DEVELOPMENT OF SELF-SUPPORTING HELICAL RIBBON LINEAR ACTUATOR FOR IMRI SURGERIES

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Abstract

Intraoperative Magnetic Resonance Imaging (iMRI) surgeries are high-risk procedures performed within an MRI suite, commonly for conditions such as brain tumors and epilepsy. During these operations, clinicians often need to adjust the patient's position to improve access to the surgical site. Currently, this repositioning is done manually with the aid of cushions, which can introduce significant risks to patient safety and increase the likelihood of complications. Moreover, manual adjustments extend the overall procedure duration, increasing the surgeon's time in the operating room and potentially affecting surgical outcomes. Addressing these challenges is critical to enhancing both patient safety and surgical efficiency.

To address this issue, clinicians and surgeons were consulted during the Voice of Customer (VOC) stage, leading to the identification of key requirements based on their feedback. These insights were translated into a clear need statement, guiding the ideation process. After exploring various concepts through brainstorming sessions, a solution involving an array of linear actuators embedded within the MRI bed was selected. These actuators can be externally programmed to adjust to common patient positions required during iMRI procedures, reducing manual intervention, enhancing patient safety, and improving surgical efficiency.

A novel single-band helical ribbon linear actuator was developed for this application. The actuator features tabs and slots that engage upon deployment into a helical structure, forming a stable cylindrical column. The actuator's dimensions were optimized through a Design of Experiments (DOE) to assess critical factors influencing the column's overall stress. Finite Element Analysis (FEA) simulations in Ansys were conducted to identify the dimensions yielding the highest stress tolerance, guiding the final design specifications.

A custom drive system was engineered to house and deploy the ribbon. Compressive testing on a prototype confirmed a yielding stress of 700 lbs, surpassing the failure threshold, validating the design's robustness. The actuator achieves an 8:1 extension ratio within a compact 3" x 3" footprint, ideal for localized actuation on MRI beds. Constructed from non-magnetic materials, the actuator is compatible with MRI environments, offering a market-leading extension ratio while maintaining a minimal spatial footprint.

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Chapter 1

1. Introduction

The field of medical devices is rapidly evolving, driven by new technologies designed to ease clinicians' challenges and enhance patient outcomes. By integrating innovation with thoughtful product design, traditional practices can be redefined to create more user-centric solutions, improving procedural efficiency and deepening the understanding of complex processes.

Certain surgeries demand highly specialized equipment to ensure successful outcomes. Robotic surgery, for instance, has become increasingly prevalent due to its ability to enhance procedural accuracy, reduce clinician workload, minimize invasiveness, and shorten overall surgery times. Notable examples include laparoscopic procedures and valve repair surgeries, where systems like the Da Vinci surgical robot have become essential tools. [1]

Figure 1: iMRI surgery

Intraoperative Magnetic Resonance Imaging (iMRI) surgeries similarly benefit from technological interventions. These high-risk procedures as depicted in figure 1, such as brain tumor removals or epilepsy treatments, often require patient repositioning to improve surgical access — a process that is currently manual and potentially hazardous. This research explores iMRI surgeries in detail, focusing on a novel solution to address one of the clinicians' most significant pain points during these procedures. [2]

1.1. iMRI

Intraoperative Magnetic Resonance Imaging (iMRI) is a procedure that generates real-time images of the brain during surgery, providing neurosurgeons with critical guidance for complex operations. iMRI is commonly used in procedures such as brain tumor removal, epilepsy treatment, and surgeries for conditions like dystonia, essential tremor, glioma, neuropsychiatric disorders, Parkinson's disease, and pediatric brain tumors. Given the delicate nature of these surgeries, patient safety and positional stability are paramount. [3]

iMRI surgeries take place within the MRI dome, where continuous imaging helps clinicians accurately locate surgical targets and determine the optimal surgical path.[2,3] This minimizes the risk of damaging healthy tissues, reduces potential injuries, and supports a minimally invasive approach. By offering real-time visualization, iMRI enhances precision and improves patient outcomes in high-risk neurosurgical procedures. This approach supports the use of iMRI during surgery, enabling real-time imaging combined with a suitable navigation or guidance system. This integration allows surgeons to precisely target the affected area while preserving surrounding healthy tissue, minimizing damage and reducing the risk of complications. As a result, patient outcomes are significantly improved.[4]

- Detect Brain Shifts During Surgery: The brain can shift during an operation, making pre-surgical imaging less accurate. iMRI provides real-time updates, ensuring surgeons have the most precise information throughout the procedure.
- Differentiate Between Healthy Tissue and Tumors: Identifying the boundaries of a tumor can be challenging. iMRI helps distinguish healthy brain tissue from abnormal growths, ensuring complete and accurate tumor removal.
- Protect Critical Structures: iMRI assists in preserving vital brain areas during procedures like laser interstitial thermal therapy (LITT), where surgeons treat epilepsy by heating targeted tissue to disrupt seizures through a minimally invasive approach. Real-time imaging helps monitor brain temperature, preventing thermal injury. Additionally, in MR-guided ultrasound, surgeons can precisely focus energy on epilepsy-causing regions without the need for invasive surgery.
- No Exposure to Ionizing Radiation: One of the key reasons MRI is the preferred imaging modality in neurosurgery is that it eliminates the risks associated with ionizing radiation. While other high-resolution imaging techniques can provide valuable guidance, they typically involve exposure to radiation. Although short-term radiation exposure in certain areas of the body is generally considered safe, its use on the head for extended periods during neurosurgical procedures is undesirable. The advantages of MRI, including its non-invasive nature, make it essential to design specialized equipment and devices that cater to the needs of neurosurgeons while ensuring compatibility with MRI environments.

1.2. Common patient positions

In the current iMRI procedure, patients are typically placed in different positions depending on the surgery being performed. These positions are critical as they help determine the optimal surgical path, and they serve as established standards for the procedures. The primary goal of these predefined positions is to offer clinicians a range of options to access the surgical site in the most efficient and risk-free manner possible.

In a typical iMRI setting, five prominent positions are commonly utilized during the procedure.[5] These positions are listed below, along with their possible occurrences, depending on the specific situation of the operation, making them the most ideal choice for each scenario:

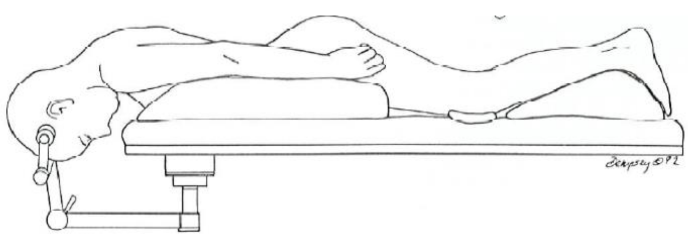

Figure 2: Prone position

The Prone position is commonly used during surgical procedures to provide access to the dorsal aspects of the patient's body, such as the spine, neck, and shoulders.[5] In this position, the patient is placed face-down with their head in a neutral alignment, avoiding excessive flexion, extension, or rotation. The prone position leads to an increase in functional residual capacity and alters the distribution of ventilation and perfusion throughout the lungs. This results in improved ventilation/perfusion matching and, therefore, better oxygenation.[6,7]

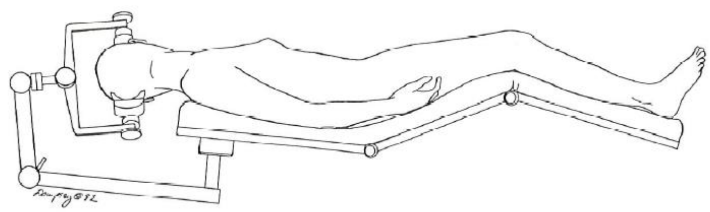

Figure 3: Supine position

In the supine position, the patient is positioned face-up with their head resting on a pad or pillow, and their neck in a neutral alignment. [5] The patient's arms, kept in a neutral thumb-up or supinated position, may be tucked at their sides or slightly abducted (less than 90 degrees) on arm boards. This position is one of the most natural for patients, allowing for optimal anatomical alignment. Most patients can maintain adequate respiratory function without any constricting external compression on the respiratory system. The supine position provides excellent access to the anterior structures of the body and is considered one of the safest for stability on the surgical table. The patient's safety can be easily ensured with proper placement of safety straps, and with the entire body supported, the risk of injury from falling is minimized.

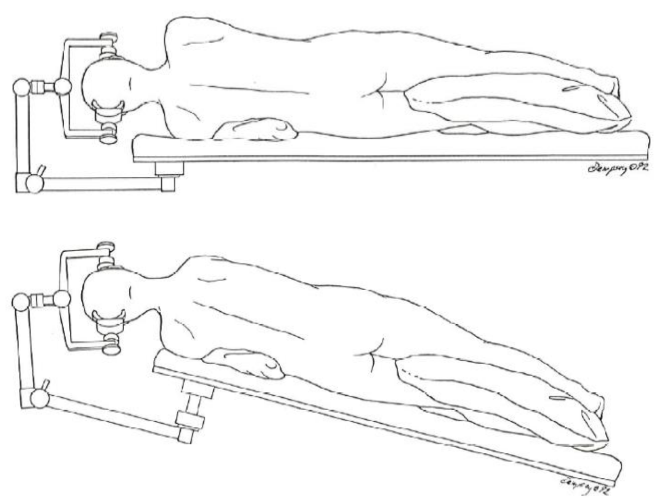

Figure 4.a: Lateral position; Figure 4.b: Modified lateral position

The lateral position is commonly used for surgical access to areas such as the thorax, kidney, retroperitoneal space, and hip.[5] Prior to being positioned laterally, the patient is first placed in the supine position. Depending on which side of the body is being operated on, the patient will then be positioned on either their left or right side. In the left lateral position, the patient lies on their left side for surgery on the right side of their body. Conversely, for surgery on the left side, the patient will be positioned on their right side.

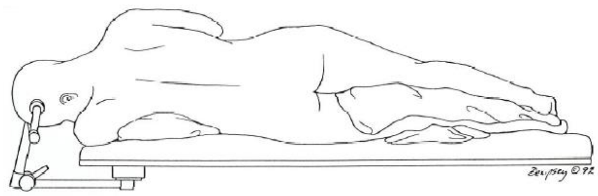

Figure 5: Park bench position

The Park bench position is a modified lateral position commonly used in surgery to enhance access to midline structures and the posterior fossa.[5] In this position, the patient is semi-prone with their head flexed and facing the floor. One or both arms may be positioned outside of the operating table, providing greater rotation of the shoulders and increased maneuverability of the head and neck.

In surgery, clinicians often do not rely on a single position but rather use a hybrid approach, combining aspects of different positions to tailor the operation to their comfort and the specific needs of the procedure.[2,3] However, all these positions come with inherent risks, particularly in iMRI surgeries, especially during the procedure itself. To mitigate these risks, it is important to follow the precautions and best practices outlined below:

- Ensure an adequate number of personnel, devices, and equipment are available during positioning activities to guarantee both patient and personnel safety.
- Respect the patient's dignity and privacy during positioning. Only essential personnel should be in the room with the patient.
- Maintain the patient in a natural, neutral alignment. Keep the head and neck in a neutral position, avoiding extreme lateral rotation or hyperextension.
- Verify that the patient's entire body is in proper physiological alignment, and ensure that the hands, fingers, feet, and toes are protected from the surgical table's articulations.
- Operating room staff should always use safe body mechanics during transfers and positioning.
- Ensure that the patient does not come into contact with any metal portions of the surgical table or positioning devices.
- Never exceed the weight limits for the table or accessories, and always follow the manufacturer's guidelines and recommendations when using surgical equipment.
- Inspect all equipment, pads, and accessories, replacing them as needed.
- Place a pillow or head positioner under the patient's head, and assess the dependent ear after positioning.
- Support and secure the patient's arms on parallel arm boards, with both arms abducted less than 90 degrees.
- Place an axillary roll under the patient's dependent thorax, distal to the axillary fold, at the level of the seventh to ninth rib.
- Verify the patient's bilateral radial pulses after placing the axillary roll.
- Maintain the patient's spinal and neck alignment.
- Flex the patient's dependent leg at the hip and knee to provide extra support and reduce the risk of tilting or falling during the procedure.
- Position the patient's upper leg straight and support it with pillows between the legs.
- Place safety straps across the patient's hips.
- Use lateral braces, kidney braces, and bean bag positioners as necessary.

The preoperative time required to achieve these positions is not insignificant, ranging from 15 to 40 minutes. This contributes a considerable portion of the overall preparation time, ultimately increasing the total procedural time. The extended duration not only raises the cost of the procedure but also increases the potential for complications. Currently, several accessories are used to assist in facilitating the procedure under these conditions, helping clinicians optimize their workflow and improve patient safety and comfort but there is still lack of a coherent solution which can reduce risk and the time required for the procedure by increasing efficiency and smooth transition between different potions.

1.3. Existing solutions

In its most basic form, the iMRI environment consists of a surgical operating room with access to an MRI machine. To maximize the machine's utilization, it is common for two operating rooms to share access to a single MRI machine. The operating rooms can access the MRI machine in one of two ways: either the patient is brought to the MRI machine, or the MRI machine is brought to the patient. In both scenarios, the surgical table must be MRI-compatible to prevent any unintended movement or alteration of the patient's position during the procedure.

There are different types of MRI tables that offer various functionalities, including segmented sections that allow for control over specific portions of the table during surgery, providing better customizability throughout the procedure.[8] The figures 6.a, 6.b, 6.c and 6.d below illustrate some of the available options for MRI tables. These MRI tables offer localized, limited actuation in different areas of the table, which can help clinicians position the patient in an appropriate orientation. However, despite these advancements, significant challenges remain regarding the overall movability and complexity of these systems. These challenges can hinder the efficiency of the positioning process and contribute to increased procedural time and potential risks.

In addition to MRI tables, accessories such as head clamps are also viable options to stabilize the head during iMRI surgeries. These clamps help stabilize the region of interest (ROI) during the procedure and can often be integrated directly into the surgical table. However, while head clamps provide stability, they can also increase the risk of injury, especially during patient repositioning mid-surgery. The additional strain on the neck and potential mishaps during the shifting process pose significant risks. Another issue with these examples is skull clamp mounting, which is shown to be unacceptable for use with iMRI. This is because the surgical table needs to fit within the confines of the magnet bore, and any part of the apparatus that extends below the table is typically deemed unacceptable. The images provided here are intended only to showcase desired patient orientations, without implying their compatibility with the iMRI setup.

Once the surgeon has positioned the patient, it is crucial that the patient maintains this orientation throughout the procedure. The accuracy of the guidance and navigation system is highly dependent on the alignment between the reference frames of the image and those of the patient. If the patient moves relative to one of these frames between the time the image is taken and the time the surgeon operates, it can lead to misalignment. This misalignment may result in the surgeon being guided to healthy tissue instead of the targeted area, potentially leading to complications and ineffective surgery. Therefore, ensuring that the patient remains stable and properly aligned throughout the procedure is vital for the success of iMRI surgeries.

Figure 6.a: Standard MRI bed; Figure 6.b: Segmented MRI bed; Figure 6.c and 6.d: Head alignment frames

This highlights the need for innovation in existing solutions to provide more flexibility for clinicians while ensuring patient safety and enhancing mobility. Currently, no solutions on the market offer smooth transitioning between positions, and existing options come with significant risks that create additional challenges during procedures. Developing a system that allows for dynamic, controlled adjustments between positions without compromising stability or increasing the risk of injury would greatly improve the workflow in iMRI surgeries. Such advancements would not only make procedures more efficient but also enhance the overall safety and precision of the surgery.

Chapter 2

2. Problem

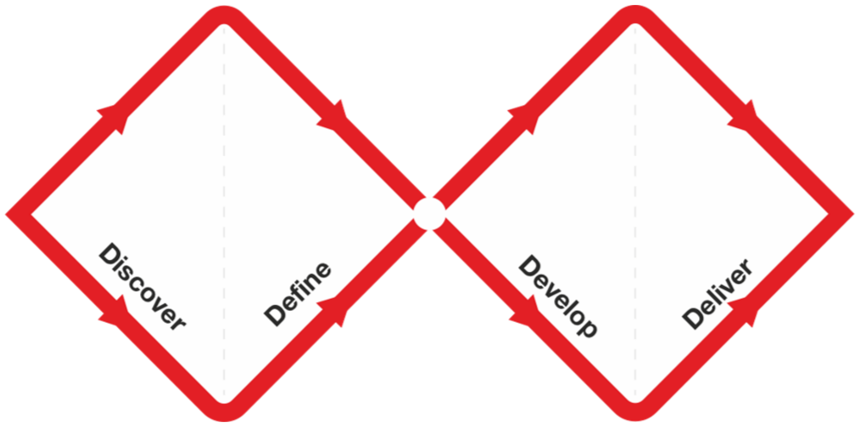

Figure 7: Double diamond methodology

In conventional product design and development, the Double Diamond method is often employed to understand and generate solutions, as it is considered one of the most effective ways to create meaningful outcomes. The Double Diamond is a visual model used to illustrate the design process. Its widespread appeal stems from its straightforward focus on both the problem and the solution. This process model serves as an excellent tool for making sense of design, as shown in figure 7 courtesy of the British Council.[9]

The process begins with an initial challenge that can be viewed from multiple perspectives. In the Discover stage, this involves analyzing the problem by identifying and listing all the potential pain points related to the challenge. These individual problems then converge in the Define stage, where they are ranked and prioritized, allowing the designer to focus on the most critical issue. Once the primary problem is defined, the Develop stage follows, where multiple solutions are generated. This stage enables the designer to approach the problem from various angles. After generating potential solutions, the Deliver stage focuses on analyzing each solution based on constraints and feasibility to determine the best course of action. This method ensures that the final solution is well-aligned with the defined problem and project requirements.[10]

After the market research phase, to further understand the problem, various surgeons were contacted to gain deeper insights and gather their perspectives as part of user research. This allowed for the generation of different possible problem statements based on their real-world experiences. By understanding their viewpoint, more subtle observations could be identified, helping to fully grasp the problem at hand.

During this phase, detailed in-person interviews were conducted to capture the clinicians' thoughts on the current solutions used in these types of surgeries. The feedback from these interviews is discussed in detail in the Voice of Customer section below, where several interesting insights emerged that significantly informed the direction of the design process.

2.1. Voice of Customer (VOC)

During this process, various surgeons that have been doing procedures like these were contacted primarily for the M-Health Fairview and U of M health department. Table 1 below mentions the personnel contacted during this stage-

Table 1: VOC participants

Name	Designation
Dr Stephen Haines, MD	Professor Emeritus, Department of Neurosurgery
Dr Andrew Venteicher, MD, PhD	Associate Professor and Neurosurgical Director of the Center for Skull Base and Pituitary Surgery
Dr Stephanie Terezakis, MD	Department Head, Department of Radiation Oncology
Dr Eric Ehler, PhD	Associate Professor, Director of Physics Residency Program, Department of Radiation Oncology

During this phase, in-person interviews were conducted, supplemented by follow-up email conversations for further clarification as needed. The interview questions focused on understanding the existing pain points of iMRI procedures, the associated risks, the current processes used, and potential alternatives that could improve the procedure. These interactions led to various insights that were crucial for designing user requirements and ultimately formulating a clear problem statement. These findings provided a comprehensive understanding of the clinicians' needs, allowing the team to move forward with a well-defined approach to solving the challenges identified in the iMRI surgery process. Additional information about the questions asked are listed in the appendix B.

After analyzing the VOC for the iMRI settings, these are the requirements that are needed to be validated by a possible solution-

- Extension Ratio: After analyzing the available space in the MRI dome, it was determined that the maximum extension required is 8:1, specifically for the modified lateral position from the base of the MRI bed. Therefore, the design should allow for this level of extension, which will accommodate all positions and customizations within that range.
- Weight-Bearing Capability: The system must be designed to accommodate the 99th percentile of patients, meaning the MRI bed should support up to 300 lbs. With a safety factor of 2, the effective weight capacity should be 600 lbs to ensure reliability and safety for a wide range of patient sizes.
- MRI Compatibility: The technology used for the system must be fully MRI-compatible and safe for use in the MRI setting. This excludes conventional motors made of ferrous materials, as they would interfere with the MRI's magnetic field.
- Localized Actuation: Due to the critical space constraints in the MRI environment and the need for localized actuation, the solution must provide discrete, precise motion control, surpassing the capabilities of traditional segmented tables. This requires the independent movement of individual table units, ensuring synchronization across the overall system for optimal patient positioning and safety during surgery.
- Footprint: While considering all the factors mentioned above, it is crucial to keep the overall footprint of the concept in mind. The design must ensure that it can be housed within the constraints of the MRI dome, without compromising the functionality, safety, or efficiency of the system. Overall, the availability of volume in the MRI is restricted due to accommodation of patient. Those constraints include:
    - ➢ the bore of the MRI scanner into which the patient must fit limits the height of the uppermost part of the patient's body
    - ➢ the need to be in the scanner means that the fixation of the head cannot be below the base of the bed as the shown by the figure 8 as the head clamp is attached accordingly. This means that the body must be raised rather than lowering the head to get the appropriate position for specifically prone position
    - ➢ tilting the table is very difficult inside the scanner, so the patient must be able to be tilted on the base of the table outside the scanner but have a flat base inside the scanner

- ➢ the need to move the patient in and out of the scanner while under anesthesia requires more secure fiction to the table than in the ordinary operating room
- ➢ except in the pure supine and prone positions, the arms must be positioned in a safe way usually resulting in an unpredictable and unusual position, avoiding pressure points that can result in pressure sores during long operations.

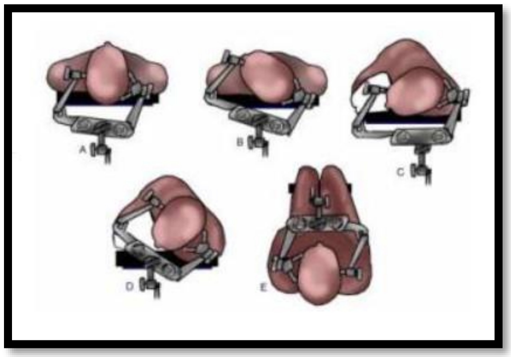

Figure 8: Common head positions during iMRI

After identifying the key pain points of the process, a need statement was formulated to address the primary problem at hand.

Need Statement: A way to automate the repositioning of the patient during surgery, ensuring minimal disruption, enhanced safety, and improved efficiency.

Based on the need statement, these user requirements-

- Position the head with the perpendicular approach vector as close to vertical as possible
- Support the body within the range of motion of the neck
- Support the body such that the head is not at a level below the heart
- Be compatible with the high-power electromagnetic field
- Not have any components which extend below the plane of the table
- Fit within the bore of the average MRI machine
- Maintain conformation throughout the procedure regardless of power state
- Be capable of repeatably producing the same configuration
- Support the weight of an adult patient
- Assume conformations quickly (less than 15 minutes to switch between conformations)
- Conform to the bidirectional curvatures of the patient
- Provide a means to eliminate pressure points if necessary

Based on the qualitative user requirements, engineering specifications are retrieved and prioritized using the importance rating matrix as described by Ulrich and Eppinger in table 2 below.[11]

Table 2: Engineering specification translation

S. No.	User requirement	Specification	Metric	Importance rating (1-5)
1	Position the head with the perpendicular approach vector as close to vertical as possible	-	-	1

2	Support the body within the range of motion of the neck	Extension ratio	7:1	5
3	Support the body such that the head is not at a level below the heart	Preset positions	-	3
4	Be compatible with the high-power electromagnetic field	MRI compatibility	Non-magnetic materials	5
5	Not have any components which extend below the plane of the table	Preset positions	-	3
6	Fit within the bore of the average MRI machine	Footprint not more than MRI bed	-	3
7	Maintain conformation throughout the procedure regardless of power state	High holding torque	>350 N-m	4
8	Be capable of repeatably producing the same configuration	Repeatability of system	Capability analysis	2
9	Support the weight of an adult patient	Max load	>700 lbs	4
10	Assume conformations quickly (less than 15 minutes to switch between conformations)	Preset positions	-	2
11	Conform to the bidirectional curvatures of the patient	Extension ratio	7:1	3
12	Provide a means to eliminate pressure points if necessary	Discretized actuation	Unit footprint of 3 inch × 3 inch	4

Chapter 3

3. Design

Building upon the requirements and need statement established in the previous section, a range of potential solutions can be developed to address the core issue. In line with the double diamond methodology of product development, several concepts will be generated, evaluated, and compared to determine the most optimal solution.[9]

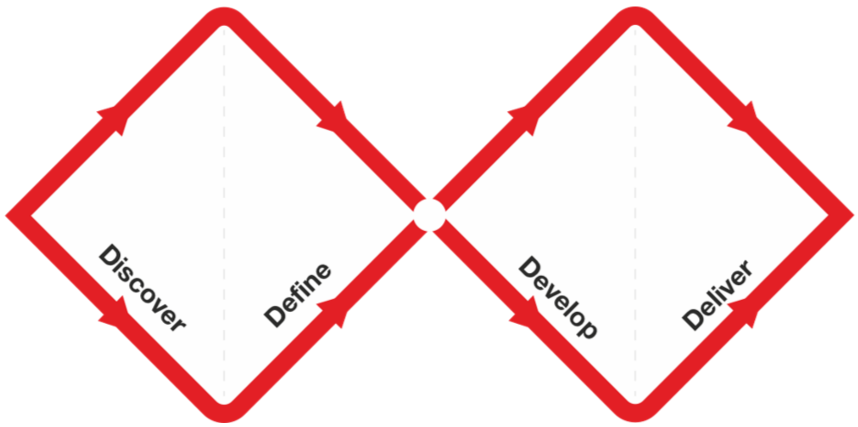

Figure 9: Double diamond methodology

A brainstorming session was held during the develop stage, where the generated ideas were assessed based on the defined constraints.

The session generated several ideas that could be utilized in the selection process for the actuation unit. Table 3 below outlines a comparison of a few concepts proposed during the brainstorming sessions, which were then evaluated using a Pugh matrix to assess their feasibility for this application.[12] The matrix serves as a decision-making tool to identify the most viable and feasible option among the proposed alternatives. In this analysis, an asterisk '*' is used as an indicator of feasibility—where a higher number of asterisks denotes greater viability, and fewer asterisks suggest lower feasibility.

Table 3: Concept selection Pugh chart

	Concepts			
Features	**Piezoelectric**	**Non-ferrite**	**Pneumatic**	**Linear actuator**
Cost	*	**	**	***
Extension ratio	*	*	**	**
Torque	**	**	***	***
Footprint	***	*	**	***
Availability	*	*	**	***
Feasibility score	8	7	11	14

The most viable solution identified was the integration of a series of linear actuators embedded within the MRI bed, working in unison to achieve the required patient orientation. The use of multiple linear actuators allows for enhanced maneuverability and customizability in localized sections of the bed. This approach not only minimizes human intervention but also enables the automation of the positioning process through an external control system. The following section provides a brief overview of linear actuators in general, as well as the need for a custom-designed actuator for this application.

3.1. Linear actuators

Linear actuators are devices that convert rotational motion into linear motion, driven by motors. They are used in a wide range of applications, depending on specific needs.[13,14] Linear actuators are classified based on various factors such as their method of actuation and scale. There are several key properties that determine the suitability of a particular actuator for a given application. These properties are-

- Extension ratio refers to the ratio between the fully extended length of the actuator and its retracted length. This ratio indicates how much the actuator can extend compared to its retracted state; a higher extension ratio signifies that the actuator can extend much farther relative to its retracted size.
- Rated torque refers to the maximum rotational force a motor can continuously generate at its specified speed and voltage under normal operating conditions. It is a crucial specification when selecting a motor for a particular application, as it determines the amount of twisting force the motor can exert on a connected load during operation.
- Holding torque refers to the maximum torque a motor can resist while stationary and energized. It represents the amount of rotational force required to move a motor from its held position when it is not rotating. This is an important parameter for stepper motors, as they are designed to maintain a fixed position without the need for additional braking mechanisms when powered on.

Based on these properties, conventional linear actuators can be classified in several categories-

Figure 10.a: Telescopic actuator; Figure 10.b: Scissor lift; Figure 10.c: Pneumatic actuator; Figure 10.d: Hydraulic actuator

Table 4: Linear actuator types

Type	Description
Telescopic	Telescoping linear actuators are specialized types of linear actuators designed for applications with space limitations. These actuators feature a range of motion that is significantly greater than the unextended length of the actuating member, allowing them to extend to a much longer length than their initial compact size, making them ideal for environments where space is at a premium.

Scissor	The scissor mechanism is a mechanical linkage system designed to generate vertical motion or extension. It is composed of a series of interconnected, folding supports that mimic the shape of a pair of scissors, which is where it gets its name. This mechanism is commonly used in various applications, such as scissor lifts, folding tables, adjustable-height platforms, and automotive jacks, due to its ability to provide stable and efficient vertical movement.
Pneumatic	Pneumatic actuators, also known as pneumatic cylinders, operate similarly to hydraulic actuators, but instead of using liquid to generate force, they rely on compressed air. They function like a piston, with air pumped into a chamber and pushed out from the other side to create motion. Pneumatic actuators are typically not suited for heavy-duty machinery or applications involving large amounts of weight, as they are generally used for lighter tasks where speed is more critical.
Hydraulic	Hydraulic actuators, or hydraulic cylinders, consist of a hollow cylinder with a piston inside. When unbalanced pressure is applied to the piston, it generates force, enabling the piston to move and act upon an external object. Because liquids are nearly incompressible, hydraulic cylinders are capable of providing highly controlled and precise linear displacement, making them ideal for applications requiring high force and accuracy.

In addition to these conventional linear actuators, there are several non-conventional actuators which are utilized in various applications due to their specificity int the respective case. These are-

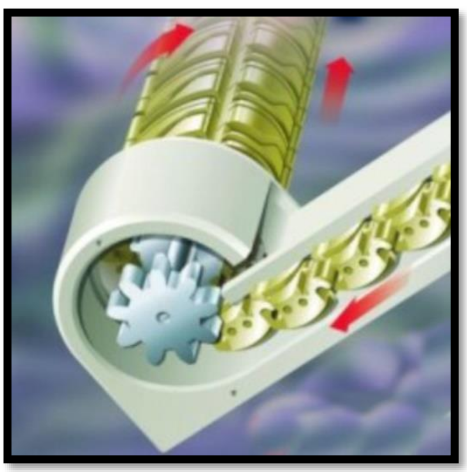

Figure 11: Kataka linear actuator

Kataka- A segmented spindle, commonly known by the trademark Kataka, consists of short, elongated housing that forms the base of the actuator. It incorporates an electrical gear drive and a storage magazine for spindle segments.[15] The drive spins a helically grooved wheel, which engages with the similarly grooved inside face of the spindle segments. As the wheel spins, it simultaneously pulls the segments from their horizontal arrangement in the magazine and stacks them along the vertical path of a helix, forming a rigid tubular column. The reverse process is used to lower the column. But fundamentally, kataka type actuators require a relatively large footprint due to the inherent storage magazine which holds the spindle segments that makes it infeasible for iMRI application.

Figure 12: Spiralift linear actuator

Spiralift- The Spiralift, patented by Paco in 1988 has developed the concept into a commercial platform and currently offers a range of actuators with various performance levels.[16] All the devices are based on a design that incorporates two helically wound bands, one with a horizontal cross-section and the other with a vertical cross-section. In the collapsed state, the bands are stored in a magazine, and through a guiding and driving mechanism, they are interlocked to form a helical column. There are two basic variations of the method used to interlock the bands: one uses a groove in the horizontal band to capture the vertical band, and the other uses tabs on the helical band to interlock with holes in the vertical band. With the groove method, the column can only support axial compressive loads, while the tab method allows the column to support off-axis loads in addition to tensile loads.

The design of Spiralift devices is quite intriguing as they combine two individually unstable structures to create a strong and rigid lifting mechanism. Anyone who has stood on an aluminum can appreciate the strength of thin-walled cylindrical structures. A flat sheet of aluminum with the same thickness and dimensions as the can would not support much load applied in the plane of the sheet. To develop stability, it is necessary to introduce some curvature. Furthermore, the stability of this curvature is limited to the axis of the curve. In the Spiralift design, the curvature of the vertical band functions similarly to the aluminum can, resulting in the formation of a stable structure from thin sheet material.

According to the manufacturers' publications, the Spiralift range includes devices with diameters ranging from 8 to 28 inches and lifting capacities between 380 to 25,000 pounds. The extension ratios of these actuators vary based on the total stroke length, with published ratios reaching up to 12.5:1 at maximum stroke. It is important to note that, due to the design's scalability, there is no inherent limit on the extension ratio, and it is only constrained by system stability, meaning that the published ratios do not represent a definitive design limit. While it is an impressive design, the smallest footprint that the company offers Spiralift is 2'×2'.

Figure 13: Tower solutions linear actuator equipped with flood-light apparatus

Tower solutions- Tower Solutions uses a distinct mechanism for linear actuation, involving three interlocking ribbons that extend simultaneously to form a triangular prism structure.[17] The motion of this structure is controlled by a central motor located at its core. The lowest specification model from Tower Solutions offers height deployment options of 12 ft or 20 ft, completing the process in under one minute. These towers can support a high payload, ranging from 100 lb to 150 lb, while weighing approximately 180 lb. Similar to Spiralift and Kataka, Tower solutions also requires a relatively wide footprint with their smallest product having 1.5'×1.5' base.

Although these linear actuators offer a variety of features, none of them are suitable for use in the iMRI setting due to specific characteristics like size, MRI compatibility, and complexity, which makes them incompatible with the unique requirements of the MRI environment.

3.2. Self-supportive helical ribbon linear actuator

The proposed design involves a single ribbon helix mechanism that incorporates tabs and slots, which engage with each other to create a self-supporting structure. This design is inspired by the Paco Spiralift mechanism but enhances it by simplifying the actuation from multiple components to a single component. This not only reduces the complexity but also minimizes the overall size, achieving a high extension ratio while keeping the unit's footprint under 3 inches by 3 inches.

The patient support system designed with this mechanism embedded in the MRI bed offers the advantage of providing customized orientations to support patients of varying sizes, within the device's dimensional limits. This flexibility enables new ways of orienting the body, allowing the head to be positioned optimally. In addition to offering more orientation options, the ability to precisely match the body's contours in the chosen position helps distribute the load evenly and minimizes pressure points. For extended procedures, the individual actuators can be cycled in succession to reduce the load, providing local pressure relief without altering the patient's orientation. Additionally, the mechanism allows for smooth transition between different positions required during the procedure alleviating the risks involved.

There are various ways the interlocking features of this device can function, with one of the simplest being the use of tabs and slots. Starting with a flat sheet of material, both features can be cut from the form, and the tab structures can be bent into position, eliminating the need for additional components and assembly. While the tab structure is easy to produce, it does shift the material further from the neutral axis, causing localized stiffening of the band. To counter this effect, the tabs must be kept small, allowing the structure to closely approximate the required curvature with a series of straight sections near the tabs. By keeping the tab features short, the overall stiffness of the system remains largely unaffected, enabling the band to function as intended.

Another challenge with removing the second band is that the lifting method used in the Spiralift design is no longer applicable. In the Paco design, the actuation of the device is driven through the horizontal band via a set of guide rollers and other apparatus. However, with a single band, the actuator must be lifted using just the vertical band. This method of actuation could potentially interfere with the tab features, as they would need to interface with the guide and lifting apparatus. While this may seem like an issue, it can be addressed by designing the tab features with this consideration in mind, ensuring that the tabs do not obstruct the guide or lifting mechanisms.

The performance of helically assembled column actuators has been demonstrated by existing products like those offered by Paco, though the field for these actuators are used in niche applications. The goal is for a single-band actuator to maintain the high performance seen in the Paco design, while simultaneously improving the collapsed height and scalability to suit the specific needs of this project. Much like the Spiralift, the stability of the single-band actuator relies on the curvature of the band, which is expected to allow for high load capacities. Furthermore, the use of interlocking features will enable the actuator to support off-axis and tensile loads, in addition to compressive loads. The development of an actuator based on this design holds the most promise for meeting all the established design goals.

3.3. Development

Development of such an actuator is not possible by conventional overlapping of ribbons as shown in figure 14.a and 14.b below. This work references Stefan Hertel's work on helical ribbon linear actuator and some of the equations are referred from his thesis. It leads to reduction of cross section of the actuator as the ribbon is extended. Thus, it was determined that the ribbon should be engaged in an angle such that the aggregate cross section can be maintained constant. To form such a structure, it was determined that a slight curvature was essential to maintain a fixed diameter during assembly. This curvature is vital for the component's functionality and must be precisely calculated to avoid alignment issues. To aid in the design of the helix band, an equation was developed to calculate the theoretical curvature. This was achieved by treating the top and bottom edges of the band as separate paths, each with a distinct length, and then defining two arc sections with a common origin to match the edge lengths. For the sake of simplification, the band is assumed to have zero thickness and to follow the neutral axis path.[18,19]

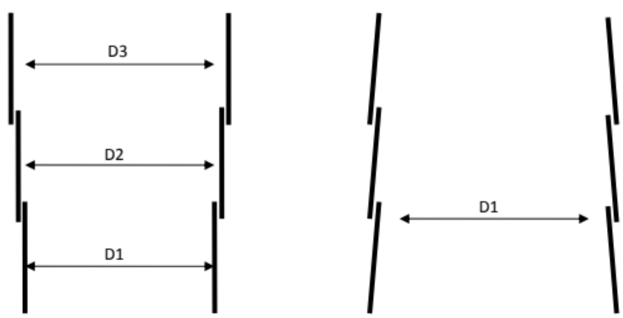

Figure 14.a: Straight overlapping ribbon band; Figure 14.b: Angled overlapped ribbon band

To begin the formulation, it is helpful to define the following variables, as illustrated in Figure 15.a and 15.b. The left-hand image shows a single wrap of the helical band, revolved around an axis, while the right image depicts the resulting flat shape when the band is unwound. The variables are defined as follows:

- D_1: Diameter of the bottom edge
- D_2: Diameter of the top edge
- P: Pitch (the length per revolution)
- C_1: Path length of the bottom edge
- C_2: Path length of the top edge
- t: Thickness of the band
- R_1: Inner radius of the flat pattern

- R_2: Outer radius of the flat pattern
- α: Swept angle of the arc in the flat pattern

These variables are used to calculate the necessary curvature and other characteristics of the helical band.

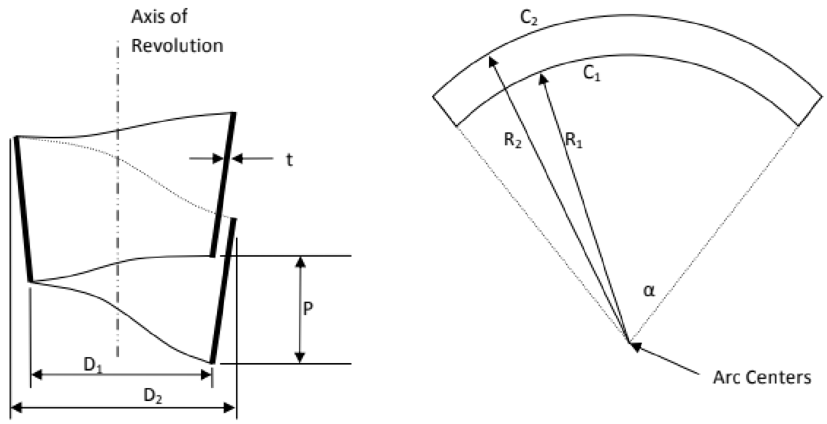

Figure 15.a: Band curve dimensions when folded; Figure 15.b: Band curve dimensions in flat sheet

The first step in developing the formula is to establish the relationship between the path length and the flat pattern radii. This can be more easily understood by using a simple cone, without considering the complications of the helix angle. The process starts by calculating the circumference of both the upper and lower edges of the cone, as shown in Figure 16. These circumferential lengths define the two arc lengths in the flat pattern as shown in figure 15.b.

When these circumferential lengths are combined with the condition that both arcs share an equivalent swept angle, the corresponding radius can be determined, as expressed in Equation (a) below. Once the inner radius is determined, the outer radius is then calculated by adding the pitch to the inner radius. This approach simplifies the calculation of the curvature required for the helical band by focusing on the fundamental geometry of the cone and its corresponding flat pattern.

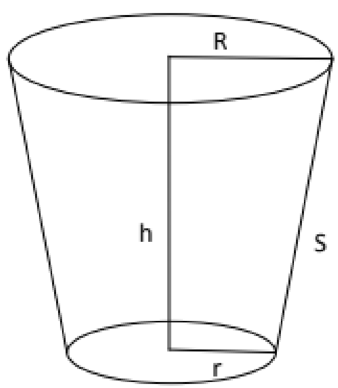

Figure 16: Frustum dimensions

$$(a) \quad C_1 = 2\pi r = R_1\alpha \qquad C_2 = 2\pi R = R_2\alpha \qquad (Equate\ circumfrence\ and\ arc\ length)$$

$$(b) \quad \frac{C_2}{R_2} = \alpha = \frac{C_1}{R_1} \qquad \frac{C_2}{C_1} = \frac{R_2}{R_1} \qquad (relate\ C_1\ to\ C_2\ using\ \alpha)$$

$$(c) \quad \frac{C_2}{C_1} = \frac{R_1 + S}{R_1} = 1 + \frac{S}{R_1} \qquad (Recognise\ R_2 = R_1 + S\ and\ simplify)$$

$$(d) \quad \frac{2\pi R}{2\pi r} = \frac{R}{r} = 1 + \frac{S}{R_1} \qquad (Substitute\ the\ circumfrence\ from\ (1)\ and\ simplify)$$

$$(e) \quad R_1 = \frac{S}{\frac{R}{r} - 1} \qquad (Rearange\ for\ R_1)$$

This process of equating path length to arc length can now be applied to the helix band with minimal modification. Since the two edges are part of the same body and the band has a repeating pattern, it is sufficient to evaluate one revolution of the band. The first modification to the previously discussed formula involves the path length. For the band, the path length is determined by the hypotenuse of the right triangle formed by the cross-sectional circumference and the pitch. This can be calculated using the Pythagorean theorem and then substituted into Equation (c).

The second modification is the sidewall length, denoted as S, which is approximated by the pitch P. This assumption is reasonable because the thickness of the band is small relative to the length S, meaning the difference between S and P is negligible. These adjustments are reflected in Equation (g).

$$(f) \quad C_1 = \sqrt{\pi^2 {D_1}^2 + P^2} \qquad C_2 = \sqrt{\pi^2 {D_2}^2 + P^2} \qquad (Path\ length\ for\ helix\ band\ edges)$$

$$(g) \quad \frac{\sqrt{\pi^2 {D_2}^2 + P^2}}{\sqrt{\pi^2 {D_1}^2 + P^2}} = 1 + \frac{P}{R_1}$$

$$(h) \quad R_1 = \frac{P}{\sqrt{\frac{\pi^2 {D_2}^2 + P^2}{\pi^2 {D_1}^2 + P^2}} - 1}$$

It is possible to express D2 in terms of D1 and t, assuming there is intimate contact between the two bands. This relationship implies that the design parameters—namely the minor diameter (D1), thickness (t), and pitch (P)—fully define the radii of the flat pattern. The remaining variable, the swept angle (α), is dependent on the desired extension of the device (H), and it can be calculated as shown in Equation (i).

$$(i) \quad C_{1\,total} = \frac{H}{P} * C1 \qquad \alpha = \frac{C_{1\,total}}{R_1}$$

When designing a band, it is essential to calculate the spacing of the tab and slot features using arc length rather than linear spacing. Just as the band must have curvature to match the overlapping geometry, the tab and slot features must also be spaced along this curved path to account for the variation in curvature. To achieve this, it is helpful to think of R1 as the baseline radius and locate the slots on a radius one pitch length larger than R1. Then, extend the strip so that it follows a radius slightly larger than the outer edge of the slot. This ensures the correct spacing and alignment of the features in the curved geometry of the band.

Proper alignment is critical for maintaining the actuator's functionality, especially when subjected to compressive loading conditions. If the alignment is not uniform, the load will not be evenly distributed across each tab, which can lead to buckling of the structure along the weaker side. To mitigate this risk and ensure the actuator's stability under load, the pitch distance between each tab is made equal to the pitch distance between each slot. This uniformity ensures that the load is sustained uniformly across the structure, preventing localized weaknesses and ensuring overall stability during operation.

3.4. Experiment design

Design of Experiments (DOE) is a branch of applied statistics that focuses on planning, conducting, analyzing, and interpreting controlled tests to evaluate the factors that influence the value of a parameter or a group of parameters.[20] DOE is a powerful tool for data collection and analysis in various experimental situations. It enables the manipulation of multiple input factors simultaneously to determine their effect on a desired output (response). By adjusting several inputs at once, DOE can uncover important interactions between factors that might be overlooked when testing one factor at a time.

In the case of optimizing the helical band design, three critical design variables were determined: the column diameter, the band width, and the band thickness. These variables are impactful as they determine the structure of a helical actuator when deployed. If the actuator is considered a hollow cylinder, then the cross-section of the cylinder is direct load bearing. The cross-section in this case is determined by band thickness and the column diameter, while the band width determines the number of ribbon overlaps per inch of column. Additionally, these variables can be controlled during the prototyping process. Each of these variables have specified limits which are based on either the constraints derived from user requirements or manufacturing limitation. Thus, the column diameter ranges from 1 to 4 inches, the band width varies from 6 to 38 mm, and the band thickness is constrained between 0.006 inches and 0.020 inches. These variables are manipulated within their respective ranges to calculate the ratio of acceptable strain to the required strain, allowing for the determination of optimal values that maximize performance while maintaining structural integrity.

These variables were incorporated into a DOE to analyze and identify the optimum values for manufacturing. The primary objective of the DOE is to virtually validate the design, thereby reducing the number of iterations required to produce the optimized part. Additionally, the DOE aims to establish a relationship between the design factors and responses, which can be valuable for prototyping adjustments that may arise during production. The primary response analyzed was the compressive load that each column unit can withstand. For this analysis, Response Surface Methodology (RSM) was employed to not only observe the optimized parameters but also to develop relationships between the factors that are necessary for Design for Manufacturability (DFM) considerations. It fits a second-degree polynomial model that optimizes (maximizes, minimizes, or attain a specific target) the response variable based on factors.

Given that there are fewer than five factors involved and no constraints on testing at the extreme parameters, Central Composite Design (CCD) within the RSM framework was chosen for the final analysis, ensuring an effective and comprehensive evaluation of the design space.[21] RSM allows orthogonality, rotatability and uniformity properties which makes it robust for this specific DOE. Additionally, four center points are included in this DOE to capture the curvature of the model with repeats restricted to one as there is no probability of repeatability errors for virtual simulation.

In addition to factors and responses, these are the following assumptions that were assumed during the DOE phase-

- Material will be SS304 due to its non-magnetic properties
- The material will be analyzed under a static load of 500N in the axial direction and 200N in the transverse direction to simulate the maximum limit during an iMRI surgery.
- The base of each model is fixed.
- Models are analyzed in a static structural condition.

Table 5 below overviews the DOE along with the Lower Specification Limit (LSL) and Upper Specification Limit (USL) for the factors along with the analyzed response in table 6-

Table 5: DOE factors levels

Factor	**LSL**	**USL**
Width (mm)	6	38
Thickness (mm)	0.1	1
Column Diameter (mm)	30	90

Table 6: DOE response variable

Response	Maximum Stress (MPa)

Based on these factors and responses, RSM was used to generate an experiment run using JMP Pro 17.2 software (a statistical software for DOE). The runs generated are listed below in table 7. These runs are used to create individual models for each run which were then analyzed in similar conditions.

Table 7: Experiment runs

StdOrder	**RunOrder**	**PtType**	**Blocks**	**Width (mm)**	**Thickness (mm)**	**Dia (mm)**
39	1	0	2	22	0.55	60
14	2	-1	2	38	0.55	60
15	3	-1	2	22	0.1	60
18	4	-1	2	22	0.55	90
16	5	-1	2	22	1	60
35	6	-1	2	22	0.1	60
38	7	-1	2	22	0.55	90
19	8	0	2	22	0.55	60
17	9	-1	2	22	0.55	30
13	10	-1	2	6	0.55	60
40	11	0	2	22	0.55	60
36	12	-1	2	22	1	60
37	13	-1	2	22	0.55	30
20	14	0	2	22	0.55	60
33	15	-1	2	6	0.55	60
34	16	-1	2	38	0.55	60
24	17	1	1	38	1	30
10	18	0	1	22	0.55	60
26	19	1	1	38	0.1	90

8	20	1	1	38	1	90
32	21	0	1	22	0.55	60
22	22	1	1	38	0.1	30
21	23	1	1	6	0.1	30
28	24	1	1	38	1	90
1	25	1	1	6	0.1	30
2	26	1	1	38	0.1	30
5	27	1	1	6	0.1	90
30	28	0	1	22	0.55	60
11	29	0	1	22	0.55	60
27	30	1	1	6	1	90
4	31	1	1	38	1	30
12	32	0	1	22	0.55	60
31	33	0	1	22	0.55	60
23	34	1	1	6	1	30
3	35	1	1	6	1	30
6	36	1	1	38	0.1	90
9	37	0	1	22	0.55	60
7	38	1	1	6	1	90
25	39	1	1	6	0.1	90
29	40	0	1	22	0.55	60

3.5. Analysis

In accordance with the boundary conditions of the static structural Finite Element Analysis (FEA) simulation, the analysis was performed on each run. Since the yield stress of SS 304 lies between 205 to 260 MPa, the specific models where the highest stress exceeded this yield stress value led to a failed iteration. As can be seen in the figures 17.a and 17.b below, analyzed in a similar load condition with different dimension models based on the run. Additionally, all models were evaluated in their fully extended positions to capture behavior under worst-case conditions. As shown in figure 17.a, the maximum stress recorded was 187.18 MPa, well below the material's yield stress, whereas figure 17.b indicated a higher maximum stress of 758.15 MPa. This clearly suggests that the dimensions from run no. 8 offer better mechanical safety than those from run no. 19.

It was found that the column's thickness and diameter had the most significant impact on the overall response. Figure 18 illustrates the stress distribution under loading conditions for one of the test runs, showing that the areas of highest stress concentration—and thus the most likely failure points—were at the tabs-ribbon bend locations. The analysis further indicated that simultaneous failure of the tabs would be ideal to prevent localized failure and maintain structural integrity. This further emphasized the prototyping consideration for the finalized model.

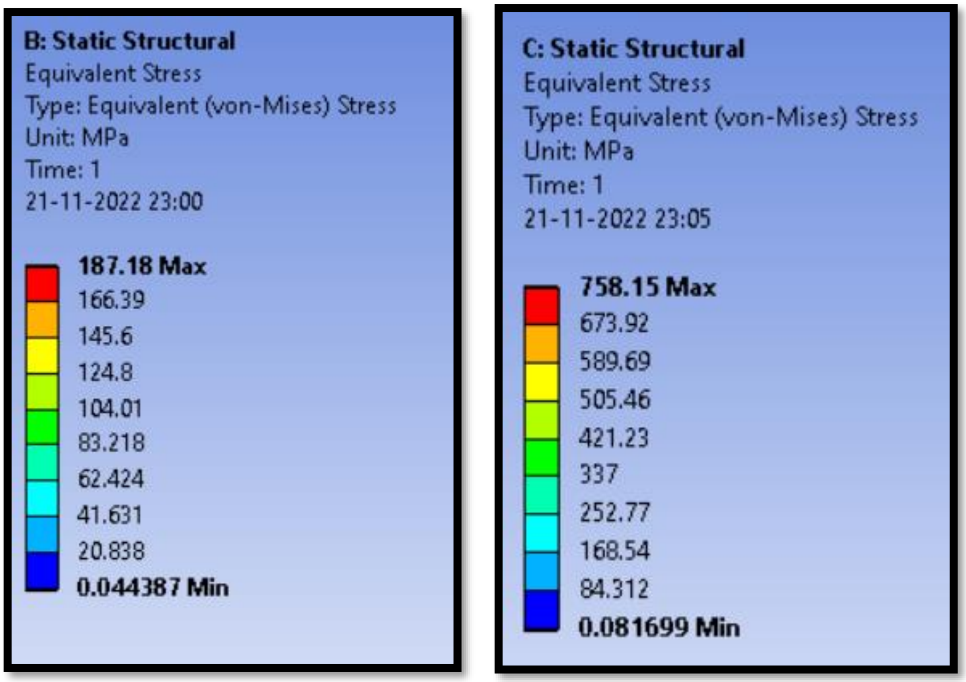

Figure 17.a: Maximum stress on the run no. 8; Figure 17.b: Maximum stress on the run no. 19

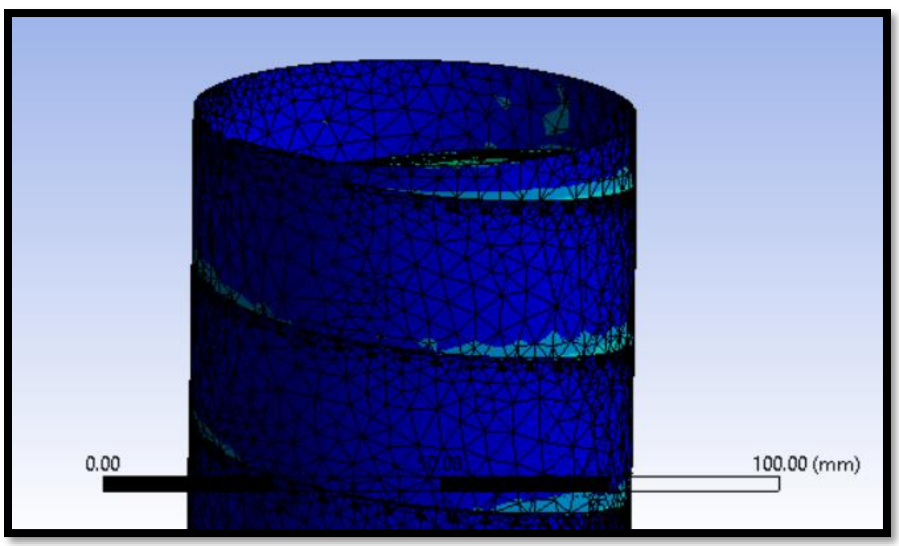

Figure 18: Stress distribution on ribbon band

Using the DOE, a statistical model is developed which suggested the optimum values of the factors based on the desired response. Using the contour plot feature, which is a 2D graphical representation of a 3D response surface, where two independent variables (factors) are plotted against each other, and lines connect points with the same response value, helping to visualize the relationship between factors and the response.[22] The statistical model proposed an optimized setting, illustrated in figure 19, where the purple box highlights the zone of maximum stress capacity. The model indicates lower stress values for band thicknesses between 0.4 mm and 1.0 mm, regardless of the diameter. However, due to the user requirement to keep the overall linear actuator diameter below 3 inches, the diameter is limited to under 70 mm. Based on the resulting response, optimized dimensions were chosen based on DFM considerations as shown below in table 8.

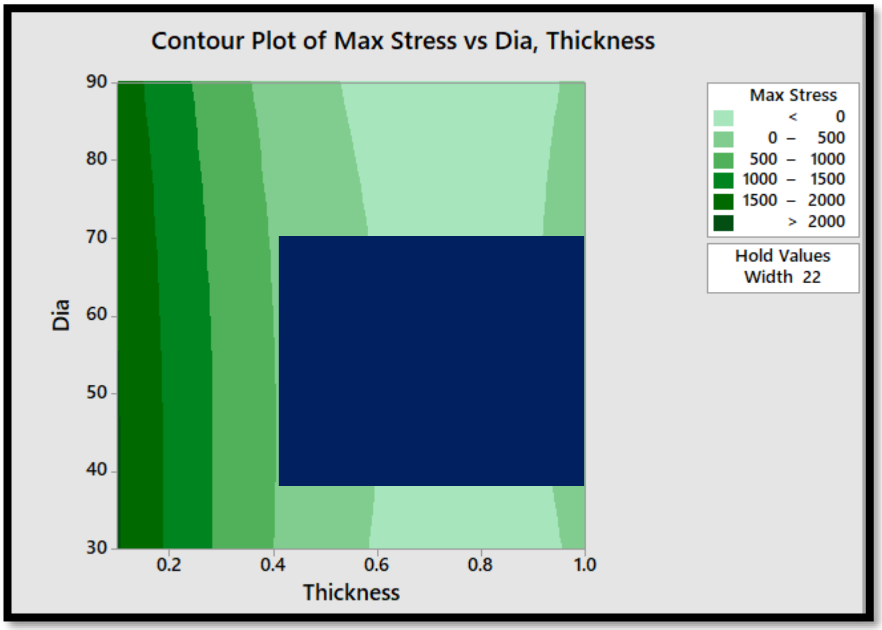

Figure 19: Optimized values contour plot

Table 8: Optimized dimensions

Thickness (mm)	Diameter (mm)	Width (in)
0.5	60	0.75

After virtually validating the design, the final dimensions were selected as shown in table 7 and used to make the final design which was eventually manufactured in its flat sheet metal format, optimizing the process for ease of production. This approach ensures that the manufacturing process remains efficient and straightforward while maintaining the accuracy required for the actuator's functionality.

Due to the complexity of the component, convincing manufacturers to produce a single, intricate part proved to be challenging. One of the key issues was the inability to source the exact thickness of sheet metal required for the manufacturing process, as the specified size was non-standard. This necessitated adjustments to the model to accommodate the closest available thickness, which could still meet the functional requirements. Additionally, several vendors were unwilling to produce one-off pieces for prototyping, further complicating the development process.

Chapter 4

4. Deployment Mechanism design

This chapter outlines the development of a design for the individual linear actuator to be integrated into the system, along with a method for controlling the actuator. The BMDC provided the design team for collaboration in the senior design project, where the mechanism was broken down into several key components, each essential for completing the overall system design. The design team consisted of Brian Pratt, Christian Strommen, Jay Manolis, Ken Uy, Tucker Blezek and the author.

4.1. Control System Architecture

The control system must be expandable, allowing for future bed size changes and modifications as necessary. This means that the system should not have intrinsic limits on how many actuators can be connected to a single console. It should also feature a centralized control panel that offers an intuitive user interface, meaning that the anticipated user population should be able to operate this system with a brief training session. This interface will likely feature buttons linked to preset bed positions as well as functionality to make further adjustments to meet patient needs. In the event of control faults, the system must be designed to return to safe positions automatically, ensuring the safety and integrity of the overall system.

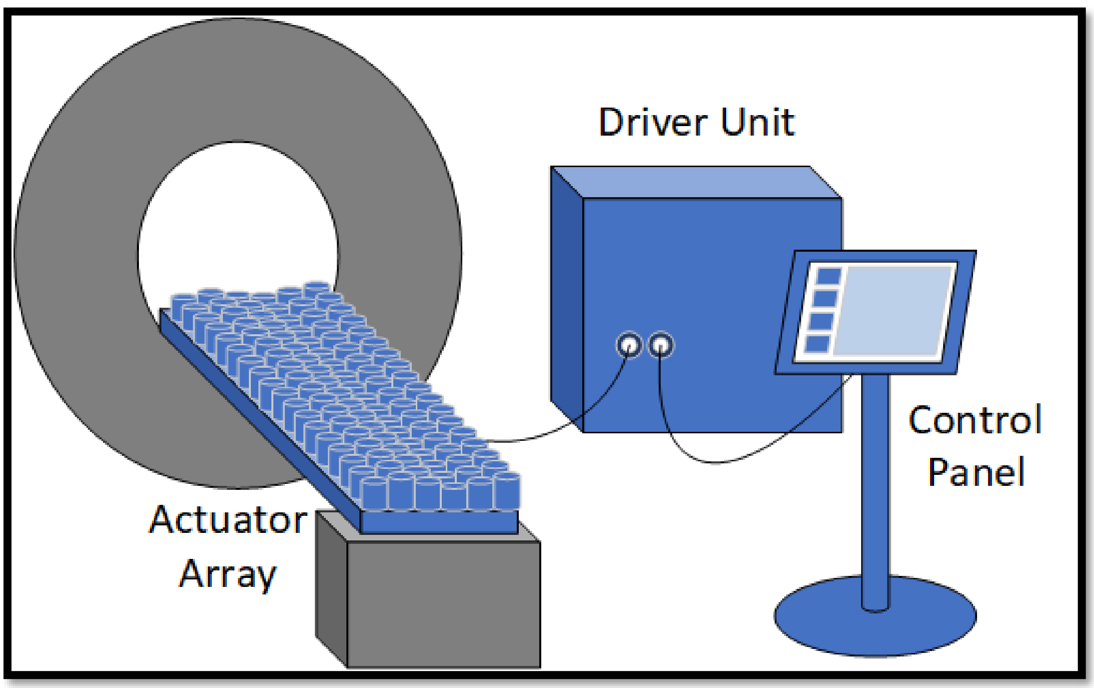

Figure 20: High-Level Depiction of Overall Array System

4.2. Power System & Interface Mechanism

The design for the drive system must meet specific technical requirements to ensure operational compatibility and efficiency. The system is required to be non-ferrous to maintain MRI compatibility. Additionally, the system must provide adequate torque to support the actuator's functions while maintaining control fidelity and adequate response times.

The team was tasked with designing a solution that can contain and organize the tape at all actuator positions. A requirement was set for the ribbon canister to adhere to the 3"x3" footprint including the rest of the actuator design. The tape canister was designed to move smoothly and prevent any snagging or tangling using a generalized organization system for the tape. The design produced consists of three distinct subsystems: a driving subsystem, an interface subsystem, and a control subsystem.

4.2.1. Drive Subsystem

The desired linear motion of the actuator necessitates some input of force and velocity into the actuator. Since the environment of an MRI rules out any sort of ferrous motor located within the actuator itself due to the high magnetic fields present, it was decided that the optimal solution was to have the source of power be located outside of the MRI field and then transmit that force into the actuator by a mechanical transmission. It was determined that a DC servo motor paired with a planetary gear set would be a suitable choice. This system has low steady state power consumption but provides low speed and high torque required by the actuator.

For the prototype, a NEMA 17 1.5A stepper motor paired with a DRV8825 driver was used. This motor driver combination was chosen because of the relative availability and competitive price of the motor standard. The DRV8825 stepper driver was chosen over the A4988 due to the features of 1/32 microstepping and 32-bit resolution providing for a smoother, quieter and more consistent actuation. The DRV8825 stepper driver was chosen over the TMC2208 driver because of the reduced price and better availability. A 3D printed gearbox was also prototyped to increase the output torque of the stepper motor. The gearbox enabled the stepper motor to meet the torque requirements of the plastic prototype model.

A dual pulley system (illustrated in Fig. 21) transmits the rotation generated by the motor. One pulley is directly connected to the shaft of the motor, with the other pulley set on a bushing located in the base of the actuator. The two pulleys are connected by a tensioned line such that the pulleys provide a 1:1 rotation with minimal losses. This means that between the motor and the actuator there should be a direct proportional relationship between their positions, and therefore a simple control system to relate their positions.

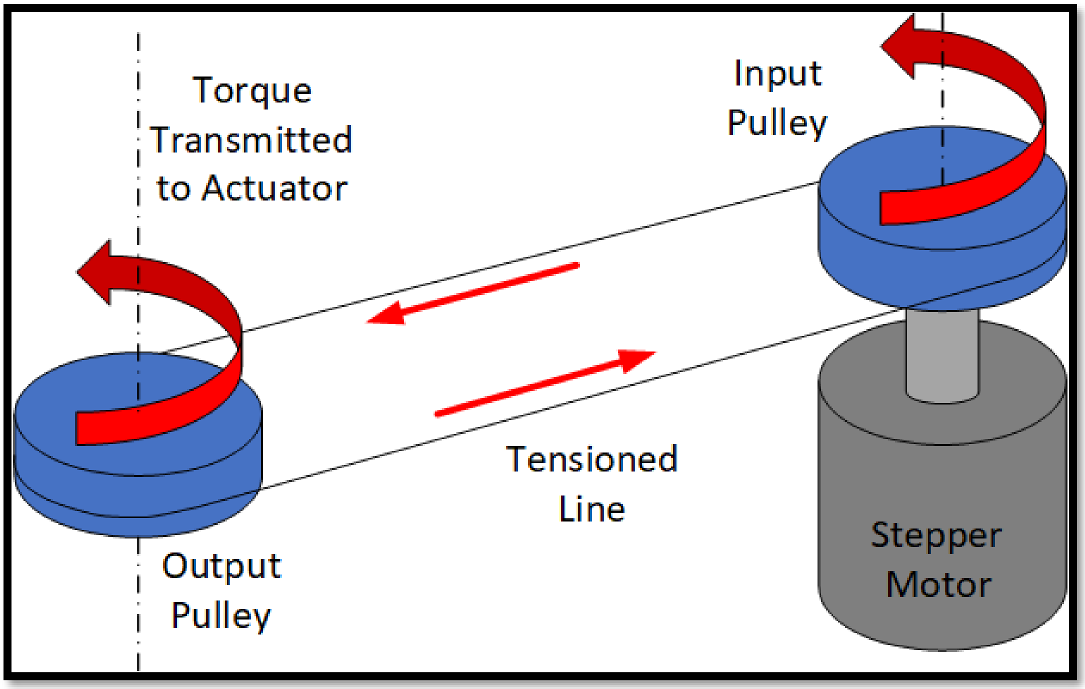

Figure 21: Dual Pulley System

4.2.2. Interface Subsystem

The interface subsystem transmits the rotational motion generated by the drive system to the self-assembling ribbon structure. Because of the nature of the actuator changing its physical size, the interface subsystem needs to either be able to vary its own position/size while still maintaining its ability to transmit torque to the ribbon or remain in the same position regardless of actuator height, without placing the portion of the ribbon where it "self-assembles" under compression. Two parallel designs were developed for the interface sub-system. The first design is a telescopic shaft that contains multiple concentric shells which allows the shaft to expand and contract vertically, but the features that "key" into each adjacent shell allows the structure to transmit torque. The innermost shell of the telescopic shaft is directly connected to the second pulley as described in the drive subsystem section. The outermost shell is connected to the top of the linear actuator, which is secured to the end of the self-assembling ribbon. The telescoping shaft is shown in figure 22.a and 22.b. Additional details about the concept selection are explained in Appendix C.

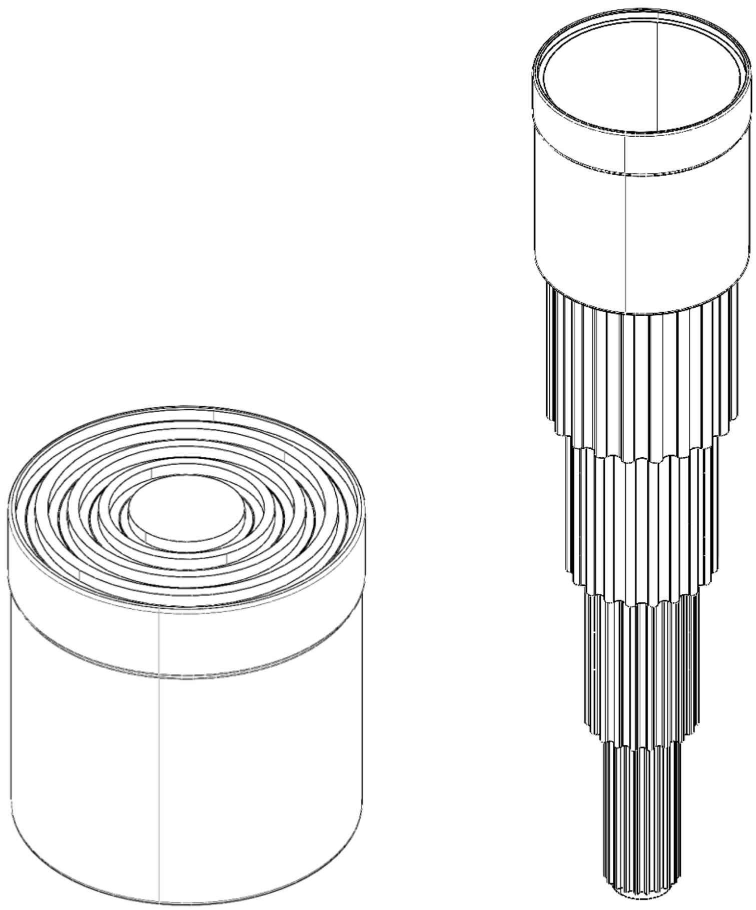

Figure 22.a: Telescopic Shaft Design Contracted; Figure 22.b: Telescopic Shaft Design Extended

When the telescopic shaft rotates, the bottom of the self-assembling ribbon is pulled through a guiding channel in the actuator base. This helically meshes the ribbon with itself and moves the top of the actuator upwards. The same will happen in reverse, where the ribbon structure will unmesh and “disassemble” itself, moving the top of the actuator downwards according to the designed pitch as depicted in figure 23.a.

The second design for the interface subsystem is a “bottom-drive” that transmits rotation from the pulley into a sprocket that meshes directly with the ribbon itself as shown in figure 23.b. While there was initially concern of placing the ribbon under compression rather than tension (which motivated the designs that drove the rotation of the ribbon from the top), upon further research it was found that the ribbon could be placed under compression so long as it was done above the point where two layers of the ribbon meshed. The design itself consists of a sprocket that is spun by the pulley located below the actuator, like the telescoping shaft design, with the notable difference that it is positioned off-center and at an angle. This allows the gear to mesh with the slots cut into the ribbon at the desired pitch. When the pulley spins and turns the gear, the ribbon is rotated, expanding or contracting the actuator proportionally to the rotation of the external electric motor.

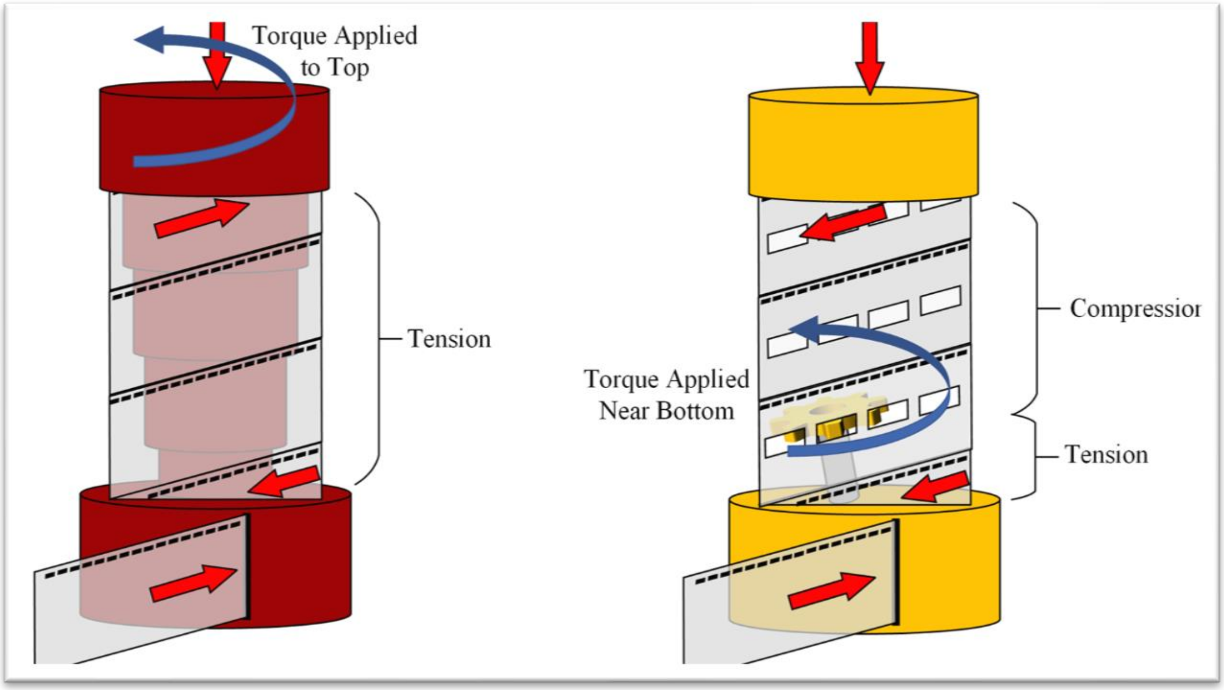

Figure 23.a: Schematic showing ribbon loads for the telescoping shaft; Figure 23.b: Schematic showing the bottom-drive mechanism design

As the ribbon is unmeshed from the actuator, it is guided into a cartridge that sits around the base of the actuator. This cartridge contains the ribbon when it is in its closed position. The cartridge is allowed to spin freely around the base of the actuator to avoid additional binding in the ribbon. The alignment cuff aligns the tabs and slots of the ribbon and supports any loads placed on the actuator. This accounts for the majority of the losses in the system, so significant effort was made to refine this geometry.

4.2.3. Control Subsystem

The control subsystem translates the desired position of the actuators, as determined by the operator to motor signals, thereby moving the actuators. The expected design for this is a console which contains a digital screen showing a selection of options to manipulate the actuator array as well as the current state of the array. A prototype for what the user interface could potentially look like is shown below in figure 24.

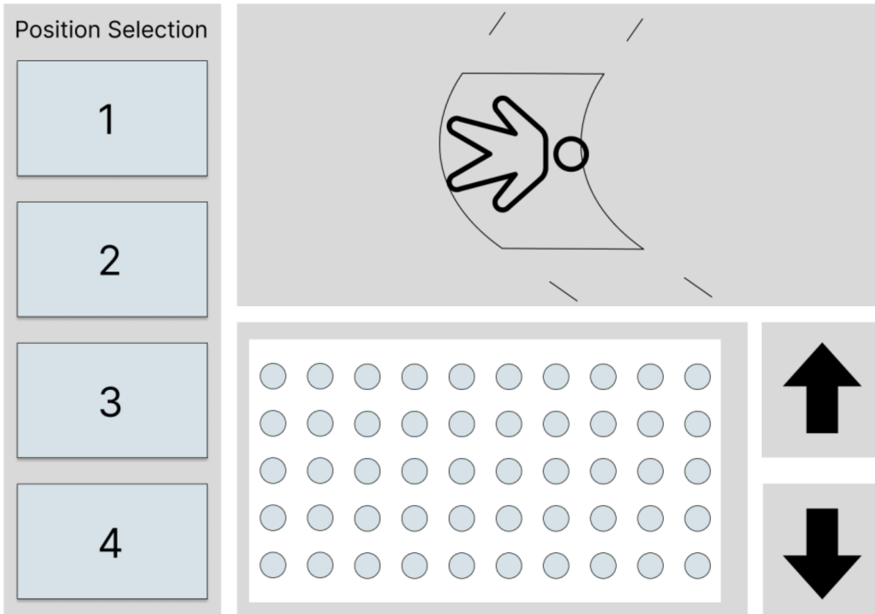

Figure 24: Actuator Array Control U.I. Prototype

The position selection buttons can be used to tell the actuators to travel to a pre-set position that the operator can program prior to an operation. The graphic on the top right stands in for a real time 3D rendering of the bed surface, like that shown in Figure 29 in the next section, to give the operator up to date information on the patient's position if they are not able to visually see the patient while operating the console. The grid of circles on the bottom middle of the user interface represents the individual actuators that the operator can control. The operator can select actuators from this 2D array, and command them to be raised or lowered using the arrows to the right of the array. All these commands would be translated into code to be delivered to the motor drivers, thus controlling the steppers and the actuators.

Chapter 5

5. Results

5.1. Actuator

The resulting actuator design was tested multiple times using plastic sheets for prototyping. The material used was soft PETG 1.5 mm sheets which was laser cut according to the flat geometry shown in figure 25. The engagement mechanism was observed to be effective and validating the calculations. After verification through plastic prototype, the final metal sheet prototype was manufactured through laser sheet metal cutting by Ramar Precision Metal Inc. The prototype was made from Stainless Steel 304, with a thickness of 0.015" (0.4 mm) as shown below in figure 26, 27.a and 27.b.

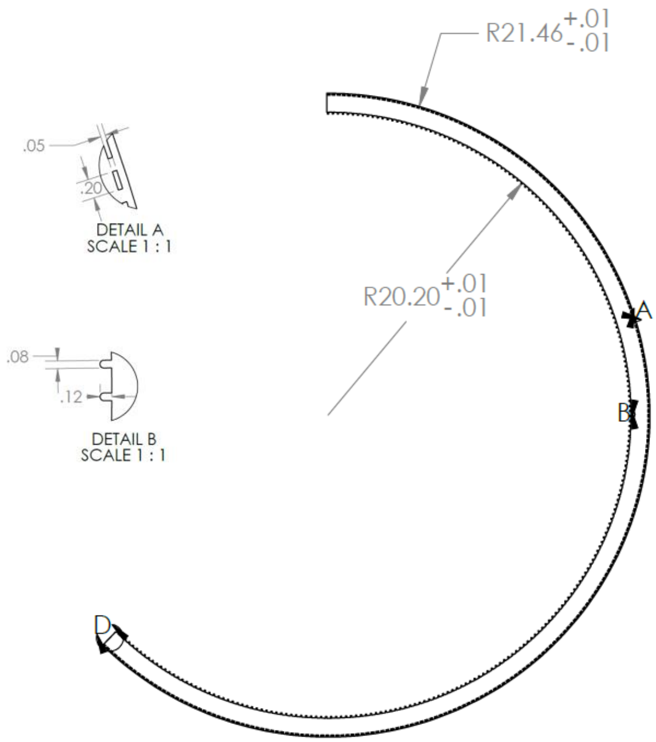

Figure 25: Flat sheet draft of ribbon

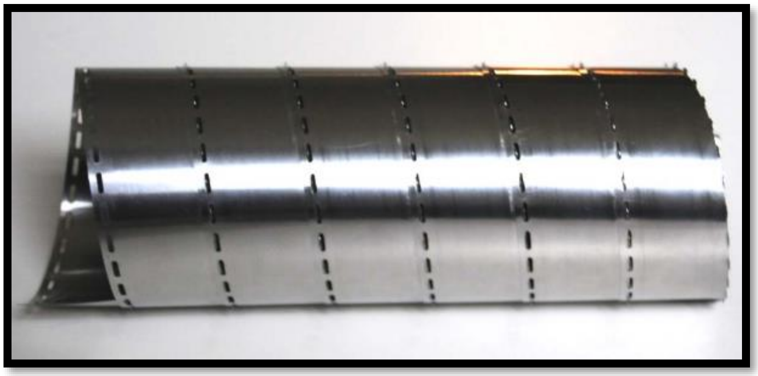

Figure 26: Helical ribbon engaged

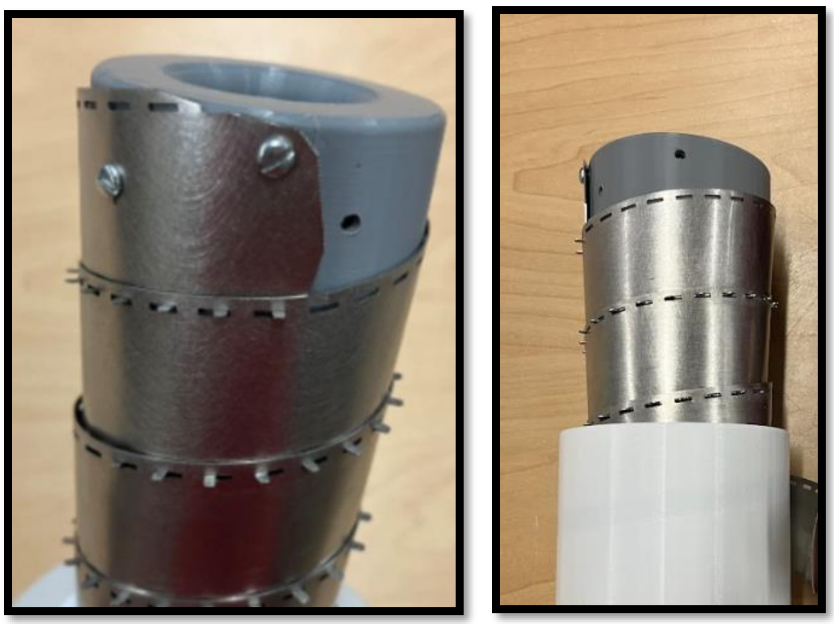

Figure 27.a: Helical ribbon with telescopic shaft; Figure 27.b: Helical ribbon with housing

The linear actuator consists of a single stainless-steel ribbon, manufactured and bent to form the helical shape of the actuator. The design incorporates features such as tabs and corresponding slots that interlock when the ribbon is rotated counterclockwise to extend. The sheet metal is fabricated so that the number of tabs matches the number of slots, ensuring proper alignment. The interlocking mechanism occurs as a tab slide from inside a slot and protrudes through the slot, creating a secure fit that locks two adjacent bands of the ribbon together. This interlocking action forms a rigid cylindrical structure capable of supporting a load independently. To retract, either the base of the linear actuator can be rotated clockwise, disengaging the tabs from their respective slots as the ribbon retracts and is stored in the bottom casing or the ribbon can rotate through bottom-drive mechanism via the slotted ribbon.

The advantage of this design is that, instead of requiring multiple positioning aids like cushions, pillows etc. to achieve various positions, the system of linear actuators allows for any combination of positions tailored to the specific needs of both the patient and the physician. Additionally, the use of linear actuators eliminates the need for technicians to manually lift and reposition patients, especially those with mobility impairments, reducing the risk of injury or discomfort. By streamlining the MRI procedure and reducing the personnel and time required, this system has the potential to improve the efficiency of MRI suites, lower costs for both patients and healthcare providers, and enhance patient outcomes. This can also increase the number of iMRI procedures done for the same time period.

This invention presents a new, highly versatile mechanical actuator with a wide range of potential applications. It excels in situations where compactness, long travel distance, lightweight design, or high load capacity is required. The inclusion of a collapsible column gives this actuator a distinct advantage over conventional guided cylinder actuators, which are typically limited to extending only about twice their initial length. The device also offers impressive ratios, such as the maximum lift distance to the minimum height and the maximum lift distance to load capacity, making it both efficient and adaptable. These advantages enhance its overall utility, allowing it to be applied in various contexts where traditional actuators may fall short. Furthermore, by combining different design aspects of the actuator, novel applications and use cases can emerge, increasing its adaptability in diverse industries.

Figure 28: Close up showing tab and slot engagement

The single band ribbon actuator, as currently designed, provides an extension ratio of 8:1. With additional modifications to the driving mechanism and dimensions, it can achieve an even higher extension ratio. However, this comes at the cost of a reduced compressive sustainable load, highlighting the balance between performance and load-bearing capacity. This adaptability further solidifies the actuator's potential in a broad range of uses. The key component of the actuator is the main support structure formed by the interlocking helical band, as shown in figure 27.a. The interlocking features of the band are based on a repeating pattern, illustrated in figure 28. Due to the overlapping nature of the band, the upper edge can have a different radius of curvature relative to the lower edge. This design ensures the proper alignment and functionality of the actuator.

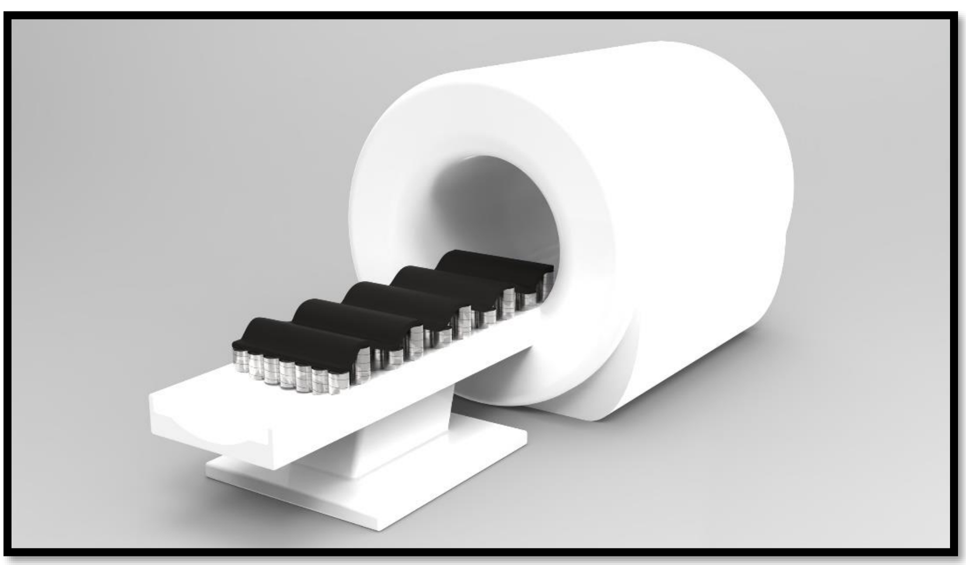

Figure 29: MRI render with actuator embedded in bed

The system design for the actuator is divided into three subsystems: the drive subsystem, the interface subsystem, and the control subsystem. Each subsystem plays a critical role in the overall function of the actuator.

- Drive Subsystem: This subsystem supplies the actuator with power. It consists of an electric motor connected to a gearbox, which drives a pulley with a tensioned line. The tensioned line transmits motion to a second pulley located in the base of the actuator, ultimately driving the actuator's movement.
- Control Subsystem: The control subsystem ensures that the operator's intended position of the actuator is accurately translated into the actual position. The control system manages the feedback and positioning of the actuator, allowing it to achieve the desired movement.
- Interface Subsystem: This subsystem connects the power from the drive system to the actuator itself, translating the motion of the drive system into vertical movement of the actuator.

In the design process, several concepts for each subsystem were considered. Two final designs were generated, both of which share similar drive and control systems. The major difference between the designs lies in the interface subsystem.

- Telescoping Shaft: In the first design, as shown in figure 23.a, the pulley located at the base of the actuator rotates the shaft, which extends vertically while still transmitting torque. This shaft is connected to the cap of the actuator. As the shaft rotates, it turns the helical ribbon, which is designed to self-assemble as it rotates. This motion drives the actuator upwards, providing the desired linear displacement.
- Bottom Drive System: In this design, the rotating pulley drives a gear located at the base of the actuator. This gear meshes directly with the helical ribbon, rotating it and thus driving the actuator upwards, as shown in figure 23.b. This system eliminates the need for the shaft and directly couples the rotational motion of the pulley to the helical ribbon, making it simpler and potentially more compact than the telescoping shaft system.

Both designs share a key feature: a directly proportional relationship between the rotational position of the electric motor and the vertical position of the actuator. This simplifies the control subsystem, as it only needs to adjust the motor's position through electrical signals provided by the console. The control system can therefore easily manage the vertical movement of the actuator by controlling the motor's rotation, ensuring accurate positioning of the actuator.

Thus, this design offers an efficient solution for repositioning patients when integrated into an MRI bed as part of an actuator array system controlled externally. Each unit achieves an extension ratio of up to 8:1, ensuring smooth and effective transitions between positions. Additionally, the current design enables the actuator array to support the weight of 99th percentile patients. Overall, this reduces procedural risks, enhances efficiency by minimizing patient repositioning time, and allows for more procedures within the same timeframe, potentially lowering room costs and reducing patient wait times.

5.2. Compressive testing

The testing phase of the prototype involved using a compressive testing machine to evaluate the ribbon's behavior under load, specifically to measure its yielding stress and maximum load capacity. This was done to understand how the tabs and slots would perform when subjected to compressive forces and whether they could properly engage and disengage under load conditions. The test was performed according to ASTM E9-09 with a strain rate of 0.005 in./in.*min.[23]

To conduct the test, a compressive test fixture was manufactured to enclose the ribbon in a column orientation, simulating the actual operating conditions the actuator would face when in use. The design of this fixture was critical as it ensured that the ribbon was tested in a way that mimicked the real-world loading scenarios as closely as possible.

However, since the ribbon could not be extended to its full length in the prototype, only a portion of the ribbon was used for testing as shown in figure 30. This section of the ribbon was subjected to compressive force to gather data that could be used to compare with the expected behavior derived from the FEA simulation of the ribbon. By analyzing the results of these tests, the team could assess the performance of the tabs and slots, their ability to interlock underload, and verify whether the component could handle the required compressive forces without failure.

For the testing phase, an MTS uniaxial tensile testing machine was used at Anderson Labs, CivE, equipped with a 6kN load cell to apply compressive forces on the prototype ribbon. The fixture's dimensions were calculated with a factor of safety of 3, meaning that the fixture was designed to withstand three times the expected load without failure.

Figure 30: Compressive test sample

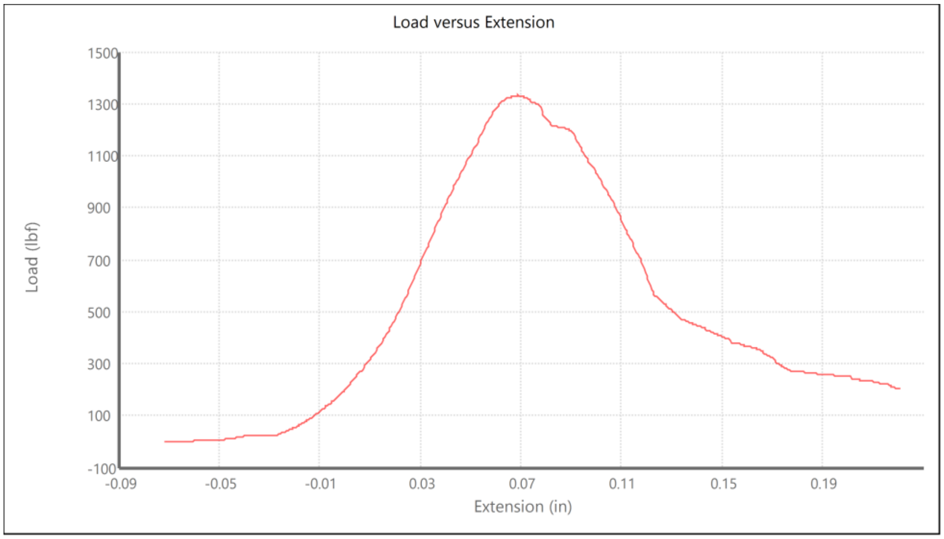

Figure 31: Load vs Extension graph

Figure 32: Tested sample

Additionally, the compressive testing revealed that a single actuator unit could handle a load of 700 lbs, with the tabs yielding at 700 lbs, which is twice the 99th percentile weight of a patient (300 lbs) that might be required in an iMRI surgery. The peak load occurred at 1330 lbs, at which point the actuator started failing, as shown in figure 31. When compared with the FEA done on the optimized dimension model, the analysis suggested similar results. While the dimensions changed from the original optimized values suggested by the model due to availability but overall, the vertical column stress peaked at 120 MPa which is close to what the FEA predicted. It was also observed that the failure of the tabs happened simultaneously, which is crucial for the integrity of the actuator as shown in figure 32. This indicates that multiple actuators used in conjunction should be sufficiently sturdy to sustain a typical patient's weight during surgery without failure. This verifies the reliability of the concept and its validation for use in actual clinical settings.

While designed for use in a clinical setting, the concept can also be applied in multiple other applications due to its high extension ratio and low overall footprint. The aerospace and agricultural domain can also be explored, where high extension ratio linear actuation is required while keeping the overall size of a unit as low as possible without compromising with its structural load bearing capacity.

Chapter 6

6. Conclusion and Future development

In conclusion, the research resulted in the development of a novel single-band helical linear actuator with self-supporting capabilities. The use of non-magnetic materials in its manufacturing makes the concept suitable for use in MRI settings. The actuator offers an extension ratio of 8:1 with an overall footprint of less than 3" x 3". Additionally, a deployment system was developed that houses the ribbon when not deployed and engages it when deployed, forming a cylindrical support.

Furthermore, verification against the user requirements was conducted through compressive testing of the unit to estimate the yielding load of a single actuator. The test results indicated a yielding load of 700 lbs, which exceeds the user requirement of 350 lbs. This allows for leveraging the design and tight tolerances on the critical dimensions, enabling further reduction of the footprint. With sufficient resources, a future array of linear actuators can be built to enhance the system's capabilities. This can potentially enhance the efficiency of the procedure by reducing the risks involved during the surgery and the time required for the procedure.

This technology has the potential to be utilized across various industries beyond healthcare, including agriculture, aerospace, manufacturing, and many others. The concept offers a new alternative in the field of linear actuators and can be customized based on specific applications, providing flexibility in terms of load support, footprint, and compatibility.

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Appendix A- Patent Draft

Inventors- Yash Soni, Paul Rothweiler, Arthur G. Erdman, Christian Paul Strommen, Brian Douglas Pratt, Jay Manolis, Tucker Blezek, Kenneth Uy, Stephen J. Haines, Stefan J Hartel

Title

Self-supporting helical ribbon linear actuator with Rotary Drive System for High-Extension Linear Actuation

Cross-references

US7213796: Linear actuator with releasable interlocking bands

US6547216: Multiple balls supported push actuator

US4875660: Push actuator

US2173685: Lifting jack

EP2385385B1: RF coil assembly for use in magnetic resonance imaging

US8513946B2: Movable table for magnetic resonance imaging

Background

In a conventional linear actuator design, there exists a potential limitation on the extension ratio, typically constrained by the structural configuration. These actuators typically feature a guide rod propelled by electromechanical, pneumatic, or hydraulic mechanisms, facilitating relative motion along the longitudinal axis between the guide rod and the actuator body. Linear actuators fundamentally extend to provide the stroke length required for the application. The ratio of the length of the linear actuator after extension and the length of the linear actuator in its retracted position is called extension ratio. Due to their reliance on solid structures, conventional linear actuators often encounter challenges in achieving extension ratios surpassing 2:1, with practical limitations often hovering around 1.8:1. However, by integrating multiple actuators into multistage units, it becomes feasible to surpass the 2:1 extension limit, although theoretical considerations may differ from practical outcomes.

Conventional linear actuators offer the advantages of well researched applications and widespread availability. They boast high load-bearing capacities and, when paired with appropriate control systems, can deliver precision in operation. While variations of these actuators cater to diverse load requirements, not all are useful for all applications, for example in magnetic environments.

The concept of combining multiple actuators in series to enhance extension ratios can be realized through various methodologies. In the case of rotary screw actuators, offsetting the screws and driving them relative to each other can boost the extension ratio, albeit with less than a twofold improvement due to stage overlap necessitated by rigidity maintenance. Additionally, each subsequent stage introduces a commensurate increase in complexity. Another category of actuators, such as linkages or mechanism types exemplified by scissors lifts or jacks, is frequently integrated with aforementioned actuator types to enhance overall functionality and extension capabilities.

Integrating a linkage mechanism with a standard linear actuator can potentially enhance extension capabilities, albeit with associated trade-offs such as diminished load capacity and altered force-to-displacement ratios. This hybrid actuator typically features a single degree of freedom linkage with a screw or cylinder exerting a load on the mechanism's input. Throughout its range of motion, the linkage geometry undergoes changes, leading to variations in the mechanical advantage of the system. Near the fully collapsed position, these devices may exhibit relatively poor mechanical advantage, contrasting with improved mechanical advantage near the end of travel.

Addressing this issue by upsizing the actuator warrants consideration of mechanical advantage, as upsizing may only partially mitigate the reduction in mechanical advantage. Consequently, substantial forces may be exerted at the pin joints, necessitating overbuilding of the structure to ensure structural integrity and stability.

While useful within their respective industries, these products are likely unsuitable for consumer, medical, and various other sectors. There is a requirement for a smaller foot print of the device to be utilized in juxtaposition with the extension ratio feature of the device. As one example, Intraoperative Magnetic Resonant Imaging (iMRI) is a procedure that creates images of the brain during surgery. Neurosurgeons rely on iMRI to guide them in removing brain tumors and treating other conditions such as epilepsy. Surgery is often the first step to treat a tumor that can be removed without causing neurological damage. Some tumors have a clearly defined shape and can be removed easily. Currently these surgeries often require patient movement while the patient is being operated on for better access of the target locations. Conventionally, clinicians manually adjust the patient according to their needs. This possesses a significant risk to the patient when patient is moved mid surgery. The linear actuator array will enable healthcare providers to manipulate patient positions in an MRI machine remotely and removes the need for technicians to move patients by hand.

The current approach is to have technicians move the patients themselves, and use different positioning aids to keep the patients in a desired position. The positioning aids themselves can consist of foam, inflated airbags, acrylics, and other materials, and every unique position requires a unique set of positioning aids.

Prior art

In the current landscape of linear actuation technology, there exists a diverse range of specific application driven options. One strategy is to use metal ribbons that join together to form cylinders and extend in a linear fashion. Several products cater to large-scale actuation applications. Notably, two prominent players in this market are Paco Spiralift and Tower Solutions. Although both companies offer products with extension ratios and high load-bearing, their designs primarily target industrial assembly lines, requiring a minimum footprint of 40 inches by 40 inches.

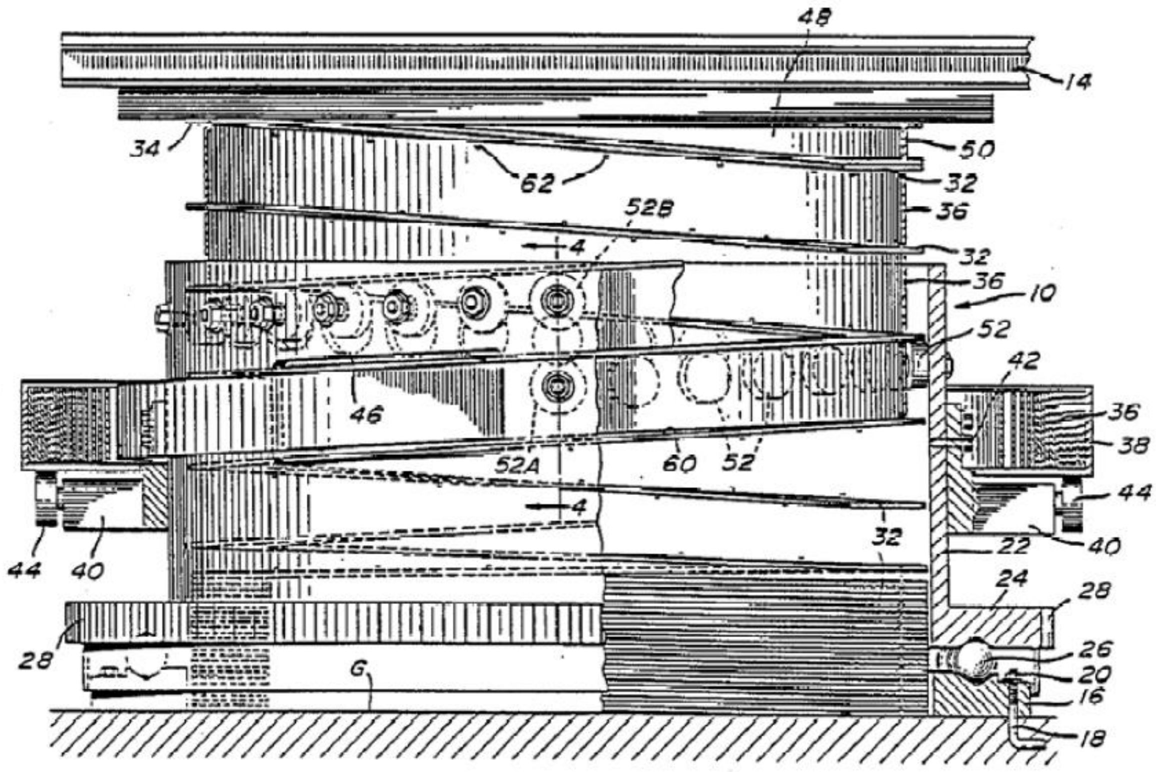


Fig A: Paco Spiralift in contracted position

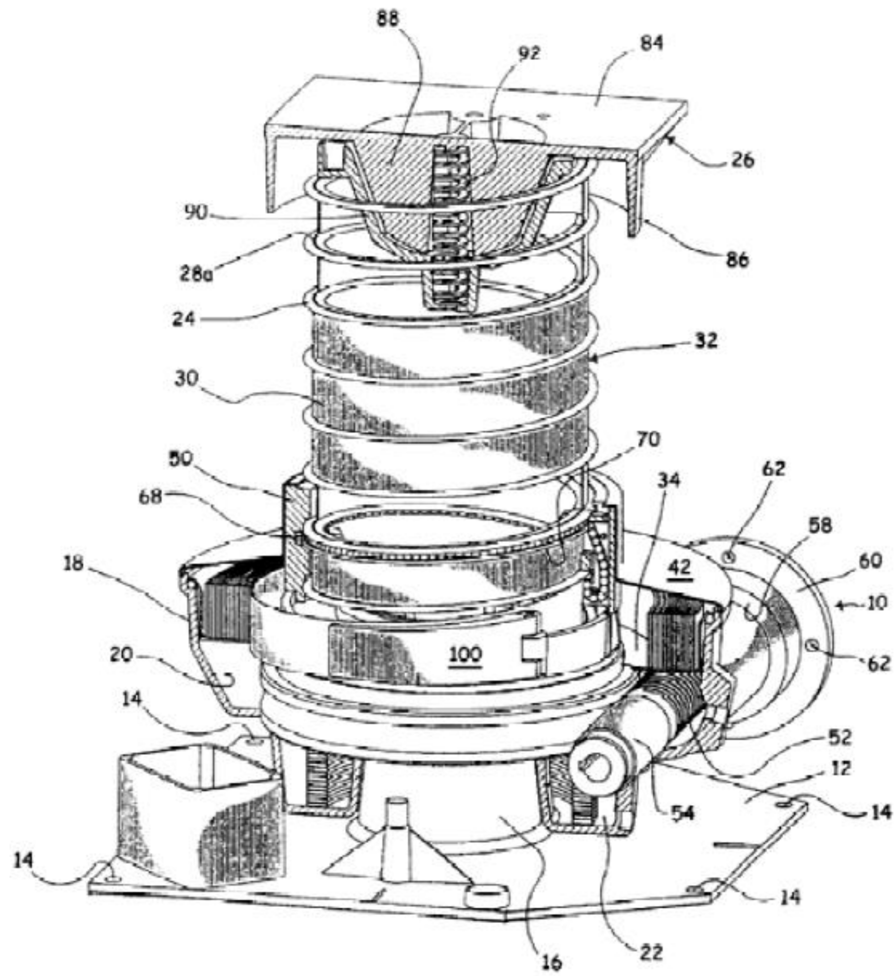


Fig B: Paco Spiralift in Extended position

The Paco Spiralift mechanism comprises two primary components facilitating linear actuation: a ribbon spiraling up in a helical shape to bear axial loads and an interlocking helical tabs ribbon that secures each section of the ribbon into slots. These components work in tandem to extend and provide an impressive extension ratio of 8:1.

In contrast, Tower Solutions employs another mechanism for linear actuation. It utilizes three interlocking ribbons extended simultaneously to form a triangular prism structure. A central motor located at the core of the structure governs its motion. Tower Solutions' lowest spec model offers height deployment options of 12 ft or 20 ft in less than one minute. These towers boast a high payload capacity ranging from 100 lb. to 150 lb. while weighing approximately 180 lb.

Although the existing products in the market boast impressive features, they are not a viable solution for linear actuation within smaller dimensions. Designed primarily for industrial applications, these products are bulky and expensive. Their complex mechanisms, comprising multiple ribbons, pose challenges for miniaturization and adaptation to settings where space is limited. Additionally, the presence of numerous components raises concerns regarding the overall power efficiency and load-bearing capabilities of each of these components.

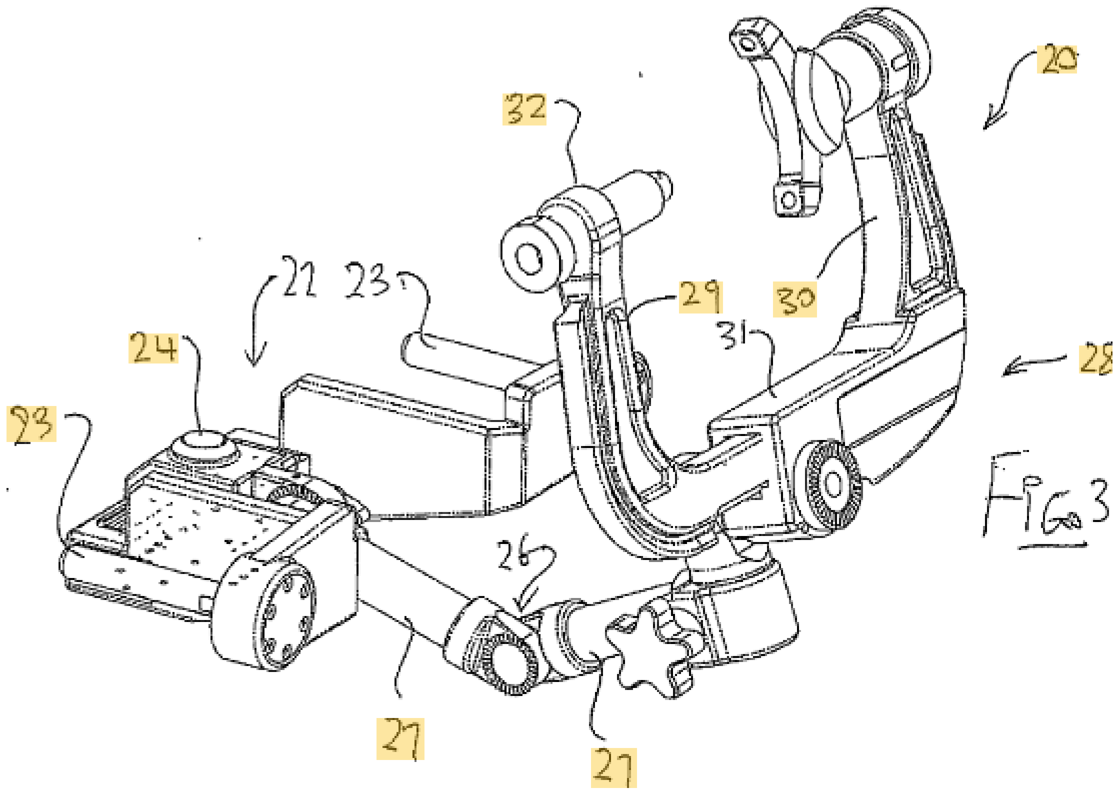


Fig C: IMRIS head fixation device

Stereotactic frames such as IMRIS Head Fixation device is being utilized to secure patient's head and enable optimal patient positioning for surgical access and intraoperative imaging. But the existing product has limited movement capability and restricts the movement just to the head as suppose to the whole body. The frame come in as an attachment to the MRI bed and is compatible with various MRI machines. Although effective, the existing product meets the unmet need partially.

Summary of the invention

The linear actuator in accordance with the present invention resolves many of the problems outlines above. Particularly, this invention allows the extension ratio of 8:1 with a small footprint of about one-tenth of the conventional linear actuators. The linear actuator utilizes a stainless-steel ribbon material which enables it to be utilized into MRI settings. Additionally, the linear actuator is self-supporting mechanism which allows the device to have such a small overall footprint while providing the adequate strength and rigidity.

In addition to the clinical setting, this linear actuator has many different applications such as in consumer products such as furniture, aerospace, automation solutions, robotics etc. Precise movement along with high extension ratio with a small form factor are core requirements of for these applications. The self-supporting helical linear actuator satisfies all these requirements and is able to provide a stable movement application with a high load capacity. This makes it ideal for not just isolated use but also for collective use with other actuators. Fundamentally, it transfers rotational motion to linear translational motion. This is achieved by the unique mechanism of self-interlocking sheet metal features.

The linear actuator comprises of single stainless-steel ribbon manufactured and bent to form the helical shape of the actuator. The invention has numerous features like tabs and corresponding slots that interlocks when the ribbon is rotated counter-clockwise to extend. The sheet metal is manufactured such that the number of tabs and number of slots matches up equally, additionally, the interlocking mechanism takes place as a tab slide from inside of a slot and protrudes through the slot to create a fit which causes two adjacent bands of the ribbon locked with each other. The interlocking produces a cylindrical rigid structure that can support load on its own. To unwind, the base of the linear actuator is rotated clockwise which disengages the tabs with the respective slots as the ribbon retracts and gets stored in the bottom storage casing. The advantage that the proposed solution offers is that rather than needing a variety of different positioning aids to achieve different positions, the system of linear actuators allows for any combination of positions that can be tailored to the patients and physician needs. The linear actuators also remove the need for technicians to lift and manipulate patients that may be mobility impaired, and reduce the risk of injuring or causing discomfort to patients. By reducing the time and personnel required to perform an MRI scan, the system can potentially increase the efficiency of MRI suites, decrease costs to patients and healthcare providers, and improve patient outcomes.

The design variables of the linear actuator include the ribbon thickness, ribbon width, helical diameter, helix angle, tab width, tab depth, tab pitch, slot pitch, slot width, slot length and sheet ribbon diameter. Optimization of these variables are critical to enable the interlocking feature of the linear actuator. The interlocking feature also allows the linear actuator to stop at an intermediate position without losing its structural integrity or back driving due to loads on the actuator.

Drawings and brief description

Fig 1 depicts the stainless-steel ribbon in its flat sheet form;

Fig 2 depicts the ribbon being bent into a helical structure to form a linear actuator support;

Fig 3 depicts the zoomed in vies of a tab engaged with a slot;

Fig 4 depicts a render of the MRI system integrated with the Linear actuators; and

Fig 5 shows the graph of the compressive load against the strain when one linear actuator was tested for its failure limits.

Figure 6 depicts the Sprocket Bottom-Driven Actuator Transmission Design with Tangent (Section F) and Centred (Section D) Cross Section Views of Actuator Cuff

Figure 7 shows the Telescoping Shaft Actuator Transmission Design with Cross Sections Tangent (Section C) and Centred (Section B) on the Pulley

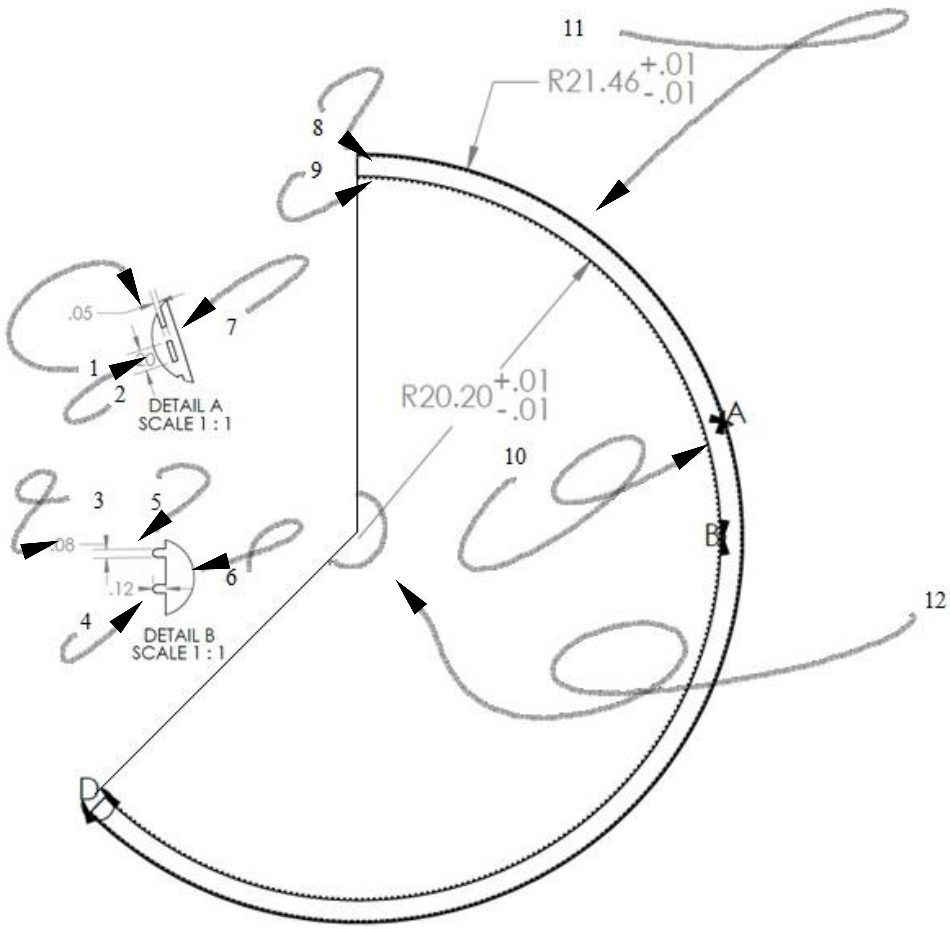


Fig 1: Flat sheet cut of ribbon

1- Width of the slot
2- Length of the slot
3- Width of the tabs
4- Thickness of the tab
5- Protrusion of the tab
6- Pitch of the tab

7- Pitch of the slot
8- Width of the ribbon
9- Thickness of the ribbon
10- Inner radii
11- Outer radii
12- Angle of ribbon band

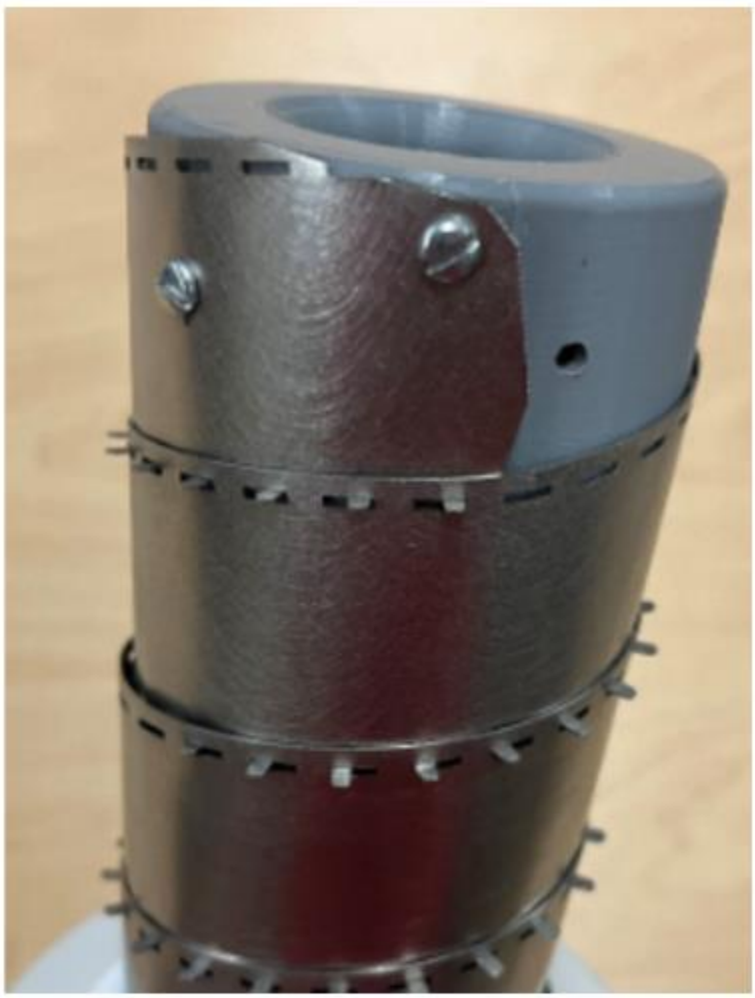


Fig 2: Developed linear actuator

1- Helix outer diameter
2- Ribbon Band
3- Support cylinder
4- Tab
5- Slot

6- Locking screw
7- Driver
8- Introducer thread
9- Driver extension slot
10- Housing unit

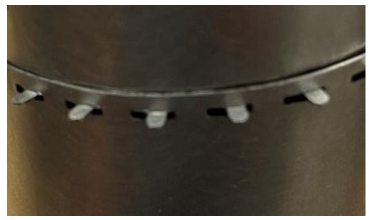


Fig 3: Close up view of the tab-slot engagement

1- Slot
2- Tab
3- Engagement between slot and tab

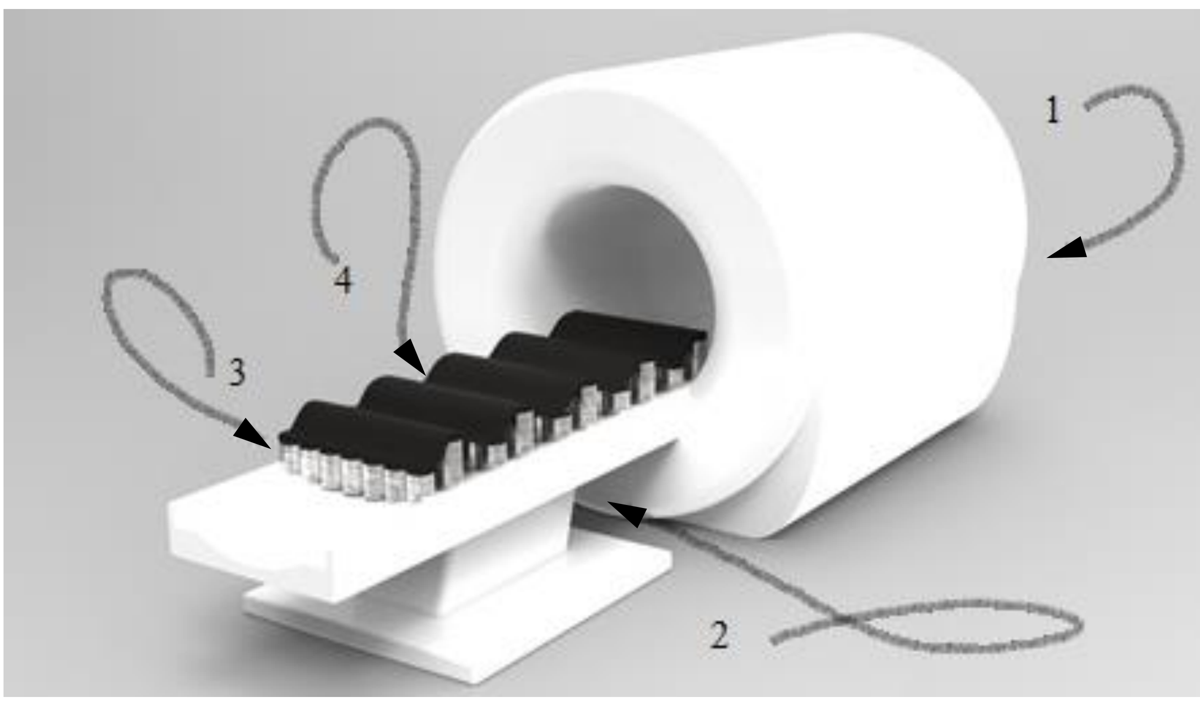


Fig 4: render image of the linear actuator integrated with iMRI system

1- MRI
2- MRI bed
3- Matrix of Linear actuators
4- Support fabric

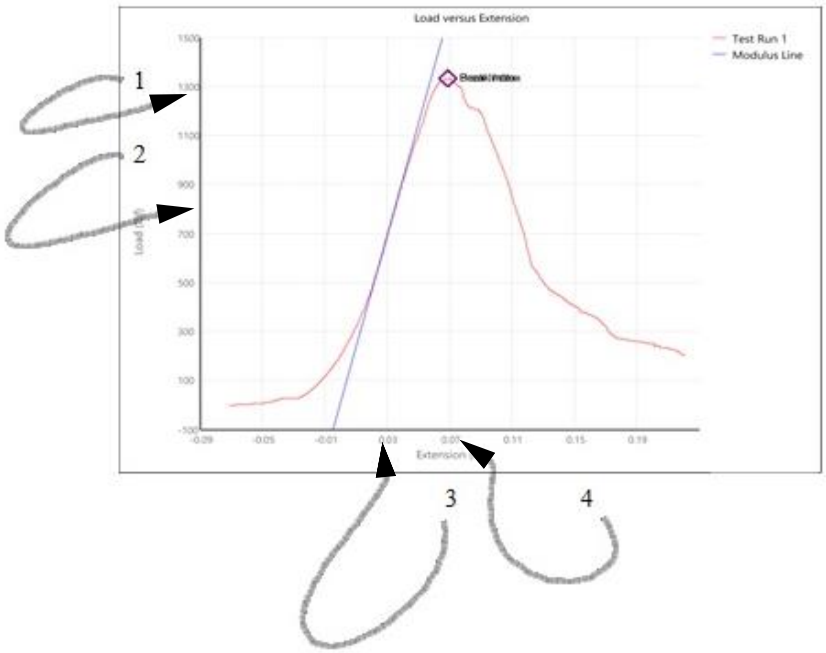


Fig 5: Load vs Extension Diagram under compressive test

1- Peak load
2- Load at yield
3- Extension at yield
4- Max extension

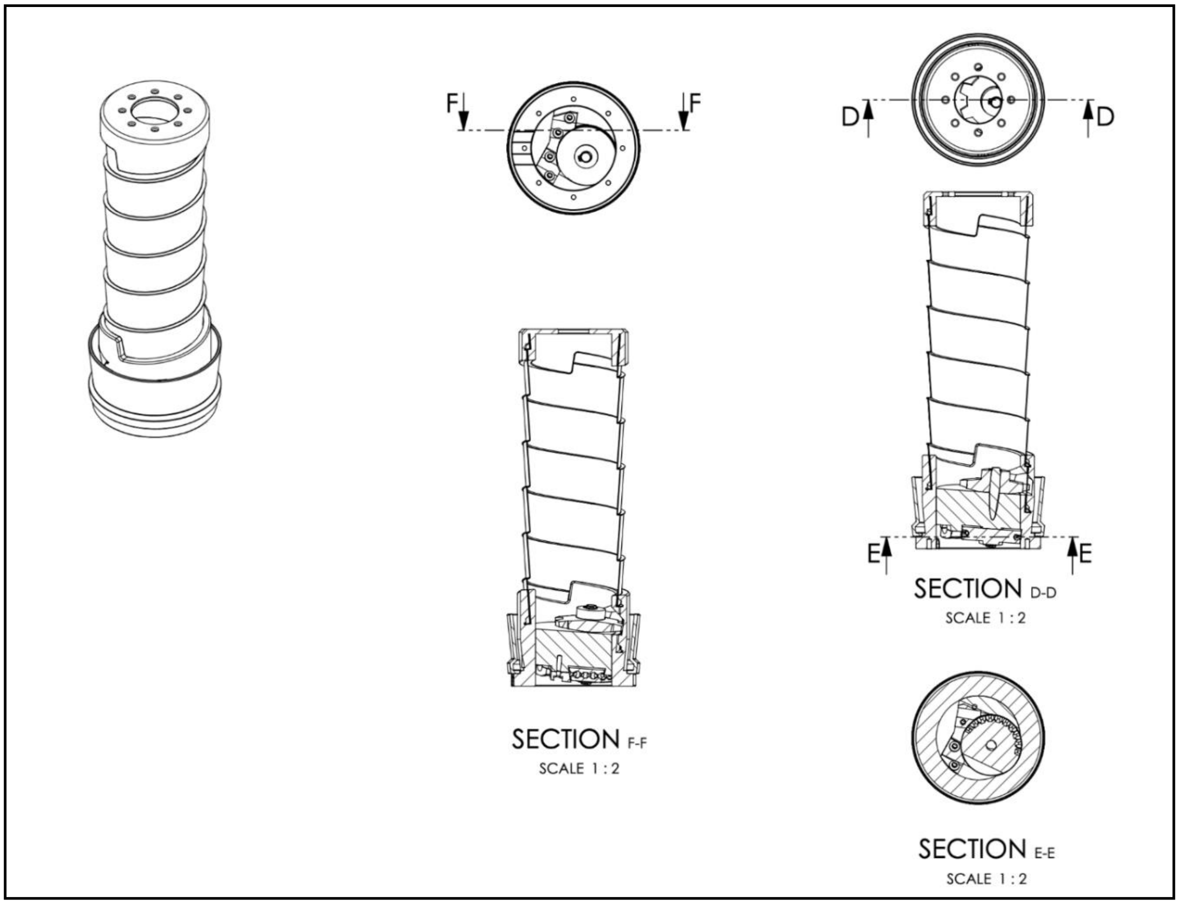


Figure 6: Sprocket Bottom-Driven Actuator Transmission Design with Tangent (Section F) and Centered (Section D) Cross Section Views of Actuator Cuff

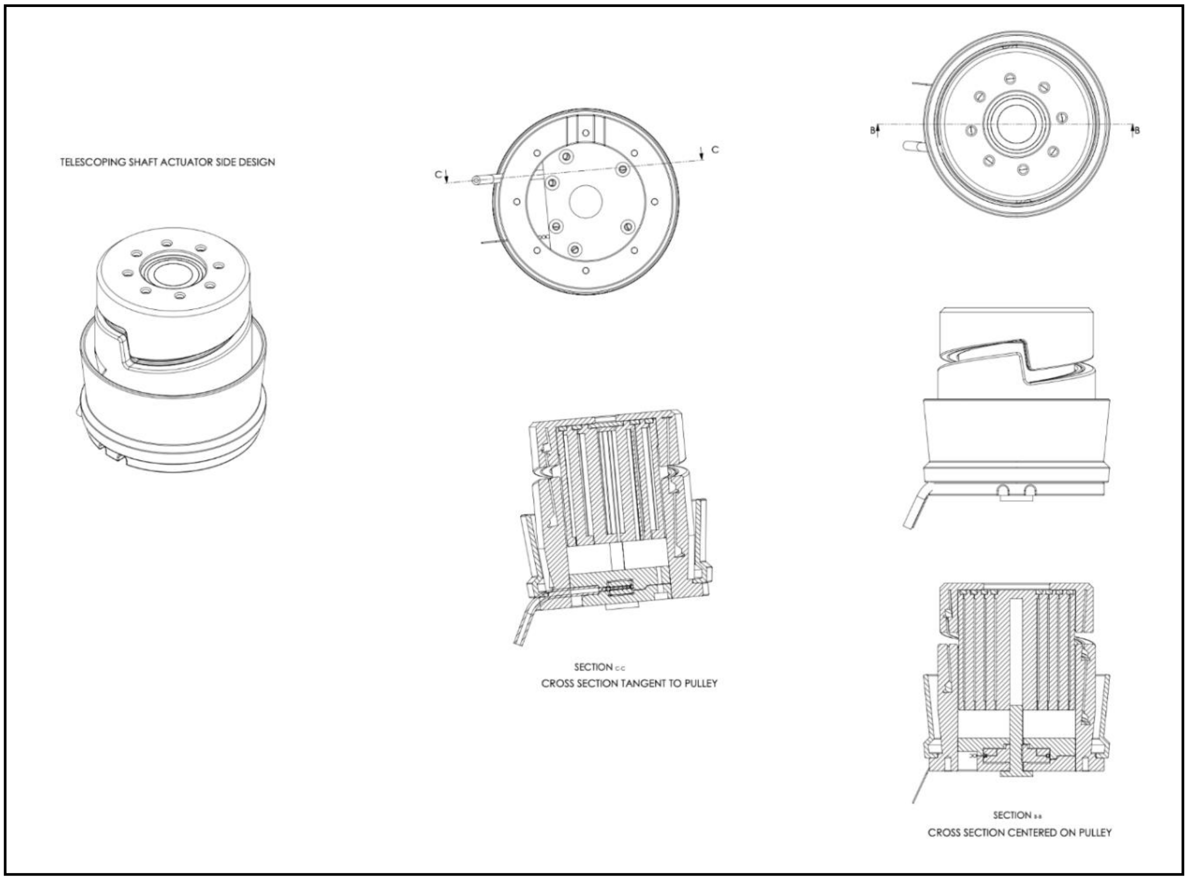


Figure 7: Telescoping Shaft Actuator Transmission Design with Cross Sections Tangent (Section C) and Centered (Section B) on the Pulley

Detailed description of the drawings

In many applications, there is a demand for a device capable of occupying minimal collapsible volume yet expanding to several times its initial length while effectively supporting a load. One exemplary solution achieves this in a simple and compact design, significantly smaller in size compared to other actuator designs.

This example actuator generates an extendable and retractable structure, facilitated by a guiding apparatus enabling its application in small-scale scenarios. Specifically, it utilizes a self-interlocking helically assembled band as its core mechanism. This assembly method allows the actuator to compactly retract while offering significant travel upon deployment.

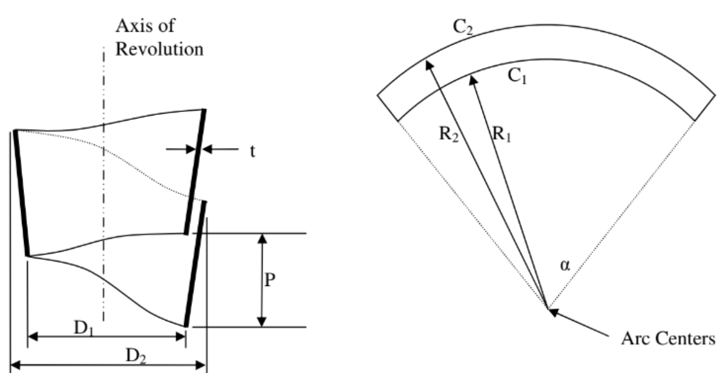
By adopting a collapsible column structure, the actuator can collapse to a mere few inches in thickness yet extend to several feet in length. Remarkably, despite its compact size, the device is engineered to withstand axial, bending, and torsion loads effectively. Furthermore, it offers precise and repeatable positioning control, enhancing its versatility and applicability across various industries.

The device described herein finds numerous applications across various industries. For instance, it proves well-suited for integration into surgical tables and medical equipment, offering precision and flexibility required in such settings. Similarly, its adaptability makes it a valuable asset in the aerospace industry, aiding in the deployment of structures and mechanisms within confined spaces. Moreover, the device's versatility extends to applications in cell phone towers and the construction of tower structures, facilitating efficient and reliable actuation in vertical installations.

This invention introduces a new generic mechanical actuator with virtually limitless potential applications. Where compactness, long travel, lightweight design, or high load capacity is desired, this device serves as a versatile solution. The incorporation of a collapsible column provides a distinct advantage over conventional guided cylinder actuators, which are typically limited to twice their initial length. Additionally, the device offers favorable ratios between maximum lift distance to minimum height and maximum lift distance to load capacity, further enhancing its utility and efficiency. Moreover, combinations of the disclosed examples can lead to the creation of novel applications and use cases.

One key component of the actuator is the main support structure of the interlocking helical band as shown by 1 in fig 3. The interlocking features are based on a repeating pattern between 3 and 4 in fig 3. Due to the overlapping nature of the band, it may be fabricated with the upper edge having a different radius of curvature relative to the lower edge. This structural design consideration ensures proper alignment and functionality of the actuator. Enabling the proper alignment is necessary for the functionality aspect of the linear actuator, when it is put under compressive loading conditions, the load should be sustained by each tab uniformly otherwise it will cause buckling of the structure along the weaker side. To maintain this overall stability, the pitch distance between each tab equals the pitch distance between each slot.

The optimum dimension of ribbon width 8 in fig 1, ribbon thickness 9 in fig 1, and helix diameter 1 in fig 3 was determined after a Design of Experiment of loading different parts of varying dimensions under a predetermined load in Finite Element Analysis software virtually, and the results were used to calculate the flat pattern dimension for metal cutting.



$$C_1 = 2\pi r = R_1\alpha \qquad C_2 = 2\pi R$$
$$= R_2\alpha \qquad (Equate\ circumfrence\ and\ arc\ length)$$
$$\frac{C_2}{R_2} = \alpha = \frac{C_1}{R_1} \qquad \frac{C_2}{C_1} = \frac{R_2}{R_1} \qquad (relate\ C_1\ to\ C_2\ using\ \alpha)$$
$$\frac{C_2}{C_1} = \frac{R_1 + S}{R_1} = 1 + \frac{S}{R_1} \qquad (Recognise\ R_2 = R_1 + S\ and\ simplify)$$
$$\frac{2\pi R}{2\pi r} = \frac{R}{r}$$
$$+\frac{S}{R_1} \qquad (Substitute\ the\ circumfrence\ from\ (1)\ and\ simplify)$$
$$R_1 = \frac{S}{\frac{R}{r} - 1} \qquad (Rearange\ for\ R_1)$$

The overall idea behind the invention rethinks the iMRI surgery procedure and integrates additional components into the infrastructure to enable the flexibility of movement without causing any patient risk during surgery. The MRI bed will incorporate a matrix of these linear actuators embedded into the MRI bed that will be controlled independently to move in cohesion for achieving the optimal position required during the surgery such as Supine, Prone etc.

The individual actuation employs pneumatic motors paired in conjunction with the controls unit that allows the clinician to maneuver the patient positions between different settings programmed into the system. Pneumatic actuation allows the system to be MRI compatible and also helps in reducing overall footprint of the system. Each unit can be controlled by individual solenoid valves to control the air pressure coming from the compressor and hence controlling the speed and movement of each actuator.

Additionally, the compressive testing reveals that a unit when extended is enough to handle a load of 700 lbs as yielding of the tabs occurs at 700 lbs and which is twice the 99th percentile weight of the patient that might be required in an iMRI surgery i.e., 300lbs. Thus, multiple actuators in conjunction should certainly be sturdy enough to be able to sustain typical patient's weight in the surgery firmly without any failure.

The actuator design was broken into three subsystems, a drive subsystem, an interface subsystem, and a control subsystem. The drive subsystem was how the actuator was supplied its power, the interface subsystem was how the power supplied by the drive subsystem was translated into vertical motion of the actuator, and the control subsystem was how the operator's intended position of the actuator was translated into the actual position of the actuator. After considering several different concepts for each category, two final designs were generated. Both designs have similar drive and control systems. The drive system consists of an electric motor with a gearbox driving a pulley with a tensioned line. The tensioned line then drives a pulley located in the base of the actuator. The interface mechanism differs between the two designs. The first is a telescoping shaft as shown in fig 6. The pulley in the base of the actuator rotates the shaft which can expand vertically while still transmitting torque. The shaft rotates the "cap" of the actuator which rotates the helical ribbon which self-assembles as it rotates, driving the actuator upwards. The second interface mechanism is a "bottom drive system" where rather than transmitting torque to the cap, a rotating gear driven by the pulley meshes directly with the helical ribbon, rotating the ribbon, driving the actuator upwards as shown in fig 7. Because both designs have a directly proportional relationship between the rotational position of the electric motor and the vertical position of the actuator, the control system simply has to change the position of the electric motor via electrical signals provided by the console.

Claims

1. An apparatus for providing linear actuation motion, comprising:

   a base;

   a mechanism configured to convert rotational motion into linear extension;

   a single ribbon arranged in a helical fashion, wherein the metallic ribbon is extendable vertically from the base;

   interlocking tabs and slots integrated into the ribbon to engage a self-locking mechanism;

   where the rotational motion is generated by the driver unit consisting of the driver which is attached to the support cylinder.
2. The apparatus of claim 1, wherein the metallic ribbon collapses to the width of the ribbon and extends vertically up to 8 times the width of the ribbon.
3. The apparatus as claimed in claim 1 offers an extension ratio of 8:1.
4. The ribbon claimed in claim 1 has protruding tabs which extends perpendicular to the plane of the ribbon and corresponding slots across the opposite width of the ribbon.
5. The apparatus of claim 4 where the tabs and slots are configured to interlock with each other while extending in a helical motion and hence forming a cylindrical support structure
6. The apparatus of claim 1 further comprising a driving mechanism including the ribbon band that is actuated via a rolling motion at the base of the mechanism of the driver and housing unit which houses the overall assembly in retracted form.
7. The apparatus claimed in claim 5 wherein the one or more first engagement features are configured to disengage with the one or more second engagement features.
8. The apparatus claimed in claim 4 allows the extension to be actuated from clockwise motion when looking towards the base of the mechanism.
9. The apparatus claimed in claim 4 retracts in the same motion but with an inverse direction of rotation.
10. The apparatus of claim 1 has a maximum footprint is 3 inch × 3 inch.
11. The apparatus claimed in claim 1 consists of a single extending component which supports the overall load of the system.
12. The apparatus claimed in claim 1 causes the volume of the overall actuator system to be reduced to 9 in^3.

Abstract

Intraoperative Magnetic Resonance Imaging (iMRI) surgeries are high-risk procedures performed within an MRI suite, commonly for conditions such as brain tumors and epilepsy. During these operations, clinicians often need to adjust the patient's position to improve access to the surgical site. Currently, this repositioning is done manually with the aid of cushions, which can introduce significant risks to patient safety and increase the likelihood of complications. Moreover, manual adjustments extend the overall procedure duration, increasing the surgeon's time in the operating room and potentially affecting surgical outcomes. Addressing these challenges is critical to enhancing both patient safety and surgical efficiency.

To address this issue, clinicians and surgeons were consulted during the Voice of Customer (VOC) stage, leading to the identification of key requirements based on their feedback. These insights were translated into a clear need statement, guiding the ideation process. After exploring various concepts through brainstorming sessions, the team selected a solution involving an array of linear actuators embedded within the MRI bed. These actuators can be externally programmed to adjust to common patient positions required during iMRI procedures, reducing manual intervention, enhancing patient safety, and improving surgical efficiency.

A novel single-band helical ribbon linear actuator was developed for this application. The actuator features tabs and slots that engage upon deployment into a helical structure, forming a stable cylindrical column. The actuator's dimensions were optimized through a Design of Experiments (DOE) to assess critical factors influencing the column's overall stress. Finite Element Analysis (FEA) simulations in Ansys were conducted to identify the dimensions yielding the highest stress tolerance, guiding the final design specifications.

A custom drive system was engineered to house and deploy the ribbon. Compressive testing on a prototype confirmed a yielding stress of 700 lbs, surpassing the failure threshold, validating the design's robustness. The actuator achieves an 8:1 extension ratio within a compact 3" x 3" footprint, ideal for localized actuation on MRI beds. Constructed from non-magnetic materials, the actuator is compatible with MRI environments, offering a market-leading extension ratio while maintaining a minimal spatial footprint.

Appendix B - VOC questions

- Q1: What are the most common positions that a patient is operated on during the surgery? It would be really helpful to know the most prominent of those.
- Q2: In continuation with the first point, does the operation require the patient to shift from one position to another? If yes, is there a common order in which this is performed, and what are the existing ways to do the same?
- Q3: Does the size of the surgical table vary from hospital to hospital (manufacturing company to company)? This would really help in designing the final one size fits all type of product.
- Q4: What are the current methods used to reposition patients during these surgeries?
- Q5: Are there any additional observations that you suggest which might need attention in these procedures?

Appendix C - Alternative Concepts & Concept Selection

Concept Generation

Using brainstorming and ideation methods, various alternative designs were created to solve this engineering problem. During the ideation process, the scope of the project was broadened to avoid narrowing in on one fixed concept. Because of the complexity of the system, the ideation process was also broken down into various subsystems. These subsystems were the control architecture, the power system, and the interface mechanism. To be through in the brainstorming phase, a small amount of time was also spent ideating on the overall actuator design. However, this design was already finalized by the client. It is still included in this section for completeness.

Actuator Design

This subsystem includes the actuator mechanism used to achieve the 7:1 extension ratio and footprint as described in the design requirements section.

Concept 1: A single ribbon linear actuator system. This system is already designed by the project client. It is a single stainless steel ribbon with slots along the top edge and tabs along the bottom edge bent outward at a 90° angle. The ribbon wraps around a 60 [mm] diameter cylinder in a helix interlocking with itself.

Control Architecture

This subsystem encompasses the method used to control the actuator array movement.

Concept 1: A Programmable Logic Controller (PLC) and a surface mesh for height definition. The surface mesh will be input by a user using an appropriate UI and modified to fit the specific needs of the user. The PLC will then pull values from that mesh and control each actuator to move to the prescribed height. The PLC would also handle all feedback and closed loop control necessary.

Power System

This subsystem encompasses the method used to power the linear actuator used in the design. During brainstorming, many types of power systems were considered. It was further broken down into power systems that would be located in the bore of the MR scanner and systems that would be outside the bore with a transmission mechanism leading into the actuator.

Concept 1: (Inside the bore) Pneumatic rotary motor with high gear ratio. This would utilize a relatively high speed pneumatic motor and a gear reduction system to provide a torque to the actuator.

Concept 2: (Inside the bore) Non-ferrous motor. A non-ferrous motor would be placed with the actuator in the MR scanner to provide a torque to drive the actuator.

Concept 3: (Outside the bore) Servo/electrical rotary actuators. Electrical rotary actuators would be placed in a corresponding array with some sort of torque transmission to transmit the power into the bore of the MR scanner.

Interface Mechanism

This subsystem describes how the power from the power system is used to articulate the linear actuator.

Concept 1: Telescoping shaft. A telescoping shaft would be used to transmit torque from a rotational power source at the base of the actuator to the top where the torque would be applied to unwind the ribbon and articulate the shaft.

Concept 2: Push shaft. A flexible shaft would be used leading from outside the MR scanner bore to the top of each actuator. The shaft would provide an upward force to the actuator to articulate it.

Concept 3: Inflatable insert. Similar to the push shaft concept, an inflatable cylinder would be placed in the center of the actuator. It could be blown up to provide an upwards force to the actuator to articulate it.

Concept 4: Mecanum wheel transmission. A collar that applied a torque but allowed freedom of movement in the vertical direction would be placed at the base of the ribbon cylinder to apply a torque. The mecanum wheels (or similar) would allow that torque transmission while allowing a vertical degree of freedom.

Concept 5: Counter-rotating ribbon. A second ribbon would be placed inside of the actuator ribbon but pitched in the opposite direction. The actuator could be articulated by applying a torque to the base of either ribbon and fixing the rotation of the other ribbon. This may also serve to reinforce the actuator.

Concept 6: Ratcheting stay with cable. A ratcheting mechanism with a ratchet wheel and reversible pawl will be placed within the actuator. The ratchet will be driven by one of the power systems interfaced with a cable so that the power system will remain outside the MRI field. The ratchet will drive a friction ring that will move the stainless steel ribbon via friction. The ratcheting mechanism will act as a mechanical brake and provide discretized movement. The mechanical brake is important as it takes the load off of the motor and provides stability to the system. Discretized movement allows for easier tracking of the position of the linear actuator.

Concept Selection

To quantitatively determine the ideal concept, a design matrix was developed. Values for weights and ratings were on a scale of 1 to 5 for better granularity. Nominally, a competing product or common solution is used as the baseline design to which all ideas are compared to. For this design, there is no existing product that fits within an MRI bore. As a result, the baseline was simply rated as 3 for all criteria. A rating of 3 is the midline rating. The total value for a concept was simply obtained by the following summation:

$$\sum_{i=1}^{n} W * R$$

Where W is the weight and R is the rating. The maximum value, 290, was obtained by multiplying the weight of the ratings and by a rating, R, of 5, which is the maximum value. The percentage rating of a concept is simply the total rating divided by maximum value, 290.

The design matrix is comprised of the following overarching categories and the criteria are nested within each category:

- **Budget:** Cost analysis
    - **Capital cost**: The overall cost of the concept. The greater the cost, the lower the score.
    - **Setup time**: How long will it take the concept to return to the default position and be ready for a new patient? The greater the time, the lower the score.
    - **Position shift time**: How long will the concept take to shift to some position, X? The greater the time, the lower the score.
    - **Consumables cost**: What are the costs for parts, materials, etc. to maintain the device (i.e. oil for hydraulic based systems, replaceable wear components, etc.)? The greater the cost, the lower the score.
- **Sourcing and fabrication**: How will parts be obtained and how will parts/assemblies be manufactured?

  - **Supply chain dependance**: Describes how difficult the parts are to obtain. The harder the parts are to source, the greater the supply chain dependence and the lower the score.
  - **Supply chain frequency**: How often must the parts be delivered? Does the concept require a daily shipment of parts? If so, then it will be rated poorly.
  - **Manufacturability**: How easy is it to manufacture the concept on a large scale. The harder the concept is to manufacture, the lower the score.
- **Robustness:** How strong the design/part/assembly is with respect to failure or the stability of the devices
  - **Scan effect:** How much will the concept affect the MRI scan? The greater the effect, the lower the score.
  - **Strength:** How much load can the concept hold before failing? The greater the load, the greater the score.
  - **Position stability**: How long can the concept hold a given height at some extension? The longer the period of time, without drift, the greater the score.
  - **Repeatability:** If the concept was given X input, how often will the concept return to exactly some output, Y? If the concept delivers Y input reliably for some input X, then the concept will be rated highly.
- **Operator considerations:** How will the user use the device and how safe will the user be?
  - **Process accessibility**: How much education or training does the operator require to run the concept? If the education/training requirements are high, then the concept will be rated poorly.
  - **Susceptibility to human error**: How easy is it to make a mistake? If the concept is error prone, then it will be rated poorly.
  - **Safety:** How safe is the concept? Does it have multiple pinch points and hazards? Will the concept hurt the patient? If so, then the concept is not safe and will be rated poorly.
- **Facility:** What are the facility requirements
  - **Power requirements**: How much power does it take for the concept to function? If the power requirement is high, then the concept will be rated poorly.
  - **Bore size**: How much space within the bore does the concept take? If it requires a significant amount of space, then the concept will be rated poorly.
  - **Console space requirements:** Does the concept require a significant amount of space at the MRI control console? If yes, then it will be rated poorly. MRI console control space is limited and excess use should be avoided.
- **Other:** Criteria that are important but do not fit in the aforementioned categories
  - **Resolution:** How finely can the concept move the linear actuator? Does the concept move the actuator in 1mm increments or 10mm increments? The finer the resolution, the greater the rating.
  - **Extension ratio**: Does the concept result in a greater extension ratio? If yes, then it will be rated well.
  - **Scalability for a single unit**: How well does the concept translate to an array? Is it difficult for the concept to become an array? If so, it will be rated poorly.
- **Misc:** Miscellaneous criteria that were added after testing the design matrix with a test case
  - **Feasibility:** Is this concept realistic to create? If so, it will be rated highly. This criteria was added AFTER the fact. This came from a test case in which a nonfunctional idea was rated.

The validity of the design matrix was tested with a nonfunctional idea. That being a power system controlled by trained bees. This concept rated 44.14% of the 100% total. This is less than 65.17%, which is the baseline rating, indicating that the design matrix is a potentially useful tool for quantitatively assessing competing concepts. The design matrix was also reiterated upon given this test concept, in which the “feasibility” criteria was added. In this situation, a power system controlled by trained bees was not feasible. (Rated 1/5) Legitimate, competing designs were assessed using this new iteration of the matrix in a future meeting. All concepts that achieved a rating less than the apiary actuator were deemed not reasonable to pursue.

It was found that the leading candidates for the interface subsystem were the Telescoping Shaft, Mecanum Wheel, and Counter Rotating Ribbons. For the power subsystem, the leading candidates were the Two-Cable Pulley Stepper System (TULiPS), the Ratcheting Stay with Cable, and the Rotary Spring and Cable. Ultimately, the team decided to move forward with the Telescoping Shaft, Mecanum Wheel and Counter Rotating Ribbon designs candidates for the interface subsystem. For the power subsystem, the team moved forward with the TULiPS design using a chain indexed by stainless steel balls.

Category	Budget				Sourcing and Fabrication			Robustness				Operator Considerations			Facility			Other			Misc	Total	Percent
Criteria	Capital cost	Setup time	Position shift time	Consumables Cost	Supply chain dependence (standardization)	Supply chain dependence (frequency)	Manufacturability	Scan effect	Strength	Position stability	Repeatability	Process Accessibility	Suceptibility to Human Error	Safety	Power requirements	Bore Size	Console space requirements	Resolution	Extension Ratio	Scalability for a single unit	Feasibility		
Weight	2	1	2	2	1	2	3	5	5	4	4	3	2	5	2	4	3	3	3	2	5	290	100
Interface																							
1. Baseline	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	189	65.17
2. Air Bag	4	2	2	3	2	3	2	5	3	2	2	3	2	4	3	5	2	1	5	3	2	189	65.17
3. Telescoping Shaft	4	5	5	4	4	2	5	3	5	5	5	5	2	2	3	1	2	5	5	5	3	234	80.69
4. Mechanum Wheel (Drive from the Botton	3	5	5	4	3	4	3	2	4	5	5	5	3	4	3	4	4	5	5	4	3	247	85.17
5. Push Shaft	2	5	5	4	2	3	2	2	2	2	2	4	3	2	4	3	2	3	2	2	1	155	53.45
6. Air Screw	3	3	3	4	3	4	2	3	3	3	2	3	2	2	2	4	2	2	4	3	2	173	59.66
7. Ants	4	1	1	4	1	2	3	5	4	1	1	1	1	1	5	3	1	1	1	1	1	134	46.21
8. Counter Rotating Ribbons	4	5	5	4	2	4	4	3	4	4	4	5	4	4	5	3	5	4	3	5	4	251	86.55
Power																							
1. Baseline	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	189	65.17
2. Rotary Spring and Cable	4	4	3	4	2	4	4	3	3	3	3	4	4	4	3	3	3	3	2	5	3	209	72.07
3. Air Bag	4	2	2	3	2	3	2	5	3	2	2	3	2	4	3	5	2	1	5	3	2	189	65.17
4. Two-Cable Pulley Stepper (TULiPS)	3	4	3	4	3	5	4	4	3	2	4	5	5	4	4	4	3	4	3	4	4	235	81.03
5. Rotary Pneumatics	2	3	4	4	4	3	4	1	2	4	5	4	4	4	1	1	1	4	1	1	2	172	59.31
6. Non-Ferrous Motor Direct Drive	2	4	1	3	2	3	4	3	1	3	3	4	4	5	3	2	4	2	2	4	2	181	62.41
7. Apiary Actuator (Bees)	3	1	3	1	1	1	1	5	2	1	1	1	1	1	2	2	3	4	4	2	1	128	44.14
8. Ratcheting Stay with Cable	3	2	2	2	4	4	4	4	3	4	4	3	3	3	4	3	3	3	3	3	4	210	72.41
																						0	0.00

Figure B.1 - Design Matrix