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TASK-SPECIFIC MULTIPLE-ARM MINIMALLY INVASIVE SURGICAL DEVICE DESIGN USING COOPERATIVE KINEMATIC ISOTROPY INDICES

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ABSTRACT

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 use 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 non-redundant 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, holds the potential to improve both the clinical value and the economy of cutting-edge, multiple-armed, single-port MIS systems.

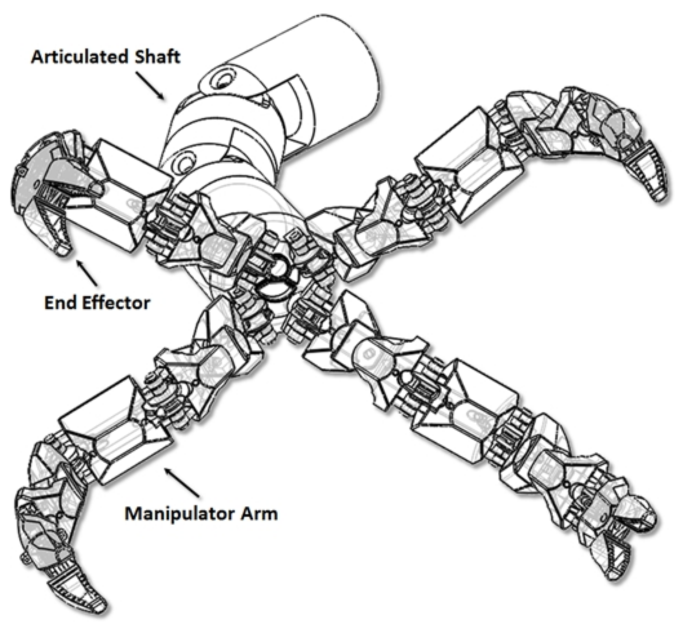

Figure 1. MIS DEVICE WITH FOUR MANIPULATOR ARMS

INTRODUCTION

The design of robotic minimally invasive surgery devices (MIS) is an important but challenging task given the elaborate nature of the procedures for which the devices are used, the precision and dexterity required by those procedures, and the many morphological and mechanical design factors that their designs entail. As robotic MIS platforms evolve from conventional, rigid multiple-port systems toward more compact, single-port systems, device design becomes significantly more complicated and expensive as mechanical power and kinematic dexterity must be achieved within a much smaller device form factor. This complexity and expense is further exacerbated in the case of multiple-channel single MIS platforms, which require the use of several, specialized manipulation tools, working cooperatively, through a single orifice or incision (Fig. 1). In order to achieve acceptable levels of clinical functionality while avoiding economically prohibitive implementation, specialized fitness metrics promote a balance of device design quality and cost must be developed.

Robotic minimally invasive surgery is widely regarded as a superior technology in medicine because of its high accuracy and precision, low risk of infection, and capacity to incorporate advanced diagnostic and interventional tools [1,2]. Robotic MIS often leads to better clinical outcomes than possible with conventional open-surgery or manual MIS [3], and has quickly gained traction in fields such urology [4] and cardiothoracic surgery [5]. As the use of robotic MIS systems has increased, so has the clinical motivation to use such systems on more advanced, less-invasive procedures such as natural orifice translumenal endoscopic surgery (NOTES) [6] and laparoendoscopic single-site surgery (LESS) [7]. These novel procedures require superior kinematic dexterity and flexibility, and demand the development of sophisticated MIS devices.

Modern MIS devices such as the da Vinci® (Intuitive Surgical Inc.) are multiple-port systems which have several robotic arms. These systems have proven value at performing procedures requiring precise, simultaneous use of several surgical tools such as endoscopic cameras, high-energy scalpels, and forceps. Despite the success of multiple-port MIS systems in decreasing infection risk and recovery time, these systems have suffered from their high cost and complexity, cumbersome design and low portability, and kinematic rigidity that make them unsuitable for geometrically complex surgical workspaces. The advanced MIS procedures that are feasible with these systems can require up to seven ports to span a surgical workspace, which effectively negates the advantages that MIS has over open-surgery.

Kinematically redundant MIS devices hold the potential to mitigate many of the functional and economic issues seen in multiple-port systems. These articulated devices can provide the same dexterity and work volume as multiple-port systems using only a single incision, and can facilitate procedures in smaller, more geometrically complex spaces with even lower risks of infection and patient. The mechanical complexity of these devices requires careful analysis of morphological and mechanical design features to ensure that the design cost is economical enough to justify the clinical benefits of improved device performance. Recent research has addressed this concern by availing new, multiobjective design techniques for reducing device design complexity while maintaining adequate levels of kinematic dexterity [8]. However, these techniques consider only single tool, single-port procedures, and do not consider the use of multiple tools required by the aforementioned advanced surgical procedures.

This paper focuses on the development of a design fitness methodology aimed at improving the functionality of multiple-arm, single-port MIS devices while ensuring their economic and technical feasibility. This design methodology is based upon the cooperative kinematic isotropy metric, which quantifies the kinematic dexterity of a group of manipulators acting in concert on a given manipulation task. Using this dexterity metric as a means of assessing multiple-arm MIS device performance, levels kinematic dexterity and redundancy resolution typically seen only in kinematically redundant manipulators can be achieved using a set of well-designed, non-redundant manipulators. MIS devices which employ several, low-complexity manipulators, specialized for specific surgical tasks, can be designed to achieve performance comparable to that of more complex devices without high design cost.

CLINICAL RELEVANCE

The design study presented here focuses on small blood vessel anastomosis, a critical capability in vascular surgery. This procedure involves the surgical connection of two blood vessels to create a viable vascular pathway, and is the foundation of limb reattachment and organ reintegration surgeries, laparoscopic surgeries, and many types of cardiac intervention. The MIS device designed here is geared toward end-to-side blood vessel anastomosis, a procedure typically performed by open-surgery and laden with coordinated, cooperative manipulation tasks (Figure 2). Successful implementation of the cooperative kinematic isotropy metric on this procedure will provide insight into the MIS device design principles and features conducive to performing complicated procedures in small, intracorporeal surgical workspaces without the need for prohibitively complex device architectures.

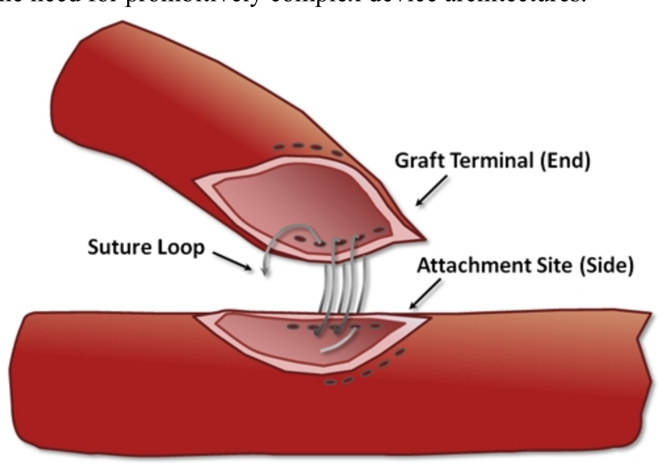

Figure 2. END-TO-SIDE BLOOD VESSEL ANASTOMOSIS

PRIOR WORK ON MANIPULATOR OPTIMIZATION

The optimization of manipulator design fitness has been studied at great length, with much of the early work focused on the achievement of primary manipulation goals such as kinematic dexterity [9], kinematic isotropy [10], and singularity avoidance [11]. Many of the metrics used to quantify the achievement of these manipulation goals are based on the manipulator Jacobian matrix $\mathbf{J}(\theta)$ [12], which for an n-DOF serial manipulator maps an nx1 joint rate vector $\dot{\theta}$ to a 6x1 Cartesian end-effector velocity vector $\dot{x}$, shown in equation (1). Because these metrics are explicit functions of a joint space to task space mapping, they are particularly useful for controlling manipulator end-effector mobility and motion quality.

$$\mathbf{J}(\boldsymbol{\theta})\dot{\boldsymbol{\theta}} = \begin{bmatrix} \mathbf{J}_{\upsilon} \\ \mathbf{J}_{\omega} \end{bmatrix} \dot{\boldsymbol{\theta}} = \begin{bmatrix} z_0 \times o_o & z_1 \times o_1 & \cdots & z_n \times o_n \\ z_0 & z_1 & \cdots & z_n \end{bmatrix} \dot{\boldsymbol{\theta}} = \dot{\mathbf{x}} \qquad (1)$$

However, because they cannot consider the constraints placed on a manipulator by its actuation specifications, joint limits, and task-related manipulation goals, including fault tolerance, pure dexterity metrics are unfit for redundant manipulator performance assessment, especially on complicated surgical workspace.

More recent research efforts [13] incorporate secondary manipulation goals, such as collision avoidance and torque minimization, into the formulation of dexterity-based design fitness metrics by factoring penalty functions into existing measures of kinematic isotropy and global kinematic isotropy. These weighted isotropy measures (2), in particular the multiobjective weighted global isotropy index (MWGII) are well-suited to the measurement of manipulator performance on tasks involving heavy use of redundancy resolution, and have proven effective in enhancing the utility and versatility of redundant manipulators on surgical procedures [8]. However, these multiobjective measures, due to the formulation of the manipulation Jacobian they are based upon, can only quantify the performance a singular, kinematically redundant manipulator, and thus lack the machinery necessary consider cooperative manipulation using non-redundant mechanisms. Methods do exist for the evaluation and improvement of multiple-arm cooperative manipulation systems, but these methods deal with parallel manipulation models [14] and object-centered controls schemes [15] that do not capture the impact of manipulator morphological structure on performance.

$$\mathrm{MWGII} = \max_{\mathbf{W}_{\mathrm{space}}}^{\min} \frac{\sigma_{\min}\sqrt{(\mathbf{J}(\theta)\mathbf{M}(\theta)\mathbf{J}(\theta)^{\mathbf{T}})}}{\sigma_{\max}\sqrt{(\mathbf{J}(\theta)\mathbf{M}(\theta)\mathbf{J}(\theta)^{\mathbf{T}})}} \qquad (2)$$

COOPERATIVE KINEMATIC ISOTROPY

One of the central motivations and most important benefits of cooperative manipulation is the achievement of high kinematic dexterity on complex tasks, such as those necessary in MIS procedures, without the employment of sophisticated, kinematically redundant manipulators. High levels of kinematic dexterity can instead be achieved by the use of multiple non-redundant manipulators, each of which has a distinct, complimentary set of kinematic properties and manipulability characteristics. When combined, the characteristics of these manipulators can comprise the range of motion and dexterity required for the complex tasks seen in MIS. However, the level of performance achieved with such a system is heavily dependent upon the morphological design of the manipulators and the delegation of manipulation sub-tasks among them.

The cooperative kinematic isotropy (CKI) metric is defined here as the average of the major motion axes of multiple kinematic linkages manipulability ellipsoids. The major and minor axes of a manipulability ellipsoid are calculated by taking the singular value decomposition of the manipulator Jacobian to obtain the unitary matrix **U**, whose columns are the axes directions, and the diagonal matrix $\mathbf{\Sigma}$ whose diagonal elements are the singular values. Since redundancy resolution is being considered for the MIS manipulators, the Jacobian matrix is scaled with the multiobjective weighting matrix **M**, derived in [8], to include torque limitation and collision avoidance penalty (Equation 3).

$$[\mathrm{U}, \Sigma, \mathrm{V}] = \mathrm{SVD}(\mathbf{J}(\boldsymbol{\theta}) \cdot \mathbf{M}(\boldsymbol{\theta}) \cdot \mathbf{J}(\boldsymbol{\theta})^{\mathrm{T}}) \qquad (3)$$

Next, the product of each singular value and the corresponding value for each manipulator in a cooperative manipulator set is calculated, and the X, Y, and Z component of all are summed and averaged by the total number of manipulators. The result is set of motion transmission magnitudes in the X, Y, and Z directions which are indicative of aggregative manipulability (Figure 3). Dividing the minimum magnitude by the maximum magnitude, we arrive at the instantaneous cooperative kinematic isotropy value CKI_x (Equation 4), where *x* is the system joint space configuration.

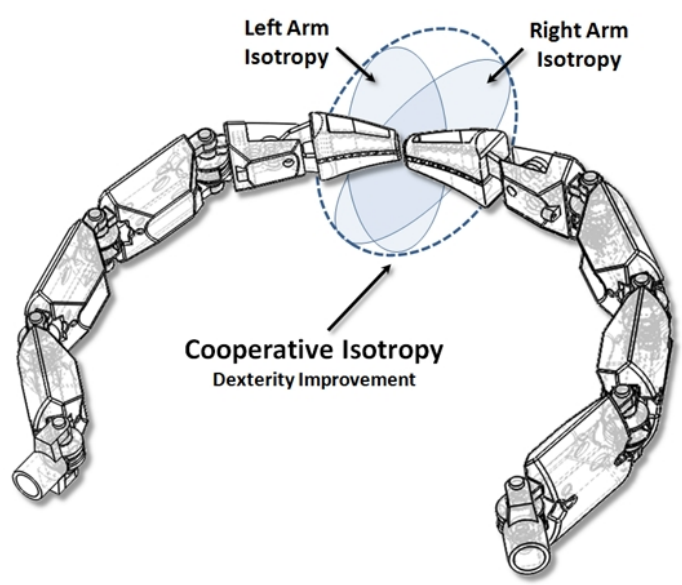

Figure 3. COOPERATIVE KINEMATIC ISOTROPY ELLIPSOID

$$CKI_x = \frac{\min\left(\sum_{i=1}^{n}\left(\sigma_{i,1}\mathbf{U}_{i,1}+\sigma_{i,2}\mathbf{U}_{i,2}+\sigma_{i,3}\mathbf{U}_{i,3}\right)/n\right)}{\max\left(\sum_{i=1}^{n}\left(\sigma_{i,1}\mathbf{U}_{i,1}+\sigma_{i,2}\mathbf{U}_{i,2}+\sigma_{i,3}\mathbf{U}_{i,3}\right)/n\right)} \quad (4)$$

The CKI can be extended from a local cooperative dexterity measure to a global measure by taking the ratio of the maximum and minimum averaged motion transmission magnitudes over an entire task, as is done in global isotropy index measures. The global extension of the CKI, called the cooperative global isotropy index (CGII) is used for the optimization of the multiple-arm MIS device design for anastomosis tasks (Equation 5).

$$CGII = \frac{\min_x\left(\sum_{i=1}^{n}\left(\sigma_{i,1}\mathbf{U}_{i,1}+\sigma_{i,2}\mathbf{U}_{i,2}+\sigma_{i,3}\mathbf{U}_{i,3}\right)/n\right)}{\max_x\left(\sum_{i=1}^{n}\left(\sigma_{i,1}\mathbf{U}_{i,1}+\sigma_{i,2}\mathbf{U}_{i,2}+\sigma_{i,3}\mathbf{U}_{i,3}\right)/n\right)} \quad (5)$$

The formulations of both CKI_x and CGII work under the assumption that all manipulators in a cooperative set have constant access to all points of interest within the manipulation workspace, and that the transfer of materials from one manipulator to another can be done without collision. It is also assumed that the coordination of manipulator motions is both feasible and desirable for the given task.

MIS DEVICE DESIGN OPTIMIZATION METHOD

Initial MIS Device Design

The multiple-arm MIS device being designed in this research is a single-port device 20mm in diameter, containing four 7DOF manipulator arms. These manipulator arms are oriented radially about the longitudinal axis of the device and are positioned so that the arms can straighten and meet along that axis when device is in compact form for entry into an endoscopic port (Figure 4). The initial device design, shown below, is not specialized for a specific surgical task. All manipulator arms are, by default, anthropomorphic (Figure 5), kinematically redundant, identical in dimension, and are fitted with the fenestrated forceps end-effectors for grasping tissue and handling suturing tools.

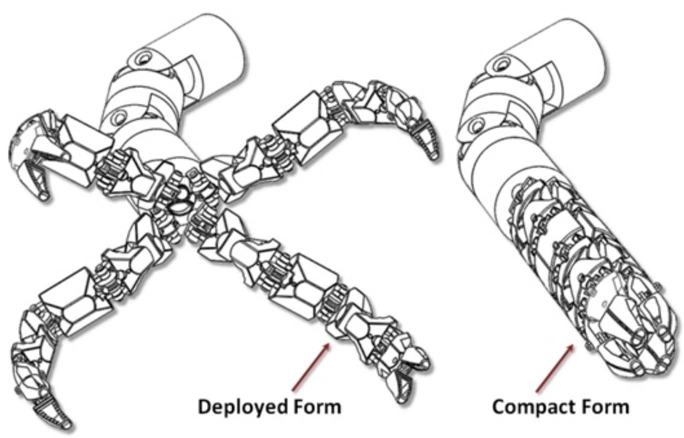

Figure 4. MIS DEVICE MODES OF OPERATION

MIS Manipulation Tasks

The multiple-arm MIS device is optimized for dexterous manipulation on two anastomosis tasks - precision tissue manipulation and suturing - which are represented in this experiment by a set of rudimentary spatial motions. The scale and geometry of the anastomosis task motions are loosely based upon surgeon hand motions observed by the author during coronary artery bypass surgery (CABG). The mechanical requirements of these motions are estimated using tissue mechanical properties and needle penetration data.

The anastomosis tissue manipulation task involves the positioning of a thin, 20mm diameter blood vessel graft cut at a 45° angle to create a suture line suitable for end-to-side grafting. For the purpose of this experiment, tissue manipulation will be comprised of a grasp-and-hold motion and a grasp-and-slide motion.

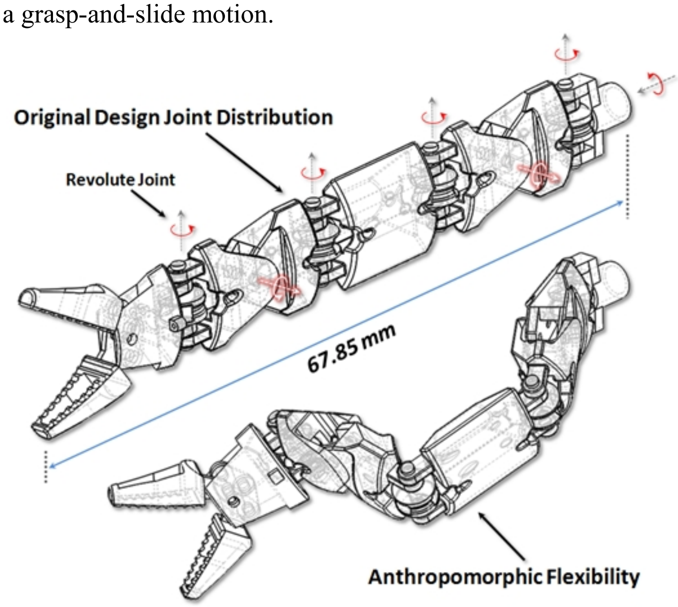

Figure 5. INITIAL 7DOF MANIPULATOR ARM DESIGN

The coordination of these motions allows the rotation of the cuff of the arterial graft as it is sewn to an oval opening cut in the side of the target site. The forces required for these motions consist of those needed to resist gravity and those encountered during the stretching of the tissue as it is pulled. Torques must be also applied to the graft during manipulation so that the circular graft end can be reoriented as the anastomosis progresses. The force and torque directions and magnitudes for tissue manipulation are illustrated in Figure 6.

The anastomosis suturing task involves the transfer of the suturing needle from one manipulator arm to another, and the application of forces and torques adequate for penetration of the tissue and tightening of the suture. For the purpose of this design experiment, this task is comprised of a sequence of small, circular, high force motions for needle penetration about the graft edge, and long, high-force strokes to tighten each suture loop. The force and torques assumed for these tasks are illustrated on Figure 7.

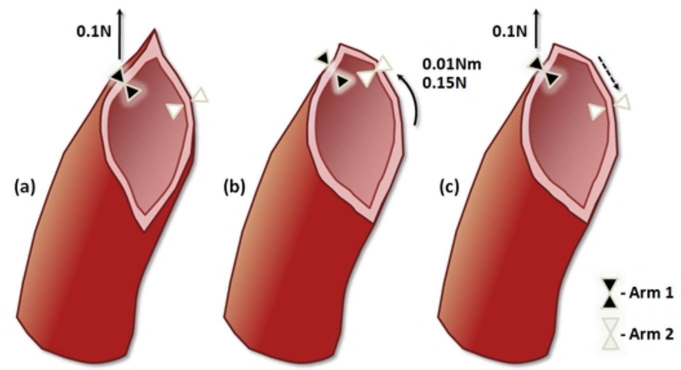

Figure 6. TISSUE MANIPULATION MOTIONS

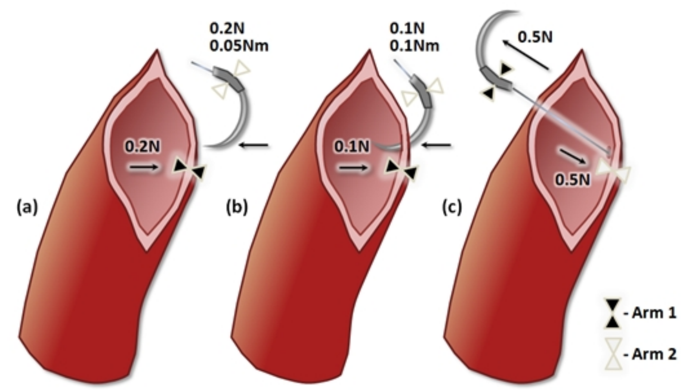

Figure 7. ANASTOMOSIS SUTURING MOTIONS

The successful completion of these anastomosis tasks requires the cooperation of at least two manipulators. Given that the MIS device design includes four manipulators, the tissue manipulation and suturing motions can be accomplished concurrently using two pairs of manipulator arms. In order to ensure specialization of each pair for a specific task, such that the manipulators will not be designed for all possible motions, the top pair of MIS manipulators will be optimized for tissue manipulation, and the bottom pair for suturing.

Design Space

The design space for the MIS device manipulator arms consists of three variable types: joint configuration, link dimension, and total number of joints. Joint configuration is a discrete design variable comprised of four distinct elements: flexion-extension revolute joints (F-E), abduction-adduction revolute joints (B-D), and pronation-supination joints (P-S). The naming convention for these MIS device joint configurations is taken from the anthropomorphic joint motions that they are intended to mimic. These revolute joints have predefined motion ranges which are dictated by mechanical stops inherent in their design (Figure 8). All joints are specified as having a maximum torque output of 0.2 Nm, beyond what is needed for gravity compensation.

Link dimension is a discrete design variable describing the length of a link segment, and ranges from 10-25mm in increments of 5mm. The length of each link in a manipulator arm is allowed vary independently of other link lengths, such that different numbers and distributions of joints can be included in a manipulator arm designs without affecting the total length of the arms. The manipulator arms are, not required to have identical total lengths.

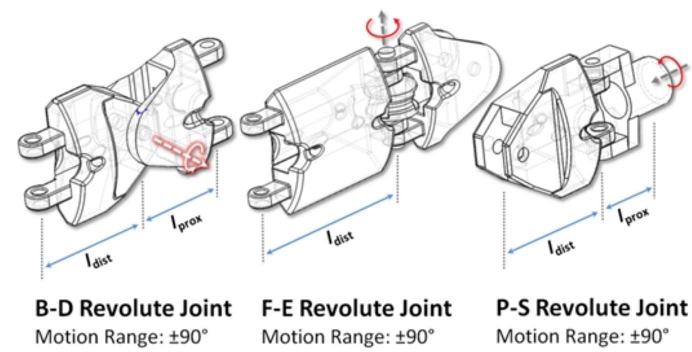

Figure 8. MANIPULATOR JOINT AND LINK VARIABLES

The total number of joints employed in a manipulator arm design is also a discrete variable. All available joint configurations are revolute, and so the total number of joints is always equal to the total number of DOF. Because this research focuses on the achievement of high kinematic dexterity without the kinematically redundant manipulator arms, and the total number of joints is limited to a maximum of 6 to eliminate the possibility of redundant linkage designs.

Optimization Method

The optimization of the multiple-arm MIS device for maximum cooperative kinematic isotropy involves three steps: device design synthesis/perturbation, task simulation, and performance-based design fitness assessment. Design synthesis was performed using genetic algorithms (GAs), supported by the MATLAB® Global Optimization Toolbox. Genetic algorithms were chosen as the optimization method because of their ability to search very large design spaces and find globally optimum solutions, regardless of the tonicity of the cost function and the number of local minima in the design space, and because of their particular efficacy on discrete search problems. The design optimization process starts with an initial population of 16 device designs, each with manipulator arms of randomly selected joint configurations, link dimensions, and total DOFs. After each MIS device design population is simulated and its members' design fitness evaluated, subsequent device generations are synthesized using elite phenotype selection, mutation, and crossover. In that MATLAB-based genetic algorithm toolbox, the elite phenotype count was set to 4 children, and crossover fraction was set to 0.6 to yield 6 crossover children, and remaining 6 children were, by default, created by mutation. Stopping criteria for the genetic algorithm were a fitness function tolerance of 1.0×10^{-12} and a maximum generation number of 500.

The simulation of the MIS device performing anastomosis tasks is accomplished using a velocity-based inverse kinematics solver, which includes several motion control sub-algorithms to ensure adherence to the mechanical and actuation specifications of the manipulators arms, and to facilitate the resolution of kinematic redundancy. These include well-recognized singularity avoidance [16], torque and energy minimization [17], and collision avoidance [18] algorithms. The formulation of these algorithms and their employment in similar simulations are discussed in detail in the author's previous work [8].

MIS device design fitness assessment is comprised of the calculation of cooperative kinematic isotropy for each cooperating pair of manipulator arms on its anastomosis sub-task, and the calculation of device design cost or complexity. Because each cooperating pair of manipulator arms has its own cooperative kinematic isotropy value, it is possible that one pair achieves a high score while the other achieved a lower score. To quantify total MIS device design fitness, the average of the two cooperative kinematic isotropy values is taken.

After the calculation of average cooperative kinematic isotropy, the total complexity and economic cost of the multiple-arm MIS device is computed using the design fitness function $f(\mathrm{D})$, equation (6), which employs the sigmoidal penalty function Γ (Equation 7). The variable and subscript D represents a particular MIS device design.

$$f(\mathrm{D}) = \mathrm{CGII_D} \cdot \Gamma(\mathrm{DOF_D}) \qquad (6)$$

$$\Gamma(\mathrm{DOF}) = \left(1 + e^{(\mathrm{DOF}-\mathrm{DOF_{max}})/\alpha}\right)^{-1} \qquad (7)$$

This function sets a maximum limit, $\mathrm{DOF_{max}}$, on the total number of DOF that the MIS device may contain, and penalizes those designs with close proximity to this limit. As the value of input DOF approaches the upper limit established by $\mathrm{DOF_{max}}$, Γ goes to zero, indicating excessive design complexity (Figure 9). The sensitivity of the penalty function Γ is adjusted using the variable α. For this experiment, $\mathrm{DOF_{max}}$ is set to 18 and α is set to 0.2, yielding the penalty profile shown in below.

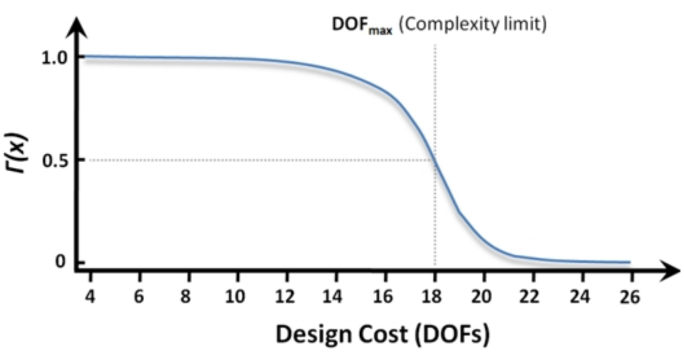

Figure 9. DESIGN COMPLEXITY PENALTY FUNCTION

Experimental Assumptions

This MIS device design study makes several assumptions to simplify the proof of concept. First, it is assumed the anastomosis motions are performed in a free-space environment where the only physical impediments to motion are the MIS device manipulator arms. Second, it is assumed that motions are performed slowly enough that the effect of device inertia on required torques is negligible. Third, it is assumed that the mechanical power needed to support the weight device linkages is included in the specification of manipulator maximum torque output such they are essentially weightless.

RESULTS

The GA-based four-arm MIS device design optimization ran for the 362 generations before reaching the fitness function tolerance stopping criteria, indicating that the CGII value for the design had reached a minima (the negative of the CGII value is was during optimization as the MATLAB® Global Optimization Toolbox works on function minimization). The maximum CGII value achieved was 0.1846 (Figure 10). This corresponding design solution contained only 21 of the original device's 28 original DOFs, yet still achieved a CGII value 87% of the 28DOF design (before complexity scaling). The increase in design economy and the maintenance of kinematic dexterity is the result of device design specialization promoted by the use cooperative kinematic isotropy as a fitness metric.

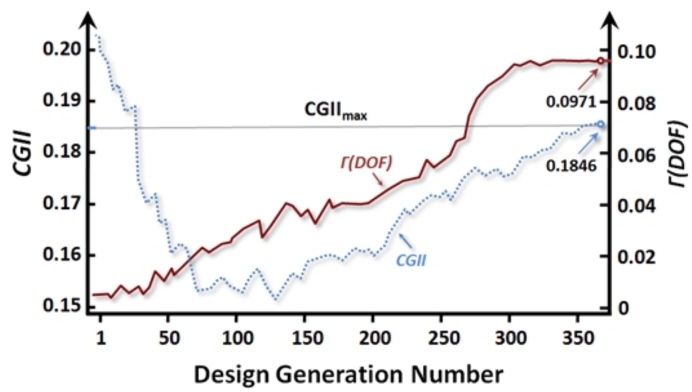

Figure 10. DESIGN FITNESS TRENDS DURING OPTIMIZATION

Noteworthy features of the optimum MIS device design solution are the variations of the joint type, number, and distribution. The lower pair of manipulators, which were optimized for cooperative suturing, have significant differences in design, with the suture tightener manipulator longer and being comprised of mainly of F-E joints for the long strokes needed for suture pulling, while the suture arm manipulator was shorter and comprised of P-S joints for twisting motions require for needle penetration (Figure 11).

The upper pair of manipulators, which were optimized for tissue manipulation, also differed in joint distribution and size. This was expected given that tissue grasper manipulator was essentially stationary during task, only grasping tissue (Figure 11), while the other manipulator contained and additional P-S joint that facilitate the reorientation of the graft end as it was transferred to the grasping arm. The MIS device complete with the specialized manipulators is shown in Figure 12.

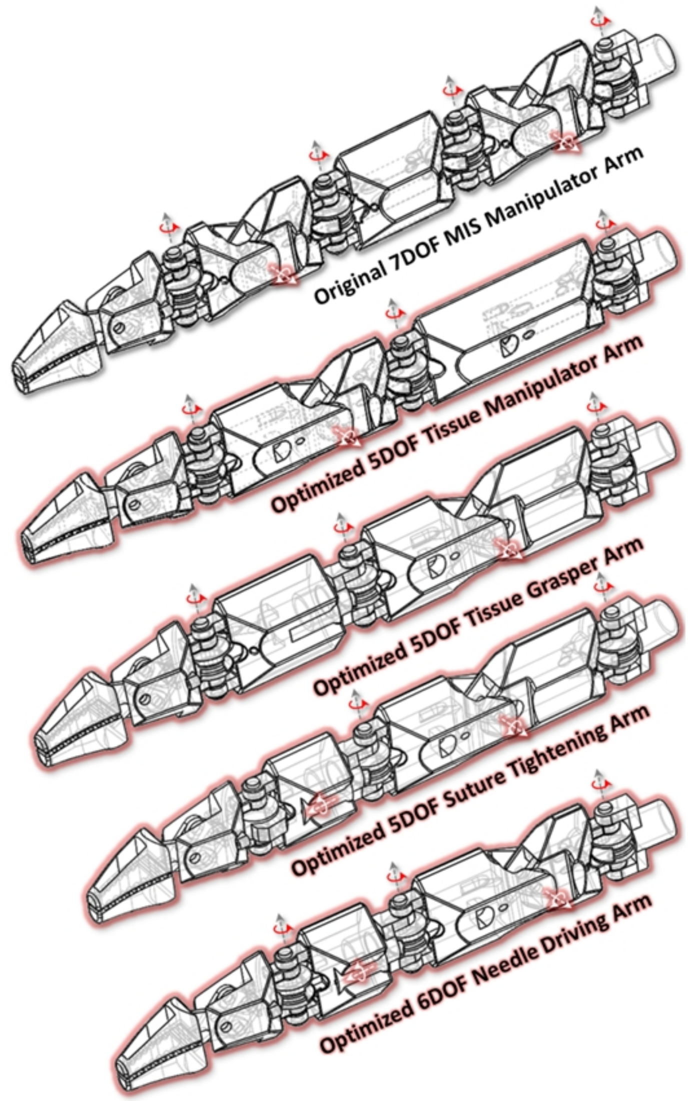

Figure 11. CGII-OPTIMIZED MIS DEVICE MANIPULATORS

DISCUSSION

The cooperative kinematic isotropy metric has shown significant sensitivity to motion paths and dynamic properties, as evidenced by changes in the manipulator design solutions for specific surgery task motions. Sensitivity to motion direction, dexterity requirements, and mechanical power are crucial in assessing manipulator performance on specialized tasks, and allows the identification (albeit by numerical methods) and incorporation of design features that serve to improve that performance (Figure 13). However, this task-specificity also has the drawback of decreasing the overall manipulator versatility. Each of the optimized MIS device manipulator arm designs exhibited dexterity comparable to that of the original design in performing the intended surgery motions, but exhibited much poorer dexterity than the original design on arbitrary, non-specific motions. This observation elicits the assertion that task-specific optimization is only as effective as the accuracy and comprehensiveness of the task set permit.

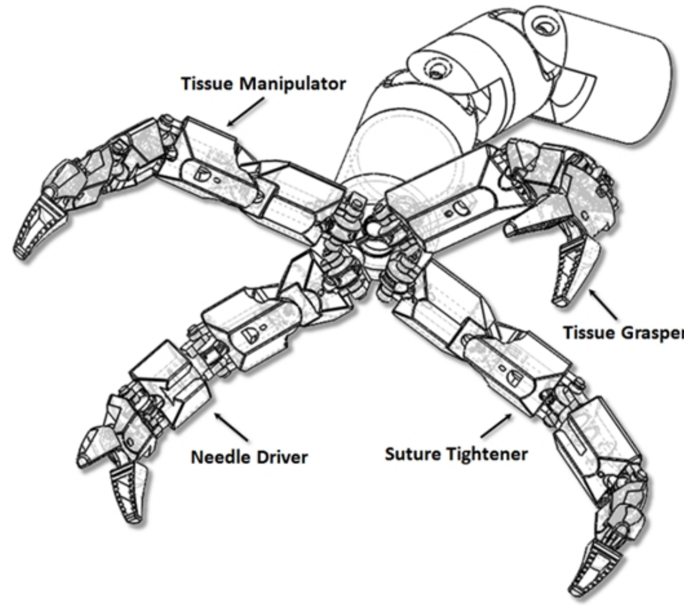

Figure 12. MIS DEVICE WITH CGII-OPTIMIZED ARMS

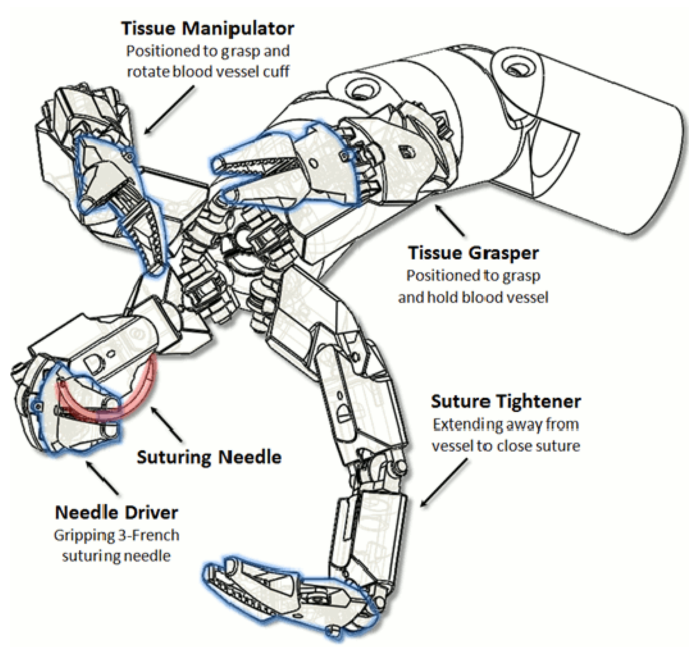

Figure 13. DEVICE ARMS PERFORMING INTENDED MOTIONS

FUTURE WORK

Several assumptions were made during this medical device design research, including those made in characterizing and approximating the tool motions used to represent the intended surgical procedure, and those made about the device design space and the nature of operating environment in order to reduce the computational heft of simulation and optimization. Future work on this topic will consider a larger set of design variables, a more detailed representation of surgery motions, and a more accurate and clinically relevant simulation environment. This increased depth of study should provide further evidence as to the efficacy of cooperative kinematic isotropy in improving the design of multiple-armed, single-port MIS robots, and should provide an indication of the potential economic and clinical value of highly-specialized MIS devices. A principal component analysis on design optimization results will help identify the more salient and impactful design features of multiple-armed MIS robots and allow more computationally efficient design optimization.

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