Snake-Like Robots for Minimally Invasive Spine Surgery

EGH400-1

Assessment 1. Project Proposal: Scope of Work

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Project: Snake-Like Robots for Minimally Invasive Spine Surgery

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Version	Date	Author	Changes/Comments

Table 1 - Version Record

General Objective

Current common surgical tools in minimally invasive spine surgery (MIS) are rigid and are unable to provide the dexterity required to access the intervertebral disc during lumbar spine procedures.

As such, this project aims to answer: Can a snake-like minimally invasive surgery (MIS) robot be optimised to enable a standard (macro) surgical robot to perform lumbar spine surgical interventions?

The main objective of the project is to propose a method to design and construct a snake-like robot suitable for the requirements of lumbar spine surgery, specifically a lumbar fusion procedure.

To answer the research question, the following questions will need to be answered:

a) What are the existing MIS approaches for lumbar spine surgery?
b) What are the existing snake-like MIS robotic approaches and can they be applied to lumbar spine surgery? i.e. can current approaches be applied to solve research problem.
c) What are the main restrictions and assumptions that must be overcome to develop these technologies to be applicable to lumbar spine surgery?

Key Finding from the Literature

Lumbar spine surgery requires high accuracy and precision due to the risks associated with working near vital and delicate anatomical structures (Santos et al, 2018).

There exist algorithms, namely the SnakeRaven design algorithm, that can design a snake-like robot that achieves optimal dexterity for specific tasks and task spaces in surgery (Razjigaev, 2022). The primary approach is to analyse a 3D scan of some anatomy and define targets and obstacles. Then by calculation of the forward kinematics of robotic systems, their dexterity and workspace can be determined. These designs achieve greater dexterity than state of the art rigid tools. However, the implementation of such algorithms is limited due to assumptions in the surgical procedure. These include the incision port and other anatomical characteristics of the workspace in a real surgery. Only limited research has been conducted on the application of such robots on spine MIS supporting for the need for such an investigation on snake-like robotics for lumbar spine MIS.

Stakeholders & Resources

During this research project, I will consult Cameron Brown (supervisor) and Will Browne (secondary supervisor). My projects potential end users and stakeholders are members of the clinical community, in particular spine surgeons. Prof. Ross Crawford will be the clinical community representative for the purposes of this research project. Additionally, several colleagues are working on related projects with potential for collaboration; these students include Taylia Barrett and Harrison Hooper.

The resources required for the completion of this project are outlined in Table 2.

Table 2 - Project Resources

Resource	Purpose	Access
SnakeRaven design algorithm code	The design algorithm platform that will be modified.	Access Acquired – Published on GitHub platform. Under permissive licence. Permissions include modification and distribution.
GitHub – developer platform	To manage coded solutions: version control.	Access acquired through free student access.
MATLAB	Programming language and platform used for development of algorithm.	Software-access acquired through free student access.
3D Printing resources	To print robot prototypes and mock spine models for testing.	Access to personal 3D printer for prototyping. Higher resolution printing is accessible through QUT's *Additive Manufacturing* service.
Raven II surgical robot	For macro-micro robot experimentation. i.e. to test the designed prototypes.	QUT has a Raven II. Access has not yet been organised.
SnakeRaven Control Software for Raven II	For experimentation phase of project. Allows for control of RavenSnake designed tool through the Raven II platform.	Access acquired. – Published on GitHub platform. Under permissive licence. Permissions include modification and distribution.
Patient scans: Lumbar spine anatomical space scans.	3D image (e.g. CT, ultrasound or MRI scan) used to create task space model.	Resource acquired – publicly available datasets: - The National Library of medicine *Visible human Project* - Anatomically detailed 3D model of the human body. - Zenobo digital library MRI dataset containing 447 MRI scans of lumbar spines.

Project Methodology

The initial stages of this project will focus on the application of current tools to the case of minimally invasive lumbar spine surgery.

Three main objectives are investigated, requiring:

1. The identification of requirements of lumbar spine surgery, within the MIS scope.
   This involves using a 3D lumbar spine patient scan and identifying targets, obstacles and other notable structures accordingly to the spine's anatomy. Existing clinical operations will inform the requirements of the surgical procedure.
2. The application of current modelling and design tools; to test the validity of current snake-like robot design methods for the lumbar spine surgery case and to identify challenges.

The SnakeRaven design algorithm will be implemented for the lumbar spine case. This stage of research will determine the suitability of this algorithm. The capabilities of the tool will be evaluated through qualitative methods: namely a routine-operation scenario will be used to identify the applications and limitations of the robot design algorithm.

3. The development of design methods and metrics definitions.
   At this project stage, methods to extend and adapt the current tools can be developed. This involves:
   a. Defining important metrics that will allow for the optimization of the tool. These may include dexterity and workspace size. Current definitions and data collection algorithms implemented (in 2.) will assist in this process.
   b. Defining new variables and constraint for design. These will likely relate to the anatomy of the lumbar spine as well as the surgical procedure's requirements. This could include: the robot's joint configurations, dexterity, size, allowable motion range and material properties.

   In the case where current methods are not applicable to the lumbar surgery case, a study will be conducted to define the specific downfalls of the approaches. Novel methods can then be ideated addressing specific or general failures of the current technologies.

The second stage is concerned with modification of the current design methods to be applicable to the lumbar spine case. Outcomes from the initial stage will inform the characteristic of these modifications. The SnakeRaven algorithm will be further developed to suit the requirements of lumbar spine surgery.

Ideally, a Raven II-compatibility design method will be developed during this stage; this will include the selection of an actuation system.

The final stage of the project aims to validate the developed methods through physical prototyping and testing. The modified algorithm shall be used to design the snake-like robot. This device should be compatible with the Raven II for experimentation.

This will involve testing the tool's ability to reach targets and avoid obstacles in a mock surgical procedure; A mock lumbar spine segment shall be constructed for this purpose.

Deliverables

The primary deliverable is an algorithm that designs a snake-like robot for the purpose of lumbar spine surgery. The algorithm shall optimise the robot design to perform surgical tasks within a specified task space by considering the lumber spine anatomy and operation constraints. The designed robot will be capable of accessing an intervertebral disc without disruption surrounding structures as per lumbar spine fusion procedure requirements.

A secondary deliverable is a built prototype of the snake-like robot; Multiple robot designs will be constructed throughout the prototyping stage.

Throughout the project timeline multiple progress tracking reports will be prepared. These include:

- Project Proposal – This document outlines the requirements and objectives of the project.
- (2) Project Progress Report – Two progress reports will be prepared: one in semester one and one in semester two. These will detail research methods and findings of the project.
- Final Report – A final report will present the main findings of the research including methods, experiment results and details of the final algorithms and prototypes.

At the end of each semester a project progress oral presentation will be conducted. This presentation will outline the main achievements of the research and be an opportunity for other engineers to inquire about the research practices employed.

A weekly informal status report to supervisors will detail progress and any challenges encountered.

Risks, Requirements & Constraints

Regulatory, safety and ethical concerns to consider:

The implementation stages of the project will rely on use of the Raven II surgical platform whose capabilities will provide constraints to the project. For example, the robot prototype designs will be limited by actuation capabilities of the Raven II.

For simulation publicly available patient scan datasets will be used. Also, for physical experimentation a mock anatomical model of the spine will be built. These approaches are appropriate for the scope of this project, avoiding ethics considerations and other complexities involved in using real patients.

Risks, likelihood, consequence, risk monitoring and mitigation:

Scope creep (Likely) – There exists a risk for the project scope to expand beyond reasonable limits. This risk shall be mitigated by the careful definition of the research questions and scope as well as continual referral to these guidelines.

Timeline extension (Highly likely) – Many factors may extend the project timeline, including scheduling errors and other unplanned setbacks. Risk is mitigated by good project management practices such as task tracking, regular revision of the project plan and proactive action to correct setbacks.

Code version control (Likely) – Code may be lost or altered beyond repair. To reduce this risk GitHub software will be used allowing for version control and overall safer research.

No access to required resources (Moderate likelihood) – Certain resources may be more difficult to acquire (e.g. Raven II). To mitigate this risk, access to these resources will be organised well in advanced. Otherwise, the requirement of this resource can be reduced or removed through simulation software testing alternatives.

Quality & Sustainability

Quality:

- Adherence to the scientific method will ensure high quality research. This involves clear question definition, experiments, and data analysis to achieve a valid and systematic research method.
- The quality of the research shall be maintained by clear definition of metrics. This will ensure data collected can be compared safely.
- Experiment measurements and outcomes will be defined clearly to ensure the validity of the tests.
- Physical experimentation will be conducted to validate the algorithm simulation outcomes.
- A rigid tool design can be analysed alongside the designed prototypes to validate design methods.

Sustainability:

- Computer simulations will be used to test designs prior to building physical prototypes.
- The proposed robots will likely be patient specific, and the tools will not be reutilised. As such, a full life cycle analysis is appropriate to define the sustainability considerations.

- Additionally, Volume-based or multi-target design approaches will be explored to limit waste. Each robotic instrument may then be capable of accessing a range of intervertebral disc spaces within a patient's anatomy.

Timeline & Deliverables

Table 3 - Timeline & Deliverables

No.	Focus	Deliverable	Dependency	Release Date/ Milestone
1	Literature Review	Literature Review Report (Included in project proposal report)		24th April
2	Project Proposal	Project Proposal Report	1	24th April
3	Initial stage questions to be answered:	Answer research questions a. and b.	1, 2	Semester 1, Week 9
4	Application of current technologies to lumbar spine case.	Answer research question b.	3	Semester 1, week 10
5	Progress Report	Progress report detailing findings and method of the project.	3, 4	Semester 1, week 13
6	Oral Presentation	A presentation of the research achieved up to this stage.	4, 5	Semester 1, week 13
7	Second Stage: Modifying current tools and algorithms.	Modified robot design algorithm. Answering and application of research question c.	4	Early, Semester 2
8	Prototype	A built prototype of snake-like robot.	7	Early to mid Semester 2
9	Implementation of prototype to Raven II robot system.	Implemented prototype.	8	Early to mid Semester 2
10	Progress Report	Progress report detailing findings and method of the project.	7, 8, 9	Semester 2, week 7 (mid semester)
11	Final modified algorithm	Final coded solution.	7	End of Semester 2
12	Final prototype	Prototype produced by final solution and implemented on Raven II.	7	End of Semester 2
13	Final Report	Report presenting the final projec'ts methods and finding.	11, 12	Semester 2, week 13
14	Project Delivery Oral presentation	Presentation of the final outcomes/achievements.	11, 12	Semester 2, week 13

Management of Project Changes

Weekly communications with project supervisors will inform progress and potential changes such that the project scope can always remain up to date. It is expected that project modifications will arise due to unforeseen circumstances.

In response to potential project alterations including requests for change by project stakeholders, partners or supervisors, the following *change management process* will be followed.

The change will be clearly defined and informed though effective communication with stakeholders and project supervisors. A project impact assessment will be carried out providing the following information:

- The nature of the change.
- Its potential impact to the project; Including the scope, timeline, deliverables, and outcomes.
- Potential risks introduced through the change and mitigation strategies.
- The importance or urgency of the change and well as benefits of implementing change.

Supervisors and other stakeholders will be consulted to ensure the validity of the impact assessment. The evaluation process should prioritise project quality and objectives.

The Project Proposal document is to be updated before implementing changes to mitigate risks, particularly scope creep. The version and nature of the change must be clear in the document's version record (Table 1). The change may then be implemented, else an alternative can be defined and evaluated.

Thorough documentation will track the evolutions of the project and its alterations including findings from impact assessments. Supervisors and stakeholder should have access to a project record to be aware of the project status and all modifications made.

The effects of the implemented changes should be monitored throughout the project timeline. And corrective actions informed by the impact evaluation may be implemented as needed.

At project completion a review of the *change management process* will be conducted. This will identify the successes and challenges encountered to inform future projects.

Sign off

	SIGNATURE	DATE
STUDENT ENGINEER		24/4/2024

Appendix: Review of Literature

Minimally invasive surgery (MIS) involves making small incisions and using endoscopic instruments to perform operations. This avoids open and invasive cuts through tissue meaning they are safer, reducing the risk of infection and complications. These methods also minimize patient recovery and rehabilitation time. As such, the advancement of these technologies is particularly important for isolated and developing areas where medical resources are scarce (Santos et al, 2024).

Current MIS approaches for lumbar spine surgery use rigid end effectors which do not achieve the dexterity required. The following literature review explores snake-like robotic solutions for MIS and their potential application for lumbar spine surgery.

Clinical Application of Flexible Robotic Systems

Flexible MIS robots are characterised by their increased number of degrees of freedom (DoFs). The redundant DoFs allow for the flexible nature of snake-like robots. These robot systems allow access to confined areas of the body during MIS and better control and instrument manipulation. Although not yet widespread, current clinical applications have enhanced surgeons' abilities to perform safe interventions.

This technology has been deployed in various endoscopic procedures (refer to Figure 1). For example, the Flex robotic platform (Medrorobotics, USA) performs otolaryngology and colorectal interventions. Other applications include gastrointestinal surgery which had been successfully enhanced by the i^2Snake robot (Omnisore, 2022).

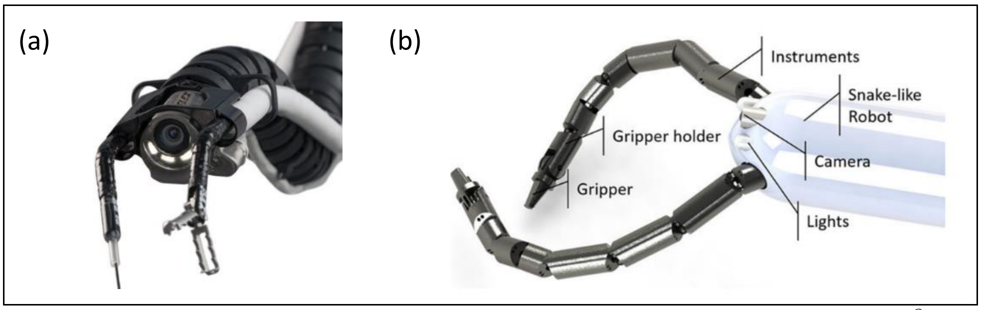

Figure 1 - Snake-like robots used in clinical applications. (a) Flex Robotic platform (Medrorobotics) (b) i^2Snake Robotic Instrumnents (Edinburgh Centre for Robotics)

MIS for Lumbar Spine Fusion Surgery

Lumbar spine surgery requires high accuracy and precision due to the risks associated with working near vital and delicate anatomical structures. Minimally invasive surgery has provided a much safer alternative to open lumbar spine surgery and is increasingly used for lumbar interbody fusion (LIF). MIS access is commonly achieved through retractors that expand small ports to allow instruments to reach the operation site (Sayari et al, 2019).

During LIF a surgeon removes a weakened intervertebral disk. This requires access to the spine by removing the lamina (Posterior LIF, PLIF) or through bone openings (Transforaminal LIF, TLIF). The aim of this surgery is to implant a spacer that promotes bone healing to fuse two vertebrae (Santos et al, 2018). It is key to protect neural structures during this manipulation (Jitpakdee et al, 2023).

Compared to traditional LIF, MIS-LIF reduces blood loss, invasive cuts through tissue and postoperative complications and thus, MIS-LIF is highly supported in medical literature. However, MIS-LIF usage is impeded by a steep learning curve and a lack of literature on optimisation solutions (Sayari et al, 2019).

Additionally, navigation and general instrument handling are difficult. LIF surgical tasks such as endoscopy have limitations in viewing angles due to tool manoeuvrability, and general surgery can become complex for single port cases where only one or few instruments may be used at a time through small surgical entrances. As such, biportal operations are considered easier to practice although they require more muscle dissection (Jitpakdee et al, 2023).

Instrumentation for minimally invasive spine surgery is restricted by lack of tool tip dexterity. For example, endoscopes are commonly constrained to set viewing angles refer to Figure 2 (a) (Goldberg, 2024). Similarly, microsurgical tools such as pituitary rongeurs (Figure 2 (b)) have limited manoeuvrability inhibiting access to occluded regions of the lumbar spine.

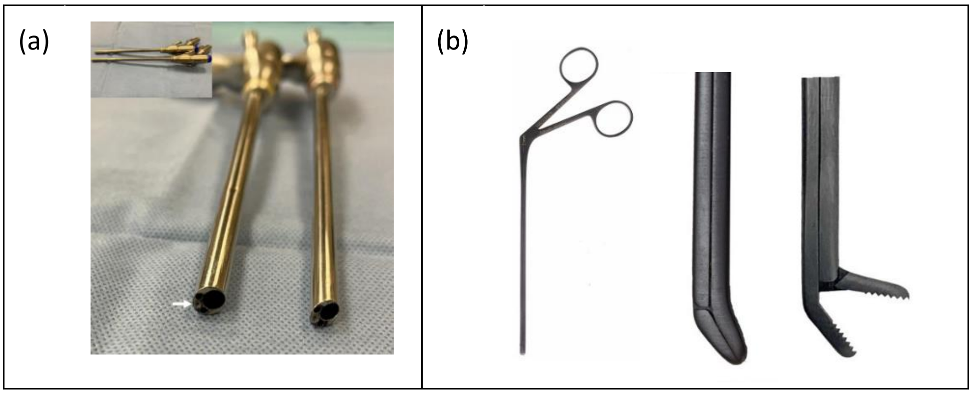

Figure 2 - Spine MIS tools. (a) Interlaminar and transforaminal surgery endoscope with 15° (left) and 30° (right) camera angles. (b) Micro Pituitary Rongeur with end effector closeup.

Snake Like Robots Designs and Considerations for Minimally Invasive Lumbar Spine Surgery

The structural designs of flexible MIS robots vary greatly and determine actuation methods, size constraints and manoeuvrability. Snake-like robots are categorised into two primary groups: serial and continuum. Serial robots are composed of rigid segments chained into a structure that can approximate a curved shape; for example, rolling joint mechanisms. Continuum robots, such as concentric tube and multi-backbone mechanisms, use curved or flexible segments to achieve their compliant nature.

Robots can be further categorised by actuations methods which can be achieved from within the robot structure (intrinsic) or outside the robot structure (extrinsic) (Refer to Figure 3).

Intrinsic motor actuation approaches do not meet the size requirements of MIS due to current limits in motor miniaturisation. Other intrinsic actuators use pneumatic or hydraulic technology. These are also limited greatly by miniaturisation complexity as well as the increased difficulty of control of both the snake-like structure and the potential end-effector tool. Intrinsic shape memory alloy (SMA) approaches offer a less imposing design and are more adaptable to the micro-robot requirements of MIS. However, SMA is easily influenced by temperature and fatigue which limits its application in MIS (Wang et al, 2021).

Extrinsic approaches typically use tendons or wires to control each robot segment. This approach is less restricted by size and can thusly apply greater power. Additionally, extrinsic actuators can be easily accessed and repaired, and end effectors can be more easily interchanged which is ideal for patient specific designs. Extrinsic tendon-driven actuation is common within the literature for snake-like robots for MIS. This is due to its flexibility and compact design though it is limited by its tendency to fatigue and slack. Novel technology such as screw-driven actuation offers greater mechanical stability in combination with multi-backboned and wire driven robots (Ahmed et at, 2022).

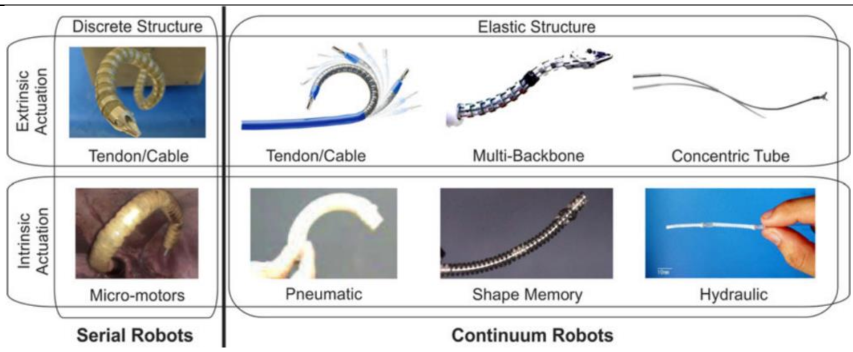

Figure 3 Snake-like robots: Structure and Actuation (Burgner-Kahrs et al, 2015)

Macro Surgical Robot Platforms & Macro-Micro Teleoperation

MIS procedures typically use robot teleoperation methods. This minimises orthopaedic injuries and exposure to hazards during operations. Surgical robots assist physicians in complex procedures however proximal dexterity remains an area for improvement; in particular, tool tip dexterity and actuation. For fine manipulation, micro-robots are docked onto macro surgical robots, extending their capabilities (Omisore et al, 2022). In this way snake-like instruments can be attached to macro surgical robot.

The da Vinci surgical robot (Intuitive Surgical Inc., Sunnyvale, CA, USA) is currently the most widespread system used for MIS (Omisore et al, 2022). This platform has been adopted in clinical operations and requires high-cost maintenance. However, it has limitations in the system's field of view and consequently surgeries often require multiple surgical access ports (Fujie, 2020).

Another telerobotic platform is the Raven II, developed by Biorobotics Laboratory (University of Washington). The Raven II is a modular teleoperation solution designed to be more accessible although its clinical application is limited. The Raven II is an open-source platform for collaborative research and the platform's accessibility encourages innovation. The Raven II has 7 DoFs and attached instruments are constrained about a remote centre of motion with 3 DoFs (Razjigaev, 2022).

Designing a snake-like robot for MIS

Defining the surgical site

Surgical requirements are largely informed by the anatomical characteristics of surgical site. Snake-like tool design often uses surgical site images; CT, ultrasound or MRI scans are commonly used. These three-dimensional models can be broken down into voxels (varying in resolution) to map and define surgical targets, areas of interest and obstacles.

Design Metrics: Measurement of reachable workspace and dexterity.

Design algorithms have commonly used workspace and dexterity measures as the main metrics to optimise in a design.

The reachable workspace refers to the regions the robot has ability to reach. For each robot design it is found through statistical observation of the robot's configurations and their ability to reach the target workspace. The reachable workspace is determined by the forward kinematic a robot design and can be computationally calculated through sampling methods such as the Monte Carlo method.

Dexterity measures the instrument's capacity to approach a voxel from different orientations. It is defined as a ratio relating the capacity to approach a voxel (or point) from some orientations to the total possible orientations. A common computational dexterity model is the service sphere model. Each voxel can be represented by a service sphere. The surface of the sphere represents all the possible orientations of the voxel. Then the service region can be defined as all the orientations achievable by the end effector.

Design and Optimisation approaches.

Snake-like robot designs can be achieved through manual or computerised methods and prototyping. Kinematic models are formulated to describe the motion of the designed robots. Additionally, mock surgery procedures and experiments are often conducted to test the validity of the design methods.

Manually selecting design characteristics and manual optimisation, rely on expertise to make decisions based on the robot's desired performance. This design method is used to explore novel approaches in snake-like robot design including robot segment shape, material, and mechanical configurations.

Wu et al (2017) investigated three manually designed 6-Dof concentric tube continuum. The robots were composed of nested curved tubes combining concentric tube mechanisms with tendon driven actuators. The robot configurations differed in their distribution of DoFs. Results showed increasing DoFs at the proximal and distal ends increased workspace and dexterity respectively. Best overall workspace and dexterity was achieved through even distribution of DoFs. This study also explored the correlation between DOF distribution and dexterity distribution in each motion axis and it was suggested that the task site should sit within the maximum dexterity position.

Monolithic compliant rolling-contact joint (CRCJ) serial snake-like structures were proposed by Zhang et al (2021), as a solution capable of a smaller bending radius. The proposed CRCJ structure was analysed against a discrete pin-joint and leaf-type compliant joint mechanisms (refer to Figure 4). The study concluded that compared to leaf type hinges, CRCJ mechanisms reduce the bending radius limitations, achieve higher flexibility and thus have more potential to achieve a greater workspace.

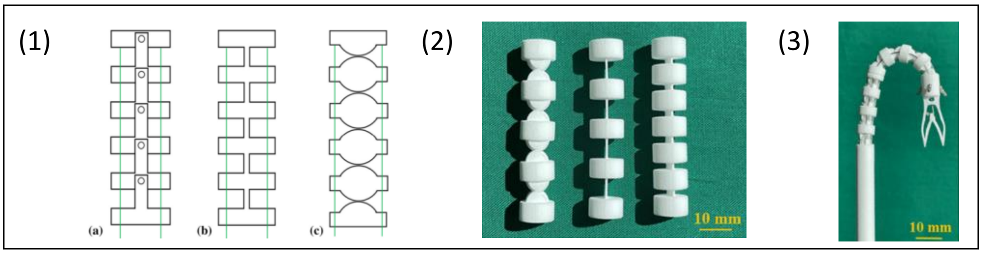

*Figure 4 – Compliant rolling contact joint snake-like structures. **(1)** Mechanisms (a) discrete pin-joint (b) leaf-type (c) CRCJ **(2)** 3D printed design prototypes. **(3)** CRCL Mechanism displaying minimised bending radius. (Zhang et al, 2021)*

Computerised design uses motion modelling to create a structure capable of the desired mechanical behaviour. Parameters are selected to design different robots. These may define size and weight restrictions, motion ranges, and other constraints. Modern design algorithms commonly use parametric evolutionary methods to optimise snake-like robot designs. Iterative simulation processes are employed such that the simulated designs increasingly improve their performance metrics (workspace and dexterity). These computerised methods converge on optimal designs within the allowed iterations. Parameters may be selected according to a range of considerations and objectives.

Computationally designed robots initially considered a discrete set of target points and restricted design parameters such as the number of segments, size, and curvature to simplify the design process and reduce the computational cost (Burgner, 2013).

Another approach is volume-based optimisation which maximise workspace coverage over the complete volume of the surgical workspace. This approach has been implemented in the computation design of concentric tube robots (Burgner, 2013). This algorithm designed concentric tube robots for volume-based objectives and further introduced the penalisation of void spaces in the robot's desired workspace. This algorithm achieved an approximate 50% increased reachable workspace in comparison to robot's designs based on parameters manually selected by experienced researchers.

Following volume-based algorithms, task-space based approaches tailor designs to a smaller task space within the surgical workspace. This method optimises parameters based on a patient specific task space. Task-space-based optimisation is implemented by Razjigaev et al (2022) in the design algorithm of a tendon-driven, roller-joint serial snake-like robot. The algorithm used parametric evolutionary optimisation in the design of a snake-like robot for knee arthroscopy. The design was optimised for 4 targets within this task space; the end effector had to reach all targets from a single incision point. The robot's dexterity performance was analysed against volume-based designs and state-of-the-art instruments typically used in knee arthroscopy; the task-space base solution achieved more than three and two times the dexterity respectively.

The same tendon-driven, roller-joint snake-like robot design algorithm was further extended for task specialisation. This approach considers specific task objectives. Analysis of the specialised design dexterity distribution showed peak dexterity shifted closer to the specified targets; thus, achieving better performance than the 4-target-based design. A limitation of this study is the unconstrained movement of the robot's proximal end. This limits it's application to lumbar spine MIS which typically uses rigid retractors to create a fixed opening at the operation incision. The robot's position could therefore move beyond the physical limits of the retractor and disrupt the task space. The study also assumed a static surgical site and does not consider deformable patient anatomies.

Modelling and Fabrication

Once the design algorithm has determined the optimal design parameters, they can be imported into computer aided design software to create a three-dimensional model of the robot end effector (refer to Figure 5). This parametrised model is exported to 3D printing software for fabrication. Once printed, actuation systems can be integrated, and the complete instrument can be used for physical experimentation.

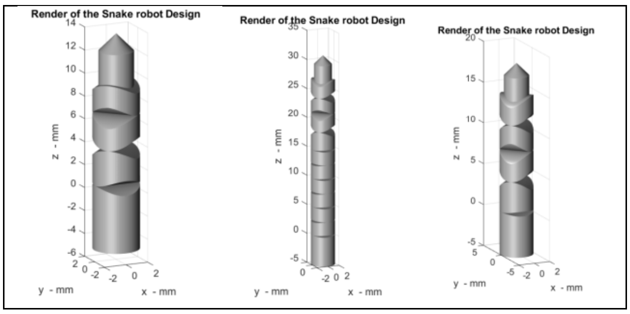

Figure 5 - SnakeRaven robot computer aided design renders. (Razjigaev, 2022).

Snake-like robots are a prospective solution for lumbar spine MIS overcoming the limitations of currently used rigid tools. Improved instrument control through increased dexterity and workspace reachability would enhance surgeon capabilities and improve intervention outcomes.

Research for snake-like applications for lumbar spine MIS will require consideration of the anatomical characteristics of the lumbar spine and its workspace including constraints in the uniportal approach to the surgical site.

Forthcoming rolling-joint configurations and extrinsic tendon-driven actuated designs perform well in the current literature. In conjunction with computerised parametric evolutionary optimisation, these robot designs are promising solutions for lumbar spine MIS.

Snake-like technology also presents future opportunities for autonomised lumbar spine surgery procedures. Which has the potential to reduce the steep learning curve associated with lumbar spine MIS. Increasing the accessibility of this intensive care intervention.

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