



**JOHNS HOPKINS**  
APPLIED PHYSICS LABORATORY

**Task 3**

**Electrical Effects – Bone Fracture  
(Vertebral Fracture)**

**Task Report  
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### Acronyms

Acronym	Definitions
HEMI	Human Electromuscular Incapacitation
JHU/APL	Johns Hopkins University Applied Physics Laboratory
JIFCO	Joint Intermediate Force Capabilities Office
CT	Computerized Tomography
MRI	Magnetic Resonance Imaging
CEW	Conducted Energy Weapon
PCSA	Physiological Cross Sectional Area
MMS	Maximum Muscle Stress

## Executive Summary

Current human electromuscular incapacitation (HEMI) devices are designed to incapacitate humans for 5 to 15 seconds. However, future HEMI designs may consider longer durations. As such, a need exists to study the effects of prolonged muscle excitation and contraction. The primary goal of this report is to estimate the chance of vertebral fracture risk due to prolonged electromuscular excitation. To achieve this goal, we take a multi-faceted approach to determine the potential for vertebral fracture due to HEMI device use in human subjects, and porcine subjects utilized in HEMI evaluation experiments.

In porcine subjects utilized to evaluate HEMI stimuli by Burns et al. (2020), it was found that lumbosacral spinal fractures occurred in at least 89% of the porcine subjects when exposed to HEMI stimuli for 30 seconds. This high percentage of fractures observed in porcine subjects compared field use data from human exposure justifies the need to evaluate the relationship between porcine subject fracture risk and human fracture risk.

We estimate vertebral fracture risk based on compressive vertebral body fracture forces generated by muscle activation. Two methods are used to achieve this. One method calculates vertebral forces based on a two-dimensional cross sectional area of the muscle in pig and human, and the other method calculates vertebral forces based on a three-dimensional computational musculoskeletal model of the human.

Key points of this study are summarized below:

- While rare, there are at least three case reports that examine thoracic spine compression in humans following conducted energy weapon exposure. All three cases report vertebral compression fractures in the mid-thoracic spine (T6-T8).
- It is important to note that the vertebral fractures seen in the human subjects are anterior wedge compression fractures, which do not cause paralysis (paraplegia or quadriplegia). This is due to the intact facet joints that stabilize the vertebral fractures around the spinal canal, and protect spinal cord.
- Results suggest that it is possible to fracture the human spine when all of the paraspinal and abdominal muscles are fully contracted, which represents the most extreme case of electromuscular stimulation.
- Computational models will help to better interpret porcine and human subject data, and may facilitate the development of a transfer function between these subjects.
- Knowledge gained from computational models will provide insight into vertebral fracture including potential mechanisms of fracture (e.g., probe position related to the volume of activation, location on spinal cord, etc.).

## **1. INTRODUCTION:**

### **1.1 Overview**

As future HEMI device designs may consider different waveforms and durations, it is useful to consider the effects of prolonged muscle excitation and contraction on the spine. Prior porcine testing revealed that spinal fractures frequently occurred when the animals were subjected to prolonged muscle contraction [1]. This leads us to consider if the human spine is also susceptible to fracture when the trunk musculature is activated under specific HEMI waveforms for prolonged durations.

The main goal in this report is to estimate the chance of vertebral fracture risk due to prolonged electro-muscular excitation. To accomplish this, we compare the likelihood of vertebral fracture due to HEMI induced muscle contraction in porcine versus human conditions. We also investigate whether individual body types, or other risk factors, may influence vertebral fracture risk and help identify vulnerable populations.

### **1.2 Background on Literature Studies**

While rare, there are at least three case reports that examine thoracic spine compression in humans following conducted energy weapon exposure. All three cases describe incidences of thoracic spine compression that were sustained during training exercises with a Taser™ device. These case reports focus on the current Taser devices on market, however, it is important to consider the susceptibility of the human spine to fracture under different waveforms and durations that could be used in future iterations of conducted energy weapons. To understand the effect of different waveforms and durations, we examined porcine fracture cases to make a comparison between human and porcine loading.

### **1.3 Human fracture cases following conducted energy weapon exposure**

One human fracture case following conducted energy weapon exposure was reported in Winslow et al. [2]. This case was of a 38 year old healthy male law enforcement officer who voluntarily received a standard 5 second discharge from a Taser X26 model. The leads were placed on the officers' right shoulder and left hip. Following exposure, a CT scan confirmed compression fracture at T6 and T8 with 30% loss of vertebral structure. However, the CT also showed age-indeterminate anterior wedging of the L2 and several posterior disc bulges of the lumbar spine.

The second fracture case was reported in Sloane et al. [3] that examined a 37 year old healthy male law enforcement officer who volunteered to receive a standard 5 second discharge from a Taser X26 model. The lead placement was on the left scapula and right of the midline on the back. An MRI was performed post exposure and confirmed compression fracture of T7 with anterior wedging. The radiologist also noted diffuse osteopenia greater than expected for the patient's age.

The final human fracture case was reported in Tyagi et al. [4] of a 23 year old male who volunteered to experience deployment of a Conducted Energy Weapon (CEW) with lead placement on the right shoulder and right ankle. CT confirmed acute compression fractures of the superior endplates of T6, T7, and T8 without retropulsion of any of the spinal fragments. This report represents the only case to date to suffer a vertebral fracture following CEW deployment without any identifiable risk for fracture. Radiographic imaging of the two previous case reports demonstrated potential risk factors for fracture or previous injury including diffuse osteopenia in one case, and a history of wedge deformity in the second case

All three cases report vertebral compression fractures in the mid-thoracic spine (T6-T8). Winslow et al. 2007 and Sloane et al. 2008 noted that neither volunteer fell during the exposure event, thus eliminating the possibility that vertebral body fracture occurred due to impact with the ground. It should also be noted that the volunteer in the Sloane 2008 study exhibited some degree of osteopenia, which potentially increased the risk of vertebral fracture during muscle contraction. The three human case studies mentioned here are meant to be a point of comparison to the spinal fracture observed in the recent porcine HEMI tests conducted by Burns and colleagues 2020 [1].

#### **1.4 Porcine Fracture Cases**

While current commercial HEMI devices are designed to incapacitate humans for 5-15 seconds, Burns et al. studied prolonged EMI device exposure of 30 seconds in porcine subjects. The researchers evaluated the risk of spinal fracture in porcine subjected to electrical stimuli for varying frequencies (19 or 40 Hz) and electric charge per pulse (60 or 80  $\mu\text{C}$ ) for 30 seconds [1]. This study found that lumbosacral spinal fractures occurred in at least 89% of animals. Additionally, audible sounds of fracture were heard during the first 3 seconds for the 40 Hz exposure, and between 20 and 30 seconds for the 19 Hz exposure. The accelerometry data and timing of audible fractures suggested that the fractures were a result of musculoskeletal fatigue-related stress in the lumbosacral region. Due to the high percentage of fracture seen in the porcine subjects compared to human data, this study demonstrates the need to translate data obtained during porcine tests to data that can be used to study human fracture. Computational models would facilitate the development of such a transfer function between porcine and human subjects.

## **2. MATERIALS AND METHODS**

A multi-faceted approach is taken to determine the potential for vertebral fracture due to HEMI device use in human subjects, or porcine subjects utilized in HEMI evaluation experiments. Here, we estimate vertebral fracture risk based on compressive vertebral body fracture forces generated by muscle activation. There are two methods to do this; one method calculates the vertebral forces based on a two-dimensional cross sectional area of the muscle in pig and human, and the other method calculates vertebral forces based on a three-dimensional computational musculoskeletal model of the human. In the first approach, we compare the compressive

vertebral loads, as estimated from a simplified cross sectional analysis, to fracture loads associated with vertebral body fracture in the literature. This was performed for both the porcine and human anatomy. In the second approach, the more sophisticated computational biomechanical model of the human torso was used to estimate compressive vertebral loads. Since the musculoskeletal model was only previously developed for the human, porcine compressive loads were omitted from this portion of the analysis.

The reason for two different approaches stems from the fact that neither method can be fully validated. Ideally, some experimental data would serve as a gold-standard against which to assess the validity of either approach. In the absence of the experimental data for both the pig and human, two different methods are compared to one another for the human. The rationale for this is that if the spinal loads are similar in the cross-sectional analysis (first modeling approach) and the biomechanical musculoskeletal model (second modeling approach), then the estimated compressive forces are reasonable and can be used in the remainder of the analysis. However, if the two different approaches give drastically different predictions of vertebral compression force, then that would suggest one (or both) methods are not suitable for the current study. Further, no complex biomechanical model was available for the porcine musculoskeletal system, and creation of such a porcine model was outside the scope of this work.

Muscle contraction correlates with electro-muscular excitation. However, the degree of muscle contraction volume as a function of applied electric field from individual to individual is an on-going area of investigation. Since the complex relationship between HEMI device lead placement, waveform characteristics, and individual geometry/anatomy differences are not well characterized, the current analysis focused on the worst-case scenario and assumed all of the paraspinal and abdominal muscles are fully contracted. Our reasoning is that if the maximum compressive loads estimated in the pig and human are well below the compressive forces associated with vertebral fracture in literature, even when the surrounding muscles are fully activated, then the chance of spinal fracture in a healthy individual due to muscle recruitment is reasonably minimal. Alternatively, if the worst-case scenario of all the muscles being activated produces a substantial likelihood of vertebral fracture, then future studies are warranted to evaluate the sensitivity of musculoskeletal injury based the graded response of muscle contraction and the associated waveform.

### **3. RESULTS**

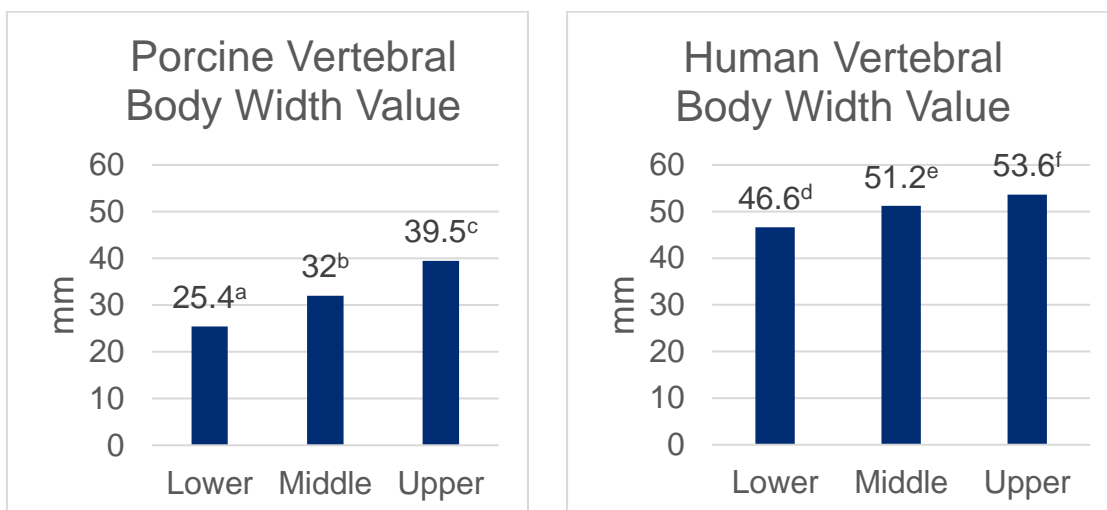
#### **3.1 Estimation of Vertebral Compression Generated by Full Muscle Excitation - Cross Sectional Force Calculations**

The first approach of estimating vertebral fracture force relies on specimen cross sectional anatomy. Here, the cross sectional area of the paraspinal and abdominal muscles at the level of the lumbar spine in the human and pig is taken from porcine Computed Tomography (CT) imaging [5, 6]. The maximum isometric muscle force ( $F_{max}$ ) at the level of the cross section is estimated by the product of the physiological cross sectional area (PCSA) and the maximum muscle stress (MMS) [7], shown in Equation (1).

$$F_{max}=PCSA*MMS \quad (1)$$

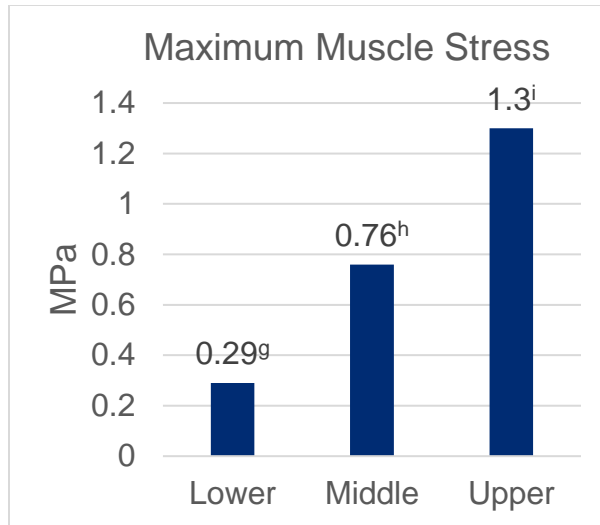
It should be noted that the PCSA and the anatomical cross section derived from the CT images from [5, 6] are not the same. PCSA is dependent on the muscle fiber pennation angle for different muscle groups, whereas the anatomical cross section is a simple measurement of muscle taken from the axial slice of the CT. Since the pennation angle information was not readily available for the porcine paraspinal and abdominal muscles at the level of the lumbar spine, the anatomical cross section was used instead for both the human and pig analysis for simplicity.

The cross section was taken from the segmented anatomy found in Bardera and Kongsro 2013 [5] and Engelke et al. 2018 [6] for the pig and human, respectively. Bardera and Kongsro 2013 created a methodology to automatically segment the different porcine tissues into muscle, fat, and bone from a series of CT images. Engelke et al. 2018 segmented muscle, adipose and visceral fat content from CT images of humans. Since the maximum compressive force generated by muscles is dependent on muscle cross sectional area, and anatomy varies within a population, three different scaling factors were used to scale the human and the pig, corresponding to lower, middle and upper range values. Scaling was performed by specifying the desired width of the human or porcine vertebral body, and uniformly scaling the segmented muscle cross sections by the same value. The range of values were taken from prior literature [8, 9]. Figure 1 shows the lower, middle and upper values used to scale the porcine and human vertebral bodies, which produced a suitable range of cross-sectional areas to calculate maximum compressive muscle force.



**Figure 1:** PCSA values from literature. a (Busscher 2010 [8]), b (Avg. Value from Multiple Studies), c (Dath 2007 [9]), d (Dath 2007 [9]), e (Avg. Value from multiple studies), and f (Busscher 2010 [8])

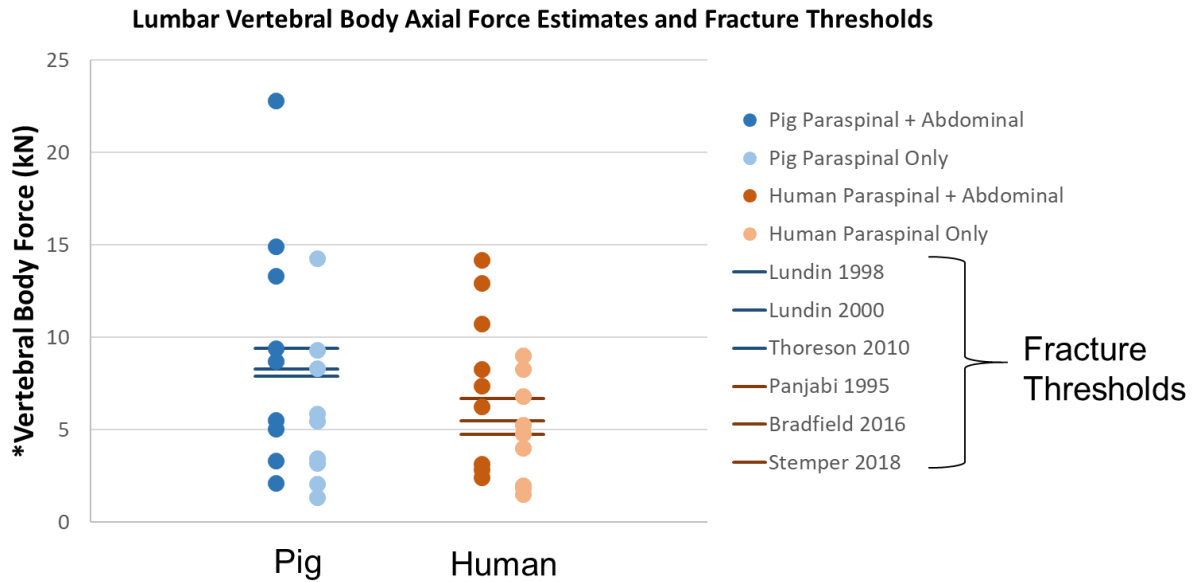
There is a wide range of reported values for MMS in the literature, which are derived from prior biomechanical research studies estimating the relative stress generated by muscle groups during various loading conditions. The MMS values used in this study ranged from 0.29 MPa to 1.3 MPa [7, 10] and can be seen in Figure 2 below.



**Figure 2:** MMS values from literature. g (Van Dieën 2005 [10]), h (Avg. Value from Burkhart 2017 [7]), i (Burkhart 2017 [7]).

Once the values of cross sectional area and maximum muscle stress were determined, the maximum muscle force was calculated for each lower, middle and upper value, giving nine potential force values for the pig and human. Figure 3 shows the estimated force values of the pig (dark and light blue circles) and human (dark and light orange circles) for each combination of the three upper muscle cross section values and the three muscle stresses. Here, the compressive force was determined for two extremes: one in which both the paraspinal and abdominal muscles were activated (darker colored circles) and one in which only the paraspinal muscle are activated (lighter colored circles). This results in a wide range of compressive forces extending from 2.0-34.2 kN for the pig and 2.3-21.3 kN for the human.

Previous experimental studies have measured the peak load associated with fracture for porcine [11, 12, 13] and human lumbar spine motion segments [14, 15, 16]. The motion segments were loaded in a pure axial manner (loading applied through the center of rotation), or a combination of flexion and axial compression (loading applied anterior to the center of rotation). In these studies, vertebral body fractures were typically observed. For the case of pure axial compression, load is shared between the intervertebral discs (and therefore the vertebral bodies) and the facet joints, where the disc supports majority of the load [17]. For the current analysis, the total compressive force was scaled by a factor of two-thirds to estimate the load supported by the vertebral body when the muscles are fully activated. The data presented in Figure 3 suggest that many of the vertebral body force estimates exceed the threshold values of fracture for both human and porcine subjects.



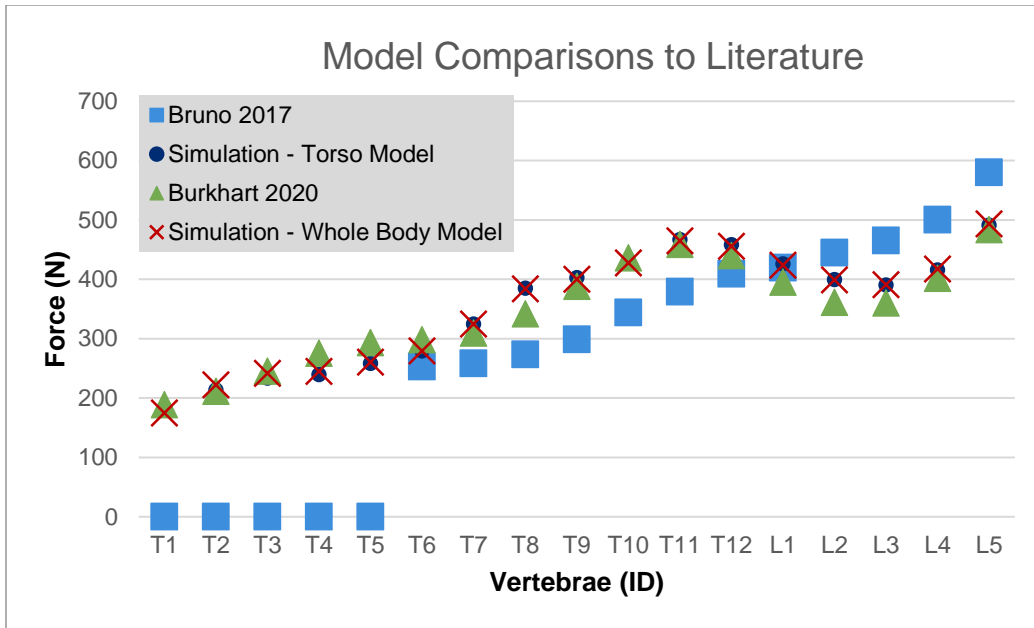
**Figure 3:** Comparison of estimated vertebral body for the pig (dark and light blue circles), human (dark and light orange circles) and failure loads measured in experimental lumbar motions segment undergoing compression (blue and orange horizontal lines).

### 3.2 Estimation of force generated by full muscle excitation – OpenSim Musculoskeletal Model Approach

Another method used for estimating the vertebral compressive loading by full muscle excitation is via an OpenSim Musculoskeletal model. The model used was an open source torso and full body OpenSim model [18 - 22]. The OpenSim model takes external force and motion files from the literature [23 - 30] as an input to perform static optimization to obtain muscle activation and forces. The Static Optimization Tool in OpenSim solves for the joint moments and individual muscle forces at each point in time. The muscle forces are resolved by minimizing the sum of the squared muscle activations. Following static optimization, joint reaction analysis was done to determine compressive loading across multiple spinal levels. The joint reaction analysis in OpenSim calculates resultant forces and moments at specified joints. This method allows us to calculate vertebral compressive loads at different spinal levels, and compare that with data reported in the literature [31, 32].

For this study, static optimization was performed on two postures to get the muscle behavior, and joint forces and moments. The two postures examined included standing in a neutral position, and standing with arms at 90° holding weights in the hands, with the weight being incrementally increased from 10 kg to 40 kg.

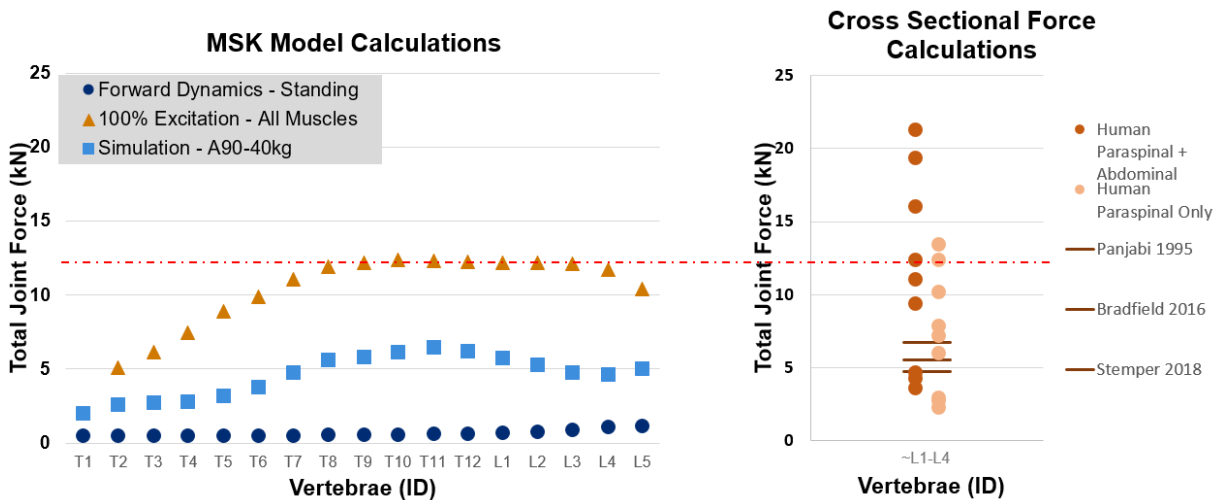
Model verification of the torso and whole body OpenSim models was completed with data found in literature [31 - 34]. As seen in Figure 4, both the torso and the whole body results match well, and are reasonable compared to results found in Burkhart 2020 [31].



**Figure 4:** Estimated vertebrae force from OpenSim whole body and torso simulations compared to data found in Bruno 2017 [7] and Burkhardt 2020 [31].

### 3.3 Comparison between MSK Model calculations and cross sectional force calculations

Figure 5 shows a comparison between the OpenSim musculoskeletal calculations and the cross sectional force calculations. The red dotted line demonstrates that both methods produce similar spinal loads when examining 100% muscle excitation.



**Figure 5:** Comparison between Musculoskeletal model results and cross sectional force calculation results.

#### **4. LIMITATIONS**

There are a few limitations that warrant discussion. First, the cross sectional area calculations in the first portion of the studies relied on a number of assumptions. For instance, since no physiological cross sectional area data were available for both the human and porcine paraspinal muscles, the anatomical cross sectional area was used instead. In practice, the anatomical cross sectional area and physiological cross sectional area are two different values, with the latter being the cross section perpendicular to the fibers, rather than being perpendicular to the longitudinal muscle direction. Once physiological cross sectional area data become available for the porcine trunk muscles, an updated analysis can be performed. Another assumption made in the current study was that the cross sectional analysis portion relied on maximum muscle stress estimates from prior studies [7, 10], which rely on various modeling approaches and are subjected to their own assumptions and limitations. Consequently, there is inherent uncertainty in the maximum muscle stress values in the current study. To the author's knowledge, direct measurement of maximum muscle stress in animal and human volunteer studies is not possible. As more musculoskeletal models are developed under a variety of loading conditions, confidence in the maximum muscle stress used will increase.

Another limitation of the current study is that vertebral fracture was correlated to compressive force, as reported by prior biomechanical experiments evaluating Post-Mortem Human Surrogate (PMHS) responses [14, 15, 16]. Compressive force was used as the fracture correlate since the musculoskeletal model analysis treated vertebrae as rigid structures. A future, and more complex study, can leverage finite element analysis to calculate the distribution of stress within the vertebrae, and use stress-based criteria to estimate the onset of fracture as a function of muscle activation.

#### **5. CONCLUSION**

These two methods suggest that it is possible to fracture the human spine when all of the paraspinal and abdominal muscles are fully contracted, which represents the most extreme case of electro-muscular stimulation. The cross sectional force estimates of the pig lumbar spine also suggest it is possible to induce fracture when all of the porcine paraspinal and abdominal muscles are fully contracted. It remains unclear if longer duration electrical muscular incapacitation (>5s) is capable of recruiting enough muscles to produce spinal compressive loads associated with fracture. Additional modeling efforts are underway that will provide a more detailed description of muscle excitation with regard to magnitude of the stimulus and location of the electrodes. These data are necessary to better estimate the risk of vertebral fracture. Based upon these more precise evaluations of individual muscle group activations, more precise estimates of vertebral fracture risk may be obtained.

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