Peer Review File

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Reviewer A

General Comments:

This is a nice review that highlights the paucity of direct measures of *in vivo* spine loading. I have a few general comments and some minor comments as well.

1. It would be nice to include a summary of the load values that were reported in the literature. Maybe as part of one of the tables. The text includes one or two mentions of measured loads. It would be nice for the reader to be able to see all of the maximum loads recorded for each activity and device. I think this would provide a more comprehensive review of the results, rather than primarily a review of the methods/technology, which is what this is now.

Reply 1: We thank the reviewer for their kind words and suggestions. The authors also agree with this sentiment have included a table with the maximum loads published in those papers.

Changes in text: Modified table 1 to include more details for each paper

2. There is no mention in the paper about loads to the cervical spine. There is ample opportunity for future devices to be placed in the cervical spine due to the growing popularity of cervical disc arthroplasty which is much more common than lumbar disc arthroplasty. It may be useful to mention this as a potential opportunity for widespread use.

Reply 2: We thank the reviewer for this suggestion. The authors do acknowledge the potential for SMART implants to be used in the cervical spine.

Changes in text (Line 260, 263): “If such designs were to be achieved, SMART implants could be implemented into the cervical spine, which anatomically smaller than the lumbar spine. This would be of great clinical relevance considering the frequency of cervical arthroplasty and anterior cervical discectomy and fusion that is performed each year”.

3. A limitation that should be mentioned about some of the devices are that they lack the ability to directly measure load sharing, that is, load to the vertebral body and simultaneously to the posterior elements. A comprehensive measurement system is needed, otherwise we are inferring or guessing that if load is decreased in posterior elements a corresponding increase occurs to the vertebral body. We need quantitative evidence to confirm that actually happens.

Reply 3: We thank the reviewer for this insight. We have added a section in the 'Challenges for SMART spinal implants' to address this.

Changes in text (Line 296): "Secondly, there are obstacles related to their capacity to directly measure the biological load sharing of spinal segments. All designs covered in this review except one discussed by Szivek et al. measure loads exerted on the implant as it performs in vivo. Whilst it may be able to infer the loads exerted on the vertebral body and the posterior elements, these inferences may not correspond to exact forces and moments acting on the in vivo biological spine. As such, future models may explore an alternative design that may be able to obtain quantitative biomechanical evidence from both the implants and the surrounding biological environment."

Minor comments:

1. In Figure 1, the second row, box on the right. Please explain why the 140 records were excluded. All of the other boxes containing excluded records contain an explanation, but not this one.

Reply 1: We thank the reviewer for pointing out this oversight. We have clarified this in the figure by adding an explanation:

Changes in figure 1: Added reason for exclusion of 140 articles, "Clinical articles in the field of spinal surgery not pertaining to implants, biomechanics or data logging."

Reviewer B

This is a review paper on SMART spinal implants. The authors demonstrated systematically assessed the available literature on SMART spinal implants and present these findings in a clinically relevant manner. 'SMART' implants refer to modified orthopedic implants that combine the biomechanical safety and efficacy of traditional devices with the intelligence of data-logging sensors—all 18 of our included studies utilized strain-gauges as their primary form of sensing technology. At present, SMART spinal implants have primarily focused on utilizing strain gauges to report loading on the implant itself. Future work includes documenting the correlation between data provided by these SMART implants and clinical findings, including complications such as pedicle screw loosening and interbody cage subsidence. It is very well written about the current status of SMART implants, including limitations. The comment from me is as follows:

1. Line 154-157, "Furthermore, intelligent data-driven devices capable of integrating sensor information with other sources of medical knowledge such as family history, genomics, and

connectomics would accelerate the current trajectory to a more personalized and individual-focused healthcare system." This sentence needs to be presented more clearly.

Reply 1: Firstly, we would like to show our appreciation for the reviewer's kind words and insights. We have clarified this statement to read more concisely and efficiently.

Change in text (Line 155): "Furthermore, intelligent sensors that can integrate its collected data with other information such as family history, genomics, and connectomics would create a more personalized and individual-focused healthcare system."

2. Line 187-188, "it still poses a minor inconvenience for day-to-day use, outside the laboratory setting." What are the inconveniences?

Reply 2: We would like to thank the reviewer for this comment. We have made the appropriate changes by listing some examples of these 'inconveniences.'

Change in text (Line 189): "And whilst these models have been successfully integrated for live biofeedback in cochlear implants and pacemakers, the need to carry or wear external electronics may pose a minor inconvenience for day-to-day use, outside the laboratory setting."

Reviewer C

1. Lines 105-110 have to be clarified as you selected 18 studies and excluded another 21 from 55, however you always refer to 18 studies in the further manuscript. Please rephrase to clarify. Besides, this is also need to be clarified in Figure 1.

Reply 1: We thank the reviewer for elucidating this point of confusion. To clarify, there were 21 studies that were excluded from 55 with notable reasons for exclusions. In addition, there were another 16 studies that were removed due irrelevancy that did not get filtered from above that we had forgotten to mention in the figures. This has been corrected both in the figures and the manuscript.

Changes in figure 1: "Articles deemed irrelevant and not pertaining to SMART implants (n = 16)"

Changes in text (Line 110): "Sixteen studies were also excluded as they featured topics not pertaining to spine surgery or SMART implants under closer inspection."

2. The designs presented in this study only focus on acquiring data, are there already implants that can "react" to the situation?

Reply 2: We thank the reviewer for this insight. To the best of our knowledge, there is currently no SMART implants that can not only detect/sense changes to the environment but also react and create a negative feedback change, e.g., actuators. However, this would definitely be most interesting to see and we have mentioned this in our revised 'Future Directions' section.

Changes in text (Line 279-287): "Finally, this review feature sensors that have been conceptualised and designed for implants in spinal surgery. In the broadest definition, sensors are devices that detects phenomena or changes in the surrounding environment. However, many day-to-day applications of engineering involve an interactive and dynamic system between a sensor and an actuator, a device that can create movement or change in its surroundings. We envision that a truly intelligent SMART spinal implant would not only be able to sense the physical changes in in vivo load sharing but also react to these scenarios and the information that is offered by the sensors. Whilst it is unclear as to what form these actuators may take, it is interesting to imagine that future spinal implants may consist of an adaptive and fluid endoskeleton that may provide additional support or stability when it detects posture or activities that pose a high risk for the spine."