BIOMECHANICS OF SEATING: BODY POSTURE, LOADING AND FRICTION IN OFFICE AND WHEELCHAIR SETTINGS

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ABSTRACT

Sitting for long periods of time has health implications; two populations affected by long durations of the seated position include office workers and wheelchair users. In office workers, poor posture combined with long hours of sedentary periods can lead to cardio-vascular diseases, musculoskeletal disorders, and other health issues. The use of a standing desk is an alternative that can break up those sedentary periods. But workers find it difficult to use standing desks regularly, one of the reasons being the pain associated with standing. Thus, there is a need for developing an alternative working position which provides an opportunity for postural change. Similar to office workers, wheelchair users are also prone to various health issues including pressure injuries (PIs), which put considerable financial and physical burdens on the user. One of the factors that increases the risk of PI formation is shear loading and associated frictional forces. Thus, there is a need to study how the choice of fabrics used for the seat pan cover and pants worn by wheelchair users affect the frictional properties and shear forces at the seat interface.

The objectives of this work were: 1) to evaluate changes in body position, body loading, and blood perfusion while in a seated, standing, and new office seating position, termed the in-between position. 2) determine the coefficients of friction of seven commonly worn pant fabrics and two seat cover fabrics using a mechanical device and a tilting seat pan 3) to determine the shear force and coefficients of friction between five commonly worn pant fabrics and two seat cover fabrics through the development and utilization of a novel *in-vivo* experimental set up that permitted sliding of the human buttocks on the seat pan.

To achieve the first objective, positions of anatomical landmarks, ground reaction forces, and blood perfusion data were obtained and analyzed during three different working positions: seated in a chair, standing, and a new 'in-between' position. Data showed that the in-between

position provided a hip and lumbar position closer to standing than the seated position. Additionally, it provided less loading on the legs in comparison to standing. There were no significant differences in anterior/posterior ground reaction forces between seated and the in-between positions. Additionally, blood perfusion increased during dynamic transitions between positions indicating changes in blood flow.

To achieve the second objective, a mechanical device with the pant fabrics attached was placed on top of a seat pan. The system was tilted until the device started sliding on the seat pan. Positional data during the sliding was captured using the motion capture system and was used to calculate the coefficient of friction. The office fabric seat cover produced smaller coefficients of friction than the vinyl seat cover for all the pant fabrics. Women’s khakis demonstrated one of the smallest coefficients of friction, and denim demonstrated one of the largest coefficients of friction with both seats covers.

To achieve the third objective, individuals were asked to sit on a wheelchair-like seat while wearing the pant fabric to be tested. A linear actuator pulled them towards the front of the seat pan, so they were sliding across it, while the forces on the seat pan and the actuator were recorded by load cells. The ratio of these forces was used to calculate the coefficient of friction. The vinyl cover exhibited higher coefficients of static friction in this study as it did with the mechanical system.

Overall, this body of work provide a knowledge basis that will be useful in design of better office workspace and develop strategies that can reduce the risk of PI formation in wheelchair users.

This dissertation is dedicated to my family.

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INTRODUCTION

Most of the people spend the majority of their time seated, both in the US and worldwide [1], [2]. During the majority of their working hours, office workers are often sedentary. Lack of physical activity and poor posture in these sedentary periods can lead to cardio-vascular diseases, musculoskeletal disorders, and other health issues [3]–[6]. Research has shown that the total seated time can be reduced and broken up by using a sit-to-stand desk to promote movement during office work [7]–[9]. However, there have been challenges in obtaining these benefits from sit-to-stand desks. These challenges were the result of individuals who experienced significant pain when standing as well as the decreased willingness of the workers to use the sit-to-stand desk after the novelty wore off [10]–[12]. Thus, there is a need for developing an alternative working position, different from standing, in order to promote movement in office workers.

Similar to office workers, long periods of sitting has health implications on wheelchair users as well. One of the notable health issues in wheelchair users is Pressure injuries (PIs), which are very costly and debilitating [13]–[15]. PIs have been documented as major concerns for wheelchair users and are prevalent in the tissues surrounding the ischial tuberosities, which are constantly compressed between the bony landmark and the wheelchair surface [16], [17]. Various factors such as increased pressure, increased shear force and decreased blood perfusion have been linked to PI formation [18], [19]. As such, researchers have studied the effects of wheelchair articulations and cushion design on these factors with an aim to understand PI prevention strategies for wheelchair users [20], [21]. Shear forces, those parallel to the skin have also been shown to play a role in tissue loading. Of the factors mentioned, there is a dearth of research on shear loading, particularly how the choice of fabrics used for the seat pan cover and pants of wheelchair users affect the frictional properties and shear forces in the seat interface. Thus, there is a need to study these factors.

To address these issues, this research aimed to understand the posture, loading and friction in the seat environment in context of both office chairs and wheelchairs. This was done by achieving three goals, addressed in chapters 2, 3 and 4, which are each written in the form of a publication. Chapter 2 has been published. Chapters 3 has been submitted and is awaiting review. Because each chapter is written as a standalone journal article, the motivations of the work, including the statistics, risk factors and prevention strategies are stated within each chapter.

Chapter 1 consists of a literature review that discusses the statistics and health problems associated to prolonged sitting in office and wheelchair seating, the strategies used to study and prevent these health implications, and knowledge gaps that must be addressed to further our understanding of these health implications and prevention strategies.

Chapter 2 describes a study conducted to better understand postures and loading in an office environment in three different working positions. The positions were seated in a chair, standing, and a new 'in-between' position which raised and tilted the seat pan forward, while keeping the knees flexed and feet flat on the floor. The goals of this study were to determine the joint angles, pelvic orientation, ground reaction forces, blood perfusion in lower legs and joint moments and compare them across positions.

Chapter 3 describes a study to determine the coefficients of friction between seven common pant fabrics and two materials commonly used in seat covers. The coefficients of friction were determined using a mechanical device and a tilting seat pan. This study also investigated the effects of a deformable foam cushion on the coefficient of friction between fabrics.

Chapter 4 describes a study to determine the shear force and coefficients of friction between five commonly worn pant fabrics and two seat cover fabrics through the development and utilization of a novel *in-vivo* experimental set up that permitted sliding of the human buttocks on the seat pan.

A synopsis of the impact of this work is presented in the **Conclusions**.

CHAPTER 1: A REVIEW OF THE STATISTICS, BODY POSITION AND LOADING CONDITIONS IN OFFICE AND WHEELCHAIR SEATING

1.1 Seating

It has been shown that people in the US and globally spend the majority of their day in a seated position [1], [2] . Office seating and wheelchair seating are two areas that involve prolonged sitting. Studies have shown that people who work in an office environment spend a majority of their day seated in an office chair [2]. Similarly, people who have disabilities in their lower extremities typically spend most of their day in a wheelchair [22]. This prolonged time spent sitting has health implications in both contexts, especially with regards to the soft tissues. Specifically, tissues such as those in buttocks and thighs are loaded for long durations. Thus, it is important to study the loading of the tissues during sitting to understand and mitigate health risks.

1.1.1 Office Seating

Offices are settings where workers often spend long durations in seated postures. The overall US workforce spent 39% of their workday seated in 2016, and people in some occupations such as accounting and auditing spent up to 90% of their workday seated [2]. The percentage of sedentary and light physical activity jobs increased steadily from 1960 to 2010, whereas the percentage of jobs requiring moderate physical activity declined from 48% to 20%, and this trend was projected to continue into the future [23]. This means that the US population increasingly spends a large portion of their days seated, often in an office chair. Furthermore, the number of workers who remain seated, as well as the duration of time spent seated, will only continue to rise. Thus, it is important to understand the health implications of prolonged sitting during office work.

Physical inactivity due to prolonged sitting has been linked to various health issues, including cardio-vascular diseases and musculoskeletal disorders in the back, neck, elbow and wrist [3]–[6]. These health issues have been linked to seated duration and poor posture, often associated with sitting. During prolonged sitting, spinal flexion (lumbar kyphosis), which was a deviation from natural or neutral spine posture, was maintained in a majority of cases [24]. This was opposed to the natural or neutral spine posture, also known as lumbar lordosis [24]. Research has shown that deviation from the neutral position increased stress on ligaments and tendons and that sustained stress, for even 20 minutes, increased ligament laxity [25]. In turn, increased laxity has been reported to lead to various issues, including lower back pain [25]–[27]. Sitting postures in general were also shown to exert higher pressures in the intervertebral discs than standing or lying [28], [29]. This was problematic because sustained pressure led to intervertebral disc degeneration, causing significant pain in the lower back and neck areas [3], [30]–[32]. Extended periods in the seated posture have also been linked to reduced blood flow and blood pooling in the legs which has been shown to lead to edema, varicose veins, and leg cramps [33]. The health issues caused by sitting for long periods of time not only caused physical pain and discomfort, but they contributed significantly to the cost of healthcare. The yearly health care expenditure related to sedentary lifestyle in 2000 was $76 billion in USA, $2 billion in Canada, and $377 million in Australia. [34]. Since the number of people working in sedentary jobs has increased steadily in the past and is projected to increase into the future, the cost of healthcare expenditure related to sedentary lifestyle is likely to increase even further [23]. Based on this information, there is a strong need to develop strategies to mitigate these health risks in office workers.

1.1.2 Wheelchair seating

Wheelchair seating is another category that has affected large numbers of people and has been shown to have a profound impact on health. In 2010, there were 3.7 million wheelchair users in the USA and 264,000 in Canada. The World Health Organization estimated that 1% of the global population required wheelchairs for increased mobility [22], [35]–[37]. Similar to office workers, health issues associated with prolonged sitting have been a concern because wheelchair users spend long periods of time seated in a single posture. They are at risk of developing various health issues such as obesity, hypertension, cardiac issues, osteoporosis, and pressure injuries (PIs) [15]. Among the health issues, PIs have been reported as a major concern. PIs occur when the soft tissue around the bony prominences are damaged due to prolonged loading, particularly in the tissue over the sacrum, greater trochanters, and in the buttocks (Figure 1) [19], [38]–[43]. The regions over the ischial tuberosities (ITs) have been known to be particularly problematic because the soft tissue in these areas get compressed between the bony prominences and supporting surface of wheelchairs for long duration of time [16], [44].

PIs put significant physical and financial burdens on the patients. Approximately 2.5 million people develop PIs in the US each year, 59% of which experienced significant pain [45], [46]. Further, reports have shown PIs cause infections, sepsis, and potentially death [13], [14]. The mortality rate in patients with sepsis as a result of PI was 55% in one study [13]. In addition to these health implications, PIs have also affected quality of life by restricting patients from performing activities of daily living, causing them to miss work, and increasing stress, anxiety, and the feeling of being a burden on others [18]. Treatment of a single pressure injury costs an average of $37,000, with costs as high as $150,000 in the US [45], [47]. Further, the annual cost for treatment of PIs in the United States was reported at $17.2 billion in 2003 [42], [45], [48]. Because of the issues patients faced, including the physical, psychological, and financial costs, a better understanding of risk factors associated with PIs, and strategies to mitigate them, is necessary.

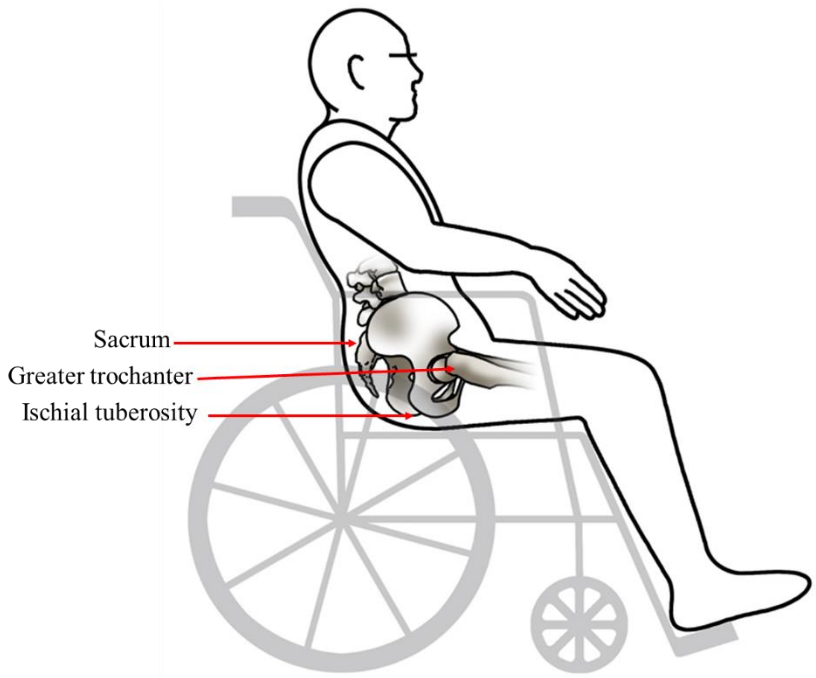

Figure 1. Illustration of anatomical landmarks where PIs commonly occur in wheelchair users

1.2 Joint Posture and Reaction Force

In this section, the effects of various body postures in office and wheelchair settings on the forces on the body, interface pressures, and blood perfusion are discussed. Joint angles have been used to assess posture, and external reaction forces have been used to evaluate the impact of those postures. Apart from the reaction forces, pressure, and joint moments have also been used to assess the body loading. Pressure is the normal force acting per unit area, and a moment is the force acting at a distance, which results in the rotatory effect of force. Posture and chair configurations in both office chairs and wheelchairs affect spinal loads, pressure distributions at the seat interface, and blood perfusion in the lower limb. Friction on the fabric cushion or chair covers has also been known to affect the shear force on the seat pan and are linked to blood flow and PI development.

1.2.1 Office Seating

1.2.1.1 Spinal Load

Research has shown that spinal load is an important parameter in seating, as it can lead to injuries and pain in the back. Posture has been shown to affect the load in the spine, especially in the intervertebral discs. Ergonomic standards provided guidelines to maintain proper posture in the workplace, which reduced spinal load by promoting neutral and relaxed body postures [49], [50]. These guidelines included a lordotic instead of a kyphotic lumbar posture (Figure 2). Similarly, neutral joint angles close to 90 degrees in the ankles, knees, and hips and 180 degrees in the neck were suggested to avoid over-flexed and over-extended joints. Research has shown that compressive loads on the lumbar intervertebral discs were relatively low in an ergonomic standing posture, larger in an ergonomic sitting posture, and even larger when people did not maintain a proper seated posture [51]. This work underscored the importance of maintaining proper posture. In particular, slouching, or crossing the legs has been shown to produce larger spinal loads in the lumbar region [51]. This is important because research showed that people commonly assumed a slouching position after 20 minutes of sitting [52]. Moreover, a study on people with a health condition such as chronic low back pain showed that they assumed more asymmetrical postures (like leaning to one side) than healthy people, which put them at additional risk of developing or worsening a back injury [52]. Hence, it is important to promote neutral body positions such as lumbar lordosis and promote ergonomic joint angles during office work to avoid larger loads, particularly in the hips, knees and back.

Figure 2. Lordotic or upright lumbar posture (left) and kyphotic or slouched lumbar posture (right)

1.2.1.2 Effects of Body Posture

Body posture and chair design have effects on lumbar lordosis and spinal loading. Larger trunk-to-thigh angles (angle between torso and thigh) have been associated with increased lumbar lordosis, while smaller knee flexion angles have been correlated with reductions in lumbar lordosis [53]. Crossing the legs while sitting was another movement associated with decreased lumbar lordosis and posterior pelvic tilt [54]. Various studies were conducted with forward tilting of the seat pan (tilting the seat pan in sagittal plane such that the anterior part of seat pan is inferior to the posterior part), with mixed results on lumbar lordosis. The general consensus of two studies was that the forward seat pan tilt increased the lumbar lordosis [55], [56]. However, there have been studies which did not find significant differences in lumbar lordosis with tilting of a seat pan [24], [57]. A computational study showed that forward seat pan tilt of 10 degrees reduced pressure in the lumbar discs, but a larger forward tilt diminished the ability of the body to use the backrest and increased the pressure in the lumbar discs, suggesting that the ability to use the backrest was important for decreased spinal loads [58]. A consistent theme across research, related to the seated posture is the promotion of lumbar lordosis.

1.2.1.3 Pressure at the Seat interface

Seated pressures in the office setting have been studied by many researchers. Pressure at the seat interface contributes to tissue loading in the buttocks and around sacrum. Typically, pressures were the highest around the buttocks and sacrum while seated in an office chair [59].

However, sitting posture and chair design were shown to significantly affect pressure distribution at the seat interface [60]–[62]. Back recline angle, head position, seat height, and even chair fabric have also been reported to affect loading [58], [62]. Some studies found that mean and peak pressures at the buttocks-seat interface decreased with increasing backrest recline [61]. Turning the head 90 degrees to the left side was shown to increase maximum pressure on the right side by 60% as compared to the left side [60]. Similarly, a lower seat height resulted in larger pressure under IT, whereas a higher seat height transferred the pressure towards thighs. In a study where 12 commercially available chairs were tested for seat interface pressure, the only consistent chair design parameter among chairs which had either smaller seat interface pressures or higher seat interface pressures was the type of fabric covering the seat [61]. The chairs with woven fabric or tensile mesh had higher seated pressure values whereas chairs with knitted fabrics had smaller values. In another study, seat interface pressure was measured in a chair with a longitudinally split seat pan, which was designed to move so as to provide alternating ankle plantar/dorsiflexion (medial/lateral tilt of both left and right sides) and alternating hip flexion/extension (anterior/posterior tilt) [62]. The peak pressures at the seat interface were higher in the chair with this split seat design compared to a regular office chair. Just as with spinal loading, the common finding was that seated posture had a significant effect on the seat interface pressure across numerous postures and chair designs. Thus, it is important to study the seat interface pressure of any posture suggested for use in the office environment and to understand to effects of the seat fabric.

1.2.1.4 Blood Perfusion

Blood perfusion is another factor associated with tissue health, and thus it has been studied in relation to office seating. It is important to study blood perfusion in regions such as the buttocks and lower legs. Prolonged sitting in the office has been shown to cause blood pooling and swelling in the lower legs [33], [63]. Specifically, research has shown that tissue perfusion is lower around the IT when compared to other regions of the buttocks and thighs while seated in an office chair, regardless of the material or fabric used in the seat [59]. This might affect tissue health in workers who spend extended durations in the seated posture. Sitting for six hours reduced the arterial blood flow in the lower legs, which was improved with 10 minutes of walking [64]. Interrupting prolonged sitting during office work with intermittent standing was shown to reduce the blood pressure and mean arterial pressure over the workday [65]. While researchers agree that both prolonged sitting and standing increased the blood pooling in the lower legs, there has been no consensus on which body position leads to more blood pooling [66], [67]. Moving reduced blood pooling, compared to the static seated and standing postures [65]. All these studies indicated that sitting for long periods of time was detrimental to the overall vascular health as well as the blood flow in the legs, and it is essential to address these issues in office workers who spend a majority of their day seated.

1.2.1.5 Standing Postures in Office Settings

Use of a sit-to-stand desk has been shown to break up and reduce the time spent seated during office work [7]–[9]. Changing body posture, such as changing position from seated to standing, also increased the blood flow in the lower legs [68]. Similarly, using standing postures frequently to take a break from sitting also reduced fatigue and musculoskeletal disorders in office workers [69]. Unfortunately, keeping workers motivated to use the height adjustable desk has been a challenge because once the novelty of the height adjustable desk wore off, the use of the sit-to-stand desk diminished [10]–[12]. High levels of pain associated with standing may also contribute to the lack of use of sit-to-stand desks [10]–[12]. Because muscles and joints are subjected to larger loads during standing, standing has been reported to result in fatigue, lower back pain, discomfort in the neck, and shoulder, and musculoskeletal disorders [70]–[78]. Moreover, as previously mentioned, prolonged standing has led to blood pooling and swelling in the lower legs [10], [68], [72], [76], [79]–[82]. Therefore, a prolonged standing posture is not a solution for the medical issues that are associated with prolonged sitting.

1.2.1.6 Joint Moments

The rotational forces at the joints of the body also need to be understood. They are especially important when considering the movement of rising from a seated position. The moments on the lower extremity joints play a large role when movement occurs from seated to standing positions. Sit-to-stand movements from a chair exert large moments on the knee and hip joints [83]. Due to these large moments, sit-to-stand tasks might be difficult for people with injuries or disorders in the knee and hip joints. One way to mitigate such difficulties has been through the use of arm supports, which reduced the moments on the knee and hip joints during sit-to-stand, as some of the forces were transmitted through the armrest [84], [85]. Increasing the seat height of a chair was also shown to decrease the knee and hip moments [83], [85], [86]. Ways to reduce the moments on the hips and knees are key to reducing pain in workers with hip and knee issues.

1.2.2 Wheelchair Seating

Much like office seating, it is important to understand the effects of body positioning and chair design on parameters such as reaction forces and blood perfusion in wheelchair seating. Prolonged sitting in wheelchairs has been linked to PIs in the soft tissues, especially in the IT region [19], [43]. Various studies have been conducted to investigate strategies to counteract and prevent PIs in wheelchair users. These studies assessed the effects of wheelchair articulation and cushion design on the risk associated with PIs in the buttocks and thigh areas [87]–[90]. Wheelchair articulations that changed posture, such as back recline and tilt-in-space (Figure 3), were studied because they have been the most common strategies used to change the pressure distribution and improve blood flow in the buttocks [87]. In addition, specialized cushions and seat covers have commonly been used to prevent PIs by reducing the shear forces on the buttocks [48], [75], [91]–[95]. Studies showed that reductions in blood perfusion, large interface pressures, and large shear/friction forces were risk factors for PIs [18], [96], [97].

1.2.2.1 Blood Perfusion

Tissue ischemia, or decreased blood flow, has been noted as one of the leading factors responsible for PIs [98], [99]. Normal and shear forces acting externally on tissue result in internal tissue stresses, which lead to local tissue ischemia [100], [101]. Because of the prevalence of PIs around the IT region and the use of seated repositioning to prevent them in that area, it is important to understand the effects of body positioning on the blood flow around the IT region [43], [45]. Increasing tilt-in-space and back recline angles have been shown to increase the blood flow in the IT region when the angles were sufficiently large [102]. However, wheelchair users who used tilt-in-space spent a majority of the time at tilt angles less than 15 degrees, which were not sufficient to produce an increase in blood flow [103]–[105]. Additionally, larger tilt-in-space and recline angles were needed to improve the blood perfusion in the muscles compared to the blood perfusion in the skin, meaning that the recline and tilt-in-space may have less of a protective effect on the tissue layers deep to the skin [106]. Thus, there are limitations in using seated repositioning to increase blood flow to the IT region.

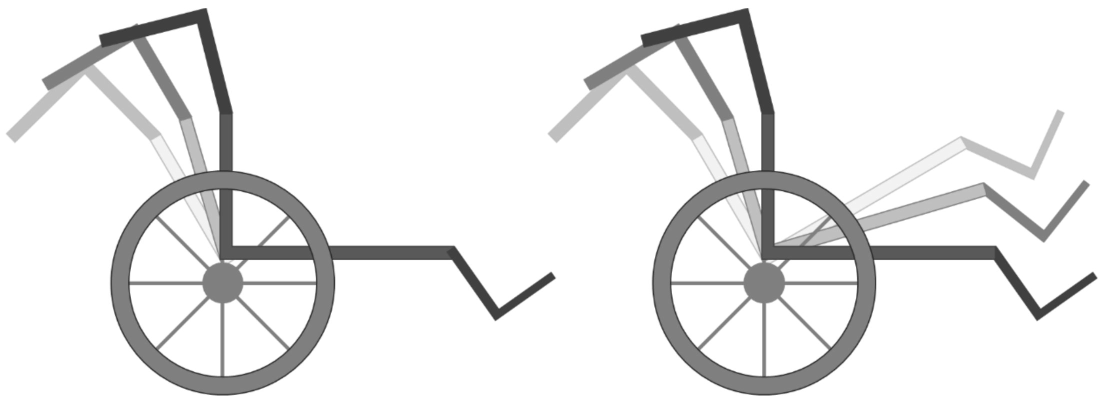

Figure 3. Wheelchair articulations commonly used to change posture: back recline (left) and tilt-in-space or whole body tilt (right)

1.2.2.2 Seat Interface Pressure

Pressure is an important consideration in wheelchair seating as sustained pressure is another known risk factor for the development of PIs [18], [107], [108]. Since the ITs are known to be subjected to the largest pressures in the buttock region while seated, it is important to relieve the pressures under the IT regions frequently to prevent the incidence of PIs [52], [104], [109]. This has been especially salient for wheelchair users because research has shown that the peak pressure in spinal cord injury (SCI) patients can be 1.5 to 2.5 times higher than healthy subjects, putting them at a heightened risk of PI development [110]. Some studies showed that tilt-in-space and recline affected the magnitude of pressure applied to the IT region [111], [112]. Various studies supported the use of tilt-in-space to decrease mean interface pressure on the buttocks as well as the pressure under the IT region in all individuals, including SCI patients. The decreased pressure in the buttocks and IT regions reduced risk factors associated with PI formation in that region [21], [110], [113]–[116]. However, tilt-in-space of at least 30 degrees was necessary to reduce the pressure in the IT region in SCI patients [102], [117]. Tilt-in-space was also shown to shift the peak pressure away from IT region, further aiding in efforts to relieve pressure on the ITs [21]. However, due to being more costly, less maneuverable and the necessity of at least 30 degrees of tilt to reduce the pressure in the IT regions, the number of users benefiting from the tilt-in-in space is low [109].

Similar to tilt-in-space, backrest recline was shown to reduce the mean pressures and peak pressures in the IT regions in healthy people and SCI patients [21], [104]. Further, larger recline angles reduced the mean pressures on the seat pan in healthy subjects [104]. Although some studies showed that the back recline decreased the mean seat interface pressure, there were some studies with contradicting findings [21], [104], [113]. In one study, recline increased the mean and peak pressure in the seat interface [110]. Similarly, one study found that using a 180 degree recline, or a supine position, reduced the normal force whereas a whole body tilt was shown to increase the normal force in SCI patients [115]. Another study showed that back recline reduced the pressure in the IT regions while increasing the pressure in the sacrococcygeal regions [118]. However, a newer study indicated that increased back recline resulted in increased pressure in the IT as well as the sacral region, whereas increased seat pan tilt shifted the pressure off of the IT region [89]. This has implications for wheelchair users, as back recline is the most common pressure relief strategy used, and this suggests a need for a different strategy to relieve pressure under the IT region.

1.2.2.3 Shear Forces

Shear forces are the forces acting parallel to a surface and can affect tissue stresses and arterial and venous blood flow [101], [119]. The effects of recline and tilt-in-space on shear forces should also be considered because of their effects on perfusion. As a result, there have been studies on the effects of back recline and tilt-in-space on shear forces in the buttocks. According to one study, tilt-in-space reduced the shear forces whereas back recline increased the shear forces in the buttocks [110]. However, the average shear force in the buttocks during a posture change from upright to recline posture decreased in some studies and remained unchanged in others [17], [120]. These same studies showed that the average shear forces increased when returning from a recline position to upright position. In healthy individuals, a posterior directed shear force occurred when seated in a wheelchair, which increased with leaning forward [121]. Strategies such as a low friction seat-covers in the back, as well as shifting the rotational axis of back support anteriorly, may mitigate the shear force increases when returning back to the upright position [88], [122], [123]. Overall, research indicated that movement between upright and reclined postures contributed to changes in the shear forces. The literature also indicated that the shear forces were larger in reclined position as compared to upright positions, which is a problem as recline is commonly used as a strategy for posture relief [62], [110]. Thus, there is a need for an alternative strategy to relieve the pressures in the ITs.

1.2.2.4 Fabric and Friction

Friction is the force that resists motion when the surface of one object comes in contact with the surface of another and is directly linked to the shear forces. A larger friction coefficient correlates to a larger capacity for generating shear force. Thus, reducing the coefficient of friction between the seat interface and a person’s clothing (i.e. pant material) can be a strategy to reduce the shear forces in wheelchair seating. The coefficients of friction of fabrics have been shown to depend on various factors, such as the yarn material, fabric construction (Figure 4), tightness, and surface finish [124], [125]. Yarn with higher frictional properties was known to produce fabrics with higher frictional properties [126]. Knitted fabrics have been known to have higher frictional coefficients compared to woven fabrics of the same material and smoothness [124]. Plain woven fabrics were seen to have lower friction coefficients as compared to twill woven fabrics [127]. In general, within the same type of weave, tighter weaves produced lower coefficients of friction [128]. Since there are many factors interacting to determine the frictional properties of a material, it is difficult to estimate the coefficient of friction without measuring it experimentally. In addition, the friction coefficient is not an inherent property of a fabric. Instead, the friction coefficient of a fabric varies depending on the other surface the fabric is sliding against. There have been studies which investigated the friction coefficients of various fabrics when sliding with themselves [125], [127], [129]. But there is a dearth of literature on frictional properties of different fabrics in contact with one another. The interaction occurring between the seat interface and pant fabric plays an important role in friction and shear. So, it is important to study the frictional properties of various pant fabrics and the seat cover for both wheelchair users and office workers.

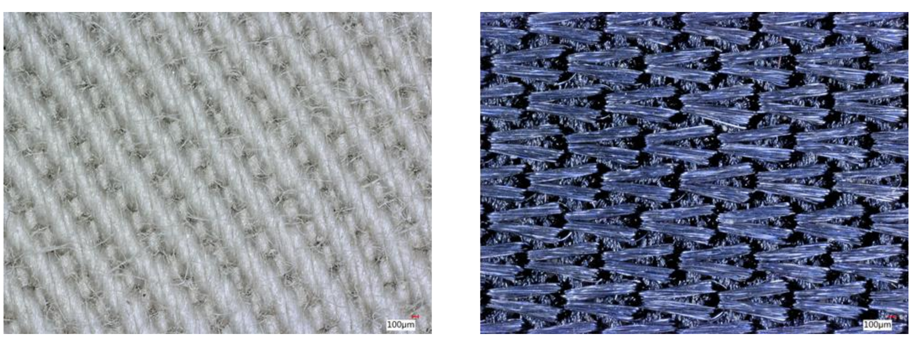

Figure 4. Different types of fabric construction: twill woven fabric (left), knit fabric (right)

CHAPTER 2: EVALUATION OF POSTURE AND LOADING IN THREE DIFFERENT OFFICE POSTURES

The contents of this chapter were originally published in the Work Journal

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2.1 Introduction

Extended periods of time in the seated position are common among office workers. In the United States, studies indicated that most working individuals sat at a workstation for more than four hours a day, while some workers spent as many as eleven hours in a seated position [130], [131]. Such long working hours while in a seated position can pose various health risks such as musculoskeletal disorders and pain in the neck, shoulders, upper and lower back [132]. Maintaining a kyphotic spinal posture (or flexed, slouched position) for prolonged periods as opposed to a lordotic posture has been shown to produce increased pressure in the intervertebral discs, particularly of the lumbar region and contributed to the degeneration of these discs [30]. Extended time in the seated position has also been linked to reduced blood flow and blood pooling in the legs, which is particularly problematic because blood flow is critical to maintaining the health of tissues and mental alertness [33], [133] So, to reduce pain, blood pooling and musculoskeletal disorders, research has suggested that office workers vary their posture throughout the workday [29], [68], [134], [135].

Sit-to-stand desks have been introduced at many workplaces in an attempt to offer another working posture besides the seated position. The goal of the standing desk is to positively influence employee cardiovascular and metabolic health outcomes by decreasing employee sitting time [69],

[136]. The musculoskeletal and health benefits of sit-stand desks come from transitioning periodically between the seated and standing postures [77], [137]. However, much like prolonged sitting, prolonged standing has also been shown to have negative health implications. Muscles and joints are subjected to large loads during standing, which can result in fatigue, lower back pain, discomfort in the neck and shoulders, and musculoskeletal disorders [70]–[74], [77], [78]. Research has shown that, much like prolonged sitting, prolonged standing can also lead to blood pooling and swelling in the lower legs [68], [72], [80]–[82]. Therefore, the authors hypothesized that introducing a different posture that supported working, in addition to the seated and standing positions, would yield different joint angles, different pelvic tilts and lumbar curvatures in comparison to seated and standing positions.

Research has shown that changing one's posture is important for decreasing health risks, promoting blood flow, and mental alertness [33], [133], [138], [139]. A multi-posture office environment has the potential to foster some movement and thereby possibly reduce some health risks associated with standard sitting. Due to the discomforts of sitting in a single posture, the necessity for a chair to support multiple postures has also been recognized by the ergonomics community [140]. Various developments and suggestions in chair designs have been made to promote movement while sitting. These include an adjustable back recline, armrests, a lumbar support and a resting feature (tilting of the whole body rearward, yielding a position with elevated feet) [141]. Researchers also tried to incorporate an inclined wedge and blocks in the seat pan to support a lordotic seating posture [142]. Similarly, the use of medial-lateral seat pan tilt has been explored in the office industry [143]. A truly multi-posture office environment requires more than just the seated and standing positions [144].

One of the notable alternative postures suggested by the literature is an elevated, seated position with a forward tilting seat pan [24], [55]–[57], [145]. Commercially available modern chairs generally have a seat pan angle of three degrees below horizontal (the buttocks portion of the seat pan is tilted three degrees below horizontal while the occupant is positioned in an upright posture). This rearward tilt in the seat pan was shown to make forward bending tasks difficult [56]. Some researchers tried forward tilting of the seat pan. The forward seat pan tilt produced mixed results, particularly when evaluating if changes occurred with the lumbar spine, which has been used as a metric of back health [24], [55], [57]. A perching posture where the person was seated on a high stool was an alternative suggested in the literature [146]. The person leaned against a seat pan (no back support) while keeping their legs extended and knees straight. The researchers suggested the use of this perching stool may induce movements while working at a desk [146]. Noguchi et. al. tested a variety of positions moving from seated to standing and suggested a range of torso to thigh angles that provided significant differences in muscle activation and ground reaction forces in a lab setting [145]. Even though there were differences in the techniques and reported findings from these prior studies, one thing that was consistent was the attempt to introduce additional postures into the office environment besides standing and the traditional seated position. This was done to help address the challenges seen with working in a single position for a prolonged period of time.

The purpose of this study was to investigate a new "in-between position". This new working posture falls between the fully seated or fully standing positions. The chair that provided this in-between posture raised and tilted the seat pan forward, which permitted the occupants to keep their knees flexed and feet flat on the floor. The seat pan of the chair was also split into anterior and posterior halves so that the forward tilt of the anterior portion of the seat was larger than the forward tilt of the posterior portion of the seat, a novel feature compared to the forward tilting chairs used in the published literature [24], [145]. The authors' primary hypothesis was that the in-between position would produce a larger pelvic tilt and therefore larger lumbar lordosis in comparison to a typical seated position. Additionally, this would occur without increased ground reaction forces as compared to the seated position. Moreover, it was hypothesized that the movement from the seated to the in-between position and the movement from the in-between to the standing position would result in a measurable change in blood perfusion in the lower legs. Therefore, the objectives of this work were: 1) to evaluate the differences in joint angles, ground reaction forces, and blood perfusion while in a seated position, a standing position, and a new office seating position, termed the in-between position and 2) to evaluate the joint moments and blood perfusion during the transition from the seated to the in-between position and the transition from the in-between position to the standing position. The moments at each joint correlate to the loading that the joints are subjected to due to the rotational effects of force. These moments are important to consider because the presence of larger joint moments can make the movement task difficult or painful, especially for people with underlying health conditions.

2.2 Methods

2.2.1 Force Data

A six-axis force plate (Bertec, Colombus, Ohio) was used to measure ground reaction forces in three directions (superior-inferior or normal force, anterior-posterior, and medial-lateral shear forces) for all test trials. Force data were collected at 100 Hz, and the plate was located under the participant's feet for all test conditions.

2.2.2 Motion Data

The positions of bony landmarks were identified using passive, reflective markers and an eleven-camera motion capture system with an accuracy to within 1 mm (Qualisys, Gothenburg, Sweden). The markers were attached on the right side of the body and included the 2nd toe (2nd metatarsal), ankle (lateral malleolus), knee (lateral epicondyle), greater trochanter, shoulder (glenohumeral joint), left and right anterior superior iliac spines (ASISs), and left and right posterior superior iliac spines (PSISs), as shown in Figure 5. A marker pod with four markers was attached to the sternum. Two rectangular openings were made in the backrest of the chair used in this study to allow the markers on the PSISs to be visible while in the seated and in-between positions (Figure 6). The backrest was reinforced to maintain the same support as it had before the holes were cut. Motion data were also collected at 100 Hz and were synchronized with the force data.

Figure 5. Demonstration of the three different postures: seated posture (left), in-between posture (middle) and standing posture (right). In the in-between posture, the seat pan angle was 5 degrees forward. The markers used for calculations are indicated by the white circles

Figure 6. Two equivalent openings were made in the backrest of the chair to allow the markers on PSIS (circled) to be visible while in the seated and in-between postures. This permitted calculation of pelvic tilt. The backrest mesh was reinforced so that the openings did not affect the support of the backrest

2.2.3 Blood Perfusion

A laser doppler perfusion monitoring system (PF 5010 LDPM Unit, Perimed, Järfälla, Sweden) was used to obtain blood perfusion measurements on the lateral side of the right lower leg at the point of the largest circumference in the gastrocnemius muscle. Perfusion was quantified in perfusion units (PU).

2.2.4 Experimental Protocol

This study was approved by Michigan State University's Institutional Review Board, and consent was obtained from all participants. Twenty volunteers (ten males and ten females) ranging from 19 to 55 years old, with an average age of 33.6 and standard deviation of 13.37 years participated in the study. None of the volunteers had any history of neck or back pain or injury. A height adjustable table and a new chair design, which supported both seated and in-between positions, was used (Figure 5). The participants were asked to conduct computer tasks that included re-typing a passage in the computer screen and then highlighting words in that passage with a mouse. Participants performed computer tasks in three positions across a one-hour test period: 1) seated in the chair, 2) seated in the in-between position in the chair, and 3) standing. The in-between position was such that the lower leg was vertical, the torso was vertical, and thigh-to-torso angle was between 118°-122°.The positions of the markers, ground reaction forces, and blood perfusion were collected at two time points: 5 minutes and 10 minutes in each position. The positions of the markers, ground reaction forces, and blood perfusion data were also obtained for the transition from the seated to the in-between position as well as the in-between position to standing.

The participants were positioned in an ergonomic posture by the test assistants at the start of each position, and they were asked to maintain the ergonomic posture throughout testing. In the seated position, the ankle, elbow, and hip joint were all at 90 degrees. In the standing position, the elbow and ankle angles were at 90 degrees and the hip angle at 180 degrees. In the in-between position, the torso and lower leg were situated vertically, while the participant's thigh-to-torso angle was between 118°-122°.

2.2.5 Calculation of Joint Angles

Vectors that contained 3-D positional data from the markers on the bony landmarks were used to compute joint angles (Figure 7). Joint angles were calculated using the two vectors parallel to the long axes of the body segments on either side of the joint in 3-D space. The cosine of the angle between two vectors was defined as the scalar product of the two vectors divided by the product of magnitudes of each vector. Joint angles were then determined by taking the inverse cosine of the scalar product of the two vectors divided by the product of magnitudes of each vector.

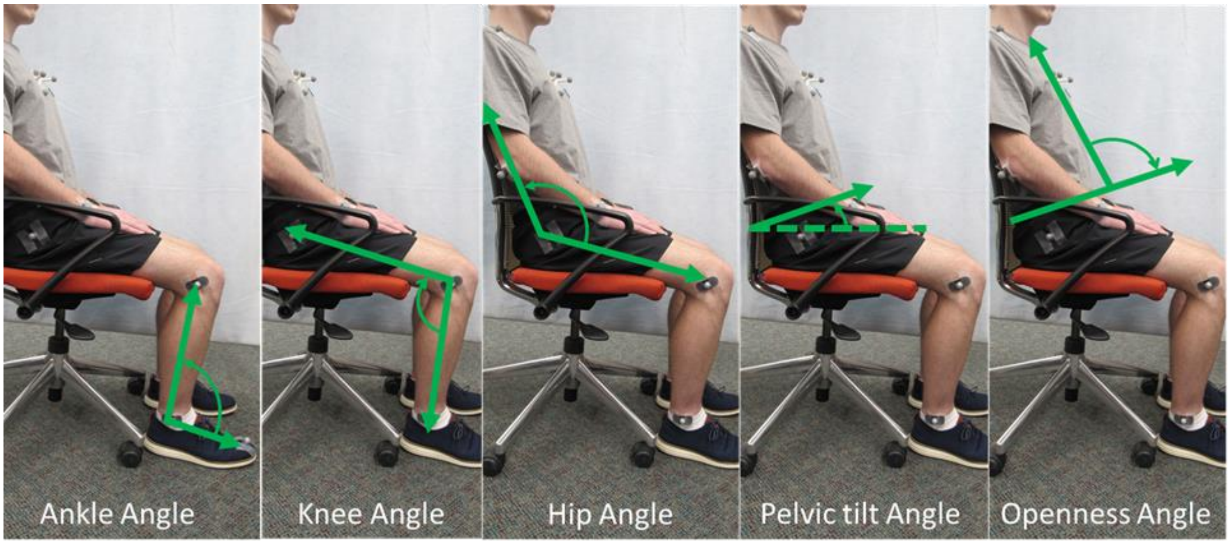


Figure 7. Five joint angles were calculated. Ankle angle was the angle between foot segment and shank segment. Knee angle was the angle between shank segment and thigh segment. Hip angle was the angle between thigh segment and normal to the pelvis plane. Pelvic tilt was the angle between the pelvis plane and a horizontal plane. The pelvis plane was a plane formed by the right and left anterior-superior iliac spines and posterior-superior iliac spines. Openness angle was the angle between the pelvis plane and thorax

The ankle angle was defined by the angle between the vectors passing through the foot (lateral malleolus and 2^{nd} metatarsal) and lower leg (lateral malleolus and lateral epicondyle of the knee). The knee angle was defined by the angle between the vectors passing through the thigh (lateral epicondyle and greater trochanter) and lower leg (lateral malleolus and lateral epicondyle). The hip angle was defined by the angle between the vector passing through the thigh (lateral epicondyle and greater trochanter) and a vector normal to the pelvis plane. The pelvis plane was a plane formed by the right and left anterior-superior iliac spines and posterior-superior iliac spines. Pelvic tilt was computed as the angle between the plane of the pelvis and the horizontal vector (parallel to ground).

The openness angle quantified the relative orientation of the pelvis and the ribcage and was shown to relate to lumbar curvature [147]. The openness angle was calculated by computing the angle between two vectors representing the pelvis and ribcage. The pelvis vector was defined as the vector passing through the midpoint of the two ASIS markers and the midpoint of the two PSIS markers. The ribcage vector was the vector passing through top and bottom markers of the marker pod placed on the sternum.

2.2.6 Calculation of Joint Moments

To calculate joint moments during the dynamic transitions (i.e., seated to in-between and in-between to standing), a link-segment model with four links was adopted [148]. The four segments were the HAT (head, arms, and trunk) segment, the thigh segment, the shank segment, and the foot segment (Figure 8). The ankle, knee, and hip joints were modeled as hinge joints. Motion was only considered in the sagittal plane. Accordingly, force and moment calculations were also conducted in the sagittal plane. The anthropometric parameters, such as masses and relative locations of the centers of gravity of each body segment, were derived from literature [149]. Inverse dynamics were used to calculate the joint moments at the ankle, knee, and hip for the transitions [148]. The ankle moment was the sum of the moment due to the ground reaction force and the moment due to the weight of the feet. The knee moment was the sum of the ankle moment, the moment due to the force transferred at the ankle, and the moment due to the weight of the lower legs. The hip moment was the sum of the moment due to linear acceleration of the HAT segment, the moment due to the angular acceleration of the HAT segment, and the moment due to the weight of the HAT segment.

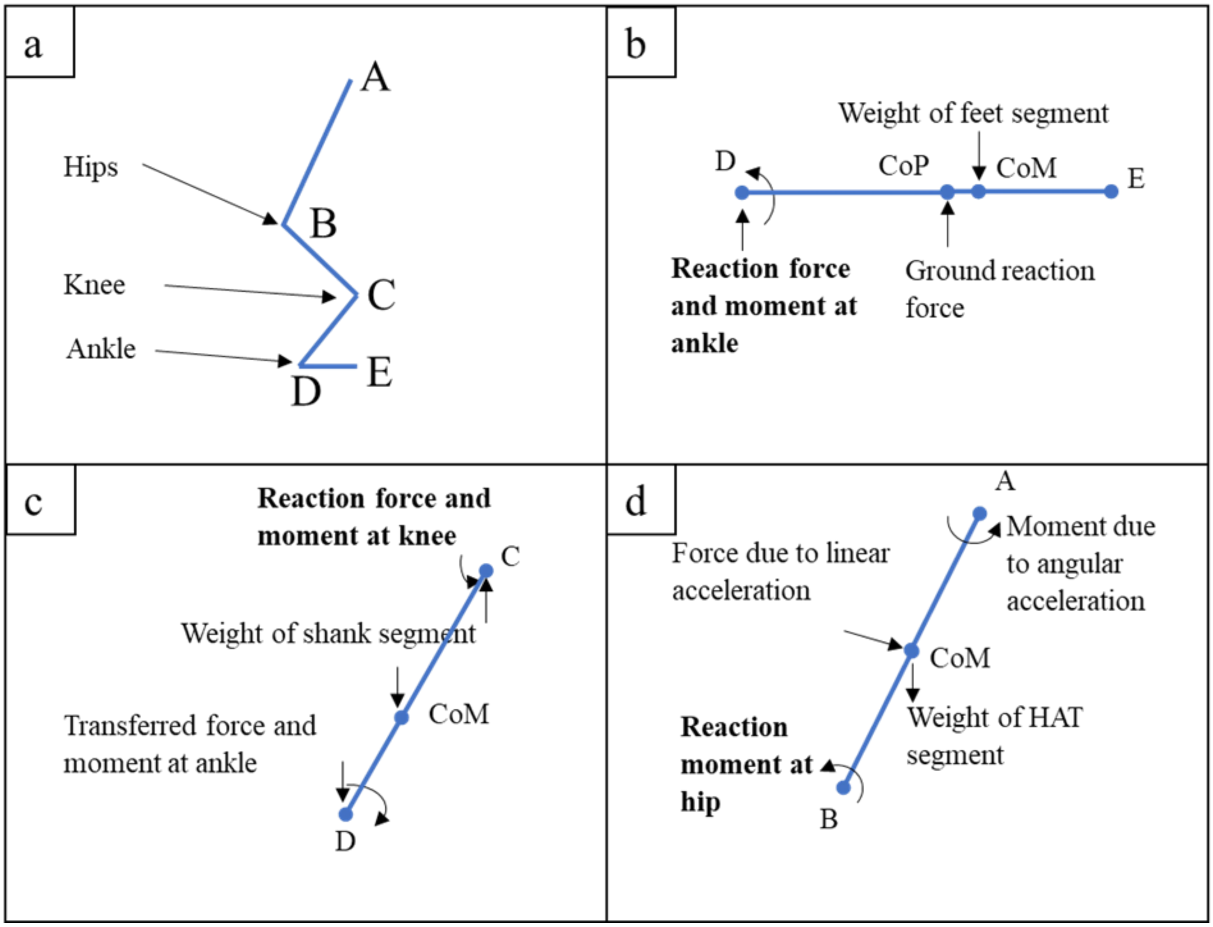


Figure 8. (a) Link segment model used to calculate the joint moments. AB is head, arms and trunk (HAT), BC is thigh, CD is Shank, DE is foot segment (b) Free body diagram for foot segment (link DE), CoP is center of pressure and CoM is Center of mass (c) free body diagram for shank segment (link CD) (d) free body diagram for HAT segment (link AB)

2.2.7 Comfort Rating

A 10-point rating scale for comfort was used for all participants [150]. After completing the computer task in each posture, the participants were asked to rate their overall comfort on a scale of 1 to 10. A rating of 1 indicated horrible and 10 was excellent. The rating of 2 and 3 indicated very bad, 4 indicated bad, 5 and 6 indicated okay, 7 indicated good and 8 and 9 indicated very good.

2.2.8 Statistical Analysis

A repeated measures ANOVA was used to compare seated, in-between and standing positions for each of the angles (ankle angle, knee angle, hip angle, pelvic tilt and openness angle), ground reaction forces, and blood perfusion. Post-hoc Tukey tests were used to determine significant differences between specific positions. Paired t-tests were conducted to determine the significant differences in peak joint moments during the seated to in-between motion and the in-between to standing motion. A larger peak moment indicated a larger loading in the joints; therefore, a reduction in the moment was desired, especially for individuals with knee or hip injuries. A p-value <0.05 was considered statistically significant. A Wilcoxon's signed rank test was performed on the comfort ratings to determine the differences between positions.

2.3 Results

2.3.1 Ground Reaction Forces

The mean vertical ground reaction forces and mean anterior-posterior ground reaction forces for the different positions are presented in Figure 9. All the ground reaction forces were calculated as a percentage of total body weight for each of the participants. The average vertical ground reaction force was largest for the standing position and was significantly smaller in both the seated and in-between positions ($p<0.0001$). The vertical forces for the in-between position were 82.9% smaller than those generated in the standing position ($p<0.0001$). The anterior/posterior ground reaction forces (or shear) were small compared to normal ground reaction forces in all positions. The difference in anterior/posterior ground reaction forces between the seated and in-between positions was not statistically significant ($p=0.4934$). However, there were significant differences between the anterior-posterior ground reaction forces in the in-between and standing positions ($p<0.0001$) as well as between the seated and standing positions (p<0.0001). The medial-lateral ground reaction forces were less than one percent of body weight in all three positions with no statistical differences. No statistically significant differences in ground reaction forces assessed relative to body weight were observed between males and females.

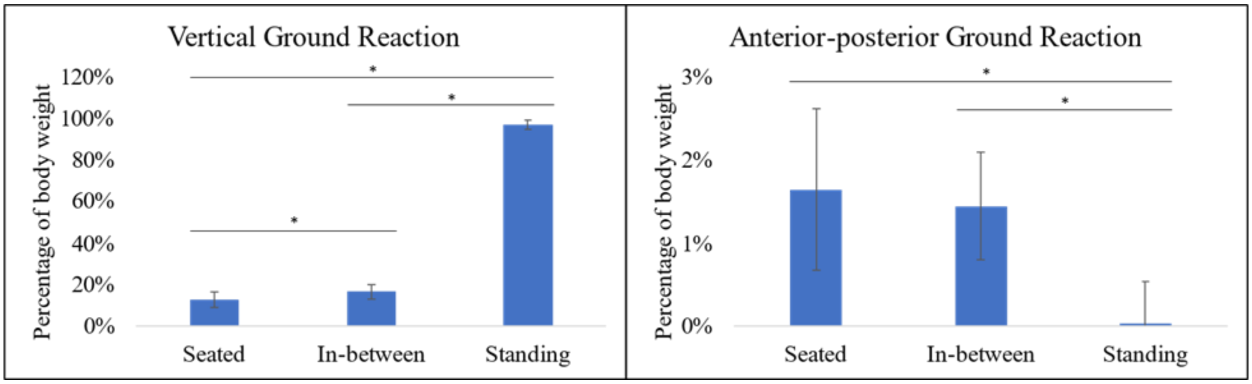


Figure 9. Mean vertical and mean anterior-posterior ground reaction forces and standard deviation for three postures. The vertical ground reaction was larger but anterior-posterior ground reaction was smaller in the in-between posture than in seated posture. Significant differences are indicated by *

2.3.2 Joint Angles

The pelvic tilt angle was positive (above horizontal) at 15.3 degrees in the seated position, then the pelvic tilt value was 6.3 degrees in the in-between position (seated vs in-between: p<0.0001), and was -8.4 degrees (below horizontal) in the standing position (in-between vs standing: p<0.0001) (Table 1). These data indicated that the pelvic tilt angle changed by 58.8% when comparing the in-between position to the seated position and the pelvis movement was toward that of the standing position. The knee, hip, and openness angles were largest in the standing position and smallest in the seated position. All the angle magnitudes for the in-between position were between that of seated and standing positions. The p-values indicated that there were statistically significant differences in all pairwise comparisons (p<0.05) between seated, in-between, and standing positions for all joint angles except for the ankle angle for the comparison of in-between vs standing (p= 0.536). All data were examined for differences between males and females. Only two statistically significant differences were identified. The ankle angle for the standing position was smaller for females (p=0.015). Similarly, the hip angle for the standing position was also smaller for females (p=0.035).

Table 1. Average joint angles in degrees and standard deviation across the subject pool for each position. All the angle values for in-between position were between that of seated and standing position. * indicates means of all three positions were significantly different from each other. ᴪ indicates significant differences only for pairwise comparisons of seated and in-between, and seated and standing

Position	Seated	In-between	Standing
Ankle Angleᴪ	101.2 (5.9)	97.3 (4.6)	93.8 (3.4)
Knee Angle*	101.1 (6.6)	111.1 (5.8)	171.7 (4.3)
Hip Angle*	116.9 (6.2)	123.0 (8.0)	169.8 (4.9)
Pelvic Tilt*	15.3 (6.6)	6.3 (6.6)	-8.4 (7.6)
Openness Angle*	96.7 (15.7)	102.1 (14.0)	116.5 (17.1)

2.3.3 Joint Moments

The peak joint moments at the knee and the hip were smaller during the transitions from the in-between position to the standing position compared to the joint moment values that occurred during the transitions from the seated position to the in-between position (Figure 10). Significant differences were seen only in the hip moment (hip: p<0.0001, knee: p= 0.2734). The hip moment was 42% smaller during the in-between to standing motion compared to seated to in-between motion. The peak joint moment at the ankle joint was larger during the in-between to standing motion compared to the seated to in-between motion (p=0.0001). No statistically significant differences in joint moments were observed between males and females.

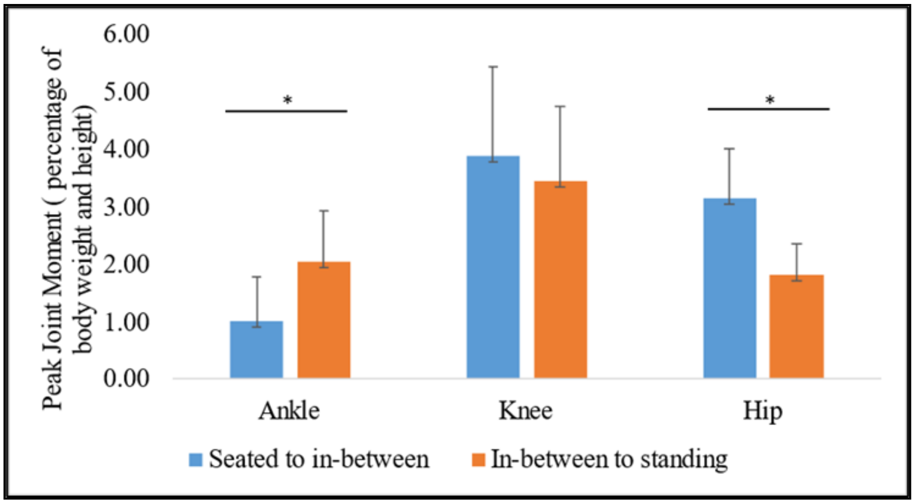


Figure 10. Peak joint moments with standard deviations at the ankle, knee, and hip for the two dynamic motions. Significant differences are indicated by *

2.3.4 Blood Perfusion

The average blood perfusion values are presented in Table 2. There were no statistically significant differences in the average blood perfusion values between the three positions (for seated and in-between, p = 0.6402; for in between and standing, p= 0.5180; for seated and standing, p = 0.1238).

Table 2. Mean blood perfusion and standard deviation values in seated, in-between, and standing positions. Blood perfusion is defined as the concentration of red blood cells times their average velocity and is measured in perfusion units (PU). There were no statistically significant differences in blood perfusion across the three positions

Position	Blood Perfusion (PU)
Seated	17.2 (9.5)
In-between	15.6 (11.4)
Standing	13.7 (11.9)

An example of the time trace for blood perfusion during the transition from seated to in-between position is presented in Figure 11. Blood perfusion data were collected for the dynamic transitions from the seated to the in-between position and for the in-between to standing position. For both dynamic transitions, blood perfusion increased during the motion. It reached a maximum value and slowly decreased. For some participants, an increased perfusion level was maintained for at least one minute past the movement, which is when the data collection of blood perfusion ended.

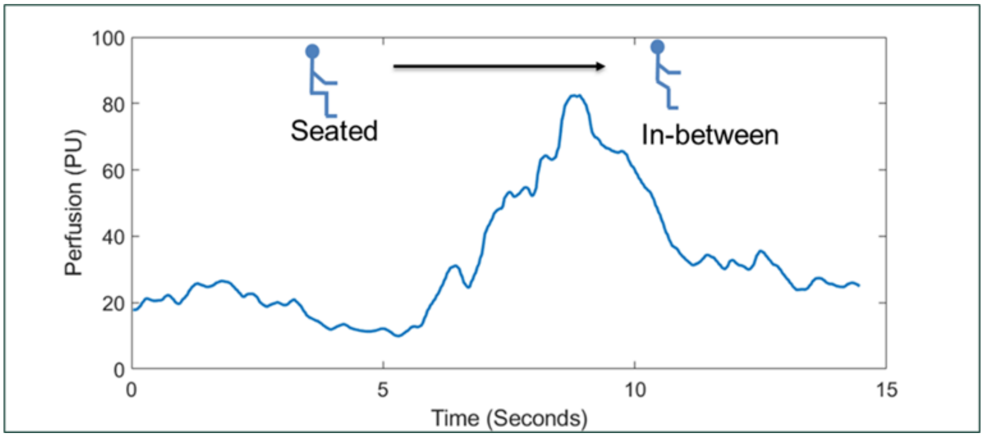


Figure 11. An example of the blood perfusion during the dynamic movement from the seated to the in-between position for one participant. The blood perfusion values increased to a maximum value during the motion and then, for some participants, decreased to the same value as before the movement within the measurement time period of one minute. For other participants, the blood perfusion values remained elevated up through the conclusion of the one-minute data recording

2.3.5 Comfort Rating

The overall comfort ratings provided by the 20 participants for the positions are presented in Figure 12. The comfort rating score ranged from 1 to 10 with 10 being the highest level of comfort. The average seated score was slightly larger than the score for the in-between position ($p=0.252$). Both the seated and in-between positions were preferred over the standing position ($p<0.005$). The in-between position also had the largest variation in comfort ratings. The Wilcoxon signed ranked test indicated no significant differences in comfort scores between seated and in-between positions (p= 0.252), but there were significant differences in comfort between the seated and standing positions (p <0.001) and the in-between and standing positions (p= 0.005).

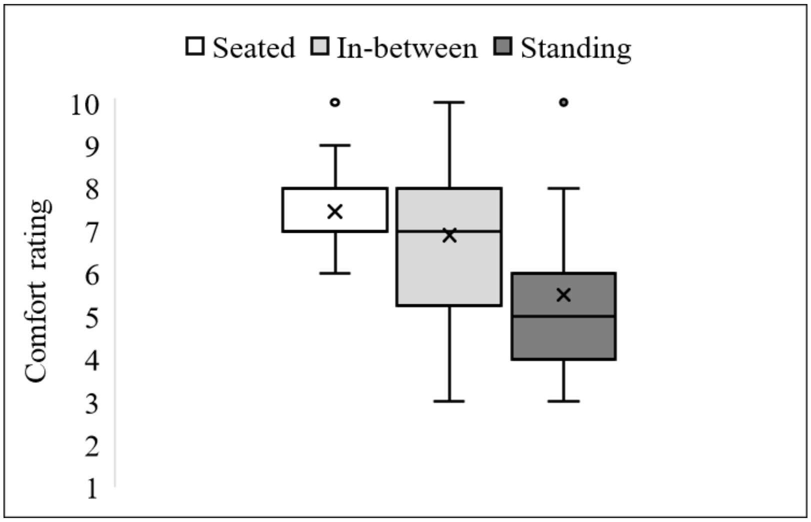


Figure 12. Box plots of comfort ratings for each of the three postures (10 is excellent). The lower and upper ends of the box represent the interquartile range, whereas the vertical line extensions represent the largest and smallest values, excluding the outliers. The horizontal lines inside the boxes represent mean and the crosses represent median. The mean comfort rating was highest for seated posture and lowest for standing postures. In-between postures had more variation in comfort rating as compared to seated and standing postures

2.4 Discussion

The goals of this study were: 1) to evaluate the differences in joint angles, ground reaction forces, and blood perfusion while in a seated position, a standing position, and a new office seating position, termed the in-between position and 2) to evaluate the joint moments and blood perfusion during the transition from the seated to the in-between position and the transition from the in-between position to the standing position. This research study was unique as it evaluated all of these parameters and compared them across three working positions. A robust set of data was collected, and a complete comparative analysis was conducted, permitting a detailed analysis of the biomechanical measures, blood perfusion and the perception of the occupant. Overall, the study found that the in-between position provided different joint angles than the seated position while transmitting smaller loads through legs than standing position. This additional in-between position demonstrated the benefits of standing (larger lumbar lordosis and pelvic tilt) as well as the seated benefits (smaller ground reaction forces). Additionally, no significant differences in shear forces at the feet were identified as a result of the seat pan tilt.

The in-between position provided pelvic orientations and lumbar curvatures closer to the standing position as compared to the seated position. It was interesting to note that the pelvis tilt in the in-between position moved to a point halfway between the pelvic tilt found in the seated and standing positions.

The increased openness angle was another measure that confirmed lumbar articulation was occurring in the in-between position, even though the person was still in the chair. Previous research has shown that a larger openness angle is correlated to an increased lordotic lumbar curvature [147]. Movement in the lumbar spine is a positive, as motion in the spine leads to promotion of nutrient flow in intervertebral discs [151]. Sitting in a lordotic or upright back posture instead of a kyphotic or slouched posture has also been associated with reduced pain in the back and leg region, as well as an increased diaphragm area, thereby providing better lung capacity and airflow [32], [152].

It should be noted that in this study, the anterior/posterior ground reaction forces were not larger in the in-between position compared to sitting. This is in contrast to a previous study where the shear forces were largest in the mid-range forward tilt posture compared to both seated and standing [145]. This prior study by Noguchi et al. evaluated the anterior posterior forces in each of the postures defined by five-degree trunk-thigh angle increments between sitting and standing with the largest anterior-posterior forces during the middle phases. The lack of large shear in the in-between position for this work is attributed to the split seat pan, which did not introduce a larger sloping surface to the buttock region but still allowed the knees to be more inferior. This has implications for future designs and research of office chairs, as this new position provides a more lordotic pelvic posture with larger lumbar curvature and minimizes the shear forces at the feet.

The use of the in-between position could also be beneficial for people with hip and knee pain, as the joint moments when standing from the in-between position demonstrated smaller values in comparison to standing from the seated position [84]. Previous research conducted on sit-stand motion indicated that an increased seat height is recommended for people who suffer from knee and hip pain. [83], [153]. Similarly, use of high stools has also been shown to reduce the joint moments [85]. The hip moment was largest for the seated to in-between motion, and this is likely a function of the control position. The participants had to lean forward in the seat to move the seat into the in-between position, which resulted in a larger moment-arm for the torso weight.

The perfusion value for both sets of transitions increased to a maximum value during the motion and then trended downward. For some participants, the perfusion value dropped to the same value as before movements within the measurement time period of one minute. For other participants, the perfusion value did not return to the initial perfusion value immediately. Rather, the blood perfusion values remained elevated until the conclusion of the data recording. This is consistent with literature, which has also shown subject dependency on perfusion values and recovery time [119]. Furthermore, for workers who cannot stand due to underlying health conditions or experience discomfort in standing, using an in-between position instead of standing can offer an additional working posture, providing an option for postural change which does not currently exist. For healthy workers, the in-between position can also serve as an additional working position.

To summarize, a chair that supports both sitting and an in-between position offers an additional solution for office workers.

2.5 Limitations

For this study, markers were attached to one side of the body only, and the posture was assumed symmetric. This could be considered a limitation of this study; however, the tasks being conducted did not involve asymmetric movements. Additionally, the order of positions was the same for all the participants. The seated position was assumed first, and the standing position was assumed last so that the blood perfusion during transitions from the seated to the in-between and the in-between to the standing positions had the same time effects. While the randomization of the position is unlikely to affect the findings related to the joint angles and joint moments, it could potentially affect the blood perfusion results and comfort ratings. Also, since the seat pan had varying inclination between the anterior and posterior regions, a future study that examines the pressure distribution on the seat pan would be an important complement to the current study. With regard to generalizing the findings of this work across the spectrum of age groups, the authors recommend that additional testing on populations younger than 19 and older than 55 should be conducted to confirm these trends in these other age groups. The authors also acknowledge that this study was conducted in a lab setting and not in an actual working space. Future studies could be of longer duration and within an office setting.

2.6 Conclusions

The findings from this study suggest that the in-between position comes with many positive benefits. It provided increased pelvic tilt, increased torso openness, and decreased leg loads (compared to standing). The motion to and from the in-between position also provided increased blood perfusion. The joints were subjected to smaller moments while standing from the in-between position as compared to standing from a seated position. Overall, the in-between position was rated more comfortable than standing. The in-between position has the potential to provide health benefits to the office workers by providing another working position.

CHAPTER 3: DETERMINATION OF COEFFICIENT OF FRICTION BETWEEN PANT FABRICS AND SEAT COVERS

3.1 Introduction

Wheelchair users spend a large amount of time seated, and because of this, have a high risk of developing pressure injuries (PIs), particularly on the bottom of the buttocks. It has been estimated that more than 130 million people globally require wheelchairs for mobility [22], [35], [154]–[156]. Specifically, there were 3.7 million individuals who required wheelchairs for mobility in the United States (US) and 1.7 million in the United Kingdom (UK) [157], [158]. The large number of wheelchair users contributed significantly to the 2.5 million people suffering from PIs in the US and nearly one million in the UK each year, making PIs a global issue. [159], [160]. Furthermore, research has shown that 50-80% of wheelchair users have developed pressure injuries at least once in their life [161].

Patients who had PIs reported significant physical, financial, and social distress as a result of these injuries. In addition to physical pain, PIs were linked to health complications such as infection, sepsis, and even death, of which there were about 60,000 annually due to PI incidences [162]–[164][165]. To combat these, the annual cost of treating PIs in the United States was reported at $25 billion, with treatment cost ranging from $30,000 to as high as $150,000 for a single PI [42], [45], [47], [159]. Furthermore, PIs decreased the quality of life, as these injuries reduced the ability of individuals to perform everyday activities, caused them to miss work, and increased their stress, anxiety, and sense of burden on others [18].

Because of the long periods of time seated, wheelchair users experienced prolonged loading in the soft tissue. This was shown to be particularly problematic for the tissues surrounding bony prominences [166]. Because of the continuous compression of the soft tissues between the bony prominences and wheelchair surfaces while seated, the sacrum, greater trochanter, and ischial tuberosity (IT) regions were extremely vulnerable to developing PIs [16], [19], [102].

In addition to normal pressures on soft tissue, shear forces and friction have been consistently linked to PI formation [18], [43], [119]. Shear forces (those parallel to a person's skin) have been shown to occur at the person-chair interface [89], [121], [167], [168], causing distortions of the skin and deeper tissues, contributing to tissue ischemia [169], [170]. Importantly, shear loads combined with normal loads (those perpendicular to the skin) have been shown to be more detrimental than equivalent normal loads alone, as they resulted in a larger decrease of blood perfusion to the tissues [101].

Larger coefficients of friction at the seat interface corresponded to increases in the maximum shear forces between the person and the chair, which has been shown to increase the likelihood of PIs [170]. Thus, in order to reduce the shear forces and incidence of PIs in wheelchair seating, one strategy is to reduce the coefficient of friction between the seat interface and clothing material the occupant is wearing, specifically their pants material.

Various factors were shown to affect the coefficient of friction of fabrics, such as the material of the yarn, the construction of the fabric, roughness of the fabric, its tightness, and its finish [124], [125], [128]. It was shown that yarns with high frictional properties produced fabrics with high coefficients of friction [126]. Knit fabrics were shown to have higher coefficients of friction than woven fabrics of the same material and smoothness [124]. The type of weave was also shown to affect the coefficients of friction, with plain woven fabrics exhibiting lower coefficients of friction than twill woven fabrics [127]. Moreover, tighter weaves produced lower coefficients of friction than looser weaves of the same yarn type [128]. Because of the multitude of factors, it is difficult to predict a material's coefficient of friction without measuring it experimentally.

Even when considering all the factors that may affect a fabric’s frictional properties, the coefficient of friction of the fabric is not an intrinsic property and is dependent on the surface on which it is in contact with. In addition, inclusion of the deformable seat cushion in the wheelchairs is likely to affect the frictional behavior of the fabrics. Most wheelchair users have a deformable cushion as part of their seating system [171]. Unrelated to seating, number of studies have been conducted to determine the coefficients of friction of different fabrics when sliding against themselves [125], [127], [129]. However, literature describing frictional properties between different fabrics in contact with each other is lacking. Similarly, information on the effect of a deformable cushion on fabric friction is also not available, as most studies conducted on fabric friction were calculated using rigid surfaces [128], [129], [172]. Specifically, for wheelchair users and the prevention of PIs, it is crucial to understand the interaction between pant fabrics and seat pan covers as well as the effect of a deformable seat cushion on that interaction. To fill this gap in information, it is imperative to study the frictional properties between various pant fabrics and wheelchair seat covers, as well as to study other potential fabrics that could be used to manufacture pants or wheelchair seat covers. Thus, the goals of this study were 1) to determine the coefficients of friction of seven commonly worn pant fabrics and two seat cover fabrics and 2) to investigate the effect of a deformable seat cushion on the coefficients of friction between fabrics.

3.2 Methods

3.2.1 Materials

The materials and devices used for this research included a chair with a seat pan able to tilt from zero degrees (horizontal) to 45 degrees of rearward tilt, a mechanical system called the 'sled' (Figure 13) which was capable of carrying a weight of 110N, seven fabrics used to make pants, two materials used in cushion covers, a multicamera motion capture system (Qualisys, Göteborg, Sweden), and reflective markers of 12 mm diameter. The weight of 110 N was used as it represented contact pressure similar to the average seat interface pressure in wheelchair users over the area of sled bottom [173]

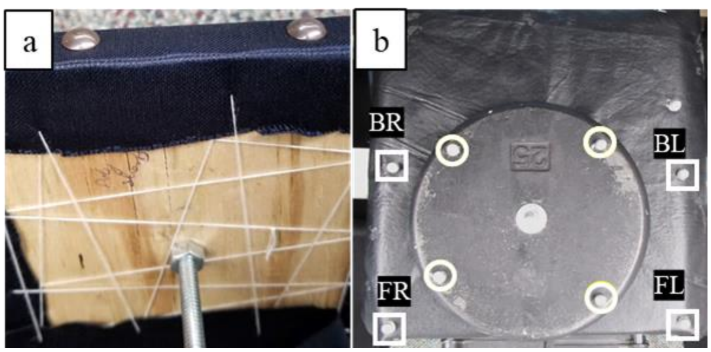


Figure 13. (a) The top of the sled. Fabric was wrapped around the wooden surface and secured so it was taut (b) A weight was secured to the top of the sled while the sled system was placed on top of seat pan and the sled system was free to slide on the seat pan. Circles denote the markers on the sled, and squares denote the marker on the seat pan

3.2.2 Experimental Protocol

The sled had a square cross-sectional area with a measurement of 15 cm x 15 cm and a thickness of one cm. It was used to carry the test weight, and segments of the pants fabrics were attached to the bottom surface of the sled (Figure 13). These fabrics were wrapped around the wooden surface and secured so they were taut (Figure 13a). To secure the fabric around the sled, the fabrics were first sewn tight and then tacked into position. The tacks were around the outer edge, so they did not interfere with the contact surfaces. Four reflective markers were attached to the sled and four to the seat pan to track their positions in space relative to one another.

The coefficient of friction was determined through monitoring movement of the sled while the seat pan was tilted. To do this, the seat pan was tilted until the sled system started sliding on the seat pan. Positional data of the markers on the sled and the seat pan for the entire duration of the trial were obtained using a motion capture camera system with sampling rate of 100 Hz and this space had an accuracy of 0.5 mm. Thus, the motion capture system was calibrated such that the X and Y axis aligned with the horizontal plane and the Z axis was vertical or pointing opposite to the direction of gravity. The calibration was performed using a L-frame unit that was calibrated at the manufacturing site and the calibration matrix was entered into the software. The two lengths of the frame defined the X and Y axes. The perpendicular to the plane of the L-frame defined the Z axis. The level of seat pan was checked for both X and Y direction to ensure that the seat pan was horizontal during calibration of motion capture space. Then the L-frame was placed on the horizontal seat pan and the space was calibrated.

The seven fabrics included in testing are listed in Table 3. Basketball shorts and sweatpants were both knit fabrics (made up of a single yarn, looped continuously to produce a braided appearance) and the rest were woven fabric (produced by interlacing two sets of yarn which crossed each other at right angles). All woven fabrics were twill weaves. Two different seat cover fabrics were tested: a vinyl seat cover common to wheelchairs and an office fabric seat cover. The office fabric had a complex woven construction. The fabric structures of all pant fabrics and seat covers are shown in Figure 14 and Figure 15, respectively. The coefficient of friction for all pant fabric-seat cover combinations were obtained from a set of ten repetitions.

Table 3. Details of the seven pant fabrics tested. The woven fabrics were all twill weaves

Pant type	Composition	Construction
Men’s khakis	100% cotton	Woven
Women’s khakis	93% cotton, 7% spandex	Woven
Men’s jeans	100% cotton	Woven
Women’s jeans	75% cotton, 24% polyester, 1% spandex	Woven
Women’s pull-on pants	100% polyester	Woven
Basketball shorts	100% polyester	Knit
Sweatpants	60% cotton, 40% polyester	Knit

To investigate the effects of a deformable cushion on the coefficients of friction measured, a piece of polyurethane foam with a density of 67 kgm^{-3} and thickness of 38 mm was secured underneath the seat cover. The seat cover was tacked onto the wooden seat pan to secure the foam and the seat cover and ensure the seat cover was taut. The coefficient of friction in the presence of foam was also collected for ten repetitions for all pant fabric-seat cover combinations. Additionally, the surface roughness and yarn thickness of each pant fabric and seat cover were measured to understand their effect on the coefficient of friction.

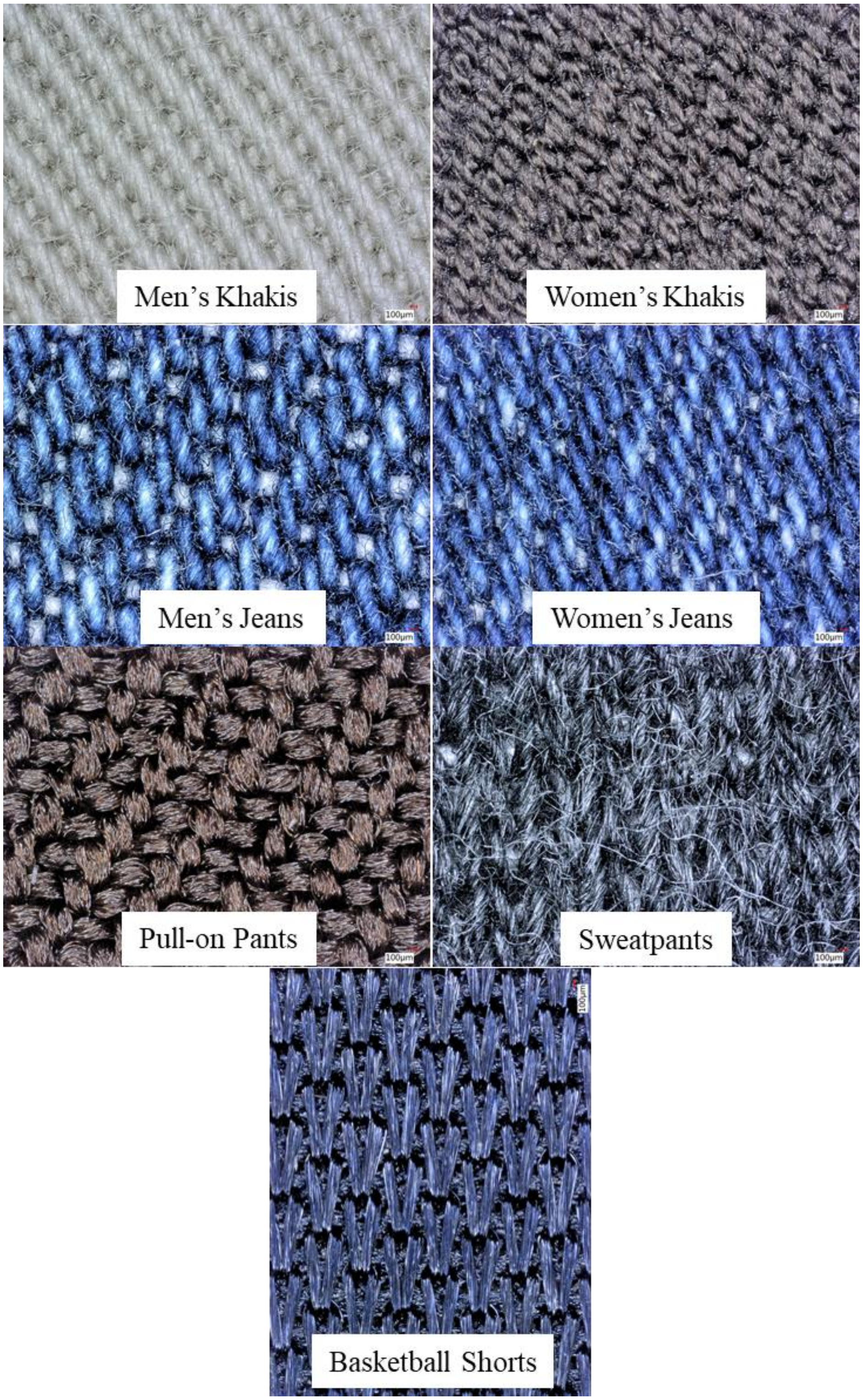


Figure 14. The fabric structure of different pant fabrics tested, obtained through digital microscope using 50x magnification. The sweatpants and basketball shorts were knit fabric, whereas the rest of the fabrics were woven with twill weave. The sliding of the fabrics occurred in the vertical direction of the fabric orientation in the picture

Figure 15. Fabric structure of vinyl seat cover, commonly used in wheelchairs (left) and office fabric seat cover (right), obtained through digital microscope using 50x magnification

3.2.3 Calculation of Coefficients of Friction

The position of the sled ($\vec{s}$) was the average position of the four markers on the sled. The orientation of the seat pan was the unit vector along the seat pan ($\hat{e}$) determined using two markers- front left (FL) and back left (BL). The direction of ($\hat{e}$) was from BL to FL (Figure 16). The position of the sled along the depth of the seat pan (r) was calculated using Equation 1.

$$r = \hat{e} \cdot (\overrightarrow{FL} - \vec{s}) \qquad (1)$$

The angle of tilt of the seat pan (θ) was determined using the components of the vector $\hat{e}$ (Figure 16) as seen in Equation 2.

$$\theta = \tan^{-1}\left(\frac{|\hat{e_z}|}{|\hat{e_y}|}\right) \qquad (2)$$

Where $\hat{e}_y$ and $\hat{e}_z$ are components of $\hat{e}$ in Y and Z directions, respectively.

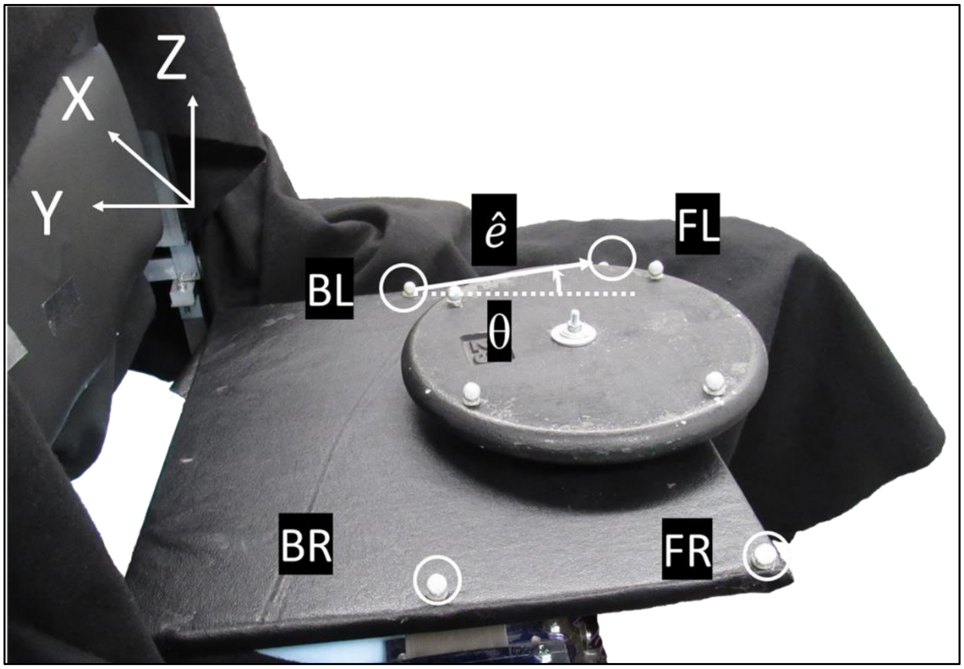


Figure 16. Illustration of vector $\hat{e}$ in the seat pan. Vector $\hat{e}$ aligned along the back left and front left marker of the seat pan. The angle of tilt (θ) was calculated using the component of $\hat{e}$ along the Y and Z direction relative to the horizontal. X axis was along the medial-lateral axis of the chair, pointing to the left, the Y axis was along the posterior direction of the chair and Z axis was along the superior direction

The coefficient of static friction was determined using Newton's second law of motion. The static coefficient of friction correlated to the frictional force that the sled needed to overcome before it slid on the seat pan. The free body diagram of the experimental setup, just before the sled started sliding on the seat pan, is shown in Figure 17a. The axis parallel to the inclined surface was denoted as the t-direction (tangent), and the axis perpendicular to the inclined surface was denoted as the n-direction (normal).

The force balance equation used to determine the coefficient of static friction (μ_s) is given in Equation 3, with the resulting definition of the coefficient of friction in Equation 4.

$$\sum F_t = \mu_s mg\cos(\theta_{max}) - mg\sin(\theta_{max}) = 0 \quad (3)$$

$$\mu_s = \tan(\theta_{max}) \quad (4)$$

Where, F_t was the total force in the tangent direction, m was the mass of the sled system, g was the gravitational constant equal to 9.8 m s^{-2}, and θ_{max} was the maximum angle of tilt just before the sled system started to slide on the seat pan.

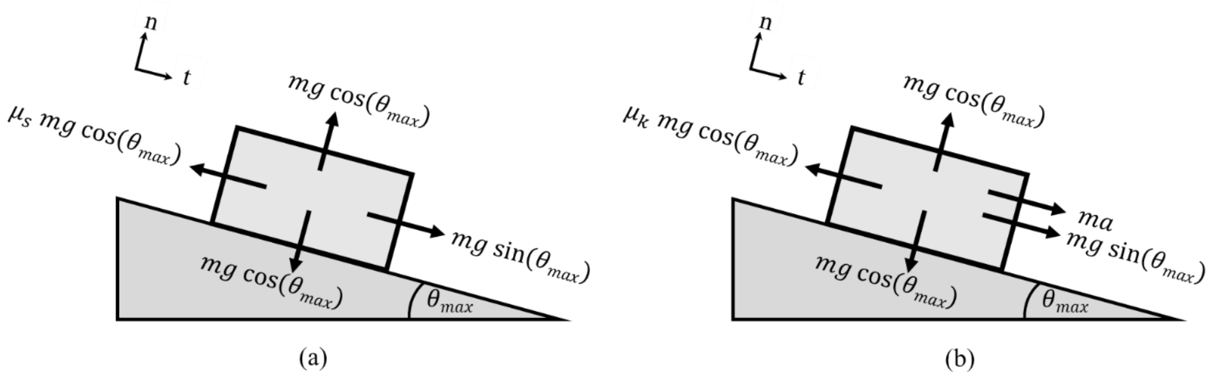


Figure 17. (a) Free body diagram for sled just before it started to slide on the seat pan. The frictional force before the sled started to slide was determined by coefficient of static friction. (b) Free body diagram for when the sled started to slide on the seat pan. The frictional force after the sled started to slide was determined by coefficient of kinetic friction. The axis parallel to the inclined surface was in the t-direction and perpendicular to the inclined surface was the n-direction

To determine the time-point when the sled started to slide on the seat pan, a difference, d, between r and the moving average of r from the 50 preceding time points was calculated at each time point. The last time point when the value of d was less than 1mm was determined as the time point just before the sled started to move (Figure 18). Thus, the coefficient of static friction was calculated at that time point, and the coefficient of kinetic friction was calculated and averaged between the 5 time points just after that time point.

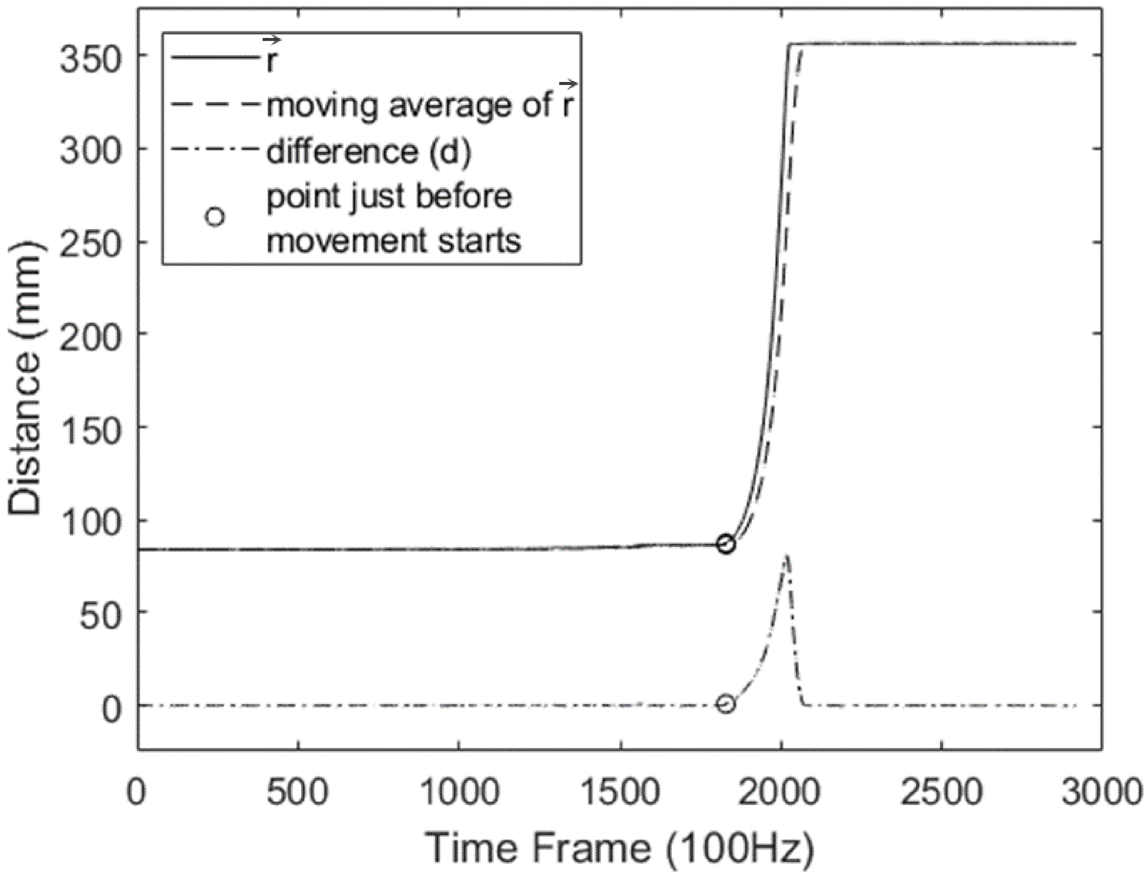


Figure 18. A sample plot showing the position of the sled along the depth of seat pan (r), the moving average of r and the difference between r and its moving average (d). The circle indicates the point just before the sled started to move. The static friction was calculated at this point and the kinetic friction was calculated and averaged among the five points just after that point

To calculate the kinetic coefficient of friction, the acceleration of the sled plays an important role as evident from Equation 6. Thus, the velocity of the sled during sliding was calculated which was then used to determine the acceleration during sliding. The velocity of the sled along the direction of motion was calculated using the position of the sled at each frame and the known frequency of data collection (100 Hz). The difference in the sled position between motion capture frames was divided by the amount of time between frames to yield the average velocity between the two frames. The acceleration of the sled between frames was determined by dividing the change in velocity between each frame and the time period between them. The average acceleration during five time points after the point when the sled started to move was used to calculate the kinetic coefficient of friction. The force balance equation used to determine the coefficient of kinetic friction is given in Equation 5, with the resulting definition of the coefficient of kinetic friction in Equation 6. Lastly, the free body diagram for the calculation of the coefficient of kinetic friction (μ_k) is shown in Figure 17b.

$$\sum F_t = m\vec{a} - \mu_k mg\, cos(\theta_{max}) + mg\, sin(\theta_{max}) = 0 \tag{5}$$

$$\mu_k = tan(\theta_{max}) - \frac{|\vec{a}|}{g\, cos(\theta_{max})} \tag{6}$$

Where, $\vec{a}$ was the acceleration of the sled system.

3.2.4 Determination of Yarn Thickness

A digital microscope (Keyence, Osaka, Japan) was used to capture magnified images of the fabric structures of all fabrics and to measure the thickness of the yarn in each fabric. All the images were captured with 50x magnification. The thickness of three random strands of the yarn in the digital image was measured and averaged to obtain the yarn thickness. In the case of vinyl, the largest diameter of three random plateaus was measured instead of the yarn thickness as the vinyl surface consisted of plateaus and valleys instead of typical, intertwined yarn (Figure 15).

3.2.5 Determination of Surface Roughness

Average surface roughness (R_a) was used as a parameter to characterize surface roughness of the fabrics (Figure 19). Surface roughness was measured using a stylus profilometer (Surfcom 50, Midwest Metrology, Holland, Michigan, USA). R_a was defined as an average of profile deviation (change of depth of the fabric) from a mean line, where the mean line was an imaginary line that divided surface profile into two halves, a peak half and a valley half (Figure 19) such that the total areas of both halves were equal. A diamond tip traversed each fabric in a straight line, measuring the surface deviation and providing the roughness measurement. Five roughness measurements were taken, averaged, and reported as a roughness value for each fabric. The roughness was measured in the direction of fabric in which sliding across the fabric took place (Figure 14), and this direction was kept the same for each repetition.

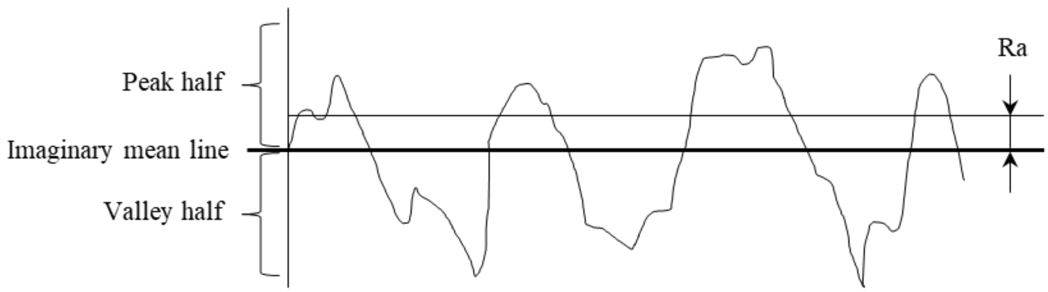


Figure 19. Illustration of surface roughness profile. Average surface roughness (R_a) was defined as an average of profile deviation from a mean line where mean line was an imaginary line that divides surface profile in two halves, peak half and valley half such that the areas of both halves were equal

3.3 Results

The trends in static friction for various conditions are presented in each of the sub-sections below. For each condition, the coefficients of kinetic friction followed similar trends as the coefficients of static friction.

3.3.1 Vinyl Seat Cover without Foam

The mean and standard deviations of the coefficients of static and kinetic friction between the seven pants fabrics and the vinyl seat cover without foam are presented in Table 4. Men's khakis and men's jeans, which were both 100% cotton twill weave fabrics, demonstrated coefficients of static friction as 0.540 and 0.585 respectively. Women's jeans and sweatpants, both comprised of cotton-polyester blend, demonstrated coefficients of static friction 0.546 and 0.539. Both women's jeans and sweatpants were smaller than men's jeans (0.585). Women's pull-on pants demonstrated the smallest coefficient of static friction (0.492) and basketball shorts the largest (0.590), despite both being comprised of 100% polyester. As expected, the fabrics with larger coefficients of static friction also demonstrated larger coefficients of kinetic friction.

Table 4 The static and kinetic coefficients of friction between tested pant fabrics and vinyl seat cover without foam on the seat pan

Fabric Type	Composition	μ_s	μs (SD)	μ_k	μ_k (SD)
Women's pull on pants	100% polyester	0.492	0.025	0.457	0.012
Women's khakis	93% cotton, 7% spandex	0.502	0.016	0.497	0.021
Sweatpants	60% cotton, 40% polyester	0.539	0.015	0.512	0.010
Men's khakis	100% cotton	0.540	0.014	0.509	0.010
Women's jeans	75% cotton, 24% polyester, 1% spandex	0.546	0.018	0.524	0.020
Men's jeans	100% cotton	0.585	0.016	0.552	0.013
Basketball shorts	100% polyester	0.590	0.031	0.553	0.015

With the vinyl seat cover, women's khakis and women's jeans demonstrated a behavior not seen in the other pants fabrics. When the seat pan was tilted, the sled started to slide but would then stop. After the sled stopped, the seat pan needed to be further tilted to start the sled sliding again. This occurred in more than 50% of the trials for the women's khakis, which contained 7% spandex. This behavior was also observed, but only for a few trials of the women's jeans, which also contained spandex (1%). In these cases, the coefficients of friction were calculated for the last angle of tilt after which there was uninterrupted sliding of the sled.

3.3.2 Vinyl Seat Cover with Foam On

The mean and standard deviations of the coefficients of static and kinetic friction between the seven pants fabrics and the vinyl seat cover with foam underneath the seat cover are presented in Table 5. With the presence of foam on the seat pan underneath the vinyl cover, the coefficient of static friction values for all the pant fabrics were larger compared to the values without foam in the seat pan. However, all the pant fabrics demonstrated similar trends in coefficient of static friction as those without the foam, except for the sweatpants and men's khakis. As with the trials without the foam, the women's pull-on pants demonstrated the smallest coefficient of static friction (0.548) and basketball shorts demonstrated the largest coefficient of static friction (0.661). With foam, the sweatpants had a larger coefficient of static friction of 0.570 where men's khakis was 0.555.

3.3.3 Office Seat Cover Without Foam

The mean and standard deviations of the coefficients of static and kinetic friction between the seven pants fabrics and the office seat cover without foam are presented in Table 6. The women's jeans demonstrated the largest coefficient of static friction (0.428), and the basketball shorts the smallest (0.281). With the office seat cover, the coefficient of static friction values for sweatpants, men's jeans and women's jeans were similar (0.414, 0.422, 0.428). The coefficient of static friction for women's khakis and men's khakis were also similar (0.343, 0.345). All the pant fabrics demonstrated smaller coefficients of static friction with the office seat cover compared to the vinyl seat cover (Figure 20).

Table 5. The static and kinetic coefficients of friction between tested pant fabrics and vinyl seat cover with foam underneath the seatcover on the seatpan

Fabric Type	Composition	μ_s	μs (SD)	μ_k	μ_k (SD)
Women's pull on pants	100% polyester	0.548	0.032	0.510	0.019
Women's khakis	93% cotton, 7% spandex	0.549	0.010	0.544	0.010
Sweatpants	60% cotton, 40% polyester	0.572	0.021	0.518	0.006
Men's khakis	100% cotton	0.555	0.021	0.530	0.022
Women's jeans	75% cotton, 24% polyester, 1% spandex	0.610	0.016	0.573	0.010
Men's jeans	100% cotton	0.635	0.017	0.612	0.007
Basketball shorts	100% polyester	0.661	0.042	0.597	0.020

Table 6. The static and kinetic coefficients of friction between tested pant fabrics and office seat cover without foam on the seat pan

Fabric Type	Composition	μ_s	μs (SD)	μ_k	μ_k (SD)
Basketball shorts	100% polyester	0.281	0.016	0.278	0.016
Women's khakis	93% cotton, 7% spandex	0.343	0.038	0.341	0.038
Men's khakis	100% cotton	0.345	0.03	0.342	0.028
Women's pull on pants	100% polyester	0.376	0.029	0.368	0.029
Sweatpants	60% cotton, 40% polyester	0.414	0.037	0.402	0.032
Men's jeans	100% cotton	0.422	0.033	0.416	0.031
Women's jeans	75% cotton, 24% polyester, 1% spandex	0.428	0.026	0.421	0.024

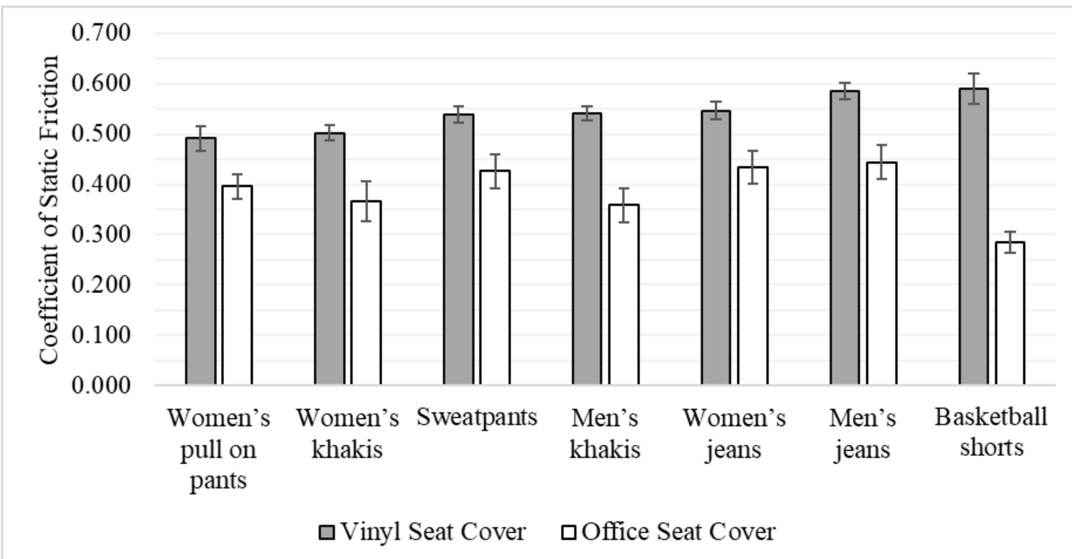


Figure 20. Coefficient of static friction between seven pant fabrics and two seat covers without the foam in the seat pan. The coefficients of static friction for each of the pant fabrics were larger with the vinyl seat cover than with the office seat cover

3.3.4 Office Seat Cover with Foam On

The mean and standard deviations of the coefficients of static and kinetic friction between the seven pants fabrics and the office seat cover with foam underneath the seat cover are presented in Table 7. With the presence of foam on the seat pan underneath the office cover, the coefficient of static friction values for all the pant fabrics were larger compared to the values without foam in the seat pan. However, overall, the coefficients of friction for were smaller compared to the vinyl cover, both with and without the foam. All the pant fabrics demonstrated similar trends in coefficient of static friction values as those without the foam. Basketball shorts demonstrated the smallest coefficient of static friction (0.308) and women's jeans demonstrated the largest coefficient of static friction (0.493).

Table 7. The static and kinetic coefficients of friction between tested pant fabrics and office seat cover with foam underneath the seat cover on the seat pan

Fabric Type	Composition	μ_s	μs (SD)	μ_k	μ_k (SD)
Basketball shorts	100% polyester	0.308	0.010	0.304	0.010
Women's khakis	93% cotton, 7% spandex	0.375	0.029	0.372	0.028
Men's khakis	100% cotton	0.379	0.027	0.374	0.026
Women's pull on pants	100% polyester	0.381	0.016	0.377	0.017
Sweatpants	60% cotton, 40% polyester	0.449	0.020	0.438	0.023
Men's jeans	100% cotton	0.486	0.037	0.475	0.036
Women's jeans	75% cotton, 24% polyester, 1% spandex	0.493	0.039	0.484	0.036

3.3.5 Yarn Thickness

The yarn thickness of the pant fabrics in micrometers (µm) are presented in Table 8. The basketball shorts had the smallest yarn thickness (207.50µm), and the women's pull-on pants had the largest (452.67 µm) among the pant fabrics. The yarn thickness of men's jeans and sweatpants were toward the larger size for this selection of fabrics with similar values (312.00 and 312.50 µm). The yarn thickness of the office fabric seat cover was 565.00 µm. The construction of vinyl was different than all the other fabrics in that it did not have distinguishable fabric yarns. The vinyl construction comprised of plateaus (raised areas) and valleys (depressed areas). The plateaus were visibly larger than the valleys. Since there were no yarns, the width of the plateaus was measured. The width of the plateau in the vinyl was 1237.50 µm.

3.3.6 Roughness Values

The roughness values of the fabrics tested are presented in Table 9. Between the seat pan covers, the vinyl had the smaller surface roughness (21.58 µm) and the office fabric had the larger roughness (73.32 µm). Among the pant fabrics, the basketball shorts had the smallest roughness (31.59 µm) and the men's jeans had the largest (55.14 µm).

Table 8. Yarn thickness of the pant fabrics tested in micrometers

Fabric	Yarn thickness in micrometers (µm)	Yarn thickness (SD)
Basketball shorts	207.50	28.63
Womens khakis	212.75	16.40
Mens khakis	233.23	13.36
Women's jeans	234.00	24.71
Men's jeans	312.00	34.26
Sweatpants	312.50	20.87
Womens pull on pants	452.67	55.43

Table 9. Surface Roughness (R_a) values of the pant fabrics and the seat covers in micrometers

Fabrics	R_a values in micrometers (Average, µm)	R_a values (SD, µm)
Vinyl	21.58	2.17
Basketball Shorts	31.59	1.15
Women's Khakis	40.17	1.27
women's pull on pants	40.88	1.17
Men's Khakis	47.04	0.70
Women's Jeans	51.00	2.77
Sweatpants	52.04	5.51
Men's Jeans	55.14	3.03
Office Fabric	73.32	4.86

3.4 Discussion

Since shear forces are a factor that increases risk for PI formation, identifying material pairings with smaller coefficients of frictional is a strategy to decrease the risk of developing PIs.

Therefore, our results indicated that fabrics such as denim and basketball shorts were not optimal pant choices when paired with vinyl as they had larger coefficients of friction. These data suggested that if seated on vinyl, women's pull-on pants and women's khakis were better choices, as they had lower coefficients of friction. Data also indicated that, when paired with vinyl, the coefficients of friction for *all* the pant fabrics were higher than with the office seat fabric cover. This is likely attributed to the larger contact area between the vinyl surface and the pants fabrics, as suggested from the microscopic images and measurements. The vinyl surface was comprised of large flat plateaus which provided large contact surface areas as compared to the office fabric. The office fabric, because of the woven construction, had regular peaks and valleys, likely resulting in a lower overall area of contact. Since vinyl is commonly used in seat covers, such as those in wheelchairs, choosing an alternative seat cover that provides lower frictional coefficients might be beneficial for wheelchair users.

With *all* of the pants fabrics, the office fabric seat cover produced smaller coefficients of friction values than the vinyl. With the office seat cover, the khakis and the basketball shorts had the smallest coefficient of friction, and therefore, they were likely more effective at reducing shear than jeans. Moreover, the largest coefficient of friction produced with the office cover (women's jeans) was smaller than the smallest coefficient of friction produced with the vinyl cover (women's pull-on pants). Traditionally, vinyl is seen as easily cleanable, durable and is the most popular choice for foldable wheelchairs. Thus, substituting the traditional vinyl seat cover for an office-type fabric seat cover might be a good approach to obtain lower friction at the seat interface.

The effect of foam on the coefficients of friction was also considered. Many customized wheelchairs have a foam cushion on the seat pan. The data from this study indicated that the presence of foam underneath the seat cover increased the coefficient of friction in the seat interface.

This difference was due to the presence of deformable material, which added a contour and additional resistance to the motion between surfaces. Foams are normally used in wheelchairs to reduce the pressure concentration around bony prominences. So, it is important to also be aware of the increase in friction due to the presence of foam.

The results obtained from this study also demonstrated the complexity of frictional behavior of fabrics. For example, there were differences in the coefficients of friction between the basketball shorts and women's pull-on pants when they interacted with the vinyl cover, even though the pants were both 100% polyester. This difference between fabrics of the same composition could be due to various factors, including the finish of the fabrics and density of the yarn used to make the fabric, although we were not able to directly measure those properties [124], [172]. Further, there were visual differences in the fabric construction or tightness of the weave. The basketball shorts were more loosely knit whereas the women's pull-on pants had tight woven construction, as evident from the microscopic images (Figure 14). Literature has shown that the tighter fabric constructions correlate to lower coefficients of friction [125]. The results from the basketball shorts and the women's pull-on pants agreed with the literature with regard to the interaction with vinyl seat cover, but not with the office cover. This is because the tighter, woven pull-on pants had a smaller coefficient of friction with vinyl, but the same was not true with the office cover. The women's pull-on pants also had a larger roughness value which might contribute to the higher coefficients of friction. But this fabric also had tighter weaves than basketball shorts which in theory should lead smaller coefficients of friction. These data indicate that it is difficult to predict the effects of a single physical property of fabric in relation to the friction behavior as there is an interaction with many factors e.g., weave, composition, finish, tightness.

Furthermore, it was interesting that while the basketball shorts demonstrated the largest coefficient of friction with the vinyl seat cover, this fabric demonstrated the smallest coefficient of friction with the office seat cover. This complexity of frictional behavior of the basketball shorts is likely attributed to the material properties of the fabrics in contact as well as the surface area in contact [174], [175]. The smaller yarn thickness and loosely knit construction of the basketball shorts led to smaller friction values with the office fabric cover. Although this work has helped us understand the general interactions associated with two seat covers, a future study focusing on assessment of all these properties would provide a more in-depth understanding of the contributions of these factors to friction.

The data also showed an interesting relationship between the roughness values of fabrics and the coefficients of friction. There was the inverse relationship between roughness values and coefficient of friction with the seat covers. The vinyl cover, with the smallest roughness yielded larger coefficients of friction with all fabrics whereas the office cover with the largest roughness value yielded in smaller coefficient of friction with all pant fabrics. Furthermore, the basketball shorts (smaller roughness) yielded the highest friction with vinyl (smallest roughness) whereas yielded lowest friction with office fabric cover (largest roughness). From these results, one can hypothesize that larger roughness values generally result in larger friction, but if the roughness values are too small, that might also increase friction as this may lead to a larger contact area between two surfaces. There might be an optimal set of roughness values for pant and the seat fabric which will decrease the coefficient of friction. There is also a possibility that due to vinyl being different than other fabrics in terms of construction and material properties, it exhibited a different trend with respect to the correlation between surface roughness and coefficient of friction.

Additionally, a phenomenon was observed only with women's jeans and women's khakis on the vinyl seat cover when data were collected without foam in the seat pan. The sled slid a small distance and then stopped. After which, a further increment of seat pant tilt angle was required before the sled could slide without interruption. Even though the fabrics were secured tightly, the women's jeans and women's khakis had some spandex content which could have resulted in a small amount of localized stretching of the fabrics during sliding. This stretching is possibly what led to an apparent increase in coefficient of friction, indicating that the friction coefficients of fabrics increased in stretched conditions compared to its original state. The stretchy athletic fabrics, which are chosen for their smaller coefficients of friction, might actually generate larger friction when they are stretched, as stretching leads to looser fabric construction, and this needs to be considered when choosing of pant fabric.

3.5 Limitations and Future Works

This study used a mechanical device and motion capture system to compute coefficient of friction. In the future, using people in the seat (in place of sled) to gather data would be ideal to identify the frictional behavior in the presence of deformable human tissue. However, this presents numerous challenges such as securing the fabric around human buttocks without bunching, or the control of the torso when tilting the seat pan, as well as the safety of participants when inducing sliding with larger seat pan tilts. Furthermore, there were likely differences in the finish of the fabric, density of the yarn or tightness of the weave that this study was not able to quantify. Analyzing those properties and their effect on the coefficient of friction would be helpful to understanding how to predict or model frictional properties. Similarly, the surface chemistry and the force of adhesion present in the fabric interface could also affect the coefficient of friction which were beyond the scope of this study.

3.6 Conclusions

In summary, the results of this study showed that the coefficients of friction varied with different pant and seat pan fabrics. Optimization of fabrics could be a potential strategy for reducing shear at the seat interface, thereby addressing one of the risk factors associated with the development of PIs. Thus, there is a need for better guidelines and an improved understanding of frictional behavior of pant fabrics and seat covers, particularly for wheelchair users. Based on the data collected in this study, fabric covers similar to the ones used in office chairs might be a better alternative to the vinyl ones used in wheelchairs; the choice of pant fabric might be of smaller concern with the office seat cover as the data suggested that every pant fabric resulted in a smaller coefficient of friction with the office seat cover. This work provides a new knowledge with regard to fabric interactions at the seat pan-pant interface. However, there is much more work necessary in this area.

CHAPTER 4: COEFFICIENT OF FRICTION BETWEEN PANT FABRICS AND SEAT COVERS: *IN-VIVO* DATA USING A NOVEL APPROACH

4.1 Introduction

Wheelchair users frequently suffer from pressure injuries (PIs), a costly and debilitating health problem [176]. These injuries develop when soft tissues are continuously compressed and affect an estimated 2.5 million people each year in the United States alone [107], [159]. Patients with PIs have experienced reduced quality of life, in addition to the physical pain as well as other health complications which can even lead to death [18], [163], [164]. Furthermore, the yearly financial burden of treating PIs in the US was estimated to be $27 billion [45], [177].

Shear force and friction are among the factors that have been known to increase the risk of PI formation [43], [101]. Research has shown that shear forces on the skin contribute to tissue ischemia and internal stresses in the tissues which can lead to PI formation [170]. When a person is seated in a chair or wheelchair, rearward-directed shear forces have been observed in the buttocks and thigh region, especially under the ischial tuberosity (bottom of the buttocks) region [121], [167], [178]. This is a factor of concern, as the tissues surrounding ischial tuberosity is one of the most common sites for PI incidence in wheelchair users. Thus, it is important to reduce the shear forces occurring in the wheelchair seat pan, and one way to achieve that is through the understanding of frictional interactions between the fabric of pants worn by the user and the wheelchair seat cover.

At the wheelchair seat interface, there are many layers of materials and corresponding frictional interaction between them. The person's skin is in contact with the pant material and underneath this is the wheelchair seat cover, seat cushion and a rigid surface supporting the cushion. Although there are frictional interactions and possible sliding between each of these pairs, the most likely pair to slide with each other are the pant fabric and the seat cover. Smaller friction between these fabrics will allow the person to slide in the seat pan easily thereby reducing the shear force. Thus, reducing the friction between the pant material and the wheelchair seat cover can reduce the shear loading on the buttocks and thigh regions. This can be especially helpful in patients who use repositioning methods for pressure relief such as back recline or seat pan tilt, as there can be large shearing if the skin is not able to slide properly during the posture change [120].

Understanding the frictional interaction between the wheelchair seat pan and occupant is challenging because there are two sliding fabrics, underneath both of which are deformable materials: human tissue underneath the pant and a foam seat cushion underneath the seat cover. In the past, researchers have tried to understand the frictional interaction between skin and fabrics [179]–[181]. Various studies have also tried to understand the factors that affect the coefficient of friction of fabrics, mostly when paired with itself [125]–[127], [129]. These studies concluded that the factors that can influence the coefficient of friction include yarn properties, type of fabric construction, tightness of fabric weave and fabric roughness [124], [125], [128]. However, to get a more realistic understanding of the friction and shear forces at the bottom of the buttocks, there is a need to study these parameters in a wheelchair like setting, where the fabrics are sliding with each other while including the deformable materials (human and foam). Thus, the purpose of this study was to determine the shear forces and the coefficient of static friction between two seat covers and five common pant fabrics through the development and utilization of a novel *in-vivo* experimental set up that permitted sliding of the human buttocks on the seat pan.

4.2 Methods

Data collection for this research was carried out using a novel experimental set up that allowed sliding of human buttocks in a wheelchair-like seat pan. The material and devices used in the experimental setup included a linear actuator, a chair with the seat cover fabrics attached in the seat pan, a multi-camera motion capture system, a six-axis force plate and a six-axis load cell.

4.2.1 Experimental Setup

A unique experimental setup and protocol was developed for this research. The diagram of the experimental setup is presented in Figure 21. The participants were seated on the custom apparatus with their buttocks positioned all the way to the back of the seat pan. A sling was wrapped around their pelvis which was then attached to the linear actuator. The actuator was operated such that the participants slid towards the front of the seat pan. The participants were asked to cross their arms on the chest and rest their feet on a platform with wheels. The floor was lined with a slippery nylon fabric to reduce friction and facilitate smooth sliding of the foot support as the buttocks were pulled forward. Moving the legs with the buttocks permitted the knees to stay at the same angle. The participants were positioned with a knee angle of 100° and a thigh to torso angle of 90°. A patella strap was attached to their knees to keep the pants tight and prevent the pant fabric from creasing during the motion. During the sliding process, the participants were instructed to keep their posture intact, as much as possible while their legs and feet slid with the moving foot system.

A MC3A load cell (AMTI, Watertown, MA) was mounted on the end of the linear actuator to measure the pulling force. The load cell was calibrated in the mounted position prior to the data collection. The force plate (Bertec, Columbus, OH) was mounted underneath the seat pan of the chair to measure the load in the seat pan. The force plate was calibrated prior to the data collection. A piece of polyurethane foam with density of 68 kg/m^3 and thickness of 3.9 cm was attached underneath the seat cover to mimic the seat of a wheelchair. Reflective markers of 15 mm diameter were attached to the left and right greater trochanter as well as left and right lateral femoral epicondyle of the participants. The position of the markers during the movement was obtained using the motion capture system with an accuracy of 1mm. The data from the motion capture system, force plate and the load cell were synchronized, and all data were collected with a sampling rate of 100 Hz. The motion and force data for each pant fabric and seat cover pair were collected for 3 repetitions with all participants.

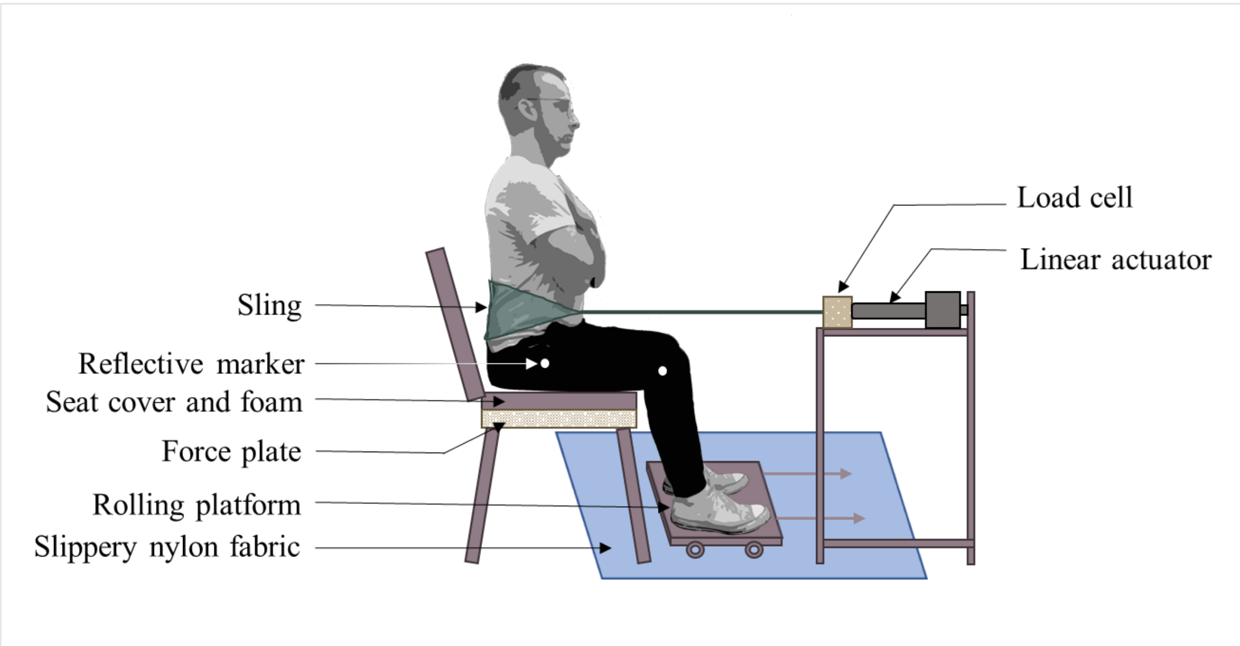


Figure 21. Schematic diagram of the experimental setup

4.2.2 Pant Fabrics and Seat Cover Materials Tested

Five different pant fabrics were tested: jeans, khakis, sweatpants, basketball shorts and women’s pull on pants. The fabric composition and fabric construction of the pant fabrics are listed in Table 10. Two different seat covers were tested: a vinyl seat cover commonly used in wheelchairs and a fabric seat cover commonly used in office chairs.

Table 10. Details of the five pant fabrics tested. The woven fabrics were all twill weaves

Pant type	Composition	Construction
Jeans	100% cotton	Woven
Khakis	97% cotton, 3% spandex	Woven
Women’s pull-on pants	100% polyester	Woven
Basketball shorts	100% polyester	Knit
Sweatpants	60% cotton, 40% polyester	Knit

4.2.3 Participants

This study was approved by Michigan State University Institutional Review Board (IRB number 8713) and consent was obtained from all participants. Individuals were eligible to participate if they were at least 18 years old, not pregnant, did not have any surgeries in the past six months and were able to sit upright without any seatback for 30 minutes. Twelve volunteers (six males and six females) participated on the study. The average age of the participants was 24.5 (±5.5) years, and their average body mass index (BMI) was 22.5 (±2.8) kg/m^2.

4.2.4 Calculation of the Static Coefficient of Friction

The force exerted by the linear actuator and the normal force acting on the seat pan during the sliding process were used to calculate the coefficient of friction between the seat pan cover and the pant fabric. Figure 22 shows a block weight system as a representation, just before the movement started. The right portion of Figure 22 presents the system of forces with a human sitting in a chair, instead of a block weight. The force balance in the Y direction is presented in Equation 1 with the resulting definition of the coefficient of static friction in Equation 2.

Having a human on the seat pan differs from the block weight system in that a certain portion of their body weight is transferred to the ground through the feet of the person. Thus, the normal force exerted on the force plate underneath the seat pan of the chair (W) was obtained from the force plate and was used calculate the coefficient of static friction using Equation 2. The external applied force (F) was obtained from the load cell attached to the linear actuator. The coefficient of static friction was calculated at the time point when the value of F (pulling force) was maximum (details below regarding the loading).

$$F = \mu_s W \qquad (1)$$

Where F is the applied external force, μ_s is the coefficient of static friction and W is the weight of the body into the seat pan.

$$\mu_s = F/W \qquad (2)$$

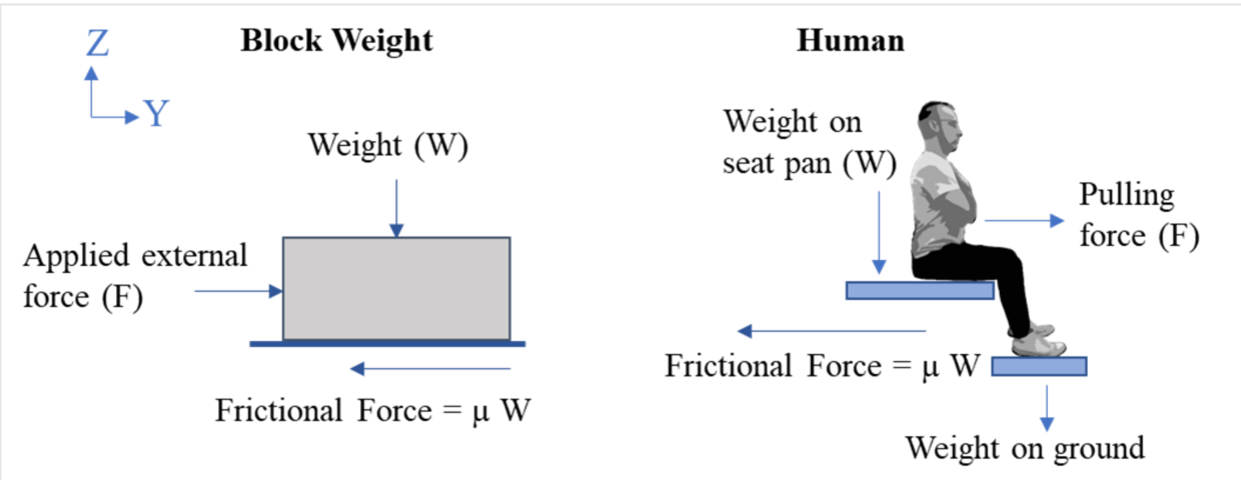
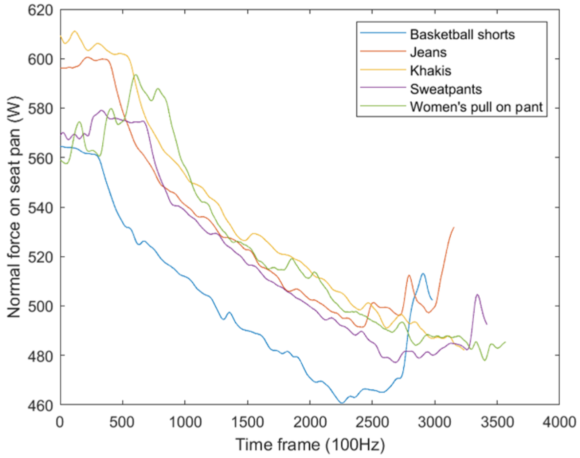


Figure 22. Diagram of a block weight system (left) and a human system (right) just before the movement started under an applied external pulling force

Because there was variation in the human weight on the seat pan, an initial analysis had to be conducted on the force data to identify the appropriate time points for calculating the coefficient of static friction. Figure 23 presents a sample plot of the normal force in the seat pan during the test. The normal load on the seat pan decreased as the participants were pulled forward and kept on decreasing as they started to slide on the seat pan. The trend of the plots was similar with both the vinyl and office covers as well as for all five pant fabrics.



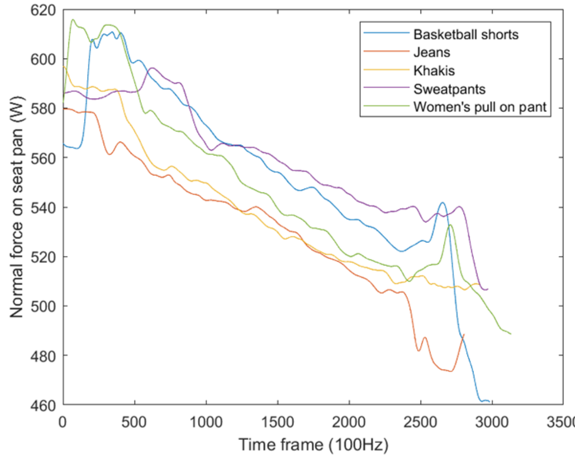


Figure 23. Sample plot of normal force in the seat pan during sliding with vinyl cover (left) and office cover (right)

Figure 24 presents a sample plot of the position of the buttocks and knees of the person as well as the change in the pulling force and shear force in the seat pan during the sliding process. The values of the pulling force and the shear force in the seat were nearly equal with slightly larger values of pulling force. Normally, the pulling force is expected to be largest just before the sliding starts and the coefficient of friction is calculated at that point. But due to the presence of deformable tissue, this was not the case with human data. The movement of the knee and buttocks started at point A whereas the pulling force was maximum at point B (Figure 24). When comparing the movement plots and the force data, the movement of the buttocks and the knees started earlier than the time point where the forces were maximum. The positional markers were applied to the bony landmarks of the body. This indicated that the anterior tissue of thigh and the bones moved as soon as the pulling force was applied, but the skin (and the pants) did not. Thus, the coefficient of friction was calculated at the time point where value of the pulling force was maximum as that was the time point just prior to when the true sliding started.

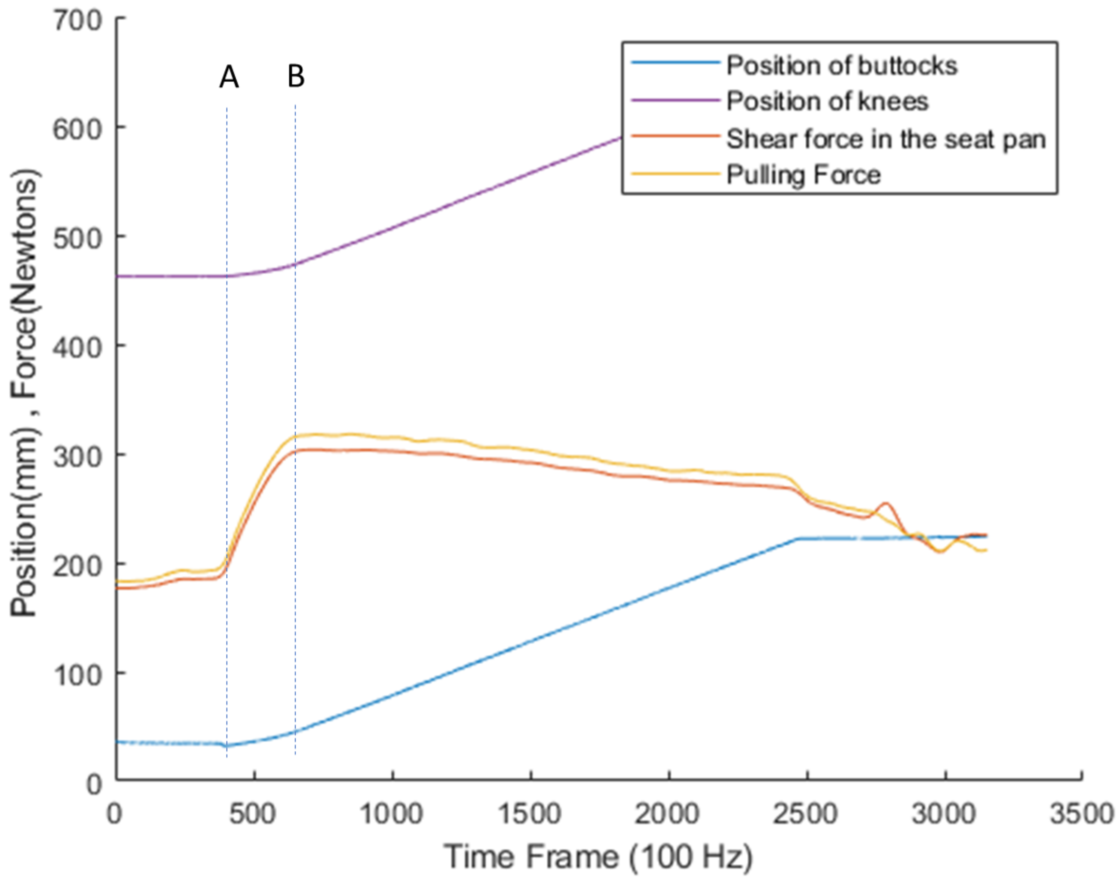


Figure 24. A sample plot showing the position of the buttocks and knees as well as the pulling force and the shear force in the seat pan during sliding process. Coefficient of static friction was computed at point B, which is the point just prior to sliding

4.3 Results

The mean and standard deviations of the coefficient of static friction between the pant fabrics and the seat cover are presented in Table 11. With the vinyl seat cover, the women's pull on pants displayed the smallest coefficient of friction (0.503) and the basketball shorts displayed the largest (0.572). With the office seat cover, the basketball shorts displayed the smallest (0.336) coefficient of friction and jeans the largest (0.448).

Table 11. Means and standard deviations of coefficient of static friction between the pant fabrics and the seat covers. Each side of the table is presented in ascending order for the friction values

Vinyl Cover			Office Cover		
Pant Fabric	Mean	SD	Pant Fabric	Mean	SD
Women's pull on pants	0.503	0.055	Basketball Shorts	0.336	0.032
Sweatpants	0.540	0.043	Women's pull on pants	0.405	0.049
Khakis	0.550	0.056	Sweatpants	0.424	0.041
Jeans	0.556	0.041	Khakis	0.445	0.049
Basketball Shorts	0.572	0.043	Jeans	0.448	0.038

Table 12 presents the mean and standard deviation of maximum shear force present in the seat pan with different pairing of seat covers and pant fabrics. Each is presented in increasing value of the coefficient. Table 13 presents the mean and standard deviation of the normalized maximum shear force (force per kilogram of body mass) present in the seat pan with different pairing of seat covers and pant fabrics. As expected, the maximum shear force followed similar patterns as the coefficient of friction. The fabric pair with larger coefficient of friction had larger force present and vice-versa.

Figure 25 presents a sample plot of the pulling force on the linear actuator during the initial application of force to the person followed by the sliding process of the person once static friction is overcome. There were clear differences in the trends that occurred in the pulling forces between the two seat covers. In general, the pulling force started to increase, reached a maximum value and then started to decrease for both the seat covers. However, with the office cover, there was a sharp decrease in the pulling force immediately after the peak value and then the rate of decrease was smaller.

Table 12. Means and standard deviations of maximum shear force (in Newtons) present in the seat pan with different seat cover and pant fabric pairing. Each side of the table is presented in ascending order for the shear force values

Vinyl Cover			Office Cover		
Pant Fabric	Mean (N)	SD (N)	Pant Fabric	Mean (N)	SD (N)
Women's pull on pants	248	45	Basketball Shorts	172	31
Sweatpants	257	47	Women's pull on pants	207	32
Khakis	266	47	Sweatpants	208	31
Jeans	268	47	Khakis	219	39
Basketball Shorts	274	48	Jeans	221	38

Table 13. Means and standard deviations of maximum shear force per unit body mass (in Newtons/kilogram) present in the seat pan with different seat covers and pant fabrics. Each side of the table is presented in ascending order for the shear force values

Vinyl Cover			Office Cover		
Pant Fabric	Mean (N/kg)	SD (N/kg)	Pant Fabric	Mean (N/kg)	SD (N/kg)
Women's pull on pants	3.57	0.34	Basketball Shorts	2.52	0.33
Sweatpants	3.71	0.37	Sweatpants	3.05	0.35
Khakis	3.85	0.40	Women's pull on pants	3.06	0.46
Jeans	3.87	0.36	Jeans	3.22	0.42
Basketball Shorts	3.95	0.30	Khakis	3.26	0.37

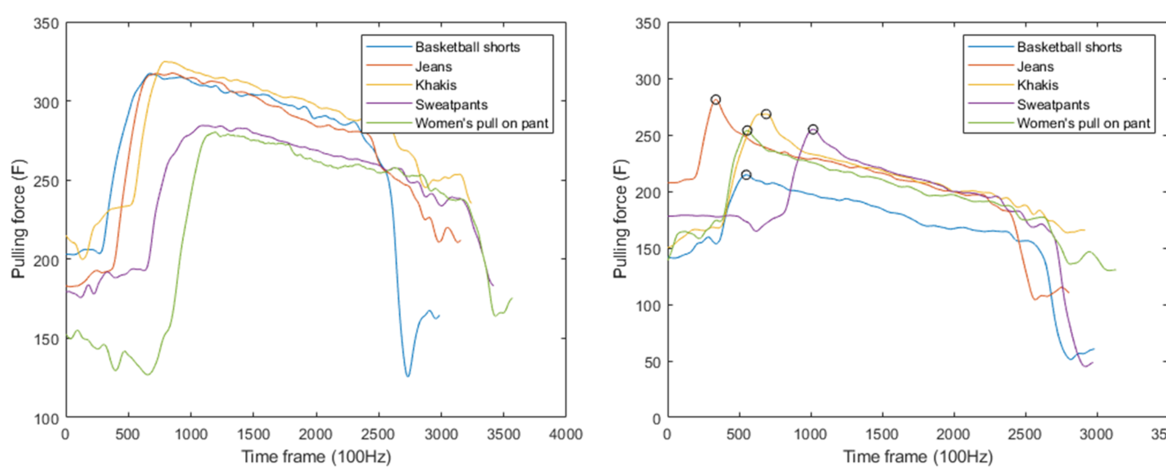


Figure 25. Sample plot of pulling force on the linear actuator during the sliding with vinyl seat cover (left) and office seat cover (right)

Figure 26 presents the sample plot for the ratio (F/W) during the sliding process. The F/W ratio just before the movement provides the coefficient of static friction and during the motion provides the coefficient of kinetic friction. The trends were similar for all the pant fabrics. For the vinyl cover, the magnitude of this force ratio started to increase as the linear actuator started pulling, reached a peak and then plateaued in the same region. With the office cover, the value of the ratio increased as the pulling started, reached a maximum value and then started to decrease. The time period between when the actuator started pulling and when the forces were maximum varied between the subjects and the pants. This is because the slack in the rope connecting the person and the linear actuator affected the length of time required for the person to slide.

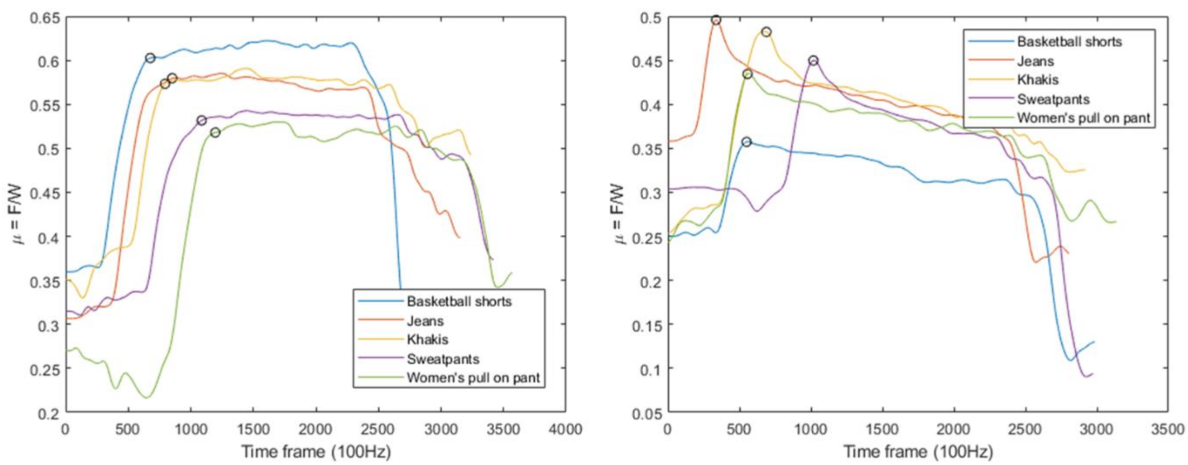


Figure 26. Sample plot of the ratio (F/W) during the sliding with vinyl cover (left) and office cover (right). Circles denote the time point where the pulling force (F) was maximum and the coefficient of friction was calculated at that point

4.4 Discussion

This study determined the shear force and coefficients of friction between two seat covers and five common pant fabrics through the development and utilization of a novel *in-vivo* experimental set up that permitted sliding of the human buttocks on the seat pan. Understanding how the human buttocks slide and the underlying forces and friction behavior of different fabrics in the present of human tissue is imperative in developing strategies to reduce the risk of PIs.

Larger coefficients of friction relate to larger shear forces which are known risk factors of PIs. Thus, identifying material pairs with lower friction and avoiding the material pairings that result in higher friction can be a good strategy to reduce the risk of PI formation. The results of this study indicated that the jeans and khakis were not optimal pant choices from the standpoint of reducing friction. These pants consistently produced larger coefficients of friction with both seat covers. The basketball shorts produced the lowest coefficient of friction with the office cover and the highest with the vinyl cover which is consistent with the results obtained in Chapter 3. The results of this study also support the finding of Chapter 3 that the seat cover used in office chairs would be a better alternative to the traditional vinyl used in wheelchairs because of the consistently smaller coefficient of friction produced by office seat cover with all the pant fabrics.

This study provided further evidence that the traditional vinyl cover is not optimal with regards to friction and shear force as the shear forces and friction were higher even after the sliding started as demonstrated by Figure 26. Generally, the frictional force is largest just before the motion starts, which is governed by the coefficient of static friction. After the body starts sliding, the kinetic friction comes into play, which is smaller in magnitude than the coefficient of static friction. With the office fabric, the ratio of the pulling force and the seat pan force (which determines the coefficient of friction) decreased once the sliding of the fabrics started. On the contrary, it did not decrease on the vinyl even after the sliding started. This means that the wheelchair users are exposed to large values of shear force at the seat interface when a vinyl cover is used and will benefit from an alternative seat cover.

There are many additional variables that need to be considered when collecting a dataset with human subjects as opposed to mechanical devices. With a dead weight system, when a body slides on a level surface, the normal force provided by the weight of the body is constant. However, in this experimental setup, the normal force in the seat pan was not constant throughout the data collection. As the pelvis experienced the forward pulling force, the normal force in the seat pan started to decrease. This was likely due to the participants shifting their weight on the feet.

Furthermore, it was expected that the shear forces would be largest just before the initiation of body movement. However, it is evident from Figure 24 that the movement of the hips and the knees started much earlier than the point of maximum shear force. This was because the markers were attached to the boney landmarks. As soon as the body started experiencing the pulling force, the anterior part of the thigh and buttocks including the bones started moving forward whereas the skin, which was in contact with the seat pan was still stationary. This leads to the conclusion that the soft tissues of the thighs and buttocks were subjected to internal shear. This is a challenge, especially in situations where they use repositioning features such as a backrest recline, or seat pan tilt; as changing positions can lead to similar phenomenon. The portion of the body not in contact with the chair will move whereas the skin will not, which will lead to internal shearing in the tissues, thereby increasing the risk of PIs. Thus, it is beneficial to identify the fabric pairs that reduce the friction and facilitate easy sliding of the skin on wheelchair surface to reduce the risk of tissue shearing and PIs in wheelchair users.

4.5 Limitations

In this study, the coefficient of friction between the pant fabric and the seat cover was determined with an assumption that there is no sliding between the pant and the skin or the seat cover and the seat cushion. However, in reality there is a possibility of a small amount of sliding in between those surfaces even though every attempt was made to limit that from occurring. This can be considered a limitation of this study. Additionally, the pant fabrics used with the mechanical device were not identical to those used in human trials; they were identical in make-up, but the exact same brand and pant was not available for every item for human testing.

4.6 Conclusions

This study determined the maximum shear force present in the seat interface as well as the coefficient of friction between various pant fabrics and seat covers in a wheelchair like settings using human buttocks. The results of this study showed that the vinyl cover which is traditionally used in wheelchairs might not be the optimal choice to reduce the friction and shear forces on the buttocks. The vinyl cover exhibited higher coefficients of static friction in comparison to the office seat cover. The results also demonstrated that with human tissue, when there are forces acting on the body, the upper part of the thigh and buttocks is likely to move while the skin is still stationary. This increases the shear stress in the internal tissue in the buttocks region, thereby increasing the risk of pressure injuries. Thus, it is essential to optimize the pant fabrics and the wheelchair seat cover to reduce the friction in the seat interface.

CONCLUSIONS

The overarching objective of this work was to understand the body posture and body loading in relation to office workers and wheelchair users. In the office setting specifically, this work aimed to understand the pelvic posture and body loading during a new 'in-between' working position and investigate how it compares with the traditional seated and standing position. In the wheelchair setting, this work aimed to understand the shear forces and coefficient of friction at the seat interface; particulary, the effects of different pant fabrics and seat covers, and how the presence of deformable materials (e.g.,a foam seat cushion and the human buttocks tissue) affected the friction and shear at the seat interface. This study developed the methodology to study friction behavior at human-seat contact surface and quantified the coefficient of friction between pant fabrics and wheelchair seat covers. This is the first work to study friction with humans. The findings of this study will be useful in identifying strategies to reduce the risk of PI formation in wheelchair users.

The results of this study indicated that the new in-between working position provided a more lordotic lumbar posture than the seated posture. In addition, this in-between position had the benefit of a much lower load on the feet in comparison to standing. There was also an increase in blood perfusion during the movement to and from the 'in-between' position. These results suggest that office workers are likely to benefit from the addition of an in-between working position in their workspace. This is because currently, sitting and standing are the only two postures available for office workers. Yet, people mostly work in seated postures, due to various reasons including pain associated with standing. Going forward, conducting these analyses in an actual office setting over a longer period of time would provide better insights, especially in regard to the blood perfusion changes. The design of the chair did not permit the analysis of forces at the seat pan, but the study investigated the ground reaction forces on the feet. The results did not show significant differences in shear forces on the feet between seated and in-between positions. Future studies could explore the shear forces in the seat pan, as shear forces on buttock tissue can be disadvantageous, especially when exposed for long durations of time. Similarly, the effects of the position of the forefoot could also be studied by future research; the position of forefoot directly affects the center of pressure, the loading in the seat pan as well as the joint moments.

A series of experiments were conducted to determine the coefficients of friction between various pant fabrics and seat covers. This study has particular relevance for wheelchair users as friction and shear have been shown to increase the risk of pressure injuries. First, the coefficients of friction between various pant materials and seat covers were determined using a mechanical device. Next, to compare the validity of those results in the presence of human tissue, a novel experimental setup was designed. The setup facilitated the evaluation of the coefficient of friction while an individual wearing a specific pant fabric slid in a seat pan similar to that of a wheelchair. For both studies (the mechanical system and the human participant) results indicated that the vinyl cover (typically used for wheelchair seats) produced a higher coefficient of friction than the office fabric seat cover for all pant fabrics. Thus, replacing the traditional vinyl cover with an alternative such as an office fabric seat cover would be beneficial to the wheelchair users. As expected, the fabric pairings with smaller coefficients of friction also demonstrated smaller shear forces under the thigh and buttocks region. The results also demonstrated the complexity of studying the coefficients of friction between two layers of fabric. The basketball shorts produced the largest coefficient of friction with the vinyl cover but the smallest with the office cover. This is an illustration of the fact that a pant fabric which is optimal with one seat cover might not be the optimal choice with another. There were similarities in the trends observed in the behavior of pant fabrics. The jeans consistently produced large coefficient of friction and the women's pull on pants the smallest. Basketball shorts produced the largest coefficient of friction with vinyl but smallest with the office fabric cover. This study assumed an absence of sliding between the skin and the pant material. However, there is a possibility of sliding between the skin-pant interface and assessing this factor was beyond the scope of methods used in this study. Thus, this is one of the areas that future research should explore.

Overall, these studies provided new information in association with a different office posture and impactful work associated with understanding the frictional behavior of various pant fabrics in concert with wheelchair covers. This research provides significant advancement in association with human seating.

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