Task-Specific Multiple-Arm Minimally Invasive Surgical Device Design Using Cooperative Kinematic Isotropy Indices

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The transition from multiple-port to single-port robotic systems in minimally invasive surgery (MIS) procedures has made flexible, dexterous manipulation an essential capability. The requirement that single-port MIS devices span an enclosed surgical workspace through only one access point while avoiding collateral damage to surrounding tissues necessitates the employment of mechanically sophisticated, kinematically redundant device architectures. These redundant architectures, while capable of achieving clinically acceptable performance levels on complicated MIS procedures, are difficult to design and can easily result in economically prohibitive or technically impractical solutions. The problem of balancing clinical functionality and design economy in single-port MIS devices becomes even more challenging when the dexterous that uses multiple surgical tools is required for a given procedure. This research presents a design methodology aimed at reducing the number of degrees of freedom needed to achieve dexterous motion for a multiple-arm single-port MIS device. This design methodology exploits the availability of multiple manipulator arms by quantifying device dexterity in terms of cooperative manipulability, such that the dexterity of two or more nonredundant manipulator arms can be synergistically combined to achieve a high level of motion redundancy. This methodology, in theory, can be used to design multiple-arm MIS devices such that each arm is specialized for a particular type of motion, thus obviating the need for more versatile, redundant manipulator arms, which innately require higher DOFs and, by extension, demand greater mechanical sophistication and device cost. The concept of cooperative kinematic isotropy, an extension of prior work on weighted global isotropy indices, is developed as a multiple-arm MIS device fitness metric. This metric quantifies kinematic isotropy as the aggregate isotropy of two or more manipulator arms and allows the treatment surgical procedures as a task-specific, hybrid set of individual and cooperative manipulation tasks. The efficacy of cooperative kinematic isotropy is demonstrated on the design of a four-armed single-port MIS device designed for blood vessel anastomosis procedures that typically require such a hybrid set of manipulation tasks. Results show that cooperative kinematic isotropy is an effective means reducing MIS device complexity while maintaining adequate levels of kinematic dexterity for specific surgical procedures. The author concludes that this new design fitness metric, while heuristic in nature and based on several key design and simulation assumptions, holds the potential to improve both the clinical value and the economy of cutting-edge, multiple-armed single-port MIS systems.

Kinematic and Workspace Comparison of Four and Five Degree of Freedom Miniature In Vivo Surgical Robot

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The adoption of laparoendoscopic single-site surgery (LESS) provides potential for surgical procedures to be performed with the use of a single incision into the peritoneal cavity. Benefits of this technique include faster recovery times, decreased chance of infection, and improved cosmetic results as compared with traditional surgery. Current technology in this area relies on multiple laparoscopic tools, which are inserted into the peritoneal cavity through a specialized port. Because of this, poor visualization, limited dexterity, and unintuitive controls occur. To mitigate these problems, this research group is developing a multifunctional, two-armed miniature in vivo surgical robot with a remote user interface for use in LESS. While this platform's feasibility has been demonstrated in multiple nonsurvival surgeries in porcine models, including four cholecystectomies, previous prototypes have been too large to be inserted through a single incision. Work is currently being performed to reduce the overall size of the robot while increasing dexterity. Using the knowledge gained from the development of a four degree of freedom (DOF) miniature in vivo surgical robot, another robot prototype was designed, which was smaller, yet was able to utilize 5DOFs instead 4. The decreased size of the 5DOF robot allows it to be completely inserted into the peritoneal cavity through a single incision for use in LESS. Each arm of the surgical robot is inserted independently before being mated together and attached to a central control rod. Once inserted, this platform allows for gross repositioning of the robot to provide surgical capabilities in all four quadrants of the abdominal cavity by rotating the control rod. The additional degree of freedom allows for reaching positions in the surgical workspace from varied angles. This paper will provide a comparison of the 4DOF and 5DOF miniature in vivo surgical robots. The implications of the added degree of freedom on the forward and inverse kinematics will be discussed and the workspace of each robot will be compared. Additionally, the increased complexity of the control system for the remote surgical interface in moving from 4DOFs to 5DOFs will be demonstrated. Finally, results from nonsurvival procedures using a porcine model will be presented for both robots. This comparison will provide useful information for further development of miniature in vivo surgical robots as the goals of decreased size and improved dexterity are approached.

