Development of Synthetic Spine for Biomechanical Research: An Overview

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Abstract. Human and animal cadaveric spines are the most common specimens used in biomechanical investigations. However, biological cadaveric spines come with a lot of disadvantages, which resulted in questionable reliability of the data obtained. This motivated the authors to look at the development of a working synthetic spine in motion segments because synthetic materials have been used widely to replace the cadaveric specimens especially for bone testing. The objective of this paper is to provide an overview of the current development of a working synthetic spine and why it is crucial to consider synthetic spine as another alternative specimens to replace human and animal cadaveric spines for biomechanical research. The development of synthetic spines studies in recent years showed a great potential to replicate the human cadaveric spine. Although some of the motions were quite stiff in comparison with human cadaveric motions, with further adjustment, the improved synthetic spine can potentially benefit and transform the spinal biomechanical investigations in the future.

1. Introduction

It is a common practise to rely on human or animal cadaveric spine for biomechanical spinal investigation. Although cadaveric spine can be considered as an ideal specimen it comes with numerous limitations and challenges. These limitations include biohazard concerns, delicate handling, high cost, and limited availability of specimens, quality, and large inter-specimen variability [1]-[2]. There are other issues such as ethical concerns and limited way to test each specimen that needs to be taken into consideration. Freezing cadaver spines are normal practise to delay decomposition and secure the soft and hard tissues attached to the cadavers. However, the handling process from extracting the spines from the donor to the subsequent process of unfreeze and freeze does significantly affect the quality of the tissues. The poor quality of the tissues will caused the inter specimen variability and sizes which resulted an incoherent data [1]-[2]. According to Wilke et al. [3] fluctuations in soft and hard tissues of cadaver spines with exposure to air over the time affected the kinematic response of the motion segments.

Animal cadaver spines such as porcine, sheep, rat and deer are normally used to replace the human cadaver spines because it is easily more accessible and cost effective. The main advantage of
using animal spines is that it reduces the inter specimen variability issues because the geometry and properties of animal cadavers are more uniform than human cadavers [4]. However, the best animal to represent the human spinal structure is still not well known because of the distinct anatomical differences between humans and animals [4]. Researchers need to carefully consider the type and animal used in their biomechanical testing to obtain optimum results because different animals provided different data which could make the reliability of the results questionable. Besides, since animal cadaver spines are from living spines it still carried similar limitation with human cadaver spines as mentioned before.

Synthetic materials have being used widely as another alternative specimen in biomechanical testing especially trabecular bone testing. There are varieties of commercially available material that can be used as synthetic bone such as polymer form, polyvinyl chloride (PVC) foam and polyurethane (PU) foam [5]–[8]. Currently PU foams are more favorable compare to other materials because it has similar mechanical properties to human bone including compression modulus and yield stress. The main advantage of PU foam as compared with composite materials is low cost and easy to handle [9]–[12]. This initiates a development of synthetic spine in a full motion segments. Sawbones (HQ?, USA?), a company that offers biomechanical materials, has recently introduced a synthetic spinal testing model for biomechanical testing and it opens a potential in research and development of a working synthetic spine to be produced. This paper aims to provide an overview of the current development of a working synthetic spine and why it is crucial to consider synthetic spine as another alternative specimens to replace human and animal cadaveric spines.

2. Development of synthetic spine

The possibility of the synthetic spine development started when Sawbones introduced a new synthetic adult lumbar spine model for biomechanical testing in 2013. Wang et al. [13] evaluated Sawbones model of L3/4 motion segments in comparison with published data of human and sheep spines. They evaluated three models of L3/4 of spinal motion segments using pure moment cyclic testing system. Moments of ±7.5 Nm were applied in all six degree of motions, flexion-extension, lateral bending and axial rotation at 1Hz for total 10000 cycles using MTS Bionix as shown in Figure 1 [13]. The study suggested that in comparison with human spines, the ROM of synthetic spine were within the range of the data except for axial rotation and even after 10000 cycles, the ROM of synthetic spines were still within the human data [13]. One of the limitations of this study is that the comparison data was drawn from published cadaver specimens hence it is difficult to make a direct comparison with the synthetic spine data [13]. However, the results promised a reasonable model to be used as another replacement for cadaver specimens especially in repetitive testing.

![Figure 1](image-url)
2.1. The Barrow Biomimetic Spine Project

In 2018, Bohl et al. [14] started the barrow biomimetic spine project aims to develop a working three dimensional (3D) printed synthetic spine to replace cadaver spines. The 3D printing manufacturing technology has improved tremendously for the past decade and it offers a great potential in the biomechanical testing. The 3D printing model has been used widely in health care system including neurosurgery, orthopaedics and plastic surgery [15-18]. As for spine area, 3D printing normally was used for complicated cases that required patient specific 3D models for preoperative planning and it also been used widely to create spinal implants model [19]. Previous 3D spine models that normally used for preoperative planning only acted as a model. The crucial part in 3D printed spine model is to ensure that it replicate cadaver tissues. Bohl et al. performed a fluoroscopic imaging technique and fidelity to human tissue of a L3-L5 spinal segment [14].

Numerous numbers of L3-L5 spinal segment were 3D printed derived from high-resolution computed tomography of a normal lumbar spine, with variable shell thicknesses and internal densities as shown in Figure 2 [14]. The fluoroscopic images were taken of these models to measure cortical thickness and gray-scale density at variable C-arm angles. The results were then validated by spine surgeons to score these images for human fidelity [14]. Pedicle screws were used into the spinal segments as additional measuring method to test if the screws placement on the 3D printed spinal model mimics cadaveric spines [14].

![Figure 2](image)

**Figure 2.** Screenshot of a 3D-rendering of the L3-L5 segment model. Blue indicates model components to be printed to mimic bone, and orange indicates components to be printed to mimic ligamentous structures [14].

The results from the study showed that the cortical thickness and gray-scale density testing demonstrated an upward trend with some changes in the print settings. For fidelity scores from the surgeons, the scores showed nearly perfect fidelity for the L3-L5 model for both with and without pedicle screws [14]. Hence, the study suggested that the 3D printed spinal models accurately mimic human tissue supported and have potential for future development. Recently, Bohl et al. performed range of motion testing on the 3D printed synthetic models comprising of L3-L5 motion segments.
The study used six synthetic spine models of L3-L5 segments that were manufactured with variable soft-tissue densities and print orientations as shown in Figure 3 [20]. Each model was printed using variables intervertebral disc density and print orientations. All specimens were tested with a torque loading to a maximum of 7.5 Nm in all six ROMs including axial compression [20]. The data were compared with historic cadaveric control data using the similar experimental protocol.

**Figure 3.** Four different synthetic spine models shown (left to right) in anterior, right lateral, posterior, and left lateral views [20].

The results from the study demonstrated that the ROM on flexion extension decreased steadily with the increased density of the soft tissues which include the intervertebral disc and spinal ligaments [20]. The important findings this study found were the 3D models performed an inverse relationship with the density of the soft tissues (intervertebral disc and spinal ligaments) and printing orientations significantly affected the model performance [20]. Overall, there were only two models (model D and E) able to obtain the maximum torque (7.5 Nm) as the cadaver spines [20] as shown in Figure 4.

**Figure 4.** Synthetic spine models D and E compared with mean data for cadaveric controls with respect to (A) flexion-extension, (B) lateral bending, and (C) axial rotation range of motion (ROM) at 7.5Nm and (D) axial compression. Error bars indicate standard deviation [20].

The results from each model were varied in comparison with the cadaver spines and there is no model has similar ROM with cadaver spines in all motions hence suggested that this synthetic
spines model required further studies before it being able to replace cadaveric spines. However, this study able to identify relevant inputs and variables that significantly affected the model and since this is an ongoing project by Bohl et al. [20], this synthetic spine models has a lot of potential to be developed into a working spine with high biomechanical fidelity to the cadaveric spines.

3. Challenges for future works
Based on previous studies conducted on developing synthetic spine, there is huge potential that a working synthetic spine can be developed which will transform the spinal biomechanical testing field. There are a lot of challenges to develop a synthetic spine that could perfectly mimic the behavior of human cadaver spines. One of the crucial points is to develop synthetic soft tissues including intervertebral discs and spinal ligaments that could mimic the natural behavior of human soft tissues. Nevertheless, the development process of synthetic spines is an ongoing projects and a lot of future studies needs to be performed before a working synthetic spine can be made. With the advance manufacturing technology, it offers a great potential to assist in developing a working synthetic spine. A working synthetic spine models will be an ideal solutions to overcome all the problems in using cadaveric specimens especially inter specimens variability which could affect the reliability of the results obtained.

4. Conclusion
The development of synthetic spines studies showed in recent years showed a great potential to replicate the human cadaveric spine. The performances of the synthetic model showed that it can mimic the movement of cadaveric motion segments in all movements; flexion, extension, lateral bending and axial rotations. Although some of the motions were quite stiff in comparison with human cadaveric motions, with further adjustment, the improved synthetic spine can potentially benefit and transform the spinal biomechanical investigations in the future.

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