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Tensile Force Limits of the Sheep Spine: Comparison to Forces Required to Extricate Grain Entrapped Victims

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ABSTRACT

Objectives: Grain storage facility entrapments continue to be of concern in the agricultural industry, with nearly 1,500 documented incidents recorded over the last 45 years. Previous research studies have shown that attempting to extricate a full-size pulling test dummy from a grain mass requires a substantial amount of tensile or pull force – e.g. up to 1.32 kN if "buried" at waist depth, 2.77 kN at chest depth, and 4.01 kN at head depth. There is, however, a paucity of studies on the amount of distraction the human lumbar spine region can endure. The objective of this research study was to test the maximum tensile force that could be exerted on a sheep's spine (comparable to the human spine) before the intervertebral discs and surrounding ligament would show signs of failure.

Methods: Eight lumbar-region sheep spine segments were axially distracted using an MTS Criterion tensile testing machine, and the maximum forces were recorded.

Results: The average maximum force that the spinal discs and ligament withstood before showing signs of failure was 2.14 kN (standard deviation of 0.31 kN). This is comparable to the force required to extricate an individual entrapped in a grain mass at chest depth.

Conclusion: The authors recommend that grain entrapment victims should not be forcefully pulled out if buried to waist level or above due to two primary reasons: (1) the large variation in failure load observed in our experiment with sheep spines and (2) the lack of knowledge regarding the victim's pre-existing medical condition. The extractive forces required to remove a victim of entrapment in grain overlaps with the force needed to cause potential damage to the sheep spine, as the 1.7–3.0 kN range is comparable to the 1.65–2.48 kN force range that causes axial failure in the spine.

KEYWORDS
Grain entrapment; grain extrication; intervertebral disc; lumbar; spinal injury; vertical extrication

Introduction

Grain entrapment remains a major safety concern in grain storage/handling facilities and continues to be a key issue addressed by many agricultural safety and health programs.[1–9] One aspect of this particular safety concern has to do with the total force that is exerted by the grain on an entrapped victim's body during an extrication attempt. Schmechta and Matz[10] found a 150 kg-rated harness could not sustain the force needed to extricate an individual entrapped in grain at chest level. Schwab et al.[11] found the force required to vertically extract a victim (in this case, a test dummy) increased exponentially as the grain level increased. For example, when a victim was entrapped at waist depth, an average force of 1.32 kN (kilonewton) was needed. When a victim was entrapped at shoulder level, 2.77 kN of force was needed, and when entrapped at top-of-head level, the average force needed increased to 4.01 kN. In a similar study, Roberts et al.[12] discovered a 22–26% increase in force was needed to extricate a dummy that was inside a coffer dam used to extricate entrapped victims. Issa and Field,[13] who tested pulling a dummy entrapped at various angles, found it took 2%-7% more force to extract the" victim" at low angles (e.g., 60°–75° from the grain surface) and 21%–44% more force to extract the "victim" at sharp angles (15°–30° from the grain surface). While these studies provided insight into the force a body experiences when being extricated from a grain mass, the

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maximum tensile force a victim's spine, or other body components, can endure during an extrication attempt before an injury occurs remains an unresolved question.

Due to numerous and debilitating injuries associated with the spine and the spinal cord,[14] there are many studies that have focused on spinal movement and injuries, particularly at the cervical, thoracic, or lumbar regions of the spine. For example, for the cervical spinal region, studies have been conducted on biomechanics, kinematics, coupling behavior, soft tissue, intervertebral disc, injuries, and finite element models.[15–25] Similarly, there are studies on biomechanics, axial rotations, kinematics, compression, injuries, interspinous ligament, annulus fibrosus, and intervertebral disc for the thoracic or lumbar spinal regions.[26–34] A few of these studies focused on measuring the maximum tensile forces during distraction. Myklebust et al.[22] conducted a study on monkeys where a tensile force was applied between the head and the shoulder; distraction forces of approximately 2.70 kN were applied, and failure of the cervical column always occurred between occiput-C4. Yoganandan et al.[23] found an individual cervical intervertebral disc could experience a maximum force of 0.64 kN before failure occurred. Additionally, Yoganandan et al.[23] found the maximum tensile force for an intact cervical specimen, while testing an intact cadaver, was 2.4–3.9 kN. Lastly, Gay et al.[29] applied predetermined compressive and distractive forces on a lumbar intervertebral disc and measured the stress outputs. They reported that under 0.09 kN of distraction, 6.4–7.3 kPa of stress was experienced by the intervertebral disc.[29]

While the studies above illuminated the potential spinal response to a distraction force, none of the studies answered how much tensile force a victim's spine could endure during an extrication attempt before an injury occurred. There have been cases where grain entrapment victims were forcibly removed using a harness or rope tied around their chest or under their arms, often resulting in injury, and in one documented case, death. Thus, the victim will experience a distraction force on his/her thoracic and lumbar regions. In a study on the type of spinal injuries, Magerl et al.[14] found injuries are most likely to occur in the thoracolumbar junction and are least likely to occur at the T10 vertebra or either end of the thoracolumbar spine. Due to the fact that there is a higher chance of injury occurring in the lumbar region of the spine, the authors decided to focus on the lumbar region, including the lumbar portion of the thoracolumbar junction. The authors of this study did not find similar studies to Myklebust et al.[22] and Yoganandan et al.[23] that measured the tensile strength of the lumbar column. This is not surprising given it is very rare for a lumbar region injury to be due to distraction only. When Magerl et al.[14] provided a classification system for spinal injuries, they reported that out of 1,445 cases investigated, about 14.5% of injuries were due to a type of distraction. They did not list a "distraction only (no flexion or extension) injury" as a specific component in their study. With this information in mind, the objective of our study was to determine the tensile force at which failure of the lumbar spine, including separation of the intervertebral discs and/or injury to the ligaments between the spinal vertebrae, would occur. To address this point, we utilized a cadaver sheep spine as a substitute for a human spine in our study.

Background

Relevant grain bin-related entrapment case studies

The following five documented grain bin-related entrapment incidents underscore the importance of determining how much tensile force the human spine can endure. This is important to assess if forceful extrication should not be recommended to emergency first responders as a safe extrication strategy. These five cases were chosen to highlight the variable outcomes that can result from attempts to forcefully extricate a victim from grain entrapment as the grain itself can cause compression around the human's body, along with the weight of the first responders standing on the surface of the grain.

Case #1

A co-worker tied one end of a rope around the entrapped victim's armpits and connected the other end of the rope to a pickup truck. The co-worker then drove the truck away from the bin in an effort to pull the victim out of the grain mass. This resulted in the victim being fatally injured.[35]

Case #2

A worker was entrapped up to his shoulders in wheat inside a concrete silo. Co-workers tried to pull the victim out, which caused his shoulder to pop. The victim yelled for his co-workers to stop, and rescue personnel were called. The rescue personnel removed grain up to the victim's waist and tied a harness and lifeline on him. The rescue personnel then tried to pull the victim out without giving him prior notice. Unprepared for the pull, the victim ended up feeling as if his spine was being pulled apart. On the second attempt, rescuers were able to remove the victim, place him on a medical backboard, and air-lift him to the hospital. The victim was initially unable to walk. Currently, the victim needs a cane to walk, as he is prone to falling due to the spinal injuries caused by his extrication.[36]

Case #3

Although buried up to his chest, the victim did not experience pain at the time of the rescue attempt. First responders placed a harness around the upper portion of the victim's body and attempted to pull him out. The victim immediately complained of chest pains. The first responders gave the victim analgesic drugs to reduce the pain and tried the extrication process again; however, the second attempt was abandoned because the vertical pulling caused the victim to experience unbearable pain, even after administration of the analgesics. Eventually, the victim was rescued using a coffer dam that allowed for the grain immediately around the victim to be removed, thereby reducing the pressure on the victim.[37]

Case #4

A worker entrapped up to his armpits was able to call for emergency help. First responders arrived within 5 min, placed a rope around the victim, and proceeded to pull him out. There was no report of specific injuries to the victim. Approximately 18 min elapsed between when the original call for help was made to successful rescue of the victim.[38]

Case #5

A farmer entered a grain bin to break up a plug over the auger and ended up buried in corn up to his armpits. He was able to extricate his phone and call for help. The farmer's son-in-law arrived, shut off the auger, and tried unsuccessfully to pull the victim out with a rope. The son-in-law then called the fire department, which was reluctant to use force because the farmer had both hips replaced. The victim was eventually rescued using a grain rescue tube and removal of grain from the bin.[38]

Methods

Selection and preparation of the spines

Sheep spines were utilized for this research study because a sheep's spine is considered comparable to the human spine for the study of spinal injury in the lumbar region, as noted by Wilke et al.[39] Wade,[40] and Bai et al.[41] Of the three main spinal regions (e.g., lumbar, thoracic, and cervical), the lumbar region was selected as the most likely location for an injury to occur in humans.[14] Furthermore, it is unlikely rescue personnel would attach a rope around the cervical (throat) region to extricate an entrapped victim. Sheep lumbar spines were obtained from the Purdue University Veterinary Teaching Hospital (West Lafayette, IN) and were prepared and tested on site.

The spines were harvested from three mixed breed sheep, aged 2 to 4 years-old, and frozen until needed. After thawing, the muscle around each spine was removed, with all ligaments kept in place. The spines were subsequently sectioned through the disc to provide a total of five segments of three to four vertebra (Figure 1). The spines were refrigerated between runs.

Preparing test samples

For each spine segment, two 5 cm (2 inch) sections of 10.2 cm (4 inch) diameter PVC pipe were used to embed the top and bottom of the spine segment. The pipe sections were attached to a MTS Criterion Model 43 (MTS, Eden Prairie, MN) by a threaded rod, and a custom-made steel link. The MTS Criterion is a two-column load frame device used to measure tensile or compression forces. The

Figure 1. Cleaned lumbar-region spine segments cut into lengths containing three to four vertebra.

spine was attached to the PVC pipe sections using a 3 mm (0.12 inch) Kevlar rope (Spearit Group LLC, Marco Island, FL), tested to withstand up to 408 Kg (900 lb) of tensile force. The Kevlar rope was wrapped three times around the transverse processes of the spine and the threaded rod at the base of each PVC pipe (Figure 2). Only one intervertebral disc was tested at a time, and eight discs were tested. This ensured the spine would be stretched equally and equal force would be placed on the transverse processes. A 5 kN load cell (Model LPS.503; 2.328 mv/v sensitivity) was used in this experiment, and the load frame was programmed to move at a rate of 0.1 mm/s. The MTS Criterion was programmed to continue to pull apart the spine until the force dropped by 90%, at which point the maximum tensile force was recorded. The experimental method was designed to be similar to Yoganandan et al.[23] for testing intervertebral disc segments. One key difference is that Yoganandan et al.[23] utilized rods through the vertebrate. However, this approach was not possible due to the amount of force needed to cause intervertebral disc failure.

Collecting/Analyzing the data

The purpose of this experiment was to compare the tensile force that the spine could endure versus the force required to pull an individual out from a grain mass. As a result, the data collected were reported as total force (kN) and not as stress (N/m^2). The slope of the yield line was estimated by measuring the slope of the linear region (elastic region) of the tensile force curve. The slope of the linear region was determined by evaluating a trend line that corresponded to an $R^2 > 0.99$ on the top part of the linear region. On average, the straight-line portion used in the trend line was from 60% to 70% of the total elongation measured by the MTS, or about 470 data points. This result can be compared to a study by Ebara et al.[42] that measured the annulus fibrosis (e.g., protective layer of the intervertebral disc) using the 75% elongation point to measure the slope of the linear region.

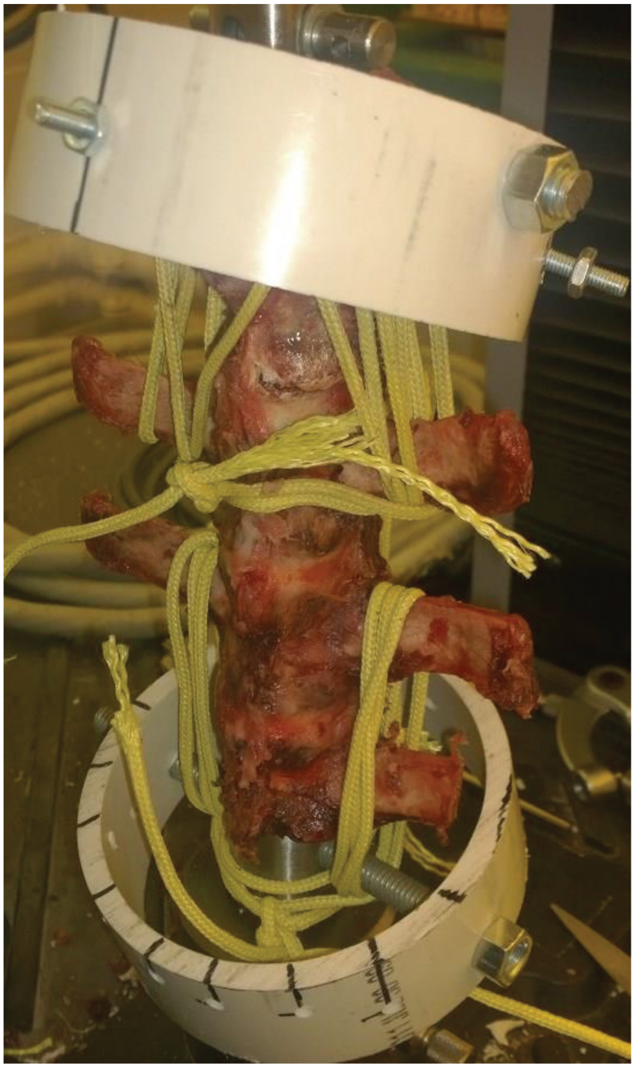

Figure 2. Sections of PVC pipe holding a spine segment, using kevlar rope, attached to the MTS criterion.

Measuring/Comparing the sample properties

After completion of the experiment, the anatomical properties of the spines were measured and

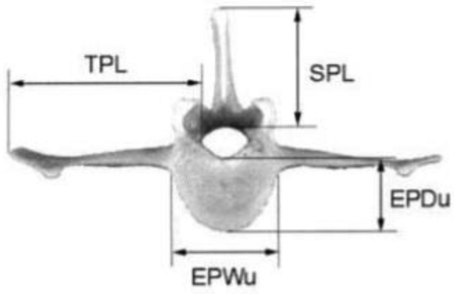

Figure 3. L4 of the sheep spine – dorsal view of the measured regions (figure from Wilke et al.[39]).

compared to values reported in the literature to evaluate if our spine samples were representative for sheep spines.[39,43] Based on the procedure provided by Wilke et al.[39] (Figure 3), the following anatomical parameters were measured using a 15.24 cm (6 in.) Fowler Sylvac Model S 235 Data Caliper (Cole-Parmer, Vernon Hills, IL): transverse process length and width (TPL and TPW), end-plate depth and width (EPD and EPWu), spinous process length (SPL), and intervertebral disc height (IDH). Intervertebral disc heights were measured only on intact discs, and all measurements for each parameter were combined regardless of the location of the vertebra in the lumbar region. These results were then compared with previously published reports to confirm that the spines we tested were representative of typical sheep spines.

Results

Anatomical measurements

The sheep spine anatomical measurements (mean ± standard deviation) were found to be as follows: transverse process length of 53.9 ± 5.3 mm, transverse process width of 118.6 ± 10.2 mm, end-plate depth of 22.0 ± 2.5 mm, end-plate width of 31.5 ± 4.2 mm, spinous process length of 29.6 ± 1.9 mm, and intervertebral disc height 3.4 ± 0.5 mm (Table 1). All spine characterization measurements were found to be within the range of values obtained from Wilke et al.[39] and Mageed et al.[43] with the exception of the end-plate depth and the intervertebral disc height. The mean EPD of 22.0 mm of our sheep spines was slightly greater than the maximum range value of 20.8 mm determined by Wilkes et al.[39] while the IDH of 3.4 mm was between the values obtained by Wilke et al.[39] and Mageed et al.[43]

Maximum spine tensile strength

The maximum tensile force for the intervertebral discs and ligaments to experience before failure was recorded in five of the eight intervertebral disc segments (Table 2). Three segments (4, 7, and 8) failed at the transverse processes, and these results were reported as well. For segments 1, 2, 3, 5, and 6, the maximum distraction force endured by the spinal segments before failure ranged from 1.65 kN to 2.48 kN, with the average force being 2.14 kN (SD = 0.31 kN) or about 482 lbf (Table 2). With regard to the tests in which the spinal transverse processes broke before the intervertebral discs and ligaments showed signs of failure, these segments were able to withstand an average of 2.02 kN (SD = 0.56 kN) of force. In one of the spinal segments where the intervertebral discs and ligaments did not fail, the two transverse processes withstood 2.66 kN and 2.35 kN of force before breaking. Rupturing the discs in this particular spine would have increased the maximum distraction average for all of the discs.

Table 1. Anatomical properties of the spine regions used in this experiment compared to those from Wilke et al. (1997) and mageed et al. (2013).

		Range of values (mm)	
Spine anatomical parameter	Values[a] (mm)	Wilke et al.[39b]	Mageed et al.[43b]
Transverse process length	53.9 ± 5.3	46.0–63.8	
Transverse process width	118.6 ± 10.2	102–140.3	94.2–130.9
End-plate depth	22.0 ± 2.5	17.6–20.8	16.3–18.3
End-plate width	31.5 ± 4.2	25.0–40.4	23.7–32.0
Spinous process length	29.6 ± 1.9	27.0–32.2	25.5–26.8
Intervertebral disc height	3.4 ± 0.5	4.2–4.5	2.6–3.3

[a] mean of each anatomical parameter ± standard deviation.

[b] measurements came from five (5 spines) with each spine containing six (6) to seven (7) lumbar vertebra. The values represent the range of the mean values across the lumbar vertebra.

Table 2. Maximum force recorded for each spine sample, before failure, under various conditions.

	Intervertebral disc Tensile (kN)	Transverse processes Tensile (kN)
Segment 1	2.20	
Segment 2	2.14	
Segment 3	1.65	
Segment 4		2.67; 2.35
Segment 5	2.48	
Segment 6	2.24	
Segment 7		1.78
Segment 8		2.11
Average	2.14	2.02

Discussion

The force-displacement graph for the spine segments (Figure 4) exhibited a toe region similar to that observed in a previous study.[43] The results of this study could be compared to the findings of Myklebust et al.[44] In Myklebust et al.[44] study, the tensile strength for each spinal ligament of human cadavers was measured in situ. Each ligament was isolated, and the force and deflection at failure was measured. For the lumbar region, this ranged from as low as 38 ± 15 N for the posterior longitudinal ligament to as high as 750 ± 159 N for the supraspinous ligament. The sum of the total measured tensile strength for all six ligaments ranged from 1.2 kN to 2.1 kN for the lumbar region, producing results comparable to this study.

The tensile strength results from this study can be compared to previous force extraction studies used to measure the force to extract a victim from a grain mass. In Issa et al.[13] a study designed to measure the vertical pull-force required to extricate a victim, the force needed was found to be 1.7 kN when the mannequin was "entrapped" in grain at waist level, 2.3 kN when "entrapped" at chest depth, 3.0 kN when "entrapped" at shoulder depth, and 4.8 kN when "entrapped" at the top-of-the-head level.[13] This 1.7–3.0 kN range is comparable to the 1.65–2.48 kN force range required to cause axial failure in the spine. It is important to note that the surrounding paravertebral musculature is expected to provide additional stability to the spine in all planes and that the baseline muscle tone will increase the ability of the spine to resist tensile forces.[44] However, the large overlap between the maximum tensile force the spine could withstand and the force needed to vertically extricate a victim remains a cause of concern. In addition, anecdotal evidence, including the case studies presented above, indicate that the possibility of an individual being injured during a vertical pull is unacceptably high.

One of the limitations of the present study is that the experiment was conducted on sheep spines rather than human spines. While the sheep spine is considered comparable to the human spine, including as it relates to biomechanical properties or motion,[40] this experiment places spines in an unnatural position/motion (extension). While the authors recommend testing the maximum distraction force a human cadaver lumber region can experience before failure, we were limited in budget and specimen access and thus chose sheep spines as the best available alternative. Validating these findings using human spines is an important future step for this research. A second limitation of our study was that the distraction force was exerted across one vertebral level and excluded muscle support. In the extraction scenario posed, multiple adjacent vertebrae will be distracted and extrication forces will be distributed. This point is of interest to further explore as part of a future study. Lastly, this study does not investigate damage that might occur at lower amounts of force, and potential future work could include investigating the spine after applying tensile force below the failure point and evaluating the condition of the individual ligaments. [Insert Figure 4 here]

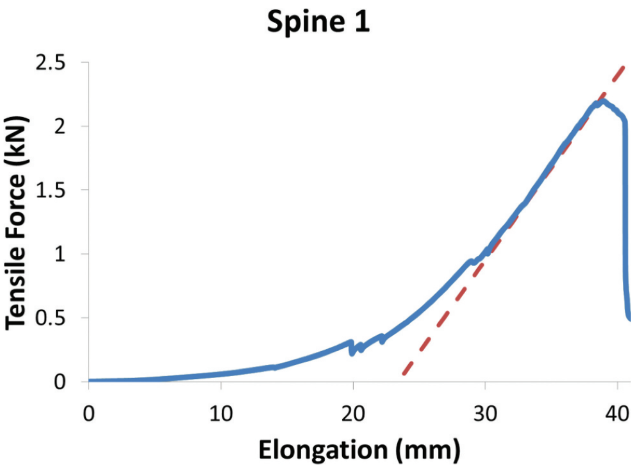

Figure 4. Sample tensile force versus elongation curve for a lumbar sheep spine segment.

The solid line represents the force experienced by the spine, and the dashed line represents the yield-elastic curve. The intersection of the solid and dashed lines is the yield strength.

Conclusion

This study determined that the maximum distraction force that the intervertebral discs and ligaments of a sheep spine could experience before failure was in the same range as the force required to forcefully extricate a victim entrapped in free-flowing grain from waist to shoulder level. These results support anecdotal evidence that extraction forces applied to the victim during extrication attempts have the potential to cause significant injury depending on the physical condition of the spinal segments. However, since how much force a specific individual's spine can handle is not known, our findings suggest that emergency first responders should be advised to avoid conducting vertical pulls as the anatomy of the spine is not designed to resist longitudinal tension. This is especially important if the anchor point is at a low angle, which greatly increases the force required to extricate the victim and causes side loading of the spine.

Further research should be conducted to confirm this study's findings by testing human spines to determine the distribution of forces on the spine during a vertical pull. In addition, utilizing a full-body harness might reduce the total force experienced by the spine, but it is unknown how significant such a reduction would be. Historically, the use of safety harnesses by entrapment victims has been so rare that first responders should err on the side of caution and not anticipate that the victim will be wearing a harness.

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Disclosure statement

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