Designing the spinal column of a quadruped robot by using additive manufacturing: A comprehensive approach

Ilo Bodi [1,*], Erald Piperi[2], Pascal Doumalin[3], Mariel Hoxha[4]
Polytechnic University of Tirana, Albania[1, 2, 4]
Institut Pprime, UPR CNRS 3346, Université de Poitiers [3]
ibodi@fim.edu.al

Abstract: *In this study, we aim to realize a methodology for designing the spinal column of a quadruped robot employing additive manufacturing techniques. Additive manufacturing processes have gained widespread usage owing to their ability to swiftly develop prototypes for research and actualize production-grade components. Our research commenced with the acquisition of vertebral dimensions sourced from real animals such as cheetahs. These dimensions were pivotal inputs for conducting kinematic analyses of the animal's locomotion cycle.*

Through meticulous kinematic analysis, it was delineated the various positions assumed by the spinal column throughout the locomotion cycle. Furthermore, we assessed the maximal force to which the spinal column could be subjected. This evaluation formed a robust foundation for exploring diverse modeling approaches to identify the optimal solutions. An innovative solution emerged through the utilization of a beam featuring a variable cross-section. This approach facilitated precise customization of the design to align with our specific requirements. To manufacture all requisite components for the spinal column, we employed a single 3D printer utilizing the Fused Deposition Modelling (FDM) technique with PLA material. To validate the computational methods, it was developed a sophisticated test bench. By juxtaposing theoretical predictions against tangible experimental data, it was affirmed the accuracy of the theoretical approach. This validation serves as a springboard for subsequent phases in the design and production processes of quadruped robots.

Keywords*: QUADRUPED ROBOT, FUSED DEPOSITION MODELLING, PLA MATERIAL*

1. Introduction

Quadruped robots are designed to emulate the locomotion of animals in the natural world. The focus of this work lies in dissecting and modeling the spine of such robots, with the initial prototype being integrated into a cheetah-inspired robot. The primary impetus behind designing a cheetah-inspired robot lies in its unparalleled speed. Achieving high-speed locomotion in robots poses a formidable challenge, yet it holds immense potential across varied applications. From exploration and surveillance to deployment in hazardous environments such as disaster zones, the versatility of quadruped robots knows few bounds. Moreover, their utility extends to domains like military, agriculture, and education. The quest for swift robotic locomotion necessitates drawing inspiration from nature, where the cheetah reigns supreme as the fastest land animal. The spinal column's significance in orchestrating the movement of quadruped robots cannot be overstated [1]. The results showed that a passive spine where dorsal stiffness is higher than ventral stiffness can run faster than a rigid case, because of the compliance of the spine, which might play a role as a nonlinear spring to enhance locomotion by transferring and storing energy. Serving as a structural scaffold, it enables fluid and coordinated motion akin to walking, running, and turning. Designing an efficacious spine demands a multidisciplinary approach, integrating principles of mechanics, electronics, control systems, and bioinspiration [2]. The forelimb musculature comprised 15.1 ± 1.2% of its total body mass, substantially less than its hindlimb at 19.8 ± 2.2% of total body mass. Kawasaki et al [3]., revealed that the bounding gait of the robots with a flexible spine is more stable and more natural than that of the robots with a rigid spine, and the robot can run faster by synchronizing the movements of their spine and legs. Matsumoto et al. showed clearly how their prototype will move its spine, i.e., when the feline is running, the main mobilities are at the animal's sacrum [4].

Ultimately, the construction of a robot mirroring the biomechanics of real animals promises invaluable insights into the complexities of emulating organic movement through mechanical means [5]. Our objective in this work is to decipher the intricacies of spine movement and apply them to quadruped robotics. Commencing with a scaled-down prototype produced with the 3D printing technique, was designed the experiment to validate the study methodology, a pivotal step necessitating the establishment of a dedicated test bench.

2. Experiment

The goal of this study was to create a panther spine. To meet the different requirements of design and production specifications, such as the accuracy of a panther spine movement, and to consider the size and weight of the system different aspects were examined. All the work done led us to design the spine of a continuous robot thanks to compatible joints. However, to dimension all the parts of the spine, it is necessary to know its rigidity, displacements, forces, and size. Unfortunately, the information in the literature on these factors is very low, so we have to find our own.

1. Geometry analysis

A fully 3D-scanned panther skeleton in STEP format was used to analyze, design, and produce it with 3D printing techniques. In this file format, we were able to see the different sizes of the vertebrae and precisely how the skeleton is made up as shown in Figure 1.

Fig. 1 *Fully 3D scanned panther skeleton.*

Thanks to the skeleton, we were able to determine the articular stops of the spine, i.e. the stops resulting from the position of the vertebrae with each other and their shape, which means that their movement can be limited. This information may be important to us because we have relatively little data on the mobility of the spine and the stops ensure that we limit our movement to something feasible for the animal. To find out the joint stops of the spine, as you can see in the following figure, we draw lines from the middle of the joint (presumed center of rotation) to the part of the vertebra most likely to come into contact with the second vertebra. In this way, we can find the joint's limit of rotation at the joint stops as shown in Figure 2.

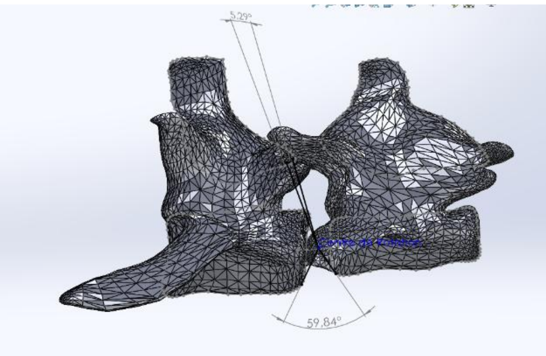


***Fig. 2** Joint stop determination*

All the vertebrae dimensions are shown in the Table 1.

***Table 1.** Vertebrates length and height.*

Vertebrates	Length (mm)	Height (mm)
T1	54.6	27.2
T2	53.6	25
T3	55.8	29.6
T4	53.8	38.8
T5	50.4	36.2
T6	48.4	36.2
T7	50.2	39.2
T8	59.2	36.2
T9	62	42.6
L1	63.6	38.4
L2	62	43.4
L3	65.2	/
L4	80	35.2
L5	86	41
L6	77	43
L7	82.16	30.3
L8	96.83	32.9
L9	108.4	37.8

2. Kinematic analysis

To dimension the spine accurately, it's essential to gather data regarding its position and the load it bears. This process involves analyzing and processing videos to extract the necessary information. To gather data on the forces exerted on the back and to ascertain the spine's stiffness, we are analyzing a cheetah's running motion. To precisely monitor the positions of the bones throughout the cheetah's run, we utilized a specialized software known as Deeplabcut [5].

DeepLabCut™ is an efficient method for 2D and 3D markerless pose estimation based on transfer learning with deep neural networks that achieves excellent results with minimal training data. We can track various body parts in multiple species. The package is open-source, fast, and robust. It can be used to compute 3D poses. The results of the cheetah running position are shown in Figure 3.

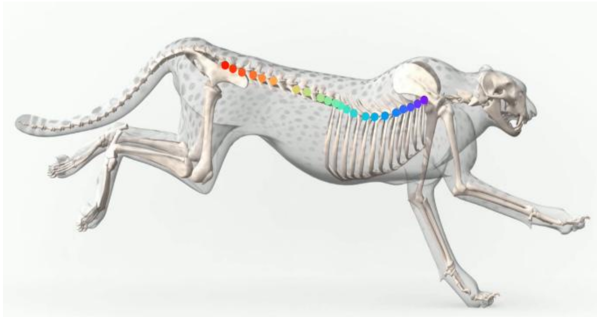


***Fig. 3** Modelisation of a running cheetah video.*

In our case, we placed, throughout the entire cycle, markers on each vertebra. Then, the software interpolates this point to trace the trajectory for each marker as shown in Figure 4.

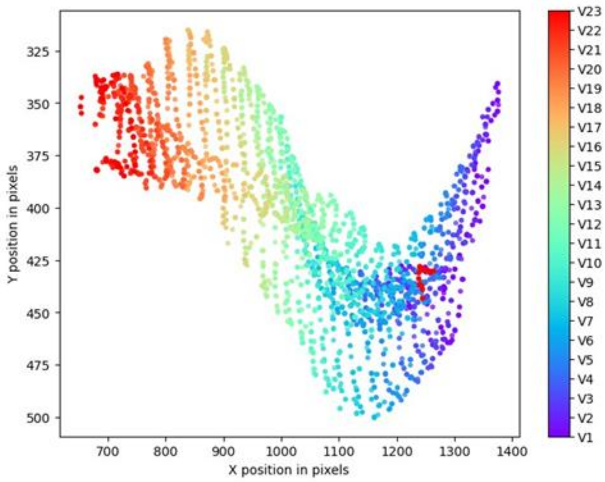


***Fig. 4** Position of each vertebrae in pixels.*

On this graph, it's evident that each vertebra doesn't move in the same way. For instance, the thoracic vertebrae display less mobility compared to the lumbar ones. Additionally, certain vertebrae show similar amplitudes of movement. Therefore, in our prototype design, we won't model all 22 individual vertebrates separately. Instead, some vertebrae will be combined. For instance, the 11th and 12th vertebrae are closely positioned and exhibit similar movement patterns. This approach was adopted in the spine's modeling process.

3. Materials and methods

The design process began by making a succession of parts corresponding to each vertebra. In the interests of efficiency, we were able to discover and use a SolidWorks software function that consists of using an Excel file to change our rib configurations to be able to make faster studies. We started by creating our column and, as presented in our calculations, by using identical vertebrae lengths as shown in Figure 5. Although this is not realistic, once again, this will simplify our system and enable us to obtain a result.

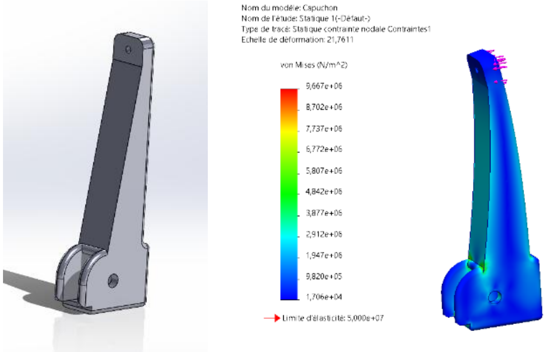


Fig. 5 *Fin of the end of the column and deformation test.*

For parts production, we utilized a 3D printer to fabricate each component of the spine using PLA material as shown in Figure 6. Following this, we meticulously cleaned and labeled each part to facilitate assembly, ensuring efficiency and accuracy in the process.

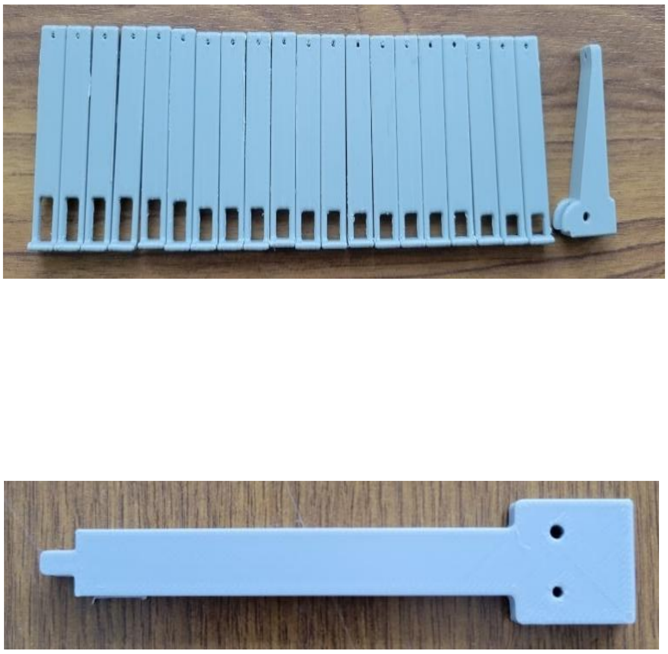


Fig. 6 *3D printed vertebra parts.*

The decision to utilize 3D printing was driven by its rapid and economical nature, given that intricate precision was not paramount for the prototype. We selected PLA material because it was easy to use and with very good characteristics in prototyping. While this method may alter material characteristics, such as anisotropy, the way impressions are done determines the direction of rigidity. For our purposes, this was inconsequential as our focus remained on prototyping. We also fulfill 100 % of each part to limit the porosity. Moreover, the final spine will be in aluminum, so the fabrication process will be way more accurate.

4. Results

A test bench is an essential component in the design and verification process of real parts. It serves as a simulated environment in which designers can test the functionality, performance, and correctness of their designs before implementing them. The main purpose of using a test bench is to catch and correct errors early in the design process, saving time and resources. The test bench must be resistant to the weight of the spine and vibrations due to movement. The spine must be placed fixed in the device because if we have movement of the spine, we get wrong test results. The weight of the spine and the forces that will act during the test were taken into consideration during the choice of the model. The test bench should be adjustable, the spine should be easily assembled, the dimensions should not be in large proportion to the dimensions of the spine, and it should be suitable for use. Monitoring and recording the results in a simple way of each test case. Identifying and documenting any problems or deviations from expected behavior as shown in Figure 7.

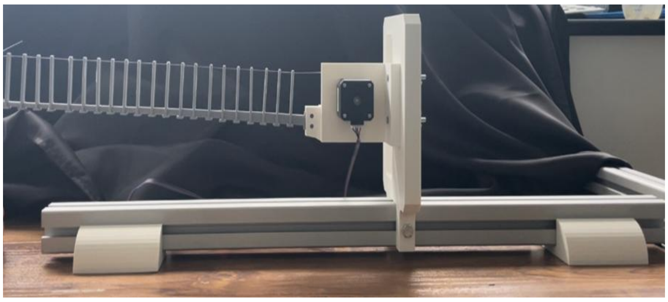


Fig. 7 *The assembly of the test bench and the spine.*

The components of the test bench are:

- NEMA 17 STEPPER MOTOR: Enables the movements required for testing
- Profile 45x45: Enables the assembly of the testbench board
- Support for Profile: It ensures stability and avoids vibration.
- Support for Motor: It enables the assembly of the motor and the spine during the test.
- Plate of bench: It is resistant to all forces and vibrations during the test.
- Pulley: Perform the necessary rotation motion during the test.

The aim of the tests we're about to carry out is, firstly, to check the reliability of the calculations we've made to dimension our column and, secondly, to verify whether it is indeed possible to activate the deformation of our column using a motor. After acquiring the beam and the bench, our next step was to assess whether the prototype would exhibit the same characteristics as the theoretical spine. To achieve this, we conducted two tests. The first test involved examining the flexion of the beam under a single-weight load (10N). Subsequently, we proceeded to test the response of the spine to various loads. To validate our calculations, we need to apply exactly the force we want to the cable to check that the displacement at the end of the column is correct. We can then compare the experimental value with the theoretical one. To do this, we had several choices. The first was to use the motor and a load cell, which we would place on the cap and retrieve the force value when the desired displacement was reached. The second was to know the load applied to the cable beforehand. Given that it would have been difficult to install a load cell on our system as we might have wished, but also to limit expenditure as much as possible and save the time we had available, we decided to use the second solution. The testing procedure is shown in Figure 8

Step	Instruction	Comment / Picture
1	Prepare the Spine: Ensure the spine is firmly built in on the bench to prevent any movement during the experiment.	

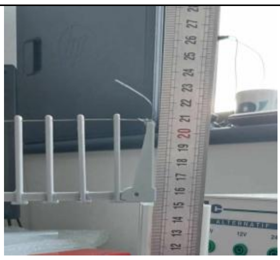
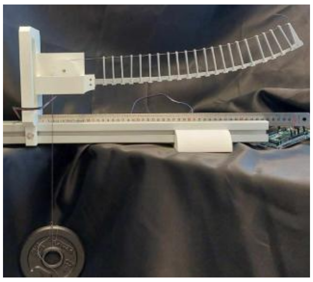
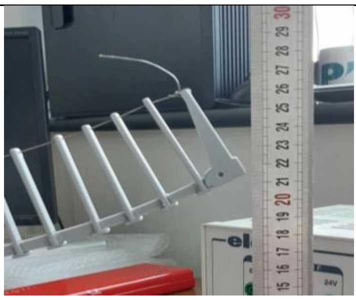
2	Wire Attachment: Affix the wire to the spine.	 *Wire attachment*
3	Calibration: Place a ruler on the same plane as the spine and wire to capture images for calibration purposes.	
4	Initial Photo: Take an initial picture of the setup before any external force is applied.	 *Initial picture with ruler*
5	Applying Weight: Place the specified weight on the wire.	 *Spine with hanging weight*
6	Final Photo: Capture a final image after releasing the weight.	 *Final picture with ruler* Using the ruler at the rear of the column, we can now calculate the displacement between the phases in which forces are applied and those in which they are not.
7	Deformation Measurement: Measure the deformation of the spine from the initial to the final photo.	

Fig. 8 *Step of weight experiment.*

We needed to program the motor to replicate the movement of the spine precisely as it occurs in the panther. To achieve this, we utilized the position of the sacrum throughout its cycle and converted it into a binary signal. This signal transitions in increments of 5 steps. Given that we determined that 6 cm corresponds to 45 steps, we could calculate the number of steps required for each centimeter of deformation. With this information, we proceeded to write the corresponding code for the schematic as shown in Figure 9.

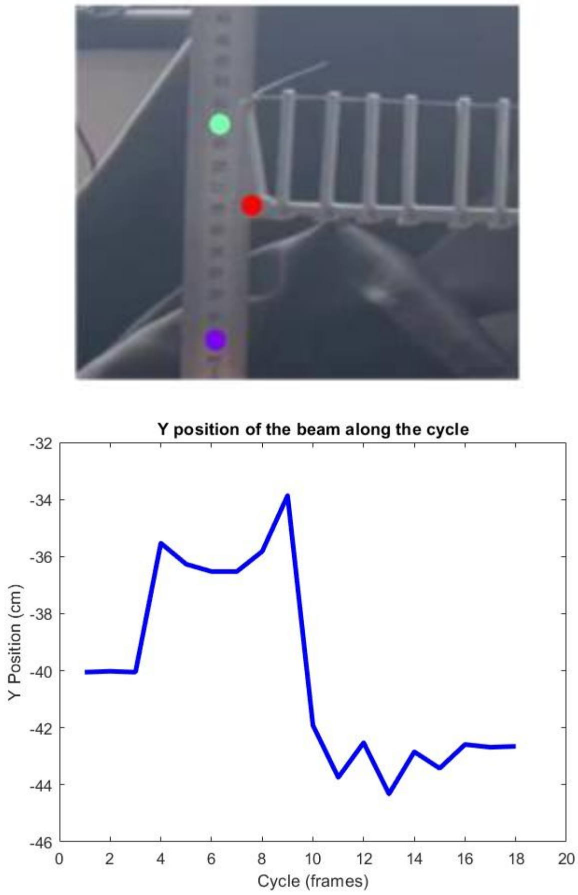


Fig. 9 *Step of weight experiment.*

As we can observe, we can find the same trace as the real position. However, the motor jumped during the test. During the test, we saw that after the movement, the sacrum position vibrates a lot. To conclude, we found another way to program the motor to suppress jumps.

5. Conclusions

To calculate and dimension the prototype of the spine, we opted for a variable-section beam activated by a cable, mimicking the mechanism of a continuous robot. This approach guided the design of our prototype and test bench. The primary objective of our system was to validate our calculation methodology. Consequently, we conducted two tests for this purpose. The first test aimed to confirm the accuracy of our intended force application by exerting a pure force on the cable. This validation ensured the fidelity of our calculations. Subsequently, the second test aimed to demonstrate the feasibility of activating our system using a motor. By successfully executing these tests, we were able to affirm the validity of our results.

The primary objective of this study was to decipher the intricate movements of a cheetah's spine to replicate them for application in a quadruped robot. Initially, our focus was on comprehending the dynamics of a cheetah's running motion, which provided essential data regarding spine behavior. Our study primarily delved into the 2D aspects of this behavior, allowing us to validate our hypotheses. However, to develop a more sophisticated spine system, a deeper exploration into the 3D movement is imperative. This necessitates delving into additional articles and studies that shed light on the intricacies of the cheetah movement.

In our spine dimensioning process, we relied on a CAD file as a reference point. However, to further validate this data, acquiring real-world measurements from an actual cheetah would be invaluable. Performing an autopsy on a cheetah would provide precise anatomical data crucial for our study.

Given our focus on 2D analysis, we opted for a beam structure. However, if our study progresses, incorporating compliant joints into the spine design becomes imperative for a more comprehensive understanding.

Regarding the iterative method used to determine the spine's sectional dimensions, we aim to enhance this process through optimization techniques. By refining the method, we can achieve the optimal distribution of sectional properties for enhanced performance.

6. References

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