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Exploring the cause of injury or death in grain entrapment, engulfment and extrication

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For the degree of Doctor of Philosophy ▼

Is approved by the final examining committee:

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Approved by Major Professor(s): William E. Field

Approved by: Bernard A. Engel 11/29/2016
Head of the Departmental Graduate Program Date

EXPLORING THE CAUSE OF INJURY OR DEATH IN GRAIN ENTRAPMENT, ENGULFMENT AND EXTRICATION

A Dissertation
Submitted to the Faculty
of
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by
Salah F. Issa

In Partial Fulfillment of the
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of
Doctor of Philosophy

December 2016
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May this work contribute to saving a man’s life

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NOMENCLATURE

Entrapment: A partial submersion in grain in which at least the head is visible and the victim must require assistance to be extricated

Engulfment: A complete submersion in which the victim’s body is no longer visible

Case: A documented grain entrapment or engulfment involving one victim

Incident: An entrapment or engulfment event that may contain one or more cases.

PACSID: Purdue’s Agricultural Confined Space Incident Database

Extricate: Any method used to rescue or recover a victim from a grain entrapment and engulfment including a vertical pull-up, use of a grain vacuum to remove surrounding grain or a rescue tube.

Vertical Pull-Up: A particular method used to rescue a victim entrapped in grain by pulling them out of grain directly using a harness and winch system. Note this method can only occur if the victim has preemptively worn a body harness or some rescue device before entering the grain bin.

Secondary injuries: Injuries to a victim caused by first responders during rescue or extrication efforts.

ABSTRACT

Issa, Salah F. Ph.D., Purdue University, December 2016. Exploring the Cause of Injury or Death in Grain Entrapment, Engulfment and Extrication. Major Professor: William Field.

Grain entrapments and engulfments are one of most common hazards associated with grain storage facilities. Since the 1970's over 1,880 incidents have been documented in agricultural confined spaces of which 65% of all recorded incidents were grain entrapments and engulfments. There have been several studies conducted on the contributing factors behind these incidents; however, there have been very few attempts to understand the environmental, physiological or psychological factors the victims experience while entrapped, engulfed, or extricated. This includes understanding how secondary injuries are caused by grain or during extrication by first responders. The research effort was divided into three segments. The first segment is a literature review to identify and better understand the environmental, physiological and psychological stresses that an individual might be exposed to during grain entrapment, engulfment or extrication. The second segment expands upon previous studies that involved vertical pull tests (Schwab, Ross, Piercy, McKenzie, & B.A, 1985; Roberts, Field, Maier, & Stroshine, 2015) by testing forceful extrication attempts under a wider set of variables, including different types of grains (corn, popcorn, wheat, oats, soybeans, canola seeds and

sunflower seeds), depths of entrapment, pull angles (15^{o}, 30^{o}, 45^{o}, 60^{o}, and 75^{o}), limb placement and grain moisture content (corn only). With the exception of the pull angle test, these experiments were conducted only in a small scale setting. Pull angle tests were conducted in a full scale setting using a full sized mannequin (185 lb) in corn and soybeans. This is an important study since grain bin roofs are not generally designed for 5,000 lb anchor points. In addition, the tensile force limits of a sheep spine were tested and compared to the force needed to extricate a mannequin. The third segment focused on measuring the actual pressure that a victim might experience by pushing wooden plates against grain (simulating a rib cage pushing against the grain) and measuring the force. These experiments also focused on localized forces on the spine and limbs and estimating forces generated when a test mannequin is extricated at different angles. The literature review provided a total of eleven factors that negatively impact a victim’s ability to survive a grain entrapment. The most important factor was asphyxiation (which includes aspiration, crush asphyxiation and postural asphyxiation). In 33 cases where the cause of death was medically reported, 63% cited asphyxiation. Another factor of notable importance is psychological, where it was found that stress could cause shortness of breath and chest pain and thus could be a contributing factor in death. In the extrication segment of the research, it was found that high moisture content could increase extrication forces by 39%. In addition, while shallow angles of pull did not significantly impact extrication force, pulling a victim at angles sharper than 45^{o} degrees increased extrication forces by 22-44%. Lastly, the author found that the maximum tensile force that a spine can handle (1.65-2.48 kN) was in the same range of forces required to extricate a victim from between waist and shoulder depth. In the third segment of

research, the author found that passive pressure on the victim was about four times larger than active pressure, thus a victim will experience four times more pressure in grain (while attempting to breath) than what a load cell measures. In conclusion, the best strategy to prevent or reduce the severity of injuries associated with grain entrapments remains prevention through compliance with accepted best workplace practices and current workplace safety regulations. It was determined that 94% of all grain entrapment and engulfment incidents were preventable. Regarding methods of victim extrication from grain entrapment it was concluded that there is a real and possible risk of causing secondary injuries, including spinal injury, if force is used to pull the victim from the grain. Reducing the pressure on the victim by removing the grain from around the victim is strongly recommended unless there are other significant medical issues that might reduce the likelihood of survival if extrication is not expedited.

CHAPTER 1. INTRODUCTION

1.1 Statement of Problem

Purdue University's Agricultural Safety and Health Program (PUASHP) has been documenting grain entrapments[1] and engulfments[2] since the 1960s. This ongoing effort to identify, document and analyze grain entrapment incidents led to the development of the Purdue Agricultural Confined Space Incident Database (PACSID). Analysis of the data has led to multiple publications such as Freeman, Kelley, Maier, and Field (1998), Kingman, Field, and Maier (2001), Kingman, Deboy, and Field (2003), Roberts, Deboy, Field, and Maier (2011), Riedel, and Field (2013), Issa, Cheng and Field (2016a), and Issa et al., (2016b) with several additional publications under review. As of December 2015, a total of 1,887 cases involving agricultural confined spaces have been documented and entered into PACSID, with the majority of the cases (74%) occurring in grain storage and processing facilities (Figure 1-1). In addition, most documented cases (1,145) were identified as grain entrapments or engulfments occurring mostly in grain storage facilities or in grain transport vehicles (Issa, Cheng, & Field, 2016c). The number of documented cases per year for entrapments and engulfments has hovered near the 40 cases/year mark for the last five years (Figure 1-2). Also grain entrapments/engulfments remain highly

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[1] Entrapment: A partial submersion in grain in which at least the head is visible and the victim must require assistance to be extricated from grain

[2] Engulfment: A complete submersion in which the victim's body is no longer visible

fatal with 45% of cases reported in 2014 being recorded as fatal and 49% of the cases over the last ten years as fatal (Issa, Cheng & Field, 2015). This indicates that entrapments/engulfments continue to be a major concern in the field of agricultural safety, due to both the frequency and the low likelihood of survival.

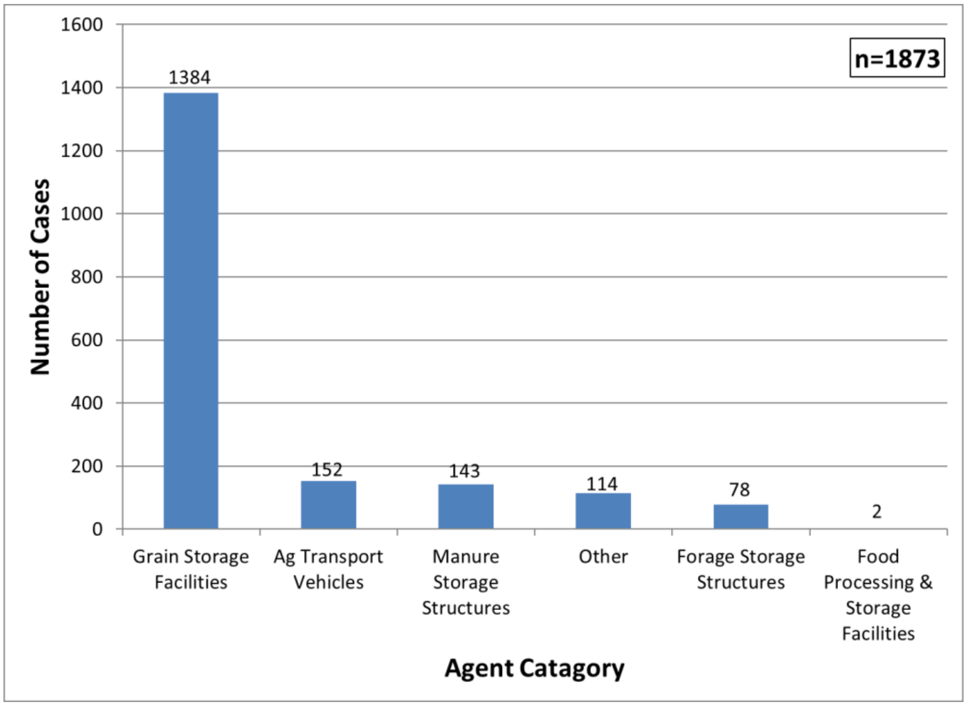

Figure 1-1 Agricultural confined space-related incidents documented between 1964-2015 based on agent category (Issa et al., 2016c).

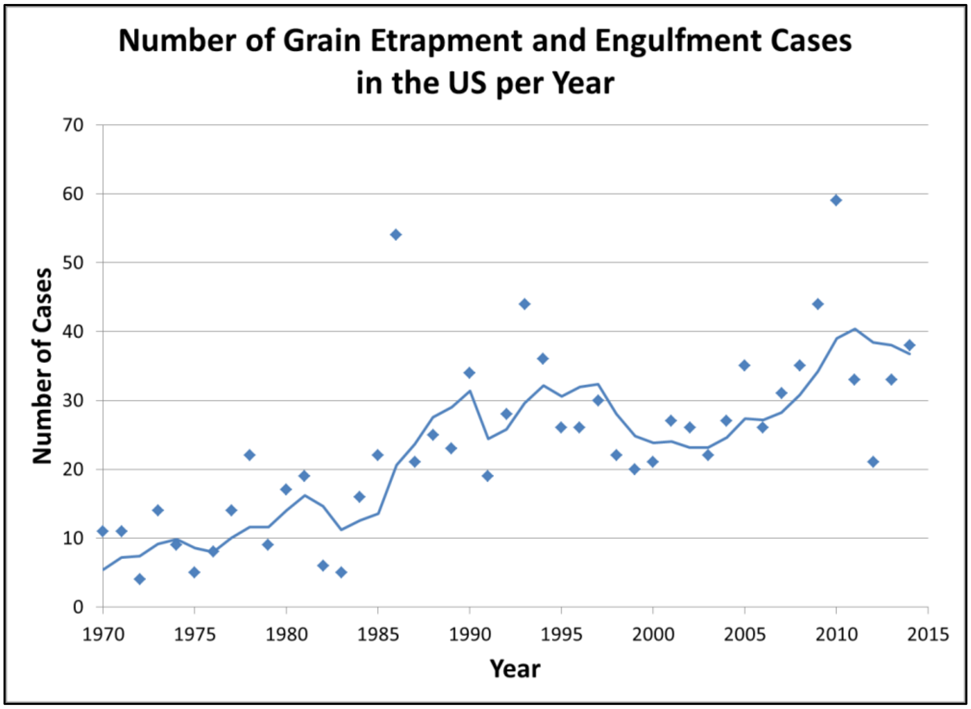

Figure 1-2 Grain entrapments by year. The diamonds represent the number of cases documented in each year and the line represents the five year moving average.

The conditions that the human body experiences during entrapment, engulfment, and during attempts to extricate the entrapped person are not well understood. These conditions can be divided in two broad categories; environmental and physiological/psychological (Table 1-1). Environmental factors are the forces that are acting directly on the body due to the weight of the surrounding grain and include friction, lateral (horizontal) pressure of grain, weight of grain (vertical pressure), availability of oxygen in the grain mass and diffusion rate of oxygen. Physiological factors are the result of the body's response to suspension in grain and include physical asphyxiation (breathing passages blocked), lack of oxygen, blood flow, heart rate and chest expansion capacity. This also includes psychological factors such as trauma, panic attacks and emotional trauma due to getting buried in grain.

Table 1-1 A list of potential environmental and physiological factors that might impact the human body during an entrapment or engulfment in grain.

Environmental Factors impacting the body	Physiological/Psychological Factors impacting the body
Oxygen • Diffusion within grain mass • Headspace	Asphyxiation • Grain in mouth and lungs • Unable to breath due to location of limbs
Grain Pressure • Lateral • Vertical • Pressure on Chest and thighs	Decreased blood flow • Lack of body movement • Cramps • Blood pooling in lower extremities
Safety Equipment • Forces transmitted to body through Harness/Ropes	Heart Rate • Limited Oxygen • Limited Blood Supply
Temperature • Hypothermia • Heat Stress	Psychological factors • Fear of buried alive • Trauma • Emotional stress

A review of published literature on grain-related entrapments reveals that most studies have focused on analysis of the causative work practice-related factors of confined space-related incidents and presentation and promotion of safer work practices and compliance with federal work place safety regulations. There has been only one study (Moore and Jones, 2016) measuring the pressure on the body and no known studies measuring the physiological/psychological stresses on the human body due to entrapment/engulfment. Moore and Jones (2016) measured the pressure that the chest experiences when entrapped in grain where they found the pressure not to be significant enough to cause postural or crush asphyxiation. This study however, used a static mannequin and load cell to measure pressure and thus did not take into account the pressure the chest cage needs to overcome to be able to expand and allow the victim to breathe. Similarly, only two studies on environmental factors were identified and in these studies, researchers used mannequins with full body harnesses to measure the extrication forces that were generated when the mannequin was pulled vertically upwards (Schwab et al., 1985; Roberts et al., 2015). Both Schwab et al. (1985) and Roberts et al. (2015) found that to pull a body out of grain would require four times as much force when entrapped to chest/arm pits level as the victim's body weight. These studies were used as a basis to generate recommendations for emergency first responders to discourage them from forcefully pulling someone out of grain (Drake, Kulkarni, & Vandevender, 2010; Maher, 1995). Further work by Roberts et al. (2015) found that the use of a grain restraint system or grain rescue tube around the entrapped victim actually increased, by as much as 26%, the forces required to extricate the victim. However, these research studies focus on idealized situations such as a mannequin wearing a full body harness, entrapped in a straight position in the center of the bin and pulled in a vertical direction. From a review of the PACSID database, most victims were found in the center of the bin in a vertical position with no safety equipment and there were multiple cases documented in which the victim's body was positioned at an angle. There were only 37 cases reported out of nearly 1,100 where it was ascertained that the victim wore a safety device before entering the grain storage facility. The type of devices varied from a simple rope, sometimes tied around the waist to a full body harness. Based upon current data, the strategy of pulling someone directly from grain, with or without safety harnesses, is problematic as the current research is based on an idealized situation that is not generally found in real life examples. This is especially true if the physical condition of the victim is unknown such as in cases of previous musculoskeletal injuries or reconstruction of joints or the presence of heart disease. There also remains uncertainty concerning situations in which the victim is entrapped in high moisture (>14%), or out-of-condition grain. Moldy grain and high moisture grain tend to stick to each other and have higher angle of repose which may substantially increase the forces involved. In conclusion, grain entrapments/engulfments remain a pressing safety issue in the agricultural community yet little effort has been made to understand the environmental and physiological forces impacting the human body.

1.2 Primary Goal

The goal of this research is to investigate and analyze certain environmental and physiological/psychological factors impacting a victim entrapped/engulfed in grain or during rescue from grain and develop a deeper understanding of the pressure on a victim of entrapment and the force required to extract them.

1.3 Hypotheses

This research aimed to test the following hypotheses:

1. A person extricated using a harness and winch will experience a significantly larger force when pulled from an angle greater than 25^o (or the limbs are at an angle) than a person pulled vertically.

2. A victim will experience a significantly greater pressure (passive pressure) when attempting to breath than what is currently measured using load cells (active pressure).
3. A healthy spine has a high risk of being injured if it experiences the pull forces needed to pull someone at an angle out of grain.

1.4 Objectives

This goal was accomplished through completing the following specific objectives:

1. Summarize the PACSID database by analyzing the frequency, severity, demographics, distribution, and trends of agricultural confined-space related incidents with special consideration to those incidents involving free flowing agricultural material including grain (CHAPTER 2).
2. Identify the physical forces exerted on a human body and the physiological/psychological effects of partial and complete engulfment in grain and extrication from grain (CHAPTER 3).
3. Review and summarize the literature on the different types of safety harnesses available, the original purpose of such devices and how they are used in grain handling, storage and processing facilities. Review the PACSID database for cases that would imply the use of any device such as a safety harness or life line during attempts either to pull an entrapped victim from grain or to prevent a victim from sinking deeper. (CHAPTER 4).
4. Investigate the amount of force experienced by a person during partial and complete engulfment in grain and during extrication from grain. This included:

   a. Conducting a small scale study to analyze the forces required to extricate a cylinder and a mini mannequin (5.5 inches) in different types and conditions of grain including corn, soybeans, wheat, canola, popcorn, oats, sunflower, and high moisture corn(CHAPTER 5).
   b. Investigate the amount of force needed to pull an entrapped or engulfed person from a grain mass at various angles and at different depths of grain (corn and soybeans) reflecting the real world incidents of entrapment (CHAPTER 6).
   c. Investigate the grain resistance to chest and lung expansion (CHAPTER 8).

5. Investigate the amount of tensile force a spine can experience without causing injury to the spine and compare with forces needed to extricate an entrapment or engulfment victim from grain as found in objective 2.c (CHAPTER 7).
6. Based on the results, develop recommendations for:
   a. Emergency first responders designed to reduce the potential of secondary injury to the victim of entrapment/engulfment including the use of safety harnesses and other rescue strategies (CHAPTER 9).
   b. Farmers and grain workers on how to protect themselves from entrapments and increase their probability of survival during a grain entrapment and engulfment (CHAPTER 9).

1.5 Limitations

1. This research used only mannequins to estimate the amount of force exerted on a human body while entrapped in grain which might not be an exact replication of what a victim actually experiences.
2. The best type of mannequin to use for this type of testing is a three-point dummy. They are used in vehicle crash testing and allow forces on the various joints of the body to be measured. However, due to financial limitations an average man sized mannequin was used.
3. The different types of grain were only tested in the 38 liter (10 gallon) cylinder experiment. Only corn and soybeans at 14% m.c. (or dryer), at optimal storage level were used in a large scale experiment that determined the forces exerted on the mannequin.
4. Chest experiments were conducted using a small 80 liter (21 gallon) tank and a system was designed to push grain horizontally simulating expansion of an entrapped victim's chest using MTS Criterion (#43) as opposed to a full scale setting.
5. In the spinal tensile strength study, representative sheep spines were used instead of actual human spines.

CHAPTER 2. SUMMARY OF AGRICULTURAL CONFINED-SPACE CASES

A modified version of this chapter has been published as

- *Issa, S. F., Cheng, Y., & Field, W. E. (2016). Summary of agricultural confined-space related cases: 1964-2013. Journal of Agricultural Safety and Health, 22(1), 33-45.*
- *Literature review section: Issa, S., Field, W., Hamm, K., Cheng, Y.-H., Roberts, M., & Riedel, S. (2016). Summarization of injury and fatality factors involving children and youth in grain storage and handling incidents. Journal of Agricultural Safety and Health, 22(1), 13-32.*

These papers was submitted for publication in 2014 and the data are up to date as of December 2013. A total of 1,887 confined spaces have been recorded of which 1,145 cases were grain entrapment cases.

2.1 Introduction

The hazards associated with confined spaces in production agriculture have historically been and continue to be significant causes of work-related injuries and fatalities (Beaver, 2005; Riedel, & Field, 2013; Issa, Cheng, & Field, 2014). Because there is no comprehensive or mandatory reporting system that collects data on agricultural confined-space incidents, it has been difficult to make evidence-based recommendations concerning the best strategies to reduce the frequency and severity of these incidents.

Since 1977, the Purdue University Agricultural Safety and Health Program (PUASHP) has managed a database with ongoing efforts to identify, document, and analyze information on injuries and fatalities on grain entrapments. This effort has led to to multiple publications, such as Freeman et al. (1998), Kingman et al., (2001), Roberts et al. (2011), and Riedel and Field (2013), that summarized and analyzed cases documented in the grain entrapment database. In addition, PUASHP has published annual summaries of U.S. grain-related entrapments and engulfments for the last decade (Roberts and Field, 2010; Riedel and Field, 2011; Roberts, Riedel, Wettschurack, & Field, 2012; Issa, Roberts, & Field, 2013).

Financial support from the U.S. Department of Labor over the period (2011-2014) gave PUASHP the capability of expanding the search for incidents and code previously undocumented incidents to include not only entrapments at grain storage and handling facilities but also asphyxiations, entanglements, falls, and electrocutions in and around all forms of agricultural confined spaces. This expanded search effort, in combination with the previous grain entrapment database, was developed into a new database called Purdue’s Agricultural Confined Space Incident Database (PACSID). This database included cases involving manure storage and handling facilities summarized by Beaver and Field (2007). In 2011, Riedel (2011) reported on the methodology for the creation and maintenance of the PACSID database and the first summary of agricultural confined-space related cases. Since then, 399 new cases have been added to the database, including 167 cases added since the publication of the 2012 Summary of Grain Entrapments in the United States (Issa et al., 2013). This article reports on this expanded effort to better understand the most critical hazards associated with a broader array of agricultural confined spaces by analyzing the frequency, severity, demographics, distribution, and trends of agricultural confined-space related incidents. The purpose of this article is to provide a better understanding of confined-space related incidents in order to influence curricula development for injury prevention and emergency first-response training that effectively targets the most significant causes of injuries and fatalities.

2.1.1 Literature Review

Workplace hazards and injuries are generally addressed by a mixture of safety education, best practices, engineering standards, and workplace safety and health regulations. For example, the problem of tractor overturns, the leading cause of farm-related fatalities, has led to a broad-based response involving more aggressive data collection, development of educational programs, drafting of new engineering standards (including the recommendation to install rollover protective structures), and attempts to regulate the age of operators. These efforts have begun to have an effect on the frequency and severity of this type of incident. This section summarizes prior efforts to address the problem of injuries and fatalities in agricultural confined spaces.

2.1.1.1 Education

Some of the earliest documented efforts to raise awareness of the risks of exposure to grain storage and handling facilities were Extension publications and fliers that included specific warnings concerning the risks of exposure to free-flowing grain (McKenzie, 1969; Baker, Field, Schnieder, Young, & Murphy, 1999; AE-1102, Nebraska; Drake et al., 2010). In 1969, McKenzie released an educational slide presentation on the hazards of flowing grain and addressed the risks to children. The resource was revised in

1978 and distributed nationally (Field, & McKenzie, 1978). This was followed by an Extension outreach project conducted by PUASHP in conjunction with the *Indiana Prairie Farmer* magazine, Brock Manufacturing, Meridian Insurance Company, and the Indiana Rural Safety and Health Council. This effort involved the placement of 15,000 to 18,000 flowing grain warning decals on grain storage and transport vehicles throughout Indiana during the mid-1980s. This effort also resulted in the development of a grain handling safety curriculum that was distributed to all (1250) secondary agricultural education teachers in Indiana, Ohio, Michigan, and Kentucky. Aherin and Schultz (1981), at the University of Minnesota, produced an educational module that included a slide set with a script. The module was distributed extensively throughout the U.S. and Canada. A portion of the materials focused on entrapment issues related to youth in bins and gravity wagons. Similarly, Schwab, Miller, and Goering (1997) produced a curriculum that teaches grain safety (particularly grain entrapments) through science and math lessons that targets secondary students.

The National Institute for Occupational Safety and Health (NIOSH), part of the U.S. Centers for Disease Control and Prevention, has awarded grants to fund research with the intent of elucidating causative factors and finding solutions to reduce the frequency of agricultural injuries. This included support of the National Children's Center for Rural and Agricultural Health and Safety, which published the North American Guidelines for Children's Agricultural Tasks (NAGCAT). The NAGCAT are recommended guidelines for farm families to follow voluntarily in deciding which jobs should be assigned to their children and at what age (MCRF, 2013). These guidelines include specific recommendations concerning exposure to agricultural confined spaces.

With support from OSHA Susan Harwood Training Grants, at least three curriculum projects developed training materials for grain industry targeting young and beginning workers, first responders, and grain storage and handling facility workers (Field et al., 2014a; Field et al., 2014b; Rylatt, Rademaker, & Salzwedel, 2014).

2.1.1.2 Regulations

Currently, two sets of regulations cover work in agricultural confined spaces under the provisions of the current OSHA workplace safety and health standards (29 CFR 1910.146: Permit-required confined spaces, and 29 CFR 1910.272: Grain handling facilities). Any agricultural production facility with less than 11 employees is exempt from these regulations. In addition feed lots and seed processing facilities are exempt from 29 CFR 1910.272. It is important to note grain storage bins, silos, or tanks may not, for political reasons, be defined as confined spaces and thus might be exempt from employer compliance with 29 CFR 1910.146.

2.1.1.3 Engineering Standards

A review of current applicable engineering standards found none that specifically addresses the safety of workers in and around agricultural confined spaces. Recommendations were found that encouraged making external ladders on some confined spaces inaccessible to children and ensuring that openings or access points are adequately covered. Even the long-standing recommendation to provide appropriate warnings regarding children on grain storage and handling facilities, including GTVs, has not made its way into engineering standards. Currently, ASABE is developing an engineering standard for steel grain storage bins. One of the motivations behind the standard is to reduce access to the structure, thereby reducing the frequency of entrapment.

2.2 Methodology

This work builds on the information gathered on the grain entrapment and confined-space related incidents documented by Kelley and Field (1996), Freeman et al. (1998), Kingman et al. (2001), Roberts et al. (2011) and Riedel (2011). The PACSID is an electronic database developed to assist in uniformly coding, storing, adding, querying, and analyzing agricultural confined-space related incidents. The definition of an agricultural confined space being used is the definition developed by the North Central Extension Research in Agriculture (NCERA) 197 committee: “any space found in an agricultural workplace that was not designed or intended as a regular workstation, has limited or restricted means of entry or exit, and has associated with it potential physical and/or toxic hazards to workers who intentionally or unintentionally enter the space.” The OSHA definition for confined spaces, under current regulatory language, was not chosen because it was not developed for agricultural confined spaces and does not, under current regulatory language, regulate most agricultural confined spaces (OSHA, 1993). Each case in the database contains the available data parameters, such as date, time, age, state, farm type, incident type, agent of injury, and name, and is searchable by each. A complete list of the data inputs the database supports is found in Table 2-1. The parameters required for the case to be entered into the database are identified with asterisks (*). These required parameters are intended to reduce the probability of duplication. A description of each parameter can be found in Riedel (2011). At any given time, there have been approximately 75 cases in the queue for entering into the database that lack sufficient information for the required parameters.

Table 2-1 List of input parameters for the PACSID.

Required input parameters	**Recommended input parameters**	**Other input parameters**
Case No.*	Narrative	Work status
Year*	Day	Relationship
Time*	Month	County
State*	Sex	Grain movement
Incident type*	Farm type 2	Residence farm
Agent of injury*	Fatality	Location
	Age	Classification
	Farm type 1	
	Medium	
	First name	

Since the publication of the 2012 Summary of Grain Entrapments in the United States (Issa et al., 2013), 167 previously undocumented cases were entered into the PACSID. This includes data both from cases (67) occurring in 2013 and from cases (100) occurring in prior years (1964-2012) but not previously documented or meeting the required parameters. Cases in the database have been obtained from internet searches, interviews, personal contacts, and recently acquired safety datasets. A more thorough summary of how the PACSID data were collected was reported by Riedel (2011).

To properly analyze the database, the following categories were created based on PACSID parameters: age group, region, agent category, and incident category. Age group is based on the input parameter “age” and is split into ten-year intervals ranging from 1 to 90. Region is based on the input parameter “state” and is divided into Midwest, Northeast, South, West, and unknown based on U.S. Census Bureau region definitions. The agent category is based on the input parameter “agent of injury,” which is the vector or agent that caused the injury, such as an auger (in entanglements), grain bin (in entrapments), or manure lagoon (in asphyxiation). The agent category is divided into agricultural transport vehicles, food processing and storage facilities, forage storage structures, grain storage facilities, manure storage structures, and other/unknown based on Table 2-2. The incident category is based on incident type and is divided into asphyxiation/poisoning, drowning, electrocution, entanglement, fall, grain entrapment, pinned by object (struck by flying/falling object or underneath/between objects), and other/unknown based on Table 2-3. The incident category can include fatal and non-fatal incidents.

For this article, the database was analyzed and queried for the following parameters: age group, year, sex, state, region, incident category, agent category, and fatality. All data involving trends use a five-year or ten-year average. This average is calculated by averaging the number of cases for the year of interest with the four or nine preceding years, respectively. In addition, grain entrapment reports for the years 2008-2012 were reviewed from published PUASHP annual summary reports (Roberts and Field, 2010; Riedel and Field, 2011; Roberts et al., 2012; Issa et al., 2013) and compared to latest number of incidents for each of those years. A standard linear regression analysis was run using Microsoft Excel, comparing the cumulative number of incidents in each state with the number of farms with grain storage capacity. In addition, a regression analysis was conducted on yearly trends of non-fatal and fatal incidents.

Table 2-2 Possible parameter inputs for the agent of injury used in developing the agent category.

Agent Category	**Agent of Injury**
Agricultural transport vehicles	Feed grinder/mixer portable, unspecified; feed wagon; forage wagon (self-unloading); grain wagon auger-type, gravity-flow, unspecified; manure transport vehicle; rail car; truck pickup, semi-tractor/trailer, straight/grain/flatbed, unspecified; wagon/cart (miscellaneous).
Food processing and storage facilities	Food storage tank/bin; fruit storage (environmentally controlled unit).
Forage storage structures	Silo bunker/pit, horizontal/bunk, non-oxygen-limiting, oxygen-limiting/airtight, unspecified[a]; silo unloader (bottom, top).
Grain storage facilities	Auger non-portable/in-bin, unspecified; corrugated steel bin; dump pit; elevator/conveyor (non-portable); feed bin; feed grinder/mixer stationary; feed storage structure (wooden); flat grain storage building; flat storage; grain bin; grain crib; grain dryer; grain storage under facility (sumps and galleys), unspecified; open pile; outside of bin, of silo; silo concrete stave/poured, grain, unspecified[b]; steel tank (grain); storage dome.
Manure storage structures	Manure lagoon/pond, pit (below ground), storage tank (above ground); slurry pit.
Other/unknown	Barn/livestock building; combine (self-propelled/unspecified), corn crib (ear corn); fertilizer tank; trench/field tile/other on-farm construction sites; wells/cisterns/dry-well/septic tank; other/unknown.

[a] Silo (unspecified) with a medium parameter of hay, molasses, screenings, or silage placed in forage storage structure.

[b] Silo (unspecified) with a medium parameter of barley, corn, corn cobs, cotton seed, rice soybeans, wheat, or unknown placed in grain storage facility.

Table 2-3 Possible parameter inputs for the incident type used in developing the incident category.

Incident Category	**Incident Type**
Asphyxiation or poisoning	Asphyxiation/poisoning in/inside multiple locations such as: pond/lagoon, livestock building, manure storage pit, manure storage tank, silo, inside tank; entrapped/covered by manure; loss of consciousness and well or cistern.
Drowning	Drowning in pond/lagoon/water tank, inside manure storage pit and flooded grain bin/silo.
Electrocution	Electrocution by contact with electricity.
Entanglement	Entanglement in augers, rotating shafts, and other equipment used inside agricultural confined spaces. Does not include portable augers used outside the structure.
Fall	Fall (from or into an agricultural confined space).
Grain entrapment	Entrapped or engulfed inside a grain storage structure including grain transport vehicles.
Other/unknown	Other/unknown.
Pinned by object	Pinned against/between/underneath object; struck by flying/falling/rotating object.

2.3 Results

2.3.1 Frequency and Geographic Distributions

Overall, the PACSID currently contains 1,654 documented cases of agricultural confined-space related injuries and fatalities. The earliest case recorded occurred in 1956; however, it is not until 1964 that cases are reported every year. Data reported included the two cases before 1964. In the last 30 years (1984-2013), the average number of documented confined-space related cases per year was 49. In the last ten years (2004-2013), the average number of confined-space cases per year was 63, indicating that the problem is increasing (Figure 2-1; Table A-1) even though the number of farms with grain storage capacity and the number of commercial, off-farm grain storage facilities has been decreasing since 1988 (NASS, 2014). However, there are significant gaps during the early years due to the lack of surveillance efforts and the lack of any requirement to report most cases. It is also believed that numerous other types of agricultural confined-space incidents occurred but were unreported, such as falls into wells and cisterns and exposure to toxic gases in forage storage structures. The fatality rate for the recent decade (2004-2013) was 50.3% (317 cases out of 630), in comparison to 68.1% (290 out of 426) for the previous decade (1994-2003) and 62.6% (1,036 out of 1,654) overall. The growth in the overall numbers of confined-space related cases since 1984 reflects more aggressive documentation of non-fatal cases and the increased media exposure given to these events, which have increased at a rate of one case per year ($\mu = 0.96$, $R^2 = 0.4$). This is in comparison to fatal cases, which have averaged around 30 cases per year since 1984, with a standard deviation of eight cases per year. The fatal cases do not show any significant trends ($\mu = 0.12$, $R^2 = 0.02$).

Agricultural confined-space related cases were documented in 43 different states (Figure 2-2; Table A-2). The only states without documented incidents were Hawaii, Maine, Nevada, Rhode Island, Vermont, West Virginia, and Wyoming. The vast majority of the cases were in the Midwest (75%), with the South a distant second (13%). In the last five years, Midwest cases have decreased to 72% of cases, with the South steadily increasing to about 18% of cases. Over time, the Western and Eastern regions of the U.S. have fluctuated between 5% and 12% of cases and together represent 10% of cases in the last five years (Figure 2-3; Table A-3).

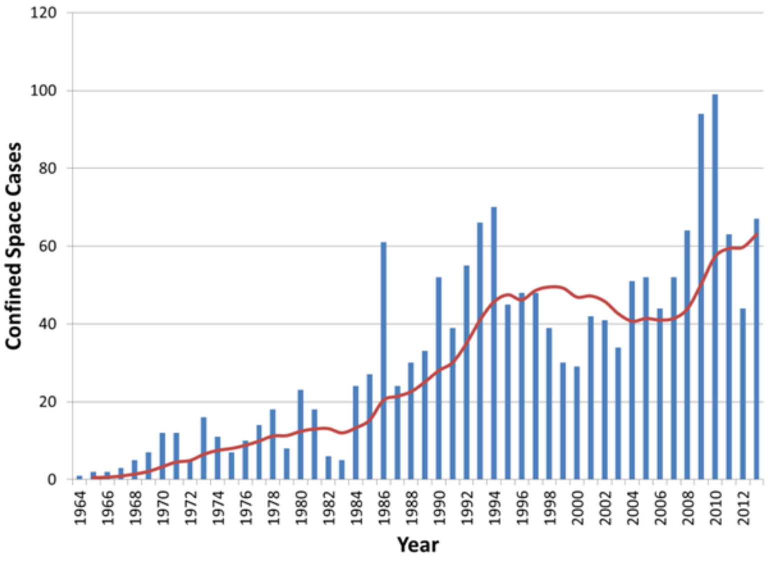

Figure 2-1 Agricultural confined-space cases distributed by year. The line represents the ten-year average.

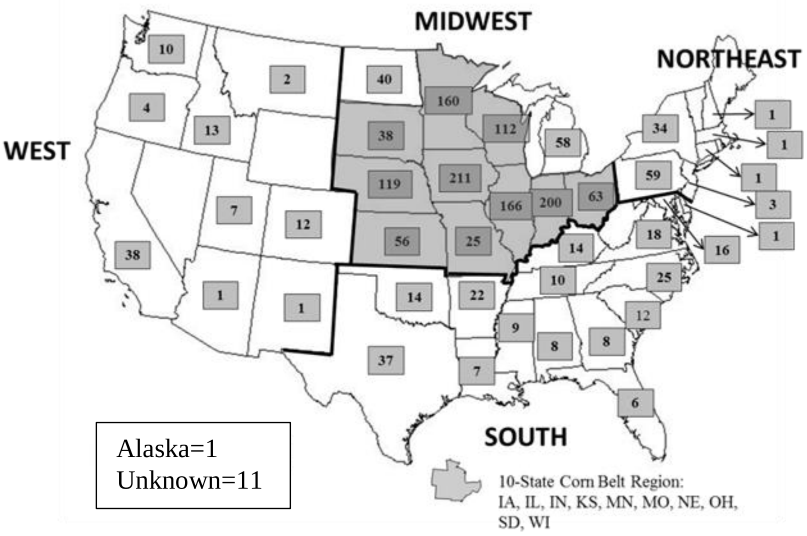

Figure 2-2 Geographic distribution of agricultural confined-space cases (1964-2013).

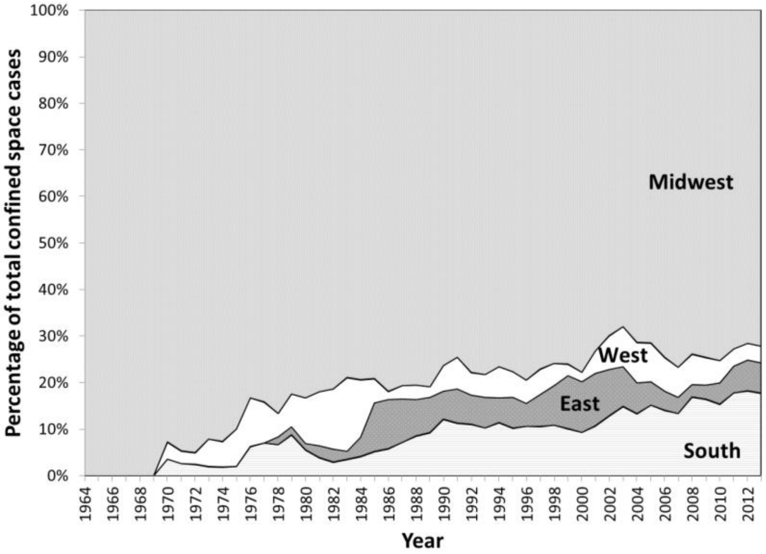

Figure 2-3 Agricultural confined-space cases distributed by region. Each year represents the percentage (by region) of the average number of cases over five years.

2.3.2 Category and Type of Confined-Space Related Cases

The vast majority of all agricultural confined-space related cases involved the storage and handling of grain and grain by-products, with almost 1,200 cases, including entrapments, falls, and entanglements (Figure 2-4). The majority (62%) of these cases involved entrapment or engulfment in free-flowing agricultural materials, primarily grain, while working inside a grain storage structure.

In the 1970s and 1980s, grain entrapments represented about 80% of all cases in the PACSID. Interest in related incidents has since increased, and the database contents were expanded with other confined-space related incidents, resulting in a greater percentage of other cases now making up the database. In 2013, the frequency of grain entrapment cases had dropped to slightly less than half of all cases documented in that year. Meanwhile, documented cases of falls involving agricultural confined spaces have steadily increased since the 1990s and now represent about 21% of all cases, the second highest category (Figure 2-5; Table A-4).

In 2013, there were no fewer than 33 grain entrapment cases, 14 falls, 12 equipment entanglements (including augers inside of confined spaces), and four asphyxiations (Figure 2-6). Grain entrapments accounted for 49% of documented cases in 2013. For any confined-space incident type with more than one case, asphyxiations were the most dangerous, with a reported 100% fatality rate, while grain entrapments ranked second with a 43% fatality rate.

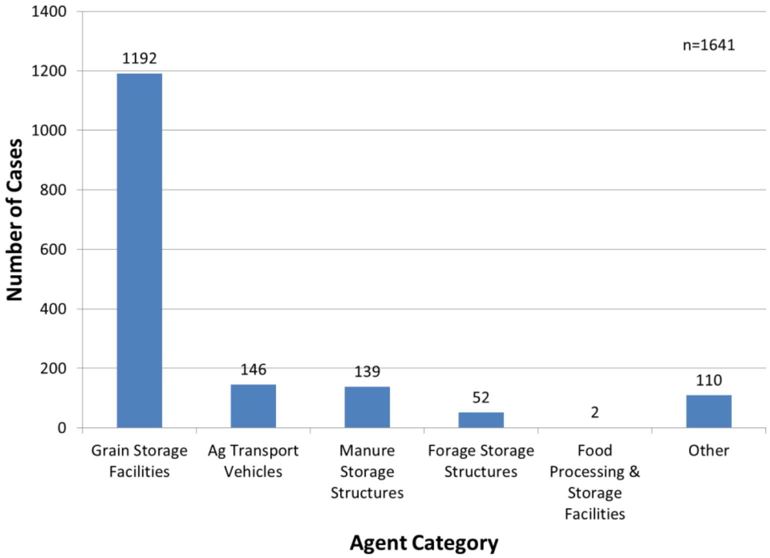

Figure 2-4 Agricultural confined-space cases documented between 1964-2013 based on agent category.

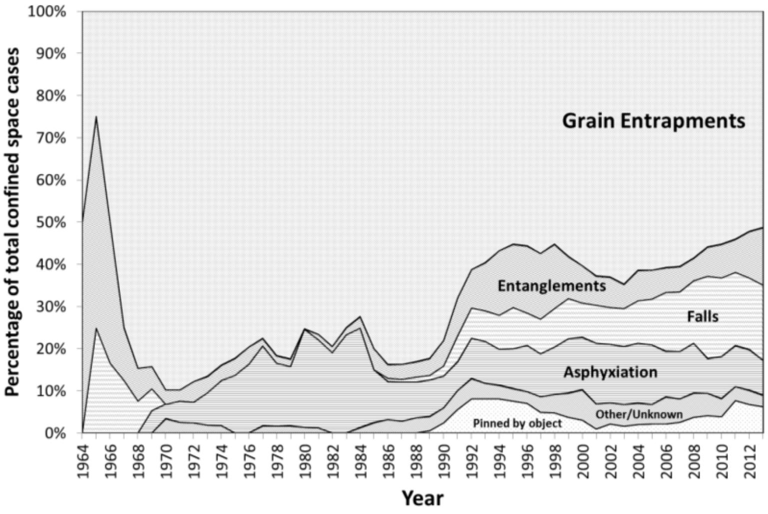

Figure 2-5 Agricultural confined-space cases distributed by type. Each year represents the average number of cases over five years.

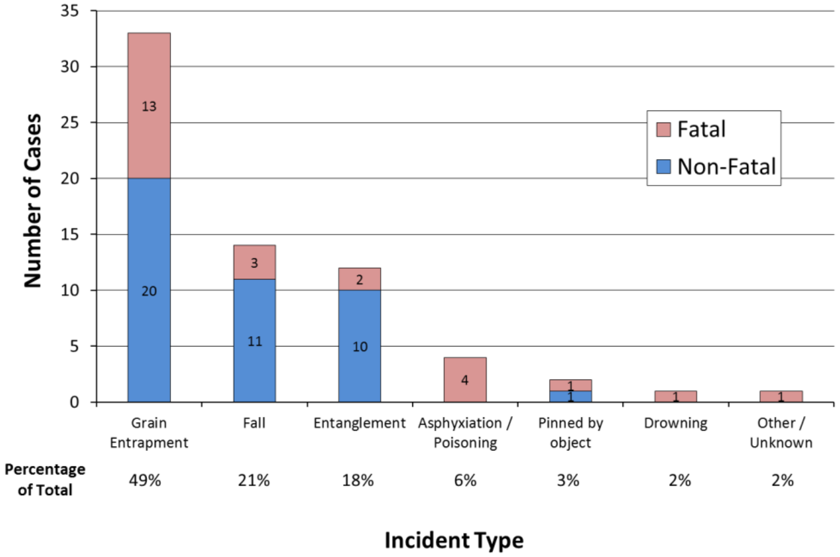

Figure 2-6 Distribution of 2013 agricultural confined-space cases by type of incident.

2.3.3 Demographics

Cases involving children and youth under the age of 21 represent a major portion of the cases contained in the PACSID. The upper threshold age of 20 was selected to understand the agricultural confined space risks as youth transition into adult workers. In other words, the study was attempting to focus on young and beginning workers. This population was involved in 26% of all documented cases, and nearly all were male (Figure 2-7). In total, there were only 47 cases involving females and eleven cases in which the gender was un-known. Together, these two groups (females and unknown) represent only 4% of all documented cases. The disproportionate number of young males involved is especially noteworthy considering the state and federal workplace safety regulations that prohibit employment of youth under the age of 16 for work inside most agricultural confined spaces found on family farms and under the age of 18 for commercial grain storage and handling facilities. These restrictions, however, do not apply to the children of farm owners. Cases were documented in which a young or beginning worker died in an agricultural confined space on the first day or first week on the job.

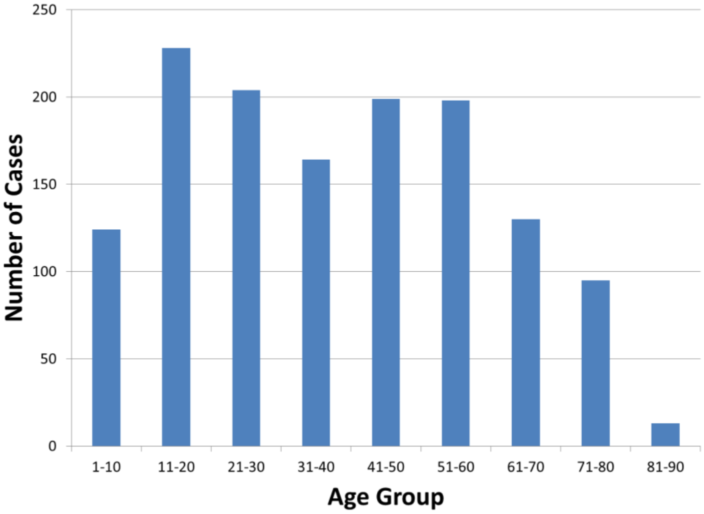

Figure 2-7 Distribution of agricultural confined-space cases by age group.

2.3.4 Trends

The addition of 167 cases in the last year significantly ($p < 0.001$) increased the number of cases reported per year. On average, the numbers of previously reported cases increased by three or more cases (M = 2.78; SD = 2.06). These new additions even changed the results for recent years, which are generally considered to be more reliable. This can be seen vividly when comparing previous grain entrapment reports (Roberts and Field, 2010; Riedel and Field, 2011; Roberts et al., 2012; Issa et al., 2013) to the latest numbers of documented cases. For example, there were 51 grain entrapment cases initially reported for 2010, which was revised to 57 in 2012 and again to 59 in 2013. Figure 2-8 compares the initially reported case totals and the current case totals for the last five years. It is anticipated that the totals will continue to be adjusted as additional cases are documented. Grain entrapments represent 41% of all new cases added, with entanglements representing 33% and falls representing 18% of new cases. All together, these three categories represented 92% of new cases entered in the database. Comparison between the number of farms with grain storage structures (grain capacity greater than 1 bushel) in each state (NASS, 2014) with the number of confined-space incidents in the last ten years shows a very strong correlation for all states (Figure 2-9; $r(40) = 0.92$). The last ten years were chosen because they represent a period of continuous effort to collect confined-space incidents on a national scale. In this period, a total of 630 incidents were collected, which is about 40% of all the incidents in the database. The number of incidents was compared against the latest (2012) census information on the number of farms with grain storage capacity as a representative snapshot of grain storage on farms. Using the earlier census data does not alter the strength of the correlation, and the result is not significantly different from Figure 2-9. This is due to the fact that while the number of farms with grain storage capacity decreased by 17% from the previous (2007) census, the decrease occurred equally in all states.

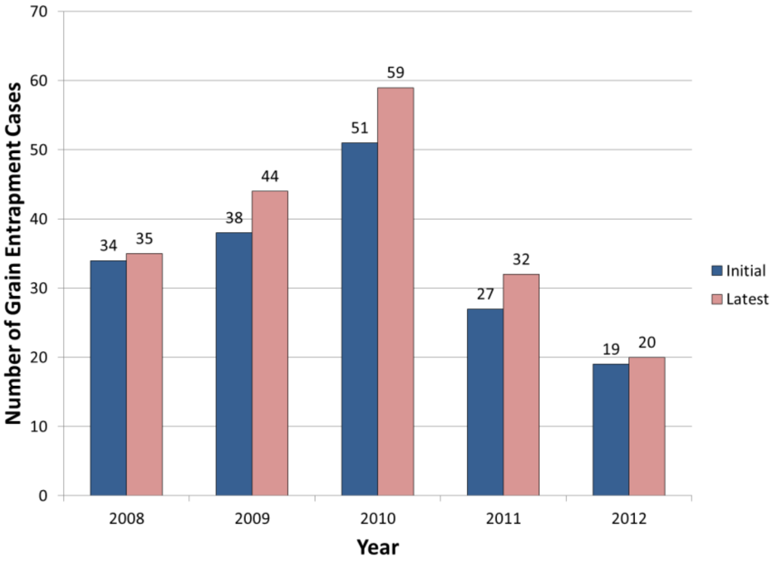

Figure 2-8 Initial numbers of cases announced for the five previous years and most recent counts.

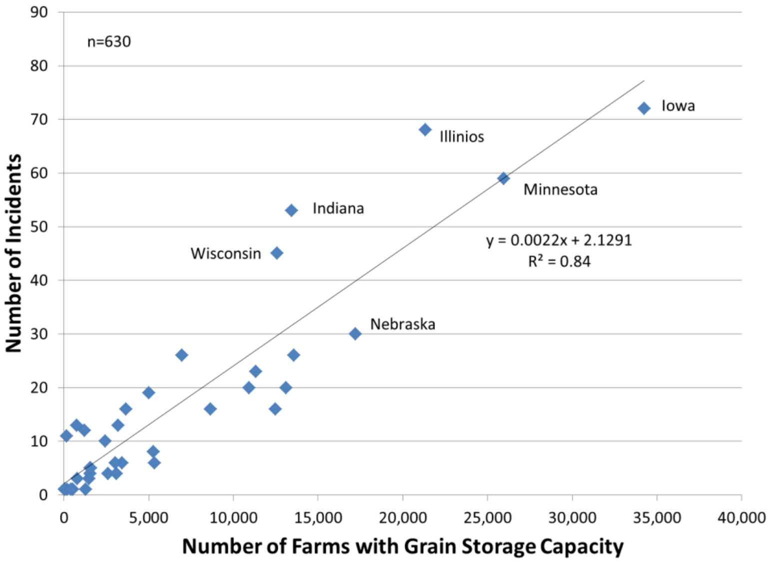

Figure 2-9 Confined-space incidents from the last ten years (2004-2013) for all U.S. states compared with the number of farms with grain storage capacity in each state according to NASS 2012 Census data.

2.4 Discussion

One of the most interesting results of this summary is that while the overall trends in confined-space related cases appear on the rise, this appears to be mainly attributed to increasing documentation of non-fatal cases, which have significantly increased at a rate of one case per year. In comparison, fatal cases appear to have plateaued at around 30 cases per year since the mid-1980s. Since fatal cases are much more likely to be reported in the media or official government documents, it is expected that fatal cases would have plateaued earlier than non-fatal cases. With increased awareness and more aggressive surveillance, it is expected that the proportion of non-fatal cases being documented will initially increase before plateauing. In other words, the increase in the frequency of these events may have been due to better documentation. However, other factors, such increasing production of grain and increasing sizes of grain bins, might also be contributing factors to the increase in incidents. Due to the fluid nature of the database and the variables contributing to the occurrence of these incidents, it remains difficult to make definitive conclusions regarding future trends in the number of agricultural confined space and grain entrapment incidents. However, the data remain the best currently available, and one can make strong recommendations on what demographics and locations to target to significantly reduce the number of incidents. It is also important to note that the database tends to undercount non-fatal occupational injuries even in situations where injury reporting is mandatory under OSHA regulations, such as at commercial grain storage, handling, and processing facilities. For example, in 1999, it was found that workplace injuries were underreported by BLS by 33% to 69% depending on occupation (Leigh, Marcin, & Miller, 2004).

Another noted trend was the increase in the number of cases occurring in the South. One contributing factor may be the significant increase in corn production in the South in the last ten years along with the corresponding increase in on-farm storage. In the last ten years, corn production in the South has increased by 54% to 1.4 billion bushels of corn (NASS, 2014). With the majority of cases in the database involving grain entrapments and about half of all grain entrapments involving corn, there is a strong correlation between corn production and storage and the number of cases (Issa et al., 2013). This can be seen by comparing documented incidents with the number of farms with grain storage reported in 2012, as shown in Figure 2-9. In addition, with the warmer, more humid weather in much of the South, there may be more situations in which out-of-condition grain be-comes a storage problem, especially for corn.

The expansion of the PACSID database has significantly altered the distribution of incident types, with grain entrapments representing 49% in 2013 and the remainder involving other confined-space related cases at the time the database was queried. This shift in distribution is likely to continue, and awareness of these trends is important for agricultural producers, safety educators, and regulators. Prevention measures should take into account all types of agricultural confined spaces, not just grain storage and handling facilities, and all related incidents including falls and entanglements, if the number and severity of incidents are to be reduced.

Lastly, it is important to state that while this database provides the best known information available on this type of agricultural workplace hazard, it is by no means comprehensive. Due to a past emphasis on grain entrapments and manure storage incidents, and a lack of aggressive surveillance efforts for all types of agricultural confined spaces, incidents involving forage silos, chemical storage structures, wells, and cisterns are definitely underreported. In addition, falls and entanglements around agricultural confined spaces, especially grain storage structures and silos, are most likely to be significantly under-reported since these incidents are rarely published in the general media. As noted, each type of incident is believed to be under-reported, including grain entrapment cases, as evidenced by the increase in the number of cases over time, even for recent years. Another factor contributing to a lack of a complete understanding of the problem is the influence that federal regulations may have, especially with respect to the documented incidents at OSHA non-exempt facilities. For example, as of December 2013, over half of grain storage capacity in the U.S. is now found on OSHA exempt farms (13.0 million bushels) versus 10.4 million bushels at OSHA non-exempt commercial operations (NASS, 2014). This raises a valid question: if both types of facilities were treated equally, including injury reporting requirements, would the frequency and severity of these incidents be substantially different from what is currently found in the PACSID?

While the findings presented might not be exhaustive, they provide a good representation of the problem, and they provide the best evidenced-based resource available to support future prevention efforts.

2.4.1 Observations

As evidenced by on-going media coverage, the level of interest regarding agricultural confined spaces, especially grain entrapments, has remained high. There continues to be ongoing development, including new prevention resources, enhanced access to training opportunities, and efforts such as by ASABE to draft engineering standards designed to make grain and manure storage and handling facilities safer for workers. This attention has been further intensified with OSHA's targeted enforcement of workplace safety standards at commercial grain storage and handling operations, which has had a trickle-down effect at exempt farms, feedlots, and seed processing operations. OSHA has also invested substantial funding in developing new training resources for grain storage and handling facilities under the Susan Harwood Training Program. Other factors that have contributed to the public attention being given to these incidents have been the high media profiles of incidents involving younger workers at grain storage operations and the large settlements and awards from civil litigation resulting from injuries and deaths at these facilities. The message is clear that future incidents have the potential to be very costly to those who fail to comply with recognized or required workplace safety and health practices.

2.5 Conclusion

Occupational safety and health resource allocation should be evidence-based and targeted for the greatest probability of effective, long-term impact. These results and discussions were presented to this end.

One of the most significant outcomes from an expanded surveillance effort to document injuries and fatalities associated with agricultural confined spaces could be a better platform from which to develop and implement more effective and comprehensive prevention strategies. For example, falls involving confined spaces in 2013 accounted for no less than 21% of documented cases, but this topic has received little attention in current discussions on risk reduction at these facilities. The confirmation of the high proportion of incidents involving young and beginning workers and the clarification of the problem of auger-related incidents inside agricultural confined spaces are other outcomes that should result in more effective prevention efforts.

Finally, it appears that the perception of injury susceptibility among those exposed to agricultural confined spaces is low. This is reflected in the literature (Pate and Dai, 2014) and the multiple incidents involving multiple victims, including first responders, in these spaces. Unlike other high-profile agricultural safety issues, such as tractor overturns, childhood injuries, and pesticide exposure, only recently have there been national initiatives to address the problem of injuries and death in agricultural confined spaces.

This includes NCERA 197 and OSHA’s Susan Harwood projects, which are currently funding efforts in Indiana, Illinois, and Iowa.

CHAPTER 3. CONTRIBUTING CAUSES OF INJURY OR DEATH IN GRAIN ENTRAPMENT, ENGULFMENT AND EXTRICATION

An earlier version of this chapter was published in the ASABE conference proceedings as

- *Issa, S. F., Schwab C.V., & Field, W. E. (2015). A review on the environmental impact and physiological conditions on the human body during an engulfment, entrapment and extrication. Paper number 152189336, 2015 ASABE Annual International Meeting, New Orleans LA.*

A modified version of this chapter has been submitted for publication in the Journal of Agromedicine

3.1 Introduction

Although agriculture has long been recognized as one of the nation’s most high-risk industries (Pickett, Brison, Niezgoda, & Chipman, 1995; Jadhav, Achutan, Haynatzki, Rajaram, & Rautiainen, 2015; Evans & Heiberger, 2016), the number of nationally documented fatal incidents in grain production has actually decreased since the 1990s (U.S. Bureau of Labor Statistics, 2014). For instance, in the five-year period 1992-1996, the number of recorded fatalities per year averaged 390; whereas in the five- year period 2010-2014, that number dropped to 253 per year (U.S. Bureau of Labor Statistics, 2014). This significant decrease, however, has not been the case when it comes to incidents involving agricultural confined spaces incidents but rather has fluctuated. For instance, confined spaces fatalities per year averaged 33 in the 1992-1996 period, peaked with a total of 54 in 2010, then decreased to 31 cases per year over the 2010-2014 period (Issa et al., 2016c).

The primary risks associated with agricultural confined spaces is grain entrapment and engulfment (Pettit & Braddee, 1994; Roberts et al., 2011; Riedel & Field, 2013; Issa et al., 2016a; 2.3.2 Category and Type of Confined-Space Related Cases, p. 22). An *entrapment* is defined as any situation in which the victim's head remains above the grain mass but he's incapable of self-extrication. While an entrapped person is usually buried between chest and shoulder levels (Bahlmann et al., 2002), one could be buried only up to the knees or waist level and still not be able to self extricate. An *engulfment* occurs when the victim's head is entirely covered by the grain and/or the victim is no longer visible. Grain entrapments and engulfments currently represent about 50% of agricultural confined spaces incidents and 61% of all documented incidents in PACSID over time (Issa et al., 2016c). While entrapments and engulfments represent a significant hazard in confined spaces, there has been no published research exploring the potential environmental and physiological conditions that the human body experiences while entrapped or engulfed or during extrication efforts by first responders. Thus a review was conducted of both published studies and data contained in the Purdue Agricultural Confined Spaces Incident Database (PACSID) to gain a deeper understanding of the factors that the body experiences and the findings summarized.

3.1.1 Previous Research Efforts

Schmecta and Matz (Schmechta & Matz, 1971) carried out some of the earliest documented research regarding grain entrapments, studying the depth at which one can no longer extricate himself and the speed at which one can become entrapped in flowing grain. They found that when the grain reached hip depth, self-rescue was no longer possible, and when at shoulder depth not only was extrication impossible, but also the harness worn (rated for 150 kg) was damaged during attempts made to extricate via rope. They also found that it took about 30 seconds for a human subject to get entrapped to shoulder level in a gravity bin with grain flowing out at 25 metric tons per hour (925 bushels per hour); and when entrapped to chest level, breathing was difficult. Schwab et al.(1985) built upon this early study by measuring the force required to vertically extricate a mannequin wearing a body harness entrapped and engulfed at various levels of grain(results discussed in subsequent section). No other physical stresses aside from the pull forces were measured.

In 1977, the Purdue University Agricultural Safety and Health Program (PUASHP) created—and continues to manage—a national database on grain entrapment and engulfment injuries and fatalities. This on-going effort has stimulated subsequent research on such topics as: entrapments in grain transport vehicles (Kelley & Field, 1996), entrapments in commercial grain facilities (Freeman et al., 1998), on-farm fatal grain incidents (Kingman et al., 2001), contributing factors to grain entrapments (Kingman, et al., 2003), incidents involving grain vacuums (Field, et al., 2014c), impact of grain rescue tubes on the forces needed to extricate (Roberts et al., 2015), entrapments involving youth and beginning workers (Issa et al., 2016b), incidents in all forms of agricultural confined spaces (Issa et al., 2016c), and auger entrapments inside agricultural confined spaces (Cheng & Field, 2016). None of these studies, however, explored the contributing causes of physical injury or death while entrapped or engulfed in grain.

3.1.2 Extrication Methods Studies

Roberts (2008) identified three rescue strategies as most commonly employed in attempting to extricate those entrapped or engulfed primarily in grain storage structures with sufficient grain depth to cause entrapment. The first involves removing grain from around a victim so he can be freed, which is attempted either by cutting holes in the wall of the storage structure (if a steel-paneled one) in order to lower the grain level, vacuuming the grain out of the structure thereby lowering the level of grain (Field, et al., 2014c), placing retaining walls (a coffer dam) around the victim then removing the grain from inside the coffer dam walls freeing the victim, or a combination of all three (Roberts, 2008) . The second strategy, which has been used for entrapments or engulfments inside a GTV, involves opening the outlet door(s) or tipping the GTV on its side in hopes the victim will flow out with the grain (PACSID, unpublished results). The third, more controversial, strategy involves pulling the victim up and out of the grain mass using a harness and/or rope being pulled manually by first responders or attached to some type of powered or manually operated mechanical winch (Schwab et al., 1985; Roberts et al., 2015).

Relative to this third method, attempting to forcefully extricate someone from a grain mass has historically been considered highly dangerous due to the large amount of force needed to do so. For instance, Schwab et al., (1985) found that, to pull out an adult size 165-pound mannequin required about 400 pounds (1800 N) of force if entrapped at waist level and 900 pounds (4000 N) if entrapped up to the neck. Roberts et al. (2015) found that extricating a mannequin even after placement of a coffer dam around it actually increased by 22-26% the force required. Also, cases have been reported in which first responders, using a rope and truck to pull one out of a grain mass, resulted in the victim's injury or fatality (Roberts, 2008).

3.1.3 Snow-avalanche Case Studies

Similar types of entrapment/engulfment cases involving victims buried in snow avalanches have been studied extensively and were reviewed since the bulk density of snow is within the same magnitude of many grains (i.e., about 800 kg/m^3). When engulfed in snow, the victims tend to be submerged from 0.5 to 3 m beneath the surface of the snow, with the survival rate being only 19% (Gray, 1987; Stalsberg, et al., 1989). In a review of 136 avalanche fatality cases, Stalsberg et al. (1989) found 67.6% were caused by suffocation, 13.2% by mechanical trauma, 3.7% by hypothermia, 2.9% by suffocation and mechanical trauma, and 11% unknown. In another study of avalanche engulfments in Utah, McIntosh et al. (McIntosh, Grissom, Olivares, Kim, & Tremper, 2007) reported 85.7% caused by asphyxiation, 5.4% by mechanical trauma, and 8.9% by a combination of trauma and asphyxiation. The variability in percentages was likely due to local typography, such as the presence of thick forests, cliffs, or rocks (Radwin, 2008).

3.1.4 Research Objectives

Unlike snow-avalanche fatalities, the causal factors involved in grain entrapments, engulfments, and extrication resulting in victim injury or death have not been extensively researched. The objective of the study presented here, therefore, was to determine the most frequent contributing factors by analyzing the literature and PASCID database. To simplify the results, the potential factors involved were split into two main categories—

environmental-related and physiological/psychological-related. Environmental factors are any that act upon the body, such as friction, pressure, and temperature. Physiological/psychological factors are those that affect internal responses by the body like asphyxiation and heart rate (physiological) and/or those that relate to the mental capacity of the victim to respond to his/her circumstances (psychological).

3.1.5 Research Questions Explored

Following are three research questions that guided this analysis, from documented incidents, about the causes of fatalities and injuries in grain entrapments, engulfments, and during extrication efforts.

1. What are the likely injury/fatality percentages in entrapment, engulfment, and extrication cases?
2. What are the environmental factors potentially impacting injury/fatality and survival rates in entrapment, engulfment, and during extrication?
3. What are the physiological and psychological factors potentially impacting the injury/fatality and survival rates in entrapment, engulfment, and during extrication?

3.2 Methodology

The literature review was conducted using the ASABE Technical Library, Google Scholar, and Purdue University article databases; and the extensive collection of resources related to grain entrapment maintained by PUASHP was likewise reviewed. These sources were used due to the generic nature of the research, since the purpose of the study was to document potential factors impacting the victim. The list of keywords applied in accessing these sources included: avalanche, psychogenic shock, suspension trauma, asphyxiation, grain pressure, grain entrapment, grain engulfment, extraction, vertical pull force, grain lateral pressure, hypothermia, heart rate, oxygen consumption rates, and any term that might be useful in understanding the impact of grain entrapment, engulfment, and extrication from grain on the human body. Several published individual case studies on grain entrapments and engulfments were reviewed as well. In addition, all cases reported in the PACSID were analyzed to a) gain a better understanding of the factors that could potentially cause grain entrapment and engulfment injury or death, and b) to address the questions regarding injury rates in entrapment and engulfment cases and during extrication. For an extensive summary of how cases were collected and analyzed, see Riedel (2011) and Issa et al. (2016a). The final list of factors was developed based on the case studies found in the PACSID and similar case reports such as snow avalanche research.

3.3 Findings

3.3.1 Research Question 1

What are the likely injury/fatality percentage in entrapment, engulfment, and extrication cases?

As of 2015, the PACSID database contained 1,873 confined spaces incidents, 1,143 of which were grain entrapment and engulfment cases. Of those 1,143, the majority were fatalities (67%). In the five-year period 2011-2015, the percentage of grain entrapment and engulfment cases resulting in fatality decreased to 42% (Table B-1), likely because of the increased reporting of non-fatal cases. This increase in reporting was probably due to multiple factors, including better surveillance efforts and more awareness of this issue (Issa et al., 2016c). Again, of the 1,143 PACSID grain entrapment and engulfment cases, 570 were identified as engulfments, of which only 68 victims survived. That represents only a 12% survival rate which is lower than what is reported for snow-avalanche engulfments (Table B-2). In 15 of the 210 identified entrapment cases (7%), the victim still died, even though his head was above the grain surface when discovered.

In the vast majority of the PACSID entrapment/engulfment-related fatality cases, no autopsies had been conducted, or reported, or cause of death was merely speculated. Where cause of death was reported, 21 had been attributed to asphyxiation, four to crushing of the body or head, three to inability to breathe or lack of oxygen (anoxic encephalopathy), and one each attributed to loss of blood, seizure, heart attack, heat stress, and spinal injury. Of those 21 asphyxiation cases, eight were directly linked to aspiration and five to crush asphyxiation. As to factors reported as contributing to surviving grain engulfments, seven of the 68 cases attributed survival with covering of the mouth and nose during engulfment. In addition, 11 of the survivors were unconscious before being resuscitated. All the resuscitated victims were less than 16 years of age and represented 50% of those under 16 who survived engulfment (22 cases total).

When it came to the grain entrapment cases, depth of entrapment varied considerably. Of the 174 cases in which the depth of the victim was reported, the surface of the grain was at face, head, or neck level in 66 cases (36%), at chest or shoulder level in 60 cases (34%), at waist or torso level in 36 cases (21%), at legs level (ankles/knees) in four cases and one case in which only the ankles were visible because the victim had gotten entrapped upside down. Lastly, in seven cases, survival victims of entrapment reported trouble breathing while entrapped.

3.3.2 Research Question 2

What are the environmental factors potentially impacting injury/fatality risks in grain entrapment, and engulfment, and during extrication efforts?

A total of six environmental-related factors were determined to impact the risk of injury and fatalities in entrapment or engulfment cases (including injuries occurring during extrication)—lateral pressure, vertical pressure, friction, oxygen availability, oxygen diffusion rate, and grain temperature. Lateral and vertical pressure have direct impacts on the body's ability to breath, friction impacts the ability to extricate a person, oxygen availability and diffusion rates impact accessibility of oxygen in the surrounding grain, and grain temperature impacts the body's ability to maintain its core temperature.

3.3.2.1 Lateral Pressure

If the person is entrapped or engulfed in an upright position, the grain's lateral force would compress his chest (although it's unclear at which depth he could no longer breathe). Thompson, Galili, and Williams (1997) found the lateral pressure of corn against the grain bin wall at a depth of 5 feet was 5-7 kPa (kilo Pascal), at 40 feet was 20-30 kPa, and did not increase beyond that depth. In a more recent experiment, Moore and Jones (2016) found that the torso experiences 2.8 kPa when corn is at shoulder level and

3.9 kPa when buried at about 3 feet below shoulder level. Compared to what a scuba diver faces underwater (i.e., 15 kPa at 5 feet and 121 kPa at 40 feet), the pressures experienced in grain are relatively low. However, water is much more “fluid” than grain as can be observed by a diver ability to move at even great depths.

It is important to note that any load cells used to measure lateral pressures might not correctly measure or estimate actual pressure on the human chest; that’s because these cells are designed to measure the active pressure in grain or pressure the grain applies to a wall. However, when one breathes, the chest is pushing against the grain mass and thus should experience a pressure closer to the grain’s passive pressure or wall pushing against the grain mass (Nedderman, 1992). The pressure on the cylindrical part of a grain bin with a hopper bottom is active while the hopper portion is considered passive (Artoni, Santomaso, & Canu, 2009). By definition, passive pressure is larger than active and might restrict a person’s ability to breathe; there are no known studies that confirm the magnitude of passive pressure at various entrapment and engulfment depths. Only one case of an entrapment resulting in death reported the cause to be asphyxiation due to chest compression (Freeman et al., 1998). However a medical record verifying either cause of death or injuries caused by the pressure on the chest could not be accessed. The placement of a coffer dam around the victim and removing the grain inside the coffer dam has been demonstrated as an effective extrication strategy by reducing the grain pressure on the victim. However, as shown by Roberts et al., (2015) the process of installing the coffer dam may actually increase the forces on the victim. As found by Roberts et al., (2015) the force required to extricate a mannequin from inside the coffer dam, without first removing the grain, actually increases.

3.3.2.2 Vertical Pressure

A victim will experience substantially more pressure if he happens to be engulfed in a horizontal position. Thompson et al.(1997), using a load cell to measure the pressure from a column of grain, found it to be about 30 kPa at 5 feet and about 90 kPa at 40 feet. This is significantly higher than the lateral pressure of grain. Even when fully engulfed in a vertical position beneath the surface, the grain mass above the person acts as a barrier to pulling him out and increases the total load on him.

3.3.2.3 Friction

While not a major force during the process of entrapment or at steady-state condition, friction can be significant when the victim is being extricated up and out of the grain. The total force on a temperature cable, for example, when being pulled from grain can be calculated by summing the force of friction and weight of grain above the cable (Thompson, 1987). Schwab et al. (1985) demonstrated that a person weighing 165 pounds buried completely under grain would experience about 7,000 N (newton) or 1,574 pound-force if pulled directly out of the grain and about 3,000 N or 674 pound-force if entrapped up to his shoulders.

If a person equipped with safety harness and lifeline is entrapped, he will experience friction forces as he is being pulled into the grain mass against the tension of the safety line. A basic temperature cable in the grain mass could experience up to two times as much force when grain is flowing than when in a steady-state condition (Thompson, 1987). Schwab et al. (1985) found no statistical difference in force measured between extricating a mannequin from static grain and suspending a mannequin in flowing grain. Depending on how deep the victim sinks before there in no slack in his lifeline, the force generated could be enough to cause the mounting brackets of a ladder attached to the grain bin wall to fail or cause structural deformity or collapse of the roof beams, depending on where the rope was attached (Roberts, 2008).

3.3.2.4 Oxygen Availability and Diffusion Rate

Porosity values depend significantly on the type of grain and its moisture content and generally range from 39% to 65% (Thompson & Isaacs, 1967). Overall, porosity values for specific grains are as follows: alfalfa 39%, yellow corn 39-48%, soybeans 41-44%, grain sorghum 43-46%, wheat 43-46%, rye 49%, barley 52-59%, sweet corn 52-59%, and oats 58-65%, indicating that 40-60% of a grain mass is potentially filled with air (Thompson & W, 1967; Coskun, Yalcin, & Ozarslan, 2006). While in theory this might mean that if a person’s airway remains unrestricted, he could still breathe under grain. What might limit the ability for one to breathe in these situations includes: low initial oxygen levels in the mass (due to mold or insect activity), the actual porosity of grain, diffusion rate of the oxygen, and amount of dust/fines in the mass. Turning ventilation fans can be a lifesaving method by creating an airflow around the victim (Field et al., 2014a). Less than 16% oxygen is considered an immediate danger to life, while between 16-19% is considered dangerous but not life threatening (Pettit et al., 1994). The following case study highlights that, in cases where the mouth and nose are protected, an individual can survive under grain.

In 2013, a 23-year-old man entered an 80,000 bushel grain bin in Iowa to unplug the outlet in the floor to allow the corn to flow. Due to asthma suffered since childhood, he entered the bin wearing a battery-powered respirator and a rope. (The respirator uses a battery-operated fan to circulate and filter out dust and mold from the surrounding air supply.) While trying to loosen the crusted material, he broke through and was drawn into the grain, being fully buried 18-24 inches below the grain surface. Without other workers nearby, the victim was engulfed for about an hour before a truck driver realized he was missing. The driver tried to pull on the rope to no avail because the victim was so far underneath the surface. By the time rescue was completed (via draining the grain from the bin), he had been engulfed for four to five hours. During the engulfment, he had drifted in and out of consciousness but was able to shout, alerting the emergency rescue crew that he was alive. The respirator had continued to function throughout the engulfment period. After rescue, his heart rate was 173 beats per minute (bpm); he had suffered an injured foot, a rope burn, and minor scratches and ended up spending two days in a hospital (Klingseis, 2013). This type of successful survival of victims fully engulfed in grain is rare but continues to be documented.

3.3.2.5 Temperature

Grain is harvested during the fall often under low daily temperatures. In addition, farmers are encouraged to lower grain temperature in the bin to around 4^{o}C (39^{o}F) through operating ventilation fans, utilizing the low ambient temperatures during the fall, to reduce microbial and insect activity (Loewer, Bridges, & Bucklin, 1994). As spring approaches and ambient temperature warms, the grain in the center of the bin can remain significantly cooler (>10°C) than the outside temperature, depending on the bin's size (Jayas, Alagusundaram, Shunmugam, Muir, & White, 1994). For example, at the end of May, the average temperature in Winnipeg, Canada, is about 15°C, while the grain in the center of a 9 m bin would be about 4°C (Jayas, et al., 1994). This means that one entrapped or engulfed in grain could be exposed to relatively low temperatures and potentially experience hypothermia.

This is important to understand because it impacts the discussion of what extrication methods are best suited for rescue. In water at about 4°C, a person can survive between 30 and 90 minutes (PFDMA, 2010). This is because water is 25 times more thermally conductive than air (0.6 W/m K [watts per meter Kelvin] for water versus 0.024 W/m K for air); thus, the body cools down 25 times faster in cold water than in air (Young, 1992). While it is not known how long a person would survive in grain at lower temperatures, the thermal conductivity of grain ranges from 0.16 to 0.20 W/m K, which is about 7-8 times greater than air (Chang, 1986). This means that a person exposed for multiple hours buried in cold grain could experience hypothermia, although not as quickly as one would experience in water.

In one case study, the victim was buried up to his armpits in grain at 0°C temperature. At the time of attempted rescue, he was conscious and experiencing no pain. The emergency first responders initially tried to free him by shoveling the grain out of the way. When this proved ineffective, they placed a harness around his upper body in order to pull him out. As they were pulling, he complained of chest pain and developed breathing problems. Although analgesic drugs were administered to reduce the pain, the pull-force required caused him such unbearable pain that the rescue attempt could not be continued. Eventually, the rescuers placed a cylinder around him, removed the grain between his body and the cylinder wall, and then pulled him out. Once extricated, his chest pain stopped completely. The rescue took about four hours; and by the time it was completed, the victim had developed mild hypothermia and had a body core temperature of 35.1°C. He was provided a blanket and hot fluids then taken to the hospital, where he was discharged the next day (Bahlmann et al., 2002).

3.3.3 Research Question 3

What are the physiological and psychological factors potentially impacting the injury/fatality risk in entrapment, engulfment, and extrication cases?

A total of five such factors were determined to affect the risk of injury and fatalities in these cases—oxygen consumption, asphyxiation, blood flow, and heart rate, and psychological-related characteristics of the victim. Oxygen consumption and asphyxiation impact the body’s ability to breathe; blood flow and heart rate impact its ability to maintain bodily functions; and the psychological factor impacts how one responds to entrapment or engulfment.

3.3.3.1 Oxygen Consumption

A person engulfed in grain will likely struggle to get enough oxygen to his lungs from the surrounding grain mass. Likely exacerbating the situation are one’s age, general health, and respiratory health. For example, the lung disease, chronic obstructive pulmonary disease (COPD), makes it hard to breathe and can cause coughing, tightness of chest, wheezing, and excessive mucus production. The leading cause of COPD is cigarette smoking (National Institute of Health, 2013). Those with the disease have significantly smaller oxygen peak consumption rates than those who don’t, thus experience a much higher level of dyspnea, or shortness of breath (Jeng, Chang, Wai, & Chen-Liang, 2003). This means that a COPD subject entrapped or engulfed in grain will likely experience significant obstacles in breathing; and if he experiences uncontrollable coughing and wheezing, the risk of aspirating grain will be even greater. In addition, a person who panics due to a natural fear of being buried alive (Soderman, 2001) will use up most of the available oxygen in a relatively short time (versus one who remains calm), thus further reducing his chances for survival.

3.3.3.2 Asphyxiation

There are three main ways in which a victim can experience asphyxiation in grain—aspiration, crush or traumatic asphyxiation, and postural asphyxiation. The primary one is aspiration, and there are a multitude of case studies of engulfed victims with their lungs filled with grain (Slinger, Blundell, & Metcalf, 1997; Arneson, Jensen, & Grewal, 2005; Jurek, Szleszkowski, Maksymowixz, Wachel, & Drozd, 2009). The flowability of grain may be enough to fill the victim’s mouth, nose, and lungs, leading to asphyxiation, as long as there is no barrier (e.g., a mask) between his face and the grain and/or he responds to being pulled into the grain by opening his mouth to shout or breathe. Crush or traumatic asphyxiation occurs when the rib cage or abdomen are fixated, as is often the case in a mining cave-in incident or if a trench collapses and buries the victim to neck level (Hitchcock & Start, 2005). The tell-tale sign of crush asphyxiation is the distribution of petechiae (small red/purple spots) across the body and face and in the eyes (Byard, 2005). Due to a lack of studies, it's unclear whether the passive grain pressure alone could cause this crush or traumatic asphyxiation due to the chest getting splinted (Moore & Jones, 2016).

The third type is postural or positional asphyxiation, where the body gets wedged in a specific position that prevents movement of the chest (Byard, Wick, & Gilbert, 2008). Having the arms and hands behind the back or above the head reduces the victim's ability for chest expansion; and the fear or stress associated with asphyxia can, in and of itself, cause death by cardiac arrest (Beynon, 2012).

3.3.3.3 Blood flow

A person entrapped or engulfed in grain loses the ability to move legs and torso, which might lead to physiological conditions similar to being suspended in a harness (regardless if they were wearing a harness or not). Weems and Bishop (2003) reported that a healthy adult suspended in a vertical position for as few as 5 minutes with no body movement can lose consciousness and, if not placed in a horizontal position, can die. The reason is that blood quickly starts pooling in the legs due to lack of muscle movement, thus reducing the supply to the heart; and straps around the thighs further cut off blood flow (Lee & Porter, 2007)—a physiological condition subsequently confirmed by Pasquier, Yersin, Vallotton, & Carron (2011).

In the earlier-sited case study by Bahlmann et al. (2002), the victim experienced chest pain until he was fully extricated, the authors suggesting that mild hypothermia may have contributed to the pains, since hypothermia is known to cause angina (Angina is the chest pain one feels when not enough blood flows to a part of the heart due to temporary blockage of the arteries; and the pain tends to dissipate quickly (WebMD, 2015)). The victim's sudden relief from chest pain after rescue indicates that, while hypothermia and his heart disease might have played a role in the pain's severity, the primary cause might have been reduced blood flow similar to what one experiences during suspension trauma. In addition, if the pain had been caused solely by the pressure of the grain on his chest, the subject should have experienced relief as soon as the grain level was below his chest. Lastly, a study on how boa constrictors kill their prey revealed that they induced circulatory arrest in their victims, causing a cardiac electrical dysfunction (Boback, et al., 2015). This is contrary to previous understanding that victims of boa constrictors die due to suffocation. This effect may have a role in some engulfment cases.

3.3.3.4 Heart rate

There are potentially multiple factors impacting the heart rate of a person engulfed in grain. The first is the availability of oxygen in the surrounding grain. A study by Dripps and Comroe (1947) to measure the impact of oxygen supply on heart rate found that decreasing the supply to 8-10% for 6-8 minutes increased heart rate of the test subjects by 20 bpm up to approximately 90 bpm. The study participants were first rested on a bed for 45-60 minutes in order to stabilize their heart rates then provided oxygen at a specific concentration through a rubber mask.

Another factor could be the surrounding grain pressure. While no studies were uncovered specifically on the impact of grain pressure on a person's heart rate, Butler and Woakes (1987) found that, when test subjects were submerged under water and remained inactive for 30 seconds, their heart rates dropped from 70 bpm down to about 50 bpm. In addition, in suspension trauma, one experiences initially an increased heart rate that then drops significantly just before he's about to faint. For one subject in a study by Pasquier et al. (2011), heart rate dropped as low as 30 bpm just before fainting. In the earlier-cited case study of the youth engulfed for 4-5 hours before being rescued, his rate immediately after rescue was 173 bpm (about 90% of the maximum heart rate). However, it is important to note that, while still engulfed in the grain mass, he was going in and out of consciousness and only awoke when he heard a fireman's radio (Klingseis, 2013). This might mean that his heart rate during the early stages of engulfment was considerably lower than what was measured, perhaps indicating the heart may be responding in a complex manner to the above and/or other psychological factors, such a fight-or-flight response and adrenaline.

3.3.3.5 Psychological factor

Human beings have a long history of fear of being buried alive, one medical historian considering it the most primal fear (Lawes, 2014). There are numerous stories of persons being buried alive and societies practicing such traditions as 'waiting mortuaries' (Soderman, 2001), and keeping unpreserved corpses for viewing for three days (Lawes, 2014)—the purpose being to prevent burying humans alive. It might be expected that getting engulfed in grain can elicit similar fears.

In addition, emotional stresses triggered by grief or fear have been known to cause chest pain and/or shortness of breath—a set of symptoms has been called takotsubo cardiomyopathy, broken heart syndrome, and stress cardiomyopathy (Wittstein, 2008). Such have been triggered by a family member's death, a car crash, surprise party, court appearance, tragic news, and even fear of choking (Rostila, Saarela, & Kawachi, 2011; Wittstein, et al., 2005). Alone, stress cardiomyopathy has a favorable prognosis, with hospital mortality rate of 1.7-3.1% and a very low recurrence rate of 11.4% over a four-year period (Wittstein, 2008). However, the psychological reactions of chest pain and shortness of breath, combined with a victim entrapped or engulfed in grain might lead to secondary or tertiary causes of death.

3.4 Conclusions and Recommendations

The low survival rate for grain engulfments and entrapments, coupled with the fact that these incidents continue to occur despite an industry-wide decrease in the number fatalities, highlight the importance of understanding the environmental and physiological/psychological factors that impact the survival rates. The author believes that the major cause of death in grain engulfments/entrapments is most likely aspiration. The specific roles that lateral pressure and oxygen availability play are unknown. Blood flow, heart rate, and psychological shock might be a secondary cause of death but, most likely, not the primary. It is also highly unlikely that cause of death will be from hypothermia or exposure to low temperatures though both could have occurred. Friction only plays a role in injury during extrication from a grain mass. However, the data clearly indicate that serious physical injury (and even death) can occur by forcefully trying to extricate the victim from the grain. This includes injury to the joints and spinal column.

3.4.1 Needed Research Efforts

Future research and case studies are needed in this area to more fully understand—and confirm—the factors that a body experiences during entrapment, engulfment, and extrication. It is suggested that such research should focus on: (1) the ability of the chest to expand under various depth of grain, (2) oxygen availability and diffusion rates in the grain mass, (3) blood flow and heart rate for victims entrapped in grain, (4) the maximum tensile force that a spine can withstand during extrication, and 5) case studies that document the primary and secondary causes of death and injury. Each of these topics would help provide credible evidence to what is occurring to a body engulfed in grain and provide insight into how to increase survival rate for victims, especially in engulfments.

CHAPTER 4. GRAIN ENTRAPMENTS AND THE HARNESS: A REVIEW ON THE EFFECTIVENESS OF THE HARNESS AS A SAFETY DEVICE

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4.1 Introduction and Background

Grain entrapments and engulfments are among the most common hazards associated with grain storage facilities. Since the 1970s, nearly 1,150 such incidents have been documented and entered in the Purdue University Agricultural Confined Space Incident Database (Issa et al., 2014; Issa, Cheng, & Field, 2015; Issa et al., 2016). The use of fall-safety equipment, specifically a safety harness, lanyard, and lifeline and positioning of an outside observer, as means of preventing or mitigating grain entrapments and engulfments has been seen as problematic for a variety of reasons. Currently considered essential personal protection equipment for workers entering grain storage structures under generally accepted best practices in the grain industry, and required by federal occupational safety regulations at OSHA non-exempt facilities, the use of these devices has not been documented as a significant contributor to reducing the frequency or severity of grain entrapments or engulfments. This is especially true at OSHA-exempt facilities where the use of such equipment or confined space entry practices are optional. In other words, it cannot be affirmed that the use of a safety harness or lifeline would have prevented a significant number of documented entrapments.

OSHA’s grain handling standard (29CFR 1910.272) currently mandates that any worker entering a non-exempt (i.e., commercial) grain storage facility must wear a full-body harness with a lifeline: “Whenever an employee enters a grain storage structure from a level at or above the level of the stored grain or grain products, or whenever an employee walks or stands on or in stored grain of a depth which poses an engulfment hazard, the employer shall equip the employee with a body harness with lifeline, or a boatswain's chair that meets the requirements of subpart D of this part. The lifeline shall be so positioned, and of sufficient length, to prevent the employee from sinking further than waist-deep in the grain” (OSHA, 2002). Currently there are approximately 14,000 grain storage and handling facilities covered by this regulation, but over 300,000 that are exempt due to their status as “agriculture”, “farm”, “feedlot” or “seed processing”.
The overwhelming majority of workers exposed to the hazards of grain entrapment are not only not required to use the very basic preventative measures contained in CFR 1910.272, but also have no clearly recognized incentives to purchase such equipment or be trained in its proper use.

In addition, there have been over 750,000 steel grain bins constructed over the past 75 years in the U.S. and the vast majority of these bins do not have anchor points that meet the minimum load capacity for use in securing a lifeline as specified by CFR

1910.272 (Bauer, 2014) The lack of adequate anchor points in most of these facilities make the use of such equipment difficult, possibly unsafe, if not impossible. Furthermore, the load capacity and lack of horizontal work platform on the majority of these structures does not allow for the safe use of current top access retrieval systems. Consequently, even if every exposed worker was equipped with a safety harness and lifeline, and mechanical retrieval system, their use would be restricted due to the design of the structure.

4.1.1 About Fall-Safety Equipment

4.1.1.1 Designed Purposes

Fall-safety equipment has been designed for four different purposes—fall arrest, positioning, suspension, and retrieval. *Fall arrest* systems stop a fall before it is complete; the equipment only comes into effect when a fall occurs; generally, a harness with 6’ expandable lanyard or self-retracting lifeline is used to stop or minimize the distance of a fall and to reduce the forces associated with stopping it. *Positioning* is the capacity of a system that allows the worker full use of both hands and only activates when the worker leans back; it might not specifically be designed for fall arrest. *Suspension* is the capacity of a system that actively supports the worker and allows him to fully utilize both hands; it is not a fall arrest system. *Retrieval* systems address the after-effects of a fall and how to safely extricate or lift a person to safety (OSHA, 2015).

4.1.1.2 Specific Equipment Items

Fall-safety equipment items have been placed into four classes according to the intended function of each (OSHA, 2015).

- *Class 1—Body belts*. Intended primarily for positioning and reducing the risk of falls (e.g., a slippery surface). They should never be used in situations where a risk of free-fall exists.
- *Class 2—Chest harnesses*. Intended primarily to retrieve a person. They can be used in a limited fall hazard as long as it's not a vertical free-fall (e.g., a sloped roof).
- *Class 3—Full-body harnesses*. Intended primarily for use in situations where there is potential for a free fall (e.g., falling off scaffolding).
- *Class 4—Suspension belts and chairs*. Intended only to suspend a worker.

Only Class 3 and Class 4 are allowable for grain storage entry at OSHA-non-exempt facilities under the provisions of 29CFR 1910.272. However, one is apt to find safety equipment from all four classes plus 'makeshift solutions' being used by some smaller commercial grain and feed operations and by farmers and/or farm workers entering grain bins and silos, which are largely exempt from 1910.272 compliance. It is also important to note again that, historically, grain storage structures (both non-exempt and exempt) have generally not been designed to support use of safety harnesses and lifelines.

4.1.1.3 Outside Observer Station

Safety harnesses and lifelines used alone, without the support of an outside observer(s), will generally be ineffective in preventing an entrapment. As with anchor points, most grain storage structures, especially steel bins, do not provide an adequate work station for an outside observer to adequately supervise the worker inside the structure or to effectively respond in the event of an entrapment. The forces on a victim being drawn into grain will exceed the lifting or braking capacity of a single person standing on a ladder or steep roof surface. Cases have been documented in which the observer lacked the strength to keep an entrapped worker attached to a lifeline from sinking into flowing grain. If an observer is used and a worker is allowed to enter a structure where the risk of entrapment exists because unloading is in process, or there is the presence of crusted grain, the observer has, in most cases, no means of controlling the unloading process due to the lack ready access to controls. In other words, the observer has only visual contact with the inside worker and in the event of entrapment may have to climb down from the observer’s station and go to another location to shut off controls in order to stop the flow of grain. There have been numerous cases in which the observer watched as the victim became entrapped or engulfed and had insufficient time to personally or through co-workers to stop the grain flow.

4.1.1.4 Equipment-Related Injuries

A search of the literature yielded very little with regard to type and extent of injuries resulting from the use of safety harnesses, lanyards, lifelines and fall restraint equipment, especially while in use during accessing grain storage facilities. Lee & Porter (2007) reported on one of the more common injuries associated with harness use—'suspension trauma' (also known as 'harness-induced pathology'). Weems & Bishop (2003) reported that a healthy adult suspended in a vertical position for as few as five minutes with no body movement can lose consciousness and, if not placed in a horizontal position, can die. The reason is that blood quickly starts pooling in the legs due to lack of muscle movement, reducing the blood supply to the heart; also, harness straps around the thighs further cut off blood flow. This situation was subsequently confirmed by Pasquier et al. (2011).

4.1.1.5 Harness/lifeline as a Retrieval System

In addition to their intended role in injury prevention, some have suggested using the harness with lifeline as a retrieval system to pull out entrapped victims directly from the grain mass. Schwab et al. (1985), Roberts et al. (2015) and Issa (2016) conducted studies with mannequins in full-body harnesses that were 'entrapped' in grain and pulled vertically upward to determine the total forces exerted on the body. They all found that to extricate a victim entrapped to chest/arm pit level in this manner required twice as much, or in some cases more, force as the victim's body weight. In other words, an outside observer attempting to pull up or brake a 200 pound entrapped victim would have to have the capacity of pulling at least 400 pounds or more to rescue the victim. These studies have led to published recommendations to avoid trying to pull someone forcefully out of a grain mass this way (Baker et al., 1999; Drake et al., 2010). If a lanyard is incorporated into the safety harness, the forces required may exceed the force required to activate the lanyard's extension allowing the victim to become buried as much as 6 feet deeper. As to the use of ropes without a safety harness for extrication, Bahlmann et al. (2002) reported a case study in which the victim experienced such unbearable pain in the rescue attempt that the effort had to be stopped. Roberts (2008) reported a case in which the victim may have died as the result of injuries sustained during a forceful extrication. Another case study reviewed noted that the victim of a forceful extrication attempt experienced permanent injuries to his back and lower limbs.

4.1.1.6 Use of Safety Harness and Lifelines in Different Types of Grain Entrapments

Before attempting to determine the effectiveness of the safety harness and lifeline as safety tools, it's important to understand the different categories of grain entrapments in which they might be used. The categories were classified into seven categories based on Field et al., (2014b). A new category, covered under grain, was added to reflect a small number of cases in which the grain was poured over the victim drowning him such as in the bottom of a grain transport vehicle (GTV). The previous categories by Field et al., (2014b) did not account for this scenario. Also, the GTV category in Field et al., (2014b) was not considered since these cases reflected a type of structure, such as grain wagons or semitrailers in which safety harnesses and lifelines are not used.

1. ***Entrapment in a flowing column of grain (Flowing Grain Entrapment).*** The typical process of flowing grain entrapment generally starts when an individual enters the top of a structure during the unloading process to clear a plugged outlet

or walk down the grain to break up clumps of grain and prevent them from entering the grain flow and to scrape off crusted material from the walls while the in-floor auger is running. (This practice is specifically prohibited by OSHA regulations.) As the structure empties, a rapidly moving column of grain forms directly over the floor outlet(s) and the victim is drawn into the column of flowing grain towards the center of the bin. Once a person is trapped in the flow, escape is nearly impossible as the victim is quickly pulled towards the center of the bin and down to the floor directly over the outlet, often plugging flow. The victim is usually found in the center of the bin, in an upright position. Flowing grain entrapments in grain transport vehicles, which largely involve children, have also been placed in this category.

In these cases, the use of a safety harness and lifeline provides very limited protection, especially if the victim is working alone. The lack of an adequate anchor point, in ability to maintain proper tension on the lifeline and the inability to shut off the unloading system reduce the probability of survival.

2. ***Collapse of horizontally crusted or bridged grain surface (Bridging).*** This type of entrapment is often the result of improper drying or rewetting of the grain, which allows moisture to build up on the grain surface, over time creating a hard crusted surface over the top of the grain mass that can appear to support the weight of the victim. Later, as the grain is augured out from the bottom of the bin, that crust maintains its shape and forms a ‘bridge’ of grain, though appearing solid, can, in fact, be a thin crust concealing a void that has formed as grain was withdrawn from the bottom of the bin The victim enters the bin in which the grain

has become caked because of spoilage often in an attempt to break up the crusted surface. As the victim walks on the hard surface, he breaks through the crust and is quickly covered by the avalanche of grain into the cavity. Often the unloading equipment is still operating, which causes the victim to be pulled deeper into the grain. The victim is generally found directly over the outlet in the floor of the bin. As with flowing grain entrapments, the use of a safety harness and lifeline has very limited or no value except in locating the buried victim. Any attempt to forcefully retrieve the victim buried below the grain surface would, most likely, expose him to forces that he could not sustain without serious injury.

3. ***Collapse of vertically crusted grain (Grain Avalanche).*** This type of engulfment can take place inside bins where spoiled grain is free standing or clinging to walls above the victim. This could occur due to water leakage through the bin roof, moisture accumulating on the sides due to condensation or weather conditions, or rain or snow entering the structure through inappropriately positioned vents. Unlike dry grain that will pile at a 25-30 degree angle (angle of repose), spoiled or caked grain can stand almost vertical in free standing columns or cling to the walls of the structure. When the worker enters the base of the structure and tries to break up crusted material from below, it can collapse entrapping and often crushing him with both free flowing grain and large chunks of grain. Falling chunks of crusted grain from off the walls of a bin or silo can weigh hundreds of pounds and can cause crushing injuries to those underneath.

Since the victim is usually entering at ground level, the risk of fall is minimal and when the crusted grain collapses without warning, the use of a safety harness and lifeline would prove ineffective except in locating the buried victim.

4. ***Entrapment while using grain vacuum machines (Vacuum Machine).*** This type of entrapment can occur when the worker uses a vacuum machine and hose instead of the in-floor auger to withdraw the grain from the structure. These machines have become more widely used especially in removing residual grain or when heavy crusting keeps clogging the auger wells. These entrapments usually involve the operator standing on the grain surface (which is clearly discouraged by warnings placed on grain vacuum machines by manufacturers) while operating the vacuum machine. As the grain is removed beneath the victim's feet, the victim is drawn deeper into the grain. Entrapment can occur in seconds with machines that can remove 1,000-2,000 bushels of grain per hour.

The role and efficacy of safety harnesses and lifelines while operating grain vacuum machines are not well documented in the literature. It is rather, assumed that everyone should use them. Applying current workplace practices and regulations to this relatively new means of removing grain may or may not result in lower risk to the worker. Cases, however, have been noted in which an outside observer watched as a worker became engulfed in grain while using a vacuum machine and equipped with a safety harness and lifeline. The observer did not have access to the controls and watched as the worker disappeared beneath the surface of the grain.

5. ***Engulfment due to getting covered with grain (Covered).*** This rare type of entrapment occurs when a worker is inside an empty or partially empty structure or GTV and another worker, unaware of that fact, loads grain into the structure/wagon. (This incident frequently involves youth playing in the space). As with flowing grain related incidents, the use of a safety harness or lifeline would contribute little to preventing this form of entrapment. The key prevention measures in those cases would be lockout/tagout provisions and use of an outside observer.

6. ***Entrapment due to unintended release of material or structural failure (Collapse/Unintentional Release).*** Workers have become entrapped or engulfed when grain or feed was unexpectedly released from an access point, such as an inspection opening on the bottom of a hopper bottom bin or due to structural failure. The force of the grain suddenly released from a large structure can quickly engulf anyone in close proximity to the structure. Since the worker is at ground level, and the flow of grain is coming from above, the efficacy of a safety harness and lifeline is questionable.

7. ***Entrapment in free-standing pile of grain (Open Pile).*** Entrapments and engulfments in free standing piles of grain are rare, but have been some of the most difficult rescues to carry out due to the substantial amount of grain involved and the tendencies for these piles to shift or avalanche. While walking on the surface of a free standing pile of grain a worker can cause an avalanche of grain from above that is impossible to stop until it reaches its natural angle of repose, usually 20-30 degrees depending on the type of grain and moisture content.

> The use of a safety harness and lifeline in successfully preventing entrapment in large free-standing piles of grain, is doubtful since the lifeline would trail the victim up the pile and could not be used to lift the victim out from above.

There were no data found on the distribution of each of these types of grain entrapments and/or on the effectiveness of a safety or harness/lifeline as an entrapment-prevention device. What is clear is that the grain industry, with the exception of OSHA-exempt facility operators, and OSHA view safety harnesses and safety lines as an essential measure for preventing grain-related entrapments and rescuing victims of entrapment.

4.1.2 Focus of This Study

The research reported here focuses on the issue of the ‘efficacy’ of fall-safety equipment (particularly safety harnesses and ropes) used in grain storage entrapment/engulfment prevention and rescue situations. Presented are the research methods that were employed, a summary of the findings, an analysis of those findings, and a review of five case studies illustrating the wide range of situations involved in the equipment safety issue and why the use of such equipment remains problematic.

4.2 Methodology

The Purdue University Agricultural Confined Space Incident Database (PACSID) is an electronic database developed to assist in storing, adding, querying, and analyzing confined-space-related incidents. Each entered case contains all the data parameters that were available (e.g., date, time, state, worker name and age, farm type, incident type, agent of injury/fatality, narrative) and is searchable by each of these parameters. A complete list of all data inputs the database supports and a description of each parameter can be found in Riedel (2011).

For this present study, the PACSID was 'mined' for any and all grain storage structure entrapment and engulfment incidents that indicated involvement of fall-safety equipment (i.e., terms such as 'chest harness,' 'full-body harness,' 'lifeline,' 'rope,' 'tool belt,' 'beltline,' etc.) In addition, any narrative recorded for each case was analyzed and the following data points were extracted from that narrative—type of entrapment, reason for/cause of entrapment, presence of observers/other workers, use of safety equipment, use of lock-out/tag-out, use of respirators or dust masks, and vertical rescue attempts.

4.3 Findings

4.3.1 Qualifying Entrapment Incidents

At the time it was queried for this study, the PACSID contained 1,145 grain bin entrapment incidents. Of that number, 820 provided enough information in their narrative sections to determine the type of grain entrapment. The remaining 325 usually contained no narrative or sparse narratives such as "suffocation in bin" or "fell into bin" and were deemed insufficient to classify the type of incident or determine use of safety equipment.

4.3.2 Categories of Entrapment

Of the 820 incidents in which type of grain entrapment could be identified, 781 had occurred inside a confined space including a bin or other grain storage structure and 39 outside a confined space. Of the confined space cases, 575 (70%) were flowing entrapments, 72 (9%) were caused by an avalanche, 56 (7%) were due to bridging, 52 (6%) were covered by inflowing grain, and 26 (3%) involved the use of vacuum equipment. Of the outside- the structure cases, 29 were structural collapse-related or unintentional release of grain entrapments and 10 open-pile-related. See Table 4.1.

4.3.3 Entrapment Incident Fatalities

Of the 1,145 total entrapment cases in the PACSID, 744 (68%) resulted in fatality; and of the 820 in which type of entrapment was known, 543 (66%) were fatal. In comparison, the fatality percentage for each grain entrapment type varies from as low as 61% for avalanche entrapments to as high as 90% for structural collapse/unintentional release entrapment (Table 4-1)

Table 4-1 Number of incidents within each entrapment category and the percent that were fatal. (*Total* is the sum of all entrapments cases in which the entrapment type is known; *Grand total* is the sum of all entrapment cases found in the PACSID

Type of entrapment	**Number of cases**	**Number of fatal cases**	**Fatality percentage**
Flowing	575	361	63%
Avalanche	72	44	61%
Bridged	56	39	70%
Covered	52	43	83%
Structural collapse	29	26	90%
Vacuum	26	22	85%
Open pile	10	8	80%
Total	820	543	66%
Grand total	1,145	774	68%

4.3.4 Reasons Given for Bin Entry

The reason for bin entry by the worker was known in 700 of the cases. The four most frequently recorded were: *dealing with out-of-condition grain* (includes unplugging in-floor auger)—316 cases, *worker fall into the grain*—93 cases, *cleaning or scooping up residual grain*—85 cases, and *playing or sitting in grain storage structure/grain transport vehicle*—91 cases. These four represented 82% of all the reasons for entry. Highest among the other 18% of reasons were: *repairs*, *observation*, *rescue*, and *installing equipment*. In 39 cases (6%), the entrapment occurred outside a grain storage facility due to open pile or structural collapse. Note, in the *fall into the grain* category, it was not clear in some cases whether or not the worker was outside the grain structure and fell into it and was entrapped or was in the grain structure and fell into flowing grain.

4.3.5 Level of Utilization of All Safety Devices/Measures

Of the 820 ‘qualifying incidents,’ there were 17 cases in which the narration specifically mentioned the use of a harness or a boatswain's chair; seven cases in which the worker was attached to a safety rope, safety line, lifeline, or lanyard (although it is unclear if those devices were attached to a harness or directly to the person); and 13 cases in which a worker tied around his waist or hand-held a rope/chain. Thus, in just 37 out of the 820 incidents (<5%) was it reported that the workers utilized fall-protection safety devices or made an attempt to (based upon the data reported). This compares as follows to incidents in which other entrapment-preventive safety-related practices were documented in the narrative:

- Either an observer was nearby or another worker was in the bin—243 cases.
- Worker had access to a communication device (e.g., phone, radio)—9 cases.
- Worker wore a mask or ventilator—6 cases.
- Auger/equipment was turned off during the incident—5 cases (no narration specifically mentioned use of lock-out/tag-out).

Of the 37 cases that identified use of safety devices, 25 (68%) nevertheless resulted in fatality, almost the same as the fatality percentage for all documented cases. In contrast, those incidents in which observers or multiple workers were present had a 51% fatality rate (123 of the 243). Table 4-2 shows that in 17 of the 25 fatality cases (plus six of the non-fatal cases), the safety rope was too long; in six cases, the victim had disconnected himself from the harness while working; and in two cases (plus three of the non-fatals), the worker was holding the rope only with his hands and had not affixed it to his body or safety harness. The table also shows two cases reported where the worker used the safety equipment and was successfully rescued.

Table 4-2 Safety-related issues experienced by workers using fall-protection equipment upon entry into the confined space (e.g., Bin).

Issue	**Fatal**	**Non-fatal**	**Total**
Safety line or rope too long	17	6	23
Worker disconnected harness	6	0	6
Rope only held by hand	2	3	5
Equipment malfunction	0	1	1
Safety equipment used properly	0	2	2
Total	25	12	37

4.3.6 Use of Harnesses and/or Ropes as Rescue Devices

There were 20 incidents that involved safety harnesses and/or ropes in an attempt to rescue an entrapped worker. In 17 of those incidents (85%), the individual survived. The following was gleaned from the PACSID relative to the utilization of harnesses and ropes as rescue devices in the 20 entrapment incidents:

- Used successfully to extricate the worker—9 cases.
- Used only to stabilize the worker or prevent further submersion—4 cases.
- Used only to recover the victim’s body—3 cases.
- Use of ropes by the rescuers was unsuccessful—4 cases.
- Use of devices resulted in injury—1 case (also a successful rescue)

Devices utilized that were specifically identified: harnesses—6 cases; ropes—11 cases; tool belt serving as makeshift harness—1 case.

4.4 Analysis and Discussion

An analysis of the data queried from the PACSID identified three main concerns relative to the 'efficacy' of current entrapment prevention equipment and practices used in grain storage and handling facilities:

1. The data clearly indicates that little safety equipment was actually utilized by workers who became entrapped in grain storage facilities. In less than 5% of the total 820 entrapment cases, where the type of entrapment could be determined, was a harness or even a simple rope reported as having been used by the workers at times of entrapment. Even if the data reflects substantial under reporting of equipment being used, the clear majority of the cases involved workers lacking appropriate personal protective equipment or not incorporating best practices such as the use of an outside observer and lockout/tagout provisions. The data also revealed that entrapped workers were more likely to have had access to only ropes as a safety measure versus having access to harnesses, which it is contrary to the OSHA standard 29CFR 1910.272 personal protective requirements. The percentage of workers using only ropes did not change significantly when accounting for the grain facility's OSHA classification—i.e., exempt vs. non-exempt. It is believed that more recent vigorous enforcement of 1910.272 has increased the use of safety harnesses and lifeline at most non-exempt operations.
2. It was found that there is a general lack of compliance with generally accepted confined space entry procedures and when used, a high incidence of incorrect compliance. The PACSID data showed that 68% of incidents resulted in

fatalities, even though the victims, in some cases, were using either a harness or a safety rope. This high percentage figure suggests that such devices were ineffective in the specific setting, were being incorrectly used or perhaps being used to provide a sense of security that eventually proved to be false. The inappropriate or misuse of these devices may actually increase the risk of entrapment. For instance:

a. The greatest cause of death of victims using some form of lifeline or rope, or a harness with lifeline, was that the rope/lifeline was too long to prevent the victim from being drawn into the grain. In essence the equipment provided no protection as the victims became entrapped in grain.

b. Victims entered a structure holding only a rope instead of having it secured to their safety harness or having it tied around their waist.

c. Victims, apparently not realizing the substantial force encountered when entrapment occurs, anchored their line to an inside or outside access ladder or a roof beam, neither of which are designed to act as sufficient anchors. This led to failure of the improvised anchor and complete engulfment. In one case the force of the victim being engulfed was great enough to pull the steel ladder free from the inside wall of the bin.

d. The use of an outside observer, who has the potential of intervening in the event of entrapment, as required by OSHA regulations, is very limited, especially at OSHA-exempt workplaces. This practice was identified in only 28% of the cases in which sufficient information was available. Cases were documented in which fatalities occurred even when an observer was present due to the inability to reach the controls for the unloading equipment in a timely manner.

   e. The reported use of lockout/tagout practices, as required by OSHA at all non-exempt facilities, was almost non-existent. In only 5 cases were their use or non-use mentioned.

3. Because of the large number of fall-related fatalities in the construction industry, fall-safety equipment has been primarily designed with construction workers in mind, not agricultural workers (especially those who work in confined spaces, such as grain storage structures). During the 1980s, almost 50% of all occupation-related fall fatalities occurred in the construction industry, compared to 10% occurring in agriculture (Cattledge, Scott, & Stanevich, 1996). Similarly, in a three-year period from 1992 to 1995, a total of 566 fall fatalities were recorded in the construction industry (Janicak, 1998); whereas in that same timeframe, only 78 grain entrapment fatalities were recorded in the PACSID. This is an important issue since the adoption of these fall-safety technologies designed primarily for the construction industry does not necessarily increase the safety of those using them who work in and around grain storage facilities. For instance, rope lanyards and self-retracting lifelines, while a necessity in the construction industry, can prove dangerous in the grain industry. For example:

   a. A lanyard, which has elasticity so as to reduce the shock during a fall arrest, usually provides an extra six feet of lifeline; in a grain storage structure, that extra length, if employed, means that a victim will be buried six feet deeper in the grain, thus greatly increasing the likelihood of engulfment.

b. Similarly, a retracting lifeline allows the construction worker flexibility and, in a free-fall incident, its brake system only works to stop the fall; this means that, in the case of a grain entrapment where the speed of entrapment is relatively slow, chances are the brake system might not be activated, again causing the victim to become fully engulfed.

c. In the construction industry, rope length is only important to ensure that a worker's fall is stopped before he hits the ground. In the grain industry, however, rope length is critical—for every extra foot of rope means that the worker will be buried a foot deeper in the grain. Thus, if the rope is attached to the harness at chest level (which is usually the case), that extra foot would be enough to allow him to be completely engulfed. If a worker entering a 32-foot-tall grain bin from the top access point, attaches his lifeline to an anchor next to the hatch and is dropped only 8.5 feet, he will need a lifeline that's 33.1 feet long to access the other side of the bin, and he would be engulfed 25 feet under the grain in the center of the bin before the line becomes taut. If the anchor was located in the center of the bin, he would still get engulfed 10 feet under the grain. (Figure 4-1). The lack of systems within most current grain storage structures to ensure that tension is maintained on the lifeline is problematic. In some commercial grain operations that are not OSHA-exempt, systems are being installed to provide a secure lifeline, however these systems have yet to be introduced to those most vulnerable to engulfment at exempt agricultural operations.

The use of general fall safety equipment in the grain industry, including the high potential for its misuse, is an issue needing further attention.

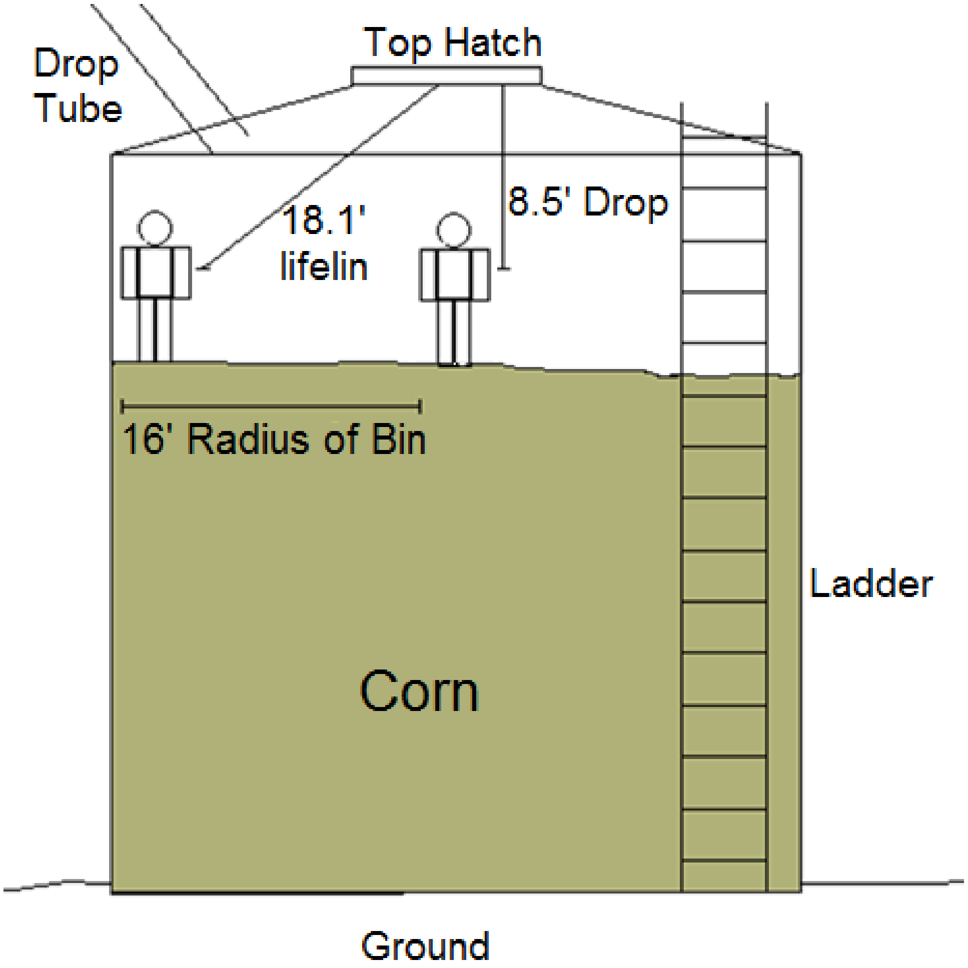

Figure 4-1 An example of how a static lifeline, attached to an anchor point in the middle of the bin, designed to give the worker access to the edge of the bin would not protect the worker from grain entrapment at the center of the bin

4.4.1 Example Case Studies

The following case studies highlight issues related to workers using a harness or lifeline to protect themselves while working inside grain storage structures. The first case highlights that a safety line and harness in of itself is not enough to keep a grain worker safe. The second case points out why adequate anchor points need to be a part of the discussion on safety harnesses and lifelines. Cases 3-5 highlight examples of safety lines and harnesses being used as an extrication tool with two of them failing and third resulting in severe injury. All cases were obtained from the PACSID database unless cited otherwise.

Case Study #1** (1993, OSHA non-exempt facility).** Upon entering a steel bin that contained approximately 80,000 bushels of corn, a worker in search of a missing co-worker could see the engulfed victim's safety line, which was taut, but not the victim himself. After trying unsuccessfully to pull on the lifeline, he sought help from first responders. It appeared to investigators that the victim perhaps had been standing over a grain pocket that collapsed. When the body was eventually recovered, the victim's one hand was gripping the rope while the other was above his head, indicating that he was drawn into the grain by a substantial amount of force. The rope was not attached to the victim or his safety harness. The preliminary cause of death was ruled asphyxiation.

Case Study #2** (2003, OSHA status unknown).** Entering a 10,000-bushel bin that was three-quarters full of corn to unclog the in floor auger, the victim, (a farm operator in his 50s) had tied a rope around himself and attached the other end to a ladder. The unloading system was energized and when the flow resumed he was drawn into the grain. As he became engulfed, the ladder, serving as an anchor, could not withstand the weight of the victim being pulled into the grain, and broke loose from the bin wall. Even though he had a radio, he was unable to use it, most likely due to the speed of entrapment. When co-workers did not hear from him for a while, they investigated to find that he had been buried in the grain. None of the co-workers were acting as outside observers. Rescuers cut a hole in the bin and recovered the body 75 minutes later. The rope was still attached to the victim's waist.

Case Study #3** (2000, international case).** The worker had become buried in the grain up to his armpits. At the time of the attempted rescue, he was conscious and experiencing no pain. The rescuers (firefighters) initially tried to free him by shoveling the grain away from him. This proved unsuccessful because the grain flowed back in the hole they were digging around the victim. They next placed a harness around his upper body in order to extricate him. As they were pulling, he experienced chest pains and developed breathing problems. Although analgesic drugs were provided to reduce the pain, the pull-force being applied by the first responders caused such unbearable pain that the rescue attempt could not be continued. Eventually, the rescuers placed a cylinder around him, removed the grain between his body and the cylinder wall, and then pulled him out. Once extricated, his chest pain immediately ceased (Bahlmann et al., 2002).

Case Study #4** (2003,* OSHA non-exempt facility).** This worker was trapped inside a 60-foot-tall silo about one-third full of soybeans. The first responders initially tied a harness under his shoulders so they could attempt to pull him out; but that proved unsuccessful due to the pressure of the beans. They then built a box around him to keep the beans from packing around his body even more tightly. Some nine hours later, he was successfully extricated. (The rescuers believed he could have been standing on the auger motor, which would have kept him from sinking deeper.) A co-worker who was in the silo when the first became trapped had been able to free himself.

***Case Study #5** (*2012, OSHA non-exempt facility) Two workers and the victim, all male, entered an 80 ft. tall concrete silo to set up a sweep auger (16 ft. in length including motor head) and remove the residual wheat in the silo. The silo was opened the day before (to ventilate) and begin emptying. A light and the auger/motor were lowered from the top into the silo earlier in the day. The three workers waited until the light was lowered and took that as a sign to enter and start working. They entered through a side door and descended down the inside ladder to the surface of the grain. The victim approached the suspended motor and auger and detached them from the cable. While walking on the grain surface, the conveyor belt underneath was turned on and the victim started to sink. Immediately the co-worker closest to the ladder went up the ladder to get the conveyor turned off. The second co-worker and the victim both tried to grab the ladder to get out of harm’s way but the victim’s hands slipped and he sunk until grain reached his mouth. The second worker then tried to shovel the grain from around the victim’s mouth and at around the same time the conveyor belt was shut down. The worker was able to shovel the grain down to chest level. The first co-worker and another worker then entered the bin and together the three workers tried to pull out the victim. The effort failed and the victim said he felt his shoulder and back pop due to being pulled by his arms. The workers then tried to put a steel panel in front of the victim’s face to protect him, but the victim complained of pain and pressure due to the panel’s sharp edges and it was removed. When the victim sank into the grain he was accompanied with the unsecured motor and the auger. The auger was near his leg and was applying pressure on his leg while the motor was buried near his stomach. After nearly an hour, 911 was called and firefighters arrived at the scene. At that time, the victim was complaining of pain in his leg and difficulty breathing. The firefighters placed plywood around the victim and vacuumed out the grain to approximately his knees. They then placed a harness and lifeline on the victim and tried to pull him out without giving him notice. He reported that he felt as if his spine popped. The firefighters adjusted the harness and re-pulled him again and were successful. They secured him on a backboard and lifted him from the silo. He was transported to the hospital in a helicopter. The victim survived the incident but suffered long term psychological damage (anxiety) and weakness in his legs. He initially needed a wheelchair for mobility and later a cane to walk. After three years he still reported leg weakness including his legs suddenly giving up on him while walking.

4.5 Conclusion

Findings clearly document an overall lack of both the utilization and the proper use of safety harnesses, lifelines, and confined space entry procedures, in and around grain storage facilities. This is especially true at OSHA-exempt agricultural operations. To address this issue, it is suggested that the following two-pronged effort be developed—(1) an education program to teach farmers and agricultural workers the appropriate application of and proper techniques in using safety harnesses and lifelines, highlighting special concerns (e.g., lifelines being too long); and (2) a review and updating (as warranted) of the regulations and standards that address the proper use of harnesses and lifelines in and around grain storage structures.

Findings also suggest that the use of current fall prevention equipment in general use in the construction industry to primarily prevent falls, may not be effective at preventing or mitigating most types of grain-related entrapments. Such equipment remains valuable, however, in preventing falls from grain storage structures, if properly used with adequate anchor points. Solely relying on the available fatality and injury data, it cannot be ascertained that requiring workers, who enter grain storage structures, to be equipped with safety harness and lifelines is justified.

To address these issues it is recommended that further attention be given to the other best practices associated with confined space entry as a means of reducing the frequency and severity of entrapments in grain.

- Never entering a grain storage structure while grain is being unloaded from the structure either by gravity or under the floor conveyors.
- Employing lockout/tagout provisions whenever a worker enters a gain storage structure to prevent unintentional energizing of unloading equipment.
- Never entering a grain storage structure where the surface of the grain is crusted.
- Never entering a grain storage structure with vertically crusted grain above the level of the worker.
- Always utilize an external observer who has line of sight with the inside worker, communication with the worker, and access to emergency assistance.

If implemented, these practices have the potential of preventing far more engulfments then the questionable use of safety harnesses and lifelines, which may contribute to a false sense of security and provide little actual protection in most types of entrapments.

Finally, consideration needs to be given to reassessing the current provisions of CFR 1910.272 regarding accessing grain storage facilities. Efforts were recently made to enhance and clarify the provisions related to exposure to sweep augers inside these structure and similar investments should be made to develop new evidence-based regulations or clarify current regulations regarding the use of safety harnesses and lifelines in these applications.

CHAPTER 5. SMALL SCALE EXTRICATION STUDY

5.1 Introduction and Background

Grain entrapments and engulfments are one of the most common hazards associated with grain storage facilities and over 1,100 incidents have been documented since the 1970’s. (Issa et al., 2016c). In approximately 32% of cases the victim is not fully engulfed and may need to be extricated from the grain. One method that has been documented to rescue the victims of partial grain entrapment is through forceful extrication. Forceful extrication involves attaching a victim, with or without a safety harness, to a lifeline and pulling him out using multiple first responders or with a mechanical winch. It has been documented that such an approach can result in secondary injuries to the victim. There have been only two research studies published on the force required to extricate a victim from grain. The first research study was conducted in the 1980’s in a grain bin specifically designed for extrication research (Schwab et al., 1985). A mannequin was dressed in a harness and lifeline and entrapped in grain at various depths and then pulled out using a mechanical winch. The authors used two different types of grain, wheat and corn, and conducted the test with a mannequin and a peg. The authors found that there were no significant difference between the grain types and as the depth increased linearly, the force required to extricate the victim increased exponentially and followed the Jansen equation (Schwab et al., 1985).

Roberts et al. (2015) repeated the experiment in a modified grain bin and found similar results. In addition, the authors inserted a coffer dam, intended as a rescue tube, around the mannequin to determine if separating the victim from the grain mass would reduce the force needed to extract the mannequin. They found that it actually increased the total force by about 24% (Roberts et al., 2015).

While the two experiments helped elucidate the forces needed to extricate a victim, a question remained if these forces are representative of what a person might experience in real life. One of the concerns is that most grain bins are not equipped with an overhead anchor point and are not capable of supporting a 5,000 lb maximum load on the roof, so it may not be possible to extricate a body vertically (Bauer, 2014). Another concern is that the largest documented reason why victims enter grain bins is due to out of condition grain (45%), while the grain tested in Schwab et al. (1985) and Roberts et al. (2015) were clean dry grain. The third concern is that the previous experiments did not take into account the limb placement of victims. Lastly, the relationship between size, bulk density, and properties of grain and force needed to extract an object out of grain is not well understood.

This research aimed to expand on previous efforts by investigating the amount of force experienced by a mannequin in a wide variety of grains selected to represent a variety of shapes, sizes, densities and moisture contents. In addition, this study also explored the impact of body placement and pull angle on the measured force. The objective was to study the effects of grain type, limb placement, pull angle and moisture content on the force needed to extricate a victim entrapped in grain.

5.2 Material and Methods

5.2.1 Grains

A total of seven grains were chosen for this experiment: corn, wheat, soybeans, sunflower seeds, canola seeds, oats and popcorn. The corn, soybean and wheat were selected because they represented the three most common mediums in which grain entrapments occur (Issa, et al., 2014). The remaining four grains were selected to provide a wide spectrum of grain sizes, shapes and densities. All the grain was obtained at stable moisture content suitable for storage at 14% or less. The canola seeds obtained and half of the wheat seed were treated seeds. In addition, a 50 pound portion of corn was wetted and mixed in a rotating drum for a day to raise the moisture content to about 22%. The moisture content of 22% was chosen as a representative of high moisture grain and within range of the moisture content of grain at harvest. The moisture content, bulk density, size, friction coefficient and porosity were measured for all grains. To obtain representative samples, the grains were poured through a Boerner divider (Seedburo Quality, Chicago, IL) several times splitting the sample into two halves, until approximately a 1 kg sample was obtained from each grain.

Figure 5-1 Boerner divider (Seedburo Quality, Chicago, IL) used to get a representative sample from the grain mass.

5.2.1.1 Moisture Content

Moisture content measurements were based on ASABE Standard S352.2 (ASABE, 2012). In total five samples were run per grain type.

5.2.1.2 Bulk Density

Bulk density was determined by filling a 1.1-liter cup using a funnel, leveling the surface, then measuring the weight of the grain (in kg) and dividing the weight by 0.001 m^3 to obtain a bulk density in kg/ m^3 (Clementon, Ileleji & Rosentrater, 2010). Three samples were measured per grain type.

5.2.1.3 Size and Shape

A hundred seeds of each grain type were measured using 15.24 cm (6 in) Fowler Sulvac Model S 235 Data Caliper (Cole-Parmer Instrument Company, Vernon Hill, IL). Three measurements were taken per seed (depth, length and width) with the exception for canola seeds which due to their size only one measurement was taken (diameter). The average and standard deviation for each grain type was calculated and reported. The shape of the grains were assumed to be ellipsoidal and the surface area and volume were calculated using the following equations

Surface Area (S.A) = $4*\pi * ((a^p*b^p+a^p*c^p+b^p*c^p)/3)^{1/p}$ (Michon, 2015) (5-1)

Volume (V) = $4/3*\pi *a*b*c$ (NIST, 2016) (5-2)

Where a, b and c and the radii of each axis of the ellipsoid and p=1.6075

Lastly, surface area and volume were used to measure the sphericity of the grains using:

Sphericity = $(a*b*c)^{1/3} / a$ where a is the max radii length (5-3)

5.2.1.4 Friction Coefficient

A plastic cylinder was filled with grain and then a wooden cap placed on top of it. The plastic cylinder is placed on the surface of interest (steel or oak). The cylinder is open from both sides allowing the grain to interact directly with the surface of interest. The cylinder was then connected to a 50 N load cell (Model LSB.501; 1.972 mv/v sensitivity) on the MTS Criterion device by an elastic line and pulley system (Figure 5-2) the MTS device then pulls the cylinder of grain across the surface at a speed of 10 mm/s and records the resistance (load). Loads were added on top of the wooden cap in increments of about 420 grams each (five total) and the resistance measured at each load increment. Three runs were conducted for each set of variables for a total of 360 runs (6 weight levels, 2 surfaces, 8 grains + controls). The average force required to pull the grain and weights was plotted against the grain and weights multiplied by gravity. The slope intercept was set to zero. The slope of the curve is the friction coefficient.

Figure 5-2 Experimental setup to measure coefficients of friction.

5.2.1.5 Porosity

True density was measured by using a micromeritics GeoPyc 1360 (Norcross, GA) powder pycnometer. GeoPyc 1360 is designed to measure envelope density, which for grains is a good estimate of true density (Figure 5-3). A grain sample is placed in GeoPyc glass chamber and then DryFlo (Norcross, GA) is poured on top of it and shaken so that the powder fully envelopes every seed. Care is taken to make sure that the grain mass is 25-30% of glass chamber volume. A 19.1 mm chamber diameter was used to measure the envelope densities of the grains. Three runs were conducted per grain. Porosity was calculated utilizing the following equation:

Equation 5-4 Porosity (%) = 1 – Bulk Density / True Density

Figure 5-3 GeoPyc 1360 machine used to measure envelope density. The chamber is filled with a grain sample and DryFlo

5.2.2 Experimental Design

A small aluminum container measuring 34 cm tall by 37 cm wide was used to represent a grain bin (Figure 5-4). A 13.8 cm tall mannequin and a 14.0 cm tall plain oak cylinder were used as the extricated objects in this experiment. The mannequin was tested in two positions, straight and stretched to measure forces at either extreme of limb placement (Figure 5-5). The mannequin was attached to the MTS Criterion Model 43 (MTS, Eden Prairie, MN) load cell by steel line. The MTS Criterion is a two column load frame device used to measure tensile or compression. Since the aluminum container could not fit inside the two column MTS frame, a pulley system was designed to allow the MTS to pull the mannequin either vertically or at a 45^o angle from the container. The 50 N load cell (Model LSB.501; 1.972 mv/v sensitivity) was used in this experiment and the mannequin was pulled at a rate of 10 mm/s. For each run, the mannequin was placed on top of the grain mass and then the grain was emptied until the mannequin reached the desired position (top of the head was either at surface level or 10 cm deep in grain). The grain was then returned on top of the mannequin to maintain grain surface level at 30 cm. The purpose was to make sure that the orientation of the grain mass in each run was identical and that the mannequin/object was pulled from the same depth each time. The mannequin and cylinder were either pulled vertically or at a 45 degree angle (measured from surface of the grain) and the maximum force experienced by the body was recorded. Five runs were conducted for each experiment (Table C-1).

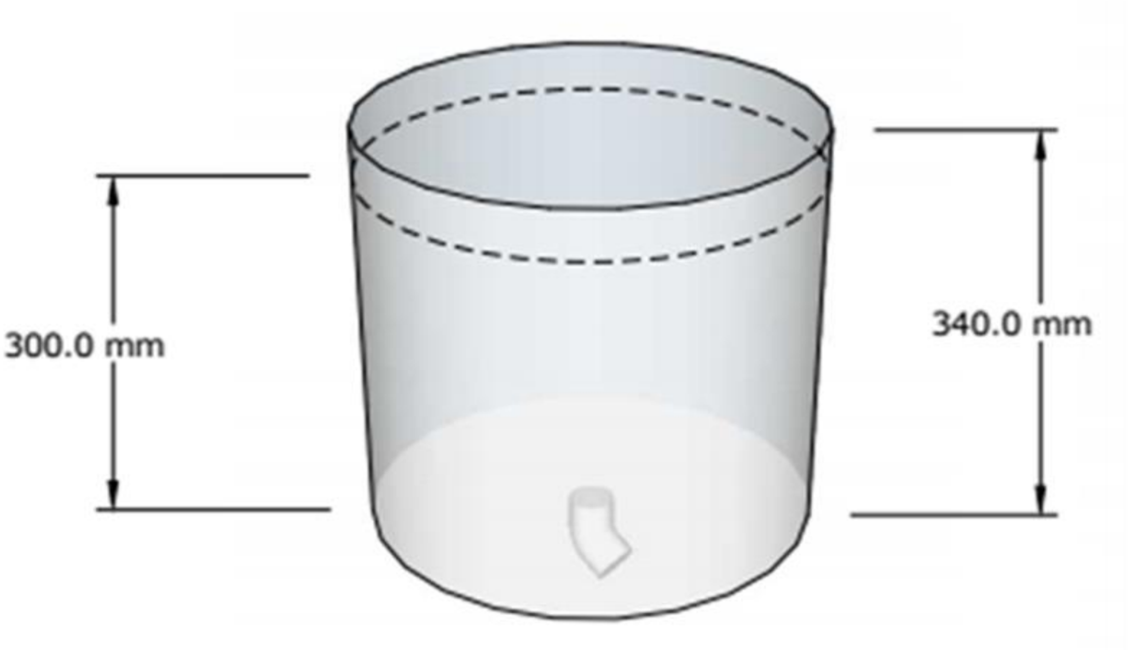

Figure 5-4 Sketch of the aluminum container used in the small scale grain extraction experiment.

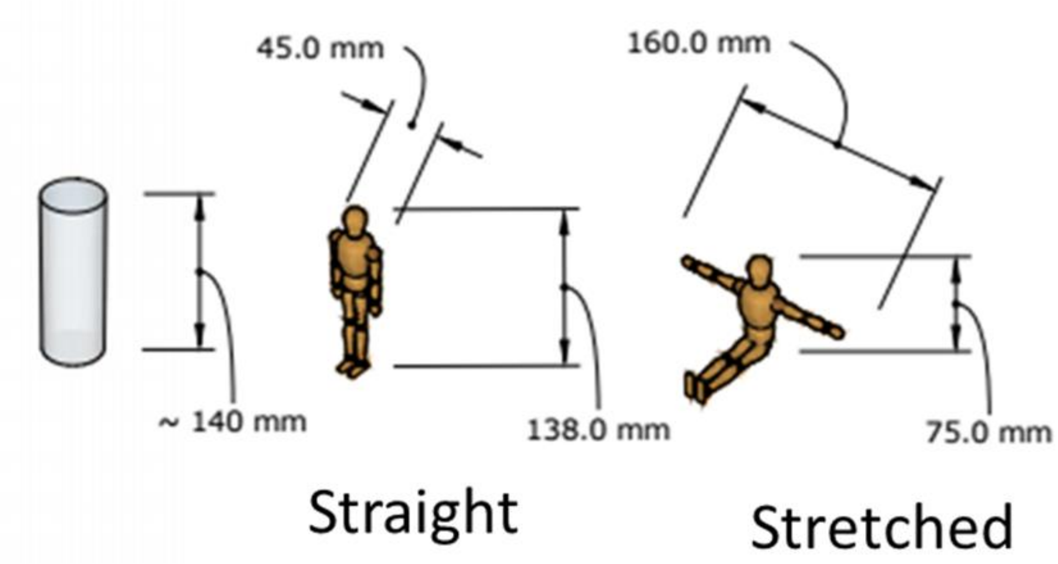

Figure 5-5 Diagrams of cylindrical wooden object and mannequin. Mannequin is shown in both configuration used in the experiment.

In total 480 runs were conducted as a complete block utilizing the following variables:

- Depth (measured from top of head): 0 cm and 10 cm
- Object type: Mannequin (straight), mannequin (stretched) and cylinder
- Grain type: Corn (dry), corn (wet), popcorn, wheat, oat, sunflower seeds, soybeans and canola seeds
- Angle (measured from the surface of the grain): 45^o and 90^o

The experiment was conducted in a semi-random manner. The depth, object type and angle were selected and then the grain types would be selected and ran in a random order until all grains were run. Next, one of the other variables would be changed (depth, angle or object) and the experiment would be repeated. If the object type was mannequin, the two configurations (straight and stretched positions) were run after each other.

5.3 Result

5.3.1 Grain Properties

Measured grain properties were as follow:

Table 5-1 Bulk density, true density and porosity for all grains utilized in the extrication experiment.

Grain Type	**Bulk Density (kg/m^3)**	**True Density (kg/m^3)**	**Porosity (%)**
Dry corn	760.5±1.4	1144.7±45.7	34%
Wet corn	649.6±1.9	1071.3±53.8	39%
Popcorn	861.9±2.0	1288.7±47.9	33%
Soybeans	744.5±1.4	1131.2±22.1	34%
Canola	665.4±2.6	1027.0±29.7	35%
Wheat	758.9±4.5	1210.7±43.0	37%
Oats	580.6±0.6	1096.4±12.2	47%
Sunflower (unshelled)	361.7±3.1	649.5±31.2	44%

Table 5-2 Moisture Content and coefficient of friction all grains utilized in the extrication experiment. Motion on oak surface was parallel to the grain.

Grain Type	**Moisture Content (%)**	**Coefficient of Friction**	
		With oak surface	**With steel surface**
Dry corn	13.7	0.168; R^2=0.98	0.213; R^2=1.00
Wet corn	22.7	0.328; R^2=0.95	0.528; R^2=0.99
Popcorn	12.0	0.175; R^2=0.99	0.270; R^2=0.99
Soybeans	9.8	0.191; R^2=0.98	0.215; R^2=0.99
Canola	5.3	0.332; R^2=0.99	0.249; R^2=1.00
Wheat	11.5	0.124; R^2=0.97	0.136; R^2=0.97
Oats	12.5	0.194; R^2=0.99	0.216; R^2=0.99
Sunflower (unshelled)	5.3	0.198; R^2=0.99	0.213; R^2=0.99

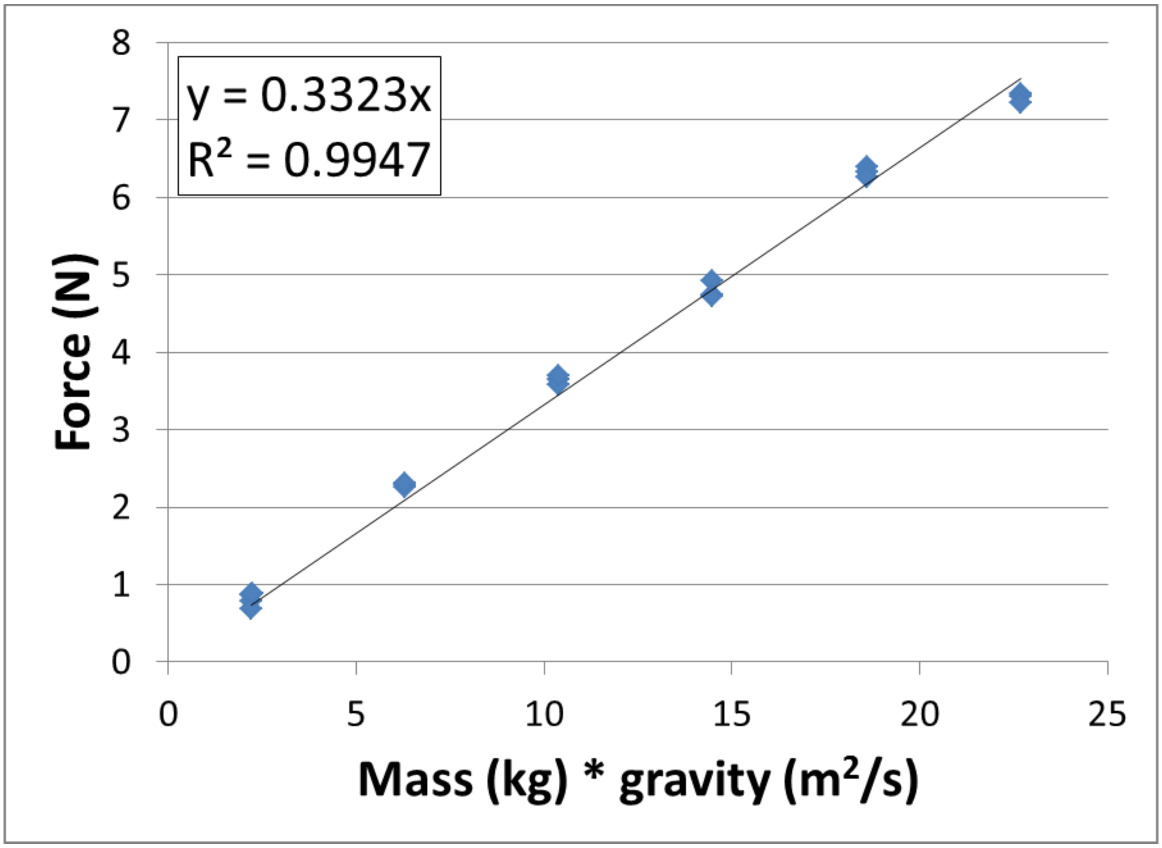

Figure 5-6 Sample curve used to calculate coefficient of friction. This curve represents the amount of force required to pull canola seeds across an oak surface with weights on top.

Table 5-3 Seed size, surface area, volume and sphericity for all grains utilized in the extrication experiment

Grain Type	**Size (mm)**[a]	**Surface Area (mm2)**	**Volume (mm^3)**	**Sphericity**[b]
Dry corn	L=12.1 ; W=8.0; D=4.9 ±0.95	227.84	241.13	0.64
Wet corn	L=12.5; W=8.6; D=5.2 ±1.08	242.17	269.32	0.66
Popcorn	L=8.8; W=5.9; D=4.8 ±0.51	129.26	125.44	0.71
Soybeans	L=6.5; W=5.6; D=6.9 ±0.39	126.37	132.43	0.92
Canola	Di=1.81 ±0.21	10.32	3.12	1.00
Wheat	L=5.9; W=3.2; D=2.7 ±0.33	47.53	27.40	0.66
Oats	L=9.9; W=3.0; D=2.5 ±0.57	68.86	38.40	0.42
Sunflower (unshelled)	L=12.5; W=5.7; D=3.8 ±0.78	150.33	131.67	0.51

[a] L=length; W=width; D=depth; Di=Diameter; Standard deviation is the average standard deviation across all three measurements

[b] Sphericity values range from 0 to 1, the larger the number the closer it is to a sphere (at 1.00 it is a sphere).

5.3.2 Limb Placement

At 0 cm depth (grain level at head level), having the mannequin in either the straight or stretched position did not significantly impact the total force measured (average -2%; $p<0.01$) regardless of angle or grain type (Table 5-4; Appendix C). The only exception where the position of the limbs increased the extraction force at the 0 cm depth was canola seeds. In the experiment where the mannequin was pulled straight up, having the limbs in the stretched positions increased the force experienced by 19%. At the 10 cm depth, having the mannequin in the stretched position significantly increased pull forces by an average of 34% regardless of angle or grain type. Popcorn, Oats and Sunflower experienced the largest force increases with an average of 44% and wheat and wet corn experienced the lowest force increase with an average 23%.

Table 5-4 Extrication force (newton) required to vertically extricate a mannequin in a straight vs stretched position.

Depth	**0 cm**			**10 cm**		
Orientation	**Straight**	**Stretched**	**Change**	**Straight**	**Stretched**	**Change**
Popcorn	4.99	4.19	-16%	7.58	10.85	43%
Oats	3.26	3.01	-8% [a]	6.09	9.02	48%
Sunflower	2.4	2.32	-3% [a]	4.26	6.47	51%
Soybeans	3.74	3.99	7% [a]	9.02	11.81	31%
Dry corn	4.42	4.04	-9% [a]	8.88	11.3	27%
Wet corn	5.9	5.14	-12%	13.13	15.62	19%
Canola	2.73	3.25	19%	6.75	9.51	41%
Wheat	3.61	3.81	6% [a]	7.45	9.96	34%
Average			-2%			37%

[a] The change in value from straight to stretched was not significant ($p<0.01$)

5.3.3 Impact of Angled Extrication

The results of angled extrication were a lot more nuanced than the limb placement and depended on depth, grain type and object type. At 0 cm depth the mannequin experiments were not significantly ($P<0.01$) different from each other regardless of angle or limb placement. In the cylinder experiments there were only four types of grain for which the force at an angle was significantly ($P<0.01$) greater than the vertical force and those were popcorn, oats, soybeans and wheat (Table 5-5; Appendix C). At the 10 cm depth, results were mixed (Table 5-6; Appendix C). For cylinder experiments, on average, the force increase due to pulling at an angle was 23%. But this was not a uniform increase; the largest increases were seen in oats (57%), canola seeds (32%) and popcorn (29%). On the other hand, wet corn and sunflower seeds saw an insignificant ($P<0.01$) increase of 1% and 3% respectively. For the mannequin in the straight position, only four grains had significant ($P<0.01$) increases: oats, sunflower seeds, canola seeds and wheat. They increased by an average of 18.5%. The remaining four experienced were insignificant

($P<0.01$) average increase of 5.5%. For the mannequin in the stretched position, only two grains experienced a significant ($P<0.01$) increase and those were popcorn and oats at 12% and 19% respectively. It is interesting to note that only oats was significantly ($P<0.01$) different in all object scenarios while wet corn was not significant in any scenario.

Table 5-5 Increase in force (%) for each extrication object at 0 cm depth due to pulling at a 45^o angle vs vertical pull

Grain type	**Cylinder**[a]	**Mannequin Straight**[a]	**Mannequin Stretched**[a]
Popcorn	23*	-9	-8
Oats	22*	-8	2
Sunflower	6	-5	8
Soybeans	28*	8	6
Dry corn	9	-4	-5
Wet corn	10	6	4
Canola	10	9	-4
Wheat	24*	-8	-8

* Significantly different ($P<0.01$) from vertical pull

[a] Each data point represents the increase/decrease in force when the object is pulled at an angle verses vertically in all eight grain types. All data points are percentages and do not reflect the absolute value. See appendix C for absolute force values

Table 5-6 Increase in force (%) for each extrication object at 10 cm depth due to pulling at a 45^{o} angle vs vertical pull

Grain type	**Cylinder**[a]	**Mannequin Straight**[a]	**Mannequin Stretched**[a]
Popcorn	29*	15	12*
Oats	57*	15*	19*
Sunflower	3	25*	6
Soybeans	23*	9	6
Dry corn	8*	-3	5
Wet corn	1	1	3
Canola	32*	12*	-4
Wheat	19*	22*	-6

* Significantly different (P<0.01) from vertical pull

[a] Each data point represents the increase/decrease in force when the object is pulled at an angle verses vertically in all eight grain types. All data points are percentages and do not reflect the absolute value. See appendix C for absolute force values

5.3.4 Grain Type

For the purpose of comparing the effect of grain type regardless of treatment, the average force from each run was converted to a relative number (actual value/ max value) and then averaged for all experiments on that particular type of grain (Figure 5-7; Table C-2). This is a simple method to understand the role that grain plays in each experiment and allows us to combine very different experimental factors together such as depth (0 and 10), angle (45^{o} and 90^{o}) and object type (cylinder, straight mannequin and stretched mannequin). Sunflower seeds and wet corn were significantly different (P<0.01) from all other grain types. Oats was significantly different from corn, soybeans and popcorn (P<0.01) but not significantly different from canola seeds and wheat. Canola seeds, wheat, dry corn, soybeans and popcorn were not significantly different from each other.

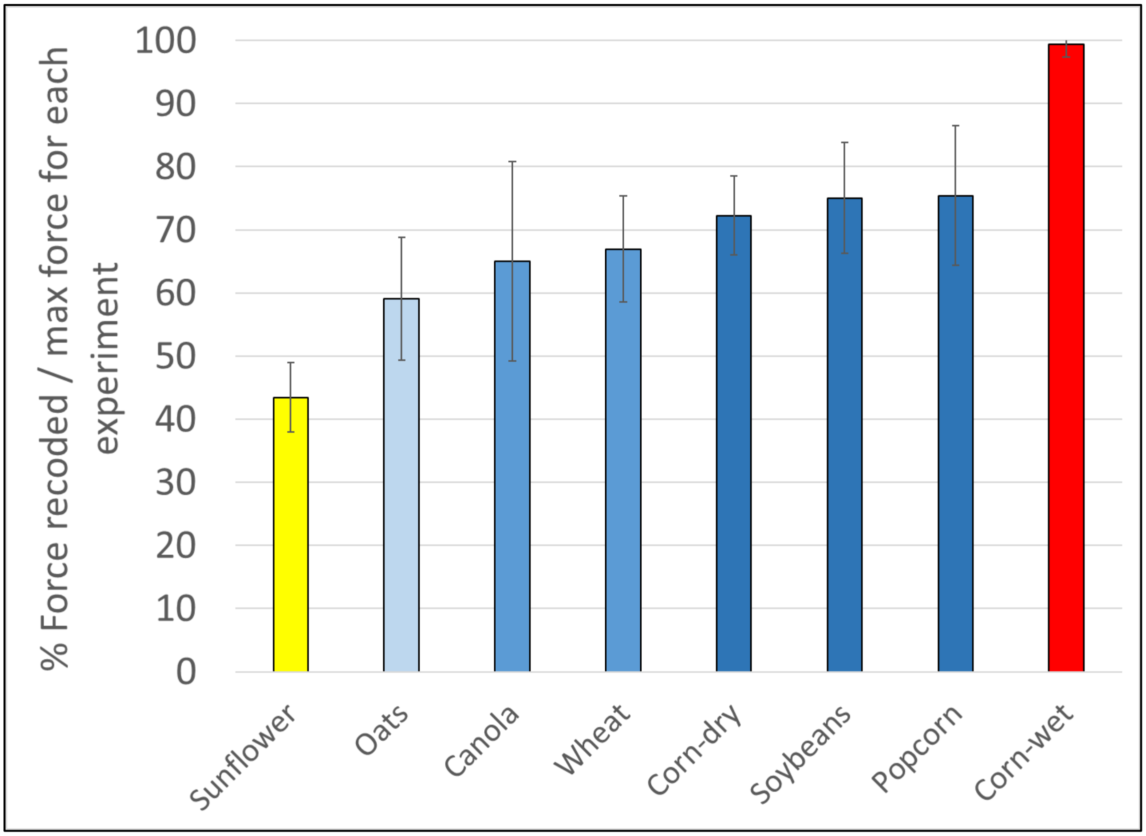

Figure 5-7 Relative force needed to remove an object from different types of grain. Sunflower (yellow) and Wet corn (red) are significantly different (P<0.01) from all other grain types. The error bars represent the standard deviation for each grain type.

5.3.5 Moisture Content

The moisture content difference between dry corn and wet corn was 9% (from 13.7% to 22.7%). In all of the experimental runs conducted, some of the greatest increases occurred when the only variable difference was moisture content. Overall the average increase regardless of depth, angle, and object was 39%. When comparing extrication force increases when pulling out the mannequin (regardless of limb position), the increase on average was 40% and was a fairly even increase regardless of variable. For the cylinder object experiments, extrication forces increased by average of 54% at 0 cm and 18% at 10 cm (Figure 5-8; Table C-1). It not clear why there is a large difference between the two depths.

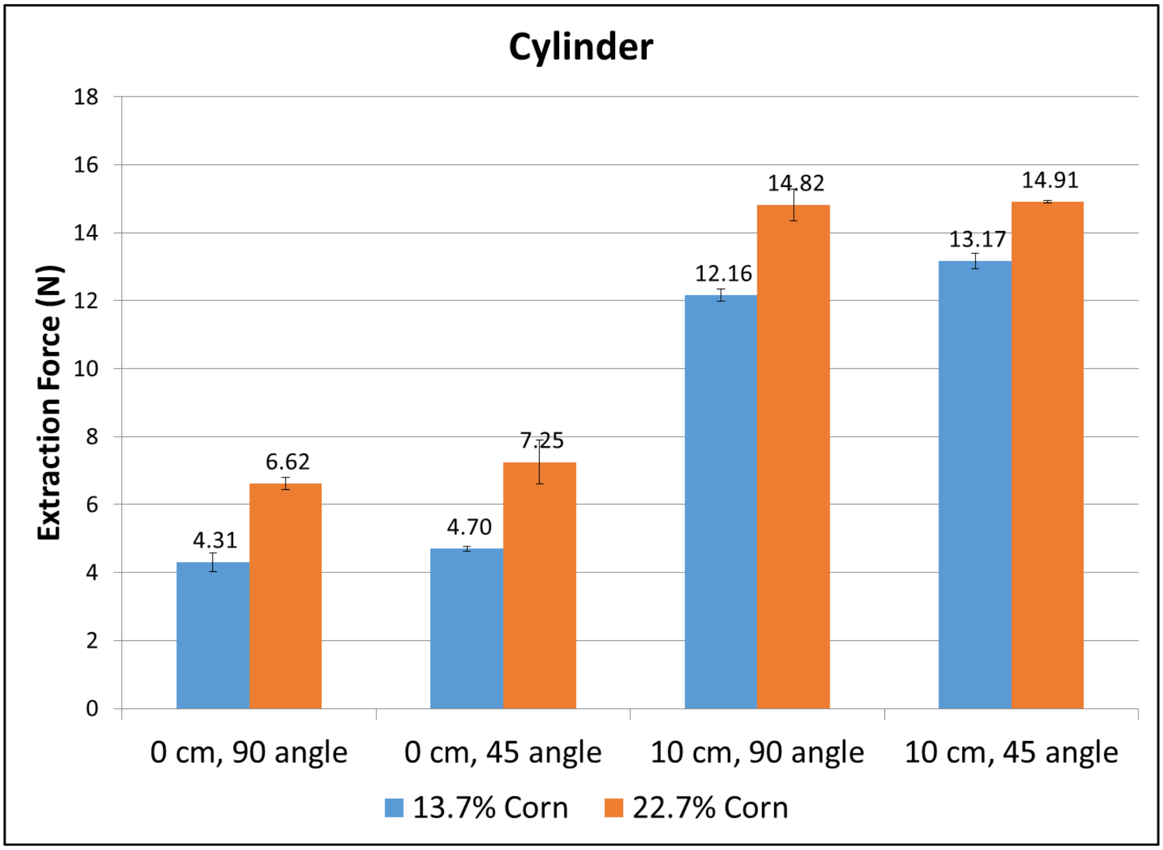

Figure 5-8 Extraction force experienced by cylindrical object at various depths, angles and moisture content levels. The error bars represent the standard deviation for five runs per bar.

5.4 Discussion

The aim of this series of extraction experiments was to answer the question regarding variables that are the most important in extrication and rank the influence of each condition on potential forces experienced by the body.

The increase in moisture content from 13.7% to 22.7% had a significant influence on the extrication forces from corn. In addition to increasing extrication forces, the 22.7%

M.C. corn had the highest absolute force value recorded of every single experiment except for one. At the 10 cm deep the 22.7% M.C. corn required 1.7-4.6 N larger extrication force than 13.7% M.C. corn in every run. The findings on moisture content was one of the most important results of the study as most grain entrapments occur in out of condition, crusted corn (due to high moisture content) while most past experiments were conducted in dry corn at levels below or at 14%.

The results on grain types were surprising. One of the hypothesis inferred that grains types will have a significant impact on the extrication forces due to the wide variety of shapes, sizes and densities. In the most extreme case, with the oak cylinder extricated at a 45^o angle and 10 cm depth, the forces ranged from 13.2 N to 15.2 N with a mean of 14.2 N (for the same experimental run) indicating that for most extrication attempts grain type was not a significant factor. The only grain that had extrication forces significantly ($P<0.01$) different from all grain types was sunflower seeds. In this particular case (cylinder, 45^o pull, 10 cm depth) the largest difference was between sunflower seeds and popcorn, and it was 8.9 N (107% increase in force). It seems that the only major grain property that influenced extrication forces was bulk density with sunflower seeds having a significantly lower bulk density than the remaining seeds.

For pull angle, at surface level, it did not make a difference for the mannequins and increased forces slightly by an average of 0.7 N for the cylinder. At 10 cm depth, the mannequins experienced on average 0.7 N more force and cylinders experienced 2.3 N. The increase in force was not equal in all grain types and mostly occurred in oats, popcorn and wheat. The grain properties might play a significant role in determining whether pull angle would cause a significant difference in extrication force.

Lastly for limb placement, no significant difference was recorded for most grain types regardless of angles when pulled at surface level. However, at 10 cm deep, the limb placement increased loads from 1.5 N to 3.7 N depending on pull or grain type. Since most forceful extrication attempts will occur when at least the victim's head is visible, these results highlight that limb placement is not an important consideration in extrication. However, extra care must be exercised regarding limb placement if the victim being extricated is already engulfed and limb placement is unknown, in grain or attempts are made to insert a coffer dam or rescue tube that may contact extended limbs.

In summary the results of this study indicate that all four experimental variables have a significant impact on forces. The most important one is moisture content due to both the significant increase in force and the likelihood that a victim will be entrapped in wet or out of condition grain. The second most important is pull angle, followed by grain type (for seeds with very low bulk densities) and limb placement. Limb placement is placed as the least important factor since forceful extrication attempts were documented only when the victim was entrapped (head is at least visible), while limb placement was only significant when the mannequin was engulfed. Two factors not considered in this study were the settling/consolidation of grain and presence of fines. Both of these factors have the ability to increase forces acting on a entrapped or engulfed victim. However, these factors are not necessarily important in flowing grain entrapment. If a person is entrapped in flowing grain, then by definition they are not getting entrapped in consolidated grain. Similarly, fines collect in the center of the bin, and thus are most likely to be the first grain to leave the bin and thus might not impact the forces an entrapped victim experiences.

5.5 Conclusion

The results of this study indicate that three of the four experimental variables (angle, limb placement, moisture content and grain type) can have a significant impact on forces. The most important factor was moisture content due to both the significant increase in force and the likelihood that a victim will be entrapped in out of condition grain. The second most important variable is pull angle, followed by grain type and limb placement. The least important factor is limb placement since it only makes a significant difference if the body is engulfed in grain and it is highly unlikely that an engulfed individual would be forcefully extricated from grain.

5.5.1 Future Research

The most surprising result was the important role that moisture content plays in increasing extrication force. However, it not known if the increase in extrication force, when moisture content is increased, follows a linear or exponential curve. The following experiments are recommended as a follow up to this experiment:

- Conduct a small scale study evaluating the impact of moisture content on extrication forces by evaluating grain with a range of moisture content values
- Conduct a large scale experiment to test if high moisture content (20%+ for corn) would still significantly increase extrication forces.
- Measure the angle at which a significant increase of force is recorded in a large scale experiment.

- Test if grain types will produce similar extrication force results in large scale experiments.

CHAPTER 6. DETERMINING THE PULL-FORCES REQUIRED TO EXTRICATE A VICTIM ENTRAPPED AT VARIOUS ANGLES IN A GRAIN MASS

A modified version of this chapter has been submitted for publication in June 2016 in the Journal of Safety

6.1 Introduction

Grain entrapments and engulfments continue to be an important issue on farms and at grain storage facilities across the U.S., there being, on average, about 35 such incidents per year over the last ten years (2.3.2 Category and Type of Confined-Space Related Cases, p. 22). In one of the first research studies on grain entrapment, Schmecta and Matz (1971) sought to determine the speed at which a human subject becomes buried in grain and the depth at which self-extrication is no longer possible in a bottom-unloading test bin. They found that (1) it took only about 30 seconds for one to get entrapped to shoulder level; (2) at hip level, self-extrication was not possible, but extrication could be accomplished with the aid of another individual; and (3) at shoulder depth, not only was self-extrication impossible, but also the safety harness employed for the test was damaged when the subject was being pulled out by rope and the test had to be discontinued because of the pain caused by the rescue effort. Schwab et al. (1985) expanded upon this study by measuring the total force that the body experiences at various depths during extrication. Using a 75kg or 165 lbs mannequin to represent an adult victim, they found that it 'experienced' about 2,700 N

(~600 lbf) at shoulder depth and 1,300 N (~300 lbf) at waist level. Similarly, Roberts et al. (2015) found that a mannequin experiences about 1,770 N (~400 lbf) and 1,260 N (~280 lbf) when pulled from armpit and waist levels, respectively; the same study also showed that, even with use of a coffer dam (or grain rescue tube), the peak force required to extricate the mannequin actually increased by 24%.

Earlier, Roberts et al. (2011) reported a case study in which a co-worker attempted to extricate an entrapped victim by tying one end of a rope around his (the victim's) chest, running the rope outside the grain bin and tying the other end to a pickup truck, then driving the truck away from the bin in an effort to pull the victim out. The victim ended up dying due to the forces applied on his body, which begs the questions—Did pulling the victim at an angle increase the total force on his body and, if so, do these forces exceed the human capacity to survive them? The study presented here sought to answer those questions and further expand on previous research by testing the amount of force required to extricate a mannequin out of grain at various angles.

6.2 Materials and Methods

Two grains were used in this experiment—soybeans and corn, by far the most common mediums involved in grain entrapment incidents (Issa et al., 2016c). Samples of each were taken and their properties tested. Moisture content measurements were based on ASABE Standard S352.2 (ASABE, 2012); and bulk density was determined by filling a 0.55-liter cup using a funnel, leveling the surface, then measuring the weight of the grain (Clementon et al., 2010).

6.2.1 Experiment Setup

The study was carried out a grain elevator in Maquon, Illinois. A bin, measuring 2.4 m (8 ft.) tall by 1.8 m (6 ft.) wide, was built on top of the elevator's grain pit. The bin floor was composed of plywood sheets, except for a 33x33 cm (13 in.) metal slide gate in the middle (Figure 6-1). The bin drained by gravity into the pit and was filled by the elevator leg, which had a maximum rate of about 7,000 bushels per hour. An overhead anchor point was placed as close to the center of the bin as possible.

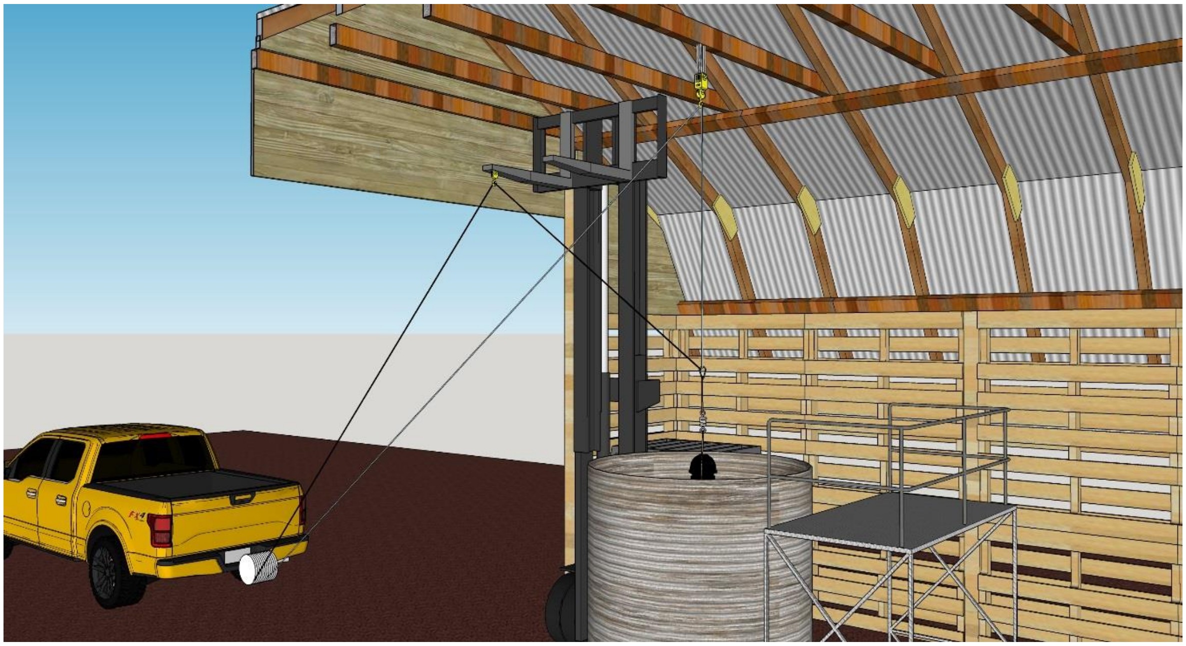

Figure 6-1 Experimental setup showing location of mechanical winch, forklift (angle anchor point) , vertical anchor point and observation deck.

The mannequin was 75 kg (165 lbs.) and measured 185 cm (73 in.) from the base of its feet to the top of its head. It was 'dressed' in a flannel shirt under bib overalls plus pull-on boots. A full-body, ANSI-rated safety harness with back-mounted D-ring was placed on the mannequin to serve as the point of attachment for the load cell (Figure 6-2, left). The mannequin with clothes, boots, harness, and attachments to the load cell weighed 82 kg (180 lb.).

The load cell (ICS516, Industrial Commercial Scales, South Carolina) was rated for 44 kN (10,000 lbf) and was attached through a pulley system to a winch rated for 454 kg (1,000 lbs.). The cell was tested by measuring a 1,300-pound concrete block and was found to accurately measure the block within 1%. It was set up to output only the peak load during each run. Two lines were attached to the cell, one for a vertical pull and the other for an angle pull (Figure 6-2, right). Only one of those lines was attached to the winch at a time.

Figure 6-2 Mannequin setup for experiment shown on the left and it being fully engulfed in grain and tied to two lines for vertical pull and angle pull on the right. Both lines are attached to the top of the load cell.

A fork lift truck was used as an anchor point for the angle line in order to be able to change the angle based on the experimental design. Each angle was measured and calibrated to the prescribed degree after the mannequin was buried in the grain, and the line was tightened via the winch. A hand-held magnetic angle finder was used to determine each test angle.

6.2.2 Experiment Design

This experiment involved two component parts—tests to determine the forces required for extrication from various depths when pulling vertically and tests to determine the forces required for extrication when pulling from various angles. The design of each component was as follows:

6.2.2.1 Vertical-Pull Experiment.

This was similar to that conducted by Schwab et al. (1985), with five grain depths chosen—two to represent full engulfment (namely, grain levels at 38 cm (15 in.) above the head and at the top of the head), and three to represent entrapment (namely, grain levels at shoulder, chest, and waist). The mannequin had been marked at each depth level to ensure that it was buried at that depth. The experiment included these sequential steps: (1) mannequin placed in test bin at almost shoulder level; (2) bin filled with grain to its rim; (3) slide gate opened and mannequin allowed to sink into grain until 38 cm marker above head reached same level as rim; (4) bin again filled and grain leveled with a rake; (5) mannequin then pulled straight up at rate of 4.2 m/min; (13.6 ft./min.) to about 1-2 feet above rim, with load cell recording peak load; (6) load cell reset; (7) slide gate opened again until mannequin sinks to second marker (i.e., top of head); (8) bin filled again and grain leveled against marker; (9) steps 1-8 repeated until peak load measurements recorded for shoulder-, chest-, and waist-level positions; (10) entire experiment repeated another two times, totaling three replications; and (11) lastly, mannequin weighed to confirm it was within initial range of 82 kg and load cell was correctly calibrated.

6.2.2.2 Angled-Pull Experiment.

The design of this experiment component was similar to the vertical-pull but with the following differences: (1) after the mannequin was engulfed in a vertical position, pull lines were switched to allow it to be pulled out at an angle; (2) mannequin buried at only one depth—top of head; (3) pull line set at each of these angles—15º, 30º, 45º, 60º, and 75º and the mannequin was pulled out at that angle; (4) peak load recorded and line switched again to the vertical line; (5) mannequin pulled further upwards until vertical again; (6) mannequin engulfed again and experiment repeated; and (7) each angle repeated three times before another angle was tested, totaling three replications. (Note, at the sharper angles [i.e., 15º and 30º], the bin was drained between runs to make sure that the methods did not impact the results, and no appreciable difference was found between draining the bin completely and partially as mentioned above.)

6.3 Results

6.3.1 Grain Properties

The bulk density of corn and soybeans used in the experiment was 754.25 kg/m3 (St Dev = 7.45) and 749.76 kg/m3 (St Dev = 1.14), respectively. Moisture content of the corn was 13.3% and of the soybeans was 9.9%. Both grains were below the maximum moisture levels desirable for long term storage.

6.3.2 Vertical-Extrication Tests

Table 6-1 shows the amounts of pull-force required to free the mannequin entrapped vertically (upright) in the corn and the soybean grain masses at the five different depths (i.e., 38 cm above-head, head, shoulder, chest, and waist levels). The last measurement point (0.0 m) shown in Table 6-1 is the mannequin held freely by the load cell.

Table 6-1 Peak extrication force (newton) w/ standard deviations required to free the mannequin entrapped vertically in corn and in soybeans at specified depth levels.

		Corn		**Soybeans**	
	Grain Depth[1] (m)	Pull Force (N)	St. Dev. (N)	Pull Force (N)	St. Dev. (N)
Above head	2.24	4,653	154	4,875	471
Head	1.85	3,072	116	3,010	74
Shoulder	1.57	2,331	79	2,337	37
Chest	1.35	1,913	62	1,928	27
Waist	1.07	1,690	27	1,741	10
Mannequin	0.0	817	19	818	9

[1] Distance from the grain surface to the bottom of the mannequin feet.

For both the corn and the soybean entrapments/engulfments, the measurements at these five depth levels were significantly different from each other at $P<0.05$; however, the recoded measurements between the two grains were not significantly different at any depth level (Figure 6-3).

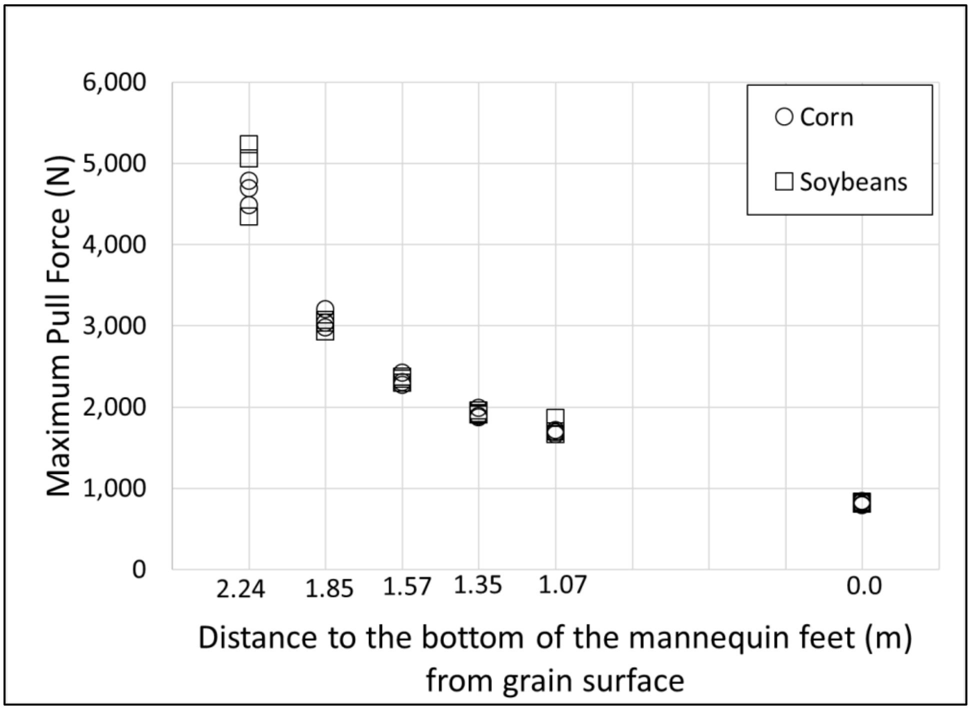

Figure 6-3 Maximum pull-force (newton) required to extricate the mannequin vertically at various depths in corn (circle) and soybeans (square

6.3.3 Angled-Extrication Tests

Table 6-2 shows the amounts of pull-forces required to free the mannequin entrapped to the top-of-the-head level in the corn and the soybean grain masses at five different angles (i.e., 15º, 30º, 45º, 60º, and 75º) and compared to the vertical (90º) pull results.

Table 6-2 Peak extrication force (newton w/ standard deviation) required to free the mannequin entrapped at specific angles in corn and soybeans at a depth of 1.85 m.

	Corn		**Soybeans**	
Angle (º)	Pull Force (N)	St. Dev. (N)	Pull Force (N)	St. Dev. (N)
15	4,416	123	3,748	85
30	3,716	31	3,891	149
45	3,413	59	3,496	50
60	3,298	116	3,348	89
75	3,126	36	3,072	72
90	3,072	116	3,010	74

For the corn entrapments, (1) the pull-forces involved at angles of 60º and 75º were not significantly different from each other or from those of the vertical-extrication (90º) tests at the same depth; (2) the 45º angle was not significantly different from the 60º angle but was significantly different from the 75º and 90º angles; and (3) the 15º and 30º angles were significantly different at $P<0.01$ from all other angles (Figure 6-4). As the angle was decreased there was a corresponding increase in the peak forces required to extricate the mannequin.

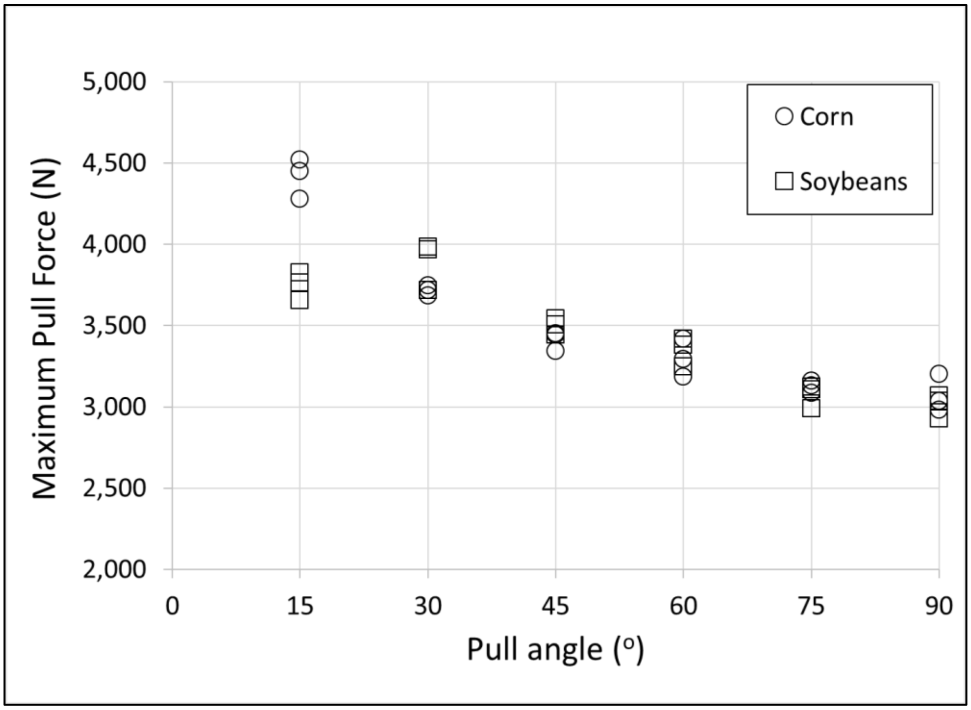

Figure 6-4 Maximum pull-force (newton) required to extricate the mannequin at various angles at a 1.8 m depth in corn (solid line) and soybeans (double line). The lines represent the range of all the repetitions at that 1.8 m depth.

For the soybean entrapments, (1) the 75° and 90° angles were not significantly different from each other; (2) the 45° and 60° angles were not significantly different from each other; (3) the 15° and 30° angles were not significantly different from each other; and (4) all other angle combinations were significantly different from each other at $P<0.05$. The measurements between corn and soybeans were not significantly different at angles of 30°, 45°, 60° and 75°, but they were for the 15° angle at $P<0.01$ (Figure 6-4). As with corn, the required peak forces for extrication increased as the angle of the pull was reduced.

6.4 Discussion

6.4.1 Comparison with the Schwab et al. Study Results

The vertical-extrication test was conducted to validate this present study's experimental methods and to compare the results with those from the study by Schwab et al. (1985). Although not an exact comparison between the two studies (since the grain depths differed somewhat), the recorded pull-force values were, nonetheless, within close proximity to each other (Table 6-3).

Two interesting results emerge from this comparison. The first one is that the vertical-pull experiment ended up with a significantly smaller standard deviation between the runs than what was reported in the Schwab et al. study. Among the possible explanations are the effects of leveling the grain and/or the limited number of runs conducted in this study. In contrast to this experiment in which the grain was leveled before each pull, Schwab et al. (1985) did not level the grain after engulfing the mannequin, but rather kept the grain mass's natural inverted conical shape. While this perhaps is more appropriate since victims will likely not be entrapped in level grain, it also seems to produce more 'noise,' as it is hard to ensure that the mannequin is at the bottom of the inverted cone during every run. The second interesting result is that the vertical-test averages were almost always lower than Schwab et al. (1985) at the same grain depth. This may also be due to the leveling of the grain, because it reduces the pressure that the extra mass in the inverted cone indirectly places on the body. However, leveling the grain was still an important method since it allows for highly repeatable results. Other potential reasons for the difference in standard deviations is that this study was completed in two days with similar weather conditions (including temperature), while Schwab et al. (1985) in comparison was a much larger study.

Table 6-3 Comparison between the current study and the Schwab et al. study results for vertical-force pull.

Current-study results		**Schwab et al. study results**		
Grain Depth (m)	Pull Force (N)	Grain Depth (m)	Pull Force (N)	St. Dev.
2.24	4,652	**2.20**	5,253	903
1.85	3,072	**1.89**	4,012	765
1.57	2,331	**1.58**	2,771	583
1.35	1,913	**1.26**	1,913	360
1.07	1,690	**0.94**	1,321	196

[1] Distance from the grain surface to the bottom of the mannequin feet.

6.4.2 Influence Due to Grain Type

In both the vertical-pull and the angle-pull experiments, the results recorded in corn and those in soybeans were not significantly different from each other, except for the 15°-angle run. This was an unexpected finding, since the two grains were chosen because they have different shapes, thus it was assumed they would ‘behave’ differently. But the fact that they behaved similarly was perhaps because of their similar bulk densities. In a study on grain pressure on the chest, Moore and Jones (2016) likewise found the differences in the corn and soybean results to be insignificant. Concerning the difference recorded between the two grains at the 15° angle, it might have been due to a limitation that occurred in the experiment setup. Installation of the anchor point at the very low angle of 15° was difficult and was slightly modified (altering location of angle anchor point/forklift) between running the soybean and corn experiments. Applying extrication forces to an actual victim at such low angles would be most unlikely.

6.4.3 Angle Extrication Test Results

Results showed that the mannequin could be extricated from as sharp an angle as 45º without significantly impacting the pull-force required. Only at the 15º and 30º angles did it make a significant difference in the maximum force needed to free the mannequin; and at 15º, it even reached the same values as the 2.24 m level (from surface of grain to feet). These findings suggest that, relative to placement of the overhead anchor points, some flexibility apparently is possible in rescue situations. However, it is important to note that, compared to a straight vertical pull additional time was required to extricate the mannequin when set up at various anchor point angles. Time was not a measured parameter; it was observed that it took more time to pull the mannequin out of grain than in a vertical.

6.4.4 Risk of Injury During Forceful Extrication

With the force required to pull the mannequin at 38 cm below grain mass found to be four to five times greater than the mannequin's weight, it is highly likely that such force would cause serious harm to one's spine and joints. Similarly, attempts to forcibly free a victim with the anchor point located at angles below 45º, would also probably result in injury. The problem becomes even more critical if the victim is not wearing a body harness that's capable of distributing the pull force over a larger portion of his body, as was often found to be the case as reported by Roberts et al., (2011) and Issa and Field (2015). In most documented cases, the victims were not wearing a safety harness at the time of entrapment and installing a safety harness following entrapment is, in most cases, impossible. At medium depths and angles, it remains difficult to specify the point at which depth and/or angle would cause injury, especially due to the variability of the victims in past entrapments. These incidents have involved victims as young as 2 and as old as 82 (Issa et al., 2016b). Physical conditions such as previous joint replacements, physical strength, levels of obesity, and heart condition could increase the risk of secondary injury during extrication. Thus, the safest recommendation is to avoid vertical extrication until more research is done on the ability of the body, especially the spine to handle tensile loads required for extrication.

6.5 Conclusions

The results of this study confirmed that (1) a large amount of pull-force is required to extricate someone entrapped in a grain mass, (2) pulling the victim at a sharp angle results in substantially greater forces being applied to the body, and (3) an inappropriate rescue strategy that applies excessive force on the victim might pose a significant risk of injury. One positive finding from this research, however, was that emergency first responders and grain storage manufacturers do have some leeway in the placement of anchor points; that is, it does not have to be exactly vertical to the center of the bin.

It is recommended that the content of the emergency first responder training be updated to include the following information: (1) extrication angles can make a difference in amount of required force to extricate an entrapment victim from grains; (2) rescue anchor points can be located at up to 30º off the center of the storage structure and be used without significantly increasing the forces required for extrication; and (3) anchor points at lower angles will require greater force increasing the risk of injury to the victim during extrication..

It is also recommended that additional research be conducted on ascertaining the physiological responses that occur during extrication, including the forces on body and the pressures on internal organs.

CHAPTER 7. MEASURED SPINE TENSILE FORCE LIMITS FOR EXTRACTING GRAIN ENTRAPPED VICTIM

7.1 Introduction

Grain entrapment remains a major safety concern in grain storage/handling facilities and continues to be a key issue in many agricultural safety and health programs (McKenzie, 1969; Field & McKenzie, 1978; Kelly & Field, 1995; Maher, 1995; Kingman, 1999; Drake et al., 2010; Issa et al., 2016a; CHAPTER 2). One aspect of that concern has to do with the total force that is exerted by the grain on a victim's body during attempts to extricate. Schmecta and Matz (1971) found that a 150 kg-rated harness could not sustain the force needed to pull out an individual entrapped in grain at chest level. Schwab et al. (1985), found that the force required to vertically extract a victim (in this case, a mannequin) increased exponentially as the grain level increased. For example, when entrapped at waist depth, an average 1.32 kN (kilo newton) of force was needed; at shoulder level, 2.77 kN; and at top-of-head level, it increased to 4.01 kN. Roberts et al. (2015), in a similar study, discovered the force increased by 22-26% to extricate a mannequin that was inside a coffer dam used to extricate entrapped victims. Lastly, as stated previously, the force of extraction placed on an entrapped mannequin was measured at various angles. It was found that it took 2-7% more force to extract the 'victim' at low angles (i.e., 60º-75º from grain surface) and 21-44% more force to extract at sharp angles (15º-30º from grain surface).

While these studies provided insight into the force that a body experiences when being extricated from a grain mass, there remains the question as to how much tensile force a victim's spine can endure during an extrication attempt before damage occurs. The specific objective of the research presented here was to measure the tensile force required to cause axial failure of the spine. More specifically the tensile force required to separate the intervertebral discs and surrounding ligament between the spinal vertebras of a sheep representing the spine of an entrapped victim.

7.1.1 Case Studies

The following three documented grain bin-related entrapment incidents, which illustrate the widely variable outcomes that can result from attempts to forcefully extricate a victim, underscore the importance of conducting research to determine just how much tensile force the spine can endure, and whether or not forceful extrication should be recommended as a safe first response strategy. These three cases were not chosen due to frequency of each case type, but to highlight the potential outcomes, leading to a more nuanced discussion.

Case #1. A co-worker tied one end of a rope around the entrapped victim's armpits, ran the rope up through the roof access door, down to the ground and connected the end to a pickup truck. The truck was driven away from the bin in an effort to pull him out of the grain mass. This resulted in the victim being fatally injured (Roberts, 2008).

Case #2. Although buried up to his chest, the victim was not experiencing any pain at the time of the rescue attempt. First responders placed a harness around his upper body, and attempted to pull him out, he immediately complained of chest pains. They gave the victim analgesic drugs to reduce the pain and tried again to extricate him. However, the attempt had to be abandoned because the vertical pulling caused him unbearable pain even after the administration of analgesic drugs. Eventually, he was rescued via the coffer dam method (Bahlmann et al., 2002).

Case #3. A worker who had gotten entrapped up to his armpits was able to call for emergency help. Arriving at the farm within just five minutes, the first responders placed a rope around the victim and proceeded to pull him out. There were no reported injury to the victim. The time from original call for help to successful rescue was about 18 minutes (PACSID Database).

7.2 Methods

Sheep spines were used for this study to represent the human spine. They were obtained from Purdue University Veterinary Hospital (West Lafayette, IN) and were prepared and tested on site. In addition, anatomical properties of the spines were measured and compared to values reported in the literature to evaluate if the spines were representative samples for sheep spine.

7.2.1 Selecting/Preparing the Spines

Sheep spines were utilized for this research study, which are considered comparable to the human spine (Wilke et al., 1997; Wade, 2005; Bai et al., 2012). And of those spines' three 'regions' (i.e., lumbar, thoracic, and cervical), the lumbar region was selected as the most likely location for an injury to occur since the thoracic region is held together by the rib cage and it is unlikely that rescue personnel would attach a rope around the cervical (throat) region to pull out a victim.

In this experiment, the lumbar region of the spines was harvested from three 2- to 4-year-old mix breed sheep and frozen until needed. After, thawing, the muscle around each spine was removed, with all ligaments kept in place, and then the spines were sectioned through the disc to provide a total of five segments of three to four vertebra (Figure 7-1). In between runs, the spines were refrigerated.

Figure 7-1 Cleaned lumbar-region spine segments cut into lengths containing three to four vertebra

7.2.2 Preparing the Test Samples

For each spine segment, two 5 cm tall sections of 10.2 cm (4 inch) diameter PVC pipe were used to enbed the top and bottom of the spine segments. The pipe sections were attached to an MTS Criterion Model 43 (MTS, Eden Prairie, MN) by a threaded rod and a custom-made steel link (Figure 7-2). The MTS Criterion is a two--column load frame device used to measure tensile or compression forces. A 5 kN load cell (Model

LPS.503; 2.328 mv/v sensitivity) was used in this experiment and the load frame moved at a rate of 0.1 mm/s. Originally, Bondo all-purpose putty (3M, St. Paul, MN) was used to anchor both ends of the spine inside the pipe sections, with the spine also anchored with a wood screw to further hold its position (Figure 7-3, left). This system, however, proved unsatisfactory for two reasons: (1) the putty, when hardened, was unable to hold the spine segment; and (2) the screws significantly weakened the top and bottom vertebrae, causing them to crack and break off when under tensile strain. Even when the screws were replaced with wire to strengthen the putty-spine bond, the putty was still not able to handle the strain and cracked. The problem was subsequently 'solved' by using 3 mm Kevlar rope (Spearit, Amazon.com), tested to withstand up to 900 lb tensile force, to tie together the spine transverse with the threaded rod bar (Figure 7-3, right). The Kevlar rope was wrapped around three times the spine transverse processes and the threaded rod at the base of each PVC pipe. This allowed it to stretch out equally and place equal force on the transverse processes. The MTS Criterion was programmed to pull apart the spine until the force dropped by 90% from maximum tensile force recorded.

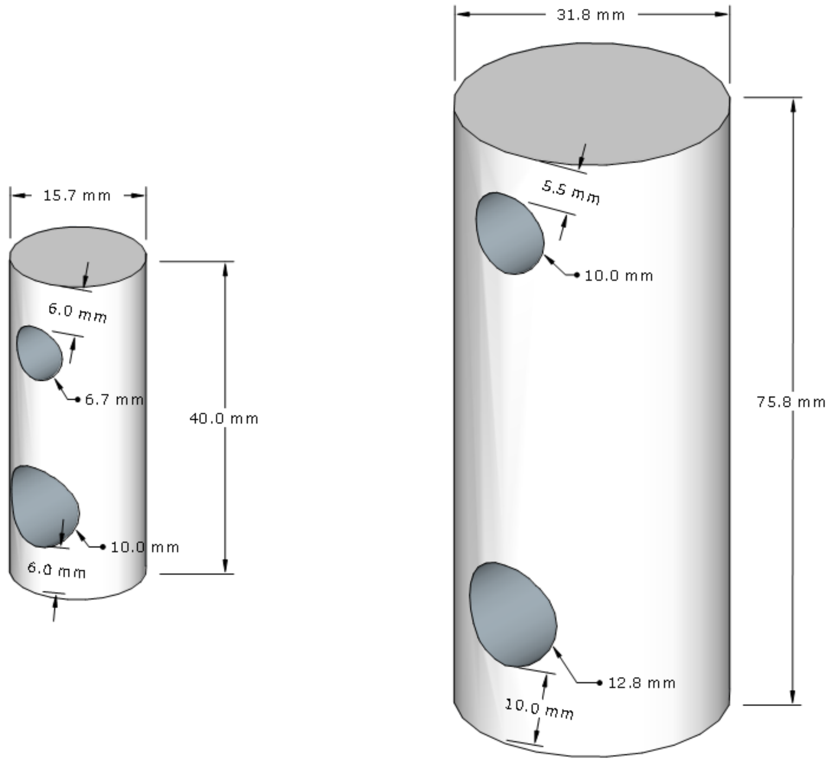

Figure 7-2 Custom made steel links used in the MTS device. The threaded rod was inserted in the right bottom hole and the left top hole. The top of the right link connected to the load cell by a pin and the bottom of the left link was connected to the MTS frame by a pin.

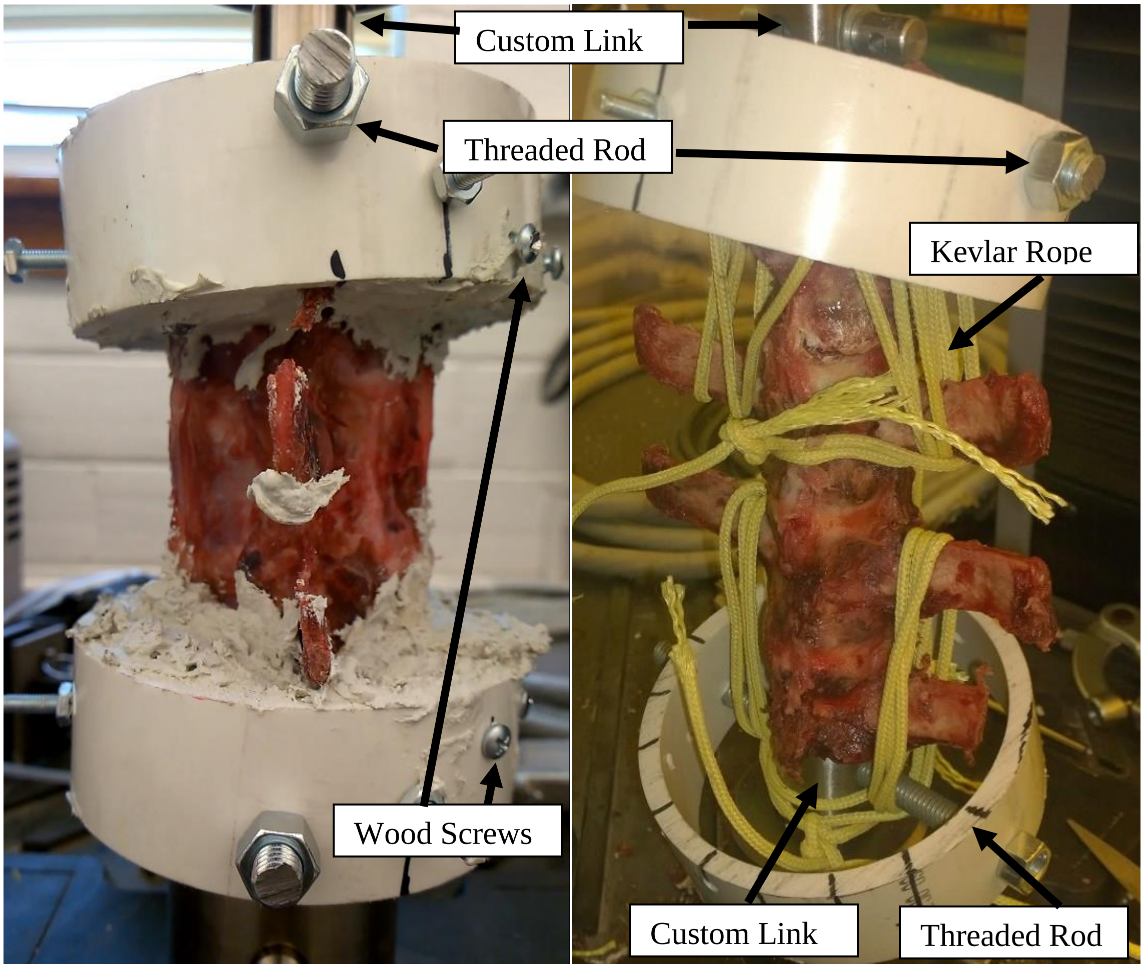

Figure 7-3 Sections of PVC pipe holding a spine segment using putty and screws (left) and Kevlar rope (right) attached to the MTS Criterion

7.2.3 Collecting/Analyzing the Data

Since 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, 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 linear region was determined by evaluating a trend line that corresponded to a $R^2 > 0.99$ on the top part of the linear region. On average, the straight-line portion used in the trend line was from 60% to 70% elongation or about 470 data points (total elongation measured by MTS). This result can be compared to a study by Ebara et al. (1996) that measured the annulus fibrosis (i.e., protective layer of the intervertebral disc), using the 75% elongation point to measure the slope of the linear region. The yield force was then calculated by displacing the straight curve by 0.2 mm, which is approximately equivalent to 0.2% yield displacement.

7.2.4 Measuring/Comparing the Sample Properties

After completion of the experiment, the sample properties were measured and compared to previous studies (Wilke et al., 1997; Mageed et al., 2013). Based on the procedure provided by Wilke et al. (1997) (Figure 7-4), the following anatomical parameters were measured using a 15.24 cm (6 in.) Fowler Sulvac Model S 235 Data Caliper (Cole-Parmer Instrument Company, Vernon Hill, IL): transverse process length and width (TPL and TPW), end-plate depth and width (EPD and EPW), 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 vertebra location in the lumbar region. These results were then compared with the literature to confirm that the spines tested were, indeed, representative of typical sheep spines.

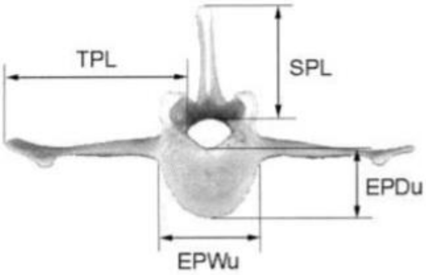

Figure 7-4 L4 of the sheep spine—dorsal view of the measured regions. (Figure from Wilke et al., 1997.)

7.3 Results

7.3.1 Anatomical Measurements

All spine characterization measurements were found to be within the range of values obtained from Wilke et al. (1997) and Mageed et al. (2013), with the exception of the end-plate depth (EPD) and the intervertebral disc height (IDH) (Table 7-1). The EPD of 22.0 mm was slightly greater than the maximum range value of 20.8 mm, while the IDH of 9.1 mm was more than twice the maximum range value of 4.5 mm. The disc height range of 9.1 mm was close to the 11-16 mm range of the human spine’s lumbar region disc height (Wilke et al., 1997). As stated earlier, spine samples were measured after tensile experiment and the larger IDH values might be due to elongation.

Table 7-1 Anatomical properties of the spine regions used in this experiment compared to those from Wilke et al. (1997).

		Range of values (mm)	
Spine anatomical parameter	**Values[a] (mm)**	**Wilke et al. (1997)[b]**	**Mageed et al. (2013)[b]**
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	9.1 ±2.4	4.2 – 4.5	2.6-3.3

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

[b] measurements came from 5 spines, with each spine containing 6-7 lumbar vertebra. The range of values is the range of the mean value across lumbar vertebra.

7.3.2 Maximum Spine Tensile Strength

For the five experiments, the maximum load endured by the spinal segments ranged from 1.65 kN to 2.48 kN, with the average being 2.14 kN (SD = 0.31 kN) or about 482 lb_f (Table 2). The yield force (at 0.2 mm displacement) ranged from 1.64 kN to 2.48 kN, with an average of 2.09 kN (SD = 0.31 kN). Also, in another five experiments, the spine transverse processes broke before the intervertebral discs and ligaments showed signs of failure. The breakage in processes was due to force exerted on them by the Kevlar rope. These transverses were able to withstand an average of 2.02 kN (SD = 0.56 kN).

The maximum tensile force for the intervertebral discs and ligament to fail were recorded in four of the five spines (Table 7-2), with one of the spines providing two measurements (spine section was composed of four vertebrates). In the spine that did not provide a maximum tensile force, the two transverse processes failed on opposite ends prior to intervertebral and ligament failure. These two transverses withstood 2.66 kN and 2.35 kN respectively before breaking. Rupturing the discs in that fifth spine would have increased the maximum load average for all the discs.

Table 7-2 Maximum force recorded for each spine sample before failure under various conditions.

	Maximum force withstood by samples (kN)					
	Spine 1	**Spine 2**	**Spine 3**	**Spine 4**	**Spine 5**	**Average**
Disc –Tensile force	2.20	2.14	1.65		2.48 2.24	2.14
Disc – Yield Strength	2.17	1.97	1.64		2.48 2.19	2.09
Transverse-Tensile force	1.78 1.20			2.67 2.35	2.11	2.02
Putty-Screw System				1.51 2.09		1.80
Putty-wire system				1.99 2.55		2.27

7.4 Discussion

The force-displacement graph for the spine segments (Figure 7-5; Appendix D) exhibited a toe region similar to that observed in other experiments (Ebara et al., 1996). In the previous study designed to measure the vertical pull-force required to extricate a victim, the force needed was found to be 1.7 kN when a mannequin was ‘entrapped’ in grain at waist level, 2.3 kN at chest depth, 3.0 kN at shoulder depth, and 4.8 kN at top-of-the-head level. This 1.7-3.0 kN range is comparable to the 1.65-2.48 kN force range required for axial failure in the spine. The surrounding paravertebral musculature provides additional stability to the spine in all planes. Baseline muscle tone will increase the ability to the spine to resist tensile forces. (Moore, Daly, & Agur, 2013). However, the large overlap between the maximum tensile force the intervertebral disc and ligaments can withstand and the force needed to vertically extricate a victim is an area of concern and supports the anecdotal evidence that individuals are likely to be injured from a vertical pull.

Perhaps the most significant limitation of the present experiment is that it was conducted on sheep spines rather than human spines. While the sheep spine is considered comparable to the human spine including biomechanical properties or motion (Wade, 2005), this experiment places spines in an unnatural position/motion (extension)   and thus it is uncertain how these results extrapolate to the human spine. Another limitation is that force loading was exerted across one vertebral level, although in the extraction scenario posed – multiple adjacent vertebrae will be loaded and distribute extrication forces.

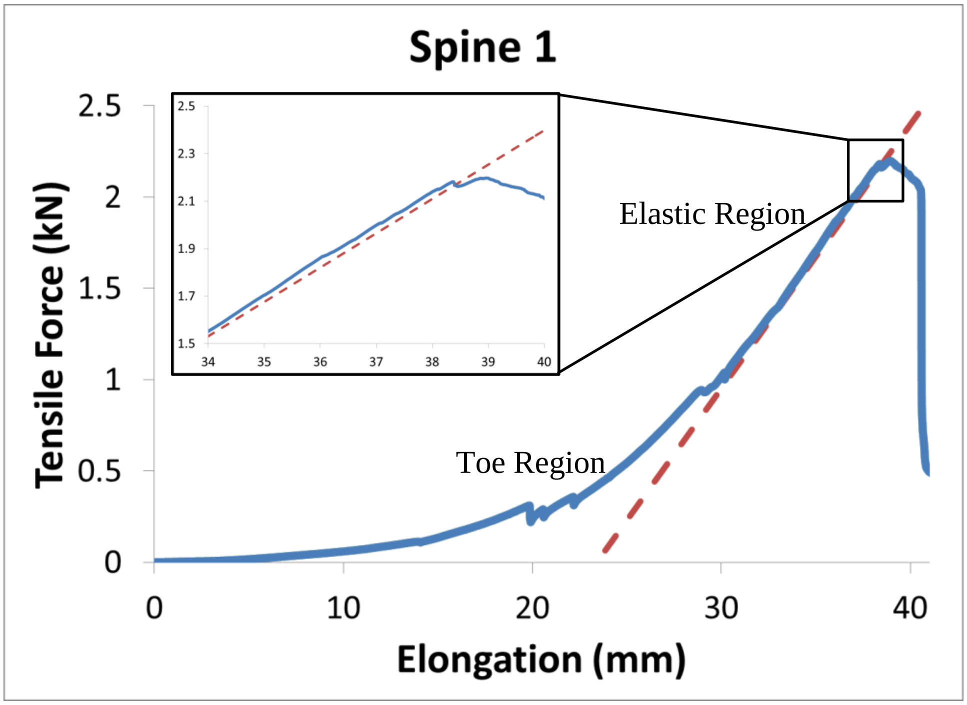

Figure 7-5 Sample tensile force vs. elongation curve for a lumbar sheep spine segment. (Solid line represents the force experienced by the spine; dashed line represents the yield-elastic curve. Intersection of the solid and dashed lines is the yield strength.)

7.5 Conclusions

The results of this study highlight that the maximum force withstood by the intervertebral discs and ligaments before failure was in the same range as the force required to forcefully extricate a victim entrapped in 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 it is not known, in advance, the amount of force a specific individual's spine can handle, the findings suggest that, at least for the present, emergency first responders 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. 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. It is expected that 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 low, that first responders should error on the side of caution and not anticipate that the victim will be equipped with a harness.

CHAPTER 8. FORCES EXPERIENCED ON THE CHEST

8.1 Introduction

Grain entrapments remain a topic of interest in the scientific and safety communities. There has been significant research on the amount of force required to pull an entrapped body (victim) out of a grain mass and the body's ability to withstand extrication forces (Schmechta & Matz, 1971; Schwab et al., 1985; Roberts et al., 2015). However, research on the pressures that a victim experiences while buried in the grain mass remains limited (Moore & Jones, 2016). Moore and Jones (2016) placed particular emphasis on the chest region, conducting the only known experiment that tests the horizontal pressures on the chest and torso. They found that at 0.23 m depth the pressure recorded on a pressure mapping system was 2.8 kPa and at a 1.12 m depth was 3.9 kPa in corn. They concluded that pressures were not significant enough of a pressure to cause positional asphyxiation. However, these results appear contradictory to grain entrapment data in which 7% of all entrapment cases (with the head visible) resulted in a fatality. In addition, from anecdotal data, many of the survivors of grain entrapments found breathing difficult even in shallow entrapments. The aim of this study was to reconcile the differences between experimental and anecdotal results. Findings are expected to assist emergency first responders in victim extrication with the hope of reducing the number of fatal entrapments and engulfments.

8.1.1 Active vs Passive Pressures

To understand the pressure that the chest and torso experiences, it is important to understand how pressure is applied on a body/surface during entrapment in grain. The first comparative example to look at is a Newtonian fluid such as water. In these types of fluids the force being applied vertically (due to gravity) transfers directly in to the force applied horizontally to the body surface. This is why Newtonian fluids can fill containers, and if poured on a flat surface will disperse into a thin puddle with only the surface tension of water holding it together. The equation for pressure in water and Newtonian fluids is $P=pgh$; where P is pressure, p is density, g is gravity and h is height; and is independent on the size of the container.

When dealing with grains or granules, the force being applied vertically by gravity does not translate completely into a lateral force; in other words vertical force will be greater than the horizontal force and will not equal each other. This is due to the internal friction between the particles, which is why granule particles forms piles when poured into a flat surface, and showcase some properties of fluids (such as the partial ability to flow). One of the direct results of the flow properties of granules is that it has two pressure values. The first one is the horizontal force that granules apply against a wall, such as the sides of a grain bin, which is defined as the active pressure. The second pressure measurement is when a wall or object is pushing against the grains, such as when emptying a hopper bin or when an entrapped victim is trying to breathe. The pressure measurement in this scenario is defined as the passive pressure (Nedderman, 1992). Since in this scenario the grain is being pushed in the direction opposite to gravity, passive pressure is greater than active pressure. In theory this should explain the difference between experimental and anecdotal results. The experiment conducted by Moore and Jones (2016) measured active pressure; grain was pushing against a pressure mat covering the torso of a test mannequin. While the chest of a living entrapped victim is expanding and contracting due to breathing thereby experiencing passive pressure as the chest is pushing against the grain. Therefore, a live victim entrapped in grain experiences a substantially larger force than what is being measured by the load cells attached to a non-breathing mannequin. The objective of this paper is to confirm that the chest is experiencing not only active pressure, but also passive pressure.

8.2 Methods

A steel box measuring 40.64 x 43.18 cm (16x17 inches) and 45.72 cm (18 inches) tall was welded together. A 8.9 x5.7 cm (3.5x2.25 inches) rectangle hole was cut into two steel panels measuring 40.64 x 43.18 cm (16x17 inches) and then the panels were placed into the box to create three cells (Figure 8-1 *A*). Each of the outlaying cells measured 15.8 cm in width. The rectangle holes were centered in the horizontal direction and were 10.16 cm (4 inches) from the bottom. These rectangular gaps allow two 7.62x5.08 cm (2x3 inches) wooden blocks to go through (Figure 8-1 *B and C*). The two wooden blocks were made from oak and the sides were sanded and sprayed with 3-in-One Lock Dry Lube (3-in-One, Budd Lake, NJ) to reduce the frictional coefficient. The blocks were attached by hinges to a 40.6 cm (16 inch) rod that attaches to the MTS load cell and frame. A 500 N load cell (LPB.502, sensitivity 2.328 mV/V) was used in this experiment. The rod was attached to the frame and placed in the middle cell. The blocks are then aligned with the steel panels and occupy the rectangular gaps. The two outer laying cells were then filled with corn to the top and leveled using a small wooden spatula. Using MTS proprietary software, MTS suite was instructed to lower the frame (with the attached rod) 18 mm vertically at a rate of 0.1 mm/s. This corresponds to pushing the blocks into the grain approximately 10.2 mm (SD 1.9 mm) in the horizontal direction (or 5.1 mm for each side). Note that the blocks were additionally tested at 1 mm/s and 0.01 mm/s and no significant differences were observed between each of the three rates. The 0.1 mm/s was chosen because it provides about 2000 data points. In addition to the 30.5 cm (12 inches) depth; data points were collected at 20.3 cm (8 inches) and 10.2 cm (4 inches) respectively. When running the experiment with no grain in the cells, the load cell recorded a maximum of 1-2 N of force and thus frictional coefficient of the blocks were not considered in calculating the passive pressure values. Six runs were conducted per depth.

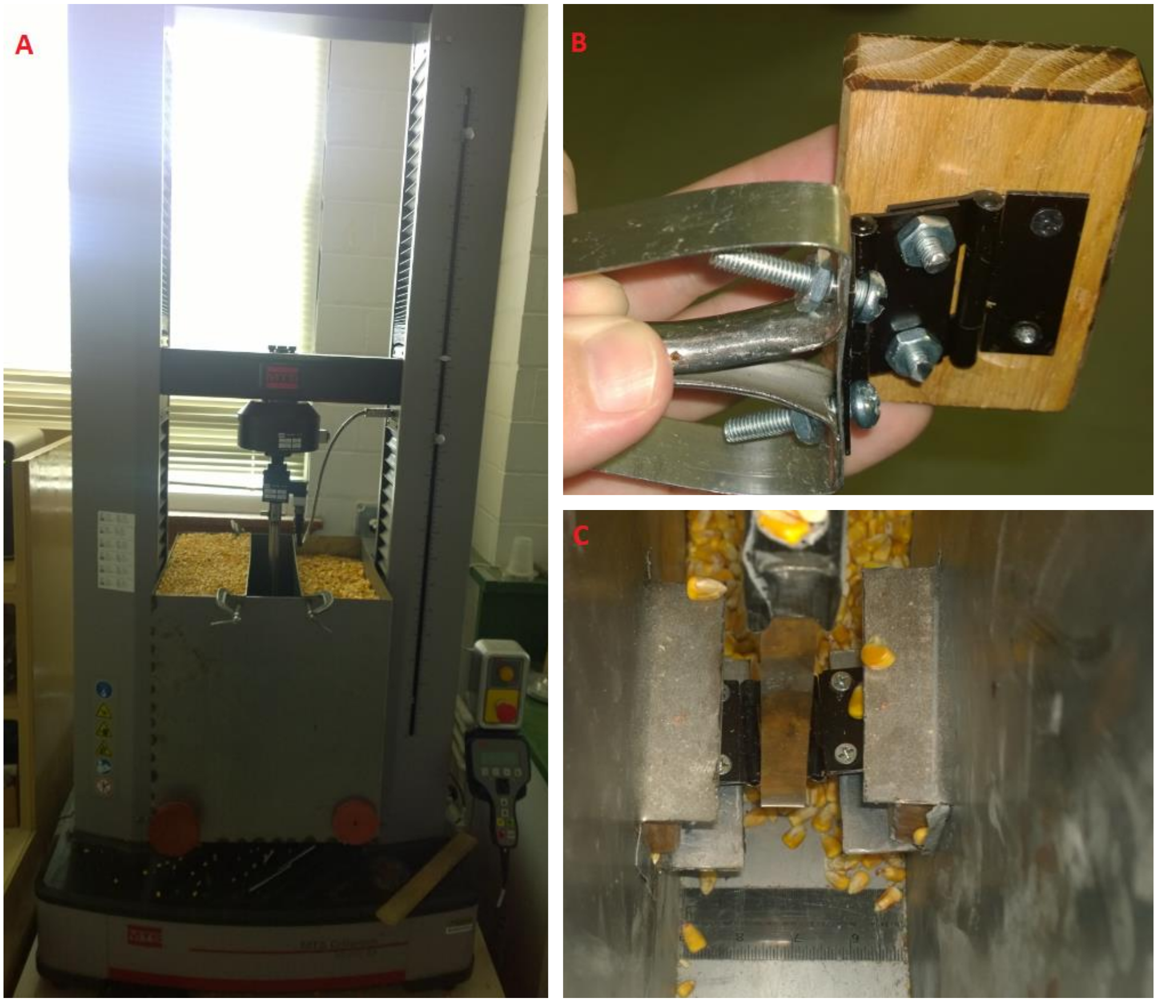

Figure 8-1 The grain system designed to measure passive pressure. A) overall system preview, MTS frame moves in the downward direction to put pressure on the grain inside the tank. B) block used to push grain, attached to hinges and rod which attaches to the load cell. C) blocks are in position in the rectangular gap and in contact with the grain.

8.2.1 Frictional Test

In order to gain a better understanding of what the load cell was measuring, a simpler experiment with known values was tested. In this experiment the rod with the wooden blocks was placed on a flat steel surface. Four steel weights approximately 418 g each were placed on either side of the blocks (2 on each side). The MTS was then instructed to lower the rod, which pushed the blocks and weights outward. Since the only force pushing against the blocks is the friction between the weights and the steel plate, the load cell values could be used to predict the frictional coefficient of steel on steel. The wooden blocks were lubricated similar to above with 3-in-One Lock Dry Lube. The load cell recorded a maximum force when using only the blocks of 0.32 N of force. The load cell used in the frictional experiment was 50 N load cell (Model LSB.501; 1.972 mv/v sensitivity). In addition, the steel blocks were placed in plastic cylinder and pulled across the same steel surface (based on work performed as part of this study) to get an independent confirmation on the frictional coefficient of steel on steel. Five runs were conducted.

8.2.2 Work Calculations

To determine the force acting on the block in both the actual experiment and the frictional test an energy balance method was utilized where the work applied to the system equals to the work on the grain. Work/energy is assumed to be conserved, thus

$$W_{in}=W_{out} \Rightarrow P*dy = R_1dx_1 + R_2dx_1 \tag{8-1}$$

Where W is work applied on the system. P is the force applied by the MTS frame to displace the rod by a distance of dy. R_1 and R_2 are the resultant forces acting on both sides of the blocks and causing the blocks to displace grain by dx_1 and dx_2. The resultant forces are considered equal on both sides of the block and thus the equation can be simplified as follows:

$$P*dy = 2 R*dx \quad (8\text{-}2)$$

The equation is solved for R

$$R = P*dy / (2*dx) \quad (8\text{-}3)$$

The load cell outputs provide the force experienced by the load cell at every 0.01 mm interval. Multiplying the force experienced by this partial displacement (in the y direction) and taking the sum over the entire experiment interval is the total work inputted in the system. Dividing the work input by the total x axis displacement provides the total force required by each block to push the grain or steel mass. To calculate the passive pressure, divide the resultant force by the area of the block. To calculate friction coefficients, divide the resultant force by the weight of the steel cylinders.

8.2.3 Theoretical Calculations

While there are many methods to theoretically calculate the pressure in the system, due to the small size of the system, hydrostatic method was utilized as an approximate value for active pressure. To determine the forces on the block as a whole, the hydrostatic equation was integrated with respect to height resulting in the following equation:

$$F_{block}=p*g*L(h_2^2/2 – h_1^2/2) \quad (8\text{-}4)$$

Where F is the force on the block, p is the density (kg/m^3), g is gravity (m/s^2), L is the length of the block (m), and h_1 and h_2 (m) mark the depth of the bottom and top of the block from the surface of the grain respectively. Pressure is calculated by dividing the above equation by the area of the block. Values for each variable and theoretical pressure values are reported in Table 8-1

Table 8-1Variables and results for the theoretical pressure using hydrostatic method

Length (L)	0.0762	m
Density (p)	760.45	kg/m3
Gravity coefficient (g)	9.81	m/s2
Height of block (h_3)	0.051	m
Pressure (P @ 10.2 cm)	0.95	kPa
Pressure (P @20.3 cm)	1.71	kPa
Pressure (P @ 30.4 cm)	2.46	kPa

8.3 Results

8.3.1 Friction Test Results

The frictional coefficient for steel on steel using the block method was on average 0.24 with SD 0.03 (Figure 8-2). The frictional coefficients using the pulley system was 0.22 (SD 0.01). These results are not significantly different from each other ($p<0.05$) and match what is currently found in the literature for kinetic coefficient of friction (0.09 – 0.6; Chen, 2004). These results indicate that the work/energy balance is a good estimate for calculating the force acting on the blocks and that the system is working and capable of measuring pressure. In addition, loss of work (non-conservation of energy) and force due to block-steel friction appears to be negligible, thus supporting the two assumptions made during calculations to 1) ignore the impact of block-steel friction force and 2) conservation of work.

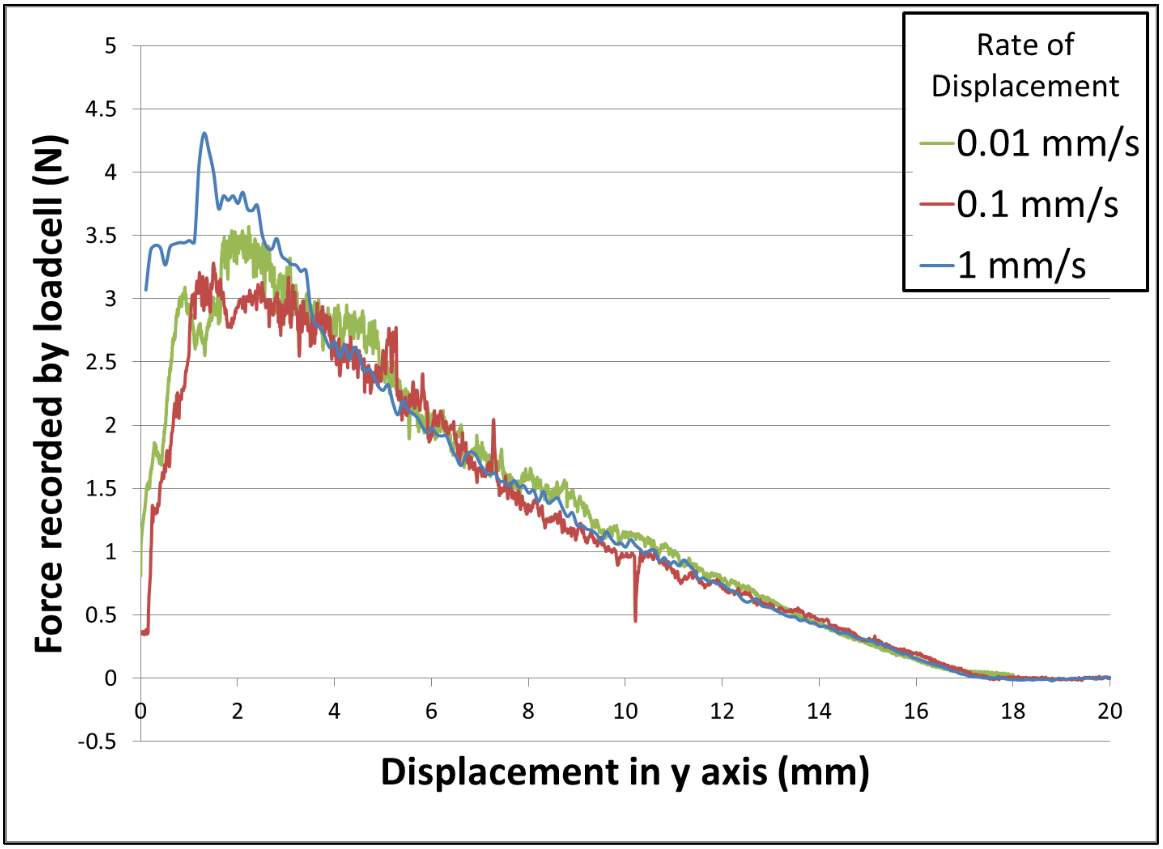

Figure 8-2 Comparison between different displacement rates for friction block experiment

8.3.2 Passive Pressure Experiment

The passive pressure measured by the experiment was 6.02 kPa (SD 0.6) at 10.2 cm depth, 7.25 kPa (SD 1.14) at the 20.3 cm depth and 8.83 kPa (SD 0.53) at the 30.4 cm depth (Figure 8-3). These pressure values were 6.3 times larger than hydrostatic pressure at 10.2 cm; 4.2 times larger at 20.3 cm and 3.6 times larger at 30.4 cm depth.

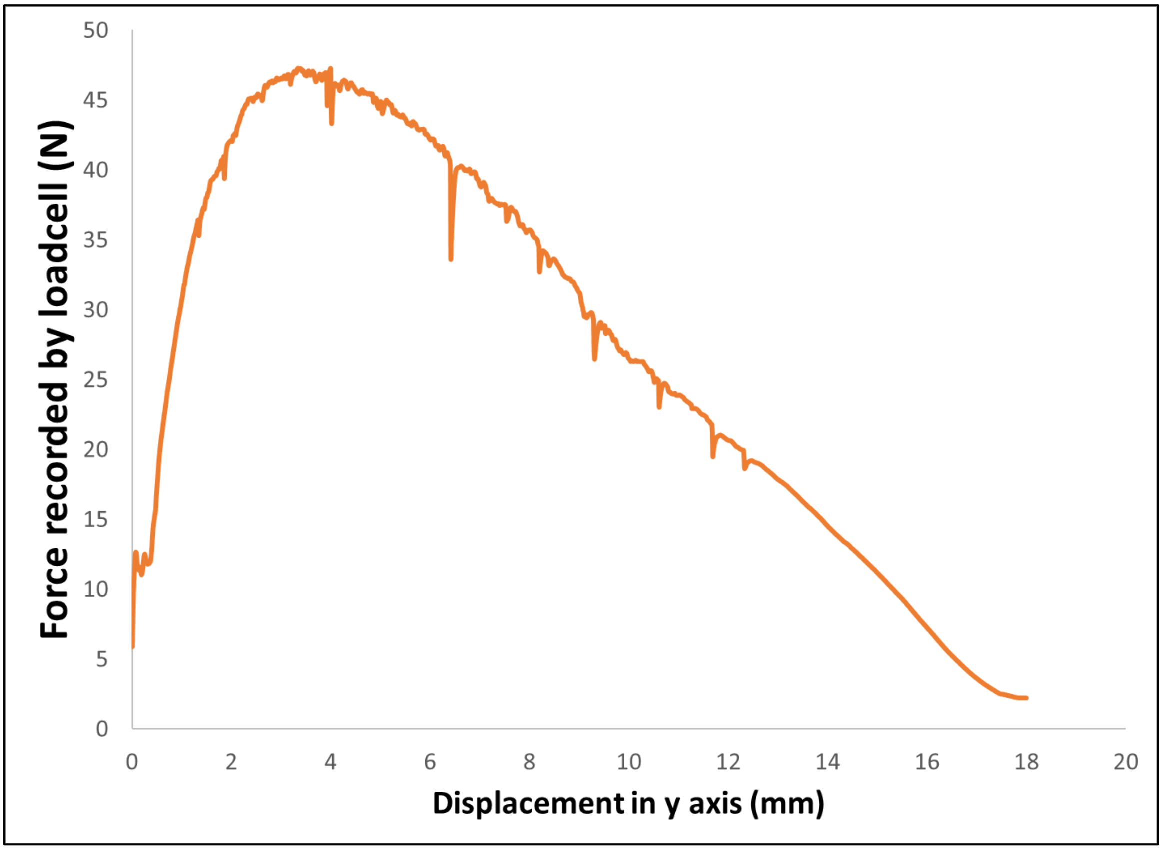

Figure 8-3 A sample force-displacement curve for block experiment

8.4 Discussion

The passive pressure values measured in the tank system were much larger than expected. In comparison, at a 23.5 cm depth in corn, Moore and Jones (2016) reported a pressure value of 2.82 kPa in a 1.83 m diameter bin. This was 2-3 times smaller than the values generated in this study even though the bin was 3.5 times larger than the tank used in this study (0.41 m vs 1.83 m). This is not necessarily an error in system design, since at low depth grain systems the pressure value tends to be very similar to hydrostatic pressure and thus independent of the bin diameter (Moore & Jones, 2016). In addition, based on the experimental setup designed by Moore and Jones (2016), the pressure values they generated were active pressure values. Thus, it is not surprising that Moore and Jones pressure values were 2-3 magnitudes smaller than this study. Lastly, In a study conducted by Thompson et al., (1997) to measure both lateral pressure (active) and vertical pressure (passive); they found that passive pressure was 2.7 greater than active pressure at a grain depth of 2 m in a 11 m grain bin.

8.5 Conclusions

Grain pressure on a victim trying to breathe can be 3-5 times larger than what is currently measured with a load cell. This is concerning as this increase in pressure might be enough to cause asphyxiation even if the victim head is above the grain surface. Future research needs to be conducted in large scale bins to confirm the results of this experiment.

CHAPTER 9. EXPERT RECOMMENDATIONS PANEL

9.1 Introduction

Based on the results from previous studies, a panel of agricultural safety professionals was gathered to review the study's findings and develop safety recommendations for grain entrapment and extrication. The focus of the panel was on rapid extrication and the use of safety harness and lifeline in grain storage facilities.

9.2 Methodology

9.2.1 Panel Members

A panel of experts in grain entrapments and rescue was convened during the International Society of Agricultural Safety and Health (ISASH) annual meeting and was composed of:

- William Field, PhD is a Professor and 39-year member in the Department of Agricultural and Biological Engineering at Purdue University and is an Extension Safety Specialist for Purdue's Cooperative Extension Service. He has conducted training nationwide and internationally on safety, health, and emergency management-related issues with approximately $17 million in external grants and contracts. He has conducted research on grain storage and handling related hazards for over 30 years.

- Gretchen A. Mosher, PhD is an assistant professor of Agricultural and Biosystems Engineering at Iowa State University in Ames, Iowa, USA. She holds a research and teaching appointment, leading undergraduate courses in Senior Technology Capstone and Total Quality Improvement. Her research investigates decision-making in quality and safety-sensitive agricultural work environments, the interaction and influence of quality systems on safety outcomes, and innovative approaches to learner evaluation in safety and quality.
- LaMar Grafft, MS is the Associate Director of the North Carolina Agromedicine Institute. The Institute conducts safety and health programs for farmers, foresters and fishermen across the state. He taught graduate level courses in both occupational safety and agricultural safety at the University of Iowa, where he was a farm safety specialist for 20 years. He was also a paramedic and flight paramedic for 25 years in Eastern Iowa. Grafft worked with the Illinois Grain Handling Safety Coalition to develop curriculum on grain bin safety.
- Davis Hill, EMT-P is a Senior Extension Associate and the Program Director for Managing Agricultural Emergencies in the Department of Agricultural and Biological Engineering at The Pennsylvania State University. In this position, Hill leads the development and delivery of the Agricultural Rescue program, the Emergency First Aid Care for Farm Families program and the Farm Family Emergency Response program. Prior to this position, Hill was the Executive Director for FARMEDIC in New York for over 12 years where he led the development of that program. A 1978 graduate of the University of Massachusetts with a B.S. degree in Agricultural Economics, Hill has also been

involved in the volunteer fire and EMS service since the mid 1970's. He is a PA licensed EMT-Paramedic.

- Bob Aherin, PhD is a Professor of Agricultural and Biological Engineering department at the University of Illinois. Aherin's research focus is in Agricultural Safety and Health with a focus on understanding agricultural injury and illness risks associated with the agricultural population in Illinois. Two projects that highlight Aherin's Extension involvement in ag safety include FARM (Fewer Accidents with Reflective Materials) and AgrAbility, a program for disabled farmers. In addition, Aherin has worked in coordination with the Illinois Grain Handling Safety Coalition to develop curriculum on grain bin safety. He has provided leadership for a OSHA Susan Harwood Gran in preventing grain related entrapments.

9.2.2 Research Presented

The panel was presented with the following research results and was instructed to use the research results below and their experience in the grain industry to discuss safety harness and lifeline use, and grain entrapment extrication recommendations:

- Most grains (soybeans, wheat, corn, oats, popcorn, canola) require similar amounts of force to extricate the victim. The only exception is Sunflower seeds and they generally require 40% less force than the rest of the grains.
- Moisture content is an important consideration. Raising corn moisture content from 13.7% to 22.7% (a 66% increase) increased the forces by 26%. It is unclear if the relationship is linear, or exponential.

- Limb placement matters (arms outstretched vs next to body) on the total forces required for extrication only in deep engulfments. Limb placement does not significantly matter in entrapments and shallow engulfments (head is just below surface of grain).
- Angle of pull during forceful extrication is only significant if the body is being pulled at an angle greater than 30^o off-center of the bin.
- A 185 lb body pulled vertically out of grain experiences 2.3 kN (517 lbf) of force when the body was buried at shoulder depth, 1.9 kN (427 lbf) at chest depth and 1.7 kN (382 lbf) at waist depth.
- Spine intervertebral discs were able to handle an average of 2.1 kN of force (472 lbf) with a range of 1.7 kN (382 lbf) to 2.5 kN (562 lbf). Standard deviation was 0.3 kN (67 lbf).
- The pressure that a person experiences on his chest while entrapped or engulfed in grain is closer to passive pressure than active pressure. Passive pressure has been measured to be 3-5 greater than active pressure. At low entrapment depth, passive pressure is even greater than the pressure the body experiences in water.
- Due to the constant pressure acting on the body and the inability of the victim to move his body or limbs, a victim might eventually experience blood flow and heart rate issues.
- Grain tends to act as an insulator and can maintain far lower temperatures than the surrounding environment. This means an entrapped person could be entrapped in low temperature grain ($0\text{-}4^o$ C) and experience

hypothermia. However, since the thermal conductivity of grain is low, it would take hours to negatively impact the victim.

- Chest compression (Postural or crush asphyxiation) is probably the most dangerous risk for entrapped victims with their heads above the surface of the grain. Fifteen cases (7% of total) have been documented in which the victim died even with their head above the grain mass.
- The vast majority of documented victims were not equipped with a safety harness or lifeline.

9.2.3 Panel Questions

The expert panel was told to focus on discussing the issue of forcefully extricating a victim from grain and whether or not they would be willing to recommend this rescue method. In particular, they were asked to answer the following three questions:

1. In what circumstances would you recommend rescue personnel to forcefully extricate a victim?
2. What recommendations would you give a safety personnel to rescue a victim who is trapped to his chest/shoulder/neck and is struggling to breathe? What if he was wearing a harness? What if he is unconscious?
3. Should wearing a harness be a safety recommendation?

9.3 Panel Discussion

All members of the panel agreed that in cases of where the victim is fully engulfed in grain or is unconscious there should not be an attempt to forcefully extricate the victim due to the risk of secondary injury. In addition, vertical extrication should not be attempted in cases in which the victim is not equipped with an approved safety harness. Attempts to use the upper limbs or ropes secured under the arm, could increase the risk of secondary injury. In all other scenarios, there was not a consensus.

One panel member believed that in cases where the victim was entrapped wearing the safety harness correctly and was suffering from heat stress or struggling to breath, then rapid vertical extrication could be considered as it offers the best chance of ensuring the survival of the victim. He repeated that he was aware of unpublished experiments conducted where test subjects in good physical condition, wearing high grade harnesses were entrapped up to shoulder level in grain and pulled out with no injuries. He noted that this approach would only be viable in cases where the victim was equipped with an appropriate harness which has only been documented in a relatively small number of cases.

Other members disagreed with the rapid vertical extrication approach and highlighted that there are too many unknowns with such a method including: whether the victim was wearing the harness correctly; was using a type that provided full body support; or had unknown medical conditions that would reduce the tolerance to excessive loading. It was again noted that most past victims of entrapment were not equipped with a harness at the time of their entrapment. This was countered with the idea that maybe the focus of forceful extrication should be at non-exempt facilities where harness use is typically required. Again this was countered by the fact that most grain facilities do not have adequate anchor points in their grain storage structures that can support the forces required to pull out an engulfed victim. In addition, one member of the panel discussed findings in an older unpublished survey where not all workers at non-exempt facilities regularly used a harness. In the end, the panel was not able to reach a consensus on the frequency of safety harness use in the grain industry and whether forceful extrication should be recommended in certain scenarios. The group as a whole however, leaned toward, not recommending the use of force to extricate a deeply entrapped or engulfed victim.

With regards to whether a harness should be a safety recommendation when entering grain storage structures where there is a risk of entrapment, most agreed that it should still be considered a safety recommendation and is currently a federal requirement at all non-exempt facilities. One was concerned by the misuse of the harness, such as the lack of adequate anchor points, use of lanyards and fall restraint devices as part of the lifeline, and how misuse places victims in danger of having a false sense of security. It was also noted that since most victims historically were not equipped with a harness to begin with, how effective would it be to recommend the use a particular harness and lifeline. Lastly, it was agreed that safety harness use is seen to have different roles in the grain industry. They are primarily required for fall protection, but also generally seen as a tool for entrapment prevention. The type of harness and lifeline need to be different for each of those two distinct functions. This is an area that needs to be studied more before any conclusions can be generated. However, it was clear that a lanyard used in construction settings with a lifeline negates the value of the lifeline in an entrapment situation.

9.3.1 Additional Comments

In relation to the discussion above, one panel member commented on the need to move toward recommending an industry standard for anchor points in the sidewall of all grain bins and other grain storage structures, and pulleys at the top center or at least near the top center of all grain bins and other grain storage structures. All entrants into grain storage structures should review the engulfment risks before entering and wear a suitable harness connected to a lifeline with a trained observer actively involved if a lifeline is required. This should become a best management practice and would be similar to the system endorsed by the Grain Handling Safety Coalition (Aherin et al., 2014).

In addition further research should be conducted looking at types of cutting implements for breaching grain bin walls, the shape and size of those cuts, how to effectively make those cuts, the heights where the cuts should be made, how to access those heights, the pressures involved at various depths of engulfment, the forces encountered when pulling a person from the grain (not just how much it takes to pull them out, but what that translates into impact on the body regarding the potential for and effect on existing back injuries, knee or hip replacements, etc). Other issues addressed included how many people should be involved in a rescue inside a grain bin and how those people are secured, best management practices regarding moving grain away from the outside of a breached bin, best management practices when dealing with a free standing or vertically crusted grain inside the structures.

There remain many unknown issues related to the prevention and response to grain entrapments and engulfments, and too much speculation regarding some of the issues to make sound, evidence-based recommendations. For example, OSHA has certain requirements that are listed, but provides few specifics regarding compliance, often leading to reactionary rather than proactive responses. OSHA regulations, especially at non-exempt facilities require an emergency action plan but with few specifics on how to meet the standard. They require training, again, with few specifics. They require a lifeline without specifics. Technically, a grain bin is not always classified as an OSHA confined space, depending on its location and use. In fact, some do not classify these spaces as a confined space at all due to the regulatory definitions and place it into a category by itself.

Another panel member highlighted his concern with recent advertising of respirators or air filtration systems as a safety measure due to a recent case in which a young man survives a 4-5 hour engulfment in grain while wearing a battery-powered respirator. It is unclear whether he survived due to the respirator providing filtered air or by preventing the victim from aspirating grain or a psychological boost that prevented him from panicking. Such devices have not be proven as an effective form of personal protective equipment in the event of entrapment.

Lastly, it must be noted that the previous comments reflect the expert panel views and might not be consistent with other findings.

CHAPTER 10. RESEARCH SUMMARY

10.1 Introduction

The purpose of this research was to explore what the human body experiences when entrapped in, and extricated from grain, and to develop entrapment prevention and rescue recommendations. The effort of this research can be split into three parts; 1) documenting the significance of this research by collecting and analyzing grain entrapment cases, 2) Analyzing documented causes of death in order to identify strategies that could increase the probability of survival from a grain entrapment and 3) analyzing the effectiveness of current rescue procedures in mitigating the risk of injury to the victim of grain entrapment.

10.1.1 Significance

The overall fatality rate historically in grain entrapments was found to be 67% and 42% over the last five years (Issa et al., 2016a; CHAPTER 2). This is compared with an overall workplace fatality rate of 0.7% of documented incidents in agriculture including fisheries and forestry (NIOSH 2014). Grain entrapments are also distributed across demographics with the youngest and oldest case reported as 2 and 82 year old respectively (Issa et al., 2016b). About a quarter of all grain entrapments occurred to young and beginning workers under the age of 21 with a higher rate of fatality (90% fatality percentage for 15-18 year olds) as compared to 67% for all grain entrapments cases (Issa et al., 2016b). In addition, 94% of all grain entrapments could have been prevented if all safety regulations were performed correctly by the workers (CHAPTER 4). The high fatality rates, the demographics of grain entrapments and the fact that the vast majority of these incidents are preventable justifies the current interest and research in this area.

10.1.2 Increasing Chances of Survival

The most frequently documented cause of death in a grain engulfment is asphyxiation with 64% of all cases where the cause of death was documented (CHAPTER 3). There are three types of asphyxiation; aspiration, crush asphyxiation and postural asphyxiation. All three can occur when the body is fully engulfed in grain and only postural and crush asphyxiation can occur in a grain entrapment where the head or airway is above the grain mass. The fatality rate for entrapments (head above the grain mass) is 7% and jumps to 88% when the body is fully engulfed (CHAPTER 3). These findings are similar to those related to human engulfment in snow avalanches where asphyxiation accounted for 68% to 86% of the deaths depending on the study (Stalsberg et al., 1989; Mcintosh et al., 2007). While there is clear evidence that aspiration occurs during grain engulfments (Slinger et al., 1997), it appears that postural and crush asphyxiation, due to the pressure generated by the grain can also contribute to the risk of fatality. In avalanche victims, no air pockets were found around the mouth and nose indicating that victims could not breathe. Multiple victims of grain entrapment who were not completely engulfed, but buried to their shoulders complained of difficulty in breathing while in grain. In other cases, victims of complete engulfment noted that they experienced considerable pressure but were able to continue breathing due to airway protection. These reports highlight that there is significant pressure on the body due to grain entrapment and must be taken into consideration in order to increase the rate of survival.

Prior to this research, the only published study on the potential pressure on the chest was conducted by Moore & Jones (2016). In this study, they concluded that the force that the chest experiences when entrapped to the shoulders in grain was 2.8 kPa and that a human should be comfortable with such pressure. These results were contrary to previous anecdotal results and when a system designed to emulate the chest was tested in this study, it was found that the pressure was 3-5 times greater than expected (CHAPTER 8). This finding appears to support Roberts et al. (2015), who found that the force required to pull out the mannequin from grain increased by about 24% when a rescue tube was inserted around the mannequin. This has been attributed to increased bulk density, but could be also due to increased pressure resulting from the cofferdam pushing against the grain and thus placing the grain pressure values closer to passive than active pressure.

Findings clearly indicate that certain grain depths can apply significant pressure to cause postural or crush asphyxiation in a flowing grain entrapment. In other words a victim is in danger of both aspiring grain and asphyxiation. In the case of entrapment an individual should follow the following advice to increase their chance of survival:

1) Cover their mouths and nose with their hands, shirt or hat to prevent grain aspiration and maximize the air pocket in front of the mouth and nose.
2) Fold arms in front of chest to reduce pressure on the chest and to give the chest cavity room to at least expand to allow shallow breaths.

10.1.3 Extrication

The primary method used historically to rescue an entrapped or engulfed individual has been to drain grain from the bin/silo until the body appears. This has been accomplished by cutting open the walls of the structure or vacuuming out the grain using a grain vacuum. Placing a cofferdam around the victim and vacuuming the grain between the body and the cofferdam until the body can be pulled out is becoming a more commonly used strategy (Field et al., 2014a). These methods can take between 30 minutes to 6 hours depending on the size of the grain bin, the depth of entrapment, and access to trained first responders. Due to lack of knowledge regarding grain pressures or concerns over the length of rescue time, some previous rescues have attempted to pull the victim straight up without removing the grain. In some cases, secondary injuries were reported. Schwab et. al. (1985) and Roberts et al. (2015) conducted experiments on pulling out mannequins from grain and found that when pulled out at a depth of shoulder level, the body experiences about 2700 N of force that introduces the risk of serious physical injury. These experiments, however, were done under ideal conditions in which the mannequin was pulled vertically from dry corn and wheat.

Research conducted in this study expanded previous knowledge by measuring forces needed for extraction under various grain types, moisture content and at various angles. It found that required extraction forces for most grain types were similar with the exception of sunflower seeds which were significantly lower than the rest (CHAPTER 5). These small scale results were consistent with both Schwab et al. (1985) and CHAPTER 6 in which the forces for extrication in corn was not significantly different from wheat or soybeans. It was confirmed that pulling the mannequin from high moisture corn (out of condition) required a significant larger force than in dry corn. It was also determined that pulling out the mannequin at various angles only increased forces significantly if pulled at an angle sharper than 45 degrees (CHAPTER 5). These results indicate that the type of grain does not matter, in most cases, and that the rescuers have some leeway in installing the anchor point for vertical extrication, but excessive forces applied during extrication can increase the risk of secondary injury to the victim. However, the moisture content of the grain is a significant concern, as at least 45% of all documented grain entrapments occurred in out of condition grain, that may be whet or crusted, that can increase the forces required for extrication (CHAPTER 4).

While the studies above highlight the force applied on the victim during extrication, they do not clarify whether a human spine can withstand such forces. Cases have been documented that excessive force applied to the victim during extrication can result in bodily harm, including injuries to the back. Using representative spinal column from sheep, research indicated that the spine can handle between 1650 – 2480 N before damage occurs to the intervertebral disc (CHAPTER 7). This is within the same range as the force required to extricate a mannequin vertically from grain at waist to shoulder depth. Since this study was conducted in vitro, it is hard to predict how the muscle system and other systems would bolster support for the spine. It is also unknown how these extrication forces can impact internal organs or joints. Thus it was concluded that even though it is inconclusive whether or not the spine or other body parts will experience an injury from extrication in every situation, the use of forceful extrication techniques could result in serious secondary injuries. A panel of experts gathered together to discuss these results also concluded that forceful extrication poses a high risk of secondary injury and requires more extensive research before recommendation as a safe rescue strategy. They also recommended the development of safety standards for grain storage structures should include features such as anchor points, and outsider observer station. The need for more clarity with respect to the co-use of safety harnesses and lifelines for both fall restraint and confined space entry was seen as significant (CHAPTER 9).

10.2 Conclusions

Grain entrapments remain a significant agricultural injury risk that is highly preventable. Incident rates could be significantly decreased if farmers and workers followed current safety guidelines with a special emphasis on lock-out/tag-out that would prevent the vast majority of all grain entrapments due to flowing grain. In addition, with the majority of grain entrapment incidents caused by out-of-condition grain, proper maintenance of grain could play a significant role in prevention. While the proper use of safety harnesses might reduce grain entrapment incidents; anchor points, harness use training and lack of outside observer has hindered the effectiveness of the harness in preventing previous grain entrapments. Lastly, the strategy of forcefully extracting a grain entrapment victim by pulling them out vertically using a safety harness, lifeline and mechanical winch remains a non-viable extraction solution due to:

- General lack of safety harness use among those most vulnerable to entrapment.
- High potential for incorrect use of harness and lifelines, and lack of adequate anchor points in most grain storage structures.
- The increase in extrication forces required from high moisture or out-of-condition grain that is present at many of the entrapment scenes.
- The forces that the spine and other body parts can withstand is within the same range as the forces required to pull out a victim in grain buried waist-shoulder depth.

10.2.1 Future Research

This research focused on the physical forces on the victim during grain entrapments or extraction. The results of this research highlight the need for more extensive research in the following areas:

- The availability of oxygen in the grain mass. This research should provide results on a) how large of an open space is needed to diffuse enough oxygen for the victim to survive; b) how long a victim can survive, c) the effect of turning on the aeration system on survivability, and d) the effect of various masks (and filters) on survivability.
- The effect of high moisture content of the grain on the forces needed to extract a victim. This research should also include more in depth study of the forces on a victim trapped in high moisture or out of condition grain.
- How a harness distributes load on the body's spine and joints during vertical extrication.

- The potential effects on blood circulation system and heart rate due to suspension in grain (using a harness or not) and grain pressure. This includes concerns of blood pooling in the leg region.
- Large scale study on the pressures the chest experiences while breathing in a grain mass.
- The effect of fines and foreign material on the forces needed to forcefully extricate a victim.
- The effect of grain consolidation on the forces impacting the body.

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APPENDICES

Appendix A Confined Space Incident Data

Table A-1 The number of agricultural confined space incidents for every year from 1956 to 2013 and the 10-year average.

Year	# of Incidents	10-year Average
1956	1	
1957	0	
1958	0	
1959	0	
1960	0	
1961	0	
1962	1	
1963	0	
1964	1	
1965	2	0.5
1966	2	0.6
1967	3	0.9
1968	5	1.4
1969	7	2.1
1970	12	3.3
1971	12	4.5
1972	5	4.9
1973	16	6.5
1974	11	7.5
1975	7	8
1976	10	8.8
1977	14	9.9
1978	18	11.2
1979	8	11.3
1980	23	12.4
1981	18	13
1982	6	13.1
1983	5	12
1984	24	13.3
1985	27	15.3
1986	61	20.4
1987	24	21.4
1988	30	22.6
1989	33	25.1
1990	52	28
1992	55	35
1993	66	41.1
1994	70	45.7
1995	45	47.5
1996	48	46.2
1997	48	48.6
1998	39	49.5
1999	30	49.2
2000	29	46.9
2001	42	47.2
2002	41	45.8
2003	34	42.6
2004	51	40.7
2005	52	41.4
2006	44	41
2007	52	41.4
2008	64	43.9
2009	94	50.3
2010	99	57.3
2011	63	59.4
2012	44	59.7
2013	67	63

Table A-2 Number of agricultural confined space incidents in U.S. states from 1956 to 2013. Total number of incidents documented was 1,654.

State	# of Incidents	State	# of Incidents
Iowa	211	Idaho	13
Indiana	200	South Carolina	12
Illinois	166	Colorado	12
Minnesota	160	Washington	10
Nebraska	119	Tennessee	10
Wisconsin	112	Mississippi	9
Ohio	63	Georgia	8
Pennsylvania	59	Alabama	8
Michigan	58	Utah	7
Kansas	56	Louisiana	7
North Dakota	40	Florida	6
South Dakota	38	Oregon	4
California	38	New Jersey	3
Texas	37	Montana	2
New York	34	New Hampshire	1
North Carolina	25	Arizona	1
Missouri	25	Delaware	1
Arkansas	22	New Mexico	1
Virginia	18	Connecticut	1
Maryland	16	Alaska	1
Kentucky	14	Massachusetts	1
Oklahoma	14		
		Unknown	11

Table A-3 Number of confined space incidents distributed across US regions.

Year	Midwest	East	South	West	Unknown	Total
1956	1	0	0	0	0	1
1957	0	0	0	0	0	0
1958	0	0	0	0	0	0
1959	0	0	0	0	0	0
1960	0	0	0	0	0	0
1961	0	0	0	0	0	0
1962	1	0	0	0	0	1
1963	0	0	0	0	0	0
1964	1	0	0	0	0	1
1965	2	0	0	0	0	2
1966	2	0	0	0	0	2
1967	2	0	0	0	1	3
1968	5	0	0	0	0	5
1969	7	0	0	0	0	7
1970	10	0	1	1	0	12
1971	12	0	0	0	0	12
1972	5	0	0	0	0	5
1973	13	0	0	2	1	16
1974	11	0	0	0	0	11
1975	4	0	1	2	0	7
1976	7	0	2	1	0	10
1977	13	0	1	0	0	14
1978	17	1	0	0	0	18
1979	6	0	1	1	0	8
1980	17	0	0	5	1	23
1981	11	1	1	3	2	18
1982	6	0	0	0	0	6
1983	5	0	0	0	0	5
1984	19	2	2	1	0	24
1985	20	5	1	0	1	27
1986	50	6	4	1	0	61
1987	19	0	3	2	0	24
1988	25	0	4	1	0	30
1989	26	2	4	0	1	33
1990	32	4	9	7	0	52
1991	30	7	0	2	0	39
1992	49	0	6	0	0	55
1993	54	3	6	3	0	66

Table A-3 continued

Year	Midwest	East	South	West	Unknown	Total
1994	51	1	11	7	0	70
1995	29	7	5	3	1	45
1996	42	3	2	1	0	48
1997	37	5	5	1	0	48
1998	30	5	4	0	0	39
1999	21	4	5	0	0	30
2000	21	4	2	2	0	29
2001	28	3	4	6	1	42
2002	26	2	8	5	0	41
2003	23	2	7	2	0	34
2004	42	2	5	2	0	51
2005	37	2	9	3	1	52
2006	37	1	2	4	0	44
2007	39	1	8	4	0	52
2008	38	1	20	4	1	64
2009	76	4	11	3	0	94
2010	75	9	13	2	0	99
2011	42	6	14	1	0	63
2012	29	4	8	3	0	44
2013	43	1	19	4	0	67
Grand Total	1,248	98	208	89	11	1,654

Table A-4 Confined Space incident by type of incident for each year from 1956 to 2013

Year	Asphyxiation / Poisoning	Entanglement	Fall	Grain Entrapment	Other / Unknown	Pinned by object	Total
1956	0	0	0	0	0	1	1
1957	0	0	0	0	0	0	
1958	0	0	0	0	0	0	
1959	0	0	0	0	0	0	
1960	0	0	0	0	0	0	
1961	0	0	0	0	0	0	
1962	0	1	0	0	0	0	1
1963	0	0	0	0	0	0	
1964	0	0	0	1	0	0	1
1965	0	1	1	0	0	0	2
1966	0	0	0	2	0	0	2
1967	0	0	0	3	0	0	3
1968	0	0	0	5	0	0	5
1969	1	0	0	6	0	0	7
1970	0	1	0	10	1	0	12
1971	1	0	0	11	0	0	12
1972	0	1	0	4	0	0	5
1973	2	0	0	14	0	0	16
1974	3	0	0	8	0	0	11
1975	1	1	0	5	0	0	7
1976	2	0	0	8	0	0	10
1977	3	0	0	10	1	0	14
1978	0	0	0	18	0	0	18
1979	2	0	0	6	0	0	8
1980	10	0	0	13	0	0	23
1981	2	1	0	15	0	0	18
1982	0	0	0	6	0	0	6
1983	0	0	0	5	0	0	5
1984	6	1	0	16	1	0	24
1985	2	2	0	22	1	0	27
1986	3	1	1	54	2	0	61
1987	2	1	0	21	0	0	24
1988	1	1	1	25	2	0	30
1989	7	2	0	22	1	1	33
1990	2	7	3	34	2	4	52
1991	0	5	7	19	3	5	39
1992	10	4	4	28	2	7	55

Table A-4 continued

Year	Asphyxiation / Poisoning	Entanglement	Fall	Grain Entrapment	Other / Unknown	Pinned by object	Total
1993	5	10	4	43	1	3	66
1994	7	17	5	36	1	4	70
1995	4	5	7	26	1	2	45
1996	5	9	2	25	3	4	48
1997	7	2	5	29	4	1	48
1998	5	5	4	22	2	1	39
1999	6	0	2	20	2	0	30
2000	1	1	3	21	3	0	29
2001	8	5	3	26	0	0	42
2002	5	2	4	25	2	3	41
2003	4	2	4	22	2	0	34
2004	10	4	6	27	3	1	51
2005	4	2	7	35	3	1	52
2006	1	3	10	26	4	0	44
2007	7	3	6	31	1	4	52
2008	9	2	10	35	4	4	64
2009	4	11	27	44	4	4	94
2010	14	9	13	59	2	2	99
2011	2	4	9	32	1	15	63
2012	6	14	3	20	1	0	44
2013	4	12	14	33	2	2	67

Appendix B Grain Entrapment Data

Table B-1 Grain entrapments over time by fatality

Year	Non Fatal	Fatal	Fatality Rate	Grand Total
1963	1		0%	1
1964		1	100%	1
1966		2	100%	2
1967	1	2	67%	3
1968	1	4	80%	5
1969	3	3	50%	6
1970		11	100%	11
1971	2	9	82%	11
1972		4	100%	4
1973	7	8	53%	15
1974	4	5	56%	9
1975		7	100%	7
1976		8	100%	8
1977	3	11	79%	14
1978	5	22	81%	27
1979	3	10	77%	13
1980	1	18	95%	19
1981	1	20	95%	21
1982	1	6	86%	7
1983	1	4	80%	5
1984	5	11	69%	16
1985	3	19	86%	22
1986	11	42	79%	53
1987	2	19	90%	21
1988	1	24	96%	25
1989	4	19	83%	23
1990	8	26	76%	34
1991	6	14	70%	20
1992	15	13	46%	28
1993	11	33	75%	44
1994	13	23	64%	36
1995	7	19	73%	26
1996	9	17	65%	26

Table B-1 continued

Year	Non Fatal	Fatal	Fatality Rate	Grand Total
1997	9	21	70%	30
1998	6	16	73%	22
1999	3	16	84%	19
2000	2	19	90%	21
2001	4	23	85%	27
2002	9	17	65%	26
2003	7	15	68%	22
2004	10	19	66%	29
2005	13	24	65%	37
2006	12	15	56%	27
2007	15	17	53%	32
2008	17	18	51%	35
2009	23	20	47%	43
2010	27	32	54%	59
2011	21	12	36%	33
2012	15	8	35%	23
2013	21	12	36%	33
2014	20	18	47%	38
2015	10	13	57%	23
Grand Total	373	769	67%	1,142

Table B-2 Grain Entrapments by type of entrapment. Engulfment are any cases where the head or airway is no longer visible. Entrapment are any cases in which at least the head or airway is still visible.

Type	Non-Fatal	Fatal	Total	Percent Fatal
Engulfment	65	468	533	88%
Entrapment	195	15	210	7%
Unknown	113	286	399	72%

Appendix C Small scale extrication experiment results

Table C-1 The force (newton) required to extricate an object out of grain in various conditions (depth, angle, grain type, limb orientation, object type).

Object	Orientation	Depth	Angle	Popcorn	Oats	Sunflower	Soybeans	Dry corn	Wet corn	Canola	Wheat
Cylinder	-	0 cm	90	4.43^{a}	3.93	3.26	4.57^{a}	4.31^{a}	6.62^{ab}	5.49	4.20
Cylinder	-	0 cm	45	5.44	4.81	3.44	5.85	4.70^{b}	7.25^{b}	6.02	5.19
Mannequin	Straight	0 cm	90	4.99^{b}	3.26^{a}	2.40^{a}	3.74^{b}	4.42^{ab}	5.90^{cd}	2.73	3.61^{ab}
Mannequin	Stretched	0 cm	90	4.19^{ac}	3.01^{ab}	2.32^{a}	3.99^{b}	4.04^{ac}	5.14^{e}	3.25^{a}	3.81^{b}
Mannequin	Straight	0 cm	45	4.55^{ab}	2.99^{b}	2.28^{a}	4.03^{ab}	4.26^{abc}	6.23^{ad}	2.98^{a}	3.31^{a}
Mannequin	Stretched	0 cm	45	3.84^{c}	3.07^{ab}	2.50^{a}	3.77^{b}	3.84^{c}	5.37^{ce}	3.13^{a}	3.51^{a}
Cylinder	-	10 cm	90	12.49	8.49	7.50^{b}	12.37^{c}	12.16^{d}	14.82^{f}	11.57	11.27
Cylinder	-	10 cm	45	16.05	13.36	7.76^{b}	15.23	13.17	14.91^{f}	15.22	13.38
Mannequin	Straight	10 cm	90	7.58	6.09	4.26	9.02	8.88^{e}	13.13^{g}	6.75	7.45
Mannequin	Stretched	10 cm	90	10.85	9.02	6.47	11.81^{c}	11.30^{f}	15.62^{fh}	9.51^{b}	9.96
Mannequin	Straight	10 cm	45	8.71	7.03	5.33	9.84	8.65^{e}	13.21^{g}	7.54	9.08
Mannequin	Stretched	10 cm	45	12.10	10.74	6.88	12.50^{c}	11.88^{df}	16.07^{h}	9.11^{b}	10.60

Notes: Experiments with same letters are not significantly different from each other at $P<0.01$

Table C-2 The relative force (%) required to extricate an object out of grain in various conditions (depth, angle, grain type, limb orientation, object type). Relative force is calculated by dividing the actual force in an experiment set (Table C-1) with the maximum force obtained in the same experimental conditions regardless of grain type.

Object	Orientation	Depth	Angle	Popcorn	Oats	Sunflower	Soybeans	Dry Corn	Wet corn	Canola	Wheat
Cylinder	-	0 cm	90	67%	59%	49%	69%	65%	100%	83%	63%
Cylinder	-	0 cm	45	75%	66%	47%	81%	65%	100%	83%	72%
Mannequin	Straight	0 cm	90	85%	55%	41%	63%	75%	100%	46%	61%
Mannequin	Stretched	0 cm	90	82%	59%	45%	78%	79%	100%	63%	74%
Mannequin	Straight	0 cm	45	73%	48%	37%	65%	68%	100%	48%	53%
Mannequin	Stretched	0 cm	45	72%	57%	47%	70%	72%	100%	58%	65%
Cylinder	-	10 cm	90	84%	57%	51%	83%	82%	100%	78%	76%
Cylinder	-	10 cm	45	100%	83%	48%	95%	82%	93%	95%	83%
Mannequin	Straight	10 cm	90	58%	46%	32%	69%	68%	100%	51%	57%
Mannequin	Stretched	10 cm	90	69%	58%	41%	76%	72%	100%	61%	64%
Mannequin	Straight	10 cm	45	66%	53%	40%	74%	65%	100%	57%	69%
Mannequin	Stretched	10 cm	45	75%	67%	43%	78%	74%	100%	57%	66%
Average				75%^{a}	59%^{b}	43%	75%^{a}	72%^{a}	99%	65%^{ab}	67%^{ab}
Standard Deviation				11%	10%	5%	9%	6%	2%	16%	8%

Notes: The averages of grains with same letters are not significantly different from each other at P<0.01

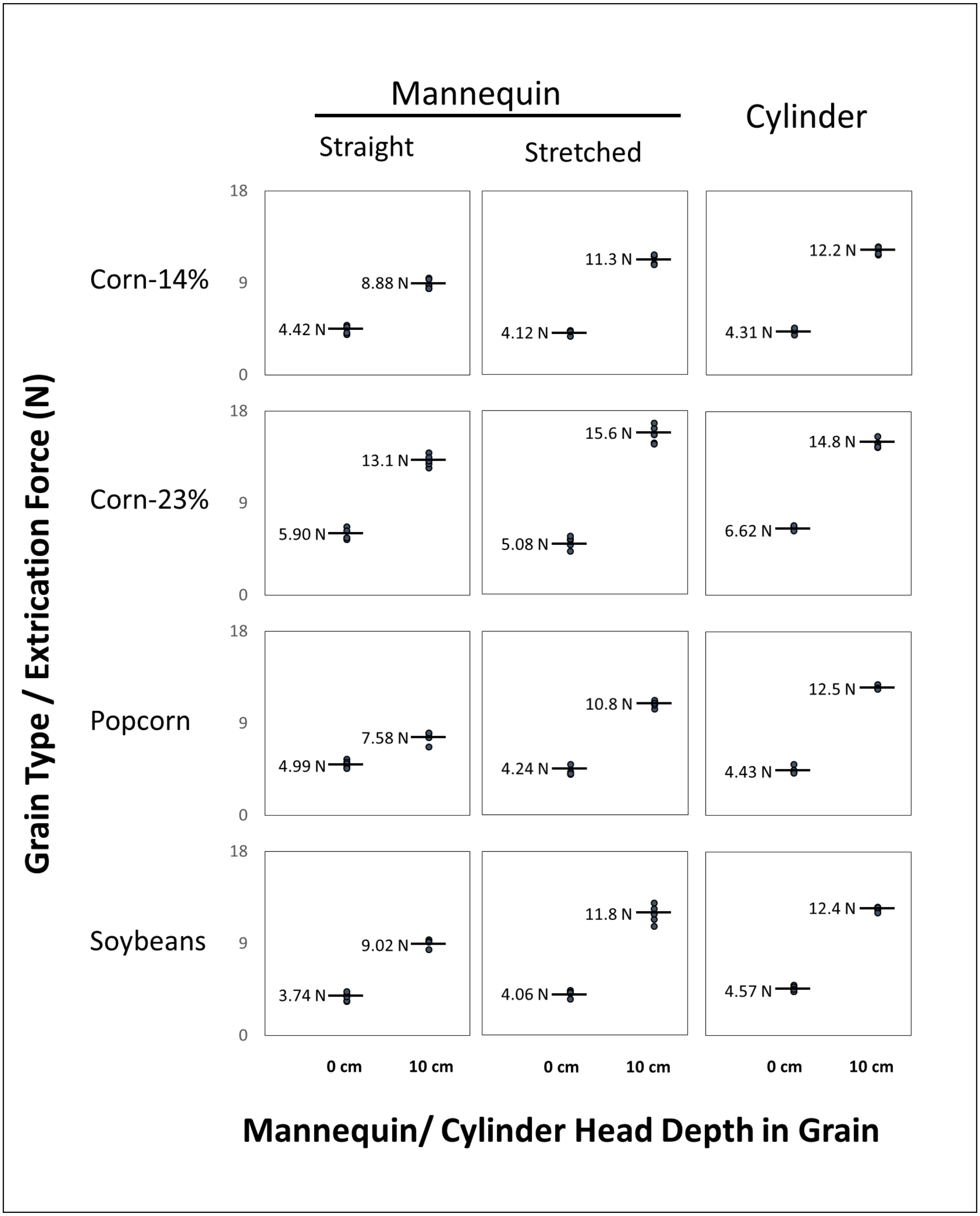

Figure C-1 Comparison between the forces required to pull an object vertically upwards from dry corn, wet corn, popcorn and soybeans at 0 and 10 cm depth.

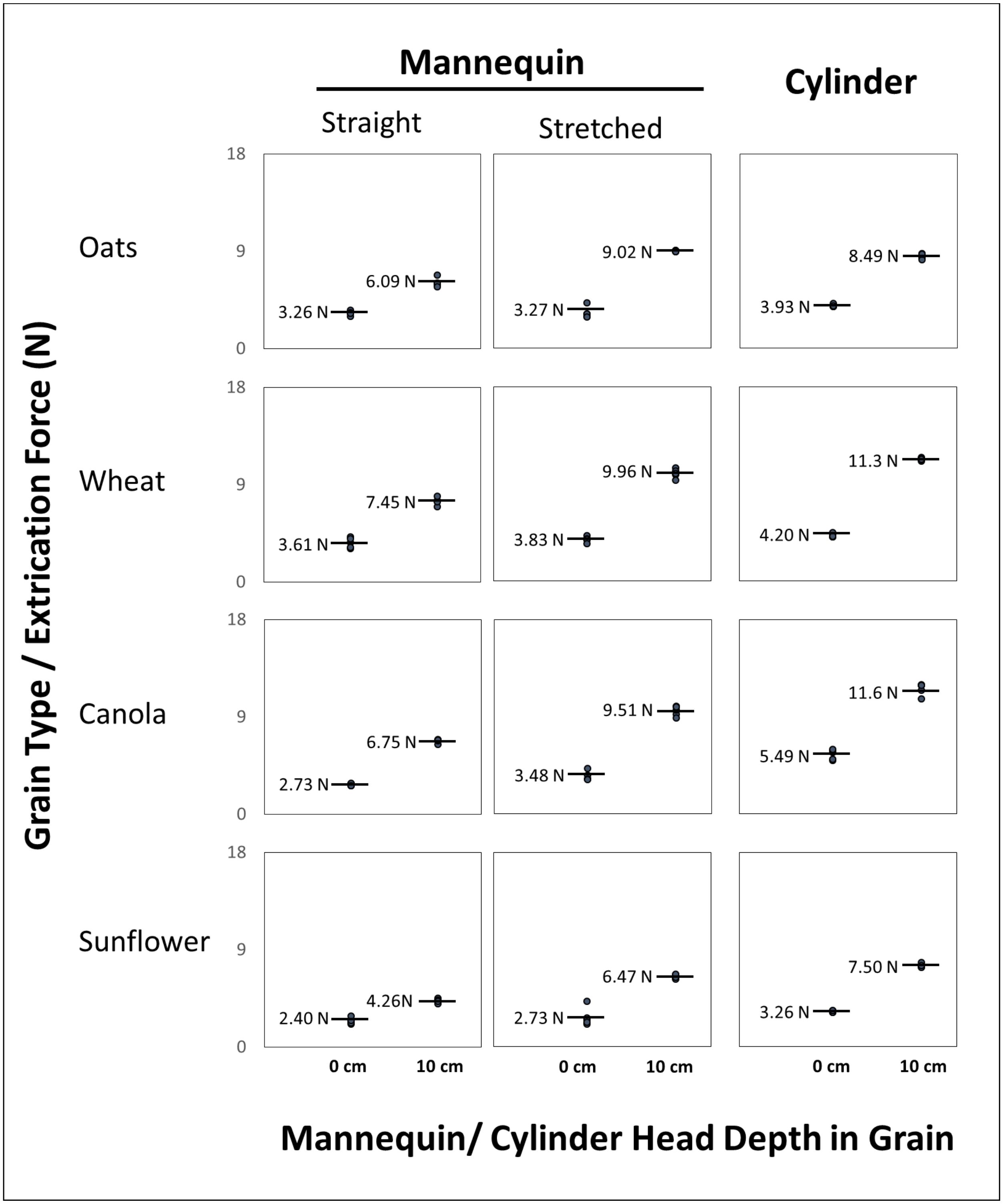

Figure C-2 Comparison between the forces required to pull an object vertically upwards from oats, wheat, canola and sunflower at 0 and 10 cm depth.

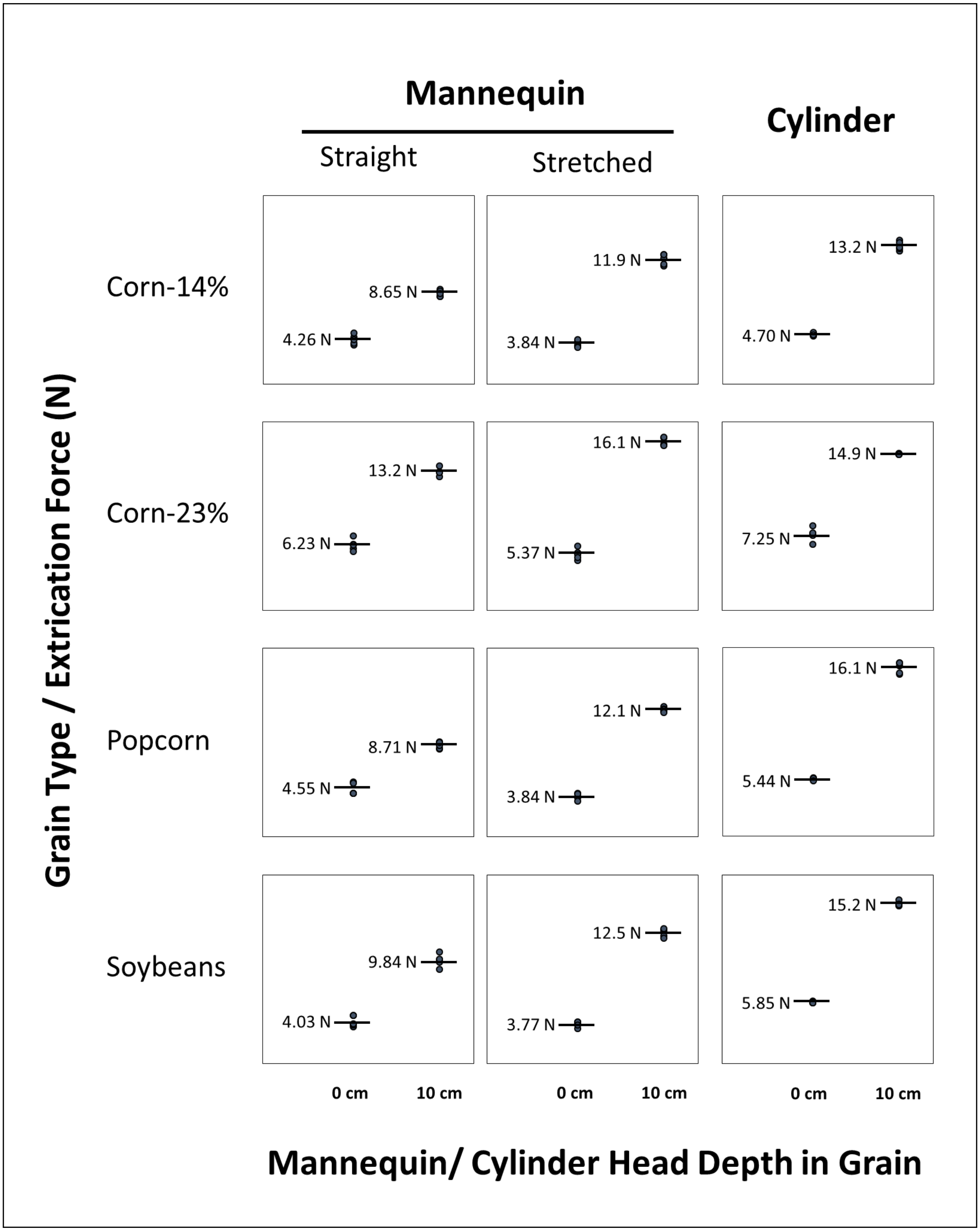

Figure C-3 Comparison between the forces required to pull an object at 45° angle out of dry corn, wet corn, popcorn and soybeans at 0 and 10 cm depth.

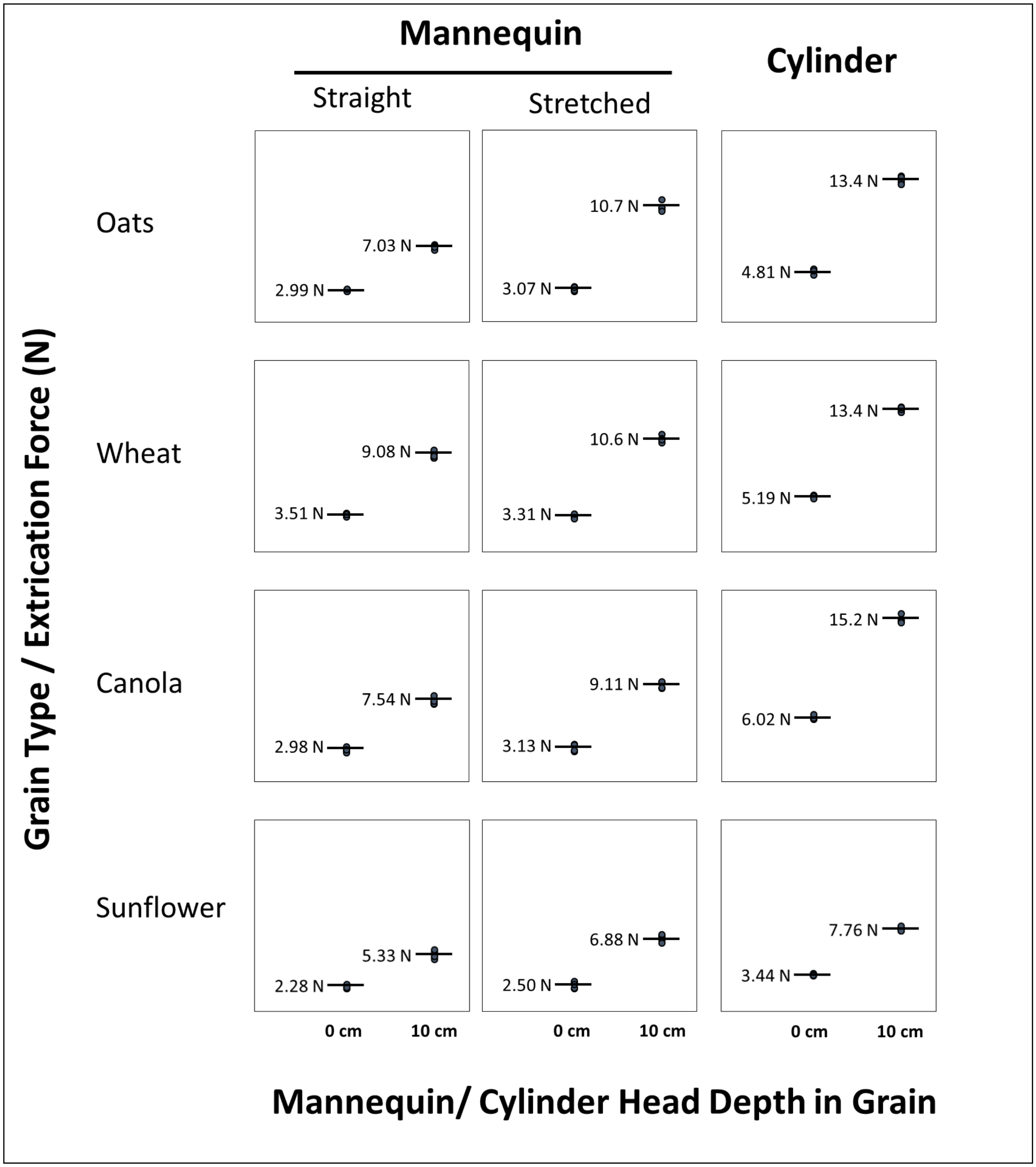

Figure C-4 Comparison between force required to pull an object at 45^{o} angle out of oats, wheat, canola and sunflower at 0 and 10 cm depth.

Appendix D Spine force curves

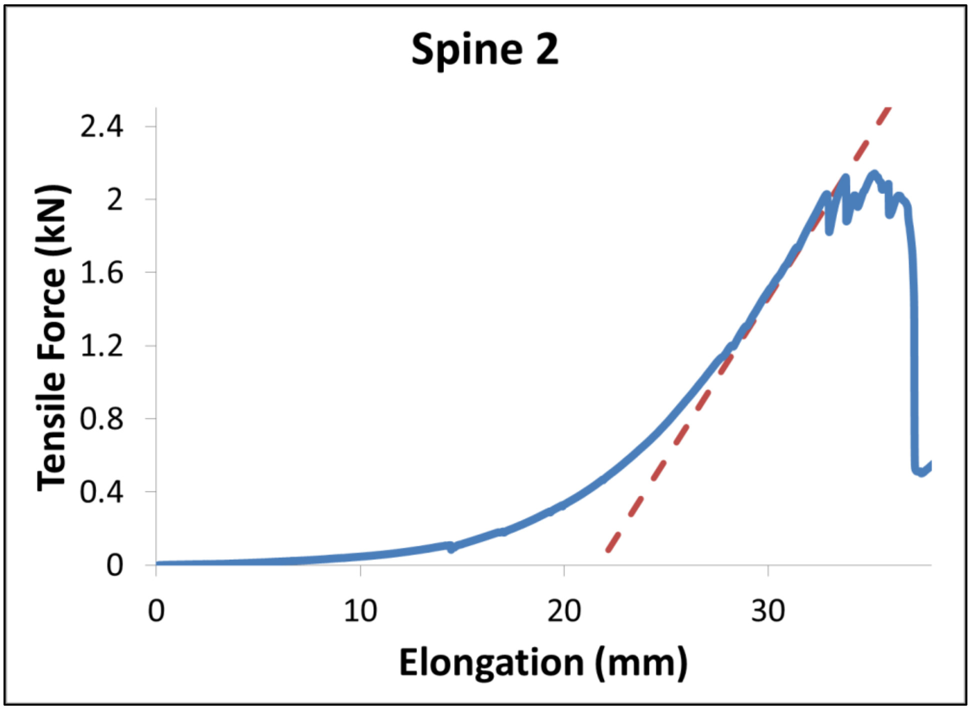

Figure D-1 Tensile force vs. elongation curve for lumbar sheep spine segment # 2. (Solid line represents the force experienced by the spine; dashed line represents the yield-elastic curve. Intersection of the solid and dashed lines is the yield strength.)

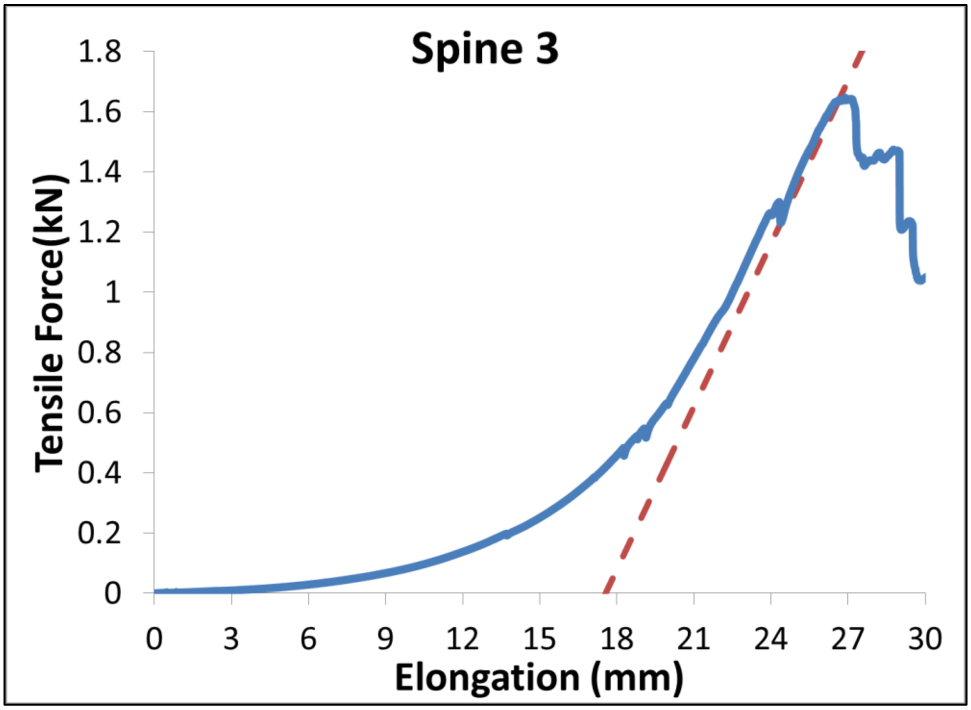

Figure D-2 Tensile force vs. elongation curve for lumbar sheep spine segment # 3. (Solid line represents the force experienced by the spine; dashed line represents the yield-elastic curve. Intersection of the solid and dashed lines is the yield strength.)

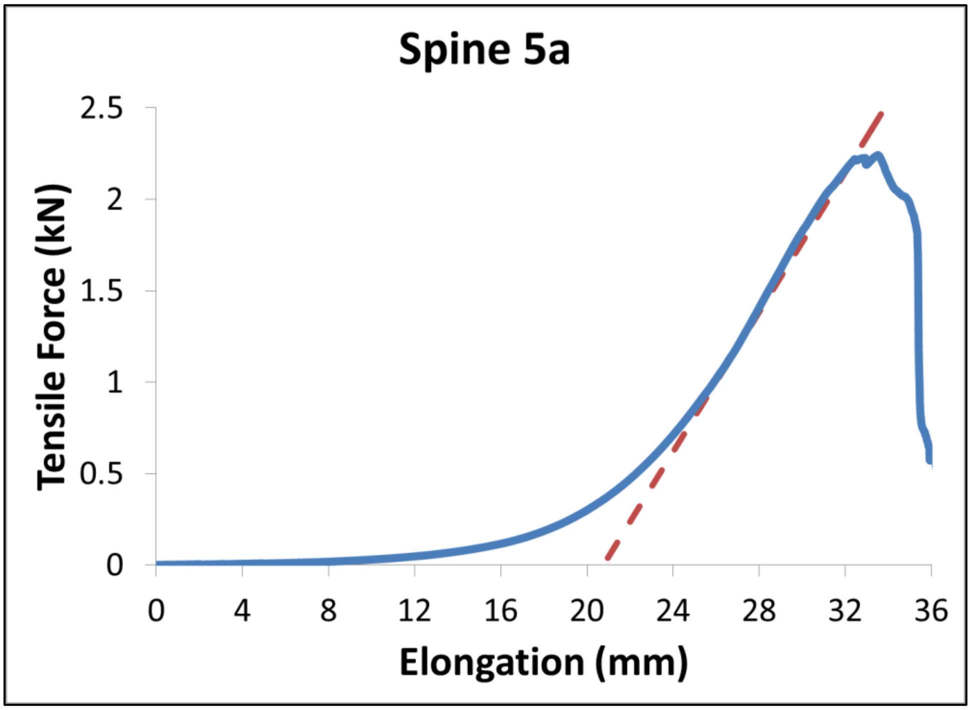

Figure D-3 Tensile force vs. elongation curve for lumbar sheep spine segment # 5a. (Solid line represents the force experienced by the spine; dashed line represents the yield-elastic curve. Intersection of the solid and dashed lines is the yield strength.)

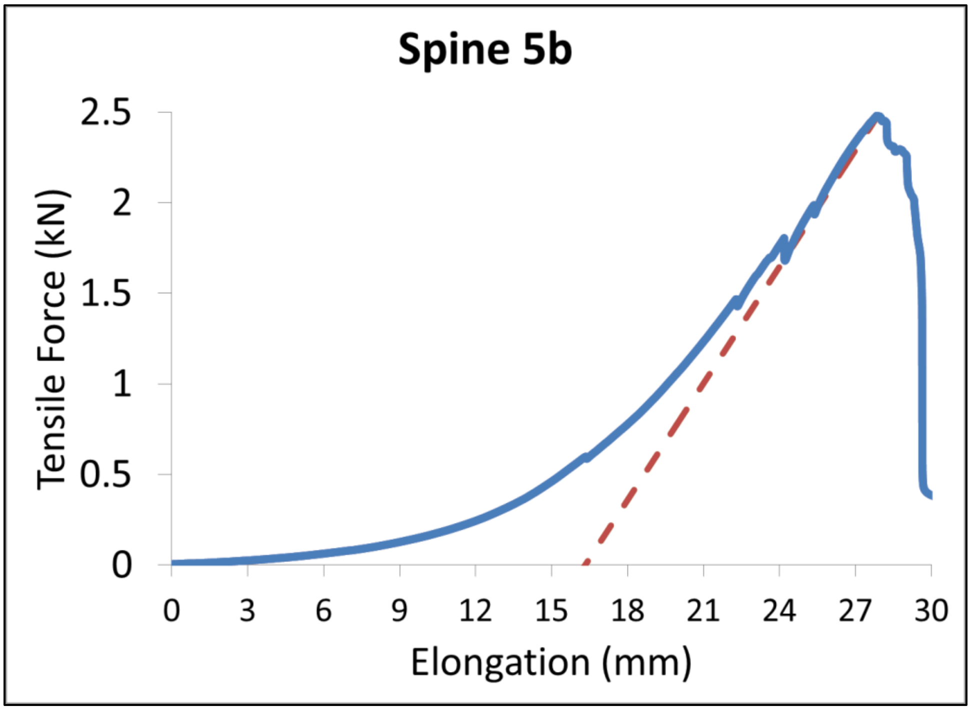

Figure D-4 Tensile force vs. elongation curve for lumbar sheep spine segment # 2. (Solid line represents the force experienced by the spine; dashed line represents the yield-elastic curve. Intersection of the solid and dashed lines is the yield strength.)

VITA

VITA

EDUCATION

PhD, Agricultural and Biological Engineering, Purdue University, 2016
MSE, Agricultural and Biological Engineering, Purdue University, 2012
Concentration: Ecological Sciences and Engineering
BS, Chemical and Biochemical Engineering, Rutgers University, 2007
Certificate, Engineer in Training, 2006

PROFESSIONAL EXPERIENCE

2008-2009	Scientist, Technology Transfer Division, Johnson & Johnson
2007	Associate Scientist, Cell Culture Process Development, Phyton Biotech, DFB Pharmaceuticals
2006-2007	Co-op Associate, Process Technology Center, Colgate Palmolive

PUBLICATIONS

JOURNAL

2016	S. F. Issa, Y. H. Cheng, & W. E. Field (2016). Summary of Agricultural Confined-Space Related Cases: 1964-2013. Journal of Agricultural Safety and Health v22 (1)
2016	S. F. Issa, W. E. Field, K. E. Hamm, Y.-H. Cheng, M. J. Roberts, & S. M. Riedel. (2016). Summarization of Injury and Fatality Factors Involving Children and Youth in Grain Storage and Handling Incidents. Journal of Agricultural Safety and Health v22 (1)
2015	S. Issa, H. Mohammad, & M.I. Sarfaz. "Restaurant hope: Engineering a choice-based service initiative to address hunger. Purdue Journal of Service-Leaning and International Engagement vol 2.

Conference Proceedings

2015	American Society of Agricultural and Biological Engineers, (July) S. Issa, and W. Field. "Study of the impact of engulfment/entrapment and extrication on the human body"
2015	International Society for Agriculture Safety and Health, (June) S. Issa, and W. Field. "How 'Safe' Is Grain Bin Fall-Safety Equipment? A Review of Entrapment Cases Where Such Equipment Was Used"

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2014	International Society for Agriculture Safety and Health, (June) S. Issa, and W. Field. "An updated summary of agricultural confined-related incidents - 1964-2013"
2013	International Society for Agriculture Safety and Health, (July) W. Field, S. Issa, K. Hamm, M. Roberts, S. Riedel and Y.H. Chang. "Estimation of the Frequency, Severity, and Primary Causative Factors Associated With Injuries and Fatalities Involving Grain Entrapments and Youth And Young Adults Under the Age of Twenty-One."

Web-based Publications

2016	S. Issa, Y.H. Chang, & W. Field. "2015 Summary of U.S. Agricultural Confined Space-Related Injuries and Fatalities". www.agconfinedspaces.org
2015	S. Issa, Y.H. Chang, & W. Field. "2014 Summary of U.S. Agricultural Confined Space-Related Injuries and Fatalities". www.agconfinedspaces.org
2014	S. Issa, Y.H. Chang, & W. Field. "2013 Summary of U.S. Agricultural Confined Space-Related Injuries and Fatalities". www.agconfinedspaces.org
2013	S. Issa M. Roberts & W. Field. "2012 summary of grain entrapments in the United States" . www.agconfinedspaces.org Reprinted in Grain Journal (June 2013)

Other Publications

2012	S. Issa. "Evaluating Hybrid-Maize model in rainfed conditions in northwestern Indiana". Agricultural and Biological Engineering, MS Thesis. Published.

AWARDS AND HONORS

2015	National Arab American Association of Engineers and Architects (NAAAEA), $750
2015	Harold Reese Memorial Scholarship, The Grain Elevator & Processing Society (GEAPS), $500
2015	Cecelia Zissis Grant for Graduate Students, Purdue University, $1000
2014	Indiana Small Conference, Purdue University
2013	Purdue Graduate Student Travel Grant, Purdue University, $1000
2012	Byron Fellowship Course, Byron Institute
2010	Tri-State Arab American Association of Engineers and Architects (AAAEA), $1000
2010	Purdue Engineering Student Council Merit Grant, Purdue University, $5000
2010	Hydrologists Helping Others (H2O) Grant, Purdue University, $10,000
2009	Lynn Fellowship, Purdue University

PRESENTATIONS

Conferences

2016	Oral Presentation “The effects of grain type and condition on the force needed to extricate a victim”. American Society of Agricultural and Biological Engineers (July).
2016	Oral Presentation “Determining the pull-forces required to extricate a victim entrapped at various angles in a grain mass”. International Society for Agriculture Safety and Health, (June)
2016	Poster Presentation “The effects of grain type and condition on the force needed to extricate a victim”. International Society for Agriculture Safety and Health, (June)
2015	Oral Presentation “Study of the impact of engulfment/entrapment and extrication on the human body”. American Society of Agricultural and Biological Engineers (July).
2015	Oral Presentation “How ‘Safe’ Is Grain Bin Fall-Safety Equipment? A Review of Entrapment Cases Where Such Equipment Was Used”. International Society for Agriculture Safety and Health, (June)
2014	Oral Presentation “An updated summary of agricultural confined-related incidents for 1964-2013” International Society for Agriculture Safety and Health, (June)
2014	Oral Presentation “Grain Entrapment Cases Involving Youth” Indiana Small Farms Conference (February)
2014	Poster Presentation “Grain Entrapment Cases Involving Youth” Indiana Small Farms Conference (February)
2013	Poster Presentation “DSSAT vs Hybrid-Maize: A comparative study between two maize (Zea mays L.) crop models”. ASA-CSSA-SSSA annual conference (November).

Campus

2014	Poster Presentation “Summarization grain entrapment cases in agriculture involving youth”. Sigma Xi poster competition, Purdue University (February)
2014	Oral Presentation “Grain entrapments”. Graduate Professional Development Course (February)
2013	Poster Presentation “Summarization of Injury and Fatality Factors Involving Youth and Grain Entrapment in Agriculture". Ecological Sciences and Engineering Annual Symposium, Purdue University (October)
2013	Poster Presentation "DSSAT vs Hybrid-Maize: A Comparative Study Between Two Maize (Zea mays L.) Crop Models" Office of Interdisciplinary Graduate Program Spring Reception, Purdue University (April)
2013	Poster Presentation "DSSAT vs Hybrid-Maize: A Comparative Study Between Two Maize (Zea mays L.) Crop Models" Agricultural and Biological Engineering Poster Symposium, Purdue University (March)

TEACHING EXPERIENCE

Workshops

Grain Entrapment Rescue Class, “Summary of grain related incidents involving youth” (8/26/13 , 8/28/13)

Train the Trainer Class, “ Agricultural confined spaces : Summary of incidents” (August 2013)

Classes – Teacher Assistant

Safety in Agriculture (Spring 2014)
Emergency Management of Agricultural Production (Fall 2013 - 2016)
Peer to Peer Leadership & Mentoring (Fall 2010, Spring 2011)

RESEARCH EXPERIENCE

2013-Current	Grain Entrapments, Research Assistant, Agricultural and Biological Engineering, Purdue University
2009-2012	Crop Model Analysis, Research Assistant, Ecological Sciences and Engineering, Purdue University

EXTRACURRICULAR ACTIVITIES

2016	President, Graduate Muslim Network, Purdue University Chapter
2015-2016	Professional Development Chair, Agricultural and Biological Engineering Graduate Student Association, Purdue University
2014-2015	Philanthropy Chair, Agricultural and Biological Engineering Graduate Student Association, Purdue University
2014	Panel Chair, Agricultural and Biological Engineering Symposium, Purdue University
2010-2011	President, Muslim Student Association, Purdue University Chapter
2009-2010	Grant writer, Engineers Without Borders, Purdue University Chapter

COMMUNITY INVOLVEMENT

2010-Current	Mentor/founder, ISGL Youth Group
2013-2014	Tutor, Lafayette Transition Housing
2011-2014	Educational Coordinator, ISGL Weekend School
2011	Teacher, ISGL Weekend School

LANGUAGES

Arabic – native
English – native

PROFESSIONAL MEMBERSHIP/AFFILIATIONS

Grain Elevator And Processing Society (GEAPS)
ASA-CSSA-SSSA
International Society for Agricultural Safety & Health (ISASH)
American Society of Agricultural and Biological Engineers (ASABE)