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Applying Modeled Hemi-Ellipsoids to the Study of Pressure Distribution in Normal and Paraplegic Seated Subjects

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Applying Modeled Hemi-Ellipsoids to the Study of Pressure Distribution
in Normal and Paraplegic Seated Subjects

by

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A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Biomedical Engineering
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DEDICATION

To all those who believe that an engineer and a physician can co-exist; to my committee members for steering my dream; to Mom, Dad, and Evan for being my cheerleaders even when I fail; to Josh for always knowing what to say at the right moment; to my many friends who served as testing subjects; to my wonderful patients who are my greatest teachers; to Lester for introducing me to “Fats” who inspired this effort and believes that “Great minds – like ours – can’t be just one thing”; and of course to Dr. Fabri, the physician and engineer I most admire.
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ABSTRACT

The three goals of this research were to investigate how normal subjects move while seated, how paraplegic patients move while seated, and whether seated movements can be modeled using a hemi-ellipsoid shape. Pressure readings were recorded at 11 Hz using a 36 by 36 sensor pressure map by XSENSOR. Subjects were instructed to move or perform pressure relief as they normally would while seated. Analysis was performed using Microsoft Excel with Solver and Matrix.xla add-ins and automated with VBA code. Major movements and time intervals between movements were calculated by locating the area of maximum pressure on each hemi-buttock for 20 normal and 6 paraplegic subjects. Statistical analysis revealed movements followed a normal distribution while time intervals followed a lognormal distribution. For both the normal (p=0.041) and paraplegic groups (p=0.007) the number of movements significantly increased from the first hour of recording to the second hour. The time interval between major movements decreased but not significantly for neither the normal subjects nor the paraplegics. No significant differences were identified between the normal and paraplegic groups over the first hour or second hour for number of movements or time intervals. Time series analysis with plotting, trend lines, ARIMA, and periodograms did not reveal patterns in the data. Preference for a side was shown. Next, all areas of identified major movements for one subject and one frame for each of the paraplegic patients were modeled as a hemi-ellipsoid shape using minimization with Solver. Eigenvalues were calculated in order to obtain the lengths of the x, y, and z axis of the hemi-ellipsoid with an average error of 39.87% for the normal subject and an error range of 5.10% to 2701.81% for the paraplegic patients.
CHAPTER 1: INTRODUCTION

1.1 Objectives

The purpose of this research is to answer the following three questions:

1. How do normal subjects move while seated?
2. How do paraplegic patients move while seated?
3. Can movement be modeled by fitting pressure readings to a hemi-ellipsoid shape?

1.2 Problem Definition

The escalating cost of health care in the United States has prompted investigation into assessing quality measures in patient care and possible sources of inefficiencies which may be contributors. In 2009, the Centers for Medicare and Medicaid Services (CMS) labeled 8 conditions for which hospitals would no longer receive reimbursement if these events occurred during a patient’s stay (Miller, 2009). One of these named preventable adverse events in patient care is the pressure ulcer. Since CMS’s decision, the medical codes for pressure sores were changed to reflect the level of wound involvement (Armstrong et al., 2008). Pressure sores are a pertinent component in health care quality, but exactly what is the significance on society?

Pressure sores cause a huge burden on the health care system with an estimated 2.5 million people affected annually in the United States, alone (House, Giles, & Whitcomb, 2011). In 2004, the Centers for Disease Control found more than 1 in 10 nursing home residents had a pressure ulcer (Park-Lee & Caffrey, 2009). In specialized subpopulations, the numbers are even higher. For example, the prevalence among spinal cord injuries measured several decades ago was reported as high as 60% in hospitalized quadriplegic patients (AHCPR, 1992). Cost estimates of pressure sore-related expenses range from 1.3 to as high as 11 billion dollars per year (Padula, Mishra, Makic, & Sullivan, 2011) (AHCPR,
Multiple analyses suggest prevention is the key to both patient management as well as cost reduction. An investment of $7,273.35 per hospitalization for prevention of pressure ulcers was shown cost-effective versus a $10,053.95 cost for standard care alone of at-risk patients in one assessment (Padula et al., 2011). The number of hospital days post-surgical procedure and resultant cost was also shown significant (Lapsley & Vogels, 1996). Clearly, the need to effectively identify and preemptively treat patients at risk for bed sores is relevant.

1.3 Pressure Sore Definition and Potential Causes

Normal subjects avoid pressure ulcers through mechanisms not entirely understood but are believed to be based on the sensation of touch. An uncomfortable or unpleasant feeling triggers a person to adjust their posture to relieve pressure build-up. This movement is the result of contraction of muscles which is thought to alter factors such as the shape of the muscle, strain, creep, and even oxygenation and ischemia (Curtis et al., 2011). For those individuals who have experienced damage to their sensory system, their inability to feel pain or discomfort serves as a factor for pressure sore development (Enis & Sarmiento, 1973; Thiyagarajan & Silver, 1984). Examining the changes that take place normally is pertinent to understanding the pathophysiology of pressure sore development in compromised individuals.

There are two types of pressure sores that can develop – superficial and deep. Superficial pressure sores develop externally on the surface of the skin whereas deep pressure sores develop deep within the tissue over bony prominences and work their way towards the surface (Gawlitta et al., 2006; NPUAP, 2005). Understandably, deep pressure sores can be hard to detect until they have traversed to the surface and potentially caused a large amount of damage without detection (Linder-Ganz & Gefen, 2007). A staging system of four different levels allows for classification of the pressures by severity. Stage 1 pressure sores involve only the epidermis, the most superficial layer of the skin. Once the wound progresses into the dermis, the pressure sore is classified as stage 2. Stage 3 sores extended into the
subcutaneous tissue while stage 4 can include muscle and even bone. Pressure sores can also be classified as "unstageable" if an eschar covers the wound preventing determination of tissue level involvement ("Pressure Ulcer Category/Staging Illustrations,"). Illustrations of normal tissue and the various stages of pressures sores are shown in Figures 1-3.

Many studies seek to identify factors which predispose patients towards developing these sores. Obvious contributors such as age, weight, and general health have been examined. Many of the studies focus on factors generally accepted in pressure sore development such as pressure, shear, temperature, ischemia, and cellular deformation (Deitrick, Charalel, Bauman, & Tuckman, 2007; Gawlitta et al., 2006; Linder-Ganz, Engelberg, Scheinowitz, & Gefen, 2006; Linder-Ganz & Gefen, 2007; Manorama, Baek, Vorro, Sikorkii, & Bush, 2010; Stadler, Zhang, Oskoul, Whittaker, & Lanzafame, 2004; Yavuz, Tajaddini, Botek, & Davis, 2008). However, other factors such as nutrition, metabolic activity, moisture, friction, infection, neurological involvement, duration of pressure loading, reperfusion injury, platelet aggregation, endothelial dysfunction, and others have also been considered (Linder-Ganz et al., 2006; Loerakker et al., 2010; Matsuyama et al., 2000; Pompeo, 2007; Struck & Wright, 2007). Despite centuries of study of this disease process, much uncertainty remains about the exact causes of pressure sores. It is likely that pressure ulcer formation is multi-factorial in nature and the contribution of each component varies by individual.

1.4 Pressure Sore Prevention

Prevention is crucial in individuals at risk for pressure sores and many assessment tools have tried to quantify the associated risks leading to their formation. Examples of tests include the Pressure Sore Prediction Score, Norton, Waterlow, Braden, Walsall, and Ramstadius tools (Gadd, 2014). While these tools or their variations are extensively used by health care professionals little has been done to assess the validity of their described risk factors. One difficulty with assessing the contribution of a hypothesized factor to sore development is that randomized control trials of this nature would be
unethical. However, (Sharp & McLaws, 2006) performed an evidence-based literature review of existing assessment tools to see if any of the risk factors could be shown to have a relationship with pressure sore development. Of the 19 factors considered from 6 screening tools only immobility was shown to have a positive predictive value as being a contributing factor to pressure sore development. Although other factors such as nutrition are likely to play a role in development of the ulcers the authors contend that mobility overshadows these contributions. If mobility is in fact one of the most important determinants of pressure sore formation, it logically follows that those with spinal cord injuries (SCI) or others who have limited or no ambulation would be at a substantially increased risk for sore development, which is in fact the case.

The current mainstay of pressure sore management includes turning protocols instructing nursing staff to move the patient every two hours. Although an internationally recognized guideline, the initial impetus for this routine appears largely anecdotal, dating back to the 1800s. Despite the uncertainty of the origination of this treatment regimen, experiments have given scientific credence. Studies by Husain and Kosiak on animals and later Reswick and Rogers on humans lead to establishment of a curve demarcating recovery vs. cellular deformation, with 2 hours serving as an important marker where the pressure-time slope changes from a steep decline and begins to level off (Hagisawa & Ferguson-Pell, 2008).

Unfortunately, a scarcity of clinical data exists to definitively answer questions on positioning. A few studies examining the frequency of turning show no significant difference between 2 hour versus 4 hour turning regimens. However, the Defloor study altered the bed type used between comparison groups, confounding the effect of turning schedule vs. surface type on pressure ulcer inducement (Defloor, De Bacquer, & Grypdonck, 2005; Reddy, Gill, & Rochon, 2006). Additionally, placement in the 30 degree lateral position versus 90 degree lateral or semi-Fowler's position has not been proven more effective and the best position for these patients remains unknown (Krapfl & Gray, 2008). Nevertheless,
documentation by nursing staff on turning patients every 2 hours is becoming mandatory in some hospitals to combat litigation. The toll on the health care system for lawsuits relating to pressure ulcer development is significant, with a single case resulting in a judgment of $312 million. Hospitals are being encouraged to learn the difference between terms such as "guideline" versus "protocol" as the wrong word can imply negligence if proper documentation of a pressure sore occurs even once during a hospital stay or episode of care (Fife et al., 2010).

Self-induced pressure relief techniques such as sitting push-ups where wheelchair users are taught to use their upper-body strength to lift their buttocks for pressure relief are also universally accepted despite a lack evidence-based research. One study based on survey results of participants shows weight shifting does not impact pressure ulcer formation but reports somewhat contradictory that "exercise" does serve as a protective factor. The terms "weight shift" and "exercise" were not defined in the study (Krause & Broderick, 2004). Alternative pressure relief movements for weight shift such as the forward lean, lateral lean, and rearward tilt are being supported based on evidence that the relief resulting from sitting push-ups is not adequate nor possible to maintain (Sonenblum, Vonk, Janssen, & Sprigle, 2014; Sprigle & Sonenblum, 2011). A better understanding of what pressure relief regimens entail and prospective studies are needed.

Devices abound for pressure relief. Multiple types of padding ranging from sheep skin to foam to gel exist for beds, operating room tables, and wheelchairs. There are so many different types of beds and bedding that they are divided into the categories of static (for not moving) and dynamic (for changing configuration such as air and fluid). One example of a dynamic system uses cyclic-pressure relief created by a special chair. Compared to a traditional wheelchair it resulted in improved healing in pressure ulcer patients determined by photographic measurement techniques (Makhsous et al., 2009).

In summary, despite many established protocols in hospitals and care settings and a myriad of devices including special beds and chairs, many questions about proper prevention of pressure sores
remain unanswered and care is often based on the logic of the caregiver versus evidence-based medicine. A need exists to better understand how individuals move.

1.5 Significance of Research

The purpose of this research is to better understand how normal subjects and paraplegic patients move. Many studies assessing pressure only look at a snapshot in time and do not assess pressure continuously whereas this study records pressures at 11Hz. Additionally, pressure readings are recorded over 2 hours to see the effects over time on movement.

Another significant contribution to the field is examining if pressure readings can be modeled as a hemi-ellipsoid shape. Many current studies only look at maximum or average pressures in individuals and may not reveal pertinent information on the movement in the x, y, and z axis.

1.6 Limitations of Research

While this research will compare and contrast normal subjects and paraplegic patients, the goal is not to seek differences between the two groups but instead to simply model and describe how these individuals move. By gaining a better understanding of how an individual moves it may be possible in the future to adjust the treatment regimens for paraplegic patients, but that is not the intent of the current study. One major limitation in this study is the low number of paraplegic patients enrolled. While more paraplegic patients were admitted to the hospital during the collection phase, these patients were excluded due to the presence of a pressure sore as there was concern sitting for a 2 hour period could be detrimental to the patient's safety.
Figure 1 Image of skin layers composing normal individual.

Figure 2 Images of four stages of pressure ulcers. (Left to right) Stage 1: Epidermis involvement. Stage 2: Epidermis and dermis involvement. Stage 3: Injury down to subcutaneous tissue. Stage 4: Involvement of muscle and or bone.
Figure 3 (Left) Unstageable pressure sore with eschar hiding level of involvement. (Right) Suspected deep tissue injury implicated by bruising of the superficial layers of the skin.
CHAPTER 2: LITERATURE REVIEW

2.1 Understanding Contributors to Pressure Sore Formation

Pressure - being included in the name - is an obvious contributor to pressure sores. However, the exact effects of pressure are uncertain. A 1938 paper by Landis entitled, “The Capillaries of the Skin: A Review,” looked at fluid flow in the body. This paper would later serve as the foundation for the pressure piece of the equation Rogers and Reswick would construct for their pressure-time curve. Landis focused on measurements involving the capillaries in the most easily observable place in the body, the skin at the base of the fingernail. He determined when the hand was placed at the level of the heart the arteriolar end of the capillary had a blood pressure of 32 mmHg. Thus, pressures that are stronger than this outward hydrostatic pressure could lead to closure of the vessel and hypoxemia resulting from lack of flow. He further discussed differences between surface blood vessels and those in deeper tissue where vessels were more abundant (Landis, 1938). Initially, it was the more accessible surface tissues that were studied using 32 mmHg as the collapsing pressure (Edsberg, Mates, Baler, & Lauren, 1999). By revealing the framework and some of the basic physiologic characteristics of the blood vessel anatomy in superficial and deep tissue Landis set the stage for further investigation into the causes of pressure sore development via a diminished flow hypothesis.

Understanding of the contributors to pressures sore formation has since expanded beyond a simple model of decreased perfusion. However, ischemia remains a pertinent contributor in the model. Tools such as laser and duplex Doppler have allowed for measurement of total blood flow as well as flow limited to the skin. Comparing blood flows between normal and SCI patients has shown the body adapts after injury. When subjects go from a supine to a sitting position both normal and SCI patients experience a decrease in skin blood flow in their lower extremities. However, Doppler has allowed a
look at the internal change in blood flow. In normal individuals there is a large reduction in total blood flow to the legs. When SCI patients are examined, however, the flows change. Tetraplegic patients have flows that can increase or decrease while paraplegic patients have flows that are lower than tetraplegic patients. It is hypothesized that in paraplegic individuals perhaps the body is adjusting its flow to the damaged tissue and diverting it to the parts of the body still functioning in a mechanism called the “Steal Effect,” resulting in decreased flows compared to the tetraplegic group (Deitrick et al., 2007). Similar effects are believed to occur in other autonomic neuropathies such as diabetes (Cobb & Claremont, 2001). The results of this and other studies support the notion that pressure sore development is a combination of superficial and deep elements affected by fluid flow.

Nearly 40 years after Landis quantified the hydrostatic pressure in a capillary Reswick and Rogers constructed the aforementioned pressure-time curve based on 980 medical cases where they measured interface pressure over bony prominences while seated and recorded whether or not the patient had a pressure sore following pressure exposure (Barbenel, 1991). Their model assumed a rectangular hyperbola where in order to stay under the danger zone signifying risk for pressure sore formation the pressure-time product had to be under a Critical Pressure Time Product of about 300 mmHg x hr. While data in the middle of the curve gave predictable results the tails of the graph did not fit reality. The first major adjustment to the model came with Linder-Ganz suggesting a sigmoid curve based on their study of the histopathology of rats with induced ulcers. This modern analysis incorporated the use of Finite Element Analysis (FE) to allow for estimation of the internal pressure as opposed to the interface pressure measured by Reswick and Rogers. Additionally, a relationship with cellular deformation was established supporting an alternative explanation for pressure sore formation. Their work showed depending on the length of time pressure was applied the factors affecting cell death and their magnitude varied. For exposure under 1 hour maximum pressure had the greatest effect resulting in cell death with pressures greater than 32 kPa. Over 2 hours maximum pressure was still the
best determinant but the maximum pressure needed to cause cell death was reduced to 9 kPa. Between 1 to 2 hours, however, exposure time became the more critical factor with maximum pressures dropping from 32 kPa to 9 kPa (Gefen, 2009a, 2009b; Linder-Ganz et al., 2006). With pressures less than the hydrostatic pressure of 32 mmHg causing cellular death it appeared that other factors besides ischemia could lead to pressure sore development giving strength to the tissue deformation hypothesis.

Scientists further investigated the effects of cellular damage as the main contributor to cellular death. Gawlitta et al performed an in vitro study of engineered murine skeletal muscle exposed to different compression levels in normoxic and hypoxic conditions. The study found that hypoxia did not lead to significant cell damage till after the first 22 hours. However, compression led to immediate destruction which worsened with time (Gawlitta et al., 2006). Linder-Ganz and Gefen performed an in vivo study with animals and FE analysis to analyze cellular deformation. Infrared thermography showed that despite histological evidence of cellular death complete ischemia of loaded muscle did not occur in the first 40 minutes of testing. After 40 minutes clotted vessels could lead to occlusion of flow, thus suggesting ischemia at longer time periods could have an increased contribution in cell death. The realization that pressure sores often develop internally and that Landis’s measurement of capillary closure pressure in the external layer of skin might be drastically different from the internal muscle capillary closing pressure could help explain these results (Linder-Ganz & Gefen, 2007).

Shear strain was also found to have an effect on inducing vessel occlusion. Even with loads of 12-120 kPa with shear strains of up to 8% added (far above the value of 32 mmHg (4.3 kPa) that Landis published for capillary closure) only a maximum of 46% of the capillaries could be completely closed (Linder-Ganz & Gefen, 2007). Many studies are now investigating the effects of shear pressure and the physiological and mechanical changes this force induces. One study examining forces while walking found that maximum pressure and shear values not only occur at different locations, but also at different points in time. Thus, perpendicular forces are not the only force acting on the skin and other
biomechanical properties need to be assessed (Brienza, Karg, Geyer, Kelsey, & Trefler, 2001; Lahmann, Tannen, Dassen, & Kottner, 2011; Manorama, Baek, Vorro, Sikorskii, & Bush, 2010; Stucke et al., 2012; Wang, Brienza, Yuan, Karg, & Xue, 2000).

Another theory for pressure sore causation is that while ischemia doesn’t directly cause injury the restoration of blood to previously occluded areas may result in an increase in oxygen free radicals. Reperfusion was shown in mice by inducing injury with a magnet and observing an initial immediate decrease in baseline temperature followed by an increase in temperature from baseline as blood flow returned (Stadler et al., 2004). Another animal study investigated ischemia alone versus ischemia-reperfusion cycles of the same total duration of ischemia and found that the cycles resulted in increased tissue damage as measured by leukocyte number, area of necrosis, and skin blood flow. Increasing the number of cycles, total duration of ischemia, and the frequency of the cycles also resulted in increased damage (Pierce, Skalak, & Rodeheaver, 2000). The mechanical effects of pressure relief were also investigated with varying results. However, it is likely that there lies an optimal point of load and load time as well as pressure relief time that affects reperfusion and damage and that once this time point is reached for load and rest both reperfusion and mechanical damage result (Edsberg et al., 1999; Loerakker et al., 2010).

If reactive hyperemia is in fact a significant contributor to pressure sore development then interventions to decrease reperfusion are desired. Jan et al showed that by decreasing the skin temperature 10°C over the sacrum where 60 mmHg of pressure was applied by a custom indenter both spinal cord injury subjects and normal controls experienced a shorter return to their baseline blood flow and less total hyperemia compared with either no change in temperature or a 10°C increase in temperature as measured by a Laser Doppler flowmetry. However, when examining the mechanisms of hyperemia a difference was noted between normal controls and spinal cord injury subjects. While both groups had reduced metabolic activity with decreased temperature, only the normal controls had
decreased neurogenic activity. The authors attribute this to loss of sensory nerves in the spinal cord injury group (Jan, Liao, Rice, & Woods, 2013). Further studies investigating the effects of temperature are currently underway.

No single factor leads directly to pressure sore development. The answer to causation is likely a function consisting of multiple factors dependent on pressure and time. Compounding variables such as diseases and differing body compositions complicate an already complex picture.

2.2 A Focus on the Study of Pressure

Scientists and engineers have looked for ways to mathematically understand and model the skin in order to prevent pressure sores from occurring. The most obvious focus is pressure. Over the past 30 years, the field of analytics and sensor development have blossomed. The result is an exponential increase in the amount of information that can be obtained from an individual. Most studies initially looked at snap-shots in time and examined where areas of maximum pressure occurred or average pressure and what those pressures were. These initial studies were helpful in assessing whether specialized beds, which are now commonly implemented in wound care, reduced pressure. As technology improved the number of sensors used in experimentation increased and sensor size decreased. Additionally, pressure sensor designs drastically changed from the simple water-filled sensors attached to transducers in the 1980s to the complex optical systems being investigated today (Ryan & Byrne, 1989). Despite huge advancements, most pressure-sensing systems range from $5,000-10,000, far outside the range that most paraplegic patients and even some health care systems can afford (Chung, Rowe, Etemadi, Lee, & Roy, 2013).

Early pressure monitoring was used in evaluating feet. Experiments on shoe sensors showed the sensors were reliable and that inserts could remove pressure from the forefoot and hindfoot and transfer pressure to the midfoot to help with pressure relief in targeted areas (Kato, Takada, Kawamura, Hotta, & Torii, 1996; Randolph, Nelson, Akkapeddi, Levin, & Alexandrescu, 2000; Randolph, Nelson,
deAraujo, Perez-Millan, & Wynn, 1999). Special sensing elements were then created which added shear measurements to pressure sensing to get a 3-dimensional analysis of stress (Mackey & Davis, 2006). These sensors were especially helpful for diabetic patients who have decreased sensation in their extremities and thus have difficulty in subconsciously adapting for increased pressures.

Pressure sensing devices were also used to help determine the optimum seating cushions for wheel-chair bound patients by examining pressures, seating positions, and surface areas. One study compared paraplegic, neurologic, and elderly subjects and found the paraplegics had the highest peak pressures while the elderly had the highest mean pressure and lowest contact surface (Ferrarin, Andreoni, & Pedotti, 2000). Additionally, elderly patients who were wheel-chair bound and developed pressure sores over a 1 to 12 month period were statistically more likely to have higher peak pressures and higher averages of the top four pressures recorded indicating higher pressures influence pressure sore development (Brienza et al., 2001).

Yet in order to analyze the movement in neurologically compromised individuals it is first necessary to understand how a normal individual moves to adjust themselves from increased pressures. Old guidelines under the US Health Department recommended pressure relief at least once an hour but as frequent as every 15 minutes for those that are in a wheel-chair but able-bodied. However, one study questioned whether even more frequent relief protocols were warranted. Normal individuals sitting in wheel chairs were measured using a potentiometer-based electrical goniometer and averaged movement every 9 minutes in the sagittal direction and every 6 min in the frontal direction when monitored over a 90 minute period meaning that patients in wheelchairs would have to move more frequently in order to mimic the movements of normals than the old guidelines suggested. Also interesting was more pressure relief occurred on the right hand side of normal subjects presumably because 9 out of 10 of these patients were right-handed (Linder-Ganz, Scheinowitz, Yizhar, Margulies, & Gefen, 2007). Another study examined center-of-pressure (COP) displacement during forward,
backward, left, and right leans. Spinal injury patients had a smaller COP in all directions versus normal subjects and patients with a pressure ulcer history had forward and backward leans with a reduced COP compared to normals indicating dynamic sitting stability is a factor in pressure sore development (Karatas, Tosun, & Kanatl, 2008). More information on the types of movements and what these movements look like on mapping surfaces are needed to compare and contrast normals and paraplegics. Another important consideration in pressure assessment is that pressure can increase for a period of time after a patient moves and that an optimal recording time may be after several minutes in the new position (Stinson, Porter, & Eakin, 2002). Analysis of questions such as these are best first answered on normal individuals before being interpreted on paraplegic patients.

As engineering of sensors and analytical methods improved, studies moved from simply assessing maximum pressures as an endpoint to including duration over a threshold pressure. A mapping system integrated into a mattress allowed for continuous recording at 1 Hz for up to 48 hours of patients post-op in the intensive care unit. While further study is warranted, a difference was noted in the sacrum measurements between pressure ulcer groups versus redness and non-redness groups in duration of time at a pressure greater than 100 mmHg and the authors suggest that 4.5 hours may be a time threshold value at this pressure limit (Sakai et al., 2009). This would imply that turning protocols of 2 hours might be extended to longer periods. However, data pertaining to the coccyx group gave contradictory results. Defloor’s previously mentioned study might also support a longer time between turns but as discussed switching bed types between time groups possibly confounded the results (Defloor et al., 2005). The question on frequency of turning time remains unanswered.

New sensor technology such as the electro-pneumatic sensor offers potentially more accurate results by reducing the hammock effect and spatial resolution challenges found in electronic transducers and pneumatic devices, respectively (Meffre, Gehin, & Dittmar, 2007). Even so, the Everon piezo-electric sensor integrated under a mattress showed a high sensitivity of 85% and specificity of 93% from its
newly created Motion Score in agreement with the assumed Gold Standard, the Norton Score (Zimlichman et al., 2011). Other new sensor technology such as the KINOTEX fiber-optic tactile sensor appears promising from validation studies showing high correlations to existing mapping systems (Sakai et al., 2008). Some sensors are even attempting to integrate multiple measurements into their capabilities such as yaw torque, normal force, and shear force at a single point in one example (Murakami, Ishikuro, & Takahashi, 2012) and interface pressure, force, tilt angle, and tissue thickness via a compound sensor that includes an ultrasound component in another example (Wang et al., 2000). Other exciting advancements include sensors that can be integrated into wound dressings to indicate need for wound care by measuring temperature and pH in addition to pressure (Mehmood, Hariz, Fitridge, & Voelcker, 2013), spectral imaging devices that can differentiate between normal and abnormal skin (Qi, Kong, Wang, & Miao, 2011), and even sensors that "smell" compression based on different chemicals emitted from the skin (Dini et al., 2013).

In addition to improved sensing capabilities, cost is also a consideration. One disposable sensor sheet capable of continuous monitoring at 12 Hz with a cost of fabrication less than $50 per meter squared has been described, however the hysteresis, drift, and sensor range needed improvement compared to other existing maps at the time of that study (Yip et al., 2009). Another map boasts cost at only $1 per pad and the goal to integrate its system into wound dressings. This map is disposable and capable of transmitting information wirelessly through a Bluetooth connection to a Nexus 7 tablet. The disadvantages of this system include devising a way to eliminate possible pressure ulcer inducement from the copper wires used in the system, creating a way to log the data, and improving the resolution (Chung et al., 2013).

Feedback systems that allow the user to correct or adjust their posture to assist in pressure relief are also being investigated as a means of prevention. Receiving auditory feedback in the form of varying tones and visual feedback in the form of a color spectrum resulted in a learned alteration of
walking in an individual over three test periods who was instructed to reduce pressure in first metatarsal head of his foot (Femery, Moretto, Hespel, Thévenon, & Lensel, 2004). Non-auditory attempts have been made to surreptitiously alert users to prevent embarrassment. Examples include vibratory wrist bands (Chenu et al., 2013), vibratory belts (Verbunt & Bartneck, 2010), and even tongue placed tactile biofeedback (Vuillerme et al., 2007) instructing individuals how to move to best reduce pressure build-up. Some mapping systems consisting of air cells may even do pressure relief for the patient on their own by inflating and deflating according to data feedback and algorithms (Arias et al., 2013).

Despite citation in the literature for centuries on sores that erupt from the skin, the categorization of pressure sores was updated less than 10 years ago. Sores that appeared initially as minor ulcers could quickly transform into cavernous wounds with extensive necrosis. The term "Deep Tissue Injury" (DTI) was added to the staging system to describe wounds that started from the bone and worked their way to the skin, masking the amount of injury in their wake. DTI has been an area of interest for many studying pressure sore formation. One theory is that cellular deformation leads to cellular stiffening. Essentially, once a maximum threshold is reached the tissue can no longer recover. The result is the properties of the tissue change and remodeling occurs. Interestingly, once this maximum threshold is reached not only are the cells under deformation affected but so are nearby cells that are below the threshold. One hypothesis is that strains in the dead tissue are altered to increase the nearby cells over the threshold needed for damage meaning once damage occurs it can move quickly and extend beyond what one might predict (Nagel, Loerakker, & Oomens, 2009).

A significant challenge with DTI is being aware it is happening, let alone quantifying it. Many state DTI can't be explained by monitoring interface pressure (IP) and argue against pressure mapping as the ideal way to investigate pressure (Oomens, Loerakker, & Bader, 2010). For example, one study placed bovine muscle on top of a human IT replica and inserted sensors into slits in the muscle as well as recorded pressure mapping values. Pressure values below the IT compared to IP values showed only a
weak correlation and ranged from 5 to 11 times higher (Gefen & Levine, 2007). Another problem with pressure mapping is two different subjects can have the same IP with extremely different anatomical features (i.e. tissue thicknesses) and hence have different internal pressures (Gefen, 2009a). In order to learn more about DTI cell and tissue culture experiments, animal testing, and computer modeling have been performed (Gefen, 2008a). Computer modeling in particular has created a branch of its own in the study of pressure sores.

Magnetic Resonance Imaging (MRI) has allowed for detailed imaging of soft tissues since the 1980s, yet it still remains a fairly expensive diagnostic tool. Application of MRI when clinically warranted in pressure sore patients allows for visualization below the skin and can show fluid accumulation and bone changes consistent with deep tissue injury which can help determine treatment options (Hencey, Vermess, van Geertruyden, Binard, & Manchepalli, 1996). But MRI serves another potential purpose in wound healing. Detailed information on an individual's anatomy is being used to create patient-specific analyses of biomechanics. Obvious information such as tissue depth and ischial tuberosity thickness can be obtained, but 3-D renderings of the subject can also be created by complex mathematical analysis. The finite element method (FEM) allows modeling of complex structures by breaking the structure's surface into tiny pieces in a process called "meshing." The mesh is a grid of one shape (or finite elements) often consisting of triangles, quadrilaterals, or polygons. Next, pieces of the larger shape are defined by (easier) equations found by minimizing the error between equations tested and the piece of the object's shape. Finally, all the pieces and equations are brought back together and inputs affecting the shape can be adjusted to predict outcomes. Thus, FEM can be combined with MRI to create a model of a patient's buttock region.

Linder-Ganz et al. extensively investigated the FE-MRI concept. First, MRIs of 6 normal, seated individuals in non-weight-bearing positions and weight-bearing were taken. Differences in parameters between the two images were calculated and used as boundary conditions in an FE model that was
created based on the non-weight-bearing images. The FE model gave predicted deformations which were then compared to the actual deformations in the weight-bearing MRI images and the differences were minimized by the sum of least squares method to get the best fit. Once the FE model was optimized, correlation coefficients greater than 0.89 and a p-values less than 0.05 were obtained, validating the model, which has since been assumed the Gold Standard in future research by the group. Adding weight in the form of water vests and the curvature of the ischial tuberosity were also noted to impact the stress and strain measured (Linder-Ganz, Shabshin, Itzchak, & Gefen, 2007).

The study further showed that higher pressures existed in the gluteal muscle than in fat, which the authors cite as evidence for why interface pressure should not be the determinant of deep tissue injury. The realization that different tissues have different pressures is important, especially when considering spinal cord injury patients have decreased muscle mass and increased fat (Gefen, 2007). As would logically follow, stress and strain calculations using FE-MRI were shown to be higher in paraplegic patients compared to normal subjects (Linder-Ganz et al., 2008). It also appears that there are ranges where low and high BMI contribute to pressure build-up as was implied by a FE study where 21 models with varying BMI in the same individual were tested (Sopher, Nixon, Gorecki, & Gefen, 2010).

Following the validation of the FE-MRI model, other more simple methods for calculating internal pressures were sought. A Hertz contact model with a half sphere was used to simulate the ischial tuberosity in a computer program and was validated with testing of an actual hemi-spherical structure using an Instron machine. The finite element method was then used to create a FE model off of the Hertz model, and this new FE model was compared to the FE-MRI model previously discussed. For paraplegics, there was no significant difference between model types, but the Hertz method was slightly harder on controls versus the FE-MRI model, although the difference was not of significance. While this model does not rely on the MRI for the basic shape of the half-sphere indenter on tissue, it does still depend upon the boundary conditions obtained through the MRI (Agam & Gefen, 2008).
Simplifying the model a step further, an equation based on parameters determined significant in FE-MRI modeling was created called the Compression Intensity Index (CII) based on the body weight, radius of curvature of the ischial tuberosity, and the thickness of the gluteus muscle. Compared with the Gold Standard FE-MRI, a correlation of 0.65 was calculated and the CII gave values 1.6 times higher in the paraplegic group versus control group (p=0.001) showing it could discern risk (Gefen, 2008b). Both the Hertz Model and the CII would be of increased utility if the boundary conditions necessary for both their models could be obtained through means other than MRI. In fact, this intent is being sought with the use of ultra-sound technology which would greatly decrease the cost associated with the measurements and make them much more feasible in large-scale implementation (Wang et al., 2000). The effects of other factors are being investigated such as the elastic modulus and poisson ratio and it is possible they could become part of a new predictive equation (Portnoy, Vuillerme, Payan, & Gefen, 2011).

2.3 Next Steps in the Study of Pressure

What induces individuals to adjust themselves normally is a simple question that remains unanswered. The pathophysiology and engineering behind pressure sores represent a complex disease process we are only still at the infancy of understanding. One area needing additional research is an understanding of what normal movement looks like in a continuous manner. By first learning how normal subjects move over time, one can compare to the movements (or pressure relief maneuvers) in neurologically impaired groups. One study attempts to understand normal movement by modeling each IT as a hemi-ellipsoid and follows the changes in the eigenvalues and eigenvectors of this ellipsoid over time at 11Hz for 2 hours (Billington, Fabri, & III, 2014). While studies such as this might not reveal the pressures underneath the IT as previously described, it is possible that examining the shape of movement in a normal subject and re-creating it in a SCI patient could be one part of the solution in pressure relief. Modeling and re-creating normal movements might not answer the "How of pressure
sore causation," but it may give the answer to a different and perhaps more important question: "How can pressures sores be prevented?" Is it possible if you can model normal movements that perhaps you can prevent pressure sores?
CHAPTER 3: EXPERIMENTAL METHODOLOGY

3.1 Institutional Review Board Approval

The intent of this dissertation was to understand how normal individuals move and to compare their movement to that of subjects with spinal cord injuries. An application to the Institutional Review Board (IRB) at the University of South Florida Morsani College of Medicine and the James A. Haley Veterans’ Hospital was submitted and approved in order to collect data from subjects for further mathematical analysis.

3.2 Subjects

Data from 20 normal and 6 patients with spinal cord injuries were collected following the guidelines of the IRB protocol. In anticipation for future stratification into subgroups, the subjects’ age, gender, race, height, and weight as given by the subject were recorded. Normal subjects were approached by the investigator and asked if they would be interested in participating in the study. If subjects expressed interest a screening questionnaire was performed to see if the subject would qualify for participation. All normal subjects had to be between the ages of 18-40 years old. Further, subjects were disqualified if they were pregnant, had a spinal cord injury, and/or had a neurological or muscular disorder. Patients with spinal cord injuries were referred to the investigator by health care professionals working at the James A. Haley VA Hospital familiar with the study. Patients were asked if they were interested in participating in the study and were also screened with the same questionnaire. Patients recorded if they had a history of a previous pressure ulcer and the level and date of their spinal cord injury in addition to the questions previously mentioned for normal subjects. Any subject with an active pressure sore was disqualified from participating in the study.
3.3 Pressure Mat

XSENSOR Technology Corporation loaned a pressure map for use in this study. The sensors on the map provided are of the X3 PX100:36:36:02 series. The map consisted of a 36 by 36 grid of sensors for a total of 1,296 sensors with an overall sensing area of 45.7cm by 45.7cm. The sensors are based on capacitive pressuring imaging technology and have a pressure range of 0.14-2.7N/cm² and a spatial resolution of 12.7mm. The sensor accuracy is +/- 10% in the calibrated mode. The response time between sensor readings was sufficient to allow a maximum sampling rate of the system was 11Hz. The pressure map was connected by a X3 Sensor Pack to a X3 Display which served as an user interface with the map to show real-time visualization of the pressure readings and control of recording and recording parameters. The X3 Display was connected to a X3 Power Supply which could be plugged into a standard 3-prong electrical outlet. See Appendix A for more detailed information on the map.

3.4 Experiment Procedure

After subjects completed the questionnaire and were deemed eligible to participate and had signed an IRB form, a HIPPA form, and been given a VA pamphlet on research, the experiment was commenced. All subjects were asked to sit in a wheelchair for two hours and to adjust themselves while seated as they normally would. For normal individuals this meant that they were allowed to cross their legs, shift their weight, or whatever other pressure relief they typically do while seated. For patients with spinal cord injuries, patients were told they could do their typical pressure relief postures such as leans and arm lifts (if they were physically able to do so). If patients typically received any assistance with these maneuvers it would also be allowed. All subjects were asked to not get out of their chair for the entire duration of the two hour recording period. In order to ensure the safety of the paraplegic patients, the first three patients were only recorded for 1 hour. All subsequent recordings were at 2 hours.
Normal subjects sat on the XSENSOR map on an ultra lightweight wheelchair without any padding. Spinal cord injury patients were allowed to sit on their own chair with their personalized cushions as it was determined to be too big of a risk to have them sit on a non-cushioned chair. The investigator remained with all subjects for the duration of the testing. The subjects were allowed to engage in whatever activities they desired during the testing period which ranged from watching television to working on a computer. Normal subjects were offered the opportunity to be tested at any location they desired and most subjects preferred being tested at home or at school in a study area. Spinal cord injury patients had to be tested onsite at the James A. Haley VA Hospital.

Once the subject was seated the X3 display was turned on and the map was rotated until the image on the display had the ischial tuberosities at the inferior portion of the screen and the legs directed towards the superior portion of the screen. The display was then set to record at a rate of 11Hz in the uncalibrated mode and a timer was set for two hours. Once 79,200 frames had been recorded the stop button was selected and the data was saved to the display. The data were then transferred to a password protected laptop as well as an external drive.
CHAPTER 4: MODELING

4.1 Visualization of Raw Data from the Pressure Map

4.1.1 Breaking the Pressure Image into Components

Sample data were collected in the first phase of the project to get an idea for the overall shapes created by the pressure distributions on the pressure map. The data were broken down into three distinct components: a spire, a platform, and a hemi-ellipsoid shape (Figure 4).

4.1.2 The Spire

The spire is simply the peak pressure recorded on half of the frame (Figure 5). Each frame is split into two so that each ischial tuberosity can be measured.

4.1.3 The Platform

Values above a certain cut-off were subtracted out removing the values of the spire and the hemi-ellipsoid shape. Values below a certain cut-off were also removed when the map was in the uncalibrated format as the cells were not zeroed in areas where no pressure was applied. The remaining values constituted the platform and each half of the frame was averaged (Figures 6 and 7).

4.1.4 The Hemi-Ellipsoid

Values above the maximum cut-off for the platform as discussed above were removed from the platform and set as the values for the hemi-ellipsoid (Figure 8). These mound values were then evaluated using solver to create predicted values for the mound by assuming the values took on a hemi-ellipsoid shape. The exact method will be elucidated below.
4.2 Defining the Equations for the Ellipsoid

4.2.1 Step 1: Applying the Equations to a 2D Model

The first step towards creating a complex hemi-ellipsoid model of actual patient data consisted of validating a simpler 2D model of an ellipse with known values. Initially, the Cartesian equation for an ellipse was used:

\[
\frac{(x - h)^2}{a^2} + \frac{(y - j)^2}{b^2} = 1 \tag{1}
\]

where \(\frac{1}{a^2} = A\) and \(\frac{1}{b^2} = B\), or

\[
A(x - h)^2 + B(y - j)^2 = 1. \tag{2}
\]

Solving the above equation for \(y\) gives the following:

\[
\sqrt{\frac{abs(1 - A(x - h)^2)}{B}} \pm j = y. \tag{3}
\]

Using known \(x\) values the actual \(y\) values were calculated for a known ellipse. Experimental \(y\) values were then created that were slightly above or below each of the calculated \(y\) values in order to simulate real data where the shape modeled would not be a perfect ellipse. The Solver Add-in was utilized to calculate \(\tilde{y}\) while allowing \(A, B, h\) and \(j\) to vary and to simultaneously minimize the objective function.

The objective function was either the sum squared:

\[
\text{sum}(y - \tilde{y})^2 \tag{4}
\]

or the absolute of the sum:

\[
\text{sum}(\text{abs}(y - \tilde{y})). \tag{5}
\]

Next, the matrix equation of an ellipse was used where the equation for an ellipse is given by:

\[
(\tilde{x} - \tilde{v})^T A^{-1}(\tilde{x} - \tilde{v}) = 1 \tag{6}
\]

where \(\tilde{x} = \begin{bmatrix} x \\ y \end{bmatrix}\), \(\tilde{v} = \begin{bmatrix} h \\ j \end{bmatrix}\), and \(A^{-1} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}\). Substitution gives the following equation:
and the fully expressed form gives:

\[(x - h)^2 A_{11} + (x - h)(\tilde{y} - k)A_{21} + (x - h)(\tilde{y} - k)A_{12} + (\tilde{y} - k)^2 A_{22} = 1.\]  

Figure 9 shows the fit of the ellipse using the Cartesian coordinate system and Figure 10 shows the fit using the matrix equation for an ellipse.

### 4.2.2 Step 2: Applying the Equations to a 3D Model

After validation that a simple 2D model was accurate and that Microsoft Excel was capable of handling the calculations the focus moved towards creating a 3D model with an ellipsoid shape. As with the 2D model, 3D analysis began using the Cartesian equation for an ellipsoid given by the following equation:

\[\frac{(x - h)^2}{a^2} + \frac{(y - j)^2}{b^2} + \frac{(z - k)^2}{c^2} = 1\]

where \(\frac{1}{a^2} = A, \frac{1}{b^2} = B,\) and \(\frac{1}{c^2} = C\) or

\[A(x - h)^2 + B(y - j)^2 + C(z - k)^2 = 1.\]  

Solving the above equation for \(z\) gives the following:

\[\sqrt{abs\left(\frac{1 - A(x - h)^2 - B(y - j)^2}{C}\right) \pm k} = z.\]  

The values calculated in the above equation are the actual \(z\) values that will be compared to the \(\tilde{z}\) values predicted from the model. The Solver Add-in was then adjusted to calculate the \(\tilde{z}\) values using minimization of the sum squared difference and summed absolute difference as in the 2D model but this time using the \(z\) and \(\tilde{z}\) variables.

Next, the matrix equation of an ellipsoid was used where the equation for an ellipse is given by:

\[(\tilde{x} - \tilde{y})^T A^{-1}(\tilde{x} - \tilde{y}) = 1\]
which is the same equation previously described in Equation 6, except where \( \bar{x} = \begin{bmatrix} x \\ y \\ \bar{z} \end{bmatrix} \), \( \bar{v} = \begin{bmatrix} \bar{h} \\ \bar{j} \end{bmatrix} \), and 

\[
A^{-1} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix}.
\]

Substitution gives the following equation:

\[
\begin{bmatrix} (x - \bar{h}) & (y - \bar{j}) & (\bar{z} - \bar{k}) \end{bmatrix} \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} x - \bar{h} \\ y - \bar{j} \\ \bar{z} - \bar{k} \end{bmatrix} = 1
\] (13)

and the fully expressed form gives:

\[
((x - \bar{h})^2 A_{11} + (x - \bar{h})(y - \bar{k}) A_{21} + (x - \bar{h})(\bar{z} - \bar{k}) A_{31} + (y - \bar{k})(x - \bar{h}) A_{12} + \\
y - \bar{k} A_{22} + y - \bar{j} A_{23} + z - \bar{k} A_{32}) + (y - \bar{k})(z - \bar{k}) A_{13} + (z - \bar{k})(x - \bar{h}) A_{23} + (z - \bar{k})(y - \bar{j}) A_{33} = 1.
\] (14)

### 4.2.3 Step 3: Testing the 3D Model Using Calculated Data Points

The following ellipsoid was used to test the 3D model:

\[
\frac{(x - 4)^2}{9} + \frac{(y - 6)^2}{25} + \frac{(z - 0)^2}{9} = 1
\] (15)

and was centered at (4,6,0) with a length, width, and height of 3, 5, and 3. By varying \( x \) and \( y \) values the actual \( z \) values were calculated according to the following input into Microsoft Excel:

\[
=\text{SQRT}((9\ast(1-(x-4)^2/9-(y-6)^2/25))).
\] (16)

However, some of the \( z \) values calculated were not real because the square root of a negative number was taken. Adjusting the above equation by inserting an absolute sign corrected the problem. Figures 11-13 show this issue graphically.

\[
=\text{SQRT}(\text{ABS}(9\ast(1-(x-4)^2/9-(y-6)^2/25)))
\] (17)

A limitation of the model was that the \( z \) values were based off of \( y \) which was based off of \( x \).

Essentially, the \( z \) values of the ellipsoid were calculated only using \( x \) and \( y \) values of an ellipse. It was necessary to determine what was going on across the entire ellipsoid by calculating other surface data points. In order to do this, a 10 by 10 matrix of values was entered into Excel with the following parameters: \( x \) ranged from 0 to 10, \( y \) ranged from 2 to 20 by 2's, and \( z \) was equal to the following equation:
Graphing \( z \) vs. \( y \) while keeping \( x \) constant showed that values off of the ellipse created a winged structure (Figures 14 and 15). Thus, it was determined that it is important for the model to only consider points actually on the ellipsoid. Points not on the ellipse and some border points will give values that will affect the model and must therefore be removed.

Once it appeared that a winged structure was occurring outside of the ellipse this hypothesis was tested in Matlab by creating an entire ellipse with a matrix of data points as was described manually above in Excel. In order to analyze all data points on the ellipsoid, a matrix of values from \( x = 0 \) to \( 10 \) and \( y = 0 \) to \( 20 \) was created in Matlab. Then the equation for an ellipsoid was set to \( z \). The result was plotted. The code for Matlab is as follows:

\[
\text{\{x,y\}=meshgrid(0:.5:10, 0:.5:20);
\}
\text{b=5+sqrt(abs((1-(1/25)*(x-5)^2)-((1/100)*(y-10)^2))/(1/25)));
\text{surf(x,y,b)}
\]

The image clearly showed outside the boundary of the surface of the ellipsoid the values calculated followed a winged shape (Figures 16 and 17). Yet, once the values off of the ellipsoid were removed the model was able to closely fit the predicted values to the actual values, as show in the Figure 18. The problem of these extra points should not occur with the actual data, as only real data points will exist from the recording of the subject’s buttocks.

4.2.4 Step 4: Testing the 3D Model Using Real Data

After verifying a 3D model was feasible in Excel and proving the model was accurate for a known ellipsoid real data were entered into the model from a patient. The real data replaced the values previously calculated using the Cartesian equation.

The XSENSOR mapping system is capable of recording data in two modes: calibrated and uncalibrated. Calibration allows for comparison of measurement between the sensors and ensures they
measure data similarly. Typically data are recorded in the calibrated mode so initially data were collected using this modality. However, one pitfall of recording in the calibration mode is that the recording range of pressures is from 0 to 256 Hz. This means that pressure readings exceeding 256 Hz will simply be recorded as 256 Hz versus a higher value (Figure 19). Thus, when pressures exceed 256 Hz a platform is created and information is lost.

Data were tested using the uncalibrated setting to work around the issue encountered with high pressures. A problem using the uncalibrated setting is that the sensors not sensing pressure are no longer zeroed and give non-zero values. A simple workaround where values below a determined threshold were removed eliminated these data points, although it is possible that a tradeoff was made where some of the values of the platform may have also been removed if they were small enough to be considered a “0” value. Additionally, the uncalibrated values represent a range and do not have an understandable meaning as does the established and reproducible Hertz pressure scale. As the goal of this project was to understand movement and how pressures change it was decided the uncalibrated mode was best suited (Figure 20).

Once the cells without pressure applied were removed the remaining data were split into components. The maximum pressure was easily located and tracked with the value and location output to a sheet in Excel. The mound values were determined based on calculating the mean and standard deviation of each time point frame and settings values greater than the mean plus 1.7 times the standard deviation as mound values. The mound values were then removed and entered into another sheet in Excel and the Solver Add-in along with Matrix.xla was used to calculate the eigenvalues and eigenvectors based on minimizing the summed squared difference between z and ẑ. The summed absolute difference was also tested, but it was decided to use the summed squared difference for the minimization equation as squaring the values would emphasize outliers. The remaining values once the mound was removed gave the platform. The average value of the platform was calculated and output to
a sheet in Excel. Modeling the platform as a convex shape was explored and the model was able to run and gave an ellipsoidal shape. However, looking at the values of the data surrounding the mound and comparing to the much larger values of the mound it appears that that the platform is generally flat. Although Solver is capable of modeling the platform as an ellipsoid, it appears an unnecessary step once the mound is considered and thus was not pursued. All of the code was written using Visual Basic for Applications (VBA) in Microsoft Excel and was automated. Due to size limitations in Excel the 79,200 frames of data were broken into 10,000 frames per file and each file was run individually.

In order to visually assess how the model was functioning with real patient data the actual z values and the values predicted from the model for the mound were compared graphically to each other using R Excel and a good fit was visually confirmed (Figure 21).

4.3 Solver and the Objective Function, Changing Cells, and Constraints

Many different constraints were tested. Ultimately, the constraints settled on were those that gave an understandable solution with the smallest possible residual values.

4.3.1 The Objective Function

The objective function is what is optimized in the Solver Add-in. This value is entered in the “Set Target Cell:” box. This is a minimization problem, so the “Min” button is selected. The cell entered is either the sum of squared residuals or the sum of absolute residuals as previously described:

\[ \text{sum}(y - \hat{y})^2 \]  \hspace{1cm} (19)

or

\[ \text{sum}(|y - \hat{y}|). \]  \hspace{1cm} (20)

The values for the constraints varied when comparing the minimum value calculated for sum squared residuals vs. sum of absolute residuals.
4.3.2 Changing Cells

The variables that change are selected under “By Changing Cells.” There are three sets of variables trying to be solved: \( \hat{z} \) values, the A matrix, and the center values for the ellipsoid \( h, j, k \).

4.3.3 Constraints

Figure 22 shows the input box in Microsoft Excel for the constraints below.

- \( \hat{z} > \text{number} \): A constraint was added to \( \hat{z} \) in order to eliminate possible solutions that Solver might explore that are not realistic. For example, if the lowest possible \( \hat{z} \) value is 5 in the previous ellipsoid example, it does not make sense to have \( \hat{z} \) with negative numbers. Through testing it was found that there is no simple way to determine which number should be less than or equal to \( \hat{z} \). Trial and error is necessary to find the optimum solution. Thus, a loop of values was tested with each run of Solver.

- \( x^T A^{-1} x = 1 \): The matrix equation must be set equal to 1 in order for the model to hold.

- Diagonal B values are equal: Diagonal values on the B matrix are set equal to each other in order to force the eigenvectors to be orthogonal. This allows for an understandable ellipsoid. Additionally, if the B matrix is not set equal, the eigenvectors equal zero. The goal is to have three eigenvectors which point in the x, y, and z direction.

- \( k=0 \): The center variable in the z direction was set equal to 0. The model was tested without a k value, with \( k=0 \), \( k>0 \), \( k>=-10 \) while z was varied. It was decided to set \( k=0 \) as a constraint because it was easier to comprehend if the ellipsoid hemisphere had its center on the xy-plane. The residuals for \( k=0 \) were comparable to the values calculated for no k, \( k>0 \), and \( k>=-10 \).

4.4 Examining Residuals and Relationship to Center Variables

Variables \( h, j, k \) were allowed to vary within minimum and maximum values and a starting \( h, j, k \) value was entered within the maximum and minimum \( h, j, k \) constraints. For example, if the exact \( h, j, k \) value was calculated to be 3,3,3, the values of \( h, j, k \) were allowed to vary between \( >=1 \) and \( <=5 \). Then,
values between $\geq 2$ and $\leq 4$ were tested to see where Solver had $h,j,k$ converge. Table 1 shows the minimum residuals gave the correct $h,j,k$ convergence to 3,3,3.

When similar testing was done for data which included values on and off a known ellipsoid, the lowest residual values did not converge to the correct $h,j,k$. Nor did any of the values within the tested range of 2-4 converge to $h,j,k$. This gave further confirmation that values not on the ellipsoid would affect the predictions for the model.

It is important to note that when actual test data from patients are used that the true center will not be known. The model that gives the lowest residuals will be assumed to be the best model. The testing previously described shows that with the calculated data the “true” center was capable of being determined. Since the “true” center for the patient data will be unknown, a cut-off value for a realistic minimum residual value will have to be determined. If the lowest residual from the model is not below this threshold, then the model is unlikely to be a “good fit.”

4.5 Limitations of Solver

Solver has size limits for the number of constraints and decision variables that can be explored in order to calculate a solution. If the limit is exceeded, there is software that can be purchased with a much larger size limit called Premium Solver. For example, the following ellipsoid problem could not be solved in Solver:

$$\frac{(x - 10)^2}{81} + \frac{(y - 10)^2}{81} + \frac{(z - 10)^2}{81}$$ (21)

and delivered a message that the problem was too large to run. Solver has a limit of 200 decision variables and 100 constraints if the problem is non-linear.

Another important limitation of Solver is that the objective function may not be finding the absolute solution. This model involves the optimization of a minimization problem. If the ellipsoid generated does not have a perfectly smooth surface, the presence of local maxima and minima are
possible. If Solver discovers one of the local minima, it may believe that this is an absolute minimum and give an incorrect solution. Testing of different h,j,k values showed the importance of testing values both on and off the ellipsoid. Values off the ellipsoid seemed to converge to the minimum while values on the ellipsoid may or may not converge depending on whether or not local minima were found as depicted in Figure 23.

4.6 Eigenvalues and Eigenvectors

Matrix.xla was used to calculate the eigenvalues and eigenvectors using VBA code. While there are alternative ways to calculate these values the Jacobi method was ultimately utilized. It is important to note that in order to use the Jacobi method the matrix must be symmetric. Thus, the values calculated for the $A^{-1}$ matrix were forced to be symmetric during minimization using the Solver Add-in. One of the main reasons the Jacobi method was used is because it makes the eigenvectors orthogonal to each other and it was decided that an ellipsoid with orthogonal eigenvectors was more comprehensible. For further details on the use of the Matrix.xla please see the Matrix.xla reference guide online.

All data were collected using an XSENSOR mapping system and were exported as Comma Sensitive Values (CSV) files from XSENSOR software to Microsoft Excel. Graphs of all data points at 11Hz and reduced data points at 1Hz were compared for three normal subjects. 1Hz provided sufficient representation of these individuals’ movements based on graphical analysis and examination of each numerically identified area of movement as shown in Table 2. It was noted that the number of movements decreased when decreasing the frequency of data collection but that these movements were usually neighboring other frames which were included in the calculations. Thus, it was decided that the major movement was still captured even if these frames were removed. The data were also visually assessed in the XSENSOR software to look for areas where “false hotspots” appeared on the edges of the map or areas where the maximum pressure was not in the area of the ischial tuberosities.
These “false hotspots” were removed on all frames. A program called “clean and condense” was written using VBA code which removed the “false hot spots” and condensed the data to include only one frame per second. The cleaned and condensed file of data was then loaded into another Excel file for pressure analysis.

Next, the program examined each frame and found the left and right maximum pressures and recorded the pressure values and locations. Areas of major movement were determined from these maximum pressures as discussed in more detail in the results and discussion section to follow.

Once the data frames of major movements were identified, VBA code was written which extracted the major movement frames and ran them through a fully automated procedure which assumed an ellipsoid shape for the maximum values isolated on each half of the frame of data and then calculated the associated eigenvalues of x, y, and z. Complete analysis of all identified movements was run for normal subject 1. The running time took several days and was complicated when the mound values were less than or equal to 1 which caused the program to stall. The stalled frames were removed and the program continued with the analysis.

![3-D Imaging of Pressure Map Data](image)

Figure 4 Raw data and model of data. (Left) XSENSOR 3D imaging of a subject seated on a XSENSOR pressure map viewed at an angle. Buttocks and thighs are visible with high pressure densities in ischial tuberosities region. (Right top) Alternate view of same data from xy-plane. (Right bottom) Simplified model broken down into three components: (1) a raised platform, (2) a hemi-ellipsoid, and (3) a spire.
Figure 5 Spire shape depicting maximum pressure recorded.

Figure 6 The platform consists of the averaged values after removal of the spire and hemi-ellipsoid shape.

Figure 7 Actual data from a subject showing platform remaining after maximum and minimum cut-off values are removed.

Figure 8 Hemi-ellipsoid shape of mound values obtained by removing values over maximum cut-off from platform.
Figure 9 Graph comparing actual, random ("experimental"), and predicted values of y given known x-value using the Cartesian equation for an ellipse. Note that the model is excellent at predicting an accurate ellipse shape based on the randomly adjusted data points. The graph generated using the matrix equation for an ellipse appeared similar.

Figure 10 Graph comparing actual and predicted values of y using the matrix equation.
Figure 11 Graph showing the border of the ellipsoid without the absolute sign used in the equation to calculate $z$.

Figure 12 Same data as in previous graph, but absolute value sign has been added under square root. Thus, more data points are on this graph.
Figure 13 Two views of all data points in Excel. Absolute value sign was used under square root. Note that opposite sides of the shape are not mirror images.

Figure 14 Looking down x=5 there are no wings on the edges of the blue points.

Figure 15 Looking down x=1 you can see an elliptical shape in the middle in blue with wings on the edges.
Figure 16 3D graph of ellipsoid in Matlab shows winging of data points off of ellipse values and on some border points.

Figure 17 3D graph in R Excel comparing actual z values in blue vs. predicted z values in green. Winged shape on border of actual values is accentuated with yellow highlighting.
Figure 18 3D graph of 10x10 matrix with values not on ellipse and some border values removed. Note that the green predicted values closely match the blue actual values.

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Figure 19 One half of buttock showing pressures exceeding maximum calibration setting give values of 256 Hz. Blank cells represent zero values of data which have been removed.
Figure 20 One half of buttock showing pressures in uncalibrated setting which allows for differentiation between maximum pressure values. Orientation of buttocks is opposite of previous figure.

Figure 21 The model shows closely fitting values between actual $z$ data (in green) and predicted $\hat{z}$ data (in blue). Spheres that have both colors represent points where the data were very closely or absolutely matched.
Figure 22  Screen shot of variables and constraints entered into Solver.

Table 1  Table of entered values and corresponding calculated values of h,j,k with residuals. The lowest residuals give the correct h,j,k output of 3,3,3.  h,j,k entered values highlighted in yellow give the correct h,j,k output values.
Figure 23 2D view of xz-plane of ellipsoid. Red arrow A finds the absolute minimum by starting off of the ellipsoid. Green arrow B finds local minima by starting on ellipsoid.

Table 2 Comparison of graphs with data collected at 11Hz (top) and 1Hz (bottom) shows overall shape of graph is maintained with reduction in data and areas of major movement are sufficiently identified.
CHAPTER 5: RESULTS AND DISCUSSION

5.1 Analysis of the Spire

5.1.1 Data Reduction

The first step in analysis involved calculations on the area of maximum pressure for each hemi-buttock. Code was written to identify the maximum pressure and location in each frame as previously discussed in the methods section. The differences in maximum pressure were then calculated between frames for the left buttock, right buttock, and the left minus right buttock to identify major movements. Visual assessment of graphs of maximum pressures on the left, right, and left minus right revealed the data were well described by the left minus right values. Focusing on the left minus right pressures reduced the amount of data needing analysis by one half while retaining information on how an individual moves both his left or right buttock as shown in Table 3.

For example, if a sitting individual lifts his left foot off of the ground and thus increases the pressure on the left ischial tuberosity it is expected that the right leg would help compensate by shifting weight from the ischial tuberosity to the distal thigh. The result would be an increased maximum pressure on the left and a decreased maximum pressure on the right in the area of the ischial tuberosities. The sign of the difference shows which hemi-buttock has a higher pressure; if the sign is positive the left side has a higher maximum pressure and if the sign is negative the right side has a higher maximum pressure. It is important to note that if a patient has an equal increase or decrease in both legs simultaneously as would occur in a perfect forward lean that this movement might be lost as the pressures would both increase but the difference between them would cancel out. However, after comparing the delta left, delta right, and delta left minus right areas where movements occurred it was determined that such perfect and equal movements are unlikely and that delta left minus right is
sufficient to show changes in movement. Figure 24 compares the three deltas for the 20 normal subjects. Further, comparison of the averaged number of movements for 20 normal subjects across each 10,000 frame interval in Figure 25 shows the same shape when comparing movements calculated by delta left, delta right, and delta left minus right and that using delta left minus right slightly overestimates the number of movements compared to either the delta left or delta right side alone.

Areas of major movement were defined to occur where significant changes in delta left minus right maximum pressures occurred. A cut-off value was set as a change in +/-10 units of pressure and cells above and below these respective thresholds were added to a counter for movement. Movements were counted across the entire data set (Figures 26-29) and also across 10,000 frame increments in order to see if changes occurred throughout the recording of the data as was just previously shown in Figure 25. The time intervals between frames of movement (Figures 30-33) were also calculated overall and across each set of 10,000 frames. Tables 4 and 5 show the average number of major movements and the time intervals between major movements for normal subjects and paraplegic patients at 1 hour and 2 hours.

5.1.2 Distribution Analysis

The time interval data for each normal subject and paraplegic patient were tested to see if any common distributions could be identified using Minitab. None of the 20 normal subjects nor the 3 paraplegic patients tested at 2 hours had P-values that supported a fit to a common distribution for their time intervals. Therefore, it was assumed that these data consisted of a uniform distribution with stochastic variability. However, patients 2 and 3 of the 6 paraplegic patients tested at 1 hour had significant P-values with the Box-Cox transformation at lambda values of 0.5 and 0, respectively. Both of these patients had very low movement counts overall. Further testing of paraplegic patients is necessary in order to be able to determine if these patients are outliers or if their reduced movements result in the better fit of a distribution.
The averaged data for both the normal and paraplegic groups were also tested to identify possible distributions. Both the averaged normal and averaged paraplegic groups were found to follow several distributions, including the normal distribution for number of movements (Figure 34). The data for time interval did not follow a normal distribution but did fit a lognormal distribution (Figure 35). P-values for each group for movement and time interval are listed in Tables 6 and 7 and more detailed results can be viewed in Appendix B.

5.1.3 Statistical Analysis

After determining whether the data were parametric or non-parametric statistical analysis of the data was performed. The number of movements significantly increased from the 1st hour to the 2nd hour of sitting. The normal subjects went from 177.1 to 232.3 average movements per hour \( (p=0.041, \text{ paired 2t-test}) \) and the paraplegic patients went from 160 to 216.3 average movements per hour \( (p=0.007, \text{ paired 2t-test}) \). It logically follows that if the number of movements increases that the time interval between movements should correspondingly decrease. While the time interval for the normal subjects decreased from 31.6 to 25.5 seconds \( (p=0.3648, \text{ Mann-Whitney}) \) and the paraplegic patients decreased from 27.06 to 20.21 seconds \( (p=0.3827, \text{ Mann-Whitney}) \) the change was not significant with significance set at \( p=0.05 \).

Next, normal subjects and paraplegic patients were compared to see if significant differences were observable. It was predicted that the paraplegic patients would have fewer movements than the normal subjects and that the paraplegic individuals would have larger time intervals between movements than normal individuals. However, no significant difference for movement was noted between normals and paraplegics at 1 hour \( (p=0.094, \text{ unpaired 2t-test}) \) nor at 2 hours \( (p=0.779, \text{ unpaired 2t-test}) \). Additionally, the time interval between normals and paraplegics also did not show any significant difference at 1 hour \( (p=0.0552, \text{ Mann-Whitney}) \) nor at 2 hours \( (p=0.9636, \text{ unpaired 2t-test}) \). The log of the time intervals was taken to transform the data to parametric form and an unpaired t-test
again failed to show significance (p=0.14). Two of the six paraplegic patients had especially large time intervals which greatly affected the mean time interval for paraplegic subjects. The low n value of 6 in the paraplegic group limits interpretation of the comparison between normals and paraplegics. Further, other confounding variables such as the level of injury, time since injury, and amputation are not taken into account in the paraplegic group which could account for variations in movement and time between movements.

5.1.4 Pattern Analysis

Minitab was used to create time series plots of the data to see if any trends could be visually assessed in the data for the time intervals. Trend lines of different subjects revealed both positive and negative slopes suggesting there was not a trend for the time intervals to increase or decrease over time (Figure 36 and 37). Autoregressive Integrated Moving Average (ARIMA) was then applied to the time series but was not capable of finding a model, further suggesting that the data were random.

Time Series Analysis (TSA) was performed to assess the changes in maximum pressure to see if any patterns emerged with regards to time via the use of the Fast Fourier Transform (FFT). TSA is based on fitting multiple cosine waves with varying amplitudes and frequencies to the data and summing these waves to obtain the best fit. A periodogram is a graph that reveals possible frequencies that could create such an oscillatory pattern. Three normal subjects and three paraplegic subjects were input in R and the package TSA was used to create periodograms of the 6 subjects (Table 8). Minimal noise occurred and no obvious frequencies were found that could represent the data. Again, the data were supported as being random in nature and do not appear to have reproducible or patterned behaviors.

While mapping the study participants it was observed that individuals may have a side preference. Graphing delta left minus right maximum pressures over the time intervals of six normal subjects revealed that subjects may prefer the left, right, and or be approximately even in their side preference (Table 9). Understanding each individual’s preference may be helpful when working with
patients at risk for pressure sore development by ensuring the preferred side has adequate relief. This may mean that patients with a side preference need to perform more pressure relief techniques on their preferred side as this area would be presumed to be at a greater risk.

5.2 Analysis of the Platform and Hemi-Ellipsoid Mound

5.2.1 Normal Subject

As described in the methods section there are three components to the model: the spire, the platform, and the hemi-ellipsoid mound. Previous discussion revolved around the spire, or the area of maximum pressure. The next step in analysis was to examined the platform and hemi-ellipsoid data obtained as previously described in order to show that pressure can be modeled as a hemi-ellipsoid shape. Data for one normal subject over 2 hours were used to show validation of the model. Frames with major movements identified by the large and small deltas of the left minus right maximum pressure were input into Microsoft Excel for testing of each frame to identify the mound and the platform. A time series plot of the platform data over 2 hours of the one subject did not reveal any trends (Figure 38), nor did analysis of the z lengths of the hemi-ellipsoid. Figure 39 shows a comparison of the z lengths and maximum pressure on the left minus right over time. The run time of one normal subject was significant. In order to test 276 identified frames of major movement it took over 3 days.

5.2.2 Normal Versus Paraplegic

Large variations were noted between paraplegic patients which can be observed in sample frames of areas of identified movement for the 6 paraplegic patients in Appendix C. Also in Appendix C are graphs of the left minus right maximum pressure over 1 hour for the paraplegic patients and over 2 hours for selected normal subjects. Some patients appeared similar to the normal subjects both graphically and in terms of calculations of movement and time interval while others were vastly different. One frame of identified movement for each paraplegic was run to obtain the x, y, and z lengths of the hemi-ellipsoid and was compared to the values of one selected frame of the normal
subject. The percent error of the predicted $z$ values were calculated and Table 10 gives the results. Thus, the model is capable of locating and describing a hemi-ellipsoid shape from the pressure recordings.

One of the differences noted between normal subjects and paraplegic patients is that the area of high pressure appeared flatter and more spread out for the paraplegic patients when viewed in 3-D using the XSENSOR software. In fact, it appeared that the mound was instead a platform shape. The number of values the program sent to the mound was compared for the 6 paraplegic patients and 6 selected normal subjects and more values were sent from the paraplegic patients than the normal subjects on average. However, the number of values determined for the normal subjects was calculated using the same factor for each subject whereas the value was adjusted for each patient as the factor used for the normal subjects often did not result in any values being set as mound values which limits the interpretation.

Additionally, the platform means of the one frame for 6 selected normals and 6 paraplegic patients were compared based on the above calculations which were affected by the adjusted factor for the paraplegic patients. The paraplegic patients were found to have a significantly greater mean the normal subjects ($p=0.037$). Conversely, when the maximum pressure was compared the normal subjects had a higher maximum pressure but it was not significant ($p=0.73$). Again, these findings must be interpreted cautiously as only one frame was used for each normal and paraplegic and the results of the paraplegic are based on an altered factor value.
Table 3 Comparison of graphs with left pressures in blue and right pressures in red for every 10 frames (top) and the left minus the right pressures for every 10 frames (bottom). (Note the images are snapshots of graphs and not all points of x-axis frame numbers are shown). Subtraction results in adjustment of the y-axis, but the general shape of the data remains consistent and major movements are sufficiently represented despite decreasing the amount of data.
Comparison of Means of deltas Left, Right, and Left Minus Right Number of Major Movements for Each Normal Subject

Figure 24 Comparison of movements on delta left, right, and left minus right side for 20 normal subjects. The delta left minus right number of movements was used as the count for major movements of the data.

Mean Number of Movements for 20 Normals per 10,000 Frames on deltas Left, Right, and Left Minus Right

Figure 25 Averaged data of 20 normal subjects across 10,000 frame intervals using comparing mean movements on the left (red), right (green) and left minus right (blue). Overall average across all frames shown by black line.
Figure 26 Graph of number of movements for each normal subject in decreasing order with cumulative percentage over 1 hour.

Figure 27 Graph of number of movements for each paraplegic patient in decreasing order with cumulative percentage over 1 hour.
Figure 28 Graph of number of movements for each normal subject in decreasing order with cumulative percentage over 2 hours.

Figure 29 Graph of number of movements for each paraplegic patient in decreasing order with cumulative percentage over 2 hours.
Figure 30 Graph of time intervals for each normal subject in decreasing order with cumulative percentage over 1 hour.

Figure 31 Graph of time intervals for each paraplegic patient in decreasing order with cumulative percentage over 1 hour.
Figure 32 Graph of time intervals for each normal subject in decreasing order with cumulative percentage over 2 hours.

Figure 33 Graph of time intervals for each paraplegic patient in decreasing order with cumulative percentage over 2 hours.
Table 4 Statistical table of the mean number of movements over 1 hour and 2 hours. Time intervals were also calculated from the start to end of the second hour for comparison to the first hour. The paraplegic group was subdivided to show data from patients 1 to 6 and 4 to 6 in the first hour and 4 to 6 in the second hour.

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>N*</th>
<th>Mean(moves)</th>
<th>StDev</th>
<th>Median</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1HR N</td>
<td>20</td>
<td>0</td>
<td>177.1</td>
<td>93.6679</td>
<td>160</td>
<td>35</td>
<td>430</td>
<td>0.795105</td>
<td>1.35435</td>
</tr>
<tr>
<td>2HR N</td>
<td>20</td>
<td>0</td>
<td>232.3</td>
<td>136.969</td>
<td>216.5</td>
<td>43</td>
<td>528</td>
<td>0.830215</td>
<td>0.172172</td>
</tr>
<tr>
<td>1&amp;2HR N</td>
<td>20</td>
<td>0</td>
<td>409.4</td>
<td>205.802</td>
<td>403.5</td>
<td>117</td>
<td>790</td>
<td>0.287554</td>
<td>-0.916389</td>
</tr>
<tr>
<td>1HR P 1_6</td>
<td>6</td>
<td>0</td>
<td>99.8333</td>
<td>85.27</td>
<td>96.5</td>
<td>13</td>
<td>244</td>
<td>0.873574</td>
<td>0.860179</td>
</tr>
<tr>
<td>1HR P 4_6</td>
<td>3</td>
<td>0</td>
<td>160</td>
<td>74.081</td>
<td>132</td>
<td>104</td>
<td>244</td>
<td>1.45786</td>
<td>*</td>
</tr>
<tr>
<td>2HR P 4_6</td>
<td>3</td>
<td>0</td>
<td>216.333</td>
<td>75.295</td>
<td>179</td>
<td>167</td>
<td>303</td>
<td>1.68269</td>
<td>*</td>
</tr>
<tr>
<td>1&amp;2HR P 4_6</td>
<td>3</td>
<td>0</td>
<td>376.333</td>
<td>149.149</td>
<td>311</td>
<td>271</td>
<td>547</td>
<td>1.59295</td>
<td>*</td>
</tr>
</tbody>
</table>

Table 5 Statistical table of the mean time intervals between major movements over 1 hour and 2 hours. Time intervals were also calculated from the start to end of the second hour for comparison to the first hour. The paraplegic group was subdivided to show data from patients 1 to 6 and 4 to 6 in the first hour and 4 to 6 in the second hour.

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>N*</th>
<th>Mean (11hz)</th>
<th>Mean (sec)</th>
<th>StDev</th>
<th>Median</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1HR N</td>
<td>20</td>
<td>0</td>
<td>316.189</td>
<td>31.6189</td>
<td>248.828</td>
<td>243.85</td>
<td>66.1651</td>
<td>1066.89</td>
<td>2.05191</td>
<td>4.14614</td>
</tr>
<tr>
<td>2HR N</td>
<td>20</td>
<td>0</td>
<td>254.805</td>
<td>25.4805</td>
<td>195.384</td>
<td>184.019</td>
<td>74.2992</td>
<td>925.116</td>
<td>2.29991</td>
<td>6.79207</td>
</tr>
<tr>
<td>1&amp;2HR N</td>
<td>20</td>
<td>0</td>
<td>263.539</td>
<td>26.3539</td>
<td>172.101</td>
<td>194.714</td>
<td>100.103</td>
<td>675.051</td>
<td>1.33786</td>
<td>0.82193</td>
</tr>
<tr>
<td>1HR P 1_6</td>
<td>6</td>
<td>0</td>
<td>969.274</td>
<td>96.9274</td>
<td>1121.19</td>
<td>391.523</td>
<td>160.496</td>
<td>3005.46</td>
<td>1.58261</td>
<td>1.80419</td>
</tr>
<tr>
<td>1HR P 4_6</td>
<td>3</td>
<td>0</td>
<td>270.627</td>
<td>27.0627</td>
<td>99.8941</td>
<td>295.992</td>
<td>160.496</td>
<td>355.394</td>
<td>-1.06895</td>
<td>*</td>
</tr>
<tr>
<td>2HR P 4_6</td>
<td>3</td>
<td>0</td>
<td>202.122</td>
<td>20.2122</td>
<td>62.9075</td>
<td>223.184</td>
<td>131.386</td>
<td>251.796</td>
<td>-1.33775</td>
<td>*</td>
</tr>
<tr>
<td>1&amp;2HR P 4_6</td>
<td>3</td>
<td>0</td>
<td>230.004</td>
<td>23.0004</td>
<td>76.4899</td>
<td>254.087</td>
<td>144.371</td>
<td>291.554</td>
<td>-1.27638</td>
<td>*</td>
</tr>
</tbody>
</table>
Figure 34 Probability plot showing various distribution graphs for average movement of normal subjects over 1 hour. Data fit a normal distribution as shown in top left graph above.

Figure 35 Probability plot showing various distribution graphs for average time interval of normal subjects over 1 hour. Data fit a lognormal distribution as shown in bottom left graph above.
Table 6 P-values for normal distribution for movement subgroups.

<table>
<thead>
<tr>
<th>Movement Averaged</th>
<th>Normal p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal 1hr</td>
<td>0.281</td>
</tr>
<tr>
<td>Normal 2 hr</td>
<td>0.211</td>
</tr>
<tr>
<td>Normal 1&amp;2 hr</td>
<td>0.722</td>
</tr>
<tr>
<td>Para 1 hr 1_6</td>
<td>0.455</td>
</tr>
<tr>
<td>Para 1 hr 4_6</td>
<td>0.249</td>
</tr>
<tr>
<td>Para 2 hr 4_6</td>
<td>0.114</td>
</tr>
<tr>
<td>Para 1&amp;2 hr</td>
<td>0.172</td>
</tr>
</tbody>
</table>

Table 7 P-values for lognormal distribution for time interval subgroups.

<table>
<thead>
<tr>
<th>Time Interval Averaged</th>
<th>Lognormal p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal 1hr</td>
<td>0.165</td>
</tr>
<tr>
<td>Normal 2 hr</td>
<td>0.712</td>
</tr>
<tr>
<td>Normal 1&amp;2 hr</td>
<td>0.371</td>
</tr>
<tr>
<td>Para 1 hr 1_6</td>
<td>0.357</td>
</tr>
<tr>
<td>Para 1 hr 4_6</td>
<td>0.299</td>
</tr>
<tr>
<td>Para 2 hr 4_6</td>
<td>0.227</td>
</tr>
<tr>
<td>Para 1&amp;2 hr</td>
<td>0.243</td>
</tr>
</tbody>
</table>
Figure 36 Time series plot with trend line showing negative slope.

Figure 37 Time series plot with trend line showing positive slope.
Table 8 Periodograms for 3 normal subjects (top row) and 3 paraplegic patients (bottom row). Only minimal noise is observed.

<table>
<thead>
<tr>
<th>Sub 1</th>
<th>Sub 2</th>
<th>Sub 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt 1</td>
<td>Pt 2</td>
<td>Pt 3</td>
</tr>
</tbody>
</table>
Table 9 Graphs of normal subjects showing individuals may have a side preference or may be approximately even in how they distribute their weight.
Figure 38 Time series plot of platform values on left side (black) and right side (red) on one subject over 2 hours.

Figure 39 Graph comparing the z length of the hemi-ellipsoid versus the maximum pressure on the left minus the right of one normal subject over 2 hours.
Table 10 Lengths of x, y, and z of hemi-ellipsoid shape of one frame for six paraplegic patients and one normal subject with error calculations.

<table>
<thead>
<tr>
<th>Sub#</th>
<th>x length</th>
<th>y length</th>
<th>z length</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt1</td>
<td>31.774</td>
<td>115.406</td>
<td>311.740</td>
<td>-14.81%</td>
</tr>
<tr>
<td>Pt2</td>
<td>874.050</td>
<td>3382.271</td>
<td>220</td>
<td>-270.18%</td>
</tr>
<tr>
<td>Pt3</td>
<td>68.229</td>
<td>51.411</td>
<td>292.429</td>
<td>-5.10%</td>
</tr>
<tr>
<td>Pt4</td>
<td>6.619</td>
<td>12.484</td>
<td>267.406</td>
<td>101.81%</td>
</tr>
<tr>
<td>Pt5</td>
<td>25.848</td>
<td>6.750</td>
<td>283.215</td>
<td>52.72%</td>
</tr>
<tr>
<td>Pt6</td>
<td>29.429</td>
<td>175.865</td>
<td>278.762</td>
<td>-44.84%</td>
</tr>
<tr>
<td>Sub1</td>
<td>59.792</td>
<td>5.409</td>
<td>278.457</td>
<td>37.56%</td>
</tr>
<tr>
<td>Ave ALL Sub 1</td>
<td></td>
<td></td>
<td></td>
<td>39.87%</td>
</tr>
</tbody>
</table>
CHAPTER 6: CONCLUSIONS

6.1 Summary of Findings

There were three primary objectives of this research. The first two goals were to describe how normal individuals move and how paraplegic individuals move. The third goal was to demonstrate if pressure values can be modeled using a hemi-ellipsoid shape.

A simple visual comparison of normal subjects and paraplegic patients can show significant differences although sometimes it may be difficult to discern a paraplegic patient from a normal patient. Normal subjects have a hemi-ellipsoid shape for their mound values. While some paraplegic patients also have a hemi-ellipsoid shape, others instead have a mound that looks like a platform. The number of values that constitute this mound are greater for the paraplegic patients than for the normal subjects. However, interpretation of this difference is limited by the fact that while normal subjects have a constant factor that goes into calculating values set as the mound the paraplegic patients have a factor which varies in order to ensure values are in fact selected for the mound. The platform pressure was found greater for paraplegic patients, but again interpretation is limited due to the altered factor.

In addition to the visual assessment above, the program performed calculations which revealed information about how normals and paraplegics move. Both normal subjects and paraplegic patients significantly increased the number of movements from the first hour to the second recorded hour. The changes in time interval decreased over the two hours but not significantly for neither the normals nor the paraplegics. No significant difference was noted when the normal and paraplegic groups were compared to each other. Additionally, paraplegic and normal subjects may have a side preference that they prefer shifting towards.
The data were analyzed for patterns such as cyclical variations through the use of time series plots with trend lines, ARIMA, and periodograms but no pattern was supported and the data were assumed to be random in nature.

Finally, validation of the model was performed with one normal subject for all frames and for one frame of each of the six paraplegic patients. The computer run-time for the hemi-ellipsoid modeling was significant, requiring over three days.

### 6.2 Future Research

A number of questions are posed by the results of this research which warrant continued investigation. 20 normal subjects were tested between the ages of 18-40 years old. Enrolling more normal subjects would increase the power of the study. Additionally, extension of the age range to include the elderly and pediatric population may reveal changes in the pressure distribution with age. For example, pediatric patients may spend more time laying down due to primitive motor development. On the other hand, elderly patients may have decreased movement due to the aging process on joint limitations. The heights and weights of subjects were recorded. With additional enrollment to the normal group, subgroup analysis could be performed to see if height and weight are confounding variables.

The number of participants in the paraplegic group was very small at n = 6. Further, the first three subjects were tested at only 1 hour in order to show the safety of the experiment. Moving forward all patients should be tested at 2 hours. As with the normal subjects, other characteristics such as age, weight, and height should be used to stratify into subgroups for analysis. Other important subgroups include location of injury and the time since the injury first occurred. The presence of other common disease processes such as heart disease and diabetes could be noted.

Paraplegic patients can at times recover some of their mobility after an initial loss as their body responds to the injury and as the patient uses rehabilitation services. Following spinal cord injury
patients over time could give insight to the recovery process. Patients could be followed immediately after their injury and at three month intervals for one year. Interesting questions could include when is a patient most at risk for pressure ulcer development after injury? Do movement patterns exist as the patient recovers?

Other groups with altered mobility such as Amyotrophic Lateral Sclerosis (ALS), Diabetes Mellitus (DM), Muscular Sclerosis (MS), and others could be tested. For these individuals where their disease process is likely to worsen their movement over time it may be important to follow them over a several year period to see how their pressure maps change.

Further analysis of the existing data could reveal more information to help with data collection. For example, what is the optimum time needed for recordings of pressure? The computer run-time is significant and reduction in the amount of data collected would allow for easier analysis. Similarly, what is the number of sensors needed for the recordings? Currently, each frame records 1,296 pressure readings.

An essential next step concerns analysis of the mound. While this project showed a hemi-ellipsoid shape can be used to model how an individual moves analysis of that movement is necessary for it to be meaningful. All subjects and patients should be run through the hemi-ellipsoid model in order to calculate the x, y, and z vectors for the areas of major movement. These movements then need to be visually explored using 3-D animation. Issues regarding the factor value that impacted the values chosen for the mound need to be resolved. A simple solution may be calculating the average pressure across each frame versus the platform pressure, which is subject to the choice of the factor.

Movement could be further categorized based on the types of movements that occur. Several studies look at a patient's position in a chair during recordings using sensors such as gyrometers. It may be that certain movements are more essential in pressure relief than others. Also, current pressure relief methods such as leans, push-ups, and tilts could be explored in both normal and paraplegic
patients to identify the pressure changes that result from these movements to see if they are beneficial. Paraplegic patients could be tested to see if they are able to perform movements that replicate the movements of normal individuals.

One of the reasons this research was initially pursued was the desire to prevent pressure sores from occurring, although this goal is outside the scope of this dissertation. Current pressure treatment might be optimized by recording pressures throughout the treatment process to see if it is possible to monitor healing. If a pressure sore is determined to not be healing from a given treatment plan alternative treatments could be attempted, for example.

Current pressure pore prevention protocols call for movement every 15 minutes in able-bodied individuals and once every hour for individuals needing assistance with pressure relief. This analysis shows normals move on average approximately every 30 seconds. Further studies are needed to determine if prevention protocols should be changed. The current guidelines are based on recommendations of experts versus evidence-based research.

Finally, there are applications for device designs which can mimic normal movements. A chair with inflatable and deflatable cells could help paraplegic patients who need assistance with relief to achieve it independent of a caretaker and in a more efficient and scientifically validated manner.

In conclusion, the movements of normal subjects and paraplegic patients have been discussed and validation of using a hemi-ellipsoid shape as a model for movement has been performed.
REFERENCES


NPUAP. (2005). *Pressure Ulcer Definitions.*


Pressure Ulcer Category/Staging Illustrations. from http://www.npuap.org/resources/educational-and-clinical-resources/pressure-ulcer-categorystaging-illustrations/


Sopher, R., Nixon, J., Gorecki, C., & Gefen, A. (2010). Exposure to internal muscle tissue loads under the ischial tuberosities during sitting is elevated at abnormally high or low body mass indices. *J Biomech, 43*(2), 280-286. doi: 10.1016/j.jbiomech.2009.08.021


Appendix A Information on XSENSOR Mapping System

Figure A.1 Product information on XSENSOR map.
### Appendix B Statistical Distributions

Table B.1 Distributions of averaged data for normals and paraplegics over 1 hour and 2 hours.

<table>
<thead>
<tr>
<th>Goodness of Fit Test</th>
<th>AD</th>
<th>P</th>
<th>LRT P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>0.428</td>
<td>0.281</td>
<td>1.000</td>
</tr>
<tr>
<td>Box-Cox Transformation</td>
<td>0.337</td>
<td>0.470</td>
<td>1.000</td>
</tr>
<tr>
<td>Lognormal</td>
<td>0.580</td>
<td>0.116</td>
<td>1.000</td>
</tr>
<tr>
<td>2-Parameter Lognormal</td>
<td>0.345</td>
<td>* 0.159</td>
<td>1.000</td>
</tr>
<tr>
<td>Exponential</td>
<td>2.235</td>
<td>0.005</td>
<td>1.000</td>
</tr>
<tr>
<td>2-Parameter Exponential</td>
<td>1.373</td>
<td>0.020</td>
<td>1.000</td>
</tr>
<tr>
<td>Weibull</td>
<td>0.338</td>
<td>&gt;0.250</td>
<td>1.000</td>
</tr>
<tr>
<td>3-Parameter Weibull</td>
<td>0.377</td>
<td>0.433</td>
<td>1.000</td>
</tr>
<tr>
<td>Smallest Extreme Value</td>
<td>1.051</td>
<td>&lt;0.010</td>
<td>1.000</td>
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<tr>
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### Averaged Paraplegic Patients 1-6 Over 1 & 2 Hours for Movement

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### Averaged Normal Subjects 1-20 Over 1 Hour for t Interval

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### Averaged Normal Subjects 1-20 Over 1 & 2 Hours for t Interval

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### Table B.1 Continued

#### Goodness of Fit Test

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#### Goodness of Fit Test

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### Table C.1

Selected frames of major movement for six paraplegic patients and one normal subject. Paraplegic patient 4 appears visually similar to normal subject 1.
Table C.2 Graphs of maximum pressure on the left minus the right for six normal subjects over 2 hours.

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Table C.3 Graphs of the maximum pressure on the left minus the right for six paraplegic patients and one normal for comparison over 1 hour. All frames have the same scale except patient 4 where the scale is shifted but has same range.

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![Graph Image](image-url)
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---

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Thank you so much for all of the help your company has provided me.

Sincerely,
Alicia Billington

---

Bruce Malkinson <bruce.malkinson@xsensor.com> 12:30 PM (25 minutes ago)

Alicia

You may use the image. Can you send a copy of your paper when complete?

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An Automated Model for Fitting a Hemi-Ellipsoid and Calculating Eigenvalues Using Matrices

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ABSTRACT

Ellipsoid modeling is essential in a variety of fields, ranging from astronomy to medicine. Many response surfaces can be approximated by a hemi-ellipsoid, allowing estimation of shape, magnitude, and orientation via orthogonal vectors. If the shape of the ellipsoid under investigation changes over time, serial estimates of the orthogonal vectors allow time-sequence mapping of these complex response surfaces. We have developed a quantitative, analytic method that evaluates the dynamic changes of a hemi-ellipsoid over time that takes data points from a surface and transforms the data using a kernel function to matrix form. A least square analysis minimizes the difference between actual and calculated values and constructs the corresponding eigenvectors. With this method, it is possible to quantify the change of a dynamic hemi-ellipsoid over time. Potential applications include modeling pressure surfaces in a variety of applications including medical.

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Appendix E Publications

Publication by author of dissertation.

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ABSTRACT

Ellipsoid modeling is essential in a variety of fields, ranging from astronomy to medicine. Many response surfaces can be approximated by a hemi-ellipsoid, allowing estimation of shape, magnitude, and orientation via orthogonal vectors. If the shape of the ellipsoid under investigation changes over time, serial estimates of the orthogonal vectors allow time-sequence mapping of these complex response surfaces. We have developed a quantitative, analytic method that evaluates the dynamic changes of a hemi-ellipsoid over time that takes data points from a surface and transforms the data using a kernel function to matrix form. A least square analysis minimizes the difference between actual and calculated values and constructs the corresponding eigenvectors. With this method, it is possible to quantify the shape of a dynamic hemi-ellipsoid over time. Potential applications include modeling pressure surfaces in a variety of applications including medical.

KEYWORDS

Modeling; Response Surfaces; Ellipsoid

1. Introduction

The Cartesian coordinate equation for an ellipsoid is given by the formula:

\[
\frac{(x-h)^2}{a^2} + \frac{(y-j)^2}{b^2} + \frac{(z-k)^2}{c^2} = 1
\]

where \(h, j, k\) represent the coordinates of the center of the ellipsoid and \(a, b, c\) represent the unit axis lengths from the center.

An alternate form of this equation is the matrix equation given by the formula:

\[
\begin{align*}
\begin{pmatrix}
\frac{x-h}{a} \\
\frac{y-j}{b} \\
\frac{z-k}{c}
\end{pmatrix}
& \begin{pmatrix}
a & 0 & 0 \\
0 & b & 0 \\
0 & 0 & c
\end{pmatrix}
\begin{pmatrix}
\frac{x-h}{a} \\
\frac{y-j}{b} \\
\frac{z-k}{c}
\end{pmatrix} = 1.
\end{align*}
\]

An alternate form of this equation is the matrix equation given by the formula:

\[
2) (A')x' = 1, \text{ where } A' = \begin{pmatrix}
a & d \\
b & e \\
c & f
\end{pmatrix}
\]

orientation. The \(A\) matrix is assumed to be positive definite. Substitution gives the long form of the equation:

\[
3) a(x-h)^2 + b(y-j)^2 + c(z-k)^2 + d(x-h)(y-j) + e(x-h)(z-k) + f(y-j)(z-k) = 1.
\]

Here, the eigenvalues and eigenvectors of the \(A\) matrix give the corresponding squared length of the axis and the orientation, respectively. Orthogonal eigenvectors are induced when the matrix is symmetric [1].

Previous papers have discussed using the method of least squares estimates (LSE) to converge on the ellipsoid best fit for a given set of data [2-5]. LSE analysis minimizes the sum of the distance (or squared difference) be-
tween the measured and predicted values of an ellipsoid. We have simplified this concept by implementing existing add-ins in Microsoft Excel such as Solver and Matrix.xla. Additionally, we have automated the process using VBA code so that as the hemis-ellipsoid alters shape and position we can continuously re-calculate the new eigenvalues and eigenvectors of the ellipsoid.

Our goal was to create a program that automatically and continuously evaluates data from a pressure map for seated individuals. Currently, most medical institutions evaluate peak pressure when assessing patients for pressure build-up which can lead to pressure ulcer development. However, peak pressure is not the sole determinant in tissue breakdown [6]. Other studies have looked at using MRI and finite element analysis, but these studies do not use continuous data, are not over extended time periods, and involve significant expense [7-10]. The purpose of this analysis was to create a method that could show movement over time continuously and could be easily incorporated into existing care via a pressure map that many hospitals already own, without additional expenses.

2. Transformation and Least Squares Estimation

2.1. Calculated Values

In order to assess the validity of the method, we first tested the ability of the program to predict the values of a known ellipsoid. We chose the simple ellipsoid defined by the following equation:

\[
\frac{(x-a)^2}{4} + \frac{(y-b)^2}{4} + \frac{(z-c)^2}{4} = 1
\]

and considered only the superior half of the shape. We calculated the \(z\) values for \(x\) and \(y\) coordinates known to have corresponding values on the surface of the ellipsoid by solving for the unknown variable \(z\):

\[
z = 3 + \sqrt{1 - (x - 3)^2 - (y - 3)^2}.
\]

2.2 Predicted Values

The predicted values for \(z\) were calculated through minimization via quadratic optimization by gradient descent using the Solver Add-in in Microsoft Excel. Two models were created minimizing the absolute difference and the squared difference between \(z\) and \(\hat{z}\). The actual and predicted values from the model can be viewed in Table 1. Multiple constraints were placed on the calculations. First, the equation for the matrix had to be satisfied (long form of equation above). Second, as previously mentioned, the \(A\) matrix must be made symmetric in order to assume orthogonal eigenvectors. Additional constraints on the \(A\) matrix were made such that the matrix could be assumed positive definite. Finally, different lower bound values for \(\hat{z}\) were tested in order to allow Solver to find the optimal solution. We found that Solver was not always able to arrive at the best ellipsoid shape by simply allowing it to explore the surface on its own, but could converge if multiple values were tested. VBA code was written to create a loop to test various \(\hat{z}\) values and to select the value which minimized the sum of squared differences or the squared absolute difference. 3-D imaging of the selected predicted versus actual values is shown in Table 2.

<table>
<thead>
<tr>
<th>(z)</th>
<th>(\hat{z})</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0000</td>
<td>3.0000</td>
</tr>
<tr>
<td>4.142</td>
<td>4.3162</td>
</tr>
<tr>
<td>4.7311</td>
<td>4.6908</td>
</tr>
<tr>
<td>4.4142</td>
<td>4.4142</td>
</tr>
<tr>
<td>3.0000</td>
<td>3.0253</td>
</tr>
<tr>
<td>4.7311</td>
<td>4.6906</td>
</tr>
<tr>
<td>5.0000</td>
<td>5.0000</td>
</tr>
<tr>
<td>4.7311</td>
<td>4.7460</td>
</tr>
<tr>
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<td>3.0000</td>
</tr>
<tr>
<td>4.4142</td>
<td>4.4142</td>
</tr>
<tr>
<td>4.7311</td>
<td>4.7455</td>
</tr>
<tr>
<td>4.4142</td>
<td>4.4142</td>
</tr>
<tr>
<td>2.0000</td>
<td>2.0640</td>
</tr>
</tbody>
</table>
The constraints are summarized here:

Objective Function:

\[ \text{objective } f = \sum_{i=1}^{n} \sum_{j=1}^{m} |z_{ij} - \hat{z}_{ij}| \]

Changing Cells:

- \( A \) matrix
- \( h, j \)

Constraints:

- \( \hat{z} > \) lower bound

\[ A(x-h)^2 + B(y-j)^2 + C(z-k)^2 + D(x-h)(y-j) + E(x-h)(z-k) + F(y-j)(z-k) = 1 \]

\( k = 0 \)

the \( A \) matrix is assumed positive definite

3. Eigenvalue and Eigenvector Calculations

After the optimum predicted values were determined and thus the corresponding \( A^+ \) matrix, the program was automated to select the \( A^+ \) matrix and calculate the associated eigenvalues and eigenvectors, as shown in Table 3. The Jacobi Method in Matrix.XLA [11] was employed in order to ensure forced orthogonal vectors. Once the eigenvalues were determined, the square roots of the values were calculated to give the axis lengths of the ellipsoid.

4. Sample Data

After the validity of the program had been tested using a known ellipsoid, a 36 x 36 sample data set of measured values from a pressure map was analyzed. An ellipsoid shape was identified from the data automatically and assessed for characteristics of shape and size. The program was able to identify center values for the ellipsoid and eigenvalues that visually made sense, as shown in Figure 1. The calculated eigenvalues of 4.83, 8.38, and 71.4265 corresponded to \( x, y, \) and \( z \) axes of 2.20, 2.90, and 267.47 respectively. Thus, we have illustrated that the program is capable of taking real data, locating an ellipsoid, and analyzing its shape.

5. Discussion

5.1 Analysis

Analysis of the data shows the strength of this program in accurately predicting the ellipsoid shape of the data.
Table 3. The calculated inverse A matrix with associated eigenvalues and eigenvectors. Note that the diagonal values of the inverse matrix are close to the actual value of 0.25 and that the distances calculated for the axis length of the ellipsoid are close to the actual value of 2 × 2 × 2 units.

<table>
<thead>
<tr>
<th>A⁻¹ Matrix</th>
<th>Eigenvalues</th>
<th>Eigenvectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.150</td>
<td>0.008</td>
<td>−0.009</td>
</tr>
<tr>
<td>0.00846</td>
<td>0.34932</td>
<td>0.00815</td>
</tr>
<tr>
<td>−0.0009</td>
<td>0.229</td>
<td></td>
</tr>
</tbody>
</table>

| 3.8423     | 1.9061      |
| 4.1495     | 2.0370      |
| 4.4135     |

Figure 1. Sample data collected from a 36 × 36 matrix. Values increase in magnitude from blue to yellow to red. Bar highlighted in black denotes cell which the program calculated as being at the center of the ellipsoid on left half of matrix.

Statistical analysis based on the 13 actual and predicted values of the known ellipsoid showed a very low average error of −0.258% and average absolute error of 0.507%. The center coordinates of the ellipsoid calculated automatically by the program were also extremely accurate, with an average 1.06% error. As discussed above, the A⁻¹ matrix gave values close to the expected value of 0.25, as seen in Table 3. The summed difference between 2 and 2 served as the optimization function in the Solver Add-in. The difference between the actual and predicted values was calculated to be only 0.266, again supporting the validity of this method in predicting the ellipsoid shape. The sum squared difference was also calculated, giving a value of 0.00019, with the above mentioned parameters also lower than with the summed difference. However, it was decided that the summed difference would be preferable to the sum squared difference as anticipated outliers will lead to distortion of the model. Finally, the square roots of the calculated eigenvalues reproduce close to the expected axis lengths of 2 units with only a 2.96% average absolute error.

For the measured sample data set, the summed absolute difference between the measured and predicted values ranged from 364.32 to 1070.4 and the average absolute percent error was 20.478%. There are several considerations for the absolute percent error. First, the measured data is an irregular shape and is not a perfect hemi-ellipsoid. Second, while the overall shape may appear hemi-ellipsoid-like, outliers can affect the overall prediction of the model. We determined the values of the mound by eliminating low extreme values, but we did not eliminate high extreme values. Thus, it may be important in future applications to consider removal of these high peak values in order to focus on the values that best fit the shape of the hemi-ellipsoid.
Acknowledgements

A B. would like to thank her faculty advisors and the Colleges of Engineering and Medicine at USF, as well as her patients, family, and Joshua M. Dugd.

REFERENCES

Visualization of the data is an important validation method when testing modeling predictability, which allows interpretation of fit as well location of extreme differences and also verifies that the resulting model is actually ellipsoidal. The Add-in R Excel was used to give 3-D graphical representation, as shown in Figure 2 below. Additionally, Matlab was used to create a hemi-ellipsoid shape that fit the actual data based on using triangle-based cubic interpolation of the given values. A 3-D representation of the ellipsoid, actual, and predicted data are shown in Figure 3.

To our knowledge, this is the first description of the ischial tuberosities being modeled as hemi-ellipsoids using the matrix equation of an ellipsoid with sum of least squares in a continuous fashion. This model allows for continuous monitoring of data over long periods of sitting time due to its automation.

5.2. Limitations and Considerations

A major limitation of using a gradient descent method is that it is possible for local maxima or minima to be discovered that are not the true absolute maximum or minimum. In order to circumvent this, we created a loop allowed for different lower bound values for z to be assumed and it initiated the search in different points on the xy grid. We termed the model to determine the best “center,” represented by a lower bound of “z”. Additionally, the assumption was made that the center of the ellipsoid was on the map. Thus, the parameter k was set equal to 0.

When automating, a trade-off has to be made between accuracy and computation time. Depending on the necessity for precision, a decreased stepping parameter may be desired to ensure the best possible fit occurs. The complexity of the problem and the running time for automation must be taken into consideration when deciding what step should be used and over what range of possible z lower bound values. For example, the running time from 0 to 1.50 with a step of 0.15 ms for 13.5 seconds while with a step of 15 ms for 38.8 s. If multiple frames of data are collected per second over a period of several minutes to hours, the computation time increases to several hours.

A point of consideration when examining the results of the eigenvalues and eigenvectors is that Matrix A has offered multiple means of calculating the eigen numbers. For example, the eigenvectors did not have to be assumed to be orthogonal with some methods. However, since we initially based our assumption of the $A^T$ matrix as being positive definite, we chose the Jacobi method that forced orthogonalization. Ultimately, we felt that in order for the results to be comprehensible, it was most logical to force the vectors to be orthogonal.

The method described allows for complex modeling of 3-D data by assuming a hemi-ellipsoid shape. While some of the assumptions and constraints force that data to fit a symmetrical shape, it allows for a means of comparison between constantly evolving shapes. This method is useful in showing trends over time and has a variety of applications in modeling systems with changing hemi-ellipsoid-like shapes.

![Figure 2. Sample data is in blue and predicted values are in green for the hemi-ellipsoid taken from the left portion of the matrix. The image on the left is a 3-D rendering of the data isolated at the mound from Figure 1. The image on the right models a different frame, and shows that the program can have difficulty in calculating the peak value at the top of the mound at times.](image-url)
Appendix F Poster Presentation

Mathematical Pressure Modeling of Continuous Movement in Seated Individuals

Alicia R. Billington, M.Eng, Peter J. Fabri, MD, PhD, Lisa Gould, MD, PhD, William Lee, PhD, David J. Smith Jr., MD, Piyush Koria, PhD

Objectives:
- Despite years of research on paraplegic patients, much remains unknown regarding how even normal subjects adjust themselves to relieve pressure while seated. First understanding how a normal subject alters their position is pertinent for the development of rigorous strategies for pressure relief in paraplegic patients.
- We have developed a quantitative, analytic method that evaluates the dynamic change in forces generated by sitting over time.

Methods:
- This method models each hemi-buttock as a complex of three pressures:
  1. flat platform pressure
  2. eccentric hemi-ellipsoid
  3. central spire.
- The hemi-ellipsoid principal directions and magnitudes are resolved from continuous pressure acquisition (36x36 cm pressure mat) using quadratic optimization by gradient descent using Microsoft Excel with the Solver and Matrix.xla Add-ins, automated with VBA code.

Methods Continued:
- Platform
  - Data from pressure map matrix is averaged and +2 standard deviations is removed from data until the average remains constant.
  - The resulting average gives the platform pressure.

- Hemi-ellipsoid
  - Data removed from the platform greater than +2 standard deviations are set as mound values.
  - Mound values are evaluated using Solder to create predicted values by assuming hemi-ellipsoid shape.
  - Matrix Equation for an ellipsoid: \( A_1 x^2 + A_2 y^2 + A_3 z^2 = 1 \)
  - The sum squared (and absolute) difference between the measured and the predicted values is minimized.

Results:
- Data were recorded at 1 Hz for 20 minutes on an Xsens pad. Characteristic frames were selected from 1200 recorded time points of data for demonstration.
- Eigenvalues and eigenvectors were derived from the model transformation matrix and are demonstrated as a vectorgram. Platform and peak pressures and the peak pressure location were additionally determined.
- The model allowed for a definition of pressure distribution and how pressure changes over time.

Conclusion:
We show with this method it is possible to quantify the dynamic effect of changes in movement while seated. Robust clinical protocols for paraplegic and insensitive subjects could be created from the basis of understanding normal pressure adaptation.

Next Steps:
- Continue automating with VBA code
- Calculate for 2 hours of data at 1Hz for 7200 frames
- Test 30 normal subjects and 30 paraplegics
- Design protocol for paraplegics based on study results
ABOUT THE AUTHOR

Alicia Billington received her Bachelor of Science in Biological and Environmental Engineering with a minor in Biomedical Engineering and her Master of Engineering in Biomedical Engineering degrees from Cornell University. She graduated from the University of South Florida Morsani College of Medicine and was accepted into the Plastic and Reconstructive Surgery residency training program at the University of South Florida Morsani College of Medicine.