

A Framework for Soft Mechanism Driven Robots

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #2

(Remarks to the Author)

The study proposes a multi-material design and printing framework, combining the strengths of soft and rigid materials to provide closed-curve movement paths for a walking robot. The tool-changer, equipped with multiple extruders, blends thermoplastics of varying Shore hardness into monolithic systems and allows for multi-material printing. The feasibility of the framework was demonstrated by 3D printing a legged soft robotic system, with different mechanism syntheses and material combinations, and it was able to move on different surfaces such as sand, soil, rock, etc. For the creation of closed-curve trajectories, classical linkage design was used, enhancing power efficiency and movement precision without requiring actuators at every joint. To achieve this, four-bar linkages controlled by rotary actuators were used.

Regarding 3D printing, usually printers with dual print heads can print two materials sequentially; however, they often use Bowden extruders. Due to the higher friction in PTFE tubing, Bowden extruders are less reliable than direct drive extruders for printing flexible filaments. On the other hand, we have single extruder printers for multi-material printing. In single extruder printers, adjusting idler tension for filaments of varying Shore hardness is challenging. To address this problem, E3D Tool Changers were used, equipped with four separate extrusion tool-heads. Each head is configured with unique printing parameters optimized for the specific properties of its designated material. So eventually, three materials were used for 3D printing the linkages (thermoplastic polyurethanes of varying Shore hardness: 75D, 95A, and 85A).

Overall, the study is scientifically consistent and presented very clearly, with the manuscript, videos, Matlab code, and data are all easy to follow, but some information seems missing that is detailed below. However, the main concern is about the novelty of their contribution. The main contribution of the paper is to propose a 3D printed framework for legged robots with multi-material analyses of chassis and mechanism designs for impact resistance, durability, and adaptability. Although the paper covers the claims and shows the feasibility of the proposed method, there is a lack of contribution in terms of the novelty of design and experimental validations. Similar work can be found at <https://doi.org/10.1115/1.4039773>.

Neither their design nor printing technology seems to be novel. In addition, the demonstration does not appear to be significant to warrant publication in a multi-disciplinary journal such as Nature Communications. I suggest this paper be sent to a more engineering-focused journal. In addition, I provide the following specific comments in hopes to improve the quality of the paper:

1. To address the challenge of material cooling while using a tool changer setup and ensure the bonding of two materials, three different interface methods were proposed: straight, dovetail, and finger joints. It could be beneficial to compare the contact surface area of these three methods together and also provide more comparative information such as differences in printing time, differences in bending deformation, and the effect of the number of fingers and tails on the stress-strain curve for these three methods.
2. Standard information regarding finite element analysis such as material modeling of TPUs, number and type of mesh, and any other assumptions need to be added.
3. As can be seen in Fig. 3b, the tensile test conducted based on the ASTM D638 standard, but it is not clear where the cyclic loading is applied to evaluate the bonding of materials in the specimens.
4. Some information is missing and adding them to the paper could be beneficial to readers: type of DC motors, total weight and dimensions of the quadruped, details of PCB, motor driver, etc.

5. What are the specific requirements for the "body" of the robot? Although each leg acts independently, how does the optimization of the body's geometry affect the overall walking? Also, how will the overall movement of the robot be affected by changing the material of the body? To ensure the flexibility of the body, why not use the lower TPU shore hardness?
6. What is the mean error of trajectory analysis of video tracking versus the theoretical (rigid) model? Also, why during the video tracking in Fig. 4d, the yellow trajectory (95A/75D) show a greater difference from the analytical trajectory compared to the red trajectory (85A/75D)? I am assuming that increasing the material Shore hardness from 85A to 95A should make the trajectory closer to the rigid trajectory.
7. How could independently actuating the legs in a trot gait fashion be improved? This can be seen in video Movie S1 that is challenging when the robot is moving on soil.
8. What was the speed of the completely rigid version of the robot compared to the 85A/95A version?
9. How will encasing rigid electronic components entirely within soft structures assure durability?
10. As can be seen from the results, the stress-strain behavior of two-material specimens is predominantly influenced by the properties of the material with lower Shore hardness. Why not include the TPU in shore hardness 50A to have a broader range of materials?
11. Is there any chance to capture the trajectory using electromagnetic tracking and compare it with video trajectory tracking?

(Remarks on code availability)

The code has been reviewed and is clear to follow and understand and should be reproducible.

Reviewer #3

(Remarks to the Author)

"I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts."

(Remarks on code availability)

"I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts."

Reviewer #4

(Remarks to the Author)

Summary:

The authors present the results of the work consisting in the design and development of a soft hybrid robot, which is composed of parts that are manufactured with 3D printing technology, actuated by 4 DC motor controlled by a microcontroller. The paper shows the process of characterization of the materials, whose stiffness can be tuned thanks to the approach they implemented, consisting in the use of softer and harder polymers linked together in multiple ways. The design of the leg's mechanism is based on the four-bar linkage. The analytical solution of the leg motion is compared with the numerical one as validation of the process. Finally, the robot's performance is tested in controlled environment for trajectory acquisition. A demonstration in real environments is also presented.

The whole process is thoroughly explained, and all design steps are supported by standard engineering practices.

The noteworthy results include the use of a novel approach to fabricate soft mechanical parts, composed of materials with different stiffness, printed on the same part, although this is not the first example of this technology, which is already present in some commercial 3D printers (e.g.: 3D Systems multi-material composites).

Major comments:

The approach used to translate a rigid four-bar linkage mechanism into a soft multi-material part is presenting elements of novelty and the results are promising for the design of cost effective and robust quadruped robots. However, there are some aspects that do not fully align with the claim of the authors and some others that would deserve better explanation. Following, a more detailed analysis of some of the sections.

Section "Material interfaces"

The material characterization is focused on the bonding force between two different types of TPU, but the solution that was implemented is the one with the lowest characteristics. It is not clear which were the requirements and what was the rationale for investigating the material interface. It seems that this type of characterization is out of scope of the paper as it is not adding value to the overall scenario that is presented.

The choice of polymer for an application where a repetitive motion is foreseen could be based on other indicators beside the young modulus, which was the only measured characteristics. There is no mention of fatigue resistance of the interface or

any characterization of the viscoelastic properties of the material, which could be more relevant for the work presented. Since the intended scope is to pave the road for power efficient soft robots, there should be a mention of the energy used for bending the soft joints. There are some questions that may raise: How is the choice of materials affecting the energy needed for locomotion? What is the efficiency of this locomotion mechanism?

Section "Locomotion tests"

As claimed by the authors, one of the benefits of soft robots is the improved stability, achieved by the intrinsic material characteristics. The locomotion tests measure the performance of the robots that were built, but without a specified scope. Some questions remain unanswered, for example: what is the ultimate goal that the authors want to achieve? If the goal is stability, how is stability measured? Is the goal maximizing the speed? Is it the capability of moving efficiently on different surfaces? Some more detailed explanations of the level of improvement compared to the state of the art would better show how this specific design is advancing in the field of soft robotics.

Section "Discussion"

The authors are aware of the limitations of the design proposed. Some aspects could have been further explored to give additional purpose to the framework that the authors are proposing. The design of the control system of this robot is purely kinematic. In the field of soft robotics, the dynamic of the walking has been widely explored (See for example, as a review on the topic, Calisti et al. "Fundamentals of soft robot locomotion", <https://doi.org/10.1098/rsif.2017.0101>). Some considerations of these aspects would have been beneficial to the scope of the paper.

Regarding the mechanical characterization of the robot, the design of the leg mechanism has been widely investigated, but the body stiffness has been kept fixed, despite the authors recognized the important role of the flexibility of the body, and apparently has not been considered in the finite element analysis. I assume that this parameter can be considered a key aspect for the stability of the robot which could have been worth exploring.

Minor comments:

- Lines 161-168. The planar design is an intrinsic feature of this 3D printed part, but in the traditional four-bar mechanism is this characteristic a real limitation and under what aspect? The authors mention that in their design the crank still needs to be offset, so, overall, this robot has the same limitation of the traditional mechanisms.

- In Figure 4 it would be interesting to compare the analytical solution, the FEM model and the video tracking on the same graph.

- In Figure 7 the lettering of the caption is incorrect.

(Remarks on code availability)

Version 1:

Reviewer comments:

Reviewer #2

(Remarks to the Author)

The authors have done a good job responding to my comments, but there are still several issues to be addressed, that are listed here:

Point 2: Your focus on using FDM printers exclusively is a point of differentiation. However, I would like to see a more detailed analysis of the trade-offs between FDM and PolyJet printing for soft robotics. How does the quality and performance of FDM-printed soft robots compare to those produced by PolyJet printing?

You claim your approach provides a versatile strategy for constructing a range of soft-legged robots. It would be helpful to see specific examples of this versatility - perhaps different configurations or applications that your framework enables.

The use of generic four-bar mechanisms is interesting, but please provide more evidence of how this translates to greater versatility in practical applications.

What metrics did you use to evaluate performance across different terrains?

Regarding independent gait control, while independent actuation offers more control, it likely comes with increased complexity and potentially higher energy consumption. Can you provide a detailed analysis of these trade-offs?

While 10,000 cycles is impressive, how does this translate to operational lifespan for a soft robot?

Point 3: Authors have addressed most parts of the comment, but while you've added information on surface contact areas, could you provide a direct comparison of the contact surface areas for the straight, dovetail, and finger joint methods? This comparison would be valuable for understanding the relative strengths of each interface method.

Point 7: Could you elaborate on the key findings from the preliminary body material testing? How significant were the differences in locomotion performance between different Shore hardness levels?

The original question about the optimization of the body's geometry wasn't directly addressed. Do you have any insights on how body geometry might affect the overall walking, even if it wasn't the focus of your study?

Point 10: It might be a good idea to add a brief note about this in the paper.

Point 11: The current method of pausing the print, manually placing components, and then resuming seems like a practical approach for prototyping, but it may present challenges for scalability and consistency in production. Have you considered how this manual insertion process might affect the structural integrity of the printed body or the reliability of the electronic connections?

(Remarks on code availability)

Reviewer #3

(Remarks to the Author)

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

(Remarks on code availability)

Reviewer #4

(Remarks to the Author)

The authors have answered the questions in a methodical manner, here are my further comments on their answer.

Q: 2. The material characterization is focused on the bonding force between two different types of TPU, but the solution that was implemented is the one with the lowest characteristics. It is not clear which were the requirements and what was the rationale for investigating the material interface. It seems that this type of characterization is out of scope of the paper as it is not adding value to the overall scenario that is presented.

Comment: The authors have answered about their specific approach of development of their framework, but in my opinion the question is not fully answered. According to the authors, the characterization is done to give a large audience a guideline for designing the interfaces. The straight interface, I quote: "exhibited separation at relatively low-stress levels". According to the supporting material, the testing has been done on a very limited number of samples, so it is not possible to conclude if the detachment at the interface appears more often than in the "dovetail" or "finger" configuration. Overall, little information can be gained by this characterization.

Q: 3. The choice of polymer for an application where a repetitive motion is foreseen could be based on other indicators beside the young modulus, which was the only measured characteristics. There is no mention of fatigue resistance of the interface or any characterization of the viscoelastic properties of the material, which could be more relevant for the work presented.

Comment: The authors have responded fully to the question

Q 4. Since the intended scope is to pave the road for power efficient soft robots, there should be a mention of the energy used for bending the soft joints. There are some questions that may raise: How is the choice of materials affecting the energy needed for locomotion? What is the efficiency of this locomotion mechanism?

Comment: The authors have responded fully to the question

Q: 5. As claimed by the authors, one of the benefits of soft robots is the improved stability, achieved by the intrinsic material characteristics. The locomotion tests measure the performance of the robots that were built, but without a specified scope. Some questions remain unanswered, for example: what is the ultimate goal that the authors want to achieve? If the goal is stability, how is stability measured? Is the goal maximizing the speed? Is it the capability of moving efficiently on different surfaces? Some more detailed explanations of the level of improvement compared to the state of the art would better show how this specific design is advancing in the field of soft robotics.

Comment: The authors have specified the scope of the paper, which is providing a general framework for future studies,

without claiming a specific area of optimization for their robot.

Q 6. The authors are aware of the limitations of the design proposed. Some aspects could have been further explored to give additional purpose to the framework that the authors are proposing. The design of the control system of this robot is purely kinematic. In the field of soft robotics, the dynamic of the walking has been widely explored (See for example, as a review on the topic, Calisti et al. "Fundamentals of soft robot locomotion", <https://doi.org/10.1098/rsif.2017.0101>). Some considerations of these aspects would have been beneficial to the scope of the paper.

Comment: The dynamics of locomotion has not been taken into consideration by the authors. This intentional choice is limiting the field of application of their framework to the design of the locomotion system in terms of materials choice and composite material performance.

Q 7. Lines 161-168. The planar design is an intrinsic feature of this 3D printed part, but in the traditional four-bar mechanism is this characteristic a real limitation and under what aspect? The authors mention that in their design the crank still needs to be offset, so, overall, this robot has the same limitation of the traditional mechanisms.

Comment: The authors have responded fully to the question

Q 8. In Figure 4 it would be interesting to compare the analytical solution, the FEM model and the video tracking on the same graph.

Comment: The authors have responded to the comment

Q 9. In Figure 7 the lettering of the caption is incorrect.

Comment: The authors have responded to the comment

Final comment:

The overall work is well structured, and the authors have responded to the comments in an appropriate manner. In the reviewed manuscript it is more clear what is the scope of the paper: giving a general overview of their advancement in the design of a soft mechanism for locomotion and give the community a framework to work on.

(Remarks on code availability)

Version 2:

Reviewer comments:

Reviewer #2

(Remarks to the Author)

The authors have addressed all our comments and I recommend for publication.

(Remarks on code availability)

Reviewer #3

(Remarks to the Author)

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

(Remarks on code availability)

Reviewer #4

(Remarks to the Author)

The authors have replied to all the comments and I have no further questions on the paper.

(Remarks on code availability)

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Response to Reviewer #2

1. *The study proposes a multi-material design and printing framework, combining the strengths of soft and rigid materials to provide closed-curve movement paths for a walking robot. The tool-changer, equipped with multiple extruders, blends thermoplastics of varying Shore hardness into monolithic systems and allows for multi-material printing. The feasibility of the framework was demonstrated by 3D printing a legged soft robotic system, with different mechanism syntheses and material combinations, and it was able to move on different surfaces such as sand, soil, rock, etc. For the creation of closed-curve trajectories, classical linkage design was used, enhancing power efficiency and movement precision without requiring actuators at every joint. To achieve this, four-bar linkages controlled by rotary actuators were used.*

We thank the reviewer for their time and for providing us with comments and suggestions. We have provided detailed responses below.

2. *Regarding 3D printing, usually printers with dual print heads can print two materials sequentially; however, they often use Bowden extruders. Due to the higher friction in PTFE tubing, Bowden extruders are less reliable than direct drive extruders for printing flexible filaments. On the other hand, we have single extruder printers for multi-material printing. In single extruder printers, adjusting idler tension for filaments of varying Shore hardness is challenging. To address this problem, E3D Tool Changers were used, equipped with four separate extrusion tool-heads. Each head is configured with unique printing parameters optimized for the specific properties of its designated material. So eventually, three materials were used for 3D printing the linkages (thermoplastic polyurethanes of varying Shore hardness: 75D, 95A, and 85A).*

Overall, the study is scientifically consistent and presented very clearly, with the manuscript, videos, Matlab code, and data all easy to follow, but some information seems missing that is detailed below. However, the main concern is about the novelty of their contribution. The main contribution of the paper is to propose a 3D printed framework for legged robots with multi-material analyses of chassis and mechanism designs for impact resistance, durability, and adaptability. Although the paper covers the claims and shows the feasibility of the proposed method, there is a lack of contribution in terms of the novelty of design and experimental validations. Similar work can be found at <https://doi.org/10.1115/1.4039773>.

We thank the reviewer for their comments. Below, we address the concerns regarding the novelty of our robot design and experimental verification and relate our answers to DeMario et al.'s work.

Summary: Our framework presents a method for creating legged soft robots exclusively using FDM printers. We examine various parameters and their influence on robot behaviors, incorporating control authority for each leg through integrated feedback from encoders. We demonstrate diverse walking behaviors, such as linear motion and point turning, in real-world environments. Unlike DeMario et al.'s work, which focuses on a specific Klann mechanism and specialized gear-driven actuation using expensive PolyJet printing, our approach provides a versatile strategy for constructing a range of soft-legged robots accessible to those with FDM printers. This distinction emphasizes our contribution to broadening the accessibility of soft robotic design and fabrication.

- **Soft robotic attributes:** DeMario et al.'s work lacks analyses of locomotion stability, impact resistance, and oscillation dampening. In contrast, our framework is specifically designed to address these critical aspects, creating soft robots capable of stable locomotion, impact resistance, and effective oscillation dampening in real-world environments. The comprehensive integration of soft materials transforms the locomotion of the robot, allowing the entire structure to function as a damping system, reducing rigidity, and enabling natural interactions with the environment. Our videos further highlight the undulation of the robot body, akin to biological systems, underscoring the significant role of the body in enhancing locomotion performance and addressing the limitations present in DeMario et al.'s approach. In summary, we demonstrate that robots built using our framework exhibit robust soft robotic behaviors.
- **Generality:** DeMario et al. focus exclusively on a Klann mechanism, conducting their analyses and experiments within this limited system. In contrast, our approach utilizes three generic four-bar mechanisms. Our study introduces a versatile framework, offering a valuable resource from which other researchers can draw inspiration to develop soft robots tailored to their specific needs.

- **Practical use:** DeMario et al.'s work lacks demonstration of practical applicability beyond controlled laboratory environments. In contrast, our framework enables the development of robots that are not restricted to laboratory conditions, as evidenced by their demonstrated ability to traverse diverse terrains. This capability distinctly differentiates our research from the majority of relevant literature, which predominantly focuses on scenarios within controlled lab settings.
- **Independent gait control:** DeMario et al. employ a transmission mechanism to drive all the legs of their robot with a single actuator, with a primary focus on miniaturization. In contrast, our design incorporates independent actuators for each leg, enabling precise and independent gait control. This allows our robots to achieve a broader range of movements beyond predefined motions, depending on operational needs, including the ability to turn in place, as demonstrated in our video.
- **Material interface investigation:** DeMario et al.'s study lacks a rigorous investigation of material interfaces and, furthermore, they were unable to prevent delamination at soft/hard interfaces (i.e., 4.3 Walking Capabilities in DeMario et al.'s publication) during motion trials. In contrast, our framework examines material interfaces, including static and dynamic testing. We have conducted static testing to elucidate the stress-strain characteristics of multi-material specimens, and for our resubmission, we extended our tests to dynamic fatigue testing. Our findings demonstrate the successful integration of soft/soft and soft/hard interfaces. Our cyclic fatigue tests indicate that the interfacing properties achieved through our framework surpass those of PolyJet printing. The literature reports the failure of PolyJet-printed soft/hard specimens after approximately 1,000 cycles; in contrast, our specimens endured at least 10,000 cycles before breaking (referring to line 140 in our revised main manuscript).
- **Effect of material combinations in motion characteristics:** DeMario et al.'s work does not examine how differences in Shore hardness affect the characteristics of motion. In contrast, our study explores how variations in Shore hardness between joints and links influence locomotion.
- **Cost-effectiveness and accesibility:** We argue that the novelty of our work partly resides in the accessibility and cost-efficiency of our framework, especially when compared to comparable literature, including the work by DeMario et al. The referenced study employs the Objet 500 Connex 3 PolyJet 3D Printer, which costs approximately \$350,000 to \$400,000. In contrast, our framework utilizes the E3D Toolchanger (formerly priced at \$2,800) and the Prusa XL (priced at \$3,499) following its release. These significant cost differences also extend to the materials used with each machine. We contend that our framework enables the rapid synthesis, prototyping, and fabrication of soft mechanism-driven robots tailored to specific needs without requiring post-processing steps. In our view, this approach emphasizes the use of accessible machinery and materials, making it particularly relevant for a broad audience, such as that of Nature Communications.

To highlight the key aspects of these differences, we have added the following paragraph to the Introduction section of our revised manuscript (line 44), including references:

'DeMario et al.'s work similarly focused on multi-material PolyJet printing of soft materials with varying Shore hardness to create locomotion mechanisms; the work, however, exhibits certain limitations. The study does not address key soft robotic attributes such as locomotion stability, impact resistance, and oscillation dampening, which are essential for performance in varied environments. The reliance on a specific Klann mechanism with a single actuator constrains the versatility of the robot's movements. There is a limited investigation into material interfaces, with observed challenges like delamination during motion trials. The impact of variations in Shore hardness on locomotion is not explored. The use of PolyJet printing poses challenges regarding accessibility and cost, restricting its fabrication to specialized laboratory settings.'

3. *To address the challenge of material cooling while using a tool changer setup and ensure the bonding of two materials, three different interface methods were proposed: straight, dovetail, and finger joints. It could be beneficial to compare the contact surface area of these three methods together and also provide more comparative information such as differences in printing time, differences in bending deformation, and the effect of the number of fingers and tails on the stress-strain curve for these three methods.*

We thank the reviewer for their comment. In response, we conducted Finite Element Analysis (FEA) while maintaining a constant applied force to illustrate the bending differences among various material

combinations. The details of this analysis are provided in the Supplementary Information. Please refer to the newly added section titled *'Deflection Analysis'* in SI.

We fundamentally agree with the reviewer's comments and added information on the surface contact areas, print times, and deflection characteristics of each specimen combination. Please refer to the newly added section titled *'Tensile Testing Specimen Comparisons'* in the SI. All print profiles and CAD models are included as supplemental data files.

We determined that altering the number of fingers and tails on the specimens is not feasible due to the constraints of the ASTM D638 standard, which limits the area where two materials can be interfaced. The low resolution of FDM systems also restricts our ability to increase the number of joint structures. To address these limitations, we included the following text in the main manuscript (Results - Material Interfaces - line 97) to clarify this point:

'We selected the dovetail and finger joint sizes and counts to maximize the contact area within the constraints of the specimen's size and the resolution of our printer.'

4. Standard information regarding finite element analysis such as material modeling of TPUs, number and type of mesh, and any other assumptions need to be added.

The COMSOL simulation file, containing all defined parameters such as mesh size, material properties, study type, convergence model, and other relevant details, was included in the supplemental documents during the initial submission. We have now added additional details of the simulation to the Supplementary Information section. Please review the new section titled *'Finite Element Analysis Information'* in the Supplementary Information (SI).

5. As can be seen in Fig. 3b, the tensile test conducted based on the ASTM D638 standard, but it is not clear where the cyclic loading is applied to evaluate the bonding of materials in the specimens. The details of this test are provided in supplemental information.

Our initial cyclic testing involved actuating the material with a DC motor for a specified number of cycles. To further extend the investigation for our resubmission, we conducted cyclic fatigue testing on newly printed specimens according to ASTM standard 7791 on a dynamic testing machine (Instron Electropuls E3000).

We share the details of this test in Supplementary Information - *'Cyclic Fatigue Testing'*. To briefly summarize, our tests demonstrated that the interfaces we formed and the material combinations used throughout the study exhibited no fatigue failure under operating conditions for 10,000 cycles per specimen.

We refer to the newly added test in the main manuscript as well (Results - Material Interfaces - Line 122).

6. Some information is missing and adding them to the paper could be beneficial to readers: type of DC motors, total weight and dimensions of the quadruped, details of PCB, motor driver, etc.

We thank the reviewer for the comment. We have added all the relevant details to the Supplementary Information. Please review the newly added section titled *'Robot Components and Properties'* in the SI.

7. What are the specific requirements for the "body" of the robot? Although each leg acts independently, how does the optimization of the body's geometry affect the overall walking? Also, how will the overall movement of the robot be affected by changing the material of the body? To ensure the flexibility of the body, why not use the lower TPU shore hardness?

We acknowledge the valid point and thank the reviewer for their comment. While we agree that this aspect of the work is interesting and significant in its own right, we believe it warrants follow-up research as a separate study. Focusing on the body design would detract from the primary focus of this work, which is on soft mechanisms, and thus falls outside the intended scope of this study. However, for our resubmission, we have extended our investigation with a preliminary study by printing the robot body using materials of different Shore hardness and conducting locomotion tests with the same leg mechanism to assess the impact of body hardness on overall motion and undulation. The details are provided in the Supplementary Information - *'Body Material Testing'*. We refer to this experiment in the main manuscript as well (Results - Locomotion Tests - Line 285).

8. *What is the mean error of trajectory analysis of video tracking versus the theoretical (rigid) model? Also, why during the video tracking in Fig. 4d, the yellow trajectory (95A/75D) show a greater difference from the analytical trajectory compared to the red trajectory (85A/75D)? I am assuming that increasing the material Shore hardness from 85A to 95A should make the trajectory closer to the rigid trajectory.*

We thank the reviewer for their comment. The yellow trajectory in Figure 4 (95A/75D) deviates the most from the analytical loop due to the higher Shore hardness of the joint material (95A) compared to the other two legs, which have joints made from softer materials (85A). The higher Shore hardness of the joints causes additional backlash, leading to larger deviations. We added a section for the trajectory analyses to the SI - 'Mean Error Analysis for Air Trajectories'. We refer to the test in the main manuscript as well (Results - Trajectory Analyses - Line 253).

9. *How could independently actuating the legs in a trot gait fashion be improved? This can be seen in video Movie S1 that is challenging when the robot is moving on soil.*

We thank the reviewer for this comment; we agree that real-time improvements in locomotion gaits could unlock many successful locomotion opportunities. Adaptation in animals relies on sensory feedback from their environment. For example, climbing a rock, crossing a river, or escaping a predator all depend on first detecting these challenges. Our robot demonstrators showcase the different design variables that our framework offers. Our work enables future studies, beyond the scope of this work, needed to integrate multiple sensors into the robot body and explore adaptive control strategies for locomotion gaits.

Our research on locomotion gaits demonstrated that the trot gait offers an optimal balance between stability and the ability to navigate rough terrain, which is why we employed it consistently throughout our experiments. To address the discussion points mentioned above, we added the following text to the main manuscript (Results - Locomotion Tests - Line 264):

'In the future, sensory feedback from sources such as cameras could enable adaptive gait changes, allowing the robot to switch gaits in response to various obstacles. To prioritize ease of fabrication, reduce costs, and maintain focus on developing mechanism-based soft robots, we conducted all our experiments using the trot gait.'

10. *What was the speed of the completely rigid version of the robot compared to the 85A/95A version?*

We constructed a fully rigid version of the robot for compression testing, but the leg mechanisms made from hard materials were insufficient to support the robot body, preventing successful operation. A fully rigid robot would require a complete redesign, which falls outside the scope of this work, as our focus is on presenting a framework for soft robotics.

11. *How will encasing rigid electronic components entirely within soft structures assure durability?*

During the fabrication of the printed body, we will pause the print halfway, place the electronic components into the body while it is on the print bed, and then resume printing to create the enclosure. We added the following part to the revised main manuscript (Discussion - Line 377):

'While the structural elements are robust, capable of bearing heavy loads and accommodating angular distortions, the inclusion of rigid electronic components constrains these capabilities. To overcome these challenges, future work will involve flexible electronics and encasing electronic components entirely within soft structures. By using soft materials to absorb the forces acting on the robot body, fragile electronic components will be protected from stress, allowing for advanced robustness.'

12. *As can be seen from the results, the stress-strain behavior of two-material specimens is predominantly influenced by the properties of the material with lower Shore hardness. Why not include the TPU in shore hardness 50A to have a broader range of materials?*

To the best of our knowledge, the lowest commercially available filament has a Shore hardness of 60A (e.g., Recreus Filaflex 60A). Filaments with lower Shore hardness increase the risk of print failures, such as buckling. Given that this work aims to present a broadly applicable framework, we opted to use filaments with higher Shore hardness that can be printed easily and reliably using standard desktop FDM printers. Notably, in our prior work with silicone rubbers (DOI: 10.1109/ROBOSOFT.2019.8722769), we found that Shore hardnesses of 30A and below compromised the structural integrity of robotic structures.

While other 3D printing methods, such as vat photopolymerization, can achieve lower Shore hardnesses, they lack multi-material capabilities, as noted in the manuscript. PolyJet printing, although offering both features, remains significantly less accessible due to its high costs. We have included the following details in the main manuscript - (Results - Material Interfaces - Line 85):

‘We selected filaments with Shore hardness levels of 75D, 95A, and 85A due to their commercial availability and balance between softness and structural integrity. Filaments with lower Shore hardness are more prone to printing challenges and higher failure rates.’

13. *Is there any chance to capture the trajectory using electromagnetic tracking and compare it with video trajectory tracking?*

After careful consideration, we have not concluded that the precision of our tracking method is insufficient for the demonstrated application.

Response to Reviewer #4

1. *The authors present the results of the work consisting in the design and development of a soft hybrid robot, which is composed of parts that are manufactured with 3D printing technology, actuated by 4 DC motor controlled by a microcontroller. The paper shows the process of characterization of the materials, whose stiffness can be tuned thanks to the approach they implemented, consisting in the use of softer and harder polymers linked together in multiple ways. The design of the leg’s mechanism is based on the four-bar linkage. The analytical solution of the leg motion is compared with the numerical one as validation of the process. Finally, the robot’s performance is tested in controlled environment for trajectory acquisition. A demonstration in real environments is also presented. The whole process is thoroughly explained, and all design steps are supported by standard engineering practices. The noteworthy results include the use of a novel approach to fabricate soft mechanical parts, composed of materials with different stiffness, printed on the same part, although this is not the first example of this technology, which is already present in some commercial 3D printers (e.g.: 3D Systems multi-material composites).*

The approach used to translate a rigid four-bar linkage mechanism into a soft multi-material part is presenting elements of novelty and the results are promising for the design of cost effective and robust quadruped robots. However, there are some aspects that do not fully align with the claim of the authors and some others that would deserve better explanation. Following, a more detailed analysis of some of the sections.

We thank the reviewer for their time and for providing us with comments and suggestions. We have provided detailed responses below.

2. *The material characterization is focused on the bonding force between two different types of TPU, but the solution that was implemented is the one with the lowest characteristics. It is not clear which were the requirements and what was the rationale for investigating the material interface. It seems that this type of characterization is out of scope of the paper as it is not adding value to the overall scenario that is presented.*

We fabricated the locomotion mechanism from various material combinations to assess how Shore hardness differences influence motion. By demonstrating how different material combinations result in stress-strain behaviors, we offer crucial insights into fundamental design characteristics, serving as a guideline for material selection. Our results indicate that joint hardness significantly impacts motion, while link hardness plays a lesser role. Thus, we used the material with the lowest Shore hardness (85A) for the joints to enhance flexibility, and selected the material with the highest Shore hardness (75D) for the links to maximize the hardness differential. This combination underscores our key point: integrating soft and hard materials enables the robot to exhibit behaviors characteristic of soft robots.

We want this work to become a practical framework for a large audience to explore soft robots operating inside and outside the laboratory. The exploration of different interfaces (straight, finger, and dovetail) serves as an examination of potential design variations that may be crucial for specific applications relevant to the reader. For instance, in scenarios demanding high-stress endurance, finger or dovetail joints may be more suitable than straight interfaces. In our application, we analyzed via FEM the maximum peak stress during cyclic motion (0.9 MPa); the straight interface with a material combination of 75D and 85A comfortably exceeds the maximum cyclic peak stress (≥ 4 MPa) (please see Results - Material Interfaces - Line 120). The straight interface met our requirements by a factor of ≥ 4 .

3. *The choice of polymer for an application where a repetitive motion is foreseen could be based on other indicators beside the young modulus, which was the only measured characteristics. There is no mention of fatigue resistance of the interface or any characterization of the viscoelastic properties of the material, which could be more relevant for the work presented.*

We thank the reviewer for their comment. While we initially used stress-strain curves and Young's moduli to characterize the materials, we recognize the importance of additional factors, such as fatigue resistance. In the revision, we included a comprehensive cyclic test according to ASTM D7791 standard. We evaluated the fatigue performance of the different materials and interfaces. The literature reports the failure of PolyJet-printed soft/hard specimens after approximately 1,000 cycles; in contrast, our specimens endured at least 10,000 cycles before breaking (referring to line 127 in our revised main manuscript). Please see Supplementary Information - 'Cyclic Fatigue Testing'.

4. *Since the intended scope is to pave the road for power efficient soft robots, there should be a mention of the energy used for bending the soft joints. There are some questions that may raise: How is the choice of materials affecting the energy needed for locomotion? What is the efficiency of this locomotion mechanism?*

We agree that the power consumption of different material combinations is an interesting aspect of the work. In the revised manuscript, we added an analysis of the power consumption, taking current measurements of the motors during the bending of soft joints. Our findings indicate that the choice of material combination significantly impacts the overall power consumption of the robot. Please see Supplementary Information - 'Mechanism Efficiency Testing'.

5. *As claimed by the authors, one of the benefits of soft robots is the improved stability, achieved by the intrinsic material characteristics. The locomotion tests measure the performance of the robots that were built, but without a specified scope. Some questions remain unanswered, for example: what is the ultimate goal that the authors want to achieve? If the goal is stability, how is stability measured? Is the goal maximizing the speed? Is it the capability of moving efficiently on different surfaces? Some more detailed explanations of the level of improvement compared to the state of the art would better show how this specific design is advancing in the field of soft robotics.*

We thank the reviewer for their comment. We understand this work as a new practical framework, that a large audience can use to develop their own inexpensive soft robots using desktop FDM printers only. The fact that trajectory, stability, or speed can be influenced by varying design parameters is the take-home message. The development of a specific soft robot that optimizes for one or even multiple of those criteria is beyond the scope of this work. Subsequent studies can take this framework and do exactly that: design, simulate, and fabricate a multi-material soft robot and optimize it for the application at hand. In the revised manuscript, we clarified our ultimate goal (Introduction - Line 74).

'The goal of this framework is to facilitate the design and implementation of mechanism-driven soft robots suitable for real-world environments, using low-cost materials and accessible desktop FDM printers.'

Different material combinations and leg designs result in varying leg trajectories. Some leg trajectories maximize speed by moving the greatest distance for a given stroke; however, these same trajectories may be inadequate for traversing obstacles in environments such as mildly stony terrain, where a trajectory with higher leg amplitude would be beneficial, or even necessary. Specific environments can only be navigated with certain trajectories. We introduce various trajectories and a systematic method for developing them, thereby enabling the creation of robots tailored to specific environments. This fits into our framework of rapidly developing robot systems using inexpensive design and fabrication tools. Our work contrasts sharply with the paper mentioned by Reviewer 2, which employs expensive fabrication tools (PolyJet printing), making it inaccessible to a wide audience.

We evaluate robot stability by tracking the centroid of the robot body and analyzing amplitude, slope, and period (Figure 5). For example, material combinations of lower Shore hardness exhibit larger periods than material combinations of higher Shore hardness. Based on feedback from another reviewer, we extended this study by varying the material of the robot body while maintaining the material combination of the legs. Robot bodies made from materials of lower Shore hardness exhibit greater angulations and more centroid movement than robot bodies made from materials of higher Shore hardness. Please see Supplementary Information - 'Body Material Testing'. We added the following paragraphs to the revised manuscript (Results - Demonstrations - Line 333):

‘We describe stability by a combination of different properties such as the vertical amplitude of centroid movement, slope of the curve of the movement plot, and the tip of the plot (being sharp or plateau like). Elastomeric leg mechanisms and bodies exhibit smaller centroid movement amplitudes; however, comparing two elastomeric bodies reveals that the softer material may display greater movement due to enhanced angulations. These angulations suggest increased energy dissipation through body movements, leading to more stable locomotion. This represents a significant advantage of our fabrication framework over rigid quadrupeds, which face higher normal forces and, consequently, increased oscillations.’

6. The authors are aware of the limitations of the design proposed. Some aspects could have been further explored to give additional purpose to the framework that the authors are proposing. The design of the control system of this robot is purely kinematic. In the field of soft robotics, the dynamic of the walking has been widely explored (See for example, as a review on the topic, Calisti et al. “Fundamentals of soft robot locomotion”, <https://doi.org/10.1098/rsif.2017.0101>). Some considerations of these aspects would have been beneficial to the scope of the paper.

For controlling the robot, we decided against model-based control due to the complexities in analytically modeling the multi-material linkages. Instead, we implemented a PID controller. While the design process and synthesis of the leg trajectory for the locomotion mechanism is kinematic, our finite element analysis of the mechanism is kinetic. In response to the reviewer’s comment, we extended our work on kinetics by conducting additional finite element analyses. In our revised manuscript, we compared deflections across mechanisms of different material combinations for the same force magnitude. Please see Supplementary Information - ‘Deflection Analysis’

Regarding the mechanical characterization of the robot, the design of the leg mechanism has been widely investigated, but the body stiffness has been kept fixed, despite the authors recognized the important role of the flexibility of the body, and apparently has not been considered in the finite element analysis. I assume that this parameter can be considered a key aspect for the stability of the robot which could have been worth exploring.

Please see answer 5.

7. Lines 161-168. The planar design is an intrinsic feature of this 3D printed part, but in the traditional four-bar mechanism is this characteristic a real limitation and under what aspect? The authors mention that in their design the crank still needs to be offset, so, overall, this robot has the same limitation of the traditional mechanisms.

We acknowledge that the limitation is not completely diminished but reduced. In conventional mechanisms, every link needs to be non-planar. In our work, only the link with 360-degree rotations has this requirement. We added the following sentence to the revised manuscript (Results - Multi-Material Mechanism Driven Soft-Hybrid Quadruped - Line 189):

‘The limitation is not completely diminished, but reduced to the only exception of the cams that connect the motors to the linkage.’

8. In Figure 4 it would be interesting to compare the analytical solution, the FEM model and the video tracking on the same graph.

We thank the reviewer for their comments. Our initial figure design combined the analytical solution, FEM model, and video tracking; however the resulting graph appeared overly complex and confusing. Therefore, we decided to split the figure into sub-figures: one sub-figure shows the FEA results; the other sub-figure shows the video tracking. To maintain the connection between the two graphs, we included the analytical trajectory plot to both sub-figures.

9. In Figure 7 the lettering of the caption is incorrect.

We thank the reviewer for their comment. We corrected the figure in our revised manuscript.

Response to Reviewer #2

The authors have done a good job responding to my comments, but there are still several issues to be addressed, that are listed here:

We thank the reviewer for providing feedback to our study, which we feel contributed to the overall quality of the paper.

Point 2: Your focus on using FDM printers exclusively is a point of differentiation. However, I would like to see a more detailed analysis of the trade-offs between FDM and PolyJet printing for soft robotics. How does the quality and performance of FDM-printed soft robots compare to those produced by PolyJet printing? You claim your approach provides a versatile strategy for constructing a range of soft-legged robots. It would be helpful to see specific examples of this versatility - perhaps different configurations or applications that your framework enables.

In our resubmission, we included a comparison table of different printing methods—PolyJet, FDM, and SLA—in *Supplementary Information - Comparison of Printing Technologies for Soft Robotics*. The section highlights the trade-offs between the different 3D printing techniques. We also added the following text in Line 54 of the main manuscript:

*To further reflect upon the variations and capabilities of different printing methods, we created a comparison table in *Supplementary Information - Comparison of Printing Technologies for Soft Robotics*.*

We believe the versatility of our work is evident in our translation of a classic four-bar mechanism into the multi-material soft domain. Multiple different implementations of the four-bar mechanism illustrate our framework, and we are eager to see how the community leverages it to develop soft adaptations of classic mechanisms. While implementing additional mechanisms and adapting them for new robotic systems is beyond the scope of this paper—and indeed the future work of both the community and our own efforts—we believe these extensions would not alter the core concept of the framework.

The use of generic four-bar mechanisms is interesting, but please provide more evidence of how this translates to greater versatility in practical applications.

Our response here builds on our previous discussion. We believe that our three implementations of the four-bar mechanism represent the core demonstrations of our framework, and we anticipate that future research will expand this framework to explore a broad range of mechanisms. To showcase the versatility of our approach, we present three distinct locomotion mechanisms with varied trajectories. For most outdoor applications, we used the 'nominal' trajectory; however, when the robot employing this trajectory was unable to climb a steep slope (see Line 345 in *Demonstrations*), we replaced it with a 'vertical' four-bar mechanism. This vertical trajectory enabled the robot to ascend the slope, illustrating the impact of mechanism design in adapting to specific environments. While the vertical trajectory proved effective for slope ascent, it introduced a trade-off by resulting in a generally slower mechanism (see Table 1 in the main manuscript). We anticipate further work from both the community and ourselves to provide additional examples of robots employing varied linkages optimized for specialized environments (e.g., Watt's linkage for translating rotary to linear motion).

To explain this capability in detail, we added the following text to the *Discussion* section (Line 401) in the main manuscript:

Our framework brings classical mechanism design principles into the soft robotics domain; enabling flexible, scenario-specific designs. This approach allows the replication of any other mechanisms, including specialized mechanisms such as Watt's linkage for converting rotary to linear motion, within soft robotics. Our goal is to equip the community with a practical method to design and build mechanisms that help soft robots meet specific operational needs.

What metrics did you use to evaluate performance across different terrains?

As mentioned above, the primary criterion for success has been whether a mechanism can traverse a given environment or obstacle, evaluated as a binary condition.

Regarding independent gait control, while independent actuation offers more control, it likely comes with increased complexity and potentially higher energy consumption. Can you provide a detailed analysis of these trade-offs?

This is another great comment. For this resubmission, we included a section in the SI titled *Comparison of Dependent and Independent Gait Control*, where we evaluate the two methods based on complexity, control flexibility, robustness, and energy consumption. We also added the following sentence in the main manuscript (Line 56):

We also compare the approach of using a single motor with a gear train to the approach of assigning individual motors to each leg in Supplementary Information - Comparison of Dependent and Independent Gait Control.

While 10,000 cycles is impressive, how does this translate to operational lifespan for a soft robot?

In our previous submission, we estimated the operational range of our robot based on its battery capacity. Our fatigue tests indicated that battery life, rather than the pre-failure cycle count of the mechanism, is the limiting factor in operational lifespan. We added the following sentence to the *Demonstrations* section (Line: 371):

The robot, with a body length of 98.46 millimeters, covered an untethered distance of approximately 250 meters (or 2500 times its body length), indicating the practical potential of our framework. As our cyclic fatigue tests showed that our interfaces can withstand at least 10,000 cycles; we deduct that the operational range of the robot is constrained by its battery capacity.

Point 3: Authors have addressed most parts of the comment, but while you've added information on surface contact areas, could you provide a direct comparison of the contact surface areas for the straight, dovetail, and finger joint methods? This comparison would be valuable for understanding the relative strengths of each interface method.

In our previous submission, we included a contact area comparison for the three methods (Supplementary Information - *Tensile Testing Specimen Comparisons*). The proportional surface contact areas can be scaled to fit other mechanism dimensions. This information has also been added to the aforementioned SI section.

In our initial submission, we had conducted static tensile tests for all material and joint combinations. The data can be found in Supplementary Data File 1. For this resubmission, we extracted the ultimate force values for the three interface types and indicated their interfacial performance in Supplementary Table 5. We added the following sentence to the main manuscript (Line 128):

Supplementary Table 5 in the SI provides the ultimate tensile forces that each material and specimen combination can withstand before failure.

Point 7: Could you elaborate on the key findings from the preliminary body material testing? How significant were the differences in locomotion performance between different Shore hardness levels? The original question about the optimization of the body's geometry wasn't directly addressed. Do you have any insights on how body geometry might affect the overall walking, even if it wasn't the focus of your study?

In our previous resubmission, we added the following paragraph in the *Body Material Testing* section in the SI:

Supplementary Figure 5 illustrates the centroid and foot tracking results for three different body hardness levels. It is evident that the non-elastomeric body (75D) results in higher amplitudes and sharper curves, indicating less stable and rougher locomotion. In contrast, the elastomeric bodies exhibit smoother curves with smaller amplitudes, demonstrating their improved oscillation dampening properties.

In the previous submission and in the same section, we also shared another interesting finding between two soft bodies:

An interesting observation emerges when comparing the 85A and 95A bodies. Although the 85A body is softer than the 95A body, the centroid oscillations observed in the 85A body appear to have larger amplitudes. Upon reviewing the experiment videos (Supplementary Movie 6), we noted that the softer 85A body undergoes greater angulations, which means more energy is dissipated through body movements. This, in turn, results in larger centroid movements. However, this does not necessarily imply less stable locomotion. On the contrary, due to this increased movement, the body dampens more oscillations, leading to more stable motion overall.

To further clarify our conclusions, for this revision, we added the following paragraph at the end of the *Body Material Testing* section in the SI:

Overall, it is evident that a degree of flexibility is required to achieve dampened, smooth motion. This conclusion arises from comparing the behavior of our hard body (75D) with the softer bodies (85A, 95A). We observe that softer elastomeric materials allow for greater angulation, indicating enhanced dampening characteristics.

In this resubmission, we additionally conducted finite element analyses to compare body geometries with varying cut-outs and thicknesses. Our goal was to demonstrate that reducing cut-outs and increasing body thickness, overall increase body stiffness; greater forces are required to achieve the same body deflections. Consequently, we expect a reduction in angulation. Please refer to the *Body Geometry Testing* section in the SI. We added the following paragraph to the main manuscript (Line 311).

As a final analysis, we explored how geometrical differentiation, in the terms of cut-out and beam usage, affects the deformation and angulation capabilities of the body. We conducted a finite element simulation comparing three different body models. Our findings indicate that bigger cutouts enable bigger angulation capabilities, but the analysis does not capture information regarding the structural integrity and load-carrying capacities of robot bodies. Our interpretation is that a balance between supports and reliefs is required to establish successful operation, and this balance may shift with operation and design needs. The details of these tests are shared in Supplementary Information - Body Geometry Analysis, and the simulation files are shared in Supplementary Data File 17.

Point 10: It might be a good idea to add a brief note about this in the paper:

In our resubmission, we added the following text to the *Results - Impact Resistance* section (Line 329):

We emphasize that this rigid robot was used solely for impact resistance tests, as design and component modifications would have been necessary to achieve locomotion with rigid materials.

Point 11: The current method of pausing the print, manually placing components, and then resuming seems like a practical approach for prototyping, but it may present challenges for scalability and consistency in production. Have you considered how this manual insertion process might affect the structural integrity of the printed body or the reliability of the electronic connections?

We thank the reviewer for their comment. We have considered the specifics of a full assembly line that allows for component enclosures using print-and-pause strategies. We expanded on this topic in the previously added text in our *Discussion*, where we discuss the potential integration of pick-and-place mechanisms and solder dispensers to minimize the need for manual intervention. Please refer to Line 414 in *Discussion*.

To ensure consistency and eliminate potential errors associated with manual operation, we are exploring the development of new tool heads, such as pick-and-place and solder dispensing, to automate the integration of electronics into the robot chassis.

Response to Reviewer #4

The authors have answered the questions in a methodical manner, here are my further comments on their answer.

Q: 2. The material characterization is focused on the bonding force between two different types of TPU, but the solution that was implemented is the one with the lowest characteristics. It is not clear which were the requirements and what was the rationale for investigating the material interface. It seems that this type of characterization is out of scope of the paper as it is not adding value to the overall scenario that is presented.

Comment: The authors have answered about their specific approach of development of their framework, but in my opinion the question is not fully answered. According to the authors, the characterization is done to give a large audience a guideline for designing the interfaces. The straight interface, I quote: “exhibited separation at relatively low-stress levels”. According to the supporting material, the testing has been done on a very limited number of samples, so it is not possible to conclude if the detachment at the interface appears more often than in the “dovetail” or “finger” configuration. Overall, little information can be gained by this characterization.

We appreciate the point of the reviewer. In our specific robot demonstration, the loads applied (≈ 1 MPa stress) did not necessitate the use of finger or dovetail interfaces, which is why we opted for straight interfaces (with a safety factor ≥ 4 , as noted in line 124). However, certain scenarios may require stronger interfaces due to different loading conditions. For our resubmission, we added a table that shows the amount of force each interface/material combination can endure before failure; which can be referred to as a reference point during design of different robotic systems (please see *Failure Force Comparison for Different Material and Interface Combinations* in SI). The table shows that the amount of force that can be endured changes significantly by altering materials and/or interfaces, which adds new degrees of freedom to the design space while exploring the property changes caused by multi-material prints. Researchers who use our framework can either simulate or prototype their robots in specific scenarios to understand the force requirements, and accordingly make design selections.

To address this further, we added the following text in *Results - Material Interfaces* (Line 126):

However, we note that dovetail or finger interfaces might be required in other specific robot applications involving greater force exertions. Supplementary Table 5 in the SI provides the ultimate tensile forces that each material and specimen combination can withstand before failure. This table is intended to serve as a reference for selecting appropriate materials and interfaces depending on the operation scenarios, creating new design selections for different robot applications.

Q: 3. The choice of polymer for an application where a repetitive motion is foreseen could be based on other indicators beside the young modulus, which was the only measured characteristics. There is no mention of fatigue resistance of the interface or any characterization of the viscoelastic properties of the material, which could be more relevant for the work presented.

Comment: The authors have responded fully to the question

No further action is taken.

Q 4. Since the intended scope is to pave the road for power efficient soft robots, there should be a mention of the energy used for bending the soft joints. There are some questions that may raise: How is the choice of materials affecting the energy needed for locomotion? What is the efficiency of this locomotion mechanism?

Comment: The authors have responded fully to the question

No further action is taken.

Q: 5. As claimed by the authors, one of the benefits of soft robots is the improved stability, achieved by the intrinsic material characteristics. The locomotion tests measure the performance of the robots that were built, but without a specified scope. Some questions remain unanswered, for example: what is the ultimate goal that the authors want to achieve? If the goal is

stability, how is stability measured? Is the goal maximizing the speed? Is it the capability of moving efficiently on different surfaces? Some more detailed explanations of the level of improvement compared to the state of the art would better show how this specific design is advancing in the field of soft robotics.

Comment: The authors have specified the scope of the paper, which is providing a general framework for future studies, without claiming a specific area of optimization for their robot.

The reviewer's comment is exactly right. This study does not aim to create a single, task-specific robot; rather, our robots serve as demonstrations of how our general framework can be implemented.

Q 6. The authors are aware of the limitations of the design proposed. Some aspects could have been further explored to give additional purpose to the framework that the authors are proposing. The design of the control system of this robot is purely kinematic. In the field of soft robotics, the dynamic of the walking has been widely explored (See for example, as a review on the topic, Calisti et al. "Fundamentals of soft robot locomotion", <https://doi.org/10.1098/rsif.2017.0101>). Some considerations of these aspects would have been beneficial to the scope of the paper.

Comment: The dynamics of locomotion has not been taken into consideration by the authors. This intentional choice is limiting the field of application of their framework to the design of the locomotion system in terms of materials choice and composite material performance.

We acknowledge that we have not conducted an analytical analysis of the locomotion dynamics due to the complexity of modeling soft linkages.

Locomotion dynamics however can be studied not only analytically but also numerically, and in this study, we took the latter approach. Therefore, we disagree with the reviewer's assertion that locomotion dynamics were entirely omitted. In fact, we analyzed the dynamics through time-dependent finite element analysis (FEA). Specifically, we applied the governing equations of motion, incorporating time-dependent displacement and acceleration terms ($\rho \frac{\partial^2 \mathbf{u}}{\partial t^2}$), along with internal stresses and external forces, to capture the dynamic behavior of the leg mechanisms under cyclic loading (see Supplementary Information, Finite Element Analysis Information). The deformation gradient ($\mathbf{F} = \mathbf{I} + \nabla \mathbf{u}$) quantifies dynamic structural deformation, while the stress tensor models the resistance of the material to such deformation. By conducting a time-dependent study, we achieved an accurate simulation of the dynamic locomotion behavior of the robot, addressing both material compliance and mechanical movement. These analyses, supported by experimental validation, ensured a comprehensive evaluation of the dynamic performance of the mechanism.

Q 7. Lines 161-168. The planar design is an intrinsic feature of this 3D printed part, but in the traditional four-bar mechanism is this characteristic a real limitation and under what aspect? The authors mention that in their design the crank still needs to be offset, so, overall, this robot has the same limitation of the traditional mechanisms.

Comment: The authors have responded fully to the question

No further action is taken.

Q 8. In Figure 4 it would be interesting to compare the analytical solution, the FEM model and the video tracking on the same graph.

Comment: The authors have responded to the comment

No further action is taken.

Q 9. In Figure 7 the lettering of the caption is incorrect.

Comment: The authors have responded to the comment

No further action is taken.

Final comment: The overall work is well structured, and the authors have responded to the comments in an appropriate manner. In the reviewed manuscript it is more clear what is the scope of the paper: giving a general overview of their advancement in the design of a soft mechanism for locomotion and give the community a framework to work on.

We thank the reviewer for their very thorough review of our study, which we feel contributed significantly to the quality of our work.