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Biomechanics of Patient Handling Slings Associated with Spinal Cord Injuries

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Biomechanics of Patient Handling Slings Associated with Spinal Cord Injuries

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
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Dedication

I dedicate this work to my family. They have been very supportive in me following my dreams and walking down my side paths along the way. Thank you for your continuous encouragement and support.

Acknowledgments

I would like to thank Dr. William Lee for providing me with an incredible amount of knowledge throughout my educational career at USF and introducing me to the VA Center of Excellence.

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Table of Contents

List of Tables

List of Figures

List of Equations

Abstract

Pressure ulcers and related skin integrity threats are a significant problem in current transfer/transport systems used for spinal cord injury patients. To understand this problem twenty-three different slings with varying type, material, and features were analyzed in hopes to identify at-risk areas for skin integrity threats such as pressure ulcers. Population samples included non-disabled (otherwise referred to as "healthy") volunteers as well as SCI patients from the James A. Haley Veterans Hospital. High resolution pressure interface mapping was utilized to directly measure the interface pressures between the patient and sling interface. Overall results provide relevant feedback on the systems used and to suggest a particular type of sling that might reduce and possibly minimize skin integrity threats as well as extend safe patient handling guidelines with sling use. It was found that the highest interface pressures convened along the seams of the sling, regardless of manufacturer or type.

Chapter 1. Background Information and Literature Review

1.1 Project Basis

The Paralyzed Veterans of America (PVA) noted that patient handling slings are more manageable for health care providers and staff compared to the alternative of lifting a patient manually (Alamgir 2009). However, investigations on whether or not the patient handling slings might be contra-indicated for vulnerable populations have been very limited. There is uncertainty whether slings may contribute to the development of pressure ulcers and other skin associated threats. This pilot study evaluates ceiling lift slings to assess different factors that may play a role in pressure ulcer development.

1.2 Introduction to Spinal Cord Injury Anatomy & Physiology

Spinal cord injuries (SCIs) are a major threat to the integrity and well being of a person's life. In the United States alone, there are approximately 10,000 to 12,000 new cases of spinal cord injury each year and fifty-five percent of new patients are between nineteen and thirty years of age (NINDS 2003). Understanding the body's functions and responses behind these types of injuries is currently being investigated to help the many victims who suffer from these injuries in hopes of decreasing related morbidity and mortality rates. This is important for obtaining knowledge about spinal cord injuries, but even more noteworthy for finding solutions for their management and therapy.

SCIs caused by trauma can be due to lateral bending, dislocation, rotation, axial loading, hyperflexion, or hyperextension (Bognamov 2009), as well as blunt trauma or blast injuries. The exceeding of normal range of motion in the spinal column can occur in a variety of injury-causing situations such as auto accidents. There can also be direct injury to the spinal cord in explosions, falls, war settings, and high impact sports accidents. There are four main sections of the spinal cord and they all may be affected by traumatic spinal cord injuries: the cervical, thoracic, lumbar, and sacral regions. When injuries arise to the cervical region, the upper limbs, the neck, and the diaphragm may be damaged or paralyzed. Thoracic region trauma generally damages the chest, core, and abdomen area, whereas the lumbar and sacral regions affect the lower limbs and excretion tracks. Each injury to a spinal cord region will affect that region as well as the regions below it. A brief description is summarized below in Figure 1 which was reproduced from the Spinal Injury Network (2009). Appendix A contains approval of copyright information for all re-used images.

Two main terms that are associated with SCIs are paraplegia and quadriplegia. These terms characterize whether a patient is paralyzed from the waist down or paralyzed in both arms and legs, respectively. SCIs can be diagnosed by using x-rays, computed tomography (CT), or magnetic resonance imaging (MRI). A functional independence measure (FIM), a neurological level of impairment (NLI), or a spinal cord injury model system (SCIMS) are a few examples of what may also be performed on the patient to try to assess their degree of injury. Spinal cord injuries are typically

categorized by the loss of motor and sensory functions and the zone in which they are absent.

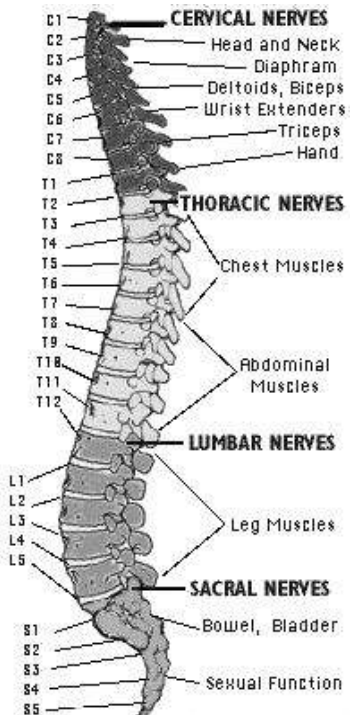

Figure 1: Summary of affected areas of the body associated with spinal cord injury regions

Most of the general public acknowledges the paralysis associated with a spinal cord injury. One must take note that SCIs don't only affect the motion and sensory of various parts of the body, but also the loss of control over units of the autonomic nervous system (ANS) and its control over other organs which plays a role in determining the severity of the injury and its classification. The ANS plays an important role in the body, as it constitutes involuntary functions such as heart rate, breathing, thermoregulation, and digestion. To illustrate this concept, one simple example of the cardiovascular and urinary systems relating to SCIs is depicted below in Figure 2. This diagram shows the parasympathetic and sympathetic cardiac innervations in red and in

blue, respectfully. The green lines symbolize the glossopharyngeal and the vagus nerves and the yellow lines represent the pudendal nerve. This picture was reproduced from Hagen et.al. of the article "Cardiovascular and urological dysfunction in spinal cord injury"(Hagen, Faerestrand et al. 2011). It is clearly shown that the upper thoracic vertebrae help to innervate the heart and the vertebrae T10 to L2 contribute to the urinary tract, in conjunction with the S2 to S4 vertebrae.

In an article by Bauman, a significant difference between lesions to the upper and lower spinal cord is presented. He declared that "In cervical and high thoracic transection (above T-6), cardiac sympathetic output is partially to completely ablated, while in those with lower cord injury, central sympathetic function remains intact but there is peripheral sympathetic denervation" (Bauman, Kahn et al. 1999). Most of the examples thus far have shown to follow this trend. Bauman also states how integrated the autonomic system is: "Regardless of the level of SCI, patients often display clinical disorders resulting from autonomic dysfunction, highlighting the importance of the relationship between the autonomic and cardiovascular systems in maintaining integrity and homeostasis" (Bauman, Kahn et al. 1999).

It is apparent why the autonomic nervous system is vital when properly understanding spinal cord injuries in patients. Besides the paralysis associated with spinal cord injuries, these patients have an increased risk of many chronic and acute complications. Not only is an understanding of the ANS essential to complete an accurate diagnosis of the injury, but also for developing an appropriate treatment and therapy plan. This must be handled in a timely manner to ensure decreased morbidity

and increased patient comfort. Increased morbidity can lead to risk of infection and an increase in costs (possibly prolonging the patient's initial hospital admission). Morbidity may also cause the need for additional surgical procedures during the current stay, or in the near future.

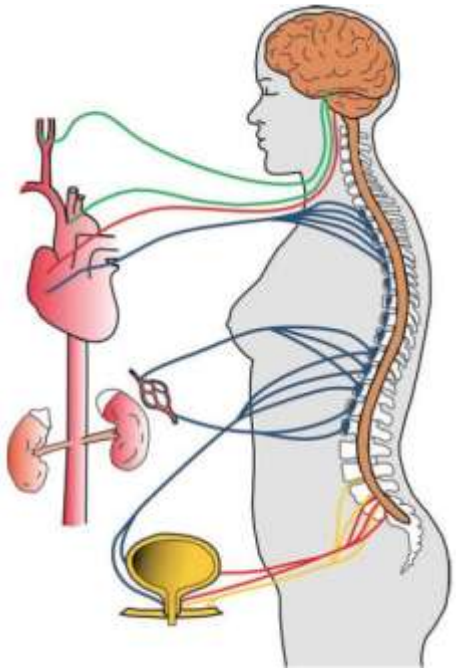

Figure 2: Autonomic system relationship of the cardiovascular and urinary systems to SCIs

These results can be seen as secondary damages or injuries, whereas primary injury is the initial physical impact or compression presented to the spinal cord. In Figure 3 below, an outline is shown of possible mechanism pathways that could be triggered (Dumont 2001). Dumont's diagram shows that once the primary injury is presented, both local and systemic pathways can be activated which leads to ischemia (a lack of blood supply in a specific area/tissue). Ischemia causes a decrease in oxygen and glucose levels, leading to less energy production and membrane depolarization within the cells. This membrane depolarization initiates an uptake of Calcium ions,

which give rise to increased concentration of intracellular Calcium. This increase can then cause mitochondrion damage, which can signal a permeability transition of Cytochrome C to be released, activating Calpain and Caspase, which play a role in protocolysis and cytoskeletal damage, finally leading to apoptosis (programmed cell death) and ultimately a non-reversible cellular necrosis.

There are many other side paths that can be taken in this one example and some even incorporate feedback loops (Dumont 2001). For example, the increase in intracellular Calcium concentration can bring about vasospasm, which will cause additional ischemia. Or, decreased Oxygen and Glucose levels cause cellular swelling and therefore also contribute to ischemia. Other common secondary injuries relayed from SCIs include, but are not limited to excitotoxicity, release of free radicals, axon damage, respiratory damage, hemorrhage, neurogenic shock, restricted blood flow, and other dysfunctional issues of the organ systems (NINDS 2003). Human physiology is indeed complex.

Numerous treatments for paralysis are currently being investigated. Many are still in the research phase, but are exhibiting interesting results. Recent advances have led to better treatments for function restoration and improvement in the quality of life of paralyzed patients. It is only a matter of time before a medically appropriate solution is presented for paralysis, as well as other complications, associated with spinal cord injuries. One aspect is currently being investigated by NSC (Neuro Synthetic Conduction) Therapy. Their therapy stimulates any remaining dormant nerve cells to create action potentials (Bryant 2011). After a few treatments, it is presumed that the

brain re-understands that the limbs exist, takes control, and the ability for voluntary movement is thereby increased.

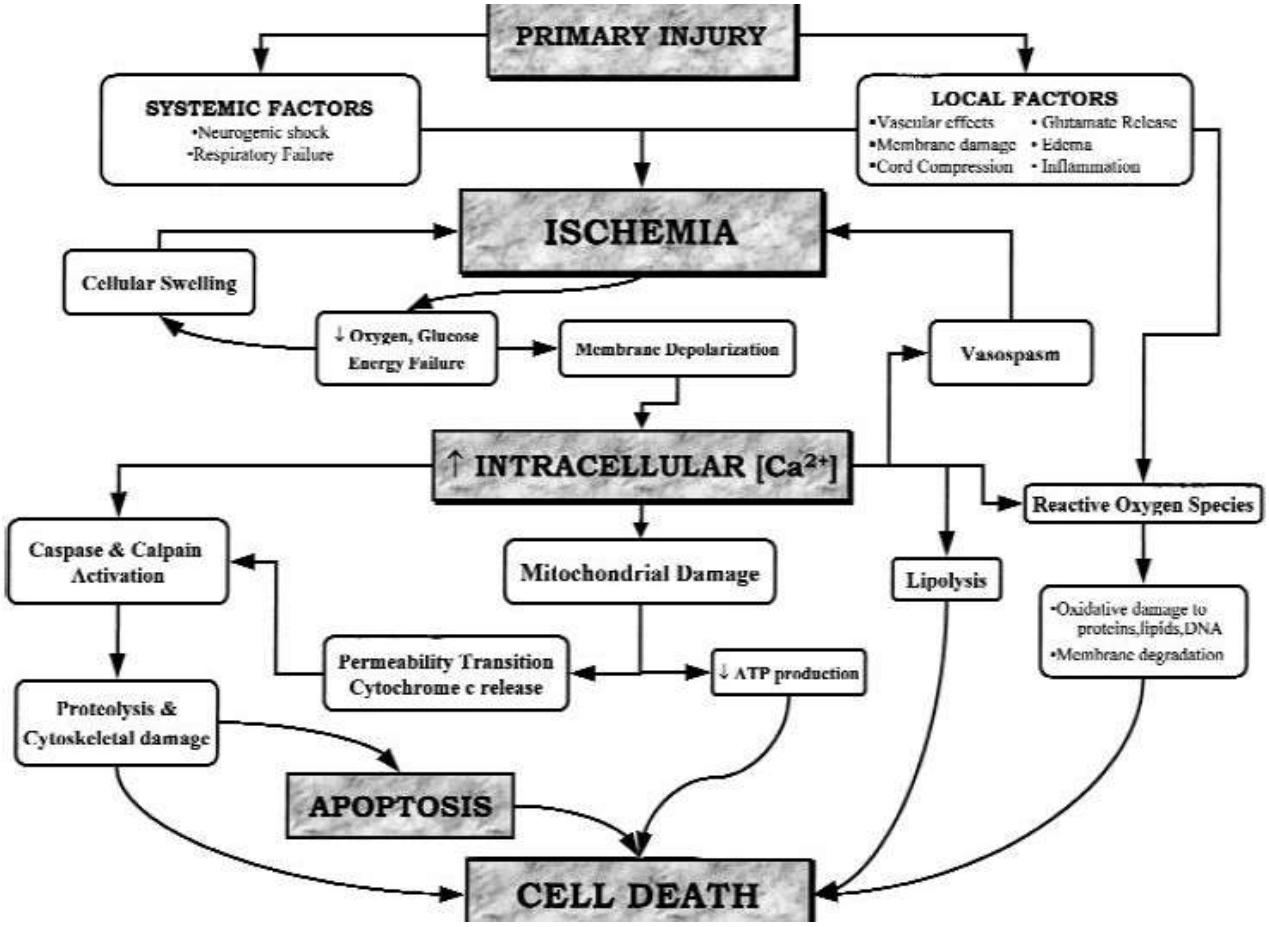

Figure 3: A few possible mechanism pathways following primary spinal cord injury

Another aspect of this type of research is through bionics. Todd Tuiken is a featured surgeon/biomedical engineer on TED Talks who uses remaining nerves to link brain impulses to a prosthetic limb (Kuiken 2011). He essentially re-links the nervous system to move a limb and experience the associated sensation known as targeted muscle reinnervation. Additional examples include an experimental treatment of adding

a stimulator into the spinal cord (Pearson 2011) and stem cell therapy where autologous adult stem cells are injected to a localized area (ChaitanyaHospital 2012).

1.3 Background on Pressure Ulcers

A common morbidity for SCI patients is the formation of pressure ulcers. Pressure ulcers are formed by a combination of shear and normal pressure forces between two surfaces (i.e. interface pressure). The risk of ulceration is increased when high pressures are experienced over prolonged periods of time. For example, since SCI patients may also present cognitive impairments, they may not understand the need to shift their body weight periodically and may not be aware of and/or capable of relieving areas of high pressures due to the sensory losses they have experienced.

It was originally believed that pressure ulcers could be avoided by implementing patient repositioning as a standard of care. There are now different protocols for manually turning or repositioning SCI patients, with a common standard of repositioning every two to four hours. A recent study showed that this was not effective even if performed correctly because areas at risk were not properly unloaded. The investigators proposed that more research be performed on the use of support materials to sustain the patient while in lateral positions (Peterson 2010).

Though it is well known that high interface pressures should be avoided, an evidence-based threshold has yet to be implemented because of the extreme variability between individuals. One value that has been referenced in similar scenarios is the average capillary closing pressure. Some researchers believe that if the pressure exceeds the capillary closing pressure within the body (averaged at 32 mmHg) that

ulcers will form due to compromised blood flow to the surrounding tissues (Burk 2011). Pressures considerably over 40 mmHg should be avoided as much as possible to prevent tissue damage.

These peak pressures ordinarily reside over bony prominences, where pressure ulcers commonly develop, primarily at the sacrum, coccyx, and ischial tuberosities which are located in the gluteal and sacral regions (Peterson 2009). Approximately eighty percent of all SCI patients encounter some type of pressure ulcer in their lifetime (Gupta 2012). Besides the corporal disadvantage associated with pressure ulcers, an article from the Wound Practice and Research journal states that they are the "most expensive medical error in the USA, costing US$3.9 billion per year" (Asimus 2011).

Pressure ulcers range in severity and are classified by stages, ranging from Stage I having a discoloration and softness, to a Stage IV having full-thickness tissue loss (which may expose bone, tendon, or muscle)(Asimus 2011). A summary of each stage is shown below in Table 1, reproduced from Asimus' article (Asimus 2011) and the National Pressure Ulcer Advisory Panel (NPUAP 2009).

Skin tears are another threat to skin integrity in which 18% of cases are associated with patient transfers (Krasner 2010). Tears are known by the separation of the dermis and epidermis skin layers commonly on the extremities of the patients and are "acute partial thickness wounds" (Edwards 1998).

Table 1: Pressure ulcer classification

Suspected Deep Tissue Injury	Purple or maroon localized area of discolored intact skin or blood-filled blister due to damage of underlying soft tissue from pressure and/or shear. The area may be preceded by tissue that is painful, firm, mushy, boggy, warmer or cooler as compared to adjacent tissue
Stage I – Non-blanchable redness of intact skin	Intact skin with non-blanchable redness of a localized area usually over a bony prominence. The area may be painful, firm, soft, warmer or cooler as compared to adjacent tissue.
Stage II – Partial thickness skin loss or blister	Partial thickness of dermis presenting as a shallow open ulcer with a red-pink wound bed, without slough. May also present as an intact or open/ruptured serum-filled blister.
Stage III – Full thickness skin loss (fat visible)	Full thickness tissue loss. Subcutaneous fat may be visible but bone, tendon, or muscle is not exposed.
Stage IV – Full thickness tissue loss (muscle/bone visible)	Full-thickness tissue loss with exposed bone, tendon, or muscle. Slough or eschar may be present.
Unstageable	Full thickness tissue loss in which actual depth of the ulcer is completely obscured by slough and/or eschar in the wound bed. Until enough slough and/or eschar are removed to expose the base of the wound, the true depth cannot be determined; but it will be either a Category/Stage III or IV

1.4 Patient Lift Categories

Patient lift systems were implemented into the healthcare setting when research had revealed that a leading cause of work related injuries was associated with patient handling tasks (Alamgir 2009). It was found that "one in every three nurses becomes injured from the physical exertion put forth while moving non-ambulatory patients" and "one in two non-ambulatory patients falls to the floor and becomes injured when being

transferred from a bed to a wheelchair" (Bostelman 2008). Using patient lift systems correctly helps to eliminate both patient falls from transfers and work related injuries.

There are various types of patient lift systems available for health care settings to choose from. The most common are listed below in Table 2, which also includes advantages and disadvantages of each type of system. This table was reproduced from the article "Patient Lifts: Balancing Safety with Recovery" (Studer 2012).

Table 2: Patient lift systems and their advantages and disadvantages

	Floor or Mobile Lift	Ceiling Lift	Stand Assist Lift	Wall Lift
Advantages	-Available from any transfer position -Non weight bearing -Toileting and hygiene possible	-No physical lift or manual crank needed -Reduce staff workload	-Rehabilitative nature with upright mobility -No sling required	-Less space -Reliable -Shower friendly -More readily installed than ceiling lifts
Disadvantages	-Difficult with carpet, thresholds, or bariatric patients -Manual crank requiring great workload from staff	-Limited by track -High costs	-Patient must sit up without assistance -Not used for toileting -Not weight bearing -Difficult with carpet or bariatric patients -Difficult for unilateral or bilateral amputees	-One wall installation with limited range -High costs

As Table 2 indicates, there are many advantages and disadvantages to each lift system currently available. It is important to consider many extrinsic (environmental) and intrinsic (patient-based) factors when choosing which system to use. For example, if the patient is paraplegic or quadriplegic, it would be a poor choice to purchase a stand assist lift system. For this study, only ceiling lifts will be investigated.

The risk of high pressures for this already vulnerable population is known to increase when utilizing patient lift systems (Peterson 2008). An example of a volunteer from this study seated in a wheelchair both without and with a sling beneath the subject is shown below in Figure 4. This provides a direct comparison between the two scenarios with the scale ranging from 0 to 200 mmHg. The high pressure areas on the right figure are a result of the seams on the sling.

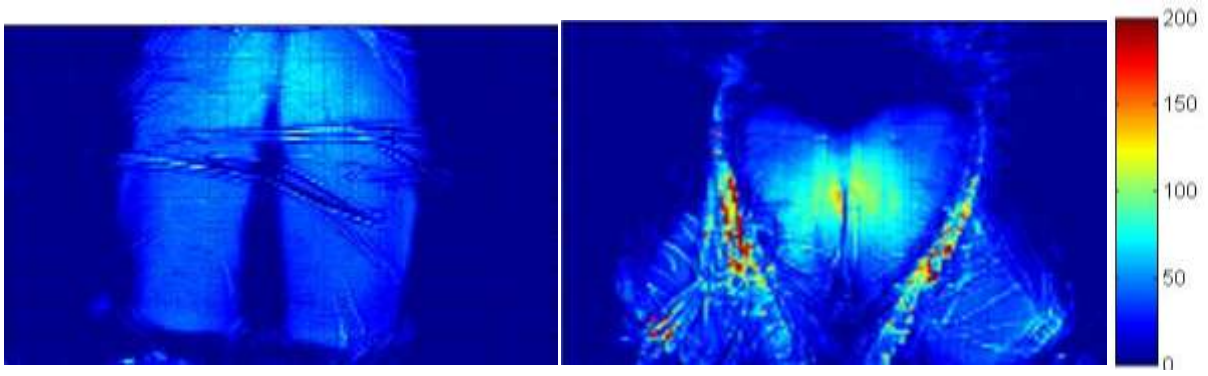

Figure 4: Comparison of a subject seated in a wheelchair without (left) and with (right) a sling beneath the subject.

Chapter 2. Research Methods and Techniques

2.1 Instrumentation

The products of three sling manufacturers were investigated: ArjoHuntleigh (Addison, IL), Guldmann (Tampa, FL), and Liko (Batesville, IN). These were selected because they are the most commonly used manufacturers at the James A. Haley VA Hospital. Two different types of slings were analyzed: seated slings and supine slings. Different slings were chosen to vary the sling manufacturer, material, and features. The study included a total of twenty-three slings; eighteen seated slings and five supine slings, which are documented below in Table 3 and Table 4. All slings are size L (L/XL) and can support up to 200 kg. It is important to note that since this is a pilot study, not every sling possibility was tested but rather a comparison made between commonly used products.

The ceiling lift consisted of an Arjo Maxi Sky 600 lift system with a lift capacity of 272 kilograms, equipped with a 2-Dimensional track system and a handset control. Either a 2-point spreader bar or an 8-point spreader bar was attached to the Maxi Sky depending on which type of sling was currently being used (2-point for seated slings, 8-point for supine slings). All instrumentation is shown in Figure 5, Figure 6, Figure 7, and Figure 8 below.

Table 3: Seated slings analyzed during study.

SLING	ABBREVIATION	MANUFACTURER	MATERIAL	FEATURE
General purpose loop sling with head support	A	ArjoHuntleigh	Polyester	
Toilet sling with head support	B	ArjoHuntleigh	Polyester	
Mesh sling with head support	C	ArjoHuntleigh	Polyester	Hygienic
Large hammock sling	D	ArjoHuntleigh	Polyester	
Loop flites	E	ArjoHuntleigh	Polyester	Disposable
Active micro plus	F	Guldmann	Polyester	
Basic basic sling	G	Guldmann	Polyester	
Basic basic sling	H	Guldmann	Polyester Net	Hygienic
Basic high	I	Guldmann	Polyester	
Basic high	J	Guldmann	Polyester Net	Hygienic
Uni-D	K	Guldmann	Nylon	
Uni-D high back	L	Guldmann	Nylon	
Uni-D high back Disposable	M	Guldmann	Polyester	Disposable
Original highback	N	Liko	Polyester	
Original highback	O	Liko	Plastic Coated Net	Hygienic
Universal sling	P	Liko	Polyester	
Universal sling	Q	Liko	Plastic Coated Net	Hygienic
Solo Highback	R	Liko	Non-Woven Polypropylene	Disposable

Table 4: Supine slings analyzed during study

SLING	ABBREVIATION	MANUFACTURER	MATERIAL	FEATURE
Repositioning sling with stretched frame	S1	ArjoHuntleigh	Polyester	
Stretcher sling	S2	ArjoHuntleigh	Polyester	
Disposable repositioning with horizontal lifting support	S3	Guldmann	Polyester	Disposable
Octo lift sheet with Octo stretch	S4	Liko	Polyester	
Repositioning sheet	S5	Liko	Polyester, Cotton	

The sensor array that was used was a High Resolution Pressure Mapping System (X3 PRO, XSENSOR Technology Corporation, Calgary, Canada) with array dimensions of 20" by 32" housing 100 x 160 sensors. It has a calibrated range from 10 to 200 mmHg, a resolution of 0.2", a sensor delay in the range of milliseconds, and an accuracy of ±10%. Additional product specifications are shown in Appendix D. The data was recorded at 5 Hz through a computer interface into X3 PRO v6.0 from the X3 Technology Series Pressure Imaging Software by XSENSOR. This frequency was chosen to accommodate the lifting process and receive a smooth transition of both static and dynamic changes. The sampling frequency should be greater than the delay time but still have a good representation of the real data. The equipment was capable of recording at higher frequencies, but since results were based on stable positions and

not musculoskeletal twitches, the data would have been too cumbersome with no extra beneficial information.

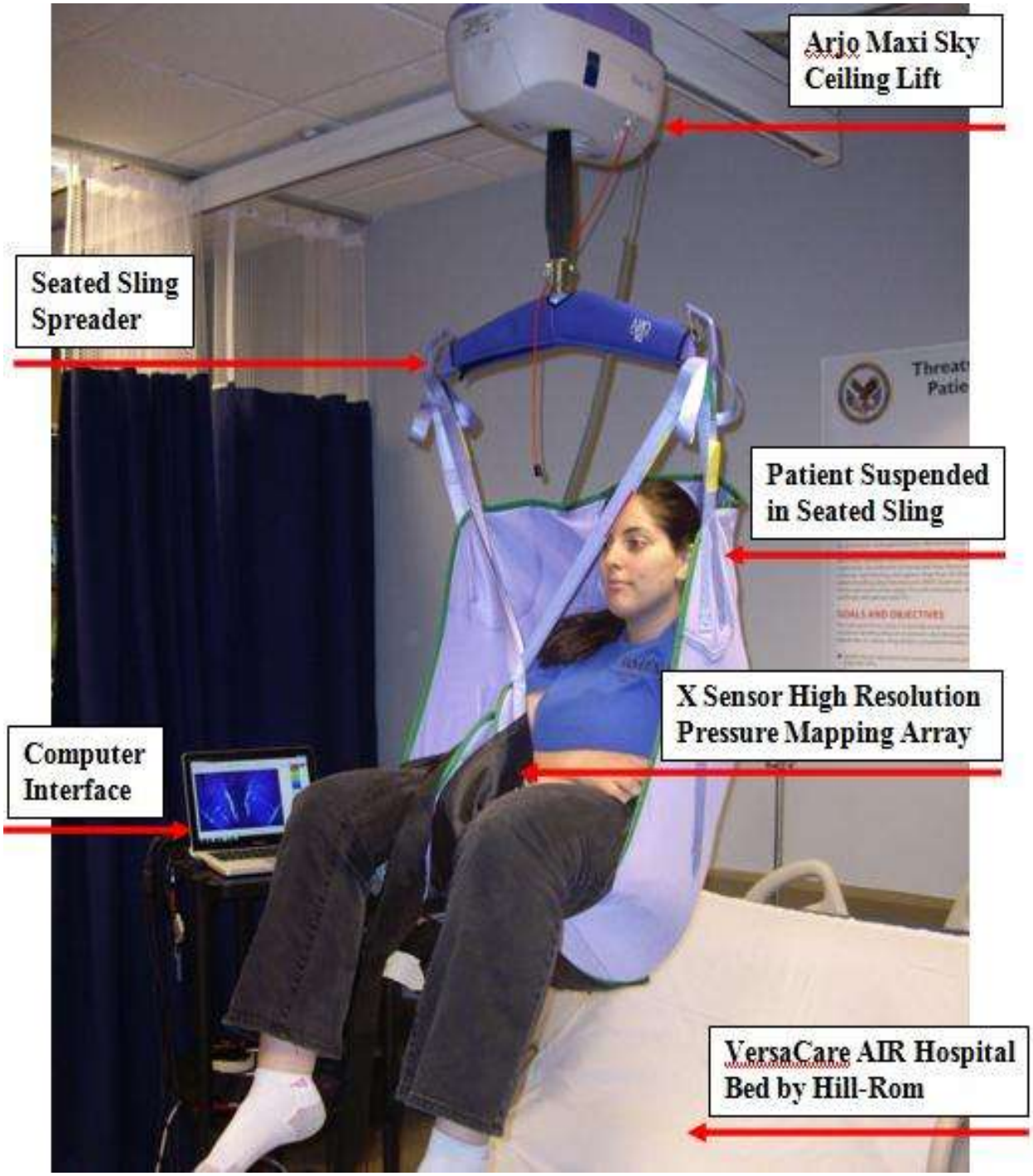

Figure 5: Instrumentation for a seated sling

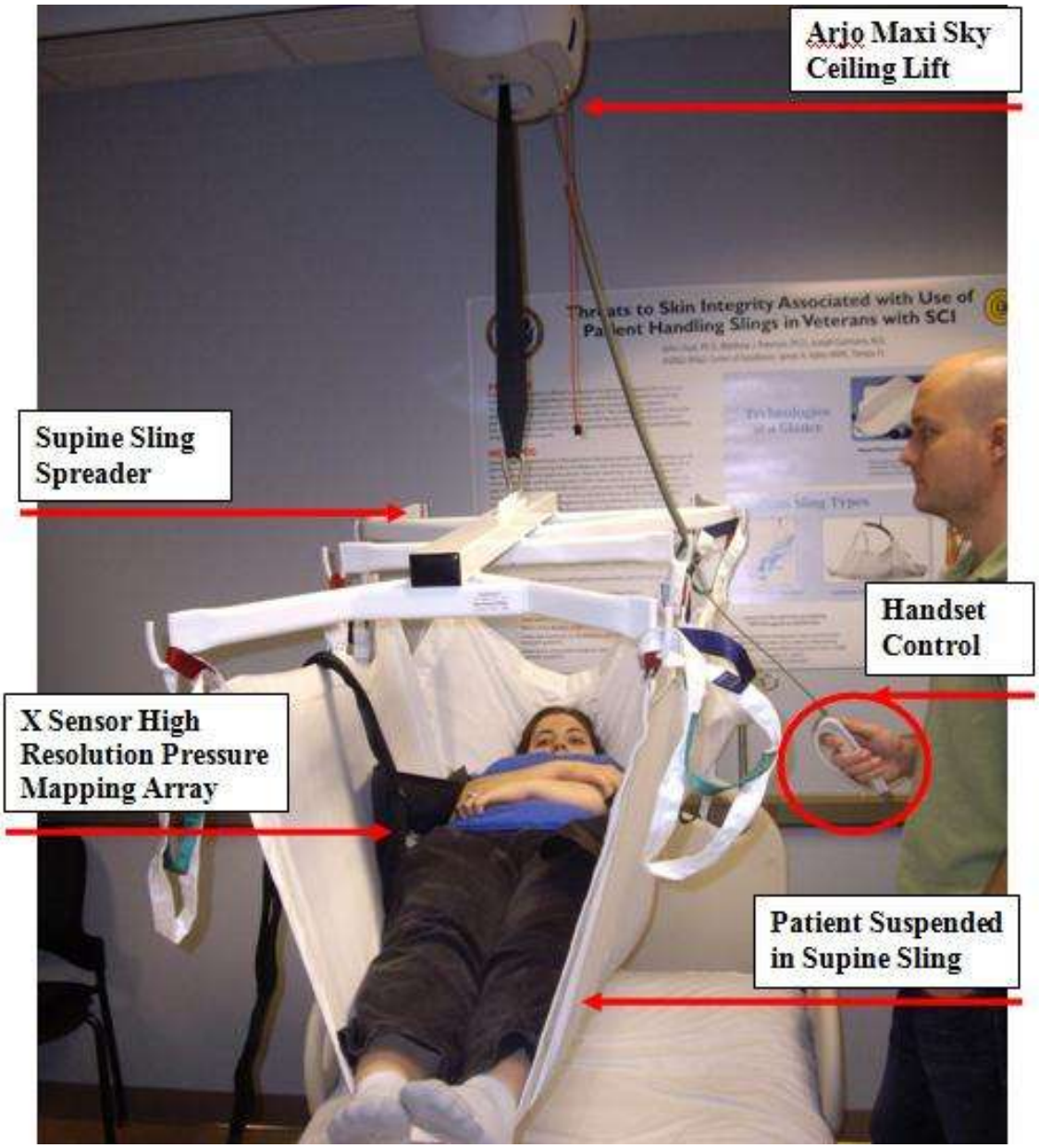

Figure 6: Instrumentation for a supine sling, not including computer interface.

The hospital bed used in this study was a VersaCare AIR by Hill-Rom (Batesville, IN). When transferring with the seated slings, all subjects were transferred from the bed to a Quickie GPV Wheelchair, with a weight capacity of 113 kilograms and an Invacare (Elyria, OH) absolute removable cushion of height 5.7 centimeters. This

equipment was selected to control the variables within the study based on standard use. Equipment specifications are documented in Appendix D.

Figure 7: XSENSOR high resolution pressure array

Figure 8: Quickie wheelchair used for study

2.2 Participants

2.2.1 Inclusion and Exclusion Criteria

Both healthy volunteers and spinal cord injury patients make up the human participant groups in this study. The SCI sample size was smaller than the desired n=15 participants due to recruitment challenges, but this is a pilot study that will be used as a basis of information for further investigation. The study was approved by both the VA and USF IRB prior to initiation. All participants were mentally and physically assessed based on the criteria below by a physician at the James A. Haley Veteran's Hospital prior to enrollment into the study.

1. Inclusion Criteria: All study participants were competent adults between the ages of 18 and 65, without any medical conditions that would prevent them from participating in the study.
2. Additional Inclusion Criteria for SCI Patients: All SCI patients were enrolled in the James A. Haley Veteran's Hospital (JAHVH) SCI Registry from the Spinal Cord Injury & Disorders (SCI/D) units in Tampa, Florida. Current inpatient participants were enrolled upon initiation of the study. Additional participants were recruited on admission for their hospital stay or outpatient clinical visit.
3. Exclusion Criteria: We excluded those participants who are medically or physically unable to perform the data collection protocol and those who exceeded 180 kg (or 400 lbs). This weight threshold was 90% of the slings' weight limit.

2.2.2 Screening and Selection of Study Participants

1. Recruitment of all study participants was by poster advertisements and word of mouth. SCI patients required both a form of Informed Consent and HIPAA.
2. Informed consent was obtained upon initiation of the study, with full detail of the likelihood and severity of potential risks to study participants during the study. Consent was obtained by the research team and occurred at JAHVH or the COE. Consent was obtained in a private place and family members or friends were present only if the participant wished and agreed. This study involved minimal risk since the participants were exposed to sling installation/removal, sitting/lying on the sling, and transfer/transport procedures, none of which are beyond the scope of what is currently being conducted in the daily activities of a person with SCI. Procedures for minimizing potential risks included making certain the participants understood the activity requirements of the protocol and that they were willing to participate.
3. Prior to the study, all participants were evaluated by on-site personnel to verify that inclusion/exclusion criteria were met as well as any additional requirements (such as Informed Consent).

2.2.3 Participant Information

All participants received a pamphlet on volunteering in research within the Veterans Health Administration and were required to complete both an Informed Consent form as well as a HIPAA Privacy Act form prior to commencement of any data collection. For the research team's analysis, a Medical Records form was completed by

each volunteer, a copy of which is presented in Appendix E. Immediately after each sling use, a Sling Questionnaire was answered by the participant. This could have been completed with the help of a member of the research team if needed. This form is documented in Appendix F.

The healthy volunteer population consisted of four healthy adults (three men and one woman). Participants aged from their 20s to 40s by decade with heights ranging from 1.70 m to 1.83 m (1.75 m ± 0.06 m), and masses from 59.1 kg to 87.3 kg (76.9 kg ± 12.6 kg). Their BMIs ranged from 20.4 to 28.4 (25.2 ± 3.4).

The SCI veterans population also consisted of four adults (three men and one woman). Participants aged from their 30s to 50s by decade with heights ranging from 1.68 m to 1.91 m (1.76 m ± 0.10 m), and masses from 61.2 kg to 104.8 kg (79.2 kg ± 18.3 kg). Their BMIs ranged from 20.5 to 37.3 (25.9 ± 7.8). The ages were recorded by decade rather than by year to limit the PHI (protected health information) for the vulnerable population.

The sample size of veterans with SCI was decreased from the original number of six due to two problems (though not adverse events). One subject with paraplegia (with motor and sensory skills in both arms) decided not to participate after realizing that a ceiling lift and patient handling slings would be used for transfers, as they avoid slings due to previous skin integrity issues. Another subject signed up to participate in the study did not show up to the recording time set and the research team was not able to contact him/her. In both cases, the subjects were scheduled to participate but did not sign an Informed Consent and therefore were not enrolled into the study.

2.3 Research Team

The research team consisted of qualified individuals who have been approved by the Veterans Affairs Association as well as the IRB. This list included engineers, researchers, nurse practitioners, and certified physicians. All members of the evaluation staff are centered in the HSR&D/RR&D Center of Excellence: Maximizing Rehabilitation Outcomes at the Tampa VA Hospital.

2.4 Data Collection Protocol

Two different procedures were used, one for the seated slings and one for the supine slings. Data collection with each seated sling took approximately thirty minutes. There were also five distinct positions associated with the seated slings and three positions for the supine slings that were used in the data analysis and are defined in the procedural steps below. The procedure for evaluation of a seated sling includes the following (all recordings take were with regards to pressure data in mmHg):

1. Set up the sling evenly on the bed with the pressure array placed on top of the sling to cover the buttocks and femurs.
2. Begin the data collection through the X3 PRO v6.0 equipment by opening a new file and pressing the record button.
3. Ask the subject to transfer onto the bed if capable, or transfer them from their wheelchair to the bed using an extra sling. If the latter task is performed, remove the extra sling from beneath the subject once they are lying on the bed. To execute this task, roll the subject to one side, bunch up the sling beneath them towards their median plane, roll the subject to the opposite side, and slide the sling out. Have

them lie on the bed in the supine position with zero degree head of bed (HOB). This is the "supine" position.

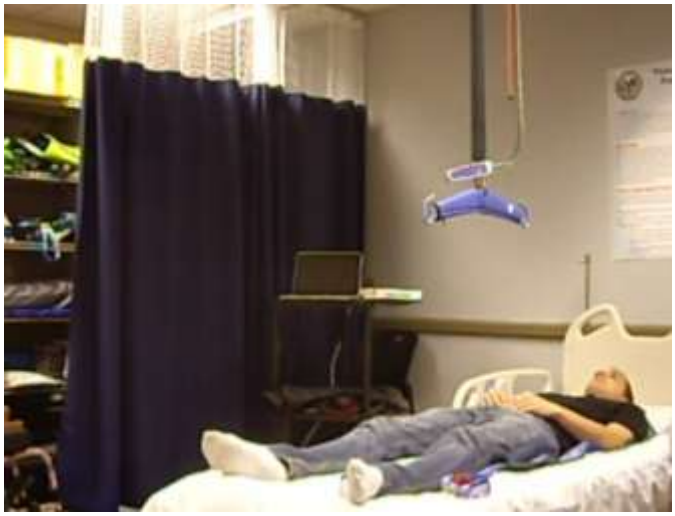

Figure 9: Seated protocol - supine position

4. Record the XSensor interface pressures for approximately two or more minutes while in a stable position.
5. Raise the head of bed thirty degrees by use of the electronic controls provided and record pressure measurements for another two minutes.

Figure 10: Seated protocol - raise HOB to 30 degrees

6. Install the sling to the ceiling lift seated spreader bar by first attaching the upper sling straps. Next lift the subject's legs one at a time to bring the lower sling straps toward the midline of the body. Cross the lower straps by inserting one through the other and attach to the spreader bar on the opposite side. Make sure the subject is correctly placed in the sling to prevent slippage or a fall.

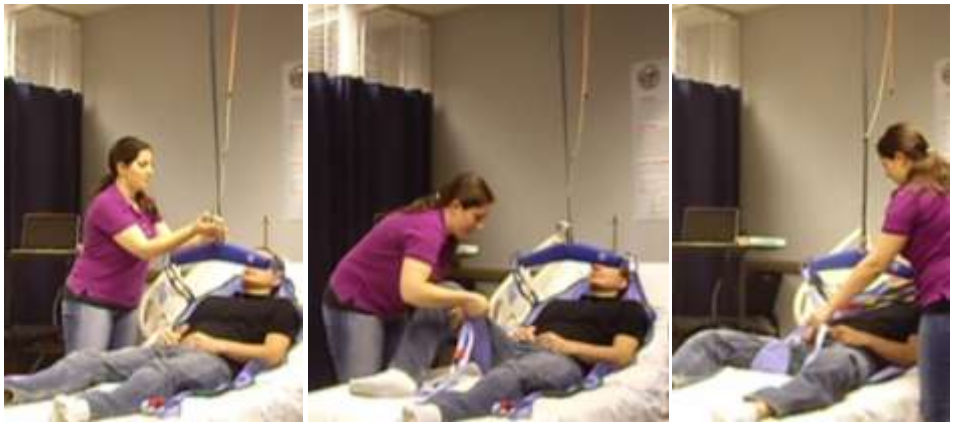

Figure 11: Seated protocol - install sling on 2 point spreader bar

7. Carefully lift the subject from the bed using the ceiling lift handset control.

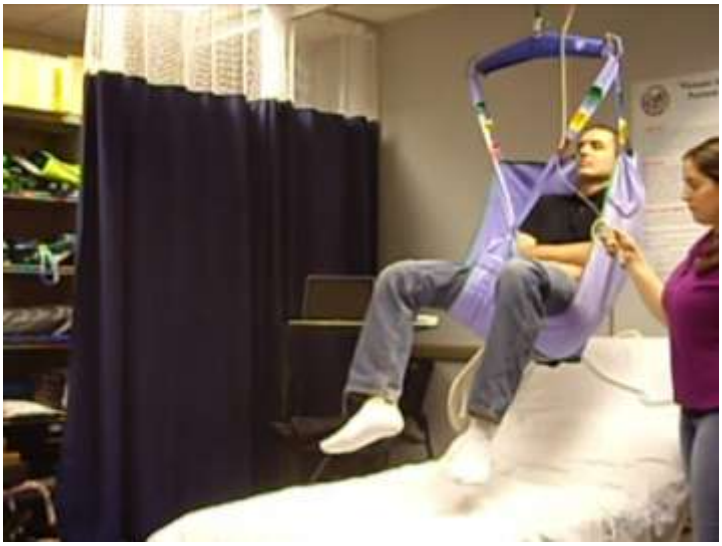

Figure 12: Seated protocol - lift subject from bed

8. Move the ceiling lift from the bed over to the wheelchair by means of the handset control as well as the sliding track. Record an additional five minutes of pressure data while the subject is still suspended above the wheelchair. This position is defined as "suspended to chair".

Figure 13: Seated protocol - suspended to chair position

9. Lower the subject into the wheelchair. If multiple staff are present, slightly tip the wheelchair backwards (will vary by subject – try to get buttocks to the back of the chair), lightly push on the subject's knees, and lower the sling with the handset control. Ensure that the subject's back is resting comfortably on the back of the wheelchair to prevent them from falling.

Figure 14: Seated protocol - lower subject into wheelchair

10. Record for five minutes while the subject is seated in the wheelchair ("seated" position).

Figure 15: Seated protocol - seated position

11. Carefully lift the subject back into suspension from the wheelchair.
12. Move the ceiling lift from the wheelchair to the bed ("suspended to bed" position). There is no need to record this position for five minutes since it will provide similar results as the "suspended to chair" position.
13. Lower the subject down onto the bed. Un-install the sling from the spreader bar of the ceiling lift and move the leg straps of the sling from underneath the subject to the side of the bed, smoothing out any apparent creases. Have them lay supine with HOB still raised thirty degrees and record for five minutes ("supine 30" position).

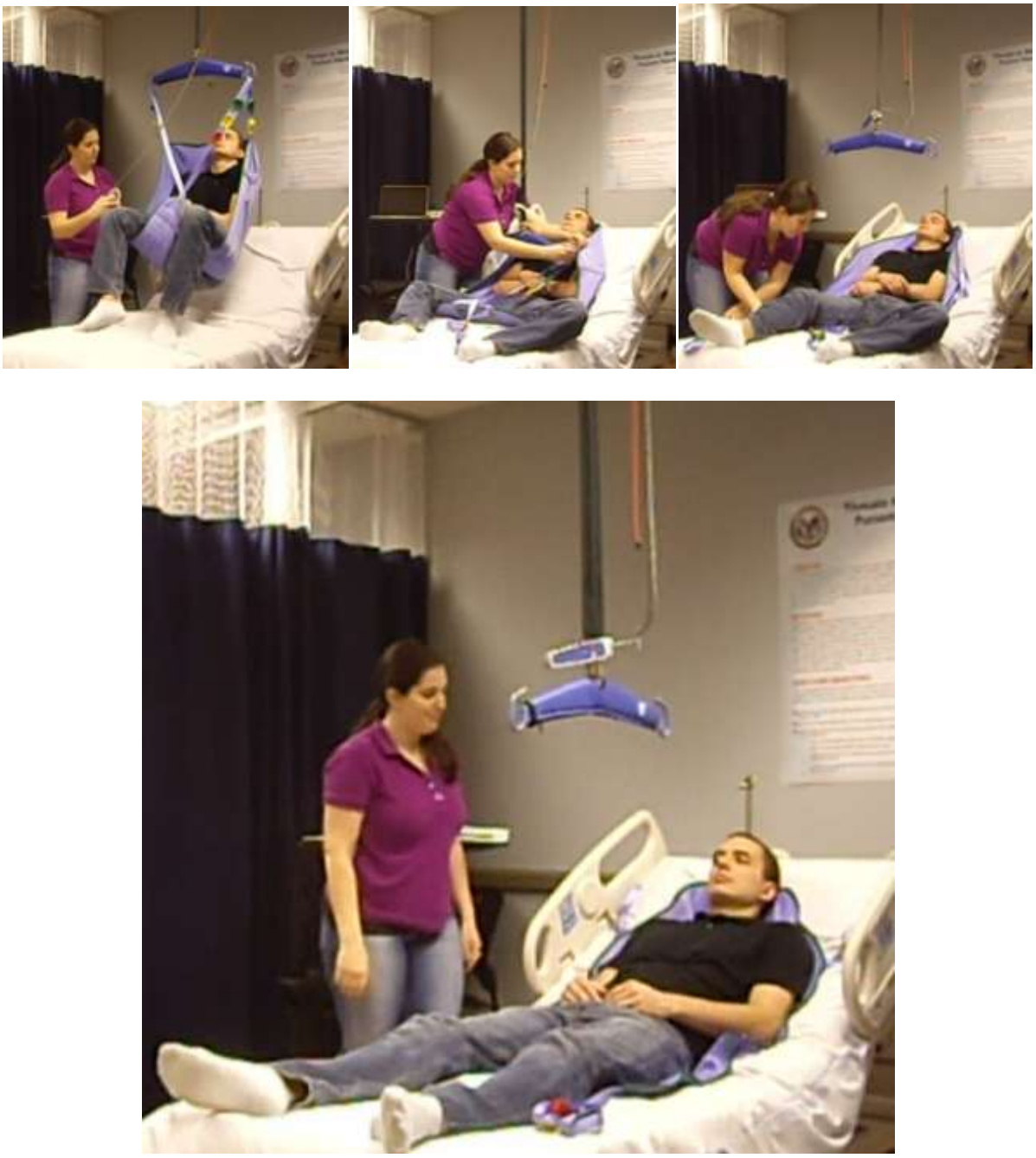

Figure 16: Seated protocol - lower subject to bed, un-install sling, remove straps, and have subject continue to lie in supine 30 position

14. Terminate the data collection, save the XSensor file labeled by the subject number and sling name, and complete the sling questionnaire documented in Appendix F. A

sample of the XSensor outputs for each position defined above is shown below in Figure 17.

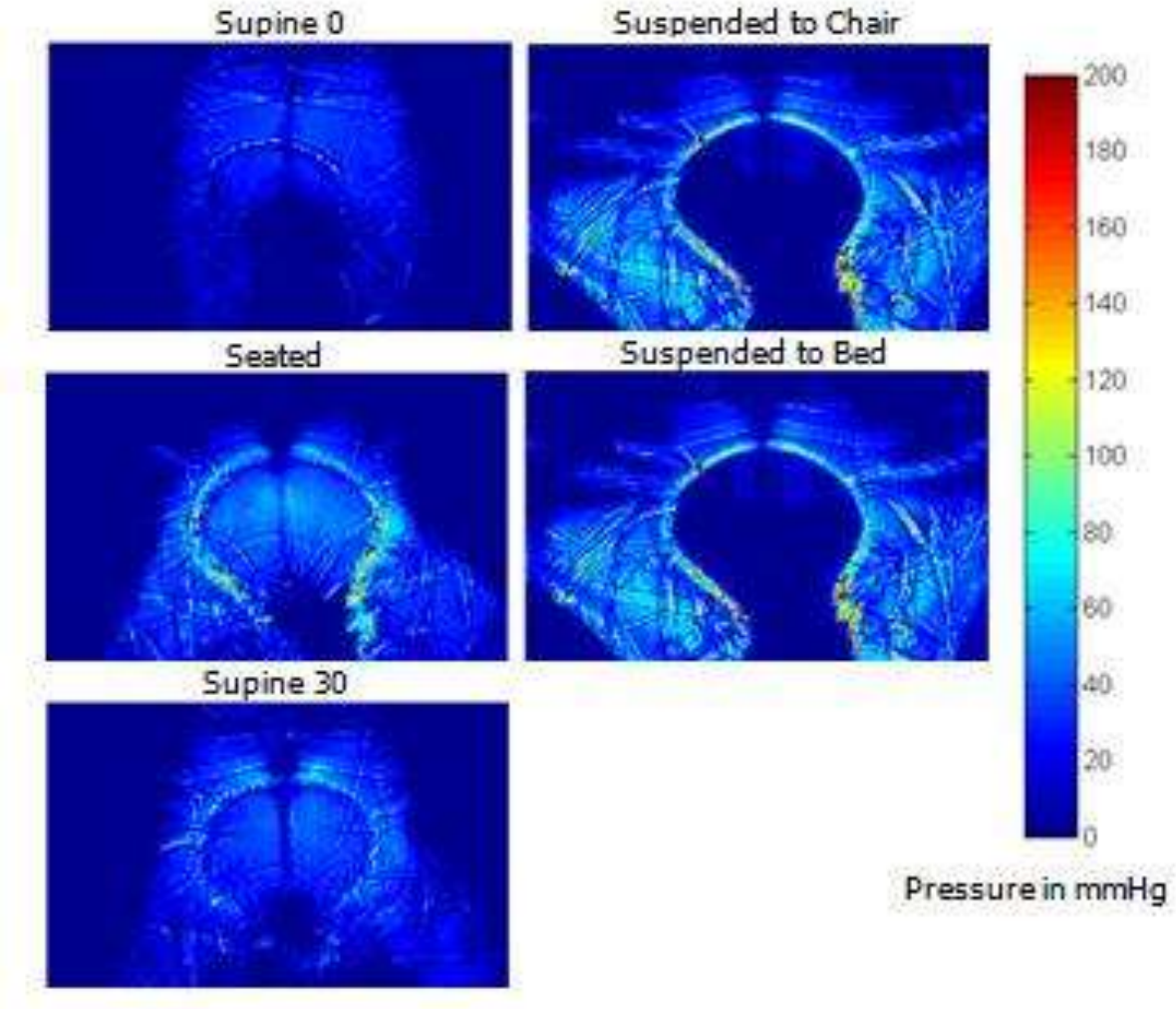

Figure 17: Example interface pressure contours for each position of a seated sling (sling D)

For the supine slings, an alternate procedure was used and took approximately fifteen minutes per sling.

1. Set up the sling evenly on the bed with the pressure array placed on top of the sling to cover the buttocks and femurs.

2. Begin the data collection through the X3 PRO v6.0 equipment by opening a new file and pressing the record button.
3. Ask subject to transfer onto the bed if capable, or transfer them from their wheel chair to the bed using an extra sling. If the latter task is performed, remove the extra sling from beneath the subject once they are lying on the bed. To execute this task, roll the subject to one side, bunch up the sling beneath them towards their median plane, roll the subject to the opposite side, and slide the sling out. Have them lie on the bed in the supine position with zero degree head of bed (HOB). This is the "supine beginning" position.

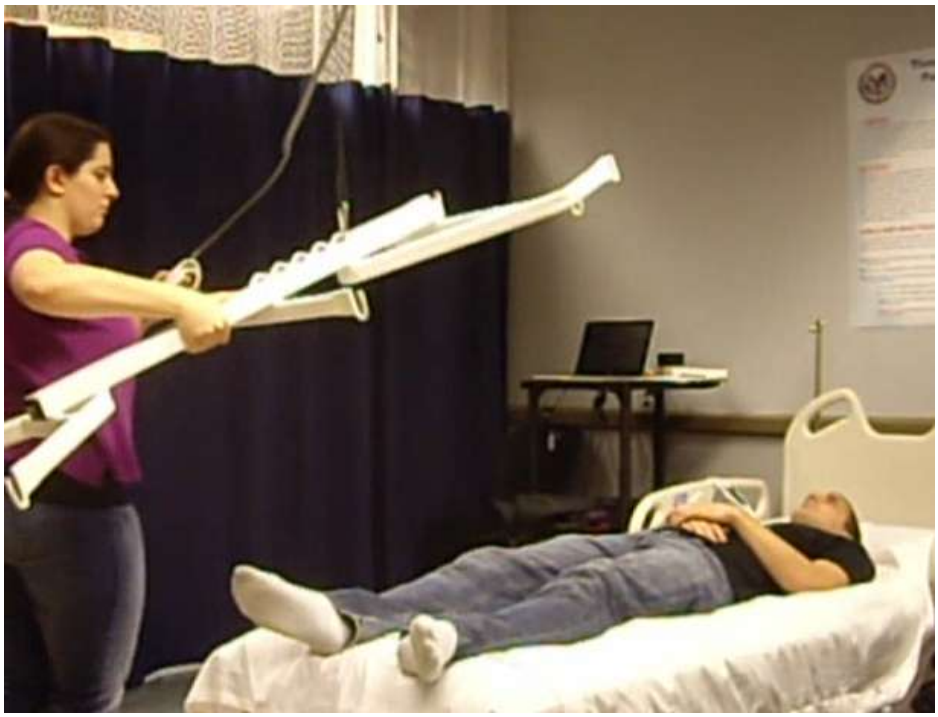

Figure 18: Supine protocol - supine position

4. Record the XSensor interface pressures in this supine position for five minutes.

5. Install the sling to the ceiling lift supine (8 point) spreader bar by attaching each sling loop to the corresponding handle on the spreader while another staff member holds the spreader bar directly above the subject. Make sure the subject is correctly placed in the sling to prevent slippage or a fall.

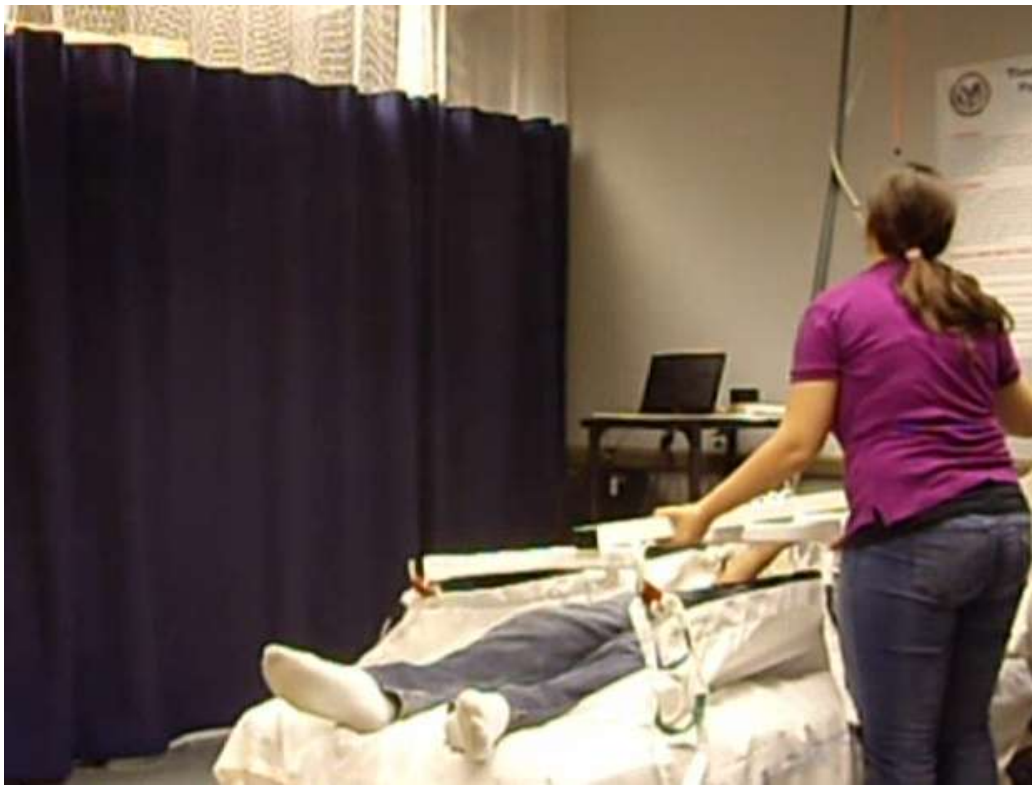

Figure 19: Supine protocol - install sling to spreader bar

6. Carefully lift the subject from the bed using the ceiling lift handset control. Make sure the subject is comfortable while being lifted and that they remain parallel with the floor.
7. Move the ceiling lift from the bed over to the side of the bed by means of the handset control as well as the sliding track. Record an additional five minutes while the subject is suspended next to the bed ("suspended" position).

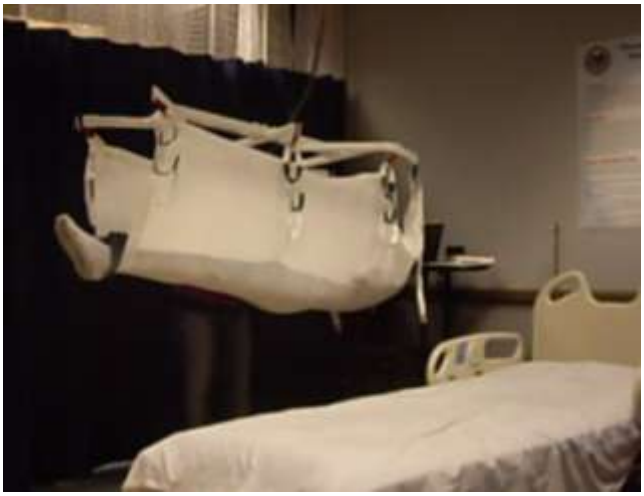

Figure 20: Supine protocol - suspended position

8. Move the ceiling lift back above the bed.
9. Lower the subject down onto the bed. Un-install the sling from the spreader bar of the ceiling lift ("supine end" position).

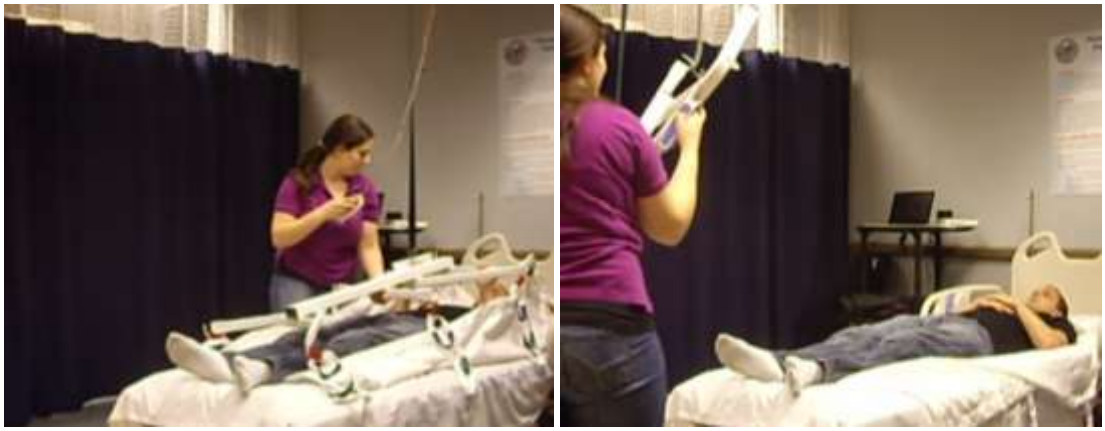

Figure 21: Supine protocol - un-install sling and have subject continue to lie in supine position

10. Record XSensor interface pressures for five minutes.
11. Terminate the data collection, save the XSensor file labeled by the subject number and sling name, and complete the sling questionnaire documented in Appendix F.

A sample of the XSensor outputs for each position defined above is shown below in Figure 22.

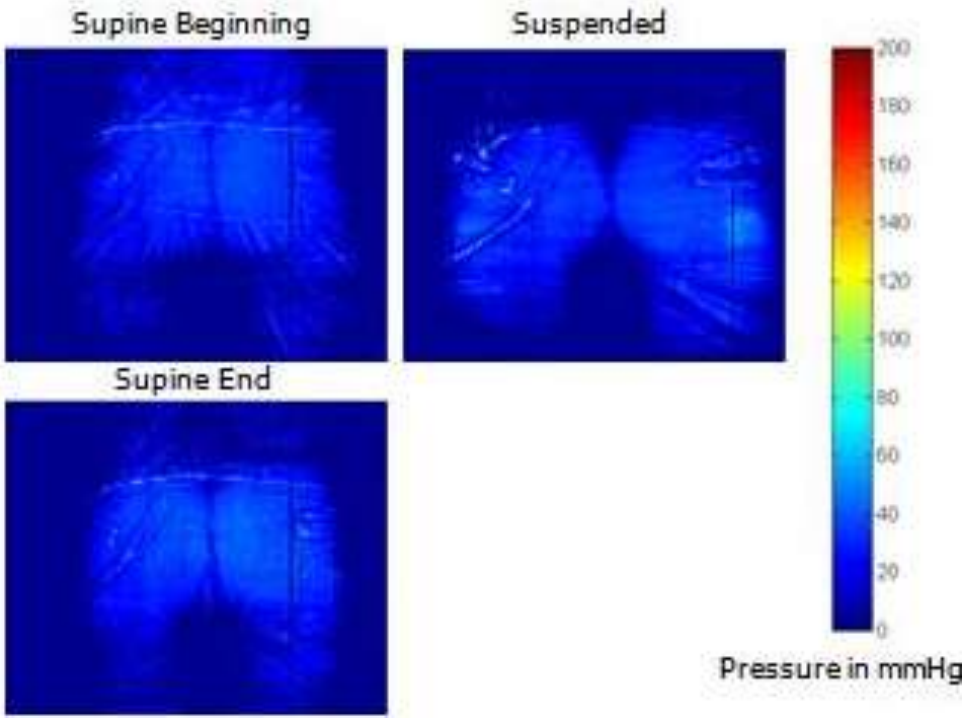

Figure 22: Example interface pressure contours for each position of a supine sling (sling S3)

Between the seated and supine slings, a typical data collection for one healthy subject could run from ten to eleven hours. Due to the extensive time frame per subject, data collection was divided into segments and completed over multiple days. All slings previously listed (Table 3) were analyzed with the healthy participants. After analysis of each sling with each healthy subject, the list was reduced from twenty-three to five slings (four seated and one supine sling). This reduction was to be more sensible with the vulnerable population. A data collection of five slings for a SCI subject ranged from two to four and a half hours depending on the subject's level of injury and was completed in one session for each subject.

Chapter 3. Data Analysis

Measurement data that were collected through the pressure mapping system were exported as text (.txt) documents and imported into MATLAB for further processing. The data was in the form of a matrix of 100x160xframes, where 'frames' is the number of frames contained within the file. The frame number varied for each sling depending on the research team's discretion of the recorded data.

As previously stated, each position was recorded for approximately five minutes, with a frequency of five hertz, therefore each data array, by position, contains about 1500 frames. One file (datum of an entire sling for one subject) contains about 7000 frames.

$$Frame\ Count = f * t \qquad \text{Equation 1}$$

where f = frequency in units of Hz (1/s) and t = time in units of seconds

Plugging in the values, we get:

$$Frame\ Count = f * t = 5\ Hz * 5\ min * \frac{60\ s}{1\ \text{min}} = 1500\ frames$$

3.1 Population Sample

The datum was reduced by choosing an appropriate sample of each population as explained below. Each sample was obtained by filtering through the XSensor files to make sure that the frames in question were in a stable position (i.e. not leading into or out of a position). The samples were also chosen so that the least amount of error

existed (i.e. user error or sensor malfunction). Once a sample was obtained for each data set, the standard deviations for each point across all of the position's frames were calculated by Equation 1 below and graphed.

Using Equation 2 then proved that the standard deviations were below 5 mmHg for 98.4% of the individual sensors when considering each position, sling, and participant (for P=2 mmHg the value drops to 94.9%). It is desirable to obtain a high percentage value from this equation, which will ensure that a relatively small number of sensors were greater than or equal to a pressure of 5 mmHg. The threshold of 5 mmHg to compare the standard deviations was chosen based on the relativity of the data. An example of this graph is shown in Figure 23.

$$S = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2} \qquad \text{Equation 2}$$

where S = standard deviation in units of mmHg, N = frame count (sample size) in units of frames, x_i = sample value observed at point i in units of mmHg, and $\bar{x}$ = mean value of the sample in units of mmHg

$$Percentage = \frac{|(Actual) - (Total)|}{Total} * 100 \qquad \text{Equation 3}$$

where Actual = actual points of S $\geq$ 5 mmHg and Total = total points of S.

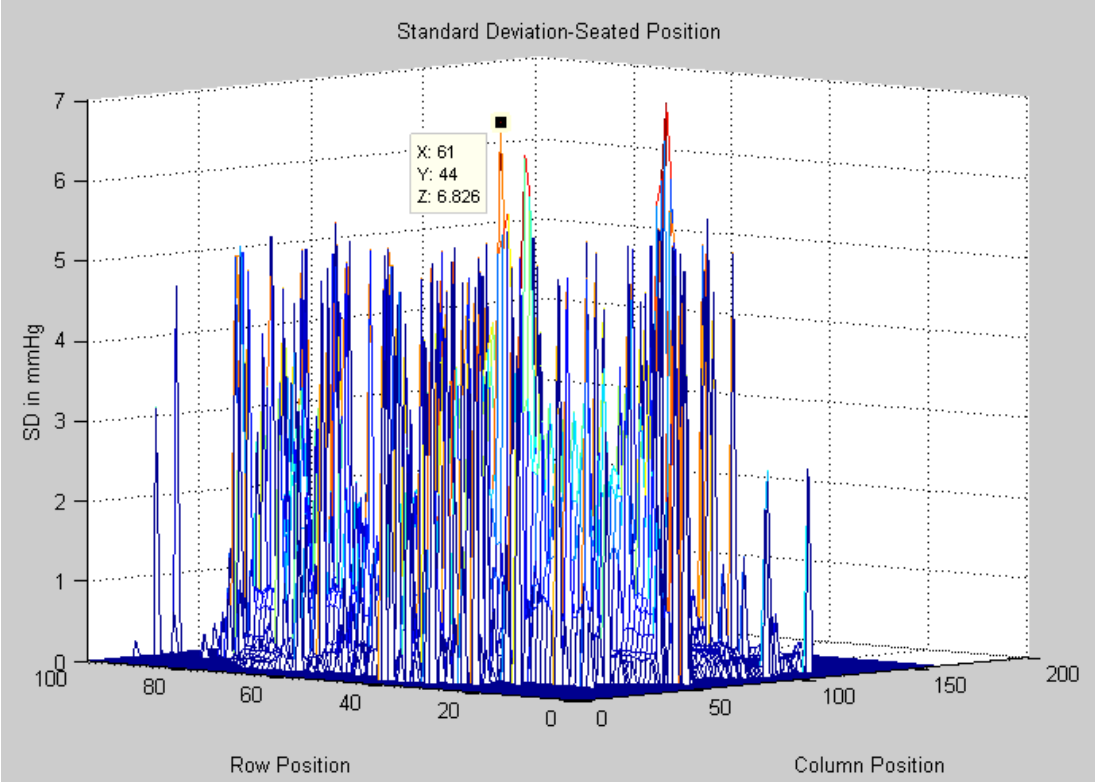

Figure 23: Standard deviation graph of the seated position

3.2 Calculated Variables/Criteria for Analysis

To begin data analysis and assess the most important variables for this study, many calculations were performed and are defined below either by a simplified MATLAB line of code or a general equation. A list of variables is documented in Appendix A and MATLAB scripts are documented in Appendix C.

1. Peak Pressure: Identify the maximum pressure values of a sample. Also note where they occur and how often they are present.

$$PeakPressure = max\big(max(SampleMatrix)\big) \qquad \text{Equation 4}$$

The peak pressure measurement was helpful in analyzing which slings reached the upper limit of the XSensor Pressure Mapping Array as well as the locations and

frequency of these high pressures. Consequently, pressure values above the calibrated range of the equipment, greater than 200 mmHg, were recorded. Even though pressure mapping is commonly limited to 200 mmHg for medical environments with tissues, it may be helpful to move to a higher calibration range, since this datum implies that top pressure values with transfers in patient handling slings have still yet to be measured.

2. Total Time: Find the total time a subject is in a sling for any given sample. This will be the addition of both static and dynamic (or transfer) times.

$$Total\ Time = \frac{Frame\ Count}{Frequency} \qquad \text{Equation 5}$$

The total time was used to measure the length of time a single participant was used per sling of data collection.

3. Mean Pressure: Compute the average pressure value of a sample.

$$MeanPressure = mean(mean(SampleMatrix)) \qquad \text{Equation 6}$$

The mean pressure calculated did not include the zero-elements within the array, which would have lowered the overall value dramatically. Technically, this corrects for the mean pressure over the surface area of the XSensor matrix that is activated.

4. Cumulative Pressure: Compute by multiplying the total time by the mean pressure of the sample.

$$CumulativePressure = TotalTime * MeanPressure \qquad \text{Equation 7}$$

5. Center of Pressure: Calculate, based on the pressure distribution, the mean location of the measurements.

$$CenterOfPressure = \frac{\sum_{i=1}^{n} P_i X_i}{P}\ ;\ \frac{\sum_{i=1}^{n} P_i Y_i}{P} \qquad \text{Equation 8}$$

6. Contact Area: Determine the amount of surface area presented with a loaded pressure value at any given time.

$$ContactArea = SenselArea * Number\ of\ NonZero\ Elements \quad \text{Equation 9}$$

7. Peak Pressure Index: Evaluate the highest mean pressure value within a 9-10 cm^2 shifting window across an array. This will imitate the estimated area of a bony prominence.
8. Coefficient of Variation: Compute the dispersion measure of the distributed pressures of a sample.

$$CV = \frac{Standard\ Deviation}{MeanPressure} \quad \text{Equation 10}$$

3.3 Distribution of Pressure within Designated Sections

The study staff believed that additional information was needed to supplement the above criteria before reducing the list to a few select slings. This is partially because information on the order of slings to select still needed to be investigated.

An analysis similar to a histogram plot was written as a script in MATLAB to compare a single position (i.e. "suspended to bed") across the different slings. This graph portrayed the number of sensors loaded within each user defined category. Two different but similar methods were used to show the data distribution, both evenly divided into ten sections based on the sensor calibration of pressures from zero to 200 mmHg. The first method used was referred to as the "exclusive" method. This method started out by counting the number of sensors from zero up to and including twenty (i.e. $0 < P \leq 20$). Note that the pressure points equal to zero were not included in the

analysis. This theme was repeated for each section (i.e. 21-40, 41-60, 61-80) for nine sections (or up to 180 mmHg) and the tenth section was set as 180 to P (max). This slight variation in the last section is due to the sensor measurements reading beyond the calibrated range of 200 mmHg. One example of this exclusion data is sampled below in Figure 24.

The second distribution method used was referred to as the "inclusive" method. Instead of defining a start and end value for the range of each section, only the start value varied. For example, the first and second sections (of ten) were the ranges 0 - P (max) and 21 - P (max), respectively. A sample graph of this data is shown below in Figure 25. Both of these methods were used to analyze the data within MATLAB and reduce the number of suggested slings.

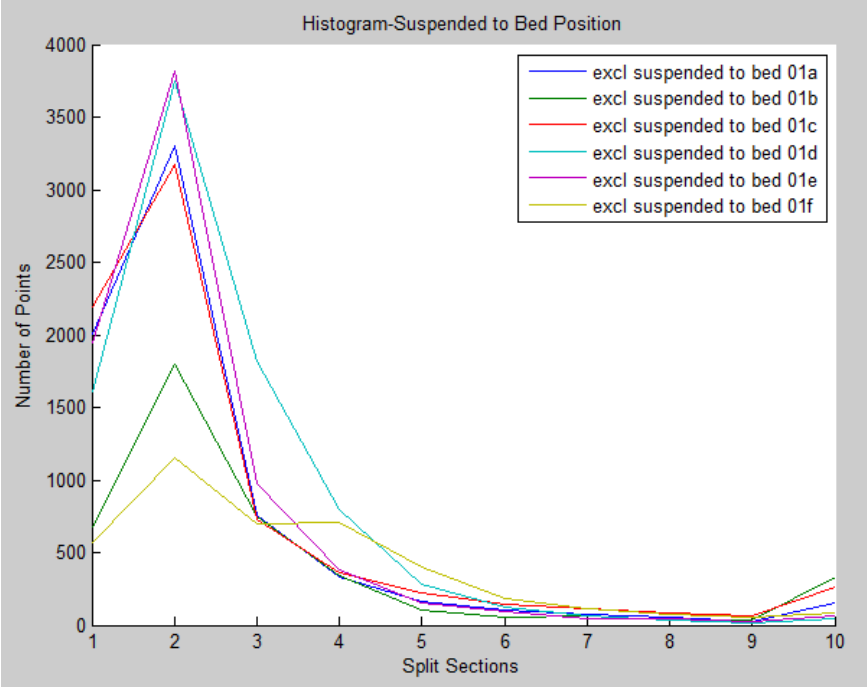

Figure 24: Histogram exclusion graph of the suspended to bed position

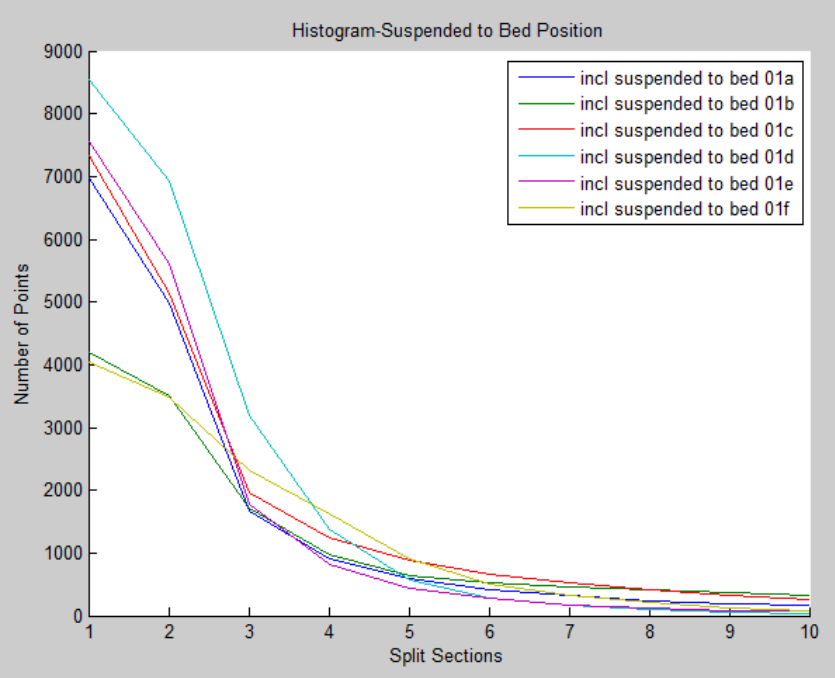

Figure 25: Histogram inclusion graph of the suspended to bed position

3.4 Comparison of Evaluated Slings by Ranking Methods

The histogram data explained above was exported from MATLAB into Microsoft Excel. After viewing the files in XSensor and running the histogram scripts in MATLAB, it was clear that the highest pressures were found in the suspended positions. Therefore, the following two of the five defined positions mentioned in the procedure (section 2.4) were studied for further analysis: "suspended to chair" and "suspended to bed". Since these two positions were nearly the same, only the "suspended to chair" was used in the analysis to ensure more accurate results since the protocol did not include a five minute recording time for the "suspended to bed" position. Also, to stay consistent, the inclusive datum mentioned in the prior section was used for each sling comparison. Two thresholds were chosen by the research team for the seated slings, at values of P=100

mmHg and P=180 mmHg. These thresholds were established based on the theory that capillary closing pressure is "normal" and on average about 32 mmHg. The first threshold (P=100 mmHg) is significantly higher than this "normal" value and should therefore be avoided since it would cause tissue damage. The upper limit of 180 mmHg was limited by the sensor's calibration. The data was then organized from highest to lowest in terms of the number of sensors at each threshold to compare individual slings. The average and standard deviation were found for each.

The supine slings were similarly compared, but with thresholds of P=60 mmHg and P=80 mmHg because the supine slings demonstrated lower pressure ranges than the seated slings.

There were two different methods used in order to choose which slings would continue on from the healthy volunteers to the SCI subjects.

The first method used was a ranking method. The seated slings were ranked from one to eighteen in order of smallest to largest number of loaded pressure sensors in two threshold regions (as discussed above, the two used were P>100 mmHg and P>180 mmHg). This was performed separately for each subject then the ranks were averaged across subjects to compare slings. Since not all positions were determining factors of which slings may have lower pressures, only the "suspended to chair" position was analyzed. Choosing this position over the "suspended to bed" position ensured the research team with a full 1500 or more frames of data. The lowest rank for each sling was chosen as the most appropriate choice for this particular method, pending the other analyses.

This method was also used for the supine slings, but the thresholds were changed to P>60 mmHg and P>80 mmHg. The supine and seated slings were not cross examined.

Another ranking method was used to compare the outcomes among the various slings while using two different groups of comparison. This analysis was used to assess the supportive pressures rather than the maximum pressures. The first comparison group for the seated slings was obtained by ranking the number of sensors loaded for each sling at the individual thresholds of (P>40 mmHg), (P>60 mmHg), and (P>80 mmHg) in ascending order (to minimize values). These ranks were then averaged across all subjects and re-ranked. The three re-ranked values were then averaged together. The latter group was obtained by subtracting the fifth section of the inclusive histogram (P>80 mmHg) from the first section (P>0 mmHg) to measure the "true supportive pressures" which would reside between zero and eighty mmHg in descending order (to maximize values). These values were then ranked for each subject and each sling, and then the ranks were averaged across all subjects. To stay consistent, a smaller rank value was considered to be superior.

The same two group comparisons were used to analyze the supine slings, but with slightly lower thresholds. The first group considered (P>20 mmHg), (P>40 mmHg), and (P>60 mmHg). The second group took into account the third section of the inclusive histogram (P>40 mmHg) subtracted from the first section (P>0 mmHg).

Once all of the methods above were completed, four different ranks were established. These four ranks were averaged and then re-ranked (to easily view the

order of slings from 1 to 5) for each sling to produce an "overall rank". Table 5 provides a summary of the four ranking methods described above for both sling types.

Table 5: Summary of ranking scenarios for both seated and supine slings

Sling Type	Rank 1	Rank 2	Rank 3	Rank 4
Seated	>100	>180	>40,60,80	>0 - >80
Supine	>60	>80	>20,40,60	>0 - >40
Average number of loaded sensors to be:	Minimized	Minimized	Minimized	Maximized

3.5 Statistical Analysis

The data was first statistically measured by using standard deviations and mean pressures. The sample sizes of 200 frames found previously were divided equally into ten sections, with twenty frames in each section.

Figure 26 and Figure 27 display an example of the difference in standard deviations between the healthy and SCI subjects. One subject from each population, with the same sling in use, is graphed below with standard deviation on the ordinate in units of mmHg and the ten defined sections on the abscissa. This scenario was interpreted that the healthy subject moved, or rather fidgeted, more frequently than the SCI subject. This trend was exhibited in most cases during the study. The amount of variation present may be dependent on the sling, position, and the subject's level of injury. It is a possibility that the constant standard deviation may not be a good

condition, but rather one that will continuously vary as the healthy subject displayed. Further analysis would be recommended to determine if this is the case.

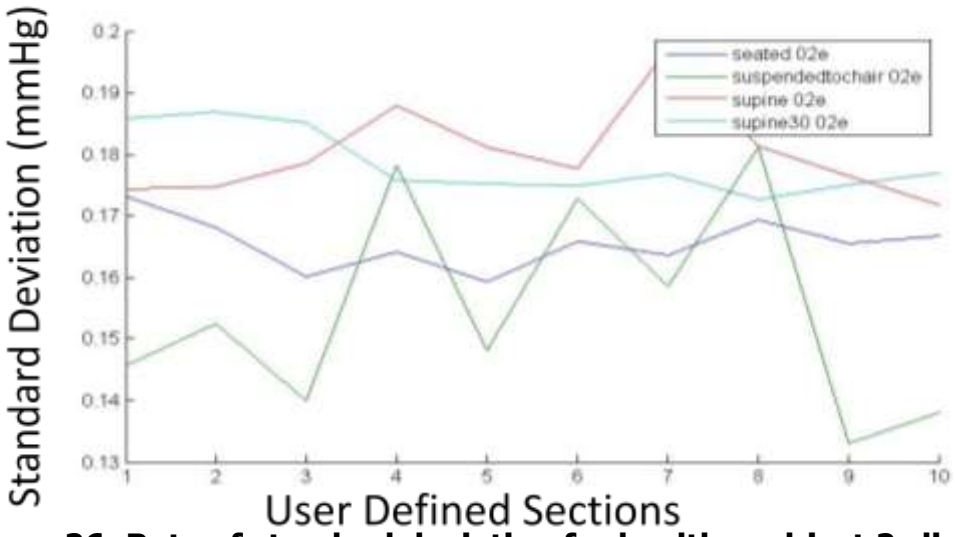

Figure 26: Rate of standard deviation for healthy subject 2 sling E

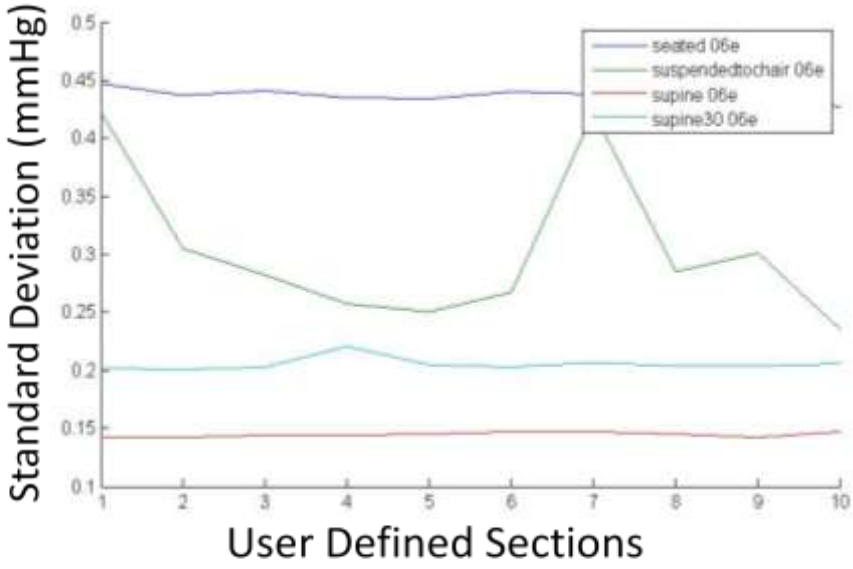

Figure 27: Rate of standard deviation for SCI subject 6 sling E

Using the ten defined sections once again on the abscissa but with the ordinate now set to mean pressure in units of mmHg, Figure 28 and Figure 29 were plotted and

are shown below. The figures both show the positions for one sling, sequentially, with respect to their mean pressures. A trend was present within most slings and the positions were determined as follows by decreasing mean pressure: "suspended to chair", "seated", "supine 30", and "supine".

ANOVA was used for four different scenarios to compute the significance level of the results: 1) Test the null hypothesis that the suspended position within one sling and one subject is greater than the seated position, 2) Test the null hypothesis that the seated position of one sling is equal to the seated sling of another sling, both using the same subject, 3) Test the null hypothesis that the seated position of one sling for one subject is equal to the seated position of one sling for a second subject, and 4) Test the null hypothesis that the suspended position for one SCI subject is equal to the suspended position for one healthy subject. The results are shown below in Table 6.

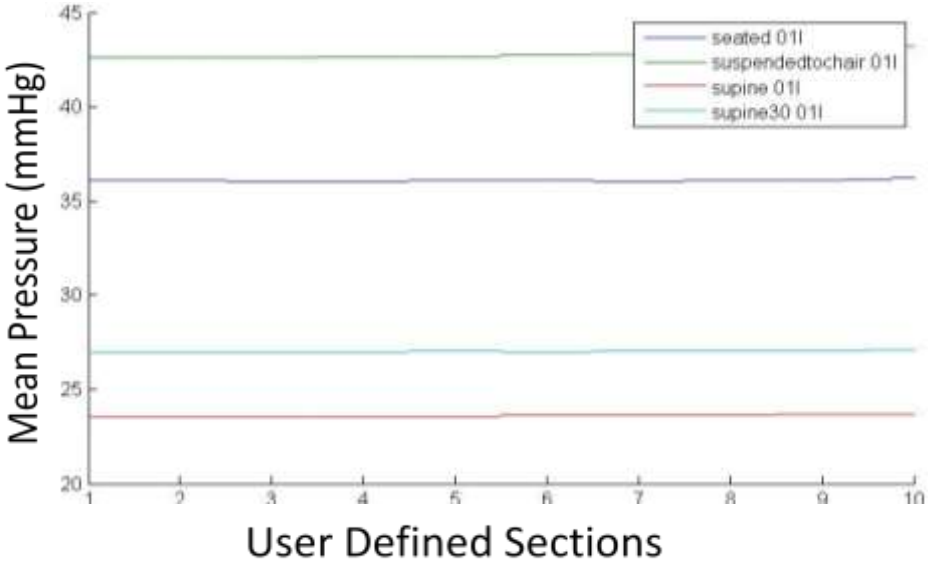

Figure 28: Rate of mean pressure for healthy subject 1 sling L

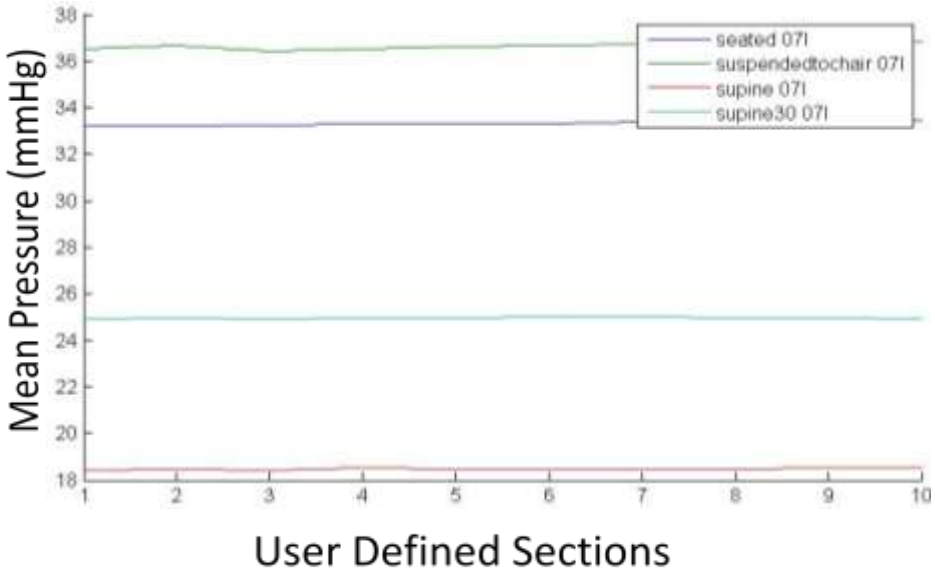

Figure 29: Rate of mean pressure for SCI subject 7 sling L

Table 6: ANOVA results for 4 scenarios with alpha level 0.10

Scenario	Test	F*	Conclude
1	One-Tailed	155.2	Conclude Null
2	Two-Tailed	213.5	Reject Null
3	Two-Tailed	7.0	Close, Review
4	Two-Tailed	92.2	Reject Null

Scenario 3 shown in Table 6 above had a calculated value very close to the critical table value. Further investigation should be performed for this scenario before any conclusions can be reached. The p-value was calculated to be approximately zero, which is less than the alpha level of 0.05, so the null hypothesis can be rejected.

Chapter 4. Results

4.1 Healthy Volunteers

The one active sling that was studied (Polyester Seated Sling – Active Micro Plus by Guldmann) was sixth in place of the overall rank. If the sling had ranked within the top four of the evaluated slings, it would have been eliminated from the study since it required a significant amount of upper body strength from the patient to operate properly, which was not noted within the inclusion/exclusion criteria for the study.

The ArjoHuntleigh seated slings studied were all in the top 50% of the slings in terms of minimized high pressure points recorded.

It was found that the high interface pressure location was dependent on each individual sling's seam locations. The manufacturer, material, and features did not necessarily play a role in this result besides that the seams may have been in different locations because of them. The high interface pressures are assumed to be directly correlated with the risk of pressure ulceration.

As expected, the seated slings produced a larger amount of high pressures than the supine slings. For this reason, the supine slings were analyzed at lower thresholds than the seated slings. This makes sense since the pressures are distributed over a larger area when using a supine sling compared to a seated sling.

When comparing the four ranks mentioned above (section 3.4), the ranks were averaged and re-ranked to create an overall rank for each sling. The purpose of an overall rank was to help define a direct comparison between each sling. From Table 7 it can be seen that in terms of overall rank, the four best seated slings were: a, d, e, and l. Reverting back to the list of slings in Table 3, slings a, d, and e are manufactured by ArjoHuntleigh and are all made of polyester, whereas sling l is manufactured by Guldmann and is made of nylon material. These four seated slings were analyzed further with the SCI subjects.

Table 8 shows the raw data collected from the histogram plots. The datum from the histogram plots shown (Table 8) exhibit a common trend of decreasing average number of sensors loaded as the pressure threshold increases from left to right. A desirable trait is to have the highest number of average sensors loaded for the low thresholds, but the lowest number of loaded sensors for the high thresholds (i.e. how the ranks were calculated).

The ranking methods used to compare the supine slings showed that sling s3, manufactured by Guldmann and made of Polyester, was the most appropriate choice to continue testing with the SCI subjects. The results are shown below in Table 9. Table 10 contains the raw data collected from the histogram plots mentioned above in Section 3.3.

Though the data has already shown that the highest pressures recorded are densely localized along the seams of the slings, it is now important to note which areas of the human body are put into jeopardy. The three manufacturers that were studied all

have similar seam placement for all of the seated slings. Most of the slings were comprised of two main seams on each side of the median plane of the posterior surface of the body (right and left halves), which crossed transversely between the medial and lateral aspects. The first seam was situated within the gluteal region, directly below the ischial tuberosity. The second seam was located in the femoral region at the midpoint of the femur.

An average output image of the pressures (across the 200 framed samples) for each of the top performing seated slings is shown below in Figure 30 with a pressure legend in units of mmHg. A visualization of the seam locations is shown below on the posterior aspect of a human silhouette in Figure 31.

Table 7: Overall rank for healthy subjects with seated slings

	>100	>180	>40,60,80	>0 - >80	Average Rank	Overall Rank
Sling						
a	2	3	1	3	2.25	1
b	6	11	5	17	9.75	10
c	6	8	2	7	5.75	5
d	1	1	10	1	3.25	3
e	3	3	3	2	2.75	2
f	4	2	6	18	7.50	6
g	16	14	18	5	13.25	14
h	18	18	12	12	15.00	17
i	12	5	17	7	10.25	11
j	11	9	6	10	9.00	9
k	17	17	15	9	14.50	16
l	5	5	3	6	4.75	4
m	14	14	14	14	14.00	15
n	15	16	16	13	15.00	17
o	8	7	9	11	8.75	7
p	10	12	11	15	12.00	12
q	13	13	8	15	12.25	13
r	9	10	12	4	8.75	7

Table 8: Average number of sensors loaded for healthy subjects in seated slings

	>0	>20	>40	>60	>80	>100	>120	>140	>160	>180
Sling										
a	8227	5550	1652	795	477	338	251	193	150	123
b	4849	3916	1949	1136	685	504	394	308	250	203
c	7790	5156	1747	997	679	502	383	292	234	187
d	9184	7016	2863	1207	474	227	122	72	45	31
e	8087	5634	2067	990	513	314	203	134	90	61
f	4303	3549	2084	1364	772	426	264	165	106	71
g	8435	5713	2340	1388	890	627	460	344	262	203
h	7787	4648	1776	1351	1111	929	783	650	547	461
i	7948	5633	2400	1431	924	650	456	318	227	164
j	7517	4341	1612	1227	939	717	548	425	345	280
k	7804	5162	1962	1267	949	764	634	526	441	368
l	7454	5202	2223	1210	736	528	396	298	225	171
m	6895	4848	2146	1367	966	722	555	424	323	249
n	7356	4908	2038	1310	903	682	518	398	315	256
o	7088	4921	1832	1091	724	539	419	335	271	222
p	6518	4344	1917	1239	838	602	460	362	292	239
q	6590	4253	1691	1076	778	629	515	422	344	283
r	7554	5463	2104	1229	787	565	423	324	252	202

Table 9: Overall rank for healthy subjects with supine slings

	>60	>80	>20,40,60	(>0)-(>40)	Average Rank	Overall Rank
sling						
s1	2	2	4	2	2.50	2
s2	4	4	3	4	3.75	4
s3	1	1	2	1	1.25	1
s4	3	3	5	5	4.00	5
s5	5	5	1	3	3.50	3

Table 10: Average number of sensors loaded for healthy subjects in supine slings

	>0	>20	>40	>60	>80	>100	>120	>140	>160	>180
Sling										
s1	6009	3956	580	74	14	5	1	1	0	0
s2	5316	3784	697	189	46	16	5	2	1	1
s3	6519	4370	321	21	3	0	0	0	0	0
s4	5419	4103	648	137	30	7	3	1	0	0
s5	4892	3172	616	397	279	206	156	119	97	76

Figure 32 provides three pictures of the seam locations on a human subject (all have the knee labeled as inferior and the groin labeled as superior; top left: medial view of left femur; top right: anterior view of right femur; bottom: posterior view of left femur).

A cluster analysis was performed for the healthy subjects in the seated slings based off the rank number and is shown below in Figure 33. The slings were divided into the following five clusters:

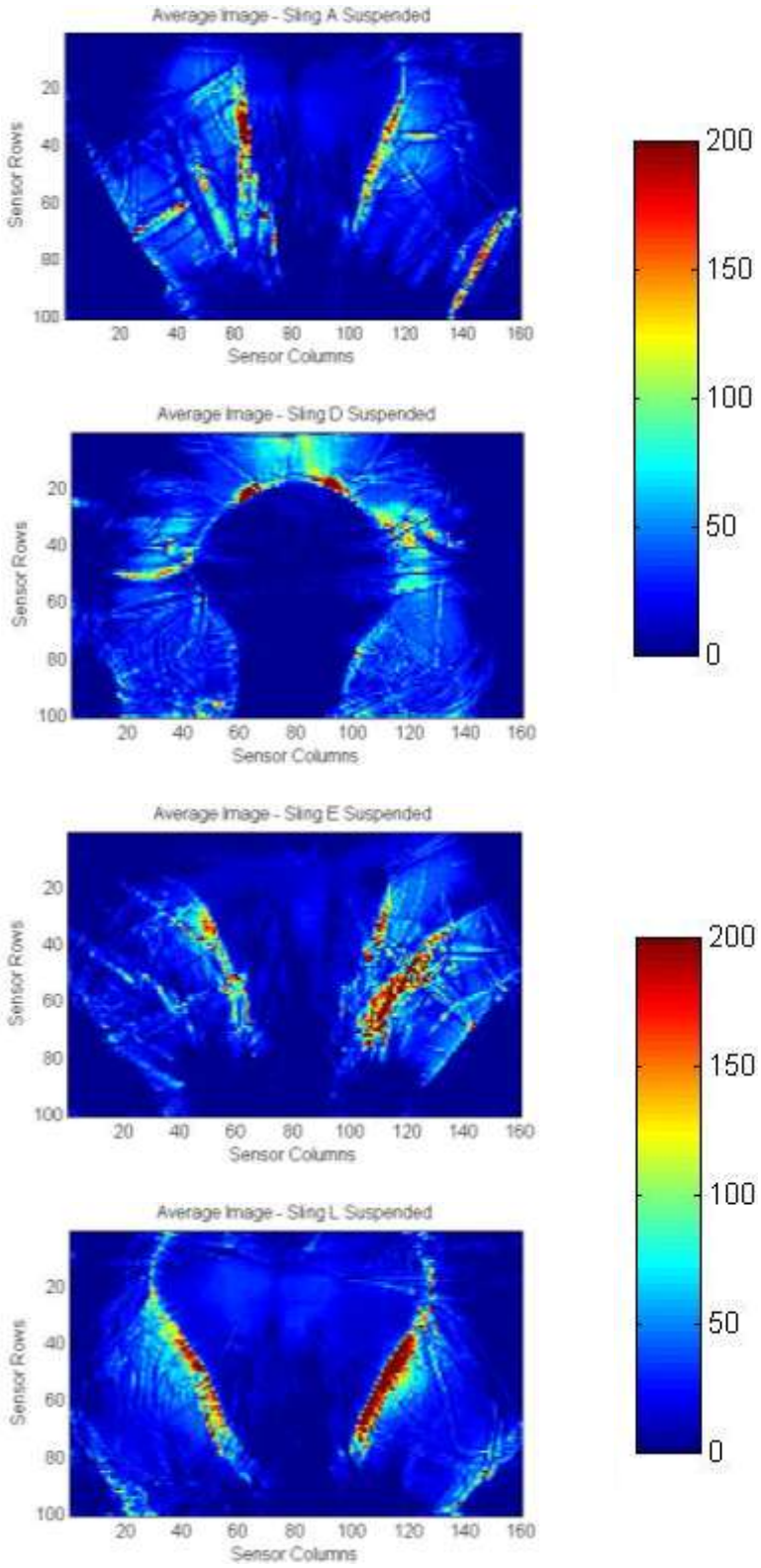

Figure 30: Average output images for seated slings A,D,E, and L

1. Slings a, e, and d
2. Slings l and c
3. Sling f
4. Slings o, j, b, i, and r
5. Slings p, g, m, k, n, h, and q

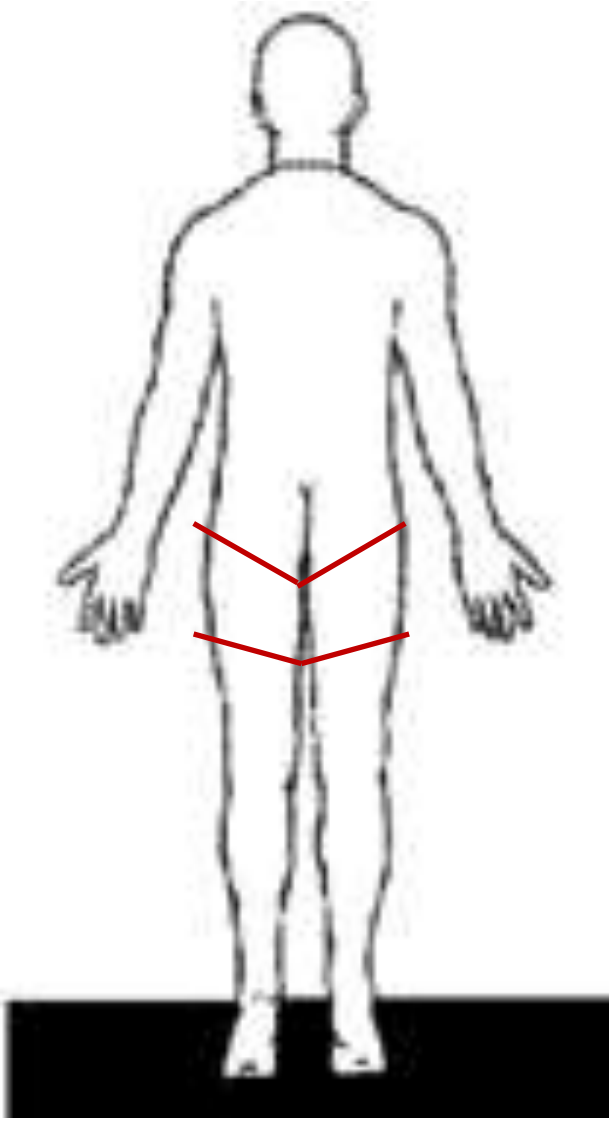

Figure 31: Seam locations relative to human anatomy

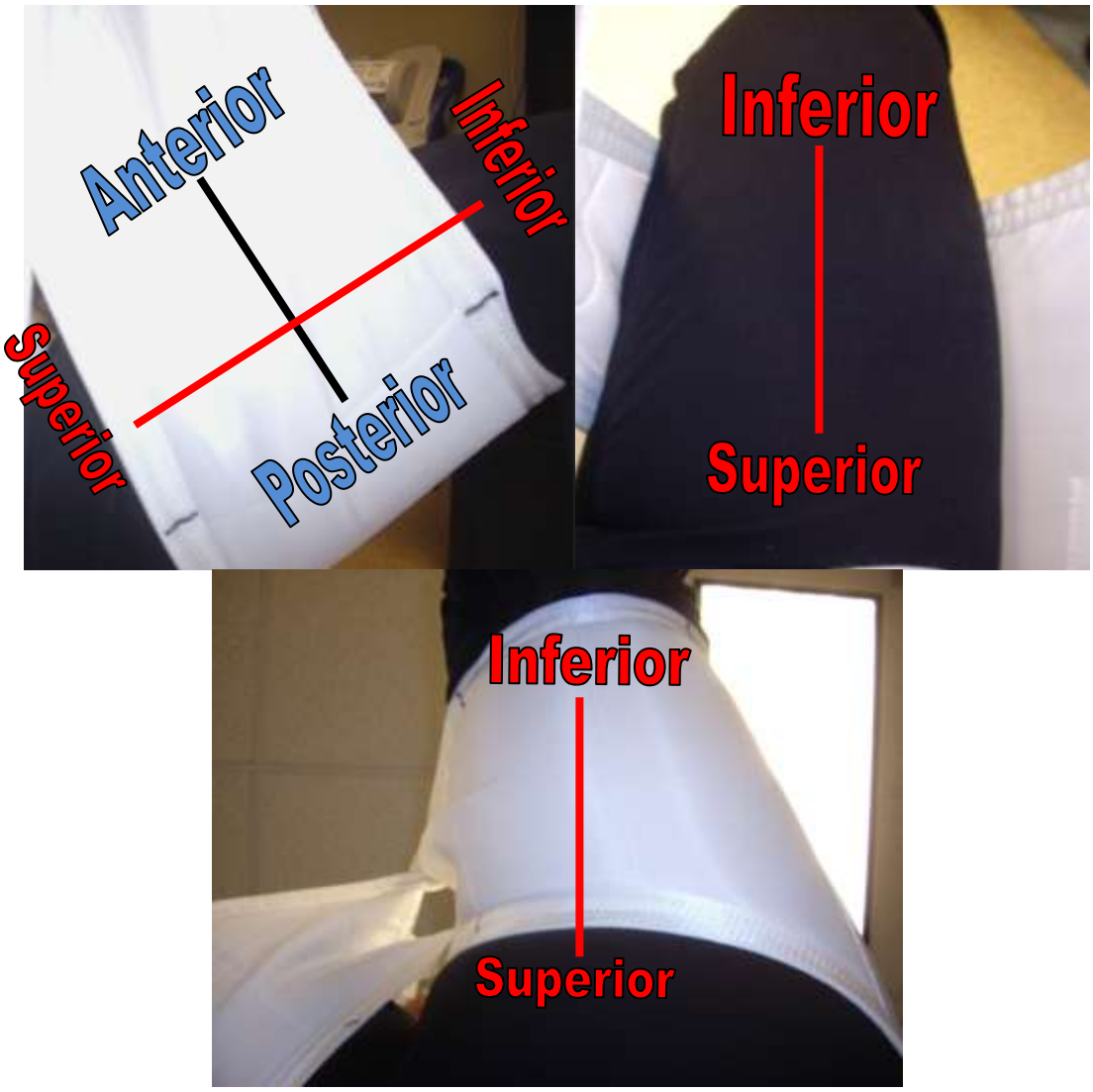

Figure 32: Seam placement on human subject – medial, anterior, and posterior views

4.2 Veterans with Spinal Cord Injuries

After conducting the data acquisition for the spinal cord injury subjects, the analyses were performed similar to the healthy volunteer analyses as described above. The overall ranks for the seated slings (see Table 11 below) did not show to be identical to the healthy volunteer overall ranks. Although the healthy volunteer ranking had sling

(a) at the top of the list, sling (d) was found to be the top performing sling for the SCI subjects.

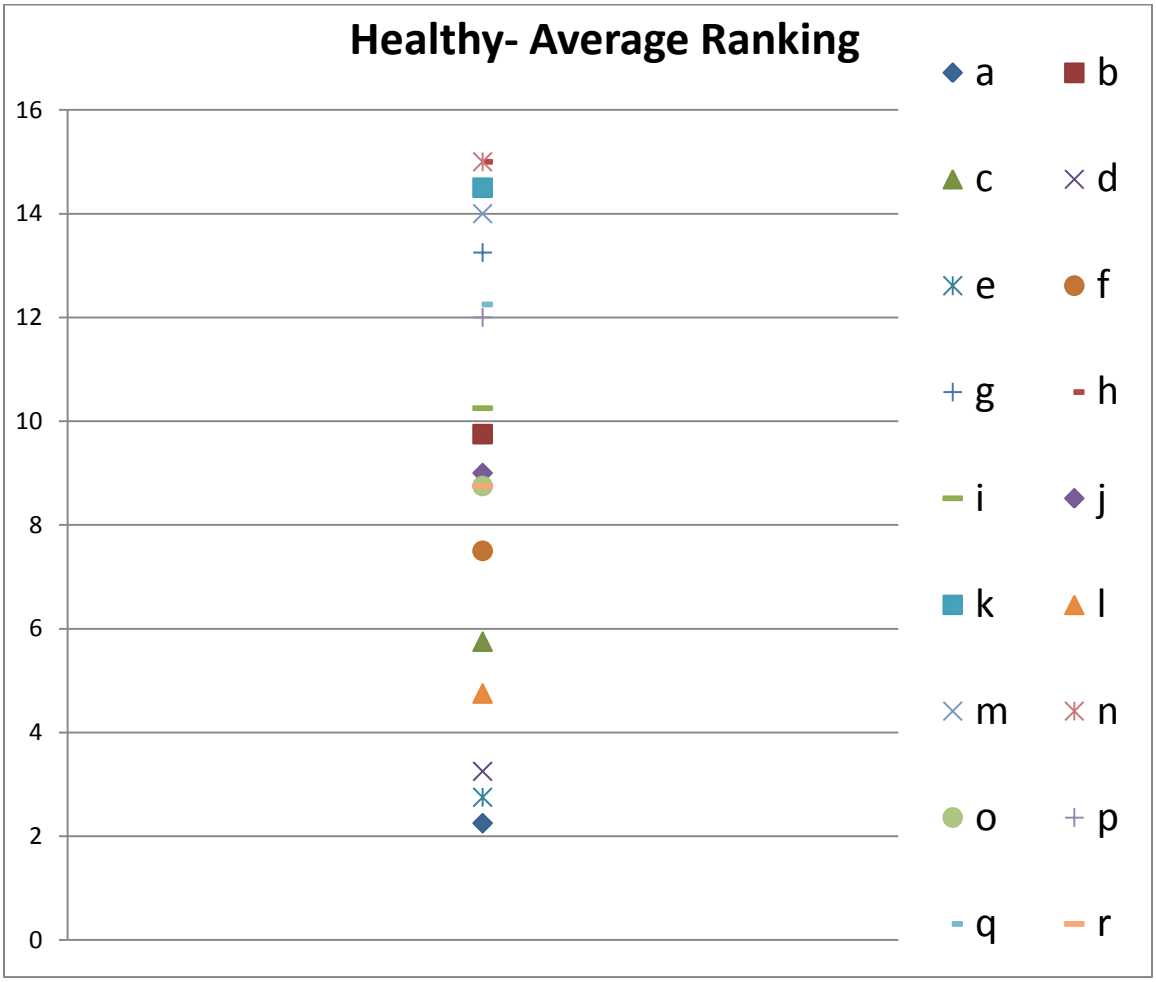

Figure 33: Cluster analysis for healthy subjects in seated slings

The rest of the order (a, e, then l) was the same with the exception of sling (d). The ranking results for the supine sling are not shown below since there was only one supine sling recorded for the SCI subjects (score of one out of one for each category). Table 12 contains the raw data collected from the histogram plots mentioned above in Section 3.3.

Table 11: Overall rank for SCI subjects with seated slings

	>100	>180	>40,60,80	>0 - >80	Average Rank	Overall Rank
Sling						
a	2	2	1	4	2.25	2
d	1	1	3	2	1.75	1
e	3	3	2	3	2.75	3
l	4	4	4	1	3.25	4

When reviewing the data of the average number of sensors loaded at the given thresholds, the four SCI subjects always presented a greater amount of loaded sensors than the healthy subjects. On average, a 39% difference was present for the seated slings and a 240% difference for the supine sling. The major differences were due to the >100 and >180 categories for the seated slings and the >60 and >80 categories for the supine sling.

Table 12: Average number of sensors loaded for SCI subjects

	>0	>20	>40	>60	>80	>100	>120	>140	>160	>180
Sling										
a	9982	6179	2051	941	572	407	306	235	186	160
d	10728	7934	3259	1281	549	287	160	100	65	45
e	10727	6636	2428	1301	813	587	446	358	294	239
l	11530	6959	2332	1342	906	688	548	443	365	297
s3	7318	4784	966	118	22	6	2	1	0	0

4.3 Questionnaire Data

The questionnaire data was obtained on a scale from 1 to 5, where 1 was none/least and 5 was the most. The following are the four questions (also see Appendix F):

1. How secure did you feel in the sling
2. How comfortable did you feel in the sling
3. How much discomfort, if any, did you feel in the sling
4. How much pain, if any, did you feel in the sling

The questionnaire data collected were averaged across subjects for each question and sling then plotted on a radar (or spider) graph. Results are shown below for both healthy and SCI subjects in Figure 34 and Figure 35, respectively.

For the healthy subjects, sling s3 was on average least secure and least comfortable, sling e had the least amount of discomfort, and sling l had the most pain. As for the SCI subjects, sling a was on average the most comfortable, exhibited the least amount of discomfort (none), and the least amount of pain (none), where as sling d felt the least secure.

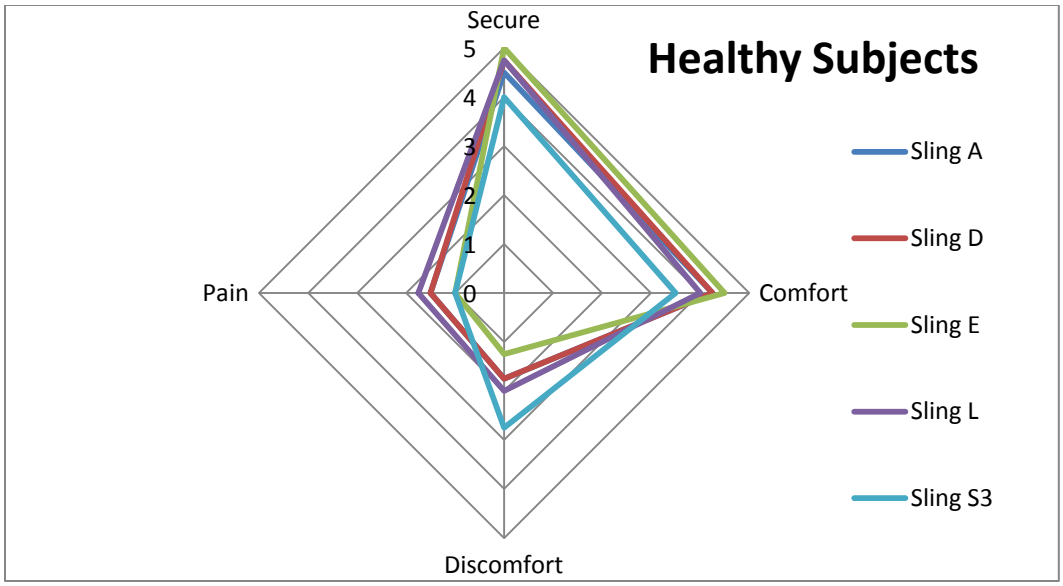

Figure 34: Healthy subjects' questionnaire data

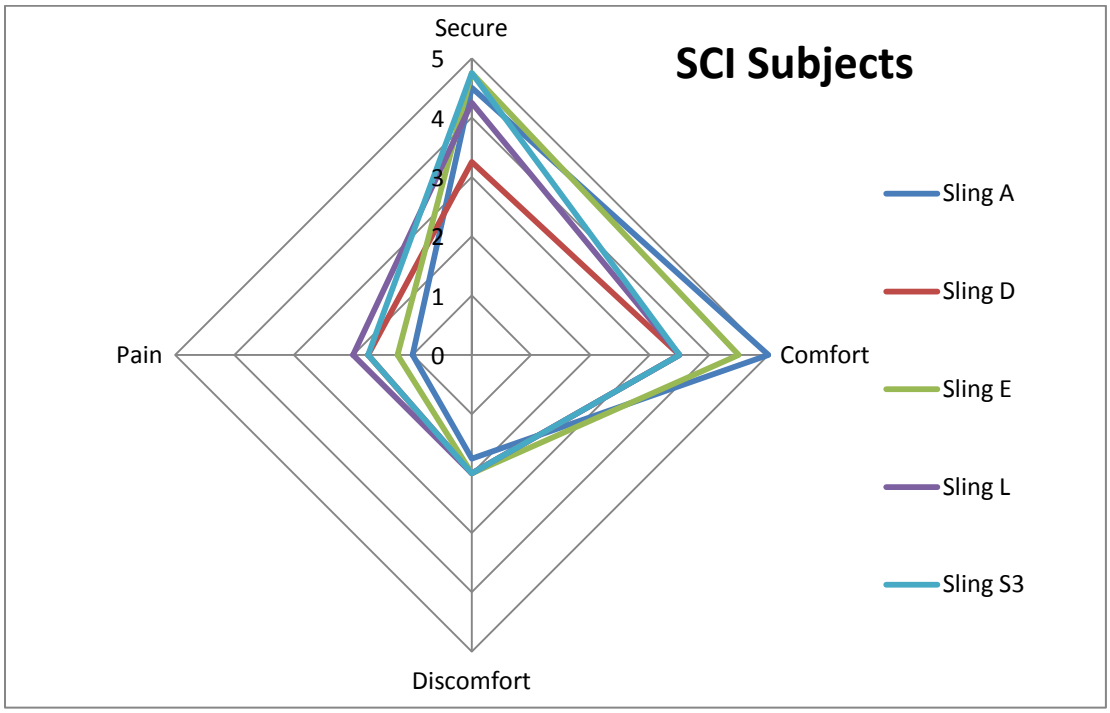

Figure 35: SCI subjects' questionnaire data

Chapter 5. Applications of this Study

The main application for this project is to reduce the risk for skin breakdown associated with transfer systems. The data acquired with the pressure mapping criteria will help determine a type of sling that may reduce the risk of pressure ulcers. Not only will this research benefit patient safety, but also safety for the care provider. Once the risk is minimized, medical costs for both patients and providers will be reduced as well as having an improved work setting. The providers will also benefit from identification of the highest performing slings based on the calculated criteria because they will be able to review this research and improve the next generation of patient handling sling design.

The study was piloted because the Paralyzed Veterans of America (PVA) was worried about patient safety and no data had previously been recorded on skin integrity risks for patients. Undeniably, using ceiling lifts is beneficial for the health care providers and their staff, but there is concern on whether it is beneficial or harmful for the patient.

Chapter 6. Limitations

6.1 Instrument Error

The least count method (LCM) was used to find uncertainties of the lab equipment. The VersaCare AIR hospital bed relies on a ball bearing to facilitate raising the head of bed. Its contribution toward angular uncertainty was found to be: $\sigma = \pm 10$ Degrees.

The XSensor High Resolution Pressure Mapping System (PX100: 100.160.05) directly measures pressure with a resolution of 0.51 centimeters and a calibration range from 10-200 mmHg. The uncertainty associated with this piece of equipment using the LCM is: $\sigma = \pm 0.01$ mmHg. The actual error of the instrument, stated by the manufacturer, is: $\sigma = \pm 10$ % (X3 PRO, XSensor Technology Corporation, Calgary, Canada).

6.2 Additional Challenges

Low sample sizes are a common problem in the Biomedical Engineering field and this project was no exception. Once inclusion and exclusion criteria are met, it can be even more challenging to the study's sample size. The analysis was not detrimental to the study in this case since it is a pilot study and the general effects were evaluated.

As previously stated, the design of this study may have deterred patients at the hospital from signing up if they have had previous awareness of slings increasing

ulceration risk. Noting that the study had a sample size of only five, participant variation may not be as extensive as it should be. This can be managed in future studies by increasing the sample size and possibly recruiting from various environments.

Another challenge presented within this study is that the sensor array would occasionally input deleted columns of data while being measured (see Figure 36 and Figure 37). These columns may very well be located along one of the sling's seams, which would affect the results calculated in the data analysis and is an error that must be accounted for. The researchers were able to see this phenomena while recording and tried to shift that particular area of the sling until it would read the column again. A possible explanation for this is the pressure mapping array construction. The sensors are arranged in a checkered pattern, with the sensors in each row, or in each column, in series. The sensor array may not be able to withstand the strenuous flexibility needed for this specific protocol.

Also important to note is that the sensors in the array would frequently flicker when recording acceptable pressure values. This control is visible when the patient is lying in the supine position on the bed, though the pressures only vary by insignificant amounts.

The environment was tested for background noise by recording the XSensor pressure values from the blank array (i.e. the array was set up flat on the bed with nothing on top of it to load any of the sensors). The sample sizes of 200 frames were divided equally into ten sections, with twenty frames in each section, and plotted on the abscissa (see Figure 38). The ordinate is shown as mean pressure in units of mmHg.

The standard deviation was calculated for the same data and showed a value of zero mmHg across the 200 frames.

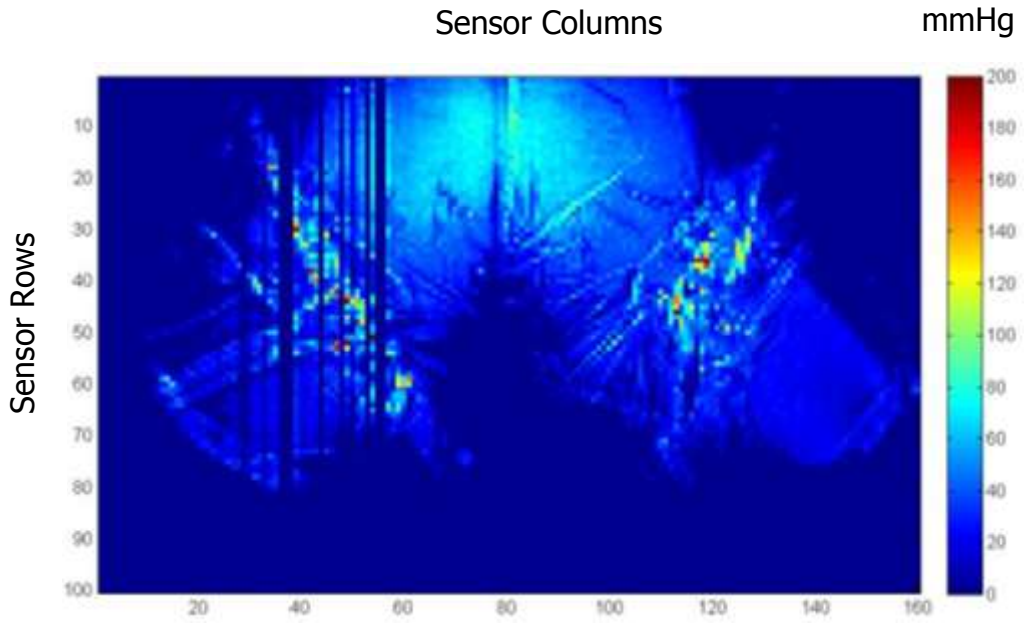

Figure 36: Sensor array error example 1

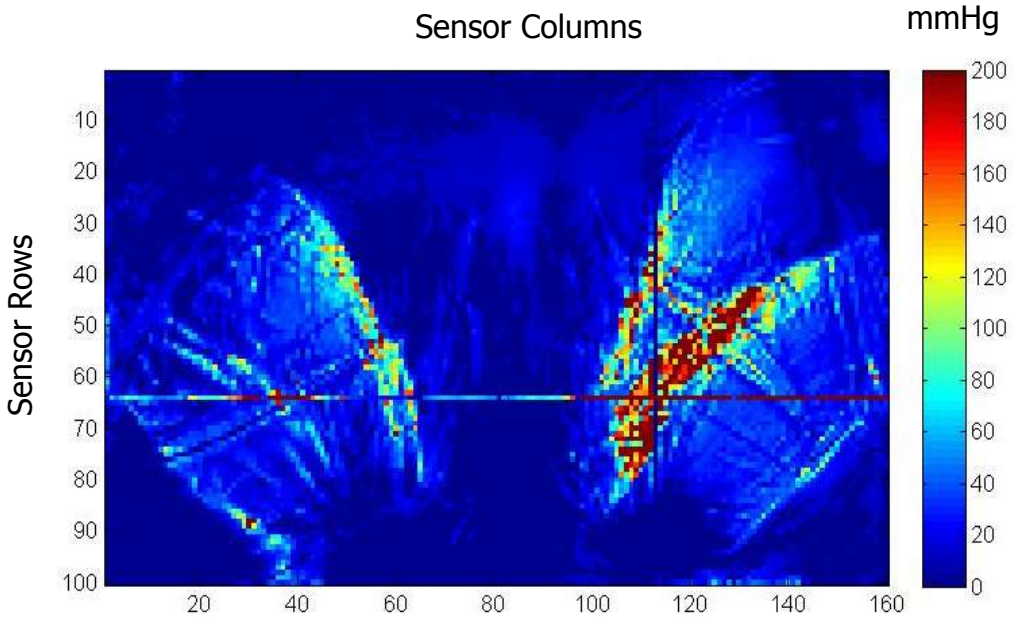

Figure 37: Sensor array error example 2

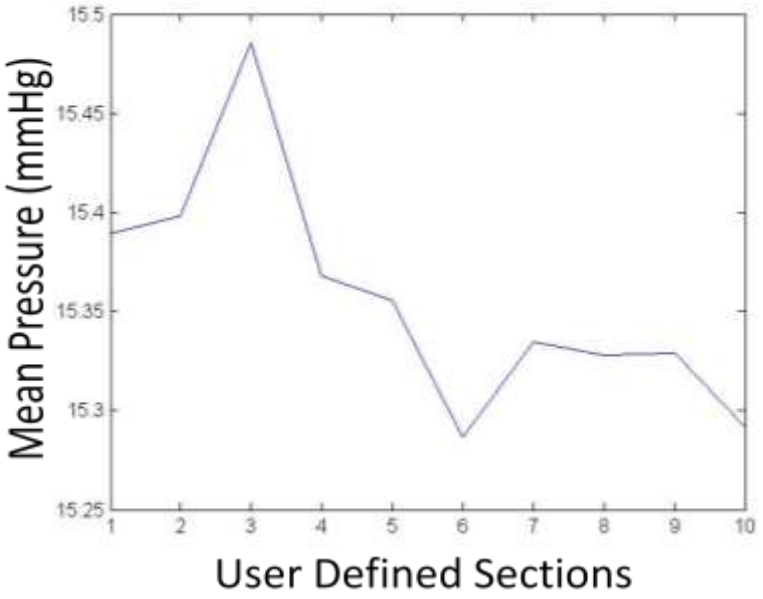

Figure 38: XSensor background noise with blank trial

The sensor was also tested with a known mass to see if the background noise would increase when weights were added. With the ordinate as mean pressure in units of mmHg and the abscissa as the ten user defined sections previously mentioned, Figure 39 shows a slight variation in values with about 5% error. The standard deviation was calculated with the datum and is shown below in Figure 40, again with minimal error.

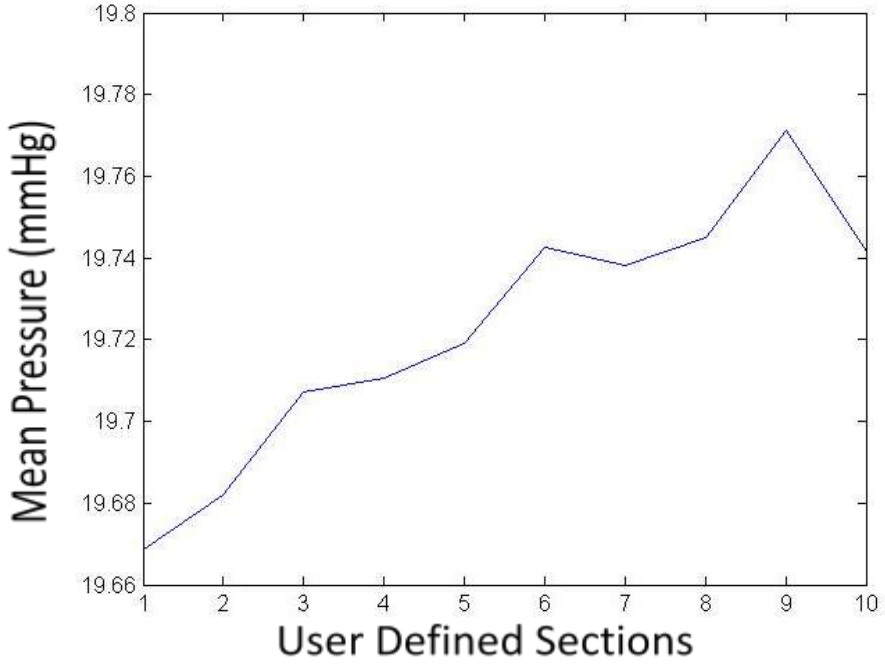

Figure 39: Background noise - known mass showing mean pressures

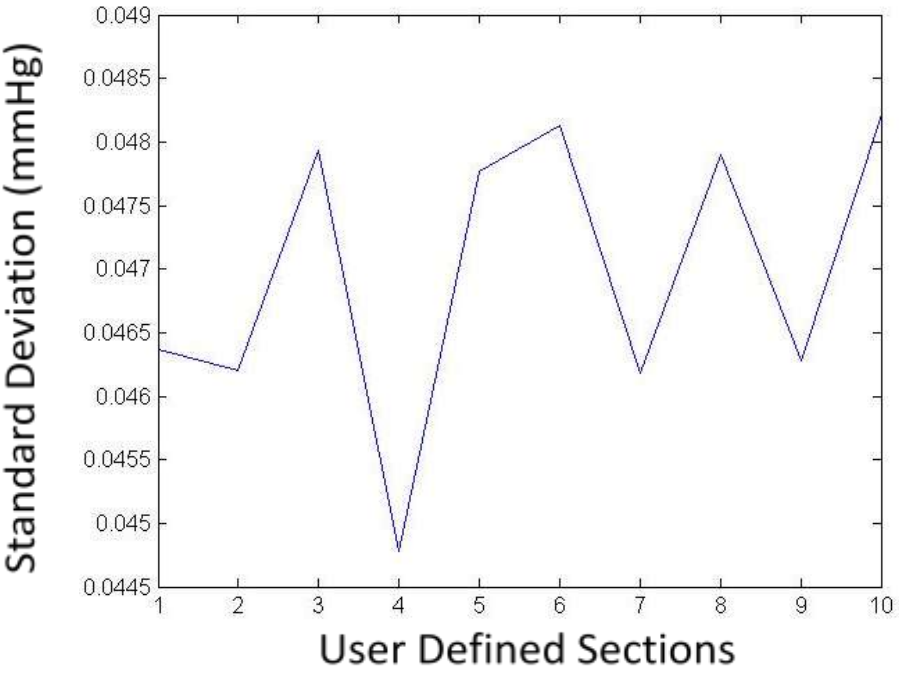

Figure 40: Background noise- known mass showing σ

Chapter 7. Conclusions and Recommendations

As previously noted, there is a lot of research being studied throughout the world in order to understand and better manage and treat patients with SCIs. Since the physiology of the human body is so complex and varies with each scenario, it is a very diverse research field. With over 250,000 people currently living with a SCI in the U.S. and approximately 10,000 to 12,000 new cases each year, it is important to be able to manage these conditions and reduce the morbidity and mortality rates pertaining to them (NINDS 2003).

Improving the quality of life for SCI patients is a key driving force for this type of research. Aware of this projected improvement, Krassioukov states how "there are no uniform operational definitions of autonomic dysfunction after SCI and changes in the autonomic control of various systems are difficult to document by way of bedside examination" (Krassioukov 2009). In addition to suggesting that the examination is hard from a bedside, where most SCI patients are limited to, another problem is the variability presented in human subjects. It is critical to recognize the existing standards and measurement systems to troubleshoot problem areas or variables that may not have been incorporated initially and hence integrate possible solutions. This could also help in long-term prevention protocols.

This study confirmed the hypothesis that the transfer of patients by use of patient handling slings will expose them to high interface pressures. Specifically, higher

interface pressures exist while in a suspended position. Though the distance a patient travels in any given sling is not a direct factor of an increased risk of skin breakdown, the amount of time spent in a sling is a major contributor. Therefore, extended suspension of a patient in a sling should be both limited and closely monitored at all times.

As previously shown in the results section in Chapter 4, the interface pressures are dominant along the seams of a sling. This result is independent of the sling material and type. Although this is dependent on the placement of seams, the three manufactures reviewed all had similar seam locations for each sling. The patient handling sling manufacturers may find it constructive to move the location of the sling's seams beyond high weight bearing regions of the person's anatomy.

It is important to note that care providers should remove the sling from beneath a patient in between transfers. If not able to remove the sling, the sling, and more importantly its seams, should be smoothed out while the patient is sitting or lying down. This act will minimize the high interface pressures that could be presented by creases in the sling. Creases or folds in the sling material can also cause unnecessary high pressures as a patient is suspended.

It would be interesting to see further research emphasizing contact area of the subject on the sling. Our results showed that the SCI subjects presented a greater amount of average number of sensors loaded at any given threshold than the healthy subjects. This is most likely a function of the person's attributes, position, and atrophy, but it would be beneficial to track and correlate the findings.

Although this study has shown significant results, future work is recommended. Being only a pilot study, every possible sling manufacturer and type were not included. If the goal is to determine the best sling to use based on the evaluated criteria, all manufacturers must be included within the study as well as having a larger sample size and a wider variation among participants.

It would be beneficial to all persons if the results were publicized throughout the medical and engineering fields. This could also promote the development of safe patient handling guidelines.

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Andy

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Appendix A (Continued)

A.3 Approval for Figure 3

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Appendix B Nomenclature

The following table provides a list of all variables used.

Table B.1: Nomenclature

Name	Variable	Units
Coefficient of Variation	CV	-
Frequency	f	Hz
Time	t	Seconds
Observed Pressure	X_i , Y_i	mmHg
Pressure	P	mmHg
Mean Pressure	$\bar{x}$	mmHg
Sample Size	N	People or Frames
Standard Deviation	S , σ	mmHg

Appendix C MATLAB Scripts

The MATLAB codes shown below are simply examples of code that have been performed for this study. Code is not complete for each sling and position described in the body of this thesis, but is merely a summary.

C.1 Import into MATLAB

```
% Julie Kahn
% VA Research
% Importing txt file data into MATLAB
% JK 9/23/12

function [FrameArray] = txtscan_23SEP2012(DataFile,FrameCount)
    tic
%  Open the file to get the FileID parameter for textscan
    DataFileId = fopen(DataFile);

%   The first textscan call will parse out the non-repeated header lines
    NumHeaderLines = 3;
%   This parameter is the number of header lines that repeats each frame
    NumFrameInfoLines = 17;
%   This is the number of data columns and rows of the pressure array
    NumDataCols = 160;
    NumDataRows = 100;

%   Initialize empty array to shorten run time
    FrameArray = zeros(NumDataRows,NumDataCols,FrameCount);

%   Read the header and print it to the screen before moving on
    DataFileHeader = textscan(DataFileId, '%s', NumHeaderLines, 'delimiter', '\n');
    disp(DataFileHeader{:}); % Reads until it doesn't match, textscan
%     starts where you leave off

%     repmat - Tell matlab that it is a 160 value line- Also notice this
%     is outside the loop so it is only built once
    DataFileFormat = repmat('%f ',1,NumDataCols); % Makes a matrix of 1 row
    % and 160 columns(1by1byn), the value of every cell in that matrix is %f
    % Telling textscan what to look for (what the values look like and how
    % they are arranged) 160 values per time instead of 1 value per time
```

Appendix C (Continued)

```
   for FrameNum = 1:FrameCount % Run a loop to get multiple frames

%       This should return a 100 x 160 cell array
       NewData = textscan(DataFileId, DataFileFormat, NumDataRows, 'delimiter', '\n',
'HeaderLines', NumFrameInfoLines);
%       This should convert the cell array to a 100 x 160 matrix of values
%       and append it to the FrameArray
       FrameArray(:,:,FrameNum) = cell2mat(NewData);

   end
% Close the file
   fclose(DataFileId);

   toc
```

C.2 Save Files into MATLAB

```
% Julie Kahn
% Save bulk positions
% Subject 8

% All positions for seated sling
supine_08a = subject_08_a(:,:,365:1839);
suspended_08a_tochair = subject_08_a(:,:,2252:3695);
seated_08a = subject_08_a(:,:,4320:5498);
suspended_08a_tobed = subject_08_a(:,:,5631:5980);
supine30end_08a = subject_08_a(:,:,6220:7503);

% All positions for supine sling
supine_08s3 = subject_08_s3(:,:,92:1928);
suspended_08s3 = subject_08_s3(:,:,1975:3460);
supine_end_08s3 = subject_08_s3(:,:,3503:4969);
```

C.3 Save 200 Frame Count Files into MATLAB

```
% Julie Kahn
% Save 200-ct positions
% Subject 8

% All positions for seated sling
supine_08a = subject_08_a(:,:,610:809);
suspended_08a_tochair = subject_08_a(:,:,2630:2829);
```

Appendix C (Continued)

```
seated_08a = subject_08_a(:,:,4890:5089);
suspended_08a_tobed = subject_08_a(:,:,5780:5979);
supine30_08a = subject_08_a(:,:,7005:7204);

% All positions for supine sling
supineBeg_08s3 = subject_08_s3(:,:,1270:1469);
suspended_08s3 = subject_08_s3(:,:,3050:3249);
supineEnd_08s3 = subject_08_s3(:,:,4710:4909);
```

C.4 Save 200 Frame Count Files into MATLAB

```
% Julie Kahn
% Find Ave of 200 frame count
% Subject 8
Seated Position
FillingArray = zeros(100,160); % Pre-Allocate the array to be filled
for frame = 1:200 % N = 200
   FillingArray = FillingArray + seated_08a(:,:,frame); % Add points
end
FillingArray = FillingArray./200; % Divide by sample number to get the mean
seated_08a_ave = FillingArray; % Save as distinct file name
limit = 200;
seated_08a_ave(seated_08a_ave>limit) = limit;
h = figure;set(h,'name','seated_08a_ave','numbertitle','off');
imagesc (seated_08a_ave);
axis image; colorbar;set(colorbar,'YLim',[0 200]);caxis([0 200]);
```

C.5 Construct Histogram Plots in MATLAB

```
% Julie Kahn
% Plot histograms graphs
% Subject 8
suspended to chair Position
trial = suspended_08a_tochair;
count1 = numel(trial(trial(:)>0)); % points greater than 0.
count2 = numel(trial(trial(:)>20));
count3 = numel(trial(trial(:)>40));
count4 = numel(trial(trial(:)>60));
count5 = numel(trial(trial(:)>80));
count6 = numel(trial(trial(:)>100));
count7 = numel(trial(trial(:)>120));
count8 = numel(trial(trial(:)>140));
```

Appendix C (Continued)

```
count9 = numel(trial(trial(:)>160));
count10 = numel(trial(trial(:)>180));
incl_suspended_08a_tochair = [count1 count2 count3 count4 count5 count6 count7
count8 count9 count10];
incl_suspended_08a_tochair = incl_suspended_08a_tochair ./ 200 ;
count1_2 = numel(trial( trial(:)>0 & trial(:)<=20 )); % i.e. 1 to 20
count2_2 = numel(trial( trial(:)>20 & trial(:)<=40 )); % 21 to 40
count3_2 = numel(trial( trial(:)>40 & trial(:)<=60 )); % 41 to 60
count4_2 = numel(trial( trial(:)>60 & trial(:)<=80 )); % 61 to 80
count5_2 = numel(trial( trial(:)>80 & trial(:)<=100 )); % 81 to 100
count6_2 = numel(trial( trial(:)>100 & trial(:)<=120 )); % 101 to 120
count7_2 = numel(trial( trial(:)>120 & trial(:)<=140 )); % 121 to 140
count8_2 = numel(trial( trial(:)>140 & trial(:)<=160 )); % 141 to 160
count9_2 = numel(trial( trial(:)>160 & trial(:)<=180 )); % 161 to 180
count10_2 = numel(trial( trial(:)>180)); % 181 and over
excl_suspended_08a_tochair = [count1_2 count2_2 count3_2 count4_2 count5_2
count6_2 count7_2 count8_2 count9_2 count10_2];
excl_suspended_08a_tochair = excl_suspended_08a_tochair ./ 200 ;

figure; hold all;
MATRIX_incl_08_suspended_tochair = [incl_suspended_08a_tochair;
incl_suspended_08d_tochair; incl_suspended_08e_tochair;
incl_suspended_08l_tochair];
plot((1:10),MATRIX_incl_08_suspended_tochair(1,:),(1:10),
MATRIX_incl_08_suspended_tochair(2,:),(1:10),MATRIX_incl_08_suspended_tochair(3,:
),(1:10),MATRIX_incl_08_suspended_tochair(4,:));
legend('incl suspended 08a_tochair','incl suspended 08d_tochair','incl suspended
08e_tochair','incl suspended 08l_tochair');

figure; hold all;
MATRIX_excl_08_suspended_tochair = [excl_suspended_08a_tochair;
excl_suspended_08d_tochair; excl_suspended_08e_tochair;
excl_suspended_08l_tochair];
plot((1:10),MATRIX_excl_08_suspended_tochair(1,:),(1:10),
MATRIX_excl_08_suspended_tochair(2,:),(1:10),MATRIX_excl_08_suspended_tochair(3
,:),(1:10),MATRIX_excl_08_suspended_tochair(4,:));
legend('excl suspended 08a_tochair','excl suspended 08d_tochair','excl suspended
08e_tochair','excl suspended 08l_tochair');
```

Appendix C (Continued)

C.6 Calculate Various Variables Needed for Analysis

```
% Julie Kahn
% VA Research
% Data Analysis of Sling Study - COMBO

% JK 01/02/13
Find the Peak Pressure (max pressure obtained) from the sensor array
% Input which array and how many frames you would like to work with
DataMatrix = input('Enter the name of the data source/matrix you wish to analyze:');
FrameCount = input('Enter the number of frames:');
% Pre-Allocate the matrix with zeroes
FrameArray = zeros(1,FrameCount);

% Run a loop to analyze each frame up to 'FrameCount' in the file
for FrameNum = 1:FrameCount
    % The first max function finds the Maximum Pressure for each column in
    % one frame. The second max function finds the Maximum Pressure of the
    % frame (by comparing each max column pressure).
    PeakPressure = max(max(DataMatrix(:,:,FrameNum))); % Finds Max P for
    % each individual frame
    FrameArray(:,FrameNum) = PeakPressure; % Fills the Max P values into
    % designated array
end

% Plot the results to show the frame-by-frame trend of the Max P
plot(FrameArray(:,:),'-or') % Solid line, Circle point, Red color
title('Peak Pressure Analysis Per Frame');
xlabel('Frame Number of the File');
ylabel('Peak Pressue in mmHg');
grid on

% Finds the Max P of the file from this array of frames
[PeakPressure, FrameNum] = max(FrameArray(:,:));
% Display the Max P value and the number of frames analyzed
fprintf('The Peak Pressure for %d frames is: %2.3f
mmHg.\n',FrameCount,PeakPressure)
% Display the Frame Number where the Max P was found in the file
fprintf('This peak pressure has been located at frame number: %d.\n',FrameNum)

% Look into getting the anatomic locations for FrameArray (max P at each
```

Appendix C (Continued)

```
% frame).... Given the frame number, find max P... FrameArray(#)

FrameNumber = input('Enter which frame you would like to know the Peak Pressure
for:');
FramePressure = FrameArray(FrameNumber)

Find the Anatomic Location of Pressure Points
v = DataMatrix;
[position]=find(ismember(DataMatrix,PeakPressure)); % Outputs character
% index assigned by matrix
% 'PeakPressure' can be replaced by any number interested in finding
[i,j,k] = ind2sub(size(DataMatrix),position); % Outputs actual position in
% (i,j,k)
Position_PeakP = [i,j,k]; % Combine the three vectors into one matrix for
% easy viewing
Find the Total Time - The sum of the static time and the
transer/transport time - Amount of time patient is in sling
% Input the total number of frames being analyzed
% FrameCount = input('Enter the number of frames:');

freq = 5; % Frequency recorded in units of hertz (5 frames/sec)

% frequency = 1/ seconds
TimeSec = 1/freq * FrameCount; % Units of seconds
TotalTime = TimeSec/60; % Units of minutes
Find the Mean Pressure
MeanPressure = mean(DataMatrix(:));
MeanPArray = zeros(1,FrameCount);
% Run a loop to analyze each frame up to 'FrameCount' in the file
for FrameNum = 1:FrameCount
    % The first max function finds the Maximum Pressure for each column in
    % one frame. The second max function finds the Maximum Pressure of the
    % frame (by comparing each max column pressure).
    Data = DataMatrix(:,:,FrameNum);
    MeanPressure = sum(sum(Data))./sum(sum(Data~=0)); % Finds the Mean P
    % without taking into account all of the zeros in the frame

    % MeanPressure = mean(mean(DataMatrix(:,:,FrameNum))); % Finds Mean P
    % for each individual frame... zeros included in calculation!

    MeanPArray(:,FrameNum) = MeanPressure; % Fills the Mean P values into
```

Appendix C (Continued)

```
   % designated array
end

Find the Cumulative Pressure
CumPressure = TotalTime .* MeanPArray; % Units of min*mmHg
Find the Center of Pressure
% MJP 10/31/12
% Edited JK 11/13/12 to use repmat

COP_Array = zeros(2,FrameCount); % Put each COP x and y value in for the
% entire FrameCount

x = 1:160;
ArrayX = repmat(x,[100 1]);

y = (1:100)';
ArrayY = repmat(y,[1 160]);

% Run a loop to analyze each frame up to 'FrameCount' in the file
for FrameNum = 1:FrameCount
    totalPressure = sum(sum(DataMatrix(:,:,FrameNum))); % Total pressure
    % for individual frame calculated one at a time (one per loop)

    COP_X=sum(sum(ArrayX.*DataMatrix(:,:,FrameNum)))/totalPressure; % Finds
    % the Column (x) COP for each individual frame

    COP_Y=sum(sum(ArrayY.*DataMatrix(:,:,FrameNum)))/totalPressure; % Finds
    % the Row (y) COP for each individual frame


    COP_Array(1,:) = COP_X; % Column COP into 1st row of array
    COP_Array(2,:) = COP_Y; % Row COP into 2nd row of array
end
Find the Symmetry of Pressure
Find the Contact Area
Pressure = Force / Area Area = Force / Pressure ... Units should be cm^2
ContactArea_Array = zeros(1,FrameCount);

Sensel_Area = (0.51)^2; % Each individual sensor area in units of cm^2
Sensel_Area = Sensel_Area * (1E-4); % Units of m^2
```

Appendix C (Continued)

```
% Run a loop to analyze each frame up to 'FrameCount' in the file
for FrameNum = 1:FrameCount
    Pressure = sum(sum(DataMatrix(:,:,FrameNum))); % Total Pressure for

    % each frame in units of mmHg
    Pressure = Pressure * 133.32; % Units of Pa

    n = nnz(DataMatrix(:,:,FrameNum)); % Number of non-zero elements in
    % the frame matrix

    Force = Pressure * Sensel_Area * n;
    % Units: Pa * m^2 = N / m^2 * m^2 = N

    ContactArea = Force / Pressure; % Units: N / Pa = N / N / m^2 = m^2
    ContactArea = ContactArea / (1E-4); % Units of cm^2

    ContactArea_Array(:,FrameNum) = ContactArea; % Fills the contact area
    % values into designated array
end
Find the Peak Pressure Index
I = DataMatrix;
fun = @(x) mean(mean(x(:))); % Function handle is to get the mean of frame

% A 6 by 6 block has been chosen because we are looking for an area of 9-10
% cm^2. Each block is 0.51 by 0.51 cm, so 6 by 6 results in an area of
% about 9.3 cm^2.
I2 = nlfilter(I, [6 6], fun); % Similar to blkproc or colfilt

% imshow(I);
% figure, imshow(I2);
Find the Coefficient of Variation
% First calculate the sample standard deviation

CV_Array = zeros(1,FrameCount);
% Run a loop to analyze each frame up to 'FrameCount' in the file
for FrameNum = 1:FrameCount
    Pi = DataMatrix(:,:,FrameNum);
    Pbar = sum(sum(Pi))./sum(sum(Pi~=0)); % Mean P not including zero
    % elements
    % Pbar = mean(mean(DataMatrix(:,:,FrameNum))); All the zeros factor
    % into this equation making the Pbar very low
```

Appendix C (Continued)

```
   N = nnz(DataMatrix(:,:,FrameNum)); % Sample size - Number of non-zero
    % elements present in each frame matrix

    ArrayP = zeros(100,160);
    for index = 1:N
        P = (Pi - Pbar).^2;
        ArrayP = P;
    end

    SD = sqrt((1/(N-1))*sum(sum(ArrayP))); % Stadard Deviation

    % Now calculate the CV directly - Ratio of the sample standard
    % deviation to the sample mean

    CV = SD / Pbar;
    % CV = CV * (1 + 1/(4*N)); % Normally distributed data, unbiased
    % estimator

    CV_Array(:,FrameNum) = CV; % Fills the CV values into designated array
end
Find the Dispersion Index
Results - Okay to use if only 1 frame, or will show LAST frame
label = ' Results '; disp(label); disp ('Total Time in min'), disp (TotalTime); disp ('Mean
Pressure in mmHg'), disp(MeanPressure); disp ('Cumulative Pressure in mmHg*min'),
disp(CumPressure); disp ('X COP (column position)'), disp(COP_X); disp ('Y COP (row
position)'), disp(COP_Y); disp ('Contact Area in cm^2'), disp(ContactArea); disp
('Coefficient of Variation'), disp(CV);
```

C.7 Configuration Setting for Standard Deviations

```
% Julie Kahn
% 1/2/13
% How to analyze the data- calculate the standard deviation of each %point compared
to that point throughout the frame count
% DataMatrix is the original file you will be using

manipulations DataMatrix = input('Enter the name of the data source/matrix you wish
to analyze:'); FrameCount = input('Enter the number of frames:');

% FrameCount = 100; % Number of frames you will be analyzing
N = FrameCount; % Number of points in each population below
```

Appendix C (Continued)

```
% First add up all the frames and save to a new variable to get one 100 by
% 160 frame (i.e. D = C(:,:,1)+ C(:,:,2)+ ...;)
PointMatrix = zeros(100,160); % Pre-Allocate the matrix with zeroes

for frame = 1:FrameCount % Analyze each frame within the file
   PointMatrix = PointMatrix + DataMatrix(:,:,frame); % Place values into
   % this new matrix
end

Pbar = PointMatrix ./ N; % Get the mean of each individual point by
% dividing each point by the sample size
% Calculate the Standard Deviation
Matrix = zeros(100,160); % Pre-Allocate the matrix with zeroes
SumofMeansMatrix = zeros(100,160); % Pre-Allocate the matrix with zeroes
for frame = 1:FrameCount % For multiple frames in the file
   Matrix = (DataMatrix(:,:,frame) - Pbar).^2; % Subtract the mean
   % pressure from each point in the matrix and square them
   SumofMeansMatrix = SumofMeansMatrix + Matrix;
end
   SD = sqrt((1./(N-1)).*(SumofMeansMatrix)); % Stadard Deviation
```

C.8 Plotting Standard Deviations

```
% Julie Kahn
% Plot given figures of the standard deviations
Seated Position
DataMatrix = seated_08a;
FrameCount = 200;
 run('C:\Users\user\Documents\MATLAB\Sling Study Data Analysis\Standard
Deviations\Figures Subject 8\SlingStudy_DA_conjFig.m')
SD_seated_08a= SD;
h = figure;set(h,'name','SD_seated_08a','numbertitle','off');
mesh (SD_seated_08a);

Seated Position
DataMatrix = seated_08a;
run('C:\Users\user\Documents\MATLAB\Sling Study Data Analysis\Standard
Deviations\TenSectionSD\SlingStudy_DA_conjFig.m')
SD_seated_08a= SDArray;
% figure; plot(SD_seated_08a);
figure; hold all;
```

Appendix C (Continued)

```
MATRIX_08_slingA = [SD_seated_08a; SD_suspendedtochair_08a; SD_supine_08a;
SD_supine30_08a];
plot((1:10),MATRIX_08_slingA(1,:),(1:10),
MATRIX_08_slingA(2,:),(1:10),MATRIX_08_slingA(3,:),(1:10),MATRIX_08_slingA(4,:));
legend('seated 08a','suspendedtochair 08a','supine 08a','supine30 08a');
```

C.9 Configuration Setting for Mean Pressures

```
% Julie Kahn
% VA Research
% Data Analysis of Sling Study

% JK 05/13/13
Find the Mean Pressure
MeanPressure = mean(DataMatrix(:));
N = 20; % Number of points in each population below
starter = 1; % Start frame location
ender = 20; % End frame location
MeanArray = zeros(1,10);

% Divide into 10 sections by finding the SD of each 20 frames
for section = 1:10 % Which section of 10 we are on
P = zeros(1,20);

% Run a loop to analyze each frame up to 'FrameCount' in the file
for FrameNum = starter:ender
   % The first max function finds the Maximum Pressure for each column in
   % one frame. The second max function finds the Maximum Pressure of the
   % frame (by comparing each max column pressure).
   Data = DataMatrix(:,:,FrameNum);
   MeanPressure = sum(sum(Data))./sum(sum(Data~=0)); % Finds the Mean P
   % without taking into account all of the zeros in the frame

%     MeanPressure = mean(mean(DataMatrix(:,:,FrameNum))); % Finds Mean P
%     % for each individual frame... zeros included in calculation!
   P(:,FrameNum) = MeanPressure; % Fills the Mean P values into
   % designated array
end
   P = sum(sum(P))./sum(sum(P~=0));;
   MeanArray(:,section) = P; % Fills the matrix
   starter = starter + 20; % Goes to next section
   ender = ender + 20; % Goes to next section
```

```
end
```

C.10 Plotting Mean Pressures

```
% Julie Kahn
% Plot given figures of the means
Seated Position
DataMatrix = seated_08a;

run('C:\Users\user\Documents\MATLAB\Sling Study Data Analysis\Standard
Deviations\TenSectionSD\SlingStudy_DA_conjMeanFig.m')
Mean_seated_08a= MeanArray;
% figure; plot(Mean_seated_08a);
figure; hold all;
MATRIX_08_slingA = [Mean_seated_08a; Mean_suspendedtochair_08a;
Mean_supine_08a; Mean_supine30_08a];
plot((1:10),MATRIX_08_slingA(1,:),(1:10),
MATRIX_08_slingA(2,:),(1:10),MATRIX_08_slingA(3,:),(1:10),MATRIX_08_slingA(4,:));
legend('seated 08a','suspendedtochair 08a','supine 08a','supine30 08a');
```

C.11 Calculating ANOVA

```
% Data = subject_01_a(:,:,72:1330);
% imagesc(Data(:,:,1));axis image; grid on;
% A = Data(:,:,1);
% B = Data(:,:,2);

% load('Subject01_200frames.mat')
% SlingStudy_PlotSDfigs_1
A = SD_seated_01a;
B = SD_suspendedtochair_01a;
MeanA = mean(mean(A(:)));
MeanB = mean(mean(B(:)));
[mA, nA] = size(A); pointsA = mA*nA;
[mB, nB] = size(B); pointsB = mB*nB;
points = pointsA + pointsB;
SumA = sum(sum(A));
SumB = sum(sum(B));
Sum = SumA + SumB;
MeanOverall = Sum / points;
AA_hat = MeanA - MeanOverall;
AB_hat = MeanB - MeanOverall;
```

Appendix C (Continued)

```
df_pos = 2-1;
df_meastot = points-1;
df_res = df_meastot - df_pos;
SS_pos = (AA_hat^2*pointsA)+(AB_hat^2*pointsB);
SS_res = sum(sum((A - MeanA).^2)) + sum(sum((B - MeanB).^2));

SS_tot = SS_pos + SS_res;
SS_tot2 = sum(sum((A - MeanOverall).^2)) + sum(sum((B - MeanOverall).^2));

% SS_tot2 should be equal to SS_tot

MS_pos = SS_pos / df_pos;
MS_res = SS_res / df_res;
F = MS_pos / MS_res;
```

Appendix D Equipment Specifications

D.1 Hill-Rom VersaCare-AIR

Table D.1: Hill-Rom Versacare AIR specifications

Specifications	
Standard Length	86 inches Fully Extended 75 inches Fully Retracted
Standard Width	35.5 inches
Therapeutic Patient Weight Limit	500 pounds
Flammability	Boston IX-11, CAL 129, 16CFR1633, 16CFR1632, CAN/CGSB 4.2#27.7

D.2 Quickie GP/GPV Wheelchair

Table D.2: Quickie wheelchair specifications

Specifications	
Seat Depth/ Length	12 – 22 inches
Seat Width	12 – 22 inches
Overall Width	23 – 31 inches
Seat to Floor Height	17.25 - 19 inches
Weight Limit	250 pounds
Overall Weight	21.5 lbs (GPV), 26 lbs (GP)
Caster Options	3, 4, 5, 6 inches
Rear Wheel Options	22, 24, 26 inches
Axle Options	Standard- stainless steel, optional Titanium, and Quad release axel nuts
HCPCS Requirement	K0005

Appendix D (Continued)

D.3 Invacare Absolute Wheelchair Cushion

Table D.3: Invacare wheelchair cushion specifications

Specifications	
Standard Length	20.04 inches
Standard Width	3.48 inches
Standard Height	18 inches
Weight	2 pounds

D.4 ArjoHuntleigh Maxi Sky 600 Lift System

Table D.4: Maxi Sky 600 lift system specifications

Specifications	
Strap Length	90 inches
Height from Floor to Ceiling	82 – 118 inches
Safe Working Load	600 pounds
Lifting Speed	1.2 inches /sec (at 600 lbs) 1.6 inches /sec (at 440 lbs) 2.3 inches /sec (at 0 lbs)
Horizontal Displacement Speed	4, 6, 8, 10 inches /sec
Unit Weight	28 pounds

D.5 XSensor High Resolution Pressure Map

Table D.5: XSensor pressure array specifications

Specifications	
Product Name	PX100:100.160.05
Dimensions	20 by 32 inches
Sensor Set Up	100 by 160 sensors
Resolution	0.2 inches
Calibration	10 – 200 mmHg
Dielectric Response Time	7 – 10 frames/sec
Sensor Delay	Matter of milliseconds

Appendix E Medical Records Review Form

(Shaded section to be completed prior to informed consent.)

1. In Tampa SCI Registry	YES NO NA (Healthy Volunteer)
2. 18-65 years of age	YES NO
3. Medically able to be in study?	YES NO Clinician Signature: _____ Clinician Name: DATE:
4. Enrolled in other studies?	YES NO If yes, what study and is dual enrollment approved Y N
5. Gender	
6. Age (by decade)	
7. Height	
8. Weight	
9. SCI level/type of injury*	
10. SCI date of occurrence*	
11. Level of function*	
12. Typical length of time in bed/wheelchair per day*	
13. Nutritional status*	
14. History of PrUs (dates and locations of occurrence)* *(continue on separate sheet as required)*	
15. Prior surgery(ies) for treatment of PrU(s): Types and outcomes* *(continue on separate sheet as required)*	

* Participants with SCI only

Appendix F Sling Questionnaire Form

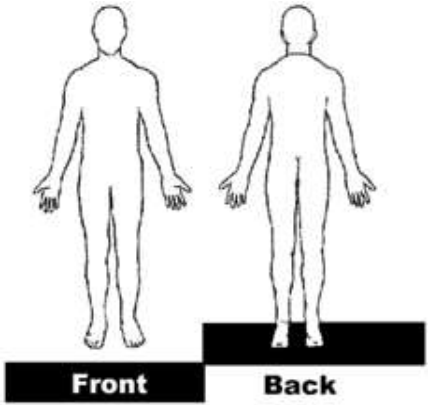
Study Participant Number: _____ Sling ID: _____

1. On a scale from 1 to 5, how secure did you feel in the sling?

   Least Secure 1 2 3 4 5 Most Secure
2. On a scale from 1 to 5, how comfortable did you feel in the sling?

   Least Comfortable 1 2 3 4 5 Most Comfortable
3. On a scale from 1 to 5, how much discomfort, if any, did you feel in the sling?

   No Discomfort 1 2 3 4 5 Most Discomfort
   Please identify any locations of discomfort: _____



4. On a scale from 1 to 5, how much pain, if any, did you feel in the sling?

   No Pain 1 2 3 4 5 Most Pain

   Please identify any locations of pain: _____