BIOMECHANICAL RESPONSES TO SEATED FULL BODY TILT AND THEIR RELATIONSHIP TO CLINICAL APPLICATION

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BIOMECHANICAL RESPONSES TO SEATED FULL BODY TILT AND THEIR RELATIONSHIP TO CLINICAL APPLICATION

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I dedicate this dissertation to the research participants with whom I had the pleasure of working. Their strength and faith were a constant inspiration and truly motivated me to work my hardest at my research goal: to improve their health, function and quality of life.

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LIST OF SYMBOLS AND ABBREVIATIONS

PU	Pressure Ulcer
SCI	Spinal Cord Injury
MRI	Magnetic Resonance Imaging
SD	Standard Deviation
TIS	Tilt-in-Space
PRT	Pressure Relieving Tilt
CI	Confidence Interval
$TcPO_2$	Transcutaneous Partial Pressure of Oxygen
LDPM	Laser Doppler Perfusion Monitor
BF	Blood Flow
AU	Arbitrary Units

SUMMARY

Tilt systems are frequently prescribed to wheelchair users who are unable to independently reposition or perform pressure reliefs for the prevention of pressure ulcers. However, little is known about how people use these systems, the biomechanical effects of their use, or how they ought to be used for maximum benefit. The overall goal of this research is to improve the use of seated tilt to increase function, health and quality of life for people using power wheelchairs. Specifically, the objective of this dissertation is to evaluate the biomechanical responses to seated full body tilt and their relationships to the actual use of tilt-in-space wheelchairs.

In the first phase of this study, researchers remotely monitored how 45 fulltime power wheelchair users used their tilt-in-space systems. Participants spent an average of 12.1 hours in their wheelchair each day. They spent more than 2 hours seated at positions greater than 15° and performed tilts of 5° or greater every 27 minutes, but rarely performed tilts past 30°.

Two distinct types of tilt behavior were identified: *uni-modal* (staying at a single position more than 80% of the time) and *multi-modal* (staying at a single position less than 80% of the time). Participants in the multi-modal group tilted significantly more frequently (4 times per hour) than the uni-modal group, and did not have a single typical position. Participants without sensation were more likely to exhibit uni-modal behavior.

In the second phase of this study, researchers used interface pressure measurements and laser Doppler flowmetry to study changes in localized loading and superficial blood flow at the ischial tuberosities across different amounts of tilt. Eleven participants with spinal cord injuries were studied in a laboratory setting. Results showed that biomechanical responses to tilt were highly variable. Pressure reduction at the ischial tuberosity was not present at 15°, but did occur with tilts to 30° and greater, and could be explained by the tilt position and upright pressure. Unlike pressure, blood flow increased with all tilts from an upright position, but did not increase when tilting from 15° to 30°. Only 4 of 11 participants had a considerable increase ($\geq$10%) in blood flow at 30° tilt, whereas 9 participants did during maximum tilt (i.e., 45°-60°). Based on the results of this study, tilting for pressure reliefs as far as the seating system permits is recommended to maximize the potential for significant pressure relief and increased blood flow.

CHAPTER I

INTRODUCTION

Specific Aims

The overall goal of this research is to improve the use of seated tilt to increase function, health and quality of life for people using power wheelchairs. Specifically, the objective of this project was to evaluate the biomechanical responses to seated full body tilt and their relationships to the actual use of tilt-in-space wheelchairs.

Tilt systems are frequently prescribed to wheelchair users who are unable to independently reposition or perform pressure reliefs for the prevention of pressure ulcers. However, little is known about how people use these systems, the biomechanical effects of their use, or how they ought to be used for maximum benefit. For this dissertation, researchers remotely monitored how people used their tilt-in-space systems, and evaluated the biomechanical responses to tilt in a laboratory setting. A descriptive analysis of the remote monitoring included participants' typical sitting positions, the magnitude and frequency of tilt maneuvers performed throughout the day, and the time spent at different tilt angles. In the laboratory, interface pressure measurement and laser Doppler flowmetry were used to study changes in localized loading and superficial blood flow at the ischial tuberosities across different amounts of tilt. Finally, tilt use was also analyzed based on the outcomes of the laboratory testing.

Pressure ulcers remain a major problem for many wheelchair users. In addition to having an obvious detrimental impact on health, pressure ulcers often disrupt the educational, vocational and community participation of wheelchair users, thus negatively affecting quality of life. Two factors, the magnitude of pressure and duration of loading, are the defining causes of pressure ulcers. Clinically, these causative factors are addressed by the selection of appropriate wheelchair cushions and by the establishment of pressure relief schedules. However, when power wheelchair users are unable to independently perform pressure reliefs, they may be prescribed powered tilt systems.

The Consortium for Spinal Cord Medicine suggested that tilt systems be utilized to perform weight shifts every 15-30 minutes for at least one minute. Although the required tilt angle to perform a pressure relief has not been defined, research has shown that interface pressure decreases as the tilt angle increases. Therefore, recommendations in the literature and clinic vary from 30° to 65°, with an emphasis on tilting "all the way back."

In preliminary studies, Sonenblum, et al. (2009) found that instead of performing pressure reliefs as prescribed, many participants performed frequent, small magnitude tilts. This alternate use of the tilt feature may be clinically important due to limitations in tilting to large angles. First, a tilted position past 30° or 45° is not functional as the user cannot maintain vision of activities in front of them. The position may cause a sensation of instability and may not be considered comfortable. In contrast, positions with small tilt angles are frequently described as comfortable, stable and functional. Therefore, this study sought to identify if the type and frequency of tilts already performed provide biomechanical benefits to the users.

As a first step, it was necessary to determine if the preliminary results on tilt use were generalizable to a larger population of wheelchair users. Given that many clinicians tend to agree with the pilot results, it was expected that the results would generalize.

Second, it was necessary to describe the relationships between tilting, and blood flow and localized loading. Finally, pressure relieving tilts were defined in the context of the measured biomechanical responses to tilt, and the definition was applied to the tilt-use data. The three phases of research are laid out in the following specific aims:

Specific Aim 1: To describe how tilt systems are used.

The tilt use of people who currently use tilt-in-space wheelchairs was monitored remotely for one week to provide a global picture of how people utilized their tilt systems. This aim was descriptive in nature. Aspects of tilt use such as the magnitude and frequency of tilts as well as the amount of time spent at each tilt angle (i.e., small, medium, large, extreme) are described. Additionally, hypotheses concerning whether participants tilted to angles currently associated with pressure relief (i.e., large or extreme angles) were tested, secondary to the descriptive analysis.

Specific Aim 2: To determine the impact of tilting on blood flow and localized tissue loading.

Laser Doppler flowmetry and interface pressure measurement were employed to measure the increase in blood flow and decrease in loading with increased tilt angle on a subset of subjects from Specific Aim 1. The overall relationship between tilt and blood flow and loading was described. Additionally, this relationship was used to define a minimum “pressure relieving tilt.” Although the efficacy of such a tilt in preventing pressure ulcers could not be defined within the scope of this study, a more justified definition of “pressure relieving tilt,” with which to analyze tilt feature use was developed.

Specific Aim 3: To reevaluate participants' tilt use in terms of the measured biomechanical responses to tilt.

The relationships between tilt angle and blood flow and loading, as well as the definition of pressure relieving tilt defined in Specific Aim 2, were used to evaluate the tilt use measured in Specific Aim 1. From this, the amount of biomechanical benefit participants received from their tilt use was determined.

The completed research informs researchers and clinicians about behaviors in everyday life that may influence pressure ulcer prevention. It also provides information on the influence of people's use of medical equipment on health. Manufacturers benefit from knowledge regarding how their wheelchairs are used as they may choose to optimize the devices for actual use rather than prescribed use. The blood flow results may allow for training to be focused on behaviors that can be more easily and comfortably integrated into a person's everyday routine, thereby lowering the incidence of pressure ulcers.

Background and Significance

High Incidence and Costs for Pressure Ulcers

Pressure ulcers (PUs) remain a leading secondary complication of spinal cord injury (SCI), affecting 29% of people with SCI during their initial hospital stay (Carlson, King et al. 1992). Furthermore, more than 50% of people with SCI experience PUs during their lifetimes (Vidal and Sarrias 1991; Salzberg, Byrne et al. 1998; Raghavan, Raza et al. 2003; Krause and Broderick 2004). A 2005 multi-center cohort study by Chen, et al. involving nine Model Spinal Cord Injury Systems showed a significant trend toward increasing PU prevalence in recent years (1994–2004 vs. 1984–1993) (Chen, Devivo et al. 2005). Annual US treatment costs for PUs in this population are approximately $1.2 billion, accounting for 25% of the total cost of medical care for SCI (Byrne and Salzberg 1996). The costs of PUs extend far beyond the medical costs incurred for treatment. Personal and societal costs from inactivity, as well as missed educational, vocational, and recreational pursuits are equally important.

Lack of Mobility Increases Risk for Pressure Ulcers

All risk assessment tools include limited mobility as a risk factor for PU development. Specifically, the Braden, Norton and Gosnell Scales include scores for both activity and mobility while the Waterlow Scale combines the two into a single category. In all scales, an activity level of chairfast or bedfast is associated with the most risk (Waterlow 1985, 2005; Bates-Jensen 1998). Similarly, risk analyses have found numerous mobility-related factors that increase risk. Salzberg, et al. (1996) described reduced activity as an important risk factor. Multiple studies have found that completeness of injury, described as complete (Young and Burns 1981; Vidal and Sarrias 1991; Carlson, King et al. 1992; Byrne and Salzberg 1996; Salzberg, Byrne et al. 1996; Salzberg, Byrne et al. 1998; Chen, Devivo et al. 2005) or by the ASIA or Frankel scores as having little or no motor function (Young and Burns 1981; Vidal and Sarrias 1991; Carlson, King et al. 1992; Fuhrer, Garber et al. 1993; Garber, Rintala et al. 2000) result in increased risk. Finally, two research groups found that spasticity, which results in movement, reduces the risk of pressure ulcer development (Vidal and Sarrias 1991; Byrne and Salzberg 1996; Salzberg, Byrne et al. 1998).

The reasons why these factors lead to pressure ulcers are numerous, but in general they relate back to the fundamental cause of pressure ulcers – external loading on tissue. Limited mobility in wheelchair users leads both to increased durations of loading (due to continuous sitting without the ability to reposition or relieve pressure) and increased magnitudes of loading (muscle atrophy causes body weight to be supported by smaller surfaces areas (Aissaoui, Kauffmann et al. 2001)). Fulltime power wheelchair users, including those prescribed tilt-in-space power wheelchairs, experience increased durations of loading – up to 16 hours each day (Sonenblum, Sprigle et al. 2009) because of their limited mobility and inability to change position. Considering this, as well as lack of sensation and incontinence (two other strong risk factors), fulltime power wheelchair users are often at the greatest risk for pressure ulcer development.

From External Loading to Pressure Ulcer Development

Bouten, et al. (2003) defined a hierarchical approach to pressure ulcer etiology. The hierarchy begins at the global level where the skin is exposed to external loading. This in turn loads and deforms the internal soft tissue which brings about pathophysiologic responses. External loading (i.e. interface pressure) has been studied regularly since the 1960's, when the first interface pressure measurement technologies emerged (Lindan, Greenway et al. 1965). Because interface pressure measurement tools are commercially available and the measurements are non-invasive and clinically meaningful, they dominate the pressure ulcer literature.

The mechanisms by which internal loading and the physiological response lead to pressure ulcers are not known, however some theories have been proposed. Oomens, et al. suggested three hypotheses for the etiology of PUs based on the seminal work of Dr. Krouskop and others (Krouskop 1983; Oomens, Bressers et al. 2003): (1) Ischaemia of soft tissues occurs as a result of the occlusion or collapse of capillaries. (2) A disruption of the equilibrium in the interstitium between cells affects terminal capillaries and lymph vessels. (3) Cell damage results from prolonged deformation. Application of this model to PU prevention modalities requires a better understanding of the body's physiologic response to such modalities.

External Loading

A variety of factors influence the external pressures. Intrinsic characteristics including ectomorphic index, gender, percent fat and stature (Moes 2007), body weight (Garber and Krouskop 1982; Moes 2007), diagnosis (Hobson 1992; Swain and Peters 1997; Vaisbuch, Meyer et al. 2000; Thorfinn, Sjoberg et al. 2002), and spasticity (Swain and Peters 1997) can greatly affect external pressures. Finally, aspects of the seating system including the wheelchair cushion, additional positioning supports and overall posture can also affect external pressures (Vaisbuch, Meyer et al. 2000; Moes 2007). In part due to the many sources of variability, interface pressure alone cannot be used to predict who will develop PUs (Gefen and Levine 2007). Instead, the allowable pressure is believed to be individualistic and dependent on a person's susceptibility as well as the durations of loading.

Research shows that the damaging effects of pressure are related to both its magnitude and duration. Over short periods of time, tissues can withstand higher external loads than over longer periods of time. Kosiak (1959) first demonstrated this characteristic 45 years ago by applying loads to the trochanters and ischial tuberosities of dogs. High loads for short durations and low loads for long durations induced ulcers with the time-at-pressure curve following exponential decay (Figure 1). Reswick and Rodgers (1976), who followed human subjects with spinal injury, determined this same pressure-time relationship.

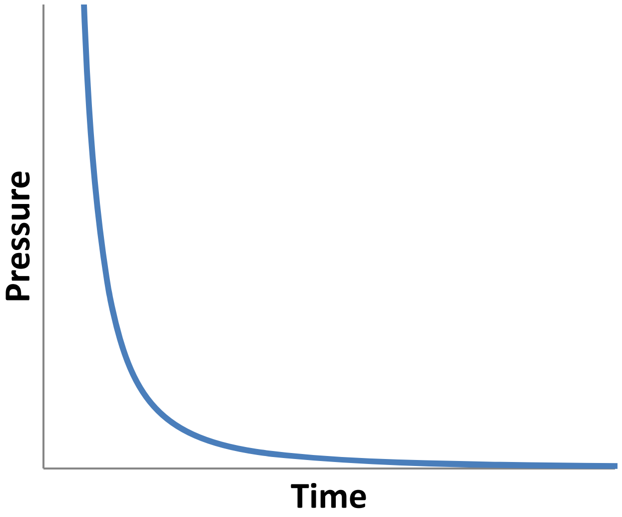

Figure 1. As time-at-pressure increases, smaller pressures can be tolerated without inducing pressure ulcers. Extremely high pressures cannot be tolerated over short durations without damage.

In a seated posture, it can be estimated that the buttocks are loaded by approximately 68% of the person's bodyweight (Winter 1990). In wheelchair sitting, that load is borne predominantly by the ischial tuberosities of the pelvis (Figure 2), with average pressures varying from 83.9 mmHg for elderly subjects seated on reference foam to 191.1 mmHg for subjects with SCI and no spasticity seated on the same reference foam (Swain and Peters 1997).

Internal Loading and Deformation

Internal loading has been studied predominantly in models and more recently in humans via MRI. Early studies used gel or elastomer models to determine internal stress and strain (Bennett, Kavner et al. 1979; Reddy, Patel et al. 1982; Sprigle, Haynes et al. 1994). More recent studies have applied finite element models to better understand internal tissue deformations and to find relationships between external loading and internal tissue deformation and loading (Todd and Thacker 1994; Ragan, Kernozek et al. 2002; Breuls, Bouten et al. 2003; Oomens, Bressers et al. 2003; Linder-Ganz and Gefen 2004; Kuroda and Akimoto 2005; Linder-Ganz, Yarnitzky et al. 2005; Linder-Ganz, Shabshin et al. 2007). The common finding of these studies was that loading relationships (internal versus external) cannot be defined without considering the individual tissue properties and geometry.

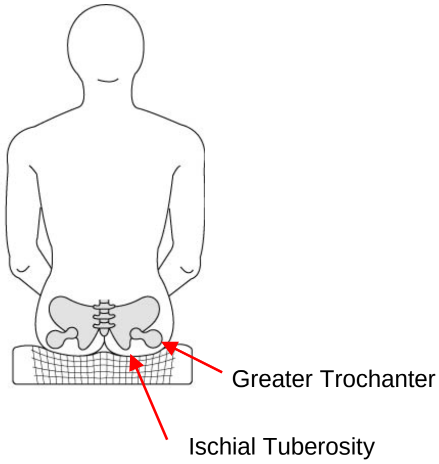

Figure 2. Distribution of upper body weight is predominantly on two ischial tuberosities.

Physiological Responses: Blood Flow Response to Loading

The most frequently studied physiological responses to external loading include blood flow and tissue oxygenation. These studies are briefly described below.

While research has clearly shown a relationship between tissue damage and pressure magnitude and duration, researchers have failed to define a single critical loading threshold above which ischaemia occurs. This may be the result of controlled, yet varying, experimental approaches aimed at determining a single critical pressure common among people. Lassen and Holstein (1974) found that the pressure required for vascular occlusion approximated diastolic pressures when the measured region approached heart level. Holloway, et al. (1976) found that blood flow decreased as external pressure approached mean arterial pressure and occlusion was reached around 120 mmHg. Ek, Gustavsson and Lewis (1987) found a “weak positive correlation” between blood flow during loading and systolic blood pressure. Sangeorzan, et al. (1989) determined that 71 mmHg was needed to occlude flow over “soft” sites but only 42 mmHg occluded flow over “hard” sites. Bennett and colleagues (1979) measured occlusion pressure in non-disabled subjects and found that 100-120 mmHg were necessary to occlude vessels in “low shear” conditions and 60-80 mmHg were needed in the presence of “high shear”. Bar (1988) reviewed the literature and concluded that a critical pressure is necessary to occlude blood flow, but that the pressure varies widely across people.

Some researchers have studied the effects of SCI on blood flow’s response to load. Holloway, et al. (1976) found no differences in blood flow between six subjects with SCI and six non-disabled subjects when applying 0-15 mmHg near the sacroiliac joint. Patterson, et al. (1986) applied 30 and 75 mmHg and found an impaired flow response to loading in SCI subjects although flow was never completely occluded. Bader (1990) found some very different blood flow responses following sacral loading across and within diagnostic groups. Sae Sia, et al. (2007) found that loading the sacrum within days of SCI caused a decrease in blood flow on the order of 40%, whereas loading on a person without SCI resulted in increased flow. These results highlight the importance of studying blood flow specifically in participants with SCI. Additionally, studying participants in their personal seating system guarantees that the analysis will occur at the relevant loading conditions.

The average power tilt-in-space wheelchair user sits in their wheelchair for 11 hours per day (Sonenblum, Sprigle et al. 2009). Given the literature described previously, it is evident that during this time under normal conditions, wheelchair users will experience impaired blood flow. In fact, research has shown considerable decreases in blood flow during sitting for able-bodied persons and persons with SCI (Thorfinn, Sjoberg et al. 2002; Thorfinn, Sjoberg et al. 2006; Makhsous, Priebe et al. 2007). This research also showed a pronounced post-loading hyperaemic response under the ischial tuberosities, indicative of blood flow occlusion during loading. (Thorfinn, Sjoberg et al. 2002; Thorfinn, Sjoberg et al. 2006).

Pressure Ulcer Prevention

While PU causation is accepted to be multifactorial, as mentioned previously, one parameter, external loading on tissue, is the most significant. External loading is the defining characteristic of PUs, distinguishing them from other ulcers such as venous stasis or vascular insufficiency ulcers. The means by which tissue loading is managed form a substantial part of pressure ulcer prevention and treatment. To address the risks mentioned above of increased magnitude and duration of loading, two interventions are utilized. Support surfaces are selected according to their abilities to distribute load. Turning and pressure relief schedules are introduced to limit the duration of continuous loading.

Interventions affecting magnitude and duration are related according to the inverse relationship previously described (Figure 1), (Kosiak 1959; Reswick and Rogers 1976). The body can withstand great loads for very short durations while even very low loads can cause damage if unrelieved for long enough. Therefore, an ideal cushion might reduce the pressure sufficiently to elongate the time between pressure reliefs, but some pressure reliefs are always necessary.

Wheelchair Cushions

Wheelchair cushions serve many purposes and affect many aspects of daily life, including: posture, upper extremity function, comfort and transfers. The function most relevant to this study is pressure reduction. Cushions reduce loading at bony prominences using two predominant approaches. First, a cushion may envelop the tissue, or deform around the contour of the buttocks, thereby equalizing the pressure across the entire region. Ideal envelopment approaches immersion in water, with equal pressure applied at every point, a situation in which pressure ulcers are unlikely to occur. The second approach utilizes off-loading. Off-loading cushions utilize cutouts or reliefs to completely unload an at-risk or affected region (Davis, Kreutz et al. 2009).

Unfortunately, the myriad of functions performed by the cushions are often conflicting. For example, a very deep and soft cushion might provide complete immersion and therefore excellent pressure reduction. However, this same cushion would make it impossible for a user to transfer in and out of their wheelchair. Therefore, cushions cannot be selected only to minimize external pressure, making the cushion alone insufficient for preventing pressure ulcers. Once pressure reduction has been optimized considering the presented limitations, pressure duration must then be considered. Pressure duration is attended to with pressure reliefs.

Pressure Reliefs

Recommendations for pressure relief frequency have typically ranged from 15-30 seconds every 15-30 minutes to 60 seconds every hour (Nawoczenski 1987; Regan, Teasell et al. 2006; Alverzo, Rosenberg et al. 2009; Davis, Kreutz et al. 2009). In some cases, dynamic wheelchair cushions are prescribed for people who cannot independently perform pressure reliefs. More frequently, however, powered tilt and/or recline systems are prescribed for power wheelchair users who are unable to independently perform pressure reliefs. The Consortium for Spinal Cord Medicine suggested that the systems be utilized to perform weight shifts every 15-30 minutes for at least one minute (2000).

Manual Pressure Reliefs

Manual pressure reliefs are recommended for persons with the ability to reposition. Little is known about whether or not manual pressure reliefs are actually performed and whether or not they are effective. A recent study of persons with SCI and no recent (i.e., in the past 1 year) history of pressure ulcers found a relatively infrequent use of complete pressure reliefs (Yang, Chang et al. 2009). Participants performed complete pressure reliefs 10 times per day, with a mean time of 97 minutes between pressure reliefs. However, it is possible that participants performed partial weight shifts at more frequent intervals, as those were not considered in this study. In Garber, et al.'s study of 130 men with chronic SCI, 75% of subjects reported doing pressure reliefs and this correlated with decreased pressure ulcer occurrence (Garber, Rintala et al. 2000). Yet, two additional studies found no relationship between self reported performance of regular weight shifts, and pressure ulcer development (Raghavan, Raza et al. 2003; Krause and Broderick 2004). One concern with the studies is that the accuracy of subject recall of retrospective activities over time is questionable. Research consistently shows that frequent behaviors are poorly represented in memory, forcing respondents to rely on estimation strategies (Pepper 1981; Schwarz 1999). In preliminary studies of tilt use, for example, many subjects claimed to perform tilts (a similarly mundane activity to manual pressure reliefs) much more frequently than observed in their data (Sonenblum, Sprigle et al. 2009). One subject claimed never to perform tilts, yet researchers observed 10 tilts during a 15 minute conversation. The activity was almost a reflex to her; she was not aware that she was tilting. It is for these reasons that the current study objectively monitored tilts rather than counting on subjective recall from participants.

One way to better understand the impact of pressure reliefs is to study their indirect affects. According to the hierarchy described earlier, this would include studying the 1) external loading; 2) internal loading; and 3) physiological responses (i.e. blood flow or tissue oxygenation) during pressure reliefs. Researchers have studied external loading and blood flow during manual pressure reliefs.

An ideal push-up manual pressure relief will relieve 100% of pressure at the ischial tuberosities. However, the ability to sustain a PR is dependent on a myriad of factors, not least of which are level of injury, strength of innervated musculature and presence of orthopedic complications (Sliwinski and Druin 2009). The length of time needed for at-risk tissue to re-perfuse has been estimated between 100 and 300 seconds (Coggrave and Rose 2003; Makhsous, Priebe et al. 2007) based on $TcPO_2$ recovery. Based on findings like this and clinical experience, many wheelchair users are taught to do partial weight shifts. Studies have shown that a sideways lean of approximately 20° can reduce peak pressures at the ischial tuberosities between 20 and 40% (Hobson 1992; Koo, Mak et al. 1996). Results from forwards leans are more variable, with pressure reductions of 20-30% in a 20° lean (Koo, Mak et al. 1996), 55-60% with a 45° lean (Vaisbuch, Meyer et al. 2000), 9% with a 50° lean (Hobson 1992), and 78% with a complete forwards lean (chest on thighs) (Henderson, Price et al. 1994).

Studies of internal pressure are typically limited to MRI or models and none have explicitly addressed manual pressure reliefs. However, Linder-Ganz, et al. (2007) showed that the addition of 5kg of body weight increases internal compressions strains on the order of 150% and stresses on the order of 250%. From this, one might assume that transferring 5kg of body weight to the arms in a push-up or lean would reduce internal stresses and strains considerably.

One recent study addressed the physiological response of tissue perfusion during manual pressure reliefs (Makhsous, Priebe et al. 2007). All subject groups increased their oxygenation from <10 mmHg during normal sitting to >50 mmHg during the pushup. Unfortunately, given the difficulties in maintaining the push-up described above, this oxygenation benefit is not frequently experienced by manual wheelchair users.

Dynamic Wheelchair Cushions

Dynamic wheelchair cushions present an alternative for people who are unable to manually redistribute their pressure. These cushions mechanically vary the load under different regions of the body. Dynamic support surfaces are more common for mattresses because they have access to power and fewer weight requirements than when used with a wheelchair. Because dynamic mattresses present an alternative to assisted pressure reliefs while dynamic cushions provide an alternative to manual, independent pressure reliefs, only the latter will be discussed here.

Dynamic wheelchair cushions typically alternate between inflation and deflation, over time resulting in higher maximum pressures at the ischial tuberosities and lower minimum pressures (Burns and Betz 1999; Stockton and Rithalia 2008). Blood flow perfusion (Stockton and Rithalia 2008) and oxygenation (Makhsous, Priebe et al. 2007) studies have demonstrated superiority of dynamic cushions over manual pressure reliefs. In a simulator wheelchair, comparable to a dynamic cushion, a recent study demonstrated an inverse correlation between pressure and blood flow with frequent pressure changes for persons with and without SCI (van Geffen 2009; van Geffen 2009). It is important to note that dynamic cushions are rarely utilized despite their potential benefits. There are many reasons including limited battery life (when the battery fails, the subject is required to stay in the loaded condition which puts them at higher risk for pressure ulcers), weight and cost. Dynamic cushions also do not provide any of the additional benefits experienced with tilt systems, as discussed below.

Tilt and Recline Systems

Tilt systems maintain constant hip and knee angles while tilting the whole system rearward (Figure 3). The goal of tilt systems is to redistribute body weight from the seat in upright sitting to the backrest in a tilted position, thereby offloading the pressure from the ischial tuberosities. Most tilt systems rotate rearwards to achieve a tilt angle of 45-60˚

from the horizontal. Tilting reduces the frictional forces at the seat interface (Hobson 1992) and permits consistent positioning and switch access throughout the range of movement. Tilt systems also provide many benefits beyond decreasing interface pressure (Sprigle and Sposato 1997; 2000; Lange 2000). Users may experience increased comfort and sitting tolerance secondary to the decreased pressure. Consequently, users may spend more time out of bed and experience increased function. Increased function may also stem from the variable positions available for access and reach in different situations, improved head and neck control and easier transfers. Improved sleep and rest, increased blood flow, easier feeding and improved respiratory function have also been reported. However, tilt systems are problematic for some people, including those who have trouble tolerating static joint positions (hip/knee) throughout the day or those who have difficulty with bladder drainage while tilted.

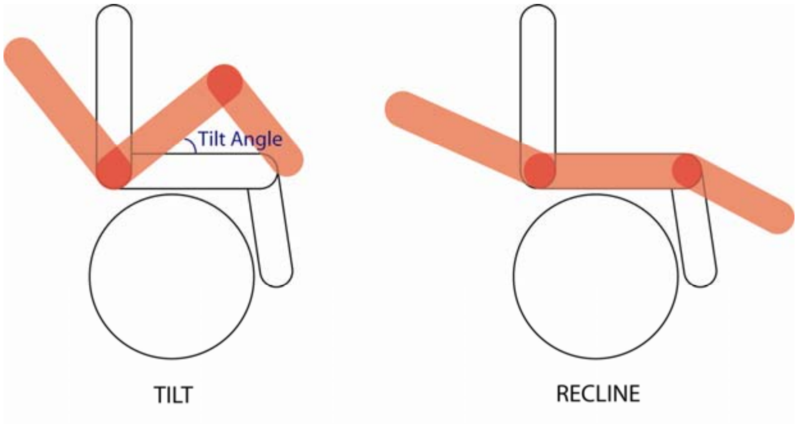

Figure 3. Tilt and recline wheelchair functions.

Recline systems move the person from a sitting position to nearly supine position by opening the seat-to-back angle and elevating the footrests (Figure 3). The goal is to re-distribute body weight from the seat to the backrest and leg rests. Recline systems have an added benefit of assisting with bladder drainage and management. Some people cannot use a recline system for pressure relief because of increased spasticity during recline (Sprigle and Sposato 1997) and increased sliding tendency (Hobson 1992) that occurs when opening the seat to back angle. Changes in posture during reclining can also impair switch access and interfere with postural support placement.

Although both tilt and recline have advantages as pressure relieving modalities, only tilt was studied in the current project for a number of reasons. First, tilt-in-space wheelchairs are prescribed more frequently at the local seating clinic. In fact, more than 125 tilt-in-space wheelchairs were prescribed in 2007 alone. This has led to considerable interest from clinicians working with clients who have tilt-in-space wheelchairs. The clinicians want to know the degree of tilt that improves blood flow because they know it is hard to convince some of their patients to tilt all the way back. Second, blood flow measurements are likely to be more accurate in tilt. Posture changes (i.e. increasing hip angle) affect the region of blood flow being monitored and result in highly variable, less reliable data. Finally, observations of tilt have suggested wide ranging benefits to the feature beyond pressure relief, making it worthy of further study.

A number of studies have used interface pressure measurements to study the effects of tilt on interface pressure at the buttocks-seat interface. These studies aimed to document the pressure relieving capabilities of tilt, consistent with its purpose as a pressure ulcer prevention intervention. In 1992, Hobson (1992) found an 11% reduction in maximum pressure under the ischial tuberosities with a 20° tilt. Henderson (1994) found a 27% reduction in peak pressure with a 35° tilt and a 47% reduction with a 65° tilt, while Burns and Bets (1999) found a 33% decrease in maximum pressure with a 45°

tilt. Finally, Aissaoui, et al. (2001) found a 27% decrease in peak pressure with a 45° tilt and 100° seat to back angle. Comparison of these and other studies can be found in Lacoste, et al. (2003). Despite the varied methods, surfaces, and subjects used throughout these studies, the message they illustrate is clear: the greater the angle of tilt, the lower the overall pressure at the buttocks-seat interface. However, the angle of tilt needed for an acceptable weight shift is not known as allowable interface pressures and resulting blood flow needed to prevent pressure ulcer formation depend on the individual and have not been determined (Bar 1988).

To date, little data has been published on the change in blood flow or perfusion of persons with SCI during different tilt positions. Thus, it is not known the degree of tilt required to relieve blood flow occlusion.

The impact of tilt in pressure ulcer prevention is dependent on its regular use. To date, few studies have tried to determine how tilt systems are used. Lacoste, et al. (2003) asked 40 people who used tilt or recline wheelchairs about how and when they tilted. 97.5% of respondents reported using their systems daily. More than 70% of the respondents said they used their tilt and recline systems for comfort, rest, relaxation, and pain, while only about 50% reported using the chairs for physiological functions, a category that included prevention of pressure ulcers. To understand how tilt systems might be used to achieve comfort, rest and relaxation or to manage pain, Lacoste, et al. asked participants about the magnitude of their tilts for each purpose. Lacoste, et al. also found that large amplitude tilts (30-45°) were used for rest and to decrease pain while small amplitude tilts (0-15°) were used to increase comfort. Middle amplitude tilts (15-30°) were used to increase stability. This self-report methodology found that most people use tilt for reasons other than pressure relief. Given the limitations of self report as previously described, there is a need for a quantitative methodology to study the magnitude, frequency and duration of tilts.

Two studies have been published looking at tilt use quantitatively. A study by Ding, et al. (2008) included 11 participants, 9 of whom had both tilt and recline available on their wheelchair. They found that participants performed 19±14 tilts per day (where a tilt required a change of 2.5°) and that subjects repositioned every 53.6 minutes. Tilts of less than 20° were found to be more frequent, but the role of recline in combination with the small tilts was not addressed and some of the wheelchairs involved did not tilt past 20°, further skewing the results. Results of a pilot study by Sonenblum, et al. (2009) suggested that participants repositioned more frequently than proposed by Ding, et al. The pilot study included 16 subjects of varying diagnoses who used wheelchairs with a powered tilt-in-space feature. The median subject performed 3.1 tilts every hour he/she was seated in the wheelchair (mean (SD) = 4.3 (3.9)). Only two subjects tilted less frequently than once per hour.

The pilot study's results on pressure reliefs were less encouraging than overall tilt use. For the purpose of the pilot study, a pressure relieving tilt was defined as occurring when the seat reached a tilt angle of $\geq 30°$ for one minute. While subjects used their tilt feature to frequently change position, few performed pressure relieving tilts. The median subject performed approximately one pressure relieving tilt every seven hours (median = 0.13/hr, mean (SD) = 0.5 (0.7)). Only one subject performed two or more pressure reliving tilts per hour, thereby meeting the recommended pressure relief guidelines (2000). Two subjects did not perform any pressure relieving tilts during an average day, and another four subjects performed only one every few days, accumulating less than 1% of occupancy time at large or extreme tilt angles.

The pilot results and results from the study by Ding, et al. motivated the current methodology in a number of ways. First, it raised the question of whether extreme tilts are needed to increase blood flow. Before tackling the problem of how to increase people's use of large and extreme tilt angles, it would be beneficial to document the biomechanical changes during such tilts. Second, it illustrated the need to study small and medium tilts in greater detail. The differences in tilt use across participants illustrated the variability in function and activity among users as well as the diverse benefits of a tilt system for different users. This disparity in use of tilt is consistent with the belief that a combination of factors including living situation, availability of assistance, daily activity and functional ability will contribute to the use of a tilt-in-space system.

CHAPTER II

THE USE OF TILT-IN-SPACE WHEELCHAIRS IN EVERY DAY LIFE

The tilt use of people who currently use tilt-in-space (TIS) wheelchairs was monitored remotely for one week to provide a global picture of how people utilized their tilt systems. This aim was descriptive in nature. Aspects of tilt use such as the magnitude and frequency of tilts as well as the amount of time spent at each tilt angle (i.e. small, medium, large, extreme) are described in the data analysis section. The hypotheses listed below were based on preliminary findings but were secondary to the descriptive analysis.

Hypotheses

H1. Small and medium tilts were used more frequently than large and extreme tilts.

H2. Pressure relieving tilts (according to the literature-based definition) were not used with the prescribed frequency.

H3. Tilt behavior can be predicted based on sensation, ability to reposition, and wheelchair and pressure ulcer history.

Methods

Participants

A convenience sample of 45 adults was recruited from a local hospital. Inclusion focused solely on the use of TIS without regard to diagnosis, gender or age. Only subjects who used a power tilt-in-space wheelchair as their primary mobility device were included. This study had IRB approval and subjects signed informed consent forms prior to beginning their participation in the study.

Because of the descriptive nature of Specific Aim 1, power analyses were not technically appropriate. Ideally, the maximum number of subjects possible would be studied, to provide a sufficiently diverse population for generalizable results. The prediction model to be tested for Hypothesis Three was selected to have four factors including function (i.e. sensation and ability to reposition), wheelchair history, and pressure ulcer history. The factors and model are discussed further in the analysis section. Given the rule of thumb that 10 subjects are needed for each factor, 45 subjects were deemed sufficient.

Instrumentation

This study utilized instrumentation previously developed to study wheelchair use and activity (Lankton, Sonenblum et al. 2005; Sonenblum, Sprigle et al. 2006; e.g. Harris, Sonenblum et al. 2007; Sonenblum, Sprigle et al. 2008). The instrumentation included three components: the accelerometer / data logger (MSR 145, MSR Electronics GmbH), an occupancy switch, and external circuitry. The MSR is a microprocessor-controlled data logger in a compact package (18mm x 14mm x 62mm, Figure 4). Also included in the package is a battery, flash memory suitable for collecting 1 week of data, and a triaxial accelerometer sensitive to ±2 g. The MSR was mounted to the seat bottom. Accelerations were sampled at 1 Hertz and converted to a tilt angle using the arcsine of the stationary acceleration parallel to the seat bottom (Figure 5). Wheelchair occupancy was ascertained by a mechanical switch (i.e. the occupancy switch) placed under the wheelchair cushion and logged through the MSR's external analog input. Occupancy was sampled every 5 seconds.

Figure 4. The MSR 145 is 18mmx14mmx62mm.

Figure 5. Mounting orientation of accelerometer.

Protocol

After providing informed consent, subjects' wheelchairs were instrumented with the MSR data logger / accelerometer and occupancy switch. Subjects were asked a number of questions to ascertain demographic information (e.g. age, gender, education, and employment status), functional and physical presentation of their disability (e.g. sensation, function, spasticity, wheelchair history) and pressure ulcer history (See

Appendix A for complete survey). Additionally, subjects' "ability to reposition" (i.e., squirm) was defined to distinguish subjects able to change posture from those unable to independently reposition. Participants were divided into two groups based on observation or measurement. If a participant had no independent mobility within their wheelchair they were placed in the "no ability to reposition" group and participants who could completely unload their buttocks were grouped as having the ability to reposition. For the remaining participants with some ability to reposition, a small pressure sensor was placed under the trochanter, opposite the side to which they could lean the farthest. If the decision as to which side to study was unclear, both sides were studied. Participants were asked to lean as far in all directions as they were able. If the pressure at the trochanter during the lean was reduced to 25% or less of their upright pressure, participants were identified as having the ability to reposition. It is important to remember that this ability to reposition represents an ability to squirm and is different than the ability to perform a weight shift, as unloading the trochanter does not necessarily mean the participant can unload the ischial tuberosity.

The instrumentation was left on the wheelchairs for one week, during which time the instrumentation operated without subject interaction. This resulted in six complete days of data to determine typical behavior. This timeframe was selected after analyzing the data of 10 pilot subjects with 12 days of data. Establishing a reliability of 0.95 (described by Cronbach's Alpha), 4.4 days of data would be needed to reliably measure the variable with the least day-to-day variability (i.e., typical position) and 7.5 days for the variable with the greatest day-to-day variability (i.e., number of tilts). Given the wide range in variables and the convenience of a one week instrumentation period (takedown 7 days following set up), six days was determined to be suitable.

This study was conducted in two phases. The first 16 participants were instrumented for 1-2 weeks and were not asked all study questions. When possible, these subjects were contacted later to ask remaining demographic, disability and pressure ulcer history questions. The remaining 29 subjects were monitored for one week and asked all questions during instrumentation.

Data Analysis

Data processing was performed using Matlab R2008a (Mathworks Inc., Natick, MA) and statistical analyses were done using Minitab 14 (Minitab Inc., State College, PA).

Accelerometer data was processed to filter noise and to identify tilt position changes. Seat position was defined as constant until the following conditions were met, at which point a new position was defined: 1) the tilt angle changed by 5°; and 2) the change was maintained (within ±2°) for 20 seconds. Because the accelerometer measures changes resulting from factors other than tilting (i.e., wheeling, bumpy ground, etc.), this algorithm was necessary to eliminate transient events and focus on changes in tilt angle only. A minimum change of 5° was selected because it exceeds the sensitivity of the accelerometer and based upon the belief that position differences of less than 5° may not be reliably differentiated by persons in wheelchairs. The 20 second threshold was selected to eliminate the transient events previously mentioned.

The variables considered in this study are described below. Unless otherwise described, variables are reported based on the median day for each subject. For a day to be included in the analysis, more than 23 hours of data were required (i.e., the first and last days of instrumentation were not included) and participants needed to occupy the wheelchair for at least 15 minutes. These thresholds were established because certain variables were dependent on the time spent in the wheelchair, and these are difficult to analyze unless some time was spent in the wheelchair. Variables requiring greater than or equal to 45° degrees of tilt were calculated only for participants having more than 45° of tilt available on their wheelchair.

Wheelchair Occupancy Time – the number of hours per day that subjects occupied their wheelchairs.

Typical Position – The position at which the subject spent the most time was defined as the mode of all the angles measured during the time the wheelchair was occupied. Angles were rounded to the nearest degree.

Time spent at small (0-14°), medium (15-29°), large (30-44°), and extreme (≥45°) tilt angles – Both absolute time and percent of total occupancy time were calculated.

Number and Percentage of small (0-14°), medium (15-29°), large (30-44°), and extreme (≥45°) magnitude tilts – These refer to the absolute value of the change in angle, regardless of the starting position. Percentage was computed based on all tilts performed by the participant.

Tilt Frequency –"Tilts" were defined as position changes of 5° or more in either direction (i.e. towards tilted or upright) that were maintained for at least 20 seconds. Tilt frequency was computed by dividing the daily total number of tilts by the number of hours of wheelchair occupancy on that day.

Pressure Relieving Tilt (PRT) Frequency – Pressure relieving tilt maneuvers were defined as position changes from below 30° of tilt to greater than 30° of tilt lasting more than one minute. 30° was selected to include all possible PRTs, as recommendations in the literature and clinic vary from 30° to 65°. PRT frequency was computed by dividing the daily number of pressure relieving tilts by the number of hours of wheelchair occupancy on that day.

Uni-Modal Behavior – Uni-Modal Behavior is a binary variable used to identify participants who spent at least 80% of their time in a single tilt range (i.e., small, medium, large, or extreme), as opposed to those who utilized multi-modal behavior by spending more than 20% of their time at multiple positions. Although this definition appears arbitrary, the variable was defined in post-hoc analysis to distinguish different behaviors. The 20% cutoff was motivated by the 81% median percent time in small tilts; therefore both groups have sufficient members for analysis.

Because most clinical research focuses on populations selected by diagnosis rather than function, two subgroups of the participants were created and compared. The demographics, wheelchair use, sensation, ability to reposition, and pressure ulcer history of participants with and without spinal cord injuries (SCI) were compared using a Kruskal-Wallis test for continuous variables and a Pearson Chi-Square test for categorical factors (Odds ratios and 95% confidence intervals were reported when the chi-square was significant) with $p < 0.05$ considered significant. Similar exploratory tests were also run across different demographic, diagnosis and wheelchair configuration factors and variables of tilt behavior.

Non-parametric statistics were used to test the first two hypotheses due to the skewed distributions in tilt behavior. Hypothesis One (Small and medium tilts are used more frequently than large and extreme tilts) was tested using a Mann-Whitney test. Specifically, the number of small and medium tilts per day was compared with the number of large and extreme tilts per day, for each subject. Hypothesis Two (Pressure relieving tilts are not used with prescribed frequency) was tested using a Wilcoxon signed rank test in which tilt frequency was compared with the conservative threshold of 1 tilt per hour.

To test Hypothesis Three, tilt behavior (PRT frequency, tilt frequency, and most frequent size of tilt) was modeled using a multiple regression model with four factors: 1) presence of sensation at the buttocks, 2) years using a tilt wheelchair, 3) ability to reposition independently in the wheelchair, and 4) history of pressure ulcers in the pelvic region. If these four factors could explain at least 50% of the variance in tilt behavior, the hypothesis would be supported. The four factors were initially tested for co-linearity but the variables were sufficiently independent to proceed.

The definitions of the model predictors warrant further explanation. The "presence of sensation at the buttocks" was defined by the self-reported responses to three questions – "are you able to feel the following on your buttocks: 1) deep pressure; 2) light touch; or 3) pain?" Participants were defined as having sensation present if they answered yes to any of the above questions. A few measures related to years of wheelchair use were documented, including years using any wheelchair, years using any tilt-in-space wheelchair, years using their current wheelchair, and a binary response to 'did their first wheelchair have a tilt-in-space feature'. Repositioning was defined in the protocol above, requiring 75% unloading of one trochanter. Finally, pressure ulcer history was documented based on self report, including the following variables: history of any pelvic pressure ulcer, presence of a current pressure ulcer, and history of a recurrent pressure ulcer (i.e. occurring more than once) at a pelvic location.

Results

Description of Sample Population

45 subjects were enrolled in this study. Participant characteristics can be found in Table 1, Table 2, Figure 6, and Figure 7. In terms of diagnosis, the majority of the participants had an SCI (n = 30, 68.2%). The second most common diagnoses were multiple sclerosis (n = 4, 9.1%) and cerebral palsy (n = 4, 9.1%). Other diagnoses included brainstem stroke, spina bifida and muscular dystrophy. Of the 30 participants with SCI, half described their injury as incomplete, 14 as complete, and 1 was uncertain. Levels of SCI varied with 29 cervical injuries and 1 thoracic injury (Figure 6).

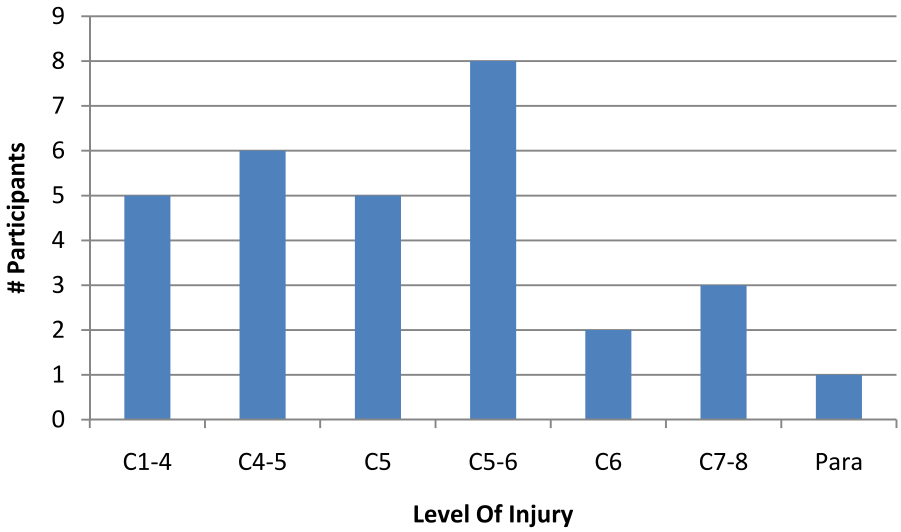

Figure 6. Level of injury in participants with SCI.

Table 1. Subject Demographics.

	ALL		**Non-SCI**		**SCI**	
	Mean (SD)	**Median (Min-Max)**	**Mean (SD)**	**Median (Min-Max)**	**Mean (SD)**	**Median (Min-Max)**
Age (years) (n=44)	45 (14)	43 (22-69)	43 (14)	39 (23-61)	45 (15)	46 (22-69)
Height (m) (n=43)	1.74 (0.11)	1.75 (1.52-1.93)	1.68 (0.12)	1.66 (1.52-1.88)	1.77 (0.09)	1.78 (1.55-1.93)
Weight (kg) (n=43)	75 (19)	75 (39 – 114)	68 (23)	64 (39-114)	78 (17)	79 (50-113)
Gender	# (n=45)	%	# (n=15)		# (n=30)	
Female	12	26.7	5		7	
Male	33	73.3	10		23	
Race	**# (n=44)**	**%**	**# (n=14)**		**# (n=30)**	
African-American	18	40.9	4		14	
Caucasian	25	56.8	10		15	
Other (biracial)	1	2.3	0		1	
Education	**# (n=43)**	**%**	**# (n=13)**		**# (n=30)**	
Some or No high school	5	11.6	0		5	
High school diploma or GED	21	48.8	7		14	
Associates degree	5	11.6	1		4	
Bachelor’s degree	5	11.6	3		2	
Graduate degree	7	16.3	2		5	
Occupation (best option)	**# (n=44)**	**%**	**# (n=14)**		**# (n=30)**	
Paid employment	3	6.8	1		2	
Non-paid work, such as volunteer/charity	1	2.3	1		0	
Student	5	11.4	2		3	
Keeping House/ Home Maker	1	2.3	1		0	
Retired	5	11.4	1		4	
Unemployed (health reasons)	23	52.3	7		16	
Unemployed (other reasons)	5	11.4	1		4	
Other	1	2.3	0		1	
Living Situation	**# (n=43)**	**%**	**# (n=13)**		**# (n=30)**	
Alone	10	23.3	2		8	
Spouse or Other Family	28	65.1	10		18	
Friend	2	4.7	0		2	
Other	3	7.0	1		2	

The data revealed a number of trends relating to aging and changes in seating over time. Not surprisingly, participants who started with an upright wheelchair and later switched to a tilt-in-space wheelchair were more likely to be long time wheelchair users (median = 15 years) as compared with those having a tilt feature on their first wheelchair (median = 5 years, $p = 0.000$). This trend existed across populations with and without SCI. Additionally, all six participants using a TIS wheelchair with lower levels of SCI (C6 or below) were more than 50 years old and yet most had spent less time in a TIS wheelchair (1.5 years) than their counterparts with higher levels of injury (6.5 years) ($p = 0.038$).

Some expected relationships among participants with a history of pressure ulcers were also found. Persons able to reposition in their wheelchair were less likely to have recurrent pressure ulcers (4/23) as opposed to those who were unable to reposition (10/19), with an odds ratio [95% CI] of 0.19 [0.04, 0.92]. However, when all pressure ulcers were considered, including single instances of ulcers, there was no relationship with the participants' ability to reposition. Additionally, participants with no self-reported sensation were significantly more likely to have a history of pressure ulcers (16/17) as compared with those who do have some sensation (12/25), with an odds ratio of 17.3 [2.3, 132.9]. Although there were too few participants in each group to analyze the statistical significance of this relationship, lack of sensation may have been related to pressure ulcers within the SCI subgroup. 15/16 participants with SCI and no self-reported sensation had a history of pelvic pressure ulcers whereas 8/14 participants with some sensation had a history of pressure ulcers (odds ratio [95% CI] = 11.3 [0.9, 136.6]). Finally, participants with a history of pressure ulcers had greater body mass (81 kg vs. 64

kg) than participants who had never experienced a pressure ulcer (*p* = 0.011). There was no relationship between current or recurrent pressure ulcers and body mass.

Table 2. Wheelchair and pressure ulcer history, ability to reposition and sensation described across the entire population, and SCI and non-SCI subgroups. *P*-values are the result of a Pearson chi-square test (for categorical variables) or a one-way ANOVA (for continuous variables).

	ALL		Non-SCI		SCI		
	Mean (SD)	**Median (Min-Max)**	**Mean (SD)**	**Median (Min-Max)**	**Mean (SD)**	**Median (Min-Max)**	***p*-val**
Years Using a WC	14.4 (13.5)	10 (0.5-50)	16.0 (14.5)	10.7 (0.6-50.0)	13.4 (13.1)	9.0 (0.5-47.0)	0.512
Years Using a TIS WC	6.1 (6.1)	3 (0.25-20)	4.7 (5.8)	1.7 (0.3-19.0)	6.7 (6.3)	4.5 (0.3-20.0)	0.178
Years Using Current TIS WC	2.2 (2.3)	1.5 (0.1-10)	1.6 (1.5)	1.0 (0.3-5.0)	2.5 (2.6)	2.0 (0.1-10.0)	0.302
	# (n=45)	**%**	**# (n=15)**	**%**	**# (n=30)**	**%**	***p*-val**
Tilt-in-Space is First Wheelchair	22	48.9	4	26.7	18	60.0	0.032
Ability to Reposition Independently (Defined by ability to unload greater trochanter)	**# (n=44)**	**%**	**# (n=14)**	**%**	**# (n=30)**	**%**	***p*-val**
	25	56.8	9	64.3	16	53.3	0.382
Self Reported Sensation (any of: light touch, deep pressure, pain)	**# (n=42)**	**%**	**# (n=12)**	**%**	**# (n=30)**	**%**	***p*-val**
	25	59.5	11	91.7	14	46.7	0.018
Pressure Ulcer History	**# (n=42)**	**%**	**# (n=14)**	**%**	**#**	**%**	***p*-val**
History of Recurrent (more than one at same location)	14	33.3	3	21.4	11 / 28	39.3	0.247
Any History of Pelvic Pressure Ulcer	28	63.6	5	35.7	23 / 30	76.7	0.009
Current Pelvic Pressure Ulcer	9	20.9	4	28.6	5 / 29	17.2	0.400

Wheelchair configurations were fairly limited, with most participants using an Invacare wheelchair in combination with a Roho Air Inflation (n = 20, 44.4%) or Jay Fluid cushion (n = 14, 31.1%). Other cushion types included layered foam, honeycomb, and various combinations of air, foam, and gel. Of 38 participants about whom complete wheelchair configuration information was known, 29 had chairs configured to tilt past 45° (range approximately 45°- 60°). Finally, on average wheelchairs were configured with approximately 100° of seat to back angle (Figure 7).

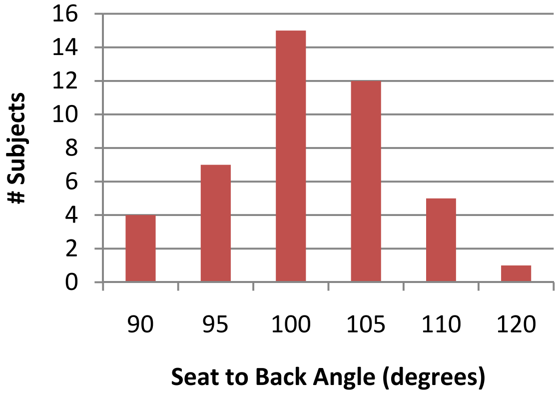

Figure 7. Distribution of Seat to Back Angles across 44 participants.

Hypotheses

The data supported Hypotheses One and Two. With a median of 21.3 small and medium tilts per day compared with 0.7 large and extreme tilts per day, small and medium tilts were used more frequently than large and extreme tilts (95% CI for difference [12.3, 25.7], p = 0.000). The median PRT frequency of 0.1 PRTs per occupancy hour was significantly less than the minimal recommended one per hour (p = 0.000).

Unlike Hypotheses One and Two, the data did not support Hypothesis Three. Hypothesis Three proposed that tilt behavior (i.e., PRT frequency, Tilt frequency, and most frequent size of tilt) could be predicted in a multiple regression model with factors of 1) presence of sensation at the buttocks, 2) years using a wheelchair, 3) ability to reposition independently in wheelchair, and 4) pressure ulcer status. As explained in the methods section, there were multiple variables for years in a wheelchair and pressure ulcer status. The different variables were tested to determine which variable explained the most variance. In terms of pressure ulcer status, having a current pressure ulcer had the most affect on behavior as compared with ever having a pressure ulcer or having a recurrent pressure ulcer. Years using any wheelchair also explained more variance than years using a TIS chair, years using their current wheelchair, or having TIS on their first wheelchair.

Even with the optimized variables, however, predicting tilt behavior was unsuccessful (Table 3). The models explained only 11.7% of the variance (R^2-adjusted) in tilt frequency and 2.5% of the variance in PRT frequency. Additionally, none of the coefficients in these models were significantly different from zero. The model to predict the most frequent size of tilt explained 26.7% of the variance. In this case, the coefficients associated with the ability to reposition and the presence of sensation were both significantly different than zero ($p = 0.048$ and $p = 0.028$), with presence of sensation and ability to reposition corresponding with a smaller typical tilt size. Overall, though, no aspects of tilt behavior were successfully predicted by the personal characteristics tested in Hypothesis Three, which required an $R^2 \geq 50\%$.

Table 3. Regression coefficients (*p*-values) for behavior models as functions of participant characteristics. Most frequent tilt size was modeled as 1 = small, 2 = medium, 3 = large, 4 = extreme.

	Tilt Freq	**PRT Freq**	**Most Freq Size Tilt**
Constant	5.915 (0.000)	0.712 (0.001)	1.478 (0.000)
Sensation	-0.906 (0.336)	-0.208 (0.212)	-0.347 (0.028)
Years in wheelchair	-0.072 (0.059)	-0.006 (0.394)	0.008 (0.199)
Reposition	-1.729 (0.070)	-0.280 (0.096)	-0.311 (0.048)
Current PU	-1.599 (0.162)	-0.024 (0.903)	0.230 (0.217)
R^2	11.7%	2.5%	26.7%

The variable ‘uni-modal behavior’ emerged as an important descriptor of behavior and was modeled using a binary logistic regression. Attempts to model the presence of uni-modal behavior using the same predictors as in the previous models were moderately successful, with only sensation contributing significantly to the model. The Somers’ D and Goodman-Kruskal Gamma were 0.62, i.e., there was a 62% reduction in predictive error of the rank of the dependent variable when the independent variables were known. Further exploration revealed that a bi-variate, binary logistic model with predictors of sensation, and typical position had Somers’ D and Goodman-Kruskal Gamma values of 0.82. Both coefficients were significant with odds ratios [95% CI] of 0.08 [0.01, 0.87] and 0.76 [0.63, 0.91], respectively.

Description of Tilt-in-Space Behavior

Participants spent a considerable amount of time in their wheelchairs, with half of the participants spending more than 12.1 hours per day in their chair (Table 4). Seven out of the 45 participants went at least one day without getting into their wheelchair at all. The median participant’s typical position was in a small tilt, but varied across subjects from 0° to 47° of tilt. Each participant’s typical position (median = 8°) was significantly larger than the minimum position allowed by their wheelchair (median = 2°, $p = 0.000$), indicating that subjects engaged the tilt feature for their typical positions.

The median participant tilted every 27 minutes, meaning half of the participants performed tilts more frequently than twice per hour (Table 4). Frequency of tilt use varied from barely once per day to every 3-4 minutes. As is typical with behavioral data in this population (Sonenblum, Sprigle et al. 2008), the distributions were skewed towards less use, making the median the appropriate descriptor despite the large sample size (Figure 8). Pressure relieving tilts were used with much less frequency than general tilts, with the median subject performing only 1 PRT every 10 hours. 26 participants failed to perform a PRT on at least one day and 6 of these participants never performed a PRT.

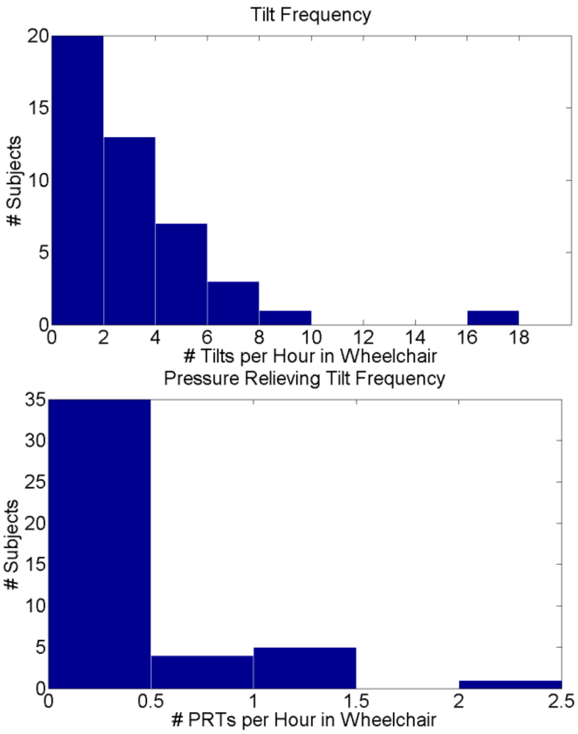

Figure 8. Distribution of frequency of tilt (TOP) and PRT (BOTTOM) use across subjects.

Table 4. Use of tilt-in-space wheelchairs across median subject days.

Variable	**Mean ± SD**	**Median (Min – Max)**
Occupancy Time (hours)	11.7 ± 3.7	12.1 (4.1 – 24)
Typical Position (^{0})	11 ± 9	8 (0 – 47)
Tilt Frequency (tilts per occupancy hour)	3.0 ± 2.9	2.2 (0.1 – 16.6)
PRT Frequency (PRTs per occupancy hour)	0.3 ± 0.5	0.1 (0.0 – 2.2)
% Time at Position		
Small Tilt (0^0 - 14^0)	65 ± 33	81 (0 – 100)
Medium Tilt (15^0 - 29^0)	26 ± 28	15 (0 – 92)
Large Tilt (30^0 - 44^0)	5 ± 8	1 (0 – 29)
Extreme Tilt ($\geq 45^0$) (n=29)	4 ± 13	0 (0 – 71)
% Tilts of Magnitude		
Small Magnitude (0^0 - 14^0)	65 ± 24	70 (5 – 100)
Medium Magnitude (15^0 - 29^0)	23 ± 19	19 (0 – 83)
Large Magnitude (30^0 - 44^0)	9 ± 13	4 (0 – 71)
Extreme Magnitude ($\geq 45^0$) (n=29)	3 ± 7	0 (0 – 28)

Most participants spent their seated time in more than one tilt position (Table 4, Figure 9). In fact, the median participant spent almost two hours in a medium tilt. Figure 9 illustrates the median daily use by each participant. The first 25 participants in the figure spent more than 80% of their time seated in a small tilt position (i.e., they utilized uni-modal behavior with a typical position between 0° and 14°). Of these participants, 9 tilted at least every 30 minutes, 11 spent more than 1 hour tilted to a medium, large or extreme tilt, and 7 spent more than 30 minutes tilted to a large or extreme tilt. These data illustrate tilt use in participants who sat at a predominantly upright posture. Only three of these participants performed PRTs more than once per hour. An example of a participant who chose to sit with a uni-modal behavior that was a fairly upright posture but still performed regular tilts is illustrated in Figure 10. This participant has a clear typical position of 5°. Similar to participants 1-25, Participants 26-28 also chose to utilize uni-modal behavior, but in this case their typical positions were in a medium tilt.

The remaining participants, 29-45, spent more than 20% of their seated time at more than one position (i.e., they used multi-modal behavior). Participants 29-45 changed positions regularly throughout the day, usually without clearly defined “pressure reliefs”, although 4 participants performed hourly pressure relieving tilts. Everyone tilted more than once every 30 minutes. Participants who used multi-modal behavior performed significantly more frequent tilts (4.0 versus 1.3, $p = 0.001$) and PRTs (0.24 versus 0.07, $p = 0.035$). Although it is less meaningful in this group of participants, the measured typical position in participants who used multi-modal behavior was significantly higher than in other participants (15° versus 6°, $p = 0.000$). Data from a participant who used multi-modal behavior is pictured in Figure 11. It is evident from the figure that this participant does not have a meaningful typical position.

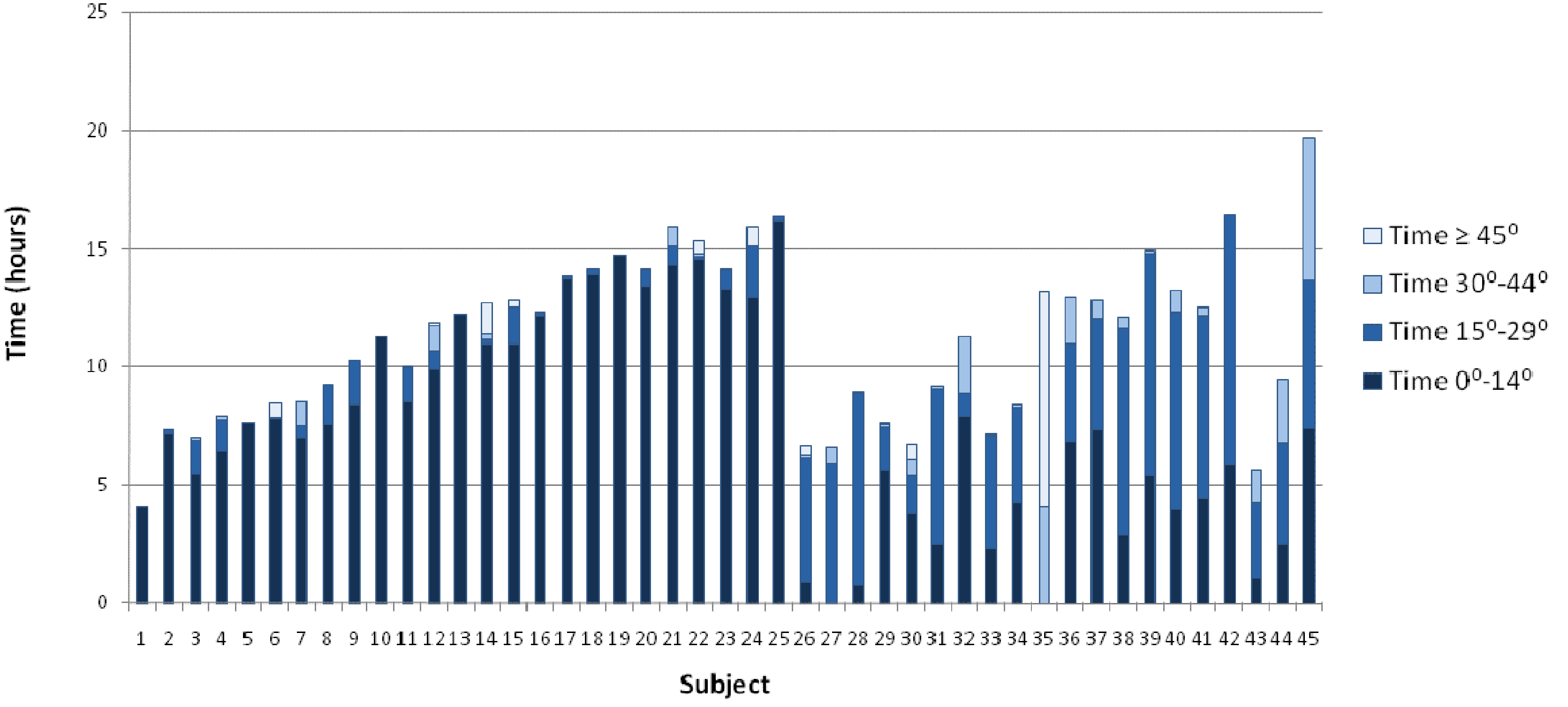

Figure 9. Breakdown of time in chair by wheelchair tilt position.

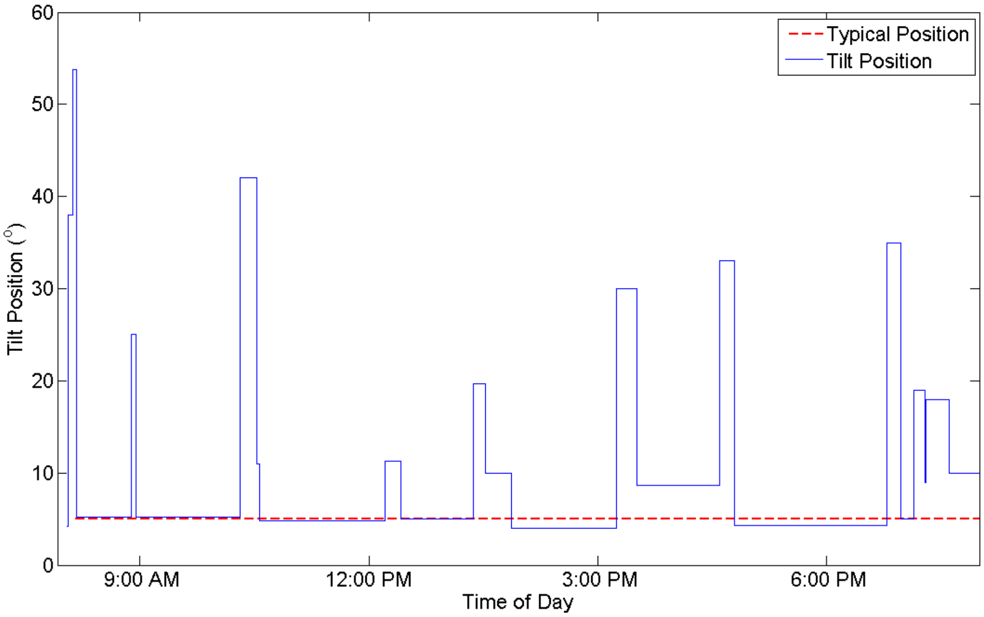

Figure 10. Example of a participant utilizing uni-modal behavior. This participant sits at a typical position of 5°, but performs small, medium and large tilts from that position. (Subject 12)

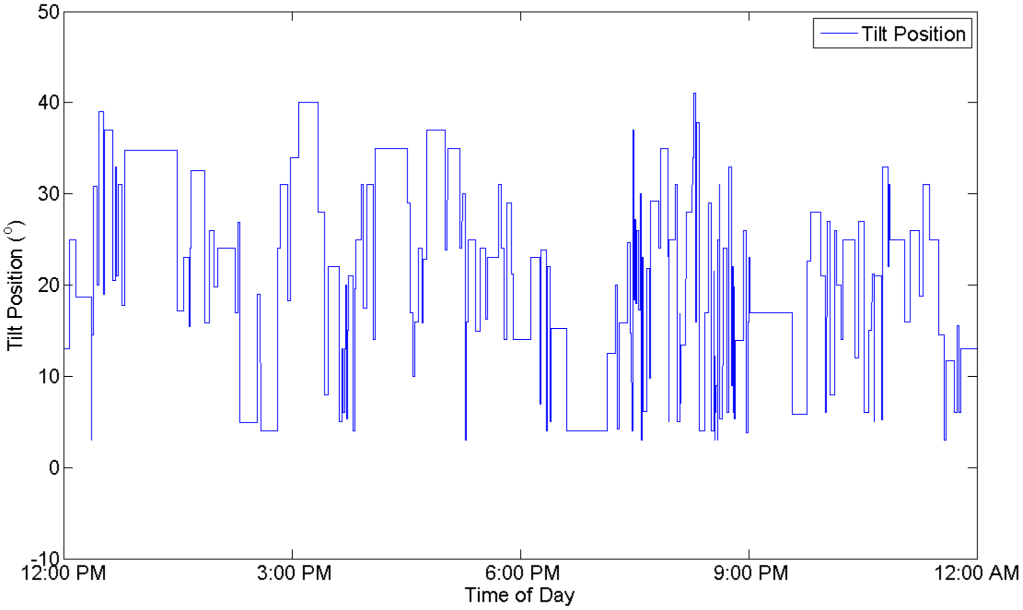

Figure 11. Example of a participant with multi-modal behavior who sits at various positions throughout the day. (Subject 44). Despite frequent position changes, this participant never reaches 45°.

Exploratory Analysis

Some exploratory analysis was done to develop an overall picture of tilt use. As previously described, the variable ‘uni-modal behavior’ emerged from the analysis. There were 17 participants who exhibited multi-modal behavior. They tended to perform more tilts and PRTs, and they typically sat at greater tilt positions. In addition, some relationships were identified between the daily time spent in the wheelchair and other tilt behaviors. For example, participants spending more time in their chair also performed less frequent PRTs (correlation = -0.345. $p = 0.020$). However, occupancy time was not related to tilt frequency. Persons who most frequently performed small tilts spent more time in their chair (13.1 hours) than participants who mostly performed medium or large tilts (n = 9, 8.1 hours, $p = 0.002$).

Given the lack of success of the predictive modeling (i.e., Hypothesis Three), further relationships between personal characteristics and wheelchair use were also explored.

Although presence of a current pressure ulcer was included in modeling attempts, the variables: history of pressure ulcers and history of recurrent pressure ulcers were also considered for inclusion. None of these pressure ulcer variables were related to the PRT frequency. Only two participants performed large tilts more often than small or medium tilts and both of these participants had current pressure ulcers. These two participants just about met or exceeded the prescribed pressure relief frequency (0.95 tilts per hour and 1.5 tilts per hour). 7 of the 9 participants with current pressure ulcers performed PRTs more frequently than the median subject (0.1/hour), but with the exception of the two participants previously mentioned, the frequency did not meet the guidelines. The number of years in a wheelchair, also included in the models, was related to less frequent tilts (Pearson's $r = -0.301$, $p = 0.047$).

The use of 'ability to reposition' and 'presence of sensation' in the models did not explain sufficient variance in tilt behavior to support Hypothesis Three. Yet the presence of sensation did play a significant role in the logistic model predicting uni-modal behavior. Unlike sensation, ability to reposition was not related to exhibiting uni-modal behavior. Finally, participants with the ability to reposition did spend significantly more time in a small tilt than participants with no ability to reposition (85% versus 50%, $p = 0.030$).

Researchers had considered the possibility that the seat-to-back angle would influence tilt use because it has an effect on interface pressure and also may have an effect on the perception of tilt position. Because tilt position was measured from the seat pan, at a 55° tilt someone with a 120° seat to back angle would have their back almost horizontal whereas someone with a 90° seat to back angle would not (Figure 12). Yet, according to the data, seat-to-back angle was not correlated with tilt behavior.

Within the SCI population, a higher level of injury was related to less time spent in a small tilt (Pearson's $r = -0.38$, $p = 0.038$). However, the diagnosis of SCI was not itself related to tilt behavior.

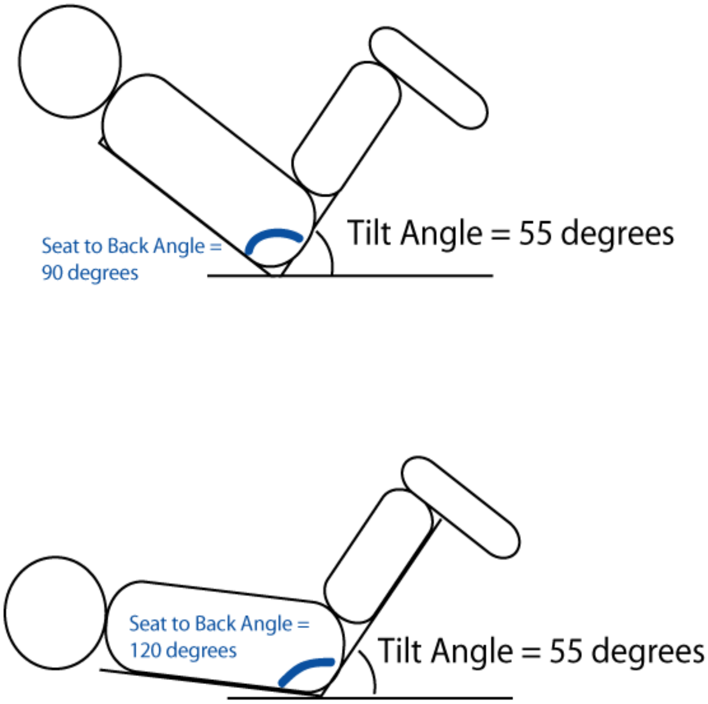

Figure 12. Seat to back angle affects the overall configuration and potential biomechanical influence of tilt.

Discussion

Sample Population

Little statistical data are available for describing all persons who use a wheelchair. However, within a given diagnosis it is possible to compare this study's sample population with the larger national population. Overall, the segment of the population with SCI was similar to that of the larger population of persons with SCI in terms of age, gender and employment (Table 1, (2009)). Currently, the average age at time of injury is 40.2 years, comparable to this study's median age of 46 years at the time of the study. The overall population of persons with SCI includes 80% men, similar to the 77% included in the present study. Additionally, unemployment rates have been estimated at 64.6% at 20 years following injury, comparable to the 67% unemployment rate found in the present study. In contrast, the study population included fewer persons who were Caucasian than the overall population (66% as compared with 50%). The study population was also skewed towards higher levels of education (2007). Fewer of the participants had not completed high school and more than 35% of the participants had a college degree compared with less than 10% in the overall population. Overall, the study population generalizes reasonably well within SCI and may also generalize to other populations using TIS wheelchairs, given the selection criteria based on function, not diagnosis. Although the higher education could be expected to result in stricter adherence to guidelines, across all participants (SCI and non-SCI) having a higher education was not associated with most aspects of tilt behavior and specifically was not associated with increased frequency of PRTs.

In terms of the wheelchair configuration the study population was considerably more homogenous. 36 of the participants were prescribed their TIS wheelchairs at the same seating clinic and the majority used one of two wheelchair cushions. It is unknown whether or not wheelchair configuration should affect tilt behavior. However, there were no significant differences in tilt behavior between participants using a Roho cushion and those using a Jay 2 cushion. 23 participants switched to a TIS wheelchair after spending between 6 months and 50 years in an upright wheelchair (median = 10 years). In clinical practice, changes to skin and function over time are common and must be factored in when assessing a person's seating needs. These changes are also important for consideration by funding agencies, as they might necessitate a new mobility device sooner than otherwise predicted. Similarly, older participants with lower levels of injury were provided with TIS wheelchairs, whereas it is possible that younger participants with the same levels of injury received upright wheelchairs, also drawing attention to functional limitations associated with age.

Most of the relationships identified between personal characteristics and pressure ulcer history amongst participants were consistent with existing research on pressure ulcer risk factors. For example, the presence of sensation is a major component of the Braden Scale for predicting pressure ulcer risk (i.e., "Sensory Perception"). Within persons with SCI, the ASIA score has also been related to pressure ulcer risk (Garber, Rintala et al. 2000). The ASIA score accounts for muscle function and sensation below the level of injury. Mobility has also been related to pressure ulcer risk within persons with SCI (Byrne and Salzberg 1996; Salzberg, Byrne et al. 1996; Salzberg, Byrne et al. 1998). Only one study has found that difficulty in repositioning does not increase pressure ulcer risk, but the study was limited to hospitalized patients over the age of 55 (Allman, Goode et al. 1995). Interestingly, body weight was shown not to be a risk factor in participants with SCI (Salzberg, Byrne et al. 1996), yet in the current study, increased body weight was associated with a history of pressure ulcers. This is also counter-intuitive because decreased body weight, not increased body weight, is typically thought of as a risk factor, as it is associated with increased interface pressures (Garber and Krouskop 1982). However, one thing to remember is that the body weight of the participants was not measured at the time of the occurrence of their pressure ulcer, but rather at the time of the study. Additionally, there was no relationship demonstrated between body weight and recurrent pressure ulcers. Potential confounders that might relate to both body weight and pressure ulcer development, such as smoking history and nutritional status, were not measured in this study.

Tilt-in-Space Behavior – Comparison with Previous Literature

Wheelchair use described in this study was similar to findings of previous studies of power wheelchair users, but different from manual wheelchair users. The median time of wheelchair occupancy (12.1 hours) was slightly higher than in previous work by Sonenblum, et al., which found that power wheelchair users spent 10.6 hours per day in their wheelchairs (Sonenblum, Sprigle et al. 2008), and that a subset of the current study population sat for 11.0 hours per day (Sonenblum, Sprigle et al. 2009). Results from the current study were also comparable to Ding, et al., (2008) who found that that 11 participants who used multi-function (i.e., tilt, recline, and elevating) wheelchairs spent an average (SD) of 11.8 (3.4) hours per day in the wheelchair. In contrast, manual wheelchair users in a study by Yang, et al. (2009) spent a median time of only 9.7 hours per day in their wheelchair. This discrepancy between manual and power wheelchair use is not surprising as only 4 participants in the current study were able to transfer independently and 24 regularly used a mechanical lift. With transferring requiring assistance and specialized equipment, fewer transfers throughout the day would be expected, compared with someone who is able to transfer independently.

The frequency of tilt use measured in this study was lower than in the initial pilot study (2.2 per hour vs. 3.1 per hour, Sonenblum, Sprigle et al. 2009). Participants in the study by Ding, et al. tilted 19±14 times per day and sat for 11.8 hours per day, or in other words their tilt frequency was approximately 1.6±1.2 tilts per hour. It is likely that this mean tilt frequency represents a high estimate of tilt frequency within their population, due to the skewness of tilt use towards smaller values. However, many of the included participants also had access to a recline feature, which permitted more frequent repositioning than is documented by the tilt frequency. Thus, it is difficult to determine the similarity of the two sets of results, although they are of the same order of magnitude.

The results of the first two hypotheses, that small and medium tilts are more common and that PRTs are not done frequently are also consistent with previous research (Ding, Leister et al. 2008; Sonenblum, Sprigle et al. 2009). Ding, et al. tested the hypotheses that tilts to positions less than 20° and time spent at positions less than 20° were greater than positions greater than 20°. While this is a common theme across all studies of wheelchair use, the results of the present study highlight the need to look more closely at the tilt behavior of individual participants, rather than just the central tendencies of the population. Addressing only the population as a whole neglects important behaviors, such as multi-modal behavior (17 of 45 participants) and having a typical position greater than 15° (14 of 45 participants). It is also possible that manual wheelchair users perform more frequent pressure reliefs than TIS users, as Yang, et al. (2009) found that the manual wheelchair users in their study performed full lifts 10 times per day, which given the average 9.7 hours of occupancy averages to approximately 1 per hour.

The finding that the median participant spent 19% of their seated time in a medium, large or extreme tilt is consistent with Ding, et al.'s finding that participants spent most of their time "not upright" (Ding, Leister et al. 2008). However, the definition of "not upright" in the study by Ding, et al. required less than 2.5° of tilt and a seat to back angle of less than 95°. Interestingly, many participants in the current study had their wheelchairs configured such that they were not capable of achieving an "upright" position according to that definition. However, the general result - that participants' self-selected typical position is not upright (median = 8°) is important when considering how to configure a wheelchair. It has been suggested that postures held longest in seating are the most stable postures (Zacharkow 1988). This is consistent with the decreasing shear forces pulling a person out of the seat as tilt increases up to 25°, where Hobson (1992) predicted the shear forces approach zero. Special attention should be paid during seating evaluations to the posture with the greatest stability.

Tilt-in-Space Behavior – Overall

The types of tilt behavior found in this study can be categorized hierarchically (Figure 13). The first level of groups are *uni-modal* (participants staying at a single position more than 80% of the time) and *multi-modal* (participants spending more than 20% of their time in more than one position). Within the *uni-modal* group are three subcategories of behavior: *minimal use*, or those who spent more than 97% of their time in a single position; *pressure relieving tilt*, or those who tilted past 30° at least once per hour, and the remaining ("*other*") uni-modal participants, some of whom tilted regularly but for shorter durations. Kruskal-Wallis testing indicated significant differences for most variables of tilt behavior (e.g. typical position, tilt frequency, and PRT frequency) across the different behavior categories (Table 5).

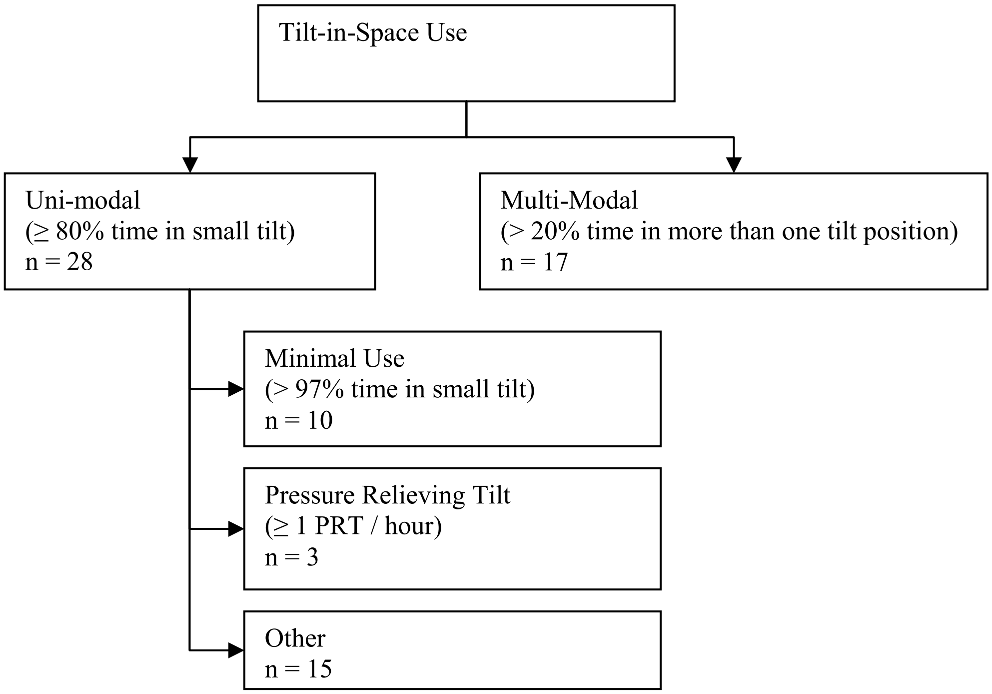

Figure 13. Four hierarchical categories of tilt behavior were identified in this study.

Table 5. Median tilt behavior differed across categories of behavior. Typical position is reported for all groups, but is not meaningful in the multi-modal group. * Kruskal-Wallis p<0.001.

	Uni-modal: Minimum Use	Uni-modal: PRT	Uni-Modal: Other	Multi-Modal
Occupancy (hours)	12.7	6.6	12.1	13.1
Typical Position* (°)	6	17	6	15
Tilt Frequency* (tilts/hour)	0.6	3.8	1.9	4.0
PRT Frequency* (PRTs/hour)	0.0	1.4	0.2	0.2

Among the ten participants who utilized uni-modal tilt behavior with minimal use of the tilt feature, the median tilt frequency was 0.6 times per hour and the median PRT frequency was zero. 5 of the 10 participants in this group never performed a PRT during the study. Participants in this group sat at a median typical position of 6° (range 0-9°).

A small group (n = 3) of participants used uni-modal tilt behavior, with most of their tilts being pressure relieving tilts. These participants used their tilts predominantly for medium (n = 1) and large (n = 2) tilts, performing at least one PRT per hour. These three participants also spent less than 9 hours per day in their wheelchairs, considerably less than other participants. Two of these participants had a current pressure ulcer and were told by their doctors to limit their seating time. The typical positions of the three participants were varied (3°, 17° and 26°).

The remaining group of participants utilizing uni-modal tilt behavior sat at a typical position of 6° (range 0°-17°) and had a median tilt frequency of 1.9 tilts per hour and 0.2 PRTs per hour.

Finally, the group of participants who used multi-modal behavior moved continuously, performing tilts 4.0 times per hour and pressure relieving tilts every 4 hours on average. Based on self-reported purposes of use, researcher observations, and previous research, it is fair to deduce that the participants in this group were moving for purposes of comfort or discomfort.

Overall, the majority of participants in the current study (77%), and studies by Ding, et al. (100%) and Lacoste, et al. (70%) reported using their tilt feature for comfort, discomfort and/or pain (Lacoste, Weiss-Lambrou et al. 2003; Ding, Leister et al. 2008). Seated comfort and discomfort are complex constructs involving many objective and subjective factors, including those related to the person, seat, and environment (de Looze, Kuijt-Evers et al. 2003). However, despite the complexity, extensive research has been performed and much is known about seated comfort in ergonomic applications. Long-term, static sitting is generally associated with discomfort and pain (e.g., Udo, Fujimura et al. 1999), and therefore ergonomic design has long included dynamic components in most task seating, such as office chairs and truck seats. Adjustable and dynamic seats affect both comfort and discomfort by allowing a variety of comfortable seated postures and by providing users with a means to address discomfort. Decades of literature have shown that increased body movements while sitting occur as a response to discomfort (reviewed in: Zacharkow 1988). Among the participants who used multi-modal tilt behavior, 14 of the 16 participants who were asked reported comfort/discomfort/pain as a purpose for use. Considering current knowledge about seating in the able-bodied population, it is not surprising that some wheelchair users (i.e. the multi-modal group) would use their tilt-in-space systems dynamically, more comparable to the use of a dynamic office chair, rather than solely as a device to perform scheduled pressure reliefs. Further evidence supporting the use of tilt for comfort comes from the fact that participants with sensation were more likely to move continuously while participants without sensation were more likely to have used uni-modal behavior.

Providing wheelchair users a means to improve comfort is very important. Survey data have shown that seated comfort is a priority for many wheelchair users (reviewed in: Hobson and Crane 2001). Additionally, people have been found to be more productive when their discomfort is minimized (Zacharkow 1988). If wheelchair users can spend more time out of bed and in their wheelchair, then their opportunities for participation are greatly increased. Although comfort is generally associated with persons with sensation (Hobson and Crane 2001), 11 of the 17 participants who reported having no sensation still reported using their tilt for comfort/discomfort/pain. Therefore, the issue of perceived comfort clearly extends beyond perceived sensation at the buttocks. This is consistent with the fact that some studies have failed to identify a relationship between interface pressure and comfort (reviewed in: de Looze, Kuijt-Evers et al. 2003). Given the aforementioned benefit of increasing seated comfort for wheelchair users, the limited use of TIS for pressure relief, and the tentative relationship between pressure and comfort, comfort should be an important design criterion for powered TIS systems in addition to pressure relief. However, because funding of power TIS wheelchairs requires medical necessity, and comfort is not defined medically, TIS wheelchairs have been designed for pressure relief rather than comfort. Future research should focus on evaluating the medical benefits of increased comfort.

Insufficient Pressure Relieving Tilts

The finding that participants did not perform pressure relieving tilts with their prescribed frequency (Hypothesis Two) is certainly one of the more important results of this study. The prescribed frequency tested in this study was one per hour, which is the minimum guideline suggested in the Clinical Practice Guidelines (2000). Many seating clinics, including the clinic from which most participants were recruited, recommend performing more frequent pressure reliefs (i.e., every 15-30 minutes). Clearly the participants in this study did not meet the more frequent guidelines. Large and extreme tilts come with a number of limitations and several wheelchair users readily proclaimed their unease with large and extreme tilts. Additionally, 22 participants did report performing other types of pressure reliefs, such as forwards or side leans, in place of or in addition to tilts. Yet the participants who reported performing other pressure reliefs also performed significantly more PRTs than those who did not perform other pressure reliefs, so it is doubtful that the ability to perform other pressure reliefs limited their use of the tilt feature for pressure relief.

Four potential explanations for the lack of use of tilt are: 1) that large and extreme tilts were uncomfortable and unstable, 2) that the perception of tilt angle may be misconceived, 3) that large and extreme angles of tilt result in a non-functional posture, necessitating the interruption of activities, and 4) that wheelchair users fail to pay attention to the need for regular pressure reliefs (Sonenblum, Sprigle et al. 2009). The issues of discomfort and instability are encountered regularly when talking with persons who use TIS wheelchairs. Although no specific questions about disuse were asked, many participants responded to questions about why they used their tilt by explaining why they did not. Six participants mentioned that they felt a full tilt was unstable, even if they knew they would not actually tip over. Another participant had concerns about bladder drainage at a full tilt. In terms of perception of tilt angle, the data suggested that this is not a primary concern. To investigate knowledge and perception of tilt angle, 41 participants were asked how far they needed to tilt for a pressure relief. 21 participants responded that they should tilt all the way back, two cited positions between 45°and 50° and 12 said that they did not know. 16 of the 21 who said "all the way back" were asked to demonstrate that position and only two of them were off by more than 5°. Overall, it seems that the perception of tilt position was not to blame for the failure to perform PRTs. The concern of a non-functional posture is debatable. At least one participant did not like that the driving feature of his wheelchair locked out at a larger tilt. However, most participants who used tilted positions simply switched to a more upright posture for activities requiring one, such as driving, eating, using the computer or sitting at a table. Whether participants paid attention to the need for pressure reliefs is a difficult question to answer. 29 participants (23 from above plus 6 with assorted other answers) believed they knew the answer to the question of how far they should tilt for pressure relief, suggesting they were aware of the need.

Improved training and education should address many of the concerns outlined above. Tilting through the range of small, medium and large tilts with a clinician present might be important to instill comfort and confidence in participants about performing such tilts. However, that requires the clinician to be present when the wheelchair is received. A full 11 out of the 39 participants asked said that no therapist was present when they received their TIS wheelchair. Although wheelchair delivery practices vary across clinics, there may be value in requiring a clinician to be present when the product is delivered or providing a follow-up appointment after delivery. For many power wheelchair users who do not have easy access to transportation, however, such a follow-up appointment might be problematic. Pressure relief compliance is an issue across all wheelchair users and should also be addressed with thorough training and education. Follow-up training based on evaluation of tilt behavior might allow for more appropriate training goals and approaches. For example, participants using the wheelchair with minimal use or other uni-modal behavior (and not regular PRTs) may need to learn and experience the variety of benefits of the tilt feature and be educated on pressure reliefs. It would help for the clinician to identify and address their reasons for disuse of the feature. In contrast, participants using multi-modal behavior without frequent PRTs are well aware of their feature's capabilities but may need more targeted pressure relief training and education. A better answer to the question of "how far of a tilt is needed to perform an acceptable pressure relief" is needed, work that is the focus of Specific Aim 2. Additional work to identify the correct frequency is also needed, but it is important to remember that the answers to both of these questions are likely to be highly individualized.

CHAPTER III

THE IMPACT OF TILTING ON BLOOD FLOW AND LOCALIZED TISSUE LOADING

Laser Doppler flowmetry and interface pressure measurement were employed to measure the increase in blood flow and decrease in loading with increased tilt angle on a subset of subjects from Specific Aim 1. The overall relationship between tilt and blood flow and loading was described. Additionally, this relationship was used to define a minimum “pressure relieving tilt.” Although the efficacy of such a tilt in preventing pressure ulcers could not be defined within the scope of this study, a more justified definition of “pressure relieving tilt,” with which to analyze tilt feature use was developed.

Hypotheses

H1. The minimum tilt position required to increase blood flow was less than 45°.

H2. There was a significant decrease in loading at the minimum tilt required for increased blood flow.

H3. Small magnitude tilts ($\Delta = 15°$) from upright resulted in increased blood flow and decreased pressure.

H4. Small magnitude tilts ($\Delta = 15°$), when starting from a tilted position (15°), resulted in increased blood flow and decreased pressure.

Methods

Participants

11 participants were recruited from the pool of subjects who participated in another research study on tilt-in-space wheelchairs (i.e., Specific Aim 1). People with spinal cord injuries who had current pressure ulcers on the ischial tuberosities were excluded, as were persons unable to tolerate sitting in an upright position. Additionally, subjects would have been excluded if they had latex allergies or sensitivities to medical adhesive; however, this situation did not arise.

Instrumentation

Doppler. The use of Laser Doppler Flowmetry (LDF) is not new to the world of PU research. It has been used to look at the efficacy of alternating pressure support surfaces (Rithalia 2004; Stockton and Rithalia 2007), as well as to monitor the viability of free flaps following surgery (Yuen and Feng 2000). The principle of LDF is similar to that of the siren of a passing ambulance – the pitch or frequency of the siren changes as the vehicle approaches and passes. Similarly, LDF uses a laser light focused at the skin. A sensor measures the frequency shift of the reflected light, which is proportional to the skin blood perfusion in a small region.

Figure 14. LDPM probe can be sat upon.

Other blood flow and perfusion measurement techniques are available, such as transcutaneous oxygen ($TcPO_2$) monitoring, tissue reflectance spectroscopy, and isotope clearance. The requirements of this study included measurement under load while seated. Therefore, the sensor and technique used must be compatible with this environment and precludes the use of most technologies. For that reason, the PeriFlux 5010 LDPM (Laser Doppler Perfusion Monitor) and a custom probe (Figure 14, Perimed AB, Sweden) were used. The laser works at 780 nm and the probe can be sat upon because it is sufficiently small, low profile (12.5 x 9.5 x 2.3 mm), and durable. This is the same probe design used by Rithalia (2004) to measure loaded blood flow of subjects in bed.

LDPM probes were calibrated prior to each data collection session using calibration solution supplied through Perimed. Doppler blood flow measurements are relative and are expressed in arbitrary units. Measurements collected at the tilted positions were normalized by blood flow in the preceding upright postures to permit comparison across participants.

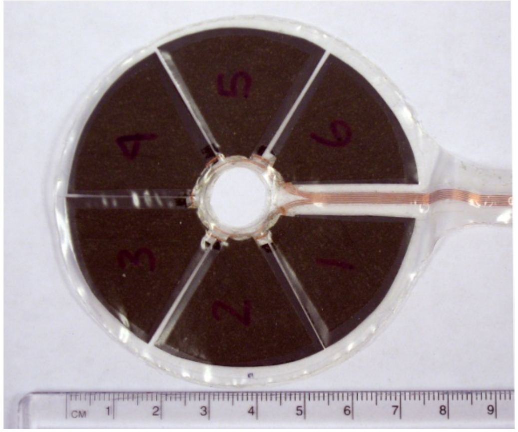

Figure 15. Interface pressure sensor.

Interface Pressure Sensor. To monitor the localized loading surrounding the LDFM probe, a custom sensor from FSA (Vista Medical, Winnipeg, Canada) was utilized. The custom sensor includes six separate, trapezoidal, resistive elements (i.e., sensels), covering a diameter of approximately six centimeters (Figure 15). The sensels are secured in an elastic substrate to accommodate the variety of buttock surfaces that will be encountered. A 1.5 cm diameter hole at the center accommodates the LDPM probe.

The interface pressure sensor was calibrated from 0 – 250 mmHg before each data collection session. A six-step FSA calibration was performed, according to the calibration wizard in FSA 4.0.

Protocol

This protocol was approved by the Institutional Review Boards at Georgia Tech and Shepherd Center. In advance of the study, participants were provided with a pair of stretchy boxer shorts to simplify access to the ischial region. Participants were asked to arrive wearing these shorts as their undergarment. Once participants had discussed the study with researchers, had questions addressed, and provided consent, subjects were assisted with removing any layers of clothing over the boxer shorts and were lifted in a Guldmann net to provide access to the ischial region. The Guldmann net was set up to maintain a relatively upright, seated posture (Figure 16). With the subject lifted using a Guldmann ceiling mounted hoist system, the apex of the ischial tuberosity was palpated and marked with a small sticker. The interface pressure sensor was attached with the opening at the marked location. The sticker was removed and the LDPM probe was then attached directly to the skin at the apex of the ischial tuberosity (Figure 17). Medical grade, double-sided adhesive (In Vivo Metric, Healdsburg, CA) was used to attach both sensors. Subjects were lowered back into their personal wheelchair and positioned in their typical seated posture so that they were comfortable and felt they could maintain that position for the duration of the study. The location of the LDPM probe was palpated to confirm its position beneath the ischial tuberosity. The net was left in place and participants were asked not to move for the duration of the study.

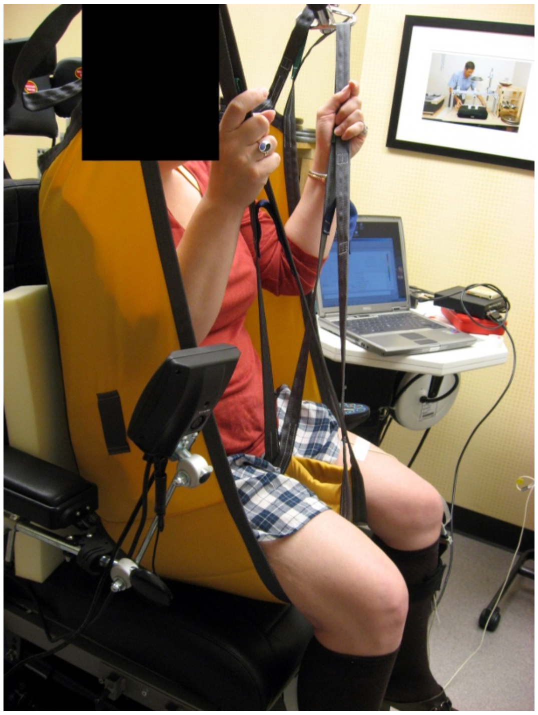

Figure 16. Subject lifted in Guldmann net before attaching probe.

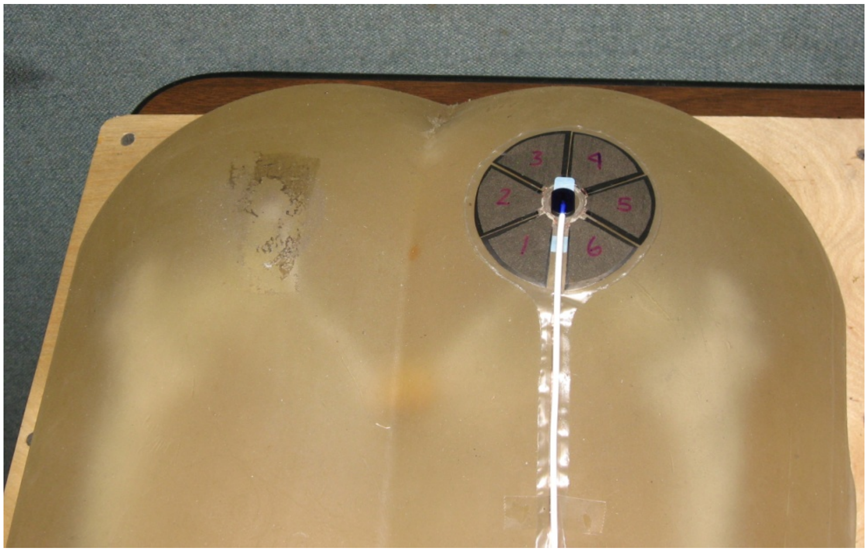

Figure 17. Sensor placement beneath the apex of the ischial tuberosity illustrated with a buttocks model containing a pelvic skeleton.

The data collection protocol involved three trials of sequences that alternated tilt with upright sitting. All seated positions were held for two minutes. Although two minutes is generally shorter than typical sitting times, it was found that for some persons with SCI, loading for as long as three to five minutes may result in a hyperaemic response lasting at least half as long as the loading. While the hyperaemic response is of interest, the measurement of steady state blood flow at the different positions was the main goal. Therefore, two minutes of loading was used to minimize the development and duration of any hyperaemic response while permitting at least one minute over which steady state blood flow could be monitored. LDFM was sampled at 32 Hz and the interface pressure sensor was sampled at 1 Hz throughout the duration of the above testing.

Tilt Sequences. Each trial was separated by five minutes of unloaded sitting (lifted in the Guldmann net, Figure 16) to allow for complete reperfusion. The sequence of tilts in each trial was randomized separately. Sequences are presented below with notations of the hypotheses to which they are associated. All positions following upright were utilized to model the overall effect of tilt on blood flow and localized loading. Upright refers to the minimum tilt possible on the participant's wheelchair, while "max tilt" refers to the maximum tilt possible on the participant's wheelchair. Upright and max tilt values were recorded. Actual tilt position was recorded continuously by an accelerometer attached to the wheelchair seat. Acceleration was sampled at 1 Hz and synchronized with the interface pressure and LDPM data in Matlab.

Table 6. Tilt sequences.

Sequence	Hypotheses
Upright → 15°→ 30°	H1, H2, H3, H4
Upright → 30°	H1, H2
Upright → 45°	H1, H2
Upright → max tilt	H1, H2

Data Analysis

All data analysis was performed with Matlab R2008a (Mathworks Inc, Natick, MA). Acceleration was converted to a tilt angle of the seat pan relative to the horizontal by taking the arcsine of the stationary acceleration values. Blood flow was filtered at 0.05 Hz using a second order low pass Butterworth filter to remove movement artifacts. Additionally, to avoid data being influenced by hyperaemic response, average blood flow was calculated as the average reading over the final minute at each tilt position. To facilitate analysis across subjects, given the arbitrary units in which flow is measured, blood flow at each tilted position was normalized by blood flow at the preceding upright position. Pressures were analyzed according to the average of the six sensels, as well as the peak pressure among the sensels.

All statistical comparisons were computed with paired, one sided *t*-tests. Absolute pressures were compared in a paired *t*-test because the values, in units of pressure, have clinical significance. The alternative hypothesis used was that tilted pressure is less than upright pressure. In contrast, blood flow was measured in arbitrary units, making the absolute differences less interpretable within and across subjects. Therefore, normalized blood flow (i.e., a ratio of tilted blood flow to upright blood flow) was compared to a mean of 1 (alternative hypothesis: normalized blood flow is greater than one). *P*-values of less than 0.05 were considered significant.

H1. The normalized blood flow at positions less than 45° of tilt (i.e., 15°, 30°) were compared to 1 to identify the smallest tilt to result in a statistically significant increase in normalized blood flow across subjects.

H2. The peak and average pressures measured at the tilt position identified in H1 were compared with the peak and average pressures computed in the upright position immediately preceding the tilt.

H3. Normalized blood flow and peak and average pressures in upright sitting were compared to those at 15° of tilt.

H4. Normalized blood flow and peak and average pressures were compared between 15° and 30° of tilt.

Finally, models of tilt angle versus blood flow and pressure were created using data recorded at all positions following upright (i.e., excluding data at 30° following

15° of tilt). Although an initial linear regression was attempted and used for modeling pressure, an exponential model was more appropriate for blood flow. Additional details pertaining to the modeling are presented in the results. From the models and the hypothesis results, guidelines for performing pressure relieving tilts were defined.

Results

Research Participants

Eleven subjects with cervical spinal cord injuries who had participated in a concurrent research study (monitoring of tilt-in-space use) were enrolled in the blood flow study (Table 7). Subjects included 9 men and 2 women with mean (SD) height 1.79m (0.04m) and weight 80kg (14kg). Seven subjects were African-American, 3 were Caucasian, and 1 self-identified as biracial. Research participants had been using a wheelchair for a mean (SD) of 9.4 (5.7) years, with a minimum of 9 months and a maximum of 18 years. Ten participants used chairs with a tilt-in-space feature and no recline. On the one wheelchair that also had the ability to recline, a constant seat-to-back angle, consistent with his typical seated position, was maintained during testing.

Wheelchair configurations were not modified for this study. The upright position in all chairs was less than or equal to 5° (mean (SD) = 2.1° (1.8°)). Seat to back angles ranged from 90° – 110°, with a mean (SD) of 101° (6°).

Table 7. Subject characteristics and wheelchair information

Subject	Age	Gender	Height (m)	Weight (kg)	Race	Level of Injury	Complete	Years in WC	Wheelchair	Cushion	Seat to Back Angle
1	47	M	1.78	73	Caucasian	C3-4	Incomplete	2.5	Invacare	Roho	98
2	33	M	1.83	77	African-American	C5-6	Complete	18	Invacare	Roho	97
3	32	M	1.80	95	African-American	C5	Incomplete	10	Quickie	Jay 2	101
4	58	F	1.78	88	African-American	C6	Incomplete	10	Invacare	Roho	90
5	78	M	1.85	100	Caucasian	C6-7	Complete	12	Invacare (+RECLINE)	Roho	110
6	44	F	1.75	86	African-American	C4-5	Incomplete	7	Invacare	Jay 2	100
7	31	M	1.83	52	Caucasian	C3-4	Complete	14.5	Invacare	Roho	106
8	42	M	1.75	73	African-American	C5-6	Complete	12	Invacare	Roho	100
9	67	M	1.70	82	African-American	C7	Incomplete	2	Invacare	Jay 2	110
10	22	M	1.80	79	Biracial	C5-6	Complete	0.75	Permobil	Roho	105
11	47	M	1.83	71	African-American	C5	Incomplete	15	Invacare	Roho	100

Description of Data

Data from a single trial of one participant (Subject 5) are shown in Figure 18. The high frequency blood flow signal (grey) is presented as well as the low pass filtered signal (black). Although the tilt and pressure time series look relatively similar across subjects, there was no ‘typical’ participant when it came to blood flow. As anticipated, blood flow during the second minute of loading was steady state. The one minute duration is presented as the red line in Figure 18B. The slope of the flow during that minute was indistinguishable from zero ($p = 0.287$).

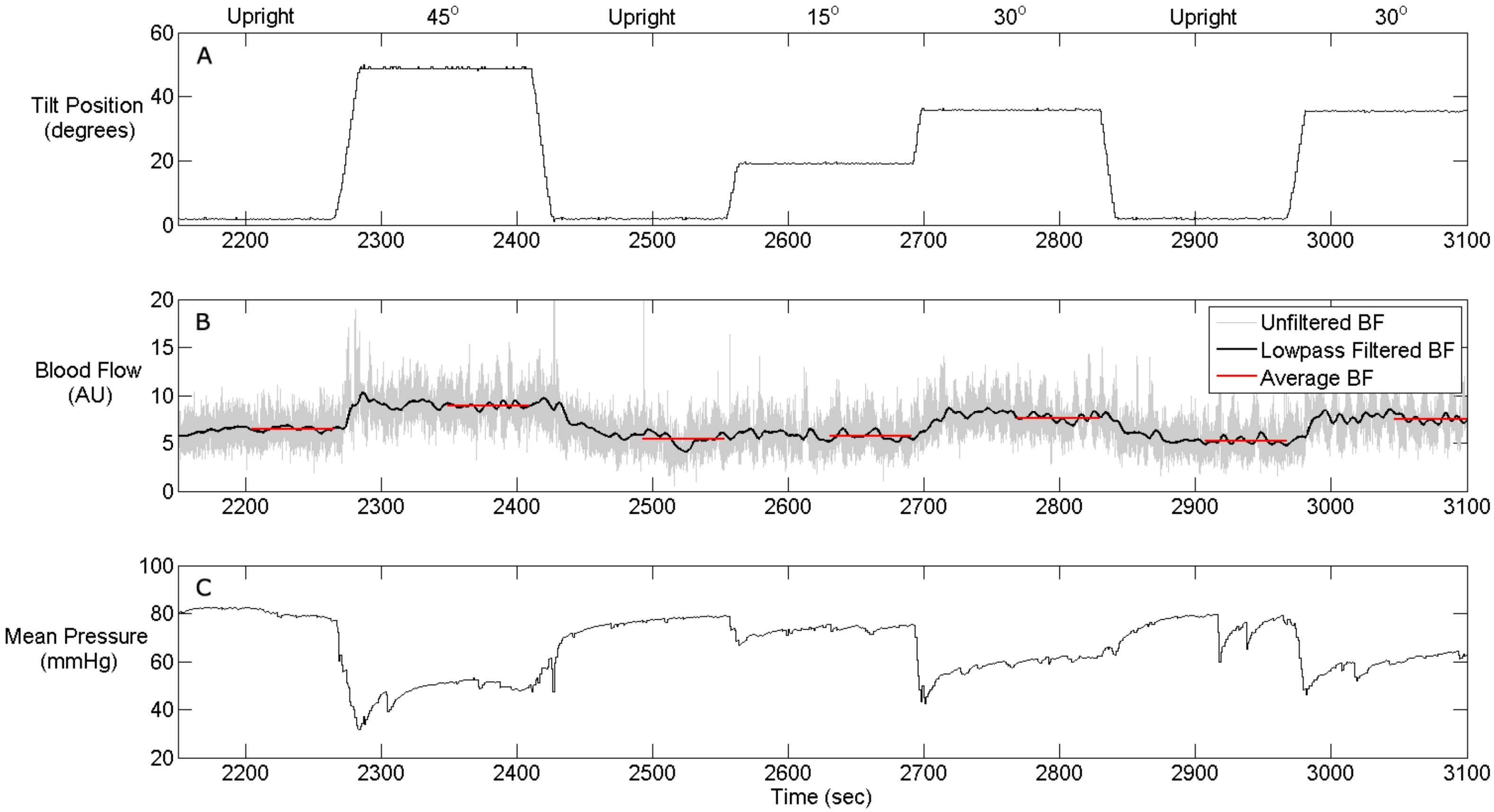

Figure 18. Sample data from a single trial of one subject (subject 5). Tilt order was randomized and three trials were conducted with 5 minutes of unloading between trials (not shown). BF = blood flow, AU = arbitrary units. Average BF in red represents the second minute spent at the tilt position. A) Tilt position. B) Blood flow. C) Mean interface pressure.

Peak pressures in the region surrounding the ischial tuberosity in upright sitting varied across participants from 27 to 176 mmHg, while mean pressures varied from 22 to 141 mmHg (Table 8). Normalized blood flow at all tilt positions varied across subjects from 0.71 to 16.5 (Table 9).

Table 8. Absolute pressure at each position. Statistics were computed on tilted pressures paired with upright. Mean (SD). † p<0.001, NS p>0.05. Note that fewer subjects were studied at 55°.

Tilt Position	# Subjects	Peak Pressure (mmHg)	Mean Pressure (mmHg)
Upright	11	91 (32)	74 (27)
15°	11	87 (30) NS	71 (25) †
30°	11	77 (28) †	62 (24) †
45°	11	63 (25) †	50 (21) †
55°	6	68 (27) †	53 (23) †

Table 9. Normalized pressure and blood flow values (normalized by preceding upright values). Statistics were computed for normalized blood flow compared with a ratio of 1.

Tilt Position	# Subjects	Peak Pressure	Mean Pressure	Mean Blood Flow
15°	11	0.98 (0.09)	0.98 (0.09)	1.08 (0.19), *p* = 0.016
30°	11	0.85 (0.11)	0.84 (0.10)	1.24 (0.48), *p* = 0.003
45°	11	0.72 (0.12)	0.69 (0.12)	1.84 (1.84), *p* = 0.007
55°	6	0.68 (0.12)	0.64 (0.12)	3.34 (5.09), *p* = 0.034

Hypotheses

In response to Hypothesis One, small tilts (15°) resulted in a significant increase in blood flow ($p = 0.016$, Table 9). The magnitude of the increase (1.08 ± 0.19), however, was relatively small and highly varied. Conversely, Hypothesis Two was not supported. The increase in blood flow at 15° did not correspond with a decrease in loading at 15°, as compared with upright ($p = 0.085$ for peak and $p = 0.131$ for mean pressure, Table 8).

In response to Hypothesis Three (and as mentioned previously), 15° of tilt from upright resulted in a significant increase in blood flow, but no significant decrease in pressure. However, the data supported only the pressure component of Hypothesis Four. Peak and mean pressures at 30° were significantly different than those at the preceding 15° tilt ($p<0.001$). However, blood flow did not increase further when participants tilted from 15° to 30° ($p = 0.118$). Additionally, pressures and blood flow at 30° following 15° of tilt were not statistically different from pressures and blood flow achieved when tilting directly to 30° from upright sitting (Table 8, Table 9, Table 10).

Table 10. Pressures and blood flow values at consecutive 15° and 30° tilts. Mean (SD).

Variable	15°	30°
Absolute Peak Pressure (mmHg)	87 (30)	75 (27)
Absolute Mean Pressure (mmHg)	71 (25)	61 (22)
Normalized Mean Blood Flow	1.08 (0.19)	1.15 (0.41)

To confirm that blood flow at 30° was still greater than that at upright, another one sided *t*-test was run and it was confirmed with $p = 0.023$ that blood flow at 30° of tilt from 15° of tilt was still greater than upright blood flow.

Modeling Tilt Amplitude vs. Pressure and Blood Flow

Interface pressures in the upright position varied widely across subjects (Table 8). This large variation in initial (upright) pressure suggested the need to consider initial pressure when modeling tilt amplitude versus pressure, which can be done in multiple ways. The normalized pressure (i.e., the ratio of pressure at the tilted position to the preceding upright pressure) can be modeled as a function of angle. However, this is less intuitive as it removes the units from analysis. Second, a multivariate regression can be used. In this case, the upright pressure and the tilt position were used to predict the tilted pressure. In the models for peak and average pressure (Equation 1, Equation 2), all coefficients (the constant, tilt position or “angle,” and upright pressure) were significantly different than zero ($p < 0.001$). It is evident in the models that the peak and mean pressures had the same relationship with tilt. That relationship is illustrated for three different upright loads in Figure 19.

Equation 1.

$$\text{PeakPressure}_{\text{Tilted}} = 25.6 - 0.718*\text{Angle} + 0.809*\text{PeakPressure}_{\text{Upright}}\ (R^2 = 88.1)$$

Equation 2.

$$\text{MeanPressure}_{\text{Tilted}} = 22.2 - 0.679*\text{Angle} + 0.820*\text{MeanPressure}_{\text{Upright}}\ (R^2 = 89.7)$$

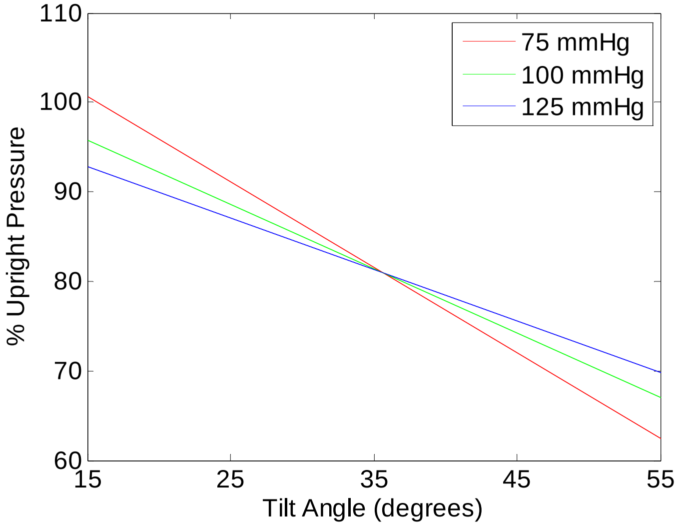

Figure 19 . Illustration of changes in peak pressure with tilt angle across three different upright loading conditions. Changes in mean pressure are similar.

The large variation in blood flow response made modeling with only 11 subjects more challenging. For instance, only five subjects demonstrated a monotonic blood flow increase with tilt angle. Two subjects had limited or no increase in flow with tilts up to 45° but had considerable blood flow increases thereafter, at maximum tilt. To justify proceeding with a model, correlations were computed between normalized blood flow and tilt position, absolute pressures, and normalized pressures. The correlations between normalized blood flow and absolute pressures were not significant, but the correlations between normalized blood flow and normalized pressures were significant (Pearson's r = -0.3 for both peak and mean normalized pressure, $p = 0.001$). Similarly, tilt position was significantly correlated with normalized blood flow (Pearson's $r = -0.3$, $p = 0.003$).

Despite the variability in the blood flow response, this provided sufficient motivation to proceed with a model. Because tilt angle and normalized pressures were strongly correlated (Pearson's r = -0.7 for peak pressure, -0.8 for mean pressure), only tilt angle was included in the model. Tilt angle was selected because of the results to Hypothesis Two, in which a change in tilt angle resulted in an increase in blood flow without a corresponding decrease in pressure. Further testing revealed that inclusion of both normalized pressure and angle did not improve the model considerably. Plots of normalized blood flow and residual plots from initial, linear models supported modeling blood flow exponentially. In the regression between the tilt angle and the logarithm of the normalized blood flow (Equation 3), the coefficient for the tilt position was significantly different from zero ($p < 0.001$), but explained only a small percentage of the variation (R^2 = 7.9).

Equation 3.

$$\text{BloodFlow}_{\text{Norm(Tilted/Upright)}} = \exp(-0.149 + 0.0118 * \text{Angle}) \ (R^2 = 7.9)$$

Discussion

The results confirmed the first hypothesis, that the minimum tilt position required to increase blood flow is less than 45°. In fact, a tilt of only 15° had a small (8%) but significant increase in superficial blood flow. Pressure did not significantly decrease at 15° of tilt; in some subjects, the pressure actually increased slightly. But, pressures were reduced by all tilts greater than 15°. This suggests that the mechanism of increased blood flow at 15° of tilt is not solely due to a change in pressure at the ischial region. As a secondary analysis, it was considered that the location of the center of pressure might have changed, contributing to a different pressure at the precise location of the LDF probe (Figure 20). A paired *t*-test between the medial/lateral positions of the center of pressure was not significant between a 15° tilt and upright. The center of pressure did move significantly in the posterior direction ($p < 0.001$) but the magnitude of the change was only approximately 0.5 mm. This value is small compared with the 19mm of displacement of the center of pressure that occurred with 25° of tilt in work by van Geffen (van Geffen, Reenalda et al. 2008). However, it is important to remember that the center of pressure in this study represents the center of pressure in a small region below the ischial tuberosity (Figure 17), not the entire seated center of pressure as in the study by van Geffen, et al. With a cushion that successfully distributes pressure in the ischial region, as all the tested cushions claim to, limited movement of the center of pressure within this region can be expected.

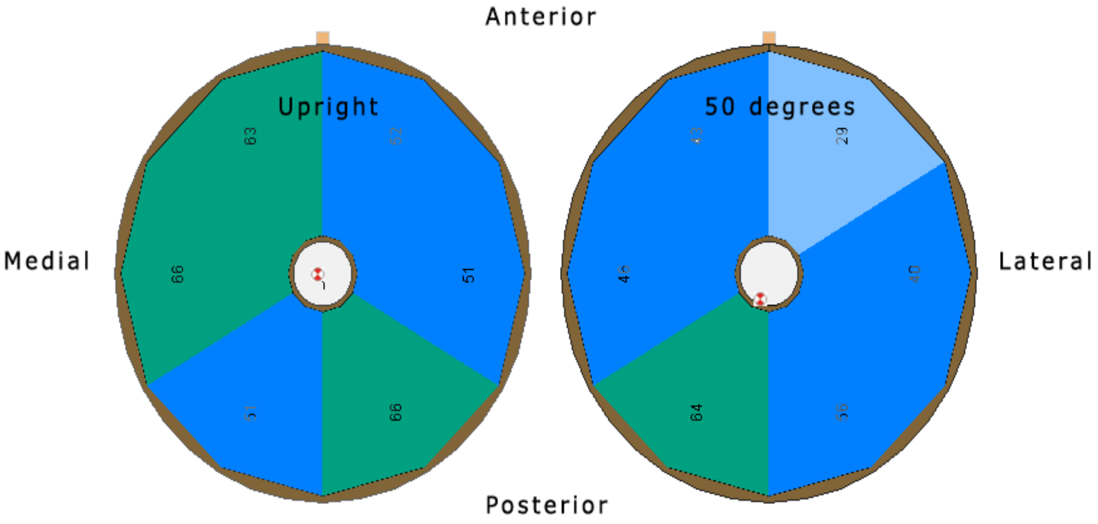

Figure 20. Illustration of center of pressure (CoP) locations (red and white circles). For this subject, CoP moves posteriorly by 3.8 mm with a 50° tilt.

The third and fourth hypotheses address small ($\Delta \approx 15°$) changes in tilt position. As discussed above, a small change from upright to 15° of tilt results in a significant increase in blood flow, but not a significant decrease in pressure. The actual change in tilt angle (variable due to the differences in “upright” position) was 13° ± 2°. A further change of 15° (from 15° to 30° of tilt) does not further increase the blood flow, despite a decrease in pressure. This lends more support to a different mechanism of increased blood flow.

The results of the hypotheses, in combination with the weak correlation between tilt position and blood flow response, suggest that there are other mechanisms affecting blood flow besides the change in normal loading. One possibility is the change in location of the ischial region relative to the heart with tilt. Blood flow to an unloaded reference point on the anterior thigh, midway between the greater trochanter and femoral condyle also increased significantly with tilt, supporting a possible gravitational influence. However, the influence of gravity would be reflected by the tilt angle, so this cannot account for much of the additional variation. Another possible explanation could be postural changes that might occur with tilt. In able-bodied participants, 25° of tilt resulted in approximately 5° of pelvic rotation (van Geffen, Molier et al. 2008). However, the same author found that manipulating pelvic posture did not influence subcutaneous blood flow or oxygenation in persons with SCI (van Geffen 2009). This suggests that the small postural changes that might be induced by tilt are unlikely to affect blood flow. Another possibility that was not addressed in this study is the effect of shearing. Although tilt does not induce as much shearing as recline, research has shown that significant changes to the global shear forces occur throughout the range of tilt positions studied. Specifically, Hobson (1992) showed that a 20° tilt reduces the global shearing forces by 85%. Presumably, at larger tilts, the shearing force is reduced by 100%, at which point it changes orientation and begins to increase again. While such shear forces are typically not reflected by interface pressure measurements, they may affect blood flow. When the global shear forces are translated to the tissue, they can result in localized shear strain. Shear strain at the blood vessels could affect the actual blood flow, while shear strain at the skin - LDPM sensor interface could change the apparent measurement region; both of these would add unexplained variability to the measurements. Shear is also an important factor because it is well known that localized shearing contributes significantly to the formation of pressure ulcers (Bennett, Kavner et al. 1979). An interesting result presented in the work of Mayrovitz and Smith (1999) suggests that alternating loading with unloading results in increased baseline blood flow, even at complete loading. In a study of elderly women on a dynamic mattress, the loading conditions were changed on a four minute cycle and resulted in an overall increase in blood flow throughout the hour long test duration. The testing in this study changed pressures every 2 minutes for 14-18 minutes between complete unloading. Yet, loaded blood flow did not increase with each sequence, except for in one participant.

Predictive modeling of the biomechanical response to tilt is very difficult, given the individual nature of the response. Variability in pressure can be explained as a function of tilt position, provided the upright pressure is included in the model. Upright pressure accounts for some of the variability across participants. According to the models, a 24° tilt was needed for a participant with the median upright pressure to achieve a 10% reduction in upright pressure. Because interpretation of a multivariate model can be confusing, Figure 19 illustrates the percent of upright loading for different upright pressures, and Table 11 presents some examples of what the model would mean at tilts of 35°, 45°, and 55° for people with different upright pressures. A 55° tilt may decrease the pressure under the ischial tuberosities somewhere between 30 and 50 percent. A recent study that measured the change in seated forces with tilt found a greater decrease in force than this study found in pressure (approximately 55% at 55° tilt; Sprigle, Maurer et al. in press). Because the change in load is distributed beneath the entire buttocks and thighs, the decrease in load is not necessarily evenly distributed. In fact, van Geffen, et al. suggested that most of the pressure change with tilt occurred underneath the thighs (van Geffen, Reenalda et al. 2008). Also, the study by Sprigle, et al. utilized a foam cushion rather than an air inflation (Roho) or fluid (Jay 2) cushion as used by participants in this study. Otherwise, the results of this study are reasonably consistent with previous research, such as the 27-33% decreases at 45° of tilt found by Aissaoui, et al. (2001)and Burns and Betz (1999). Considering the different methods, equipment and participants, the similarity in results across studies is reassuring. The inclusion of initial pressure in the model may also help to explain some of the differences between studies.

Table 11. Estimated peak pressures based on Equations 1 and 2. Estimated mean pressures are nearly identical.

	35° Tilt		45° Tilt		55° Tilt	
Upright Pressure (mmHg)	mmHg	%	mmHg	%	mmHg	%
50	41	82	34	67	27	53
100	81	81	74	74	66	66
150	122	81	115	76	107	72

The model for blood flow as a response to tilt explained little variance. This is not surprising, as previous literature has addressed the individual nature of blood flow response (Bader 1990; Mayrovitz, Macdonald et al. 1999; van Geffen 2009). Bader first suggested the idea of a "non-responder" in his 1990 paper. In the study, he observed persons with disabilities (predominantly multiple sclerosis and SCI) who experienced decreased blood flow with loading, but no increase in flow with partial unloading. He suggested that this might reflect a person who is more at risk for tissue breakdown (Bader 1990). Van Geffen extended the concept of "non-responders" as he identified able-bodied persons who also did not experience an increase in blood flow with unloading. Unlike Bader's assessment, however, he hypothesized that some participants might have sufficient blood flow in the loaded position (i.e., no occlusion) such that there is no need for increased blood flow with unloading. Interestingly, of the 11 participants in this study, nine had an increase in blood flow of more than 13% during at least one tilt. Of the remaining two (Subjects 4 and 8), Subject 8 demonstrated a significant hyperaemic response to complete unloading in between trials (data not reported), suggesting that he has the potential to respond. He also had sensation at the buttocks and no history of pressure ulcers. Subject 4 had considerable scar tissue under the ischial tuberosity that might have influenced her blood flow response or measurement. Her absolute blood flow was also much higher than all other participants and it increased throughout the test session, independent of tilt position. Thus, only these two participants might be classified as "non-responders" according to the work of Bader and van Geffen. Subject 8's blood flow response was consistent with a non-responder as defined by Bader (1990): having no blood flow response to partial unloading, but responding to complete unloading.

However, given his lack of previous pressure ulcers, it calls into question whether the lack of response puts him at additional risk. Subject 4 is more consistent with the able-bodied non-responders seen in the study by van Geffen (2009), as her blood flow was significantly higher than other participants in the upright seated position.

Previous research has suggested that additional individual factors should be addressed when studying blood flow. These include physical measurements such as the initial thickness of the tissue, the deformation associated with loading, and the geometry of the ischial tuberosities (Sacks 1989; Gefen 2007). Additionally, demographic and physiological measurements such as skin color, age, blood pressure, and smoking history could also be important.

With only 11 participants, it is difficult to classify what characteristics might have resulted in the different responses to tilt. Participants with the greatest blood flow responses spanned race, gender, level of injury, and completeness of injury. Similarly, participants with the least blood flow response, even at 45° of tilt, were highly varied. Nine of the 11 participants showed a considerable increase in blood flow (≥ 13%) during the maximum tilt allowable on their wheelchair. However, only 4 of 11 participants had an increase in blood flow of ≥ 10% at 30° tilt.

Based on these results, some preliminary guidelines for pressure relieving tilts can be proposed. First, a tilt for pressure relief should tilt as far as the seating system permits. Additionally, until more research is conducted, the potential impact of small tilts should not be neglected. As described previously, small tilts produce a statistically significant, albeit small, increase in blood flow that cannot be attributed entirely to a decrease in pressure. Therefore, it is unknown whether these small tilts might provide a different benefit as compared with pressure reliefs from a maximum tilt. As described previously (Sonenblum, Sprigle et al. 2009), small tilts have many functional benefits over large tilts and might be a helpful option in between large tilts, rather than as a replacement for large tilts. Finally, it is important to remember that the response to tilt is individualistic and affected by many factors. In particular, the upright pressure will influence the amount of pressure relief achieved at a given tilt, and thus should not be neglected.

Limitations

Defining a “pressure relieving tilt” based on these results must be done cautiously. With only 11 participants, most of whom were sitting on a Roho air inflation cushion, it is unclear whether the results will generalize to a larger population and other wheelchair cushions. In Stockton and Rithalia’s blood flow work, they found that forward leans on a Roho cushion resulted in a smaller pressure reduction and blood flow increase than a gel cushion, suggesting that the pressure relief benefits of tilting might vary with wheelchair cushion design (Stockton and Rithalia 2007). However, the recommendation put forth in this study does err on the side of caution. Future research may suggest that some people will not need to tilt as far as this paper recommends. Additionally, the blood flow analyzed in this study included only steady state flow in vessels in the most superficial one millimeter of tissue. It is possible that changes to deeper vasculature were different than those presented here. Hyperaemic responses, which were not considered in this study, might also contribute to the efficacy of a pressure relief. Based on observations of the data, hyperaemic responses were not typically seen with tilts, but movement artifacts could have masked hyperaemic responses of short durations. Preliminary studies suggested that two minutes was sufficient to cause occlusion.

Additionally, complete unloading of the tissue following each trial produced a hyperaemic response in some participants, indicative of previous occlusion. But it is possible that after durations of loading more consistent with daily use, i.e., approximately 30 minutes between position changes, the transient blood flow response to a tilt might be different than seen in this study.

Blood flow is only one component of pressure ulcer prevention. Research has shown that cell deformation in the presence of sufficient oxygen may also cause cell death (Gawlitta, Li et al. 2007). This study did not measure tissue compression or shear; both factors that should be considered in future research.

Future Work

Although 11 subjects were sufficient for testing some of these hypotheses and laying out some general tilt guidelines, more work is needed to determine how well these results will generalize across different populations, diagnoses, and seating systems. To that end, additional study is needed with a larger, more heterogeneous population. In a future study, it would be beneficial to test participants on different types of wheelchair cushions in order to determine the impact of wheelchair cushions on participants' biomechanical responses to tilt.

Future research should also aim to explain additional variability in the blood flow response and determine the mechanism of blood flow changes. Later studies should consider more demographic and physiologic factors to help explain more of the variation. The use of seated MRI to capture tissue properties and deformation would help both to explain variability in individual responses and identify the tissue properties' contribution to blood flow changes. Similarly, measurements of shear forces would be helpful.

Finally, some more controlled protocols can be created to isolate independent factors contributing to blood flow. For example, participants can be tilted and then provided with a weighted vest to compensate for the decrease in pressure resulting from tilt. Remaining changes to the blood flow could be assumed to be caused by non-pressure related mechanisms.

Conclusion

This study found that biomechanical responses to tilt are highly variable across the homogenous population studied. Pressure reduction at the ischial tuberosity can be explained by the tilt position as well as the upright pressure. However, most of the variability in the blood flow response could not be explained by tilt and pressure, the factors considered in this study. Thus, much remains to be understood about the mechanism of blood flow changes in response to tilt. Based on the results of this study, tilting for pressure reliefs as far as the seating system permits is recommended to maximize the potential for significant pressure relief and increased blood flow. The use of interim small tilts is also supported, as they also provide some benefit.

CHAPTER IV

THE APPLICATION OF BIOMECHANICAL RESPONSES TO EVERYDAY TILT USE IN PARTICIPANTS WITH SCI

The relationships between tilt angle and blood flow and loading, as well as the definition of pressure relieving tilt defined in the laboratory-based study (i.e., Specific Aim 2), were used to evaluate the tilt use measured in Specific Aim 1. From this, the amount of biomechanical benefit participants received from their tilt use was determined.

Hypotheses

H1. Pressure relieving tilts (according to the definition from Specific Aim 2) were not used with prescribed frequency.

H2. Participants did not decrease loading or increase blood flow at regular intervals.

Methods

The data for Specific Aim 3 were analyzed in two sections: the *individualized analysis* and the *group analysis*. The biomechanical responses to tilt, measured in Specific Aim 2, provided two approaches to analyzing everyday tilt use. For the individualized analysis, the individual biomechanical responses measured in Specific Aim 2 were applied to those individuals' tilt use. This analysis provided greater accuracy; but with only ten participants, generalization was limited. For the group analysis, the average responses computed in Specific Aim 2 were applied to all 30 participants with SCI whose tilt use was measured in Specific Aim 1. Although applying an average model is less accurate due to the individual nature of biomechanical responses, this provides a more generalizable picture of the benefits of tilt use. No new data were collected for Specific Aim 3.

Both the individual and group analyses utilized the filtered position data from Specific Aim 1. Tilt position was collected with a uniaxial accelerometer, sampled at 1 Hz and then filtered according to the following algorithm: Position was defined as constant until the following conditions were met, at which point a new position was defined: 1) the tilt angle changed by at least 5°; and 2) the change was maintained (within ±2°) for 20 seconds. Because the accelerometer measures changes resulting from factors other than tilting (i.e., wheeling, bumpy ground, etc.), this algorithm was necessary to eliminate transient events and focus on changes in tilt angle only. A minimum change of 5° was selected because it exceeds the sensitivity of the accelerometer and is based upon the belief that position differences of less than 5° may not be reliably differentiated by persons in wheelchairs. The 20 second threshold was selected to eliminate the transient events previously mentioned.

Metrics of tilt behavior unrelated to their biomechanical effects were described for participants of both the individualized and group analyses, including wheelchair occupancy time (hours per day that subjects occupied their wheelchairs), typical position (position at which the subject spent the most time), percent or absolute amount of total occupancy time spent at small (0-14°), medium (15-29°), large (30-44°) and extreme (≥45°) tilt angles, and tilt frequency (number of position changes, ≥ 5° lasting at least 20 seconds, per hour of wheelchair occupancy). Additionally, participants were categorized based on their tilt behavior. As defined in Specific Aim 1, the *uni-modal* category included participants staying at a single position more than 80% of the time, while the *multi-modal* category included participants staying at a single position less than 80% of the time.

Individualized Analysis

In the individualized analysis, real world tilt use by ten participants from Specific Aim 2 was analyzed. One participant from Specific Aim 2, whose wheelchair had the ability to recline, was excluded because the biomechanical responses to recline were not studied.

Hypothesis One, that pressure relieving tilts (PRTs) were not used with prescribed frequency, was based on the results of Specific Aim 2. The data collected in Specific Aim 2 resulted in preliminary guidelines which stated that a tilt for pressure relief should tilt as far as the seating system permits. To simplify analyses measuring whether people followed these guidelines, the frequency of tilts to a position greater than 40° lasting longer than one minute were analyzed. Forty degrees was chosen for a number of reasons: 1) each participant had a different maximum tilt position ranging from approximately 45° to 60° and the position was not known for all participants; 2) some amount of error is expected from the sensor and 40° included tilts within a few degrees of the maximum position; 3) results from Specific Aim 1 indicated that few participants performed tilts past 30°. Therefore, the details of the PRT definition would not be likely to change the overall result.

Hypothesis Two required defining “decreased loading” and “increased blood flow.” For the purpose of this hypothesis, small changes in loading and blood flow were considered. Specifically, a 10% decrease in loading was selected because that is generally believed to be outside of the range of measurement error. For the individualized analysis, an increase in blood flow of 5% was selected because of the generally smaller changes in blood flow over the entire range in tilt. A regular interval was defined as at least once every 30 minutes (i.e., a tilt frequency of 2 tilts per hour).

For the individualized analysis, Hypothesis Two was tested with participants' personal biomechanical responses to tilt. To calculate these responses, individuals' median normalized blood flow and pressures at tested positions were linearly interpolated to identify the biomechanical responses corresponding with each tilt position. In addition to testing the tilt frequencies, the amounts of time spent with increased blood flow (i.e., > 105% of upright blood flow) and decreased pressure (i.e., < 90% of upright pressure) were also described.

Group Analysis

The group analysis utilized the 30 participants from Specific Aim 1 with SCI. Research has demonstrated differences in blood flow response based on diagnosis (Bader 1990; Thorfinn, Sjoberg et al. 2002; Li, Leung et al. 2006; Thorfinn, Sjoberg et al. 2006). Therefore, it would not be appropriate to apply the biomechanical responses achieved in persons with SCI to those with other diagnoses.

Hypothesis One, that PRTs were not used with prescribed frequency, was tested by comparing the frequency of tilts past 40° to one tilt of this magnitude per hour, the same approach used in the individualized analysis.

Hypothesis Two consisted of two separate tests: the frequency of tilts that reduce pressure and the frequency of tilts that increase blood flow compared with a regular interval of every 30 minutes (i.e., 2 tilts per hour). The amount of pressure reduction considered in this test was 10%, the same as was used in the individualized analysis. To determine the pressure reduction, the models of peak (Equation 4) and mean (Equation 5) pressure created in Specific Aim 2 were applied to participants' tilt positions. The upright pressure values used in the model were the median values from Specific Aim 2: 72 mmHg for mean pressure and 89 mmHg for peak pressure. Normalized pressures (i.e., tilted pressures divided by the upright pressures of 72 and 89 mmHg) were analyzed because the hypotheses relate to percent changes in pressure relative to upright. According to both peak and mean pressure models, any tilt angle greater than 24° would reduce pressure by 10% or more, relative to pressures when sitting upright. Therefore, the tilt frequencies and percent of occupancy time with decreased pressures were identical for both the peak and mean pressures and are only presented once.

Equation 4.

$$\text{PeakPressure}_{\text{Norm(Tilted/Upright)}} = (25.6 - 0.718 * \text{Angle}) / \text{PeakPressure}_{\text{Upright}} + 0.809$$

Equation 5.

$$\text{MeanPressure}_{\text{Norm(Tilted/Upright)}} = (22.2 - 0.679 * \text{Angle}) / \text{MeanPressure}_{\text{Upright}} + 0.820$$

Unlike the calculations of decreased pressure, the model for blood flow was not used to identify tilts that increased blood flow. The blood flow model failed to explain sufficient variance, and interpretation of its application would be unclear. Instead, the minimum tilt angle found to increase blood flow (15°) was applied to test Hypothesis Two. Specifically, the frequency of tilts from less than 15° to more than 15° was compared with 2 tilts per hour. In addition to testing the tilt frequencies, the amount of time spent with increased blood flow (i.e., tilted past 15°) and decreased pressure (i.e., < 90% of upright pressure) was also described.

Statistics

The frequency of tilts past 40° was compared with one tilt per hour using a one sided, one sample Wilcoxon test. Non-parametric analysis was utilized because of the small sample size in the individualized analysis and the non-normal distributions of all tilt variables. For the second hypothesis, a one sided one sample Wilcoxon test was used to compare the frequency of tilts yielding a 10% decrease in pressure or an increase in blood flow with two tilts per hour. Finally, comparisons of tilt use across categories of tilt behavior were performed using Kruskal-Wallis tests.

Results

Individualized Analysis

As described in Specific Aim 1, use of tilt is highly varied and very individualistic. Among the ten participants, occupancy time varied from approximately 6 to 14 hours per day, with typical positions ranging from 6°-26° (Table 12, Figure 21). Most participants tilted regularly throughout the day (i.e., tilt frequencies greater than two tilts per hour). As highlighted in Figure 21, every participant in this smaller subset utilized his/her tilt features on the average day, sitting at multiple different positions daily. The subset of participants included in Specific Aim 2 was comparable to the overall population, in terms of tilt behavior and wheelchair use.

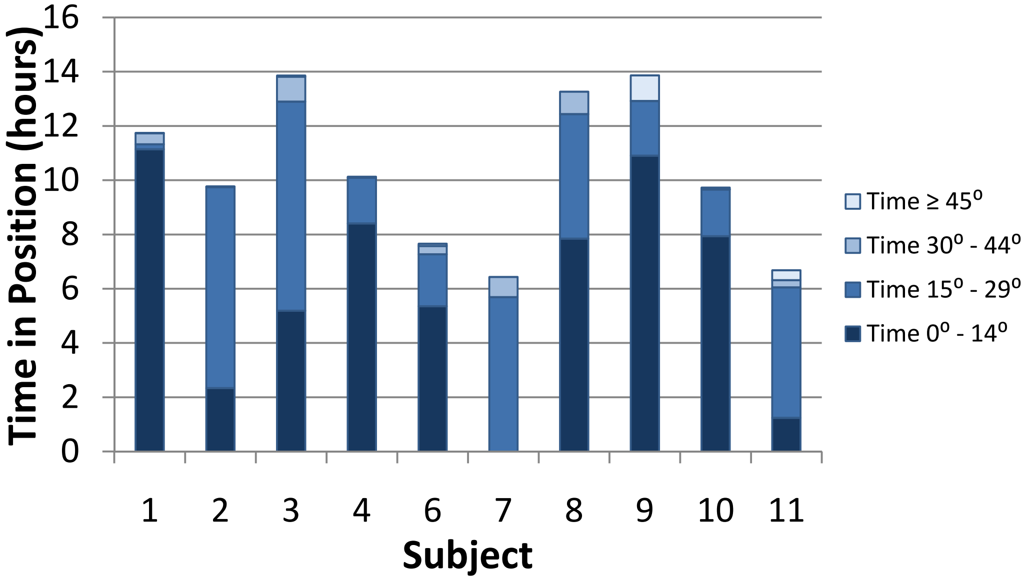

Figure 21. Breakdown of time at tilt angle for each subject from Specific Aim 2.

From Table 12, it is evident that participants did not perform PRTs with prescribed frequency. Specifically, PRTs past 40° were performed 0.3 times per hour, significantly less than once per hour (*p* = 0.007). Tilts reducing the pressure by at least 10% were performed a median (range) of 0.7 (0.0 – 3.1) times per hour for peak pressure and 0.5 (0.0 – 3.9) for mean pressure. In response to Hypothesis Two, tilt frequencies for reducing peak pressure were significantly less than twice per hour (*p* = 0.016), while tilt frequencies for reducing mean pressure were not significantly less than twice per hour (*p* = 0.063), but only 3 of 10 participants performed such tilts more than two tilts per hour (Figure 22). In terms of blood flow, participants tilted with increased blood flow a median (range) of 0.0 (0.0 – 1.0) times per hour, significantly less than two tilts per hour (*p* = 0.003).

Table 12. Median (range) of tilt use for participants from Specific Aim 2.

Subject	Occupancy Time	Typical Position	Tilt Frequency	PRT > 40° Frequency	Tilt Behavior Category
1	12.4 (7.4 – 14.7)	6.5 (5 – 11)	0.5 (0.2 – 0.9)	0.0 (0.0 – 0.1)	Uni-Modal
2	9.3 (7.2 – 12.2)	17 (14 – 18)	0.4 (0.1 – 0.8)	0.0 (0.0 – 0.1)	Uni-Modal
3	14.6 (8.4 – 17.3)	17.5 (10 – 25)	2.3 (1.4 – 3.2)	0.2 (0.1 – 0.4)	Multi-Modal
4	10.2 (9.7 – 10.5)	6 (3 – 9)	7.0 (5.4 – 9.8)	0.0 (0.0 – 0.0)	Uni-Modal
6	7.4 (5.8 – 10.3)	8 (4 – 13)	5.6 (4.3 – 8.8)	0.3 (0.2 – 0.4)	Multi-Modal
7	6.6 (5.5 – 7.4)	26 (23 – 29)	3.8 (2.6 – 4.2)	1.2 (0.9 – 1.5)	Uni-Modal
8	13.5 (11.1 – 15.1)	11 (6 – 29)	6.5 (5.7 – 12.7)	0.2 (0.1 – 0.5)	Multi-Modal
9	15.7 (6.0 – 16.1)	9 (2 – 19)	1.1 (0.6 – 1.7)	0.0 (0.0 – 0.3)	Uni-Modal
10	11.9 (2.3 - 12.9)	13 (8 – 17)	2.2 (1.7 – 2.7)	0.2 (0.1 – 0.4)	Uni-Modal
11	6.5 (5.0 – 8.1)	17 (17 – 18)	5.1 (3.9 – 6.9)	1.5 (0.6 – 2.0)	Uni-Modal

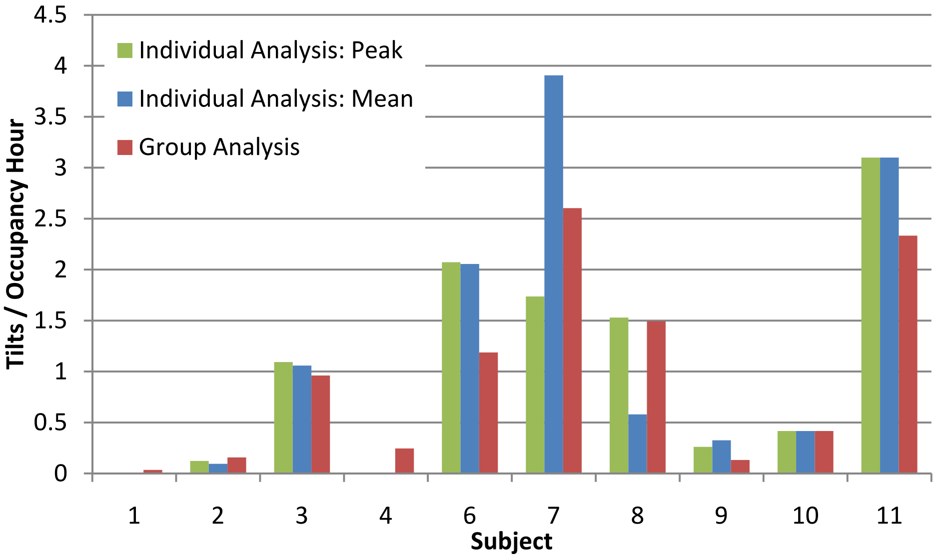

Figure 22. Tilt frequencies for tilts that decrease pressure.

It is also important to consider the time spent at positions with increased blood flow and decreased pressure by individual participants (Figure 23). Half of the participants spent more than 25% of their time at positions giving themselves more than 5% more blood flow, but fewer participants spent that much time with a pressure reduction of more than 10% from upright (Figure 23).

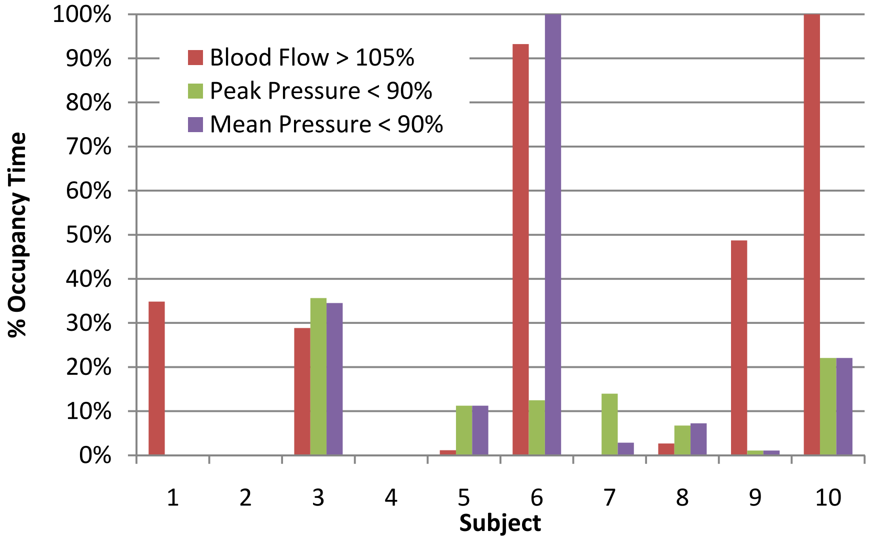

Figure 23. Percent of occupancy time spent at positions with pressure less than 90% of upright or blood flow more than 105% of upright. Values determined by analysis of individual biomechanical responses.

Group Analysis

The participants with SCI from Specific Aim 1 had varied tilt behavior, comparable to the larger population described in Specific Aim 1 (Table 13). Overall, participants' behaviors could be categorized into uni-modal (n=19) or multi-modal (n=11) types of tilt behavior.

Table 13 . Tilt behavior by participants with SCI.

Variable	Median (Range)
Occupancy Time (hours)	12.0 (6.5 – 16.4)
Typical Position (°)	9 (0 – 47)
Tilt Frequency (tilts / occupancy hour)	2.7 (0.4 – 16.6)
PRT > 40° Frequency (tilts / occupancy hour)	0.1 (0.0 – 1.5)
% Time 0°-14°	82 (0 – 99)
% Time 15°-29°	14 (0 – 92)
% Time 30° - 44°	1 (0 – 29)
% Time ≥ 45°	0 (0 – 71)

In response to Hypothesis One, the median participant tilted past 40° 0.1 times per hour, significantly less than the once per hour that is recommended ($p = 0.000$). Tilts that decreased pressure were more frequent, at a median (range) of 0.5 (0.0 – 7.6) times per hour, still significantly less than two tilts per hour ($p = 0.000$). Tilts that increased blood flow occurred at the same frequency, 0.5 (0.0 – 7.0) times per hour, also less than two tilts per hour ($p = 0.000$). Participants spent a median (range) of 7% (0% - 100%) of their time at pressures less than 90% of upright and 18% (0% - 100%) tilted to positions greater than or equal to 15°.

As with other metrics of tilt behavior, tilt use that resulted in decreased pressure and increased blood flow varied based on category of tilt behavior (Table 14). Participants in both groups (uni-modal and multi-modal), performed significantly less than one PRT past 40° per hour ($p \leq 0.002$). In terms of Hypothesis Two, although participants in the multi-modal group reduced pressure and increased blood flow more frequently than participants in the uni-modal groups, it was still typically less often than twice per hour ($p = 0.06$ and $p = 0.08$ respectively), with only three multi-modal and two uni-modal participants tilting regularly with increased blood flow and decreased pressure.

Table 14. Median tilt frequencies (per hour of occupancy) and percent time at positions with increased blood flow and decreased pressure, split by uni-modal and multi-modal behavior. P-value in response to Kruskal-Wallis testing.

	All Participants (n= 30)	Uni-modal (n=19)	Multi-Modal (n = 11)	p-value
PRT > 40° (tilts/hour)	0.1	0.1	0.1	0.846
Decreased Pressure				
Tilt Frequency (tilts/hour)	0.5	0.3	1.0	0.015
Percent Time (%)	7	0	29	0.003
Increased Blood Flow				
Tilt Frequency (tilts/hour)	0.5	0.5	1.1	0.05
Percent Time (%)	18	12	59	0.001

Discussion

On the whole, the application of biomechanical responses to actual tilt behavior suggests that participants did not use their tilt-in-space wheelchairs to perform regular pressure relieving tilts. This conclusion was independent of the details of the PRT definition (30° or 40°). Interestingly, the few participants in the uni-modal group who regularly performed pressure reliefs performed most of those tilts past 40°, while participants in the multi-modal group who performed regular PRTs tilted to positions between 30° and 40°, suggesting a different approach to PRTs. PRTs performed by participants in the multi-modal group may not have been intended as a PRT; rather, the pressure relieving benefits may have been secondary to use for another purpose.

The use of the tilt feature to achieve minimal offloading or increased blood flow was more common than PRTs, as participants achieved minimal offloading or increased blood flow every 2 hours. Even minimal biomechanical changes, however, were not performed regularly (defined as twice per hour). The group of participants with multi-modal tilt behavior performed more frequent tilts with biomechanical impact. More significant than the frequency of tilts to beneficial positions was the time spent with improved pressure and blood flow as compared with upright sitting. Participants spent 1-2 hours per day at positions with increased blood flow and decreased pressure. This suggests a considerable benefit over an upright power wheelchair.

Although the physiological benefit of small increases in blood flow and decreases in pressure is not known, it is worthy of additional research. In the meantime, it is reasonable to assume that any improvement in blood flow or pressure is just that - an improvement. Linder-Ganz, et al. (2007) demonstrated, through an MRI study, that small changes in load on the buttocks could have considerable effects on internal stresses and strains. The small tilts would also be beneficial if the small increase in blood flow experienced over 1-2 hours even slightly increased the acceptable amount of sitting time. Perhaps wheelchair users who do not remember to perform pressure reliefs could be encouraged to spend more time at positions in a small or medium tilt to reduce the necessary frequency of pressure relief.

Limitations

It is important to remember that the decrease in pressure across the entire population was determined based on median interface pressures. Because the model of pressure change with tilt was dependent on the initial pressure, participants with pressures initially lower than the median would have experienced greater benefit than participants with pressures initially higher than the median, although this is not reflected in the data.

The accuracy of the pressure model is illustrated in Figure 22. Of course, these data are only available for the participants from whom the model was defined. Still, it is reassuring to see that when applying the model based on average upright pressures, the results are comparable to those from the individualized analysis.

CHAPTER V

CONCLUSIONS

The overall goal of this research was to improve the use of seated tilt to increase function, health and quality of life for people using power wheelchairs. Specifically, the objective of this project was to evaluate the biomechanical responses to seated full body tilt and their relationships to the actual use of tilt-in-space wheelchairs.

For this project, researchers remotely monitored how people used their tilt-in-space systems and also evaluated the biomechanical responses to tilt in a laboratory setting. A descriptive analysis of the remote monitoring included participants' typical sitting positions, the magnitude and frequency of tilt maneuvers performed throughout the day, and the time spent at different tilt angles. In the laboratory, interface pressure measurement and laser Doppler flowmetry were used to study changes in localized loading and superficial blood flow at the ischial tuberosities across different amounts of tilt. Finally, tilt use was analyzed based on the outcomes of the laboratory testing.

To accomplish the goal of improving the use of seated tilt to increase function, health and quality of life requires several steps. First, the potential impacts of tilt-in-space seating systems and the mechanisms by which they occur must be understood. Second, the benefits people did and did not receive from their TIS wheelchairs should be evaluated. Finally, the application of this knowledge to improve function, health and quality of life for people using power wheelchairs can be addressed.

Rearward tilt systems maintain a constant seat-to-back angle while both the seat and back rotate. Load on the buttocks is reduced by transferring greater load to the backrest. This change in load translates to a number of changes on the surface of the buttocks and internally within the soft tissues of the buttocks. At a full tilt (45°-60°), there is a 30-50% reduction in peak and mean interface pressure at the ischial tuberosities, a small posterior displacement in the center of pressure, and a significant increase in blood flow compared with upright. There may also be a small shift in the pelvic angle and a change to the strain on the soft tissue. At a large or extreme tilt, shear forces work to keep the person in the chair, and the vertical distance between the heart and the buttocks is reduced. The large or extreme tilt position is typically accompanied by reduced visibility due to the change in line of sight and a feeling of unease often due to fear, a sensation of instability, or the lack of mobility (given the inability to drive the wheelchair from this position).

Small changes in tilt position from upright had a different impact than large or extreme tilts. Blood flow increased but pressure did not decrease during a 15° tilt from upright. Small tilts may decrease global shear forces, resulting in increased stability. In contrast, small changes in tilt position starting from a small tilt (i.e. 15°) reduced interface pressure but did not result in a further increase in blood flow. According to the work of Hobson (1992), shear forces are minimized at 25°, meaning shear forces might play a smaller role across position changes within the 15° to 30° range.

According to the results of the tilt monitoring study, participants benefited from having a tilt feature. Participants achieved at least occasional increases in blood flow and decreases in pressure. Participants also experienced long durations with increased blood flow (2.2 hours per day) and decreased pressure (51 minutes) compared with upright. It is possible that participants also experienced changes in internal compression and shear strain due to the displaced center of pressure, reduced interface pressure and slight pelvic shift. Participants regularly benefited from sitting at a small tilted position with reduced global shear, potentially resulting in improved posture and stability. Posture may also have been improved for many participants through the single large tilt they performed following transfers. It is often easier for caregivers to position their clients with the wheelchair positioned in a large tilt. Having a better seated posture has functional and medical implications as it is associated with improved pressure distributions, greater reach (Sprigle, Wootten et al. 2003) and an improved ability to perform mobility related activities of daily living. The ability to sit at multiple positions throughout the day helped the subjects in this study to participate in multiple activities, each activity benefiting from a different position. Self-reported purposes of use suggested a few typical examples of how the tilt might have been used in different activities: participants might have tilted back a small amount for eating, to keep objects better balanced on their lap tray during use, or for improved reach and stability. They might have tilted farther to assist in transferring and positioning, or to control dizziness or swelling. Participants might have switched to a more upright posture to sit at a desk or table or to enter or drive a vehicle. Because some of these activities only occur intermittently throughout the day, they are not well reflected by the tilt frequency. In fact, many participants with lower tilt frequencies reported these uses of their tilt feature. Finally, participants achieved greater comfort as a result of their tilt feature. Whether they accomplished this by dramatically changing their position occasionally (i.e., a large tilt) or by sitting dynamically throughout the day, most participants enjoyed the ability to respond to discomfort and proactively achieve comfort more comparably to their able-bodied experience.

Some potential benefits of TIS were not achieved by participants in this study. Participants did not experience regular, large decreases in pressure or increases in blood flow. This was both a result of limited efficacy of the tilt feature at reducing pressure in a full tilt and of participants' limited use of large and extreme tilts.

The use and disuse of tilt-in-space has implications for clinical practice, policy, and design. In terms of clinical practice, the use and disuse of TIS may influence the prescription process, delivery of the wheelchair, and follow-up care. When a tilt-in-space system seems appropriate for a client, it is worth addressing the client's concerns and factors that might limit its use (e.g., transportation, environment, and comfort in a tilted position). When selecting a seating system for that client, the differences in maximum tilt position lauded by the manufacturers may not be an important selection criterion. That is because currently it can be assumed that few participants will regularly utilize the maximum range of the wheelchair, regardless of whether it can tilt to 45° or 55°. For some clients, clinicians might want to consider alternative approaches to pressure relief such as combined tilt-recline systems or standing wheelchairs. Although blood flow has not been evaluated in either of these variable position seating system, both are effective at unloading the buttocks. Standing wheelchairs have the additional benefit that they provide a more functional and potentially more stable terminal position, addressing some of the concerns raised by participants about TIS. Standing also provides greater load reduction at intermediate positions (Sprigle, Maurer et al. in press). Finally, clinicians might want to consider prescribing TIS for clients who would not have traditionally received a tilt feature. For example, a client might not need the pressure relieving benefits of tilt, but may be able to take advantage of the various functional, postural and comfort benefits. Of course, funding would dictate the feasibility of this prescription.

Following prescription, wheelchair delivery and client training may be affected by the results of this study. Although delivery practices vary across clinics, there may be value in requiring a clinician to be present when the product is delivered, or providing a follow-up appointment after delivery. Pressure relief compliance should also be addressed with thorough training and education. Initial training should include tilting through the range of small, medium and large tilts with a clinician present to instill comfort and confidence in clients with regards to performing tilts. Pressure mapping the participant while they tilt might provide helpful biofeedback regarding how far to tilt, although this can be time consuming and the benefit has not yet been tested. Further training efforts might be put towards teaching clients the additional benefits of their tilt feature. Demonstrating how tilting might help in transfer or postural adjustments, reach, wheeling on a ramp or on rough terrain might give the client new opportunities for greater participation. The clinician might also suggest dynamic use of the wheelchair to simulate how able-bodied persons sit throughout the day, in an effort to provide improved comfort. Finally, follow-up is exceedingly important. Speaking with clients to make sure the system still works for them after delivery, including asking about reasons of disuse could be very informative and allow simple problems to be addressed. Additionally, follow-up training based on evaluation of tilt behavior might allow for more appropriate training goals and approaches. For example, participants using the wheelchair with minimal tilt use or other uni-modal behavior (and not regular PRTs) may need to learn and experience the variety of benefits of the tilt feature and be educated on pressure reliefs. It would help for the clinician to identify and address their reasons for disuse of the feature. In contrast, participants using multi-modal behavior without frequent PRTs are well aware of their feature's capabilities but may need more targeted pressure relief training and education.

The policy and design implications of the results are also significant and highly related. First, participants spent more than 12 hours per day in their wheelchair, more than most task seating. Across twelve hours, the wheelchair serves many functions, both medical and non-medical, and ideally the varied functions should be reflected in the design and funding. There are some potential medical benefits of improving posture and providing the ability for dynamic sitting, including reduced pressure ulcer incidence and decreased pain. Outcomes studies would help to evaluate the medical benefits and the cost effectiveness of providing a tilt system, but such studies are very difficult to perform. In addition to considering the duration of sitting in the design, designers should consider the main reasons for disuse, the lack of stability and non-functional position in a full tilt, in future designs. Finally, there may be benefit to adding a more limited, less expensive tilt feature (0-15° or 5-20°) on upright power wheelchairs, as it might provide improved function and quality of life for users who do not qualify for a tilt-in-space wheelchair.

In conclusion, this dissertation evaluated the biomechanical responses to seated full body tilt and their relationships to the actual use of tilt-in-space wheelchairs. From the results, a number of research studies, clinical interventions and design changes are implicated that might help to accomplish the overall goal of improved function, health and quality of life for people using power wheelchairs.

APPENDIX A: TILT MONITORING SURVEY

Mounting date: ___________ Dismount date: ___________

Mounting time: ___________ Dismount time: ___________

Wheelchair

Wheelchair Make and Model: ___________________________________

Cushion Make and Model: _____________________________________

Wheelchair Features:

- ☐ Tilt
- ☐ Elevate
- ☐ Elevating Leg Rest
- ☐ Other
- ☐ Recline
- ☐ Stand

Tilt Range

Minimum Tilt Position
Seat Angle (to horizontal) _____________
Back Angle (to horizontal) _____________
Seat to Back Angle _______________________

Maximum Tilt Position
Seat Angle (to horizontal) _____________
Back Angle (to horizontal) _____________

Any comments about mounting, subject, etc.

____

____

Demographics & Other Personal Information

Demographics

DATE OF BIRTH: __________________

GENDER: Male Female

HEIGHT _________________ **WEIGHT** __________________

HIGHEST LEVEL OF EDUCATION COMPLETED:

(Select single best option)

☐ Some or No high school

☐ High school diploma or GED

☐ Associates degree

☐ Bachelor’s degree

☐ Graduate degree

☐ Other (*please specify*):

____

CURRENT OCCUPATION: (*Select single best option*)

☐ Paid employment

☐ Non-paid work, such as volunteer/charity

☐ Student

☐ Keeping House/ Home Maker

☐ Retired

☐ Unemployed (health reasons)

☐ Unemployed (other reasons)

☐ Other (*please specify*) ______________________________

RACE OR ETHNICITY: *(You may select more than one option)*

☐ Asian American

☐ American Indian / Alaskan Native

☐ Black / African American

☐ Native Hawaiian / Other Pacific Islander

☐ White

☐ Hispanic or Latino

☐ Other (*please specify*):

____

LIVING SITUATION: *(You may select more than one option)*

☐ Lives alone

☐ Spouse

☐ Other Family

☐ Friend

☐ Caregiver support

☐ Other *(please specify)*:____

Disability-Specific

- Diagnosis: ____

  If SCI: Level of Injury ______________________________

  ☐ Complete ☐ Incomplete

- Years using a wheelchair: ___________
- Years using a tilt in space wheelchair: __________
- Years using current tilt in space wheelchair: _________
- Do you have any sensation below the waist?

  ☐ Yes ☐ No

  If Yes, Can you feel your buttocks? ☐ Yes ☐ No

  ☐ Light touch

  ☐ Deep pressure

  ☐ Pain

- Do you have any controlled movement below the waist?

  ☐ Yes ☐ No

  If Yes, How much? ___________________________

  ☐ Can you march your legs up and down in sitting

  ☐ can you kick your foot out

  ☐ can you squeeze your buttocks?

- Do you experience spasticity?

☐ Yes ☐ No

__Functional status__

TRANSFERS: *(Select single best option)*

☐ Independent

☐ Independent with sliding board

☐ Sliding board with assist

☐ Mechanical lift

☐ Person assist

__Skin History__

- Before you began using your first tilt-in-space wheelchair, did you have any pressure ulcers?

☐ Yes ☐ No

If Yes, in what locations ___________________________

If Yes, how frequently (per location) ___________________________

- Since you started using a chair with power tilt, have you had any pressure ulcers?

☐ Yes ☐ No

If Yes, in what locations ___________________________

If Yes, how frequently (per location)___________________________

- Do you currently have any pressure sores?

☐ Yes ☐ No

If Yes, in what locations ___________________________

__Pressure Relief Knowledge__

- How far are you supposed to tilt for a pressure relief? _________
- Have subject demonstrate a pressure relief and measure angle: _________
- Has subject ever had a pressure ulcer scare (situation where they or someone they know was seriously inconvenienced / quality of life affected by a pressure sore)?

☐ Yes ☐ No

__Tilt system__

- Where were you prescribed your tilt system?

☐ Shepherd

☐ Other: ________________________

- Was tilt prescribed because of a problem with pressure ulcers?

  ☐ Yes ☐ No

  If No, Why was it prescribed? _______________

- Who was present when you received tilt (current chair)? *(check all that apply)*

  ☐ Therapist

  ☐ Supplier / vendor

  ☐ family member

  ☐ care giver

  ☐ other ______________________

- Did you receive any training about how to use your tilt system?

  ☐ Yes ☐ No

<u>Tilt System Use</u>

- For which of the following purposes do you use your tilt system? (Follow up with asking them to demonstrate tilt. Measure angle)

  ☐ comfort/discomfort/pain (Angle: ________)

  ☐ rest/relaxation (Angle: ________)

  ☐ posture (Angle: ________)

  ☐ functional independence (Angle: ________)

  ☐ pressure reliefs / weight shifts (Angle: ________)

  ☐ physiological functions other than pressure relief (e.g. bowel and bladder, spasticity, etc) (Angle: ________)

  ☐ other: ________________________ (Angle: ________)

<u>Wheelchair use</u>

- In a typical day, for what activities do you get out of the chair?

  ☐ to sit in a different chair (i.e. couch/recliner)

  ☐ Bowel and bladder routines

  ☐ Vehicle travel,

  ☐ To use other wheelchairs

  ☐ Ambulation.

  ☐ Sleep

  ☐ Shower

☐ Other: ___________________

- About how long do you sit in your chair each day: ____________________
- How often do you tilt to perform pressure reliefs? _______________
- How long do you stay tilted when tilting for pressure reliefs? ________________
- Do you perform pressure reliefs in other ways besides tilting?

  ☐ Yes ☐ No

  If Yes, How?

  ____

- Do you move/squirm in your chair without tilting (if yes, measure pressures under trochanter)?

  ☐ Yes ☐ No

- If you are uncomfortable in your chair, what can you do to fix it?

  ____

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VITA

Sharon Eve Sonenblum earned a Bachelor of Science in mechanical engineering from Brown University, during which time she pursued research into the impact properties of coconut coir and the biomechanics of the wrist with Dr. Joseph "Trey" Cisco, III. She continued her research in wrist biomechanics, specifically the scaphotrapezio-trapezoidal joint, to earn a Master of Science in Bioengineering at Brown. Ready for a change in focus and climate, Sharon moved south to Atlanta, Georgia after graduation so she could begin work as a research engineer in the laboratory of Dr. Stephen Sprigle. After two years of research on detecting erythema, analyzing wheelchair transfers, and monitoring activity and participation, Sharon succumbed to the itch to return to school. With the goals of training under Dr. Sprigle, increasing her medical and physiological background, learning to lead her own research and preparing to teach, she started a PhD program in Bioengineering at the Georgia Institute of Technology. Sharon was the recipient of an NSF Graduate Research Fellowship and a Georgia Tech Presidential Fellowship. During her time at Georgia Tech, she was a member and chair of the Bioengineering Graduate Student Advisory Committee and was heavily involved with graduate student recruiting and orientation. Conducting clinical research, Sharon discovered that she enjoyed spending time in the clinic and working with research participants as much as she enjoyed data analysis. Four years later, she has finished a dissertation on the biomechanical responses to full body tilt and their relationship to clinical application. Sharon looks forward to a career of conducting clinical research and educating students.