creating a fulcrum effect. According to the paper, this allows for at most 4 degrees-of-freedom (DOF): translation along the tool axis, tilting about the pivot point, panning about the pivot point, and spinning along the tool axis. Though the entry port is not a singularity in reality, it is easier and safer to consider it a point to avoid exerting unnecessary stress on the tissue surrounding the port. The paper uses the 4 DOF movement of laparoscopic surgery as the general MIS tool motion when formulating kinematic design considerations, acknowledging the fact that some procedures (i.e. laryngeal surgeries) require less DOF. Another motion constraint is the extracorporeal workspace of the tool mechanics. All moving components in this workspace must operate at a reasonable distance away from the patient to avoid contact between the patient and robot. These considerations are very similar to those of the project because smooth tool motion and remote actuation of the tool is also needed. In the future, the REMS may be modified to conduct anastomoses as MIS via laparoscopy, making these constraints more relevant.

The authors define eight design goals for MIS robots: kinematic constraint at the entry point, collision-free workspace, decoupled rotational and translational DOF, low output displacement/input displacement ratio, inverted hand-eye coordination, rotational ability of the end-effector, hand tremor reduction, and surgical movement scaling. The first three increase the confidence of safety by ensuring that all robotic movement is confined to one area. In the event that a malfunction occurs, decoupling all rotational and translational motions mitigates the impact that faulty actuator would have on the integrity of the robot by simply disabling that DOF. The fourth design goal quantifies accuracy of the system as the ability of the end-effector to achieve maximum displacement at its instrument tip based on the minimum displacement of joint spaces. This may increase the volume of the extracorporeal workspace leading to a compromise in safety. Thus, the paper suggests striking a balance between safety and accuracy when designing an MIS robot. The fifth and sixth goals deal with the ergonomics of the user's motion. With the fulcrum effect, a motion by the user outside the patient naturally translates to an inverted motion of the tool tip inside the patient, so this phenomenon must be preserved when designing the MIS robot. The last two goals relate to the dexterity of the system, where the full advantage of MIS robots is shown. The paper states that hand tremor reduction and surgical movement scaling are undertaken with the help of the computer-controlled system and the match-up of manipulator dimensioning. These last few goals are extremely relevant to the project as the main advantage of the REMS is tremor reduction for microsurgeries.

In the kinematic considerations, the tool motion is represented mathematically and the previously mentioned design goals are refined by considering the pivoting motion, decoupling motion, and workspace determination. A Jacobean matrix transforming actuator joint velocity space to end-effector velocity space is determined to define fully isotropic manipulators. Isotropy is a measure that indicates the motion and force/torque transmission abilities of a robotic manipulator in a given configuration. A robotic manipulator is said to be in an isotropic configuration when its actuation motions and forces can be best reflected onto the end-effector in this configuration. According to the paper, the task-oriented fully-isotropic robot is a superior candidate to pursue not only kinematic decouplability but also force sensibility; however, this is very difficult to create. Backdrivability is also an important (but controversial) kinematic consideration because backdrivable transmissions allow manual intervention in emergency situations while non-backdrivable transmissions increases confidence in safety by immobilizing the manipulator in a power failure. Another kinematic consideration, redundancy, can be divided into two parts: actuation redundancy and kinematic redundancy. Actuation redundancy occurs when the number of actuations is larger than the mobility of the mechanisms. Kinematic redundancy is achieved by adding kinematic links and joints as well as actuations to the mechanism such that the mobility and number of actuations of the mechanism are increased. For surgical robot specifically, redundancy is an important means of increasing the confidence of safety by providing controlled flexibility. Decoupling is another means of increasing safety and in subcategorized in the paper into five types, each of which differs in number of translational and rotational decoupled DOF. The most prevalent kind of decoupling is that which has the translational and some rotational DOF decoupled. Although these kinematic concerns are not the main focus of the project, optimizing the movement mechanisms of the REMS is a goal for the near future.

Based on the kinematic design issues discussed, the kinematic characteristics of the eight RCM mechanism types are compared. The authors categorize existing MIS robots based on their RCM mechanism and evaluate different RCM mechanisms based on their experience and study of the literatures and devices in both fields of kinematics and surgical robotics. They classify the Stead Hand robot, which was built in 1999 and from which the REMS tremor reduction was based, as a synchronous belt RCM with 2 rotational DOF. The REMS has a 3 DOF translational component as well, so this classification applies only somewhat. According to the paper, only 1 translational DOF is required for RCM, so there would be redundancy in the REMS if modified for RCM. The extra translational actuators should be decoupled to preserve confidence in safety. As of now, the REMS is non-backdrivable, meaning it remains motionless when powered down and making it safer for OR use. Although this paper is a synthesis of article and lacks any original results, it is invaluable as a guide for designing MIS robots with RCM capabilities. The information gathered here from nearly 100 peer-reviewed articles might assist in the achievement of the REMS project's maximum deliverable goals.

Though this paper was a satisfactory overview of the kinematic design considerations for MIS robots and of the RCM mechanism, it suffered many drawbacks as well. The methods and all conclusions drawn from them were very qualitative, based solely off information in other journals and the authors' experiences. There are three authors for this paper, each of which is undeniably knowledgeable in this field. However, the inclusion of more authors would have benefited this paper by adding more "experiences" by which their postulations could be supported. Some quantitative data could have easily been integrated to emphasize how decoupling, isotropy, backdrivability, and redundancy affect the safety, accuracy, ergonomics, and dexterity of the MIS robot. This data could then be used to clearly rank existing systems and suggest an optimal MIS design or RCM implementation. The paper also lacked a solid conclusion, instead providing a plethora of knowledge from which the reader can draw his or her own conclusion. While this is acceptable as a source of background information, it makes the paper less substantial on its own. This paper would provide a more thorough analysis of design suggestions gathered from nearly 100 articles if these drawbacks are rectified.