Responses are in green text

Meta Reviewer

This article describes a tool to keep the head and neck of patients stationary during cancer radiation therapy. The authors propose to use soft robotic continuum mechanisms for this purpose. While this is an application of soft robotics with significant potential impact, the reviewers point out a number of significant problems with the article at its current stage.

In general, some of the claims within the paper are very difficult to verify and the work is very difficult to replicate by the readers, thus reducing the utility of this paper at its primary purpose: a means to disseminate knowledge.

More specifically, the proposed mechanism is not described or validated in sufficient detail. The work does not include experimental data to support the included models and numerical simulations. The explanation of the numerical FEA approach and results is limited and difficult to study. Some of the design and manufacturing decisions are not justified appropriately.

Response to Meta Reviewer:

This work is mostly a mathematical model of the continuum robot and its validation. Experimental data are currently being worked on.

Reviewer 1

The concept appears original for the most part, although the authors should probably cite [1] which describes using airbags for head and neck positioning. Note: this reviewer is not affiliated with the authors of [1].

The motivation for the work is explained clearly. The idea seems relevant and worth investigating. That said, there are a number of serious problems with the manuscript. This reviewer does not recommend publication without complete revisions and another review cycle.

If the authors were to construct and test a prototype device it would go a long way toward improving the paper. A more detailed design and explanation of the kinematics would also help.

Response to Reviewer 1

- [1] has been cited

Serious Problem 1

The "mechanism" is not explained at all clearly. The illustration in Figure 2 does not indicate how the "links" and "joints" mentioned in the Gruebler-Kutzbach expression are actually arranged. How are the IAB's connected to the springs and/or fixed framework? What exactly does it mean that "each IAB joint is constrained along 2 DOFs"? What do the "three kinematic chains" look like, what is anchored, what is mobile, where are the springs and IABs and how exactly are the springs and IABs connected? etc etc. For an example of the type of diagram this reviewer would expect to see instead of Figure 2, see the attached image. (This is just a representative image taken from an arbitrary paper [2] this reviewer found. This reviewer is not affiliated with the authors of [2].)

So, to summarize Problem 1, the surrounding framework that hold the IABs around the head, and the exact nature of the resulting kinematic chains created by the framework + IABs + head is not explained clearly.

Response to Reviewer 1

- The mechanism has now been described without using the Gruebler's-Kutzback mobility condition since it is rarely mentioned in the rest of the paper. To describe the freedom, constraints and connectivities, I have followed the style of Hunt, 77 (see [27] in references).

Serious Problem 2

The explanation of the IAB mechanism is inadequate, and the authors do not seem to have actually prototyped a functional IAB (so all of the discussion is modeling of a hypothetical device).

The IAB's are described as having an "internal cavity surrounded by two shells, which are made out of incompressible materials". The cross section of the IAB in Figure 6 does not indicate what is internal cavity and what are the two shells. How is this to be constructed? What materials are the two shells? Are they bonded together, or is there space between them? The image in Figure 6 shows (1) an inner gray circle, (2) a white circle, (3) a gradient-colored annulus, and (4) an outer black circle. Is the white circle the inner shell and the black circle the outer shell? If so, then what is the gradient-colored region in between? Which part of the device obeys the isochoric (constant volume) constraint? Is the air pumped into the central cavity?

Response to Reviewer 1

- Okay, we have explicitly stated that this paper's scope is limited to the model of the system only

- The figure in question has been redrawn and the labels have been inserted to further elucidate the texts that allude to the figure in the paper.

Serious Problem 3

The assumption for spherical symmetry of the IAB does not seem to be valid at all. In Section IV C, the authors state:

"the amount of dent that would be caused by a patient cannot be accurately predicted without extensive statistical analysis before treatment. And if at all this is baked into our model, the constituent spherical harmonics model for the dents would only complicate the overall model increasing kinematic solve time. To avoid this, we have chosen stronger material moduli for the outer IAB shell."

If I read this correctly, it means the authors have chosen the IABs to be so stiff that they do not deform or "dent" when they are pressing against the patient's head. But the deformability is equivalent to compliance (or softness) and the compliance is the whole point of using IABs in the first place, as stated in the Introduction. It doesn't make sense that the "compliant" IABs are assumed, for the sake of model simplicity, to be so stiff that they are not, in fact, actually compliant.

A realistic model of an IAB that includes its primary function (i.e. compliance to the patient's head) must include the ability to dent and/or deform into an ellipsoid in response to external force from the patient's head.

Response to Reviewer 1

- This language has been removed. This property has been verified in our new IAB designs in the lab but we do not include this sentence in this paper because this new hardware design is different from the one in the paper.

Minor Problems

The labels in Figures 6 and 7 are very difficult to read.

In Figures 8, 9, 10, 11 the authors mix Imperial and metric units (psi = pounds per square inch, and centimeters). The units for modulus C1 and C2 are not provided, so the author is left to guess whether it is Imperial or metric.

If the material properties are compared to Shore Durometers of common materials it would help the reader intuitively understand how stiff the IAB material is.

Response to Reviewer 1

- The material strength has not been described because this paper is model-based only and it is written to be general enough for any silicone material users may so choose.

The deformation pattern shown in Figures 8,9,10,11 appear nearly identical, so perhaps not all four figures are required.

Response to Reviewer 1

- Two of the figures have been removed consistent with this observation.

References

[1] A Remote-Controlled Airbag Device Can Improve Upper Airway Collapsibility by Producing Head Elevation With Jaw Closure in Normal Subjects Under Propofol Anesthesia, 2014 Satoru Ishizaka et. al. Digital Object Identifier 10.1109/JTEHM.2014.2321062

[2] Kinematics and Dynamics of a Translational Parallel Robot Based on Planar Mechanisms, 2016 Mario A.

Reviewer 2

The presented paper focuses on H&N stabilization mechanisms during cancer radiotherapy. The head and neck motions during the therapy lower the accuracy of such operations, and therefore, a C3 soft-robot-inspired mechanism is studied towards understanding the improvement of accuracy with such a mechanism. The previous works [13-15] have studied the mechanism's performance by considering lumped parameters for patient+treatment couch+IABs as also explained in this paper. The major contribution of this paper is providing the derivation of constitutive models for IAB chains, and the provided results are confirmed with simulation results.

The paper is organized well. Images and tables could have been organized better. The style of writing is clear in most of the sections. The presentation is fine. The citations are sufficient. The paper has a good amount of technical content.

Major Concerns:

1. In terms of content and contribution to the field, in addition to the theoretical and simulation studies for such a practical problem of H&N stabilization in clinics, it is important to provide physical experimental results. For publishing such a study into RA-L, the proposed solution and model should be validated with proof-of-concept designs or with practical applications. Otherwise, this study remains incomplete.

Response to Reviewer 2

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+ Okay, but this cannot be described for now owing to the limited scope of t
his paper.
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2. There is highly limited information on FEA simulations used in this paper. We can not evaluate if the FEA results are accurate and can be used to validate the constitutive model. Additionally, more technical details for the simulations should be provided: knowing the boundary conditions, assumptions, simulation parameters such as mesh size, solver type, tolerance, simulation environment (any FEA software or custom software) are important for a proper evaluation of the simulations which are used for validation of the constitutive models.

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    + This paper uses finite elastic deformation, not finite element modelin
g, sorry.
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3. Equation (1) and the paragraph below is not written well. The Reuebler-Kutzbach mobility condition provided in Eq.(1) is not clear since typically N includes the fixed link as well. To my understanding, N presented in this paper does not have a fixed link, which causes a modified Gurebler-Kutzbach mobility condition as presented in (1). Providing more information on this section would be appreciated. Again for the same section, it is not very well-explained how you claim \sum_i=1,^g f_i = 16 DOFs. Please provide more technical details here. How can an IAB represented as a joint, what are those DOFs etc.? Lastly, the paragraph right after Eq.(1) has incomplete sentences and poor explanations. This section should be revised carefully. "IAB joint is constrained along 2DOFs": It is confusing, if it is constrained in 2DOFs, then there is 4DOFs for each IAB joint and this makes the calculation for (1) highly off. Lastly, and the most importantly, I do not see how this section is relevant/used in the rest of the paper. The rest of the paper analyzes a single IAB module, while the DOF analysis is for a whole system-level concept. Again, if there'd be an experimental study, then it'd make sense to analyze the overall performance of the whole system.

Response to Reviewer 2

- This was addressed in response to reviewer 1's comments above

Minor comments: We chose a Poisson ratio of 0.45-0.5..." Please provide brief information about why you did not choose only a single Poisson ratio but two distinct values, and what was your Poisson ratio for each simulation.

Response to Reviewer 2

- a fixed Poisson ratio has been used

"Our goal was to radially expand the internal shell by a 3cm." Why do you pick 3 cm? Please explain briefly why you picked such desired simulation goals throughout the paper.

Response to Reviewer 2

- 3cm was chosen heuristically

Small edits: In abstract: "... and then present results that", please change to "... and then present the finite element analysis (FEA) simulation results that"

Response to Reviewer 2

- fixed

In Fig.2: The figure should be more clear for a better understanding. Please include some arrows pointing to each cartoon element for IABs, links etc.

Response to Reviewer 2

- done

"... and sensing cost does not justify the..." replace by "... and sensing cost does not justify such..." **Response to Reviewer 2**

- done Lots of punctuation errors before/after/on the equations, i.e. before eq.2, after eq.11, before and on eq.17, on eq. 19.

Response to Reviewer 2

- fixed

shellβ -> typo under section IV.A

Response to Reviewer 2

- fixed

The tables in 8-9-10-11 are blocking the actual figure's coordinate frames.

- needs fixing on sunday

Reviewer 3

The paper describes a new mechanism and its model for use in a medical robot for cancer radiotherapy. The paper was well written and well organized. It presents an interesting idea on the mechanism and also provide modeling. Overall, the paper is nice, but it would be great if the authors could provide more information and a little bit of more results on the proposed work.

Fig. 2 shows the mechanism, but it would be great if the authors could provide more details on the mechanism with figures. The reviewer understands the concept in general. However, it is difficult to imagine the mechanical system from the figure.

Although the paper is focused on presenting the mechanism and also providing analytical models for the mechanism, it would be great if the authors can provide any prototype of the proposed systems even though it is preliminary. Also, any preliminary results from the prototype will be appreciated.

The authors show nice and thorough modeling of the proposed mechanism. However, to be used in the actual application. It should be integrate with a control system for closing the loop. In this case, the reviewer is wondering if the authors have done any analysis in consideration of control, such as bandwidth. If the procedure does not need to be quick, it would be easier to control the system. Otherwise, the authors need to think about how fast the system can react to set the control frequency.

The authors present nice modeling with simulation result on an individual IAB. However, when multiple IABs are integrated in the system with existence of the patient's head. The dynamics will be different. It would be great if the authors could provide any analysis on the system level in addition to the individual actuator level.

Response to Reviewer 2

- this is being worked upon for our next paper

The reviewer feels that the paper is too much focused on theory. It would be great if the authors could provide any experimental results with an actual prototype that validate the mechanism as well as the models provided in the manuscript although the results are preliminary.

The reviewer is also interested in knowing the right dimensions of the proposed system and also the influence of the size of the system on the performance. Is there any minimum or maximum size for the system?

How is the damping of the air filled in the IAB takes care of? The damping effect of the air will cause a delay of the system.

The reviewer would appreciate if Fig. 4 could be improved. It is not easy to understand how many parts exist and how they work.

It seems the manuscript was written in a bit rush. There are typos or grammatical errors in multiple places in the manuscript. The reviewer suggest proofreading of the entire manuscript. The followings are only a few examples of errors.

- Page 1: from target => from the target
- Page 2: enable us write => enable us to write

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Poisson ration => Poisson’s ratio
played significant role => played a significant role
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- Page 3: Poisson ratio => Poisson’s ratio

Response to Reviewer 2

- all fixed