JERBOA INSPIRED ROBOTIC TAIL: CONTROLLING TAIL MOTION WITH VARYING TENDON ATTACHMENTS

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ME 490

Animal tails serve various functions ranging from locomotion to communication with other animals. One function of tails that has yet to be investigated is its impact on mobility and correlation with inertial maneuvering. Additionally, the impact of tendon attachment and tendon branching patterns within the tail on observed tail motions has not been clearly identified. This study focuses on exploring the complexity of different tendon branching styles and attachment points within animal tails, particularly Jerboas, and how these branching patterns affect control in 3D motion. To better understand the impact of tail anatomy on tail motion, a modular mechanical tail "test bed" is developed and different tendon branching patterns are tested. The proposed "test bed" will begin by assuming a constant bone and ligament size to better understand the effect of tendons on tail motion. The motions created by this physical model are then compared to the motions of an OpenSim model that simulates various tendon branching patterns. This comparison of observed mechanical tail behavior will be used to determine the validity of the simulation and ability to utilize branching in physical robots. Validation of the mechanical model and simulation will provide a better understanding of the impact of tendons on tail behavior. Characterizing the effect of different types of tendon branching patterns and attachment points can provide key insights for the development of underactuated mechanisms with large degrees of freedom.

Keywords: Biologically-inspired, Robotics, Jerboa, Tails, Tendons, OpenSim, Underactuated, Inertial Maneuvering

1.0 INTRODUCTION

Given that nature has demonstrated success in creating efficient and adaptable systems for a variety of different terrains, scientists and engineers can use these biological principles for inspiration in the realm of robotics and mechanical design [1]. For this research, the anatomy of a Jerboa tail is observed and used to develop a representative tendon-driven mechanical tail. It has been observed that during locomotion, the Jerboa tail has varying degrees of freedom and control which is hypothesized to assist with locomotion and balance. The tail employs a variety of different tendon connection points and branching patterns to achieve varying shapes and curvatures. This complex tendon branching comes together to a muscle at the base of the Jerboa's vertebra. For mechanical systems, this muscle can be treated as a single actuator. The use of different tendon configurations with a single actuator (muscle) creates a highly underactuated mechanism that has not previously been investigated. While tendon-driven robotics is not a new field, prior research has primarily focused on simpler tendon layouts such as single cable mechanisms [2][3] as opposed to leveraging the use of unique tendon branching to achieve tail motion and tail stiffening for use in robotic mechanisms.

1.1 IMPACT OF TENDON ANATOMY ON TAIL MOTION

The Jerboa tail has approximately 28 caudal vertebrae with varying tendon configurations over the span of its tail. As shown in Fig. 1 it has been observed that several of the caudal vertebrae have channel-like

features on the dorsal (upper) and ventral (lower) regions that guide the layout of tendons along the length of the tail.

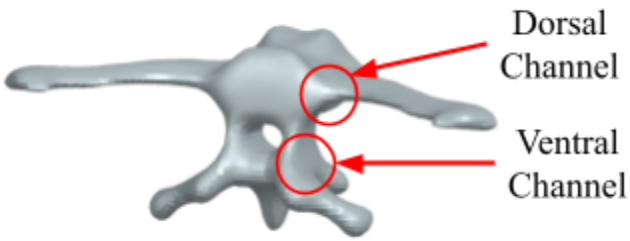


Figure 1. 3D-Scan of Caudal Vertebra-1. It is observed that there are channel-like features on both sides of a given vertebrae on the dorsal (upper) and ventral (lower) regions. Channels have been observed to serve as "guides" for tendons running along the length of the tail.

As shown in Fig. 2, the layout of these tendons and their respective attachment points is very complex. Several tendons such as DL6, DL7, and VL4 are "unbranched" and have been observed to be single tendons attached to different vertebrae. Other tendons such as DL3, DL8, and VL4 have been observed to be "branched" tendons attached to different vertebrae. Developing a model to study the impact of these "branched" and "unbranched" configurations on the dynamics of tail motion has not previously been investigated and is the focus of this study.

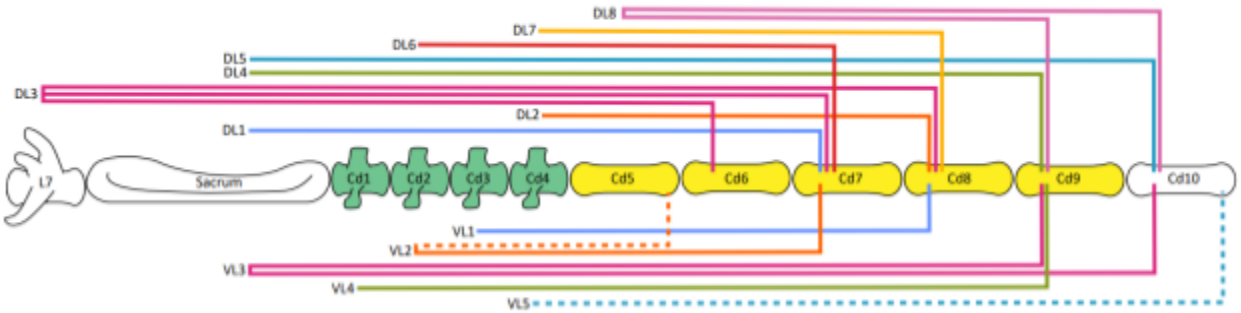


Figure 2. Zoomed-in View of Jerboa Tail Anatomy. Blocked segments represent the bones along the tail where "Cd-" represents the "caudal" vertebrae. Colored lines represent tendons where "DL-" represents tendons along the dorsal region of the vertebrae and "VL-" represents tendons along the ventral region of the vertebrae.

All tendons come together to a single muscle at the base of a Jerboa's tail (to the left of the diagram in Fig. 2, not pictured) which drives the motion of the tail. The impact of using different tendon branching configurations for creating stiffening along different regions of the tail has not been previously investigated either.

1.2 DEVELOPMENT OF TENDON DRIVEN ROBOT

Using different tendon branching patterns, it is hypothesized that a highly underactuated tail mechanism can be developed for use in assisting robotic motion or balance. As shown in Fig. 3, two "unbranched" tendons would require the use of two separate actuators to create motion. It is hypothesized that using "branched" tendons, a similar range of motion can be achieved with the use of a single actuator.

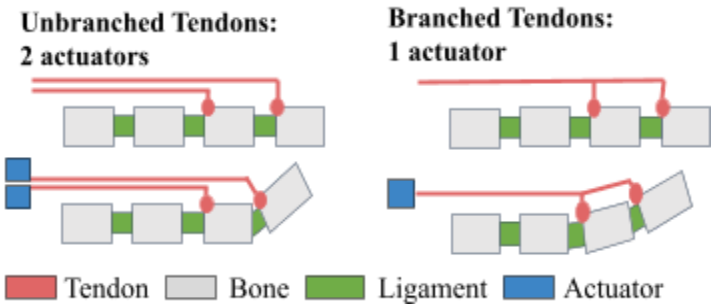


Figure 3. Representative Diagram using Branched and Unbranched Tendons with an Actuator. Two "unbranched tendons require two actuators to create motion whereas one "branched" tendon requires a single actuator to create motion.

While there are trade-offs between using a fully actuated or underactuated mechanism for each degree of freedom, using fewer actuators allows for designs that are less bulky, less costly, and use less complex control algorithms [4].

2.0 MODULAR TAIL DESIGN

A highly modular mechanical tail "test bed" is developed to test the impact of different tendon branching patterns on the dynamic behavior of tails. The tail test bed will be used to validate findings from a musculoskeletal simulation software, OpenSim, in future research. A variety of different requirements for the tail needed to be met such that the design would be close to the anatomy observed for animal tails and could test the impact of bone anatomy and tendon configurations on tail motion.

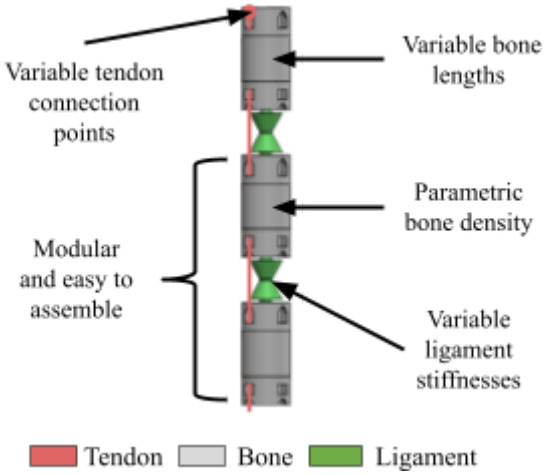


Figure 4. Requirements for Modular Tail Test Bed. Several components needed to be modular such as bone densities, lengths, and ligament stiffnesses.

The design of the modular tail followed a two-part design approach. First, the design of the bone needed to incorporate a variety of different features such as tendon attachment points, varying bone lengths, and varying bone densities as observed in Fig. 2. Second, a ligament feature needed to be developed to create compliance in the tail with the ability to vary ligament stiffness easily. These features needed to have the ability to be interchangeable and easy to assemble as well. The stiffnesses and lengths tested could then be used as input parameters for a dynamic simulation of the tail to validate the accuracy of the observed tail behavior using OpenSim.

2.1 DEVELOPING BONE MODEL

An iterative approach was taken to develop a modular bone design for testing. Initially, scanned models of the bone were 3D-printed using FDM printing techniques with PLA filament. While anatomically correct, these scanned models were difficult to make adjustments towards in CAD software and had significantly long print times. Additionally, the purpose of this study is to investigate the impact of tendons on tail motion and introducing bones with complex geometries would make it difficult to isolate what aspects of the tail contribute to different types of motion. A much more simplified design was used where the bone was approximated to a cylindrical shape.

For the first iteration, loops were used such that tendons (represented by an elastic-like string material) could be attached to the bone. Additionally, the ligaments in this design also used a similar elastic-like string for adding compliance to a series of bones. This design had a variety of shortcomings, mainly coming from the fact that using strings as "ligaments" is far too compliant and a more stiff intermediate material would need to be used. Additionally, having a loop at the top of the design was not anatomically close to the channel-like features that were observed in Fig. 1. For the second iteration, multiple adjustments were made and dorsal-ventral channels were added to guide an elastic string representing the "tendon" through. A small hole feature was added to the design such that a compliant 3D-printed material could be glued in place to act as the ligament. While this design performed much better, it was observed that using a rectangular slot for the tendon connection points to tie off an elastic string "tendon" was not entirely consistent. Additionally, gluing the ligament to the bone severely limited the variability of the model. With the third iteration, notches were incorporated with the tendon attachment points to ensure consistent tie-off points for the elastic string being used to represent the tendon. A key slot feature was used such that a ligament with a key feature could be "keyed in" and easily interchanged. It was observed that with testing this design, the C-shaped channel features would interfere with adjacent bones at a 90° bend. These protrusions were also not anatomically analogous to the channel-like features observed in Fig. 1 that appeared to be "built into" the bone as well.

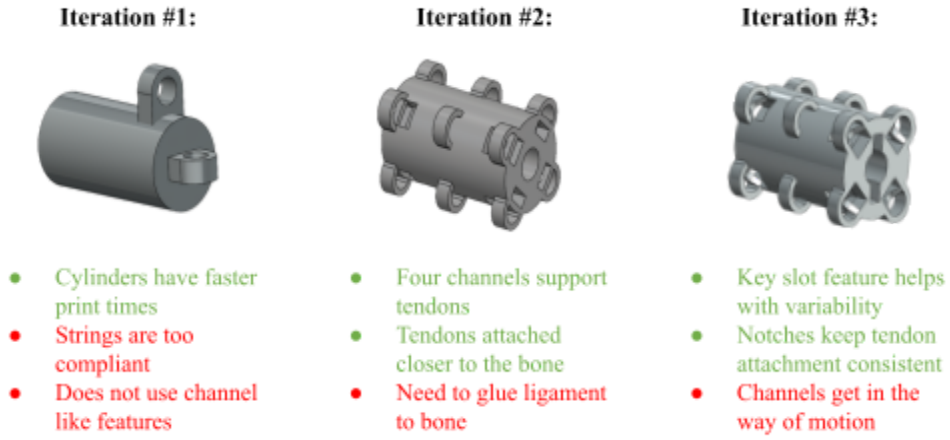


Figure 5. Bone Iterations. Notable features between each iteration include simplifying the geometry of the bone to a cylinder, using tendon "guide-channels", implementing a key slot feature to allow for ligament variability.

For the final design, several of the improvements made in the iterations were carried through to develop a modular, "snap-in" like design as shown in Fig. 6.

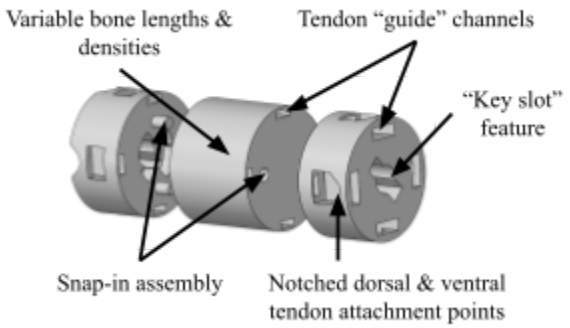


Figure 6. Final Design for Modular Bone. Through an iterative approach, several improvements were made to ease in testing and make the design anatomically close to actual animal vertebrae.

The final design allows for significant variability in bone lengths and bone densities that can be adjusted in 3D-Printing slicing software. The C-shaped channels used in previous iterations were removed such that a string representing the tendon could be routed much more closer to the bone as was observed in Fig 1.

2.2. DEVELOPING LIGAMENT MODEL

For the ligaments, a similar iterative approach for developing the bone design was used. Initially, as shown in the first iteration in Fig. 1, a string was used between two adjacent bones to create compliance in the tail model. However, using strings for the ligament created far too much compliance and made it difficult to test different material stiffnesses. Instead, 3D-Printing techniques were used using FDM and SLA methods that would allow for creating unique ligament designs with compliant materials.

For the first two iterations FDM Printing techniques were used using TPU filament. In the first iteration, a cylinder was used to serve as the ligament and a concentric infill with varying infill densities was tested. This design yielded inconsistent bending which was remedied in the second iteration where a concavity was introduced to control the bending such that the ligament would consistently bend in the middle when placed between two adjacent bones. However, with both iterations the interchangeability requirement was not fulfilled as the ligament would need to be glued into the bone. Additionally, due to the geometry of the design, the ligaments were printed in separate pieces and attached together using super glue and a heat gun to fuse the parts together. Despite maintaining a consistent assembly approach, it was found through experimentally determining the stiffness that the ligaments had very inconsistent stiffnesses as outlined in 3.1. This was undesirable as the purpose of the study is to ensure that the ligaments and bones are consistent to isolate their impact on the dynamics of the tail. To prevent this, SLA printing methods using Elastic 50A resin were used to increase the fidelity of the prints and produce more consistent models. For the third iteration, the second iteration was printed with a key feature using a 10% infill density. However, it was observed that varying the infill density for SLA prints would result in "blowouts" [5] which caused multiple failed prints. For the fourth iteration a 100% infill print was tested with a small thicker region in the middle. Through testing, this iteration was found to produce inconsistent bending similar to the TPU prints and a concavity needed to be used similar to the second iteration to control the bending.

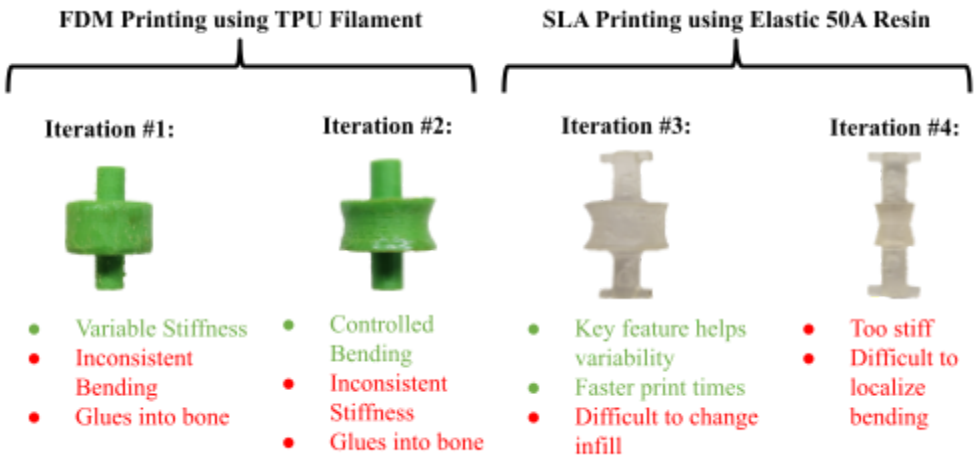


Figure 7. Ligament Iterations. Notable features between each iteration include changing printing techniques from FDM to SLA, changing the geometry to an hourglass to control bending, and implementing a key feature to allow for variability in testing.

Similar to the bone model, several of the improvements made in each iteration were incorporated into the final ligament design that allowed for controlled bending using an hourglass geometry and variability in stiffnesses with different materials.

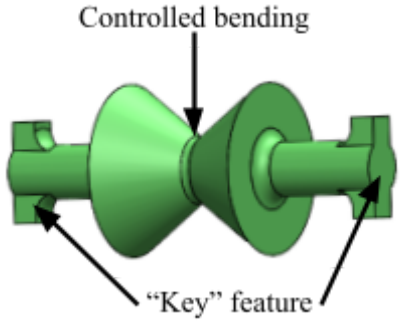


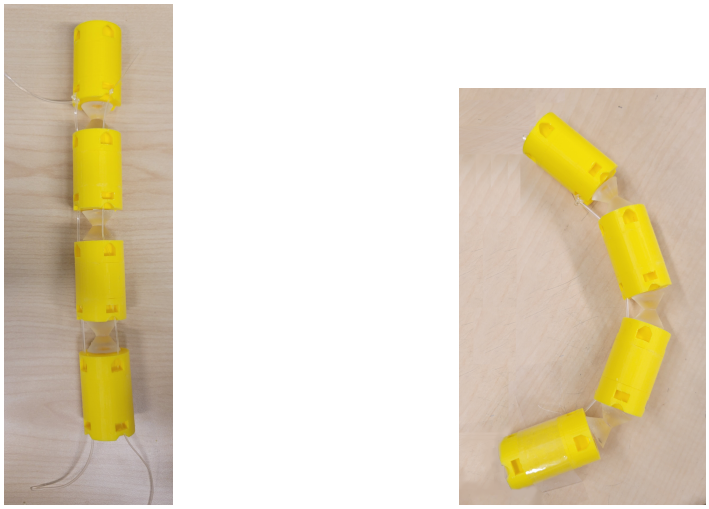
Figure 8. Final Design for Modular Ligament. Through an iterative approach, several improvements were made to ease in testing and make the design anatomically close to actual animal vertebrae.

The final design allows for controlled bending and ensures that the ligament consistently bends in the middle between two adjacent bones. The key feature allows for ease in interchangeability and testing different stiffness ligament configurations as well.

3.0 MODULAR TAIL TESTING

To test the impact of different tendon branching patterns, the proposed test bed can be used with high degrees of modularity. For the bone design, the middle portion of the bone design can be adjusted to test the impact of varying bone lengths. Additionally, the ligament stiffnesses can be varied by adjusting the geometry (increasing or decreasing the angle of the hourglass, changing the grade of resin used, etc.). For preliminary testing, different tendon materials were tested such as nylon strings and elastic cords. Once attached, the tendons were pulled and the motion of the tail was observed. The material properties of an

actual tendon have yet to be determined such that a more appropriate tendon material can be used for testing.



(a) **(b)**

Figure 9. Modular Tail design with (a) "Unbranched" Tendon Attached to Bone and (b) Force Applied to "Unbranched" Tendon. Constant bone lengths and ligament stiffnesses were tested using an elastic string to represent the tendon.

3.1 IMPACT OF LIGAMENT STIFFNESSES

Through iterating the ligament design, it was observed that the TPU based ligaments would result in inconsistent tail motion when doing a simple "tendon pull test". Intuitively, a more stiff region would be less inclined to bend and a less stiff region would be more inclined to bend. A 3-point bending test was performed to experimentally determine the stiffness of the ligaments to determine the variability of the ligament stiffnesses. A ligament with two adjacent bones was simply supported by a distance L where calibrated weights were used to apply a load P on the ligament and the displacement □ was recorded. To simplify the calculations, the ligament was assumed to have a cylindrical geometry with radius R.

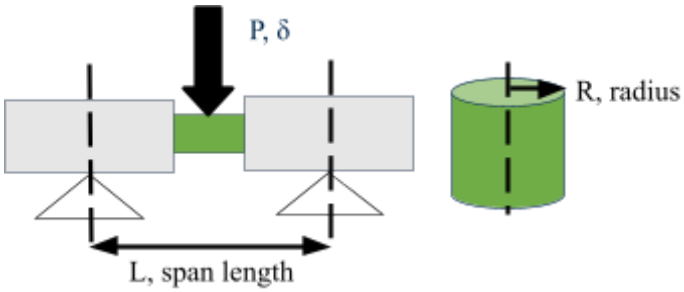


Figure 10. 3-Point Bending Test Diagram. Different ligaments were tested by suspending them in between two adjacent bones that were simply supported. The ligaments were assumed to have a cylindrical geometry.

Using the recorded displacements observed for the different weights, a stress-strain curve was plotted to determine the modulus of elasticity of the materials. Equation 1 was used to determine the flexural stress and Eq. 2 was used to determine the flexural strain.

$$\sigma_{Flexural\ Stress} = \frac{PL}{\pi R^3} \quad (1)$$

$$\epsilon_{Flexural\ Strain} = \frac{12R\delta}{L^2} \quad (2)$$

The modulus of elasticity was found by taking a linear fit in the elastic region of the data for the TPU and Elastic 50A ligaments that were developed.

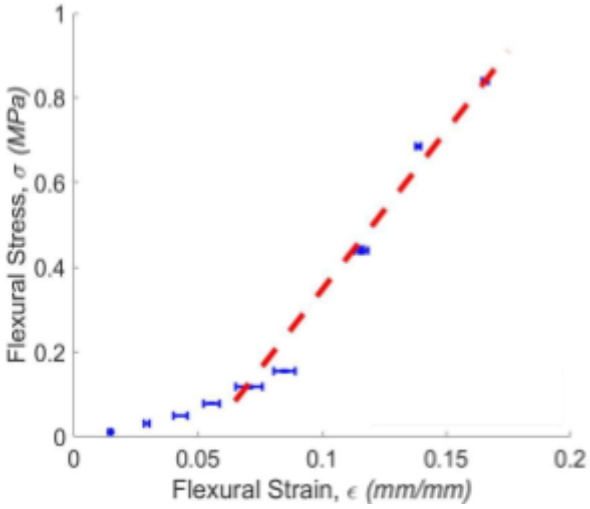


Figure 11. Stress-Strain Curve for SLA Printed Ligament. The modulus of elasticity was found to be 5.66 ± 0.03 MPa.

The second ligament iteration in Fig. 7 printed with TPU filament and the final ligament design in Fig. 8 printed with Elastic 50A resin were tested and their modulus was found to be 0.25 ± 0.10 MPa and 5.66 ± 0.03 MPa, respectively. Through testing it was observed that the FDM method using TPU filament yielded stiffness with significant uncertainty whereas the SLA method using Elastic 50A resin yielded much more consistent results. Large variations in the uncertainty with the TPU method could be due to the assembly technique used of printing the part in different pieces and gluing them together.

4.0 CONCLUSION

A highly modular tail test bed has been developed that can be used to test the impact of different tendon branching patterns on the dynamic motion of an animal tail. The proposed design satisfies several requirements that allows for modularity and ease of assembly. The impact of ligament stiffness was also studied as it was observed that different printing methods yielded parts that would greatly affect the motion of the tail test bed.

The following tail design can be used to validate against the OpenSim software with different parameters such as bone lengths, bone densities, ligament stiffness, and tendon attachment points. Given that ligament stiffness had a significant impact on the dynamics of the tail, further research needs to be conducted to determine if tail anatomy incorporates variable ligament stiffness along the length of the tail.

5.0 ACKNOWLEDGEMENTS

I would like to thank Maggie Zhang and Professor Talia Moore for their guidance and support on all aspects of this research as well as Juri Miyamae for providing guidance on Jerboa anatomy and Xun Fu for providing background on OpenSim tail simulations.

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