Effect of Product Design Characteristics on Biomechanical Performance and User Preferences in the Selection of Wearable Hip Protectors

by

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Ethics Statement

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Abstract

Wearable hip protectors represent a promising strategy for preventing fall-related hip fractures in high-risk older adults. However, research reveals conflicting evidence on their effectiveness, due in part to poor user compliance in wearing the device. This thesis investigates the effect of pad geometry and material properties on both the biomechanical effectiveness and user preferences in product selection. Pad geometry and material properties were found to significantly influence the biomechanical effectiveness of hip protectors. Pads of high thickness, moderate hardness and large surface area provided highest levels of force attenuation (max = 46%). Hip protectors with high level of perceived comfort and protective value achieved the greatest success for overall user acceptance. Participant preferences changed substantially after education on biomechanical performance, shifting to pads of higher thickness and hardness. The optimal pad design was found to possess a thickness of 35mm, hardness of 43 durometer, and surface area of 365 cm^2.

Keywords: Falls; hip fractures; hip protectors; user compliance; biomechanical performance

To my grandparents

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A heartfelt thank you to everyone who has been a part of my graduate studies experience, for without their guidance and consistent support, this thesis would not have been possible.

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To my family, thank you for your love and dedication. To all my friends, I am eternally grateful for the care that you have shown me. Thank you for being by my side during the hard times, cheering me on and celebrating each accomplishment. Your heart-warming kindness and emotional support will forever be remembered and appreciated.

Lastly, a grand thank you to the Almighty for having made everything possible. For giving me the power to believe in my passion and pursue my dream. Thank you for the wisdom and perseverance that you bestowed upon me during my life, for this, I will forever be grateful.

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List of Acronyms

AL	Assisted Living
GT	Greater Trochanter
LT	Lesser Trochanter
SH	Shore Hardness

Glossary

Assisted Living	housing facility for elderly or disabled individuals that provides assistance with activities of daily living, housekeeping, nursing care and meal preparation. Its goal is to ensure the health, safety and well being of the resident, while promoting independence and dignity.
Greater Trochanter	a protrusion on the shaft of the femur, proximal to the femoral neck where attachment to the gluteus medius, minimus and several other muscles is provided. It is palpable at the lateral aspect of the hip joint.
Lesser Trochanter	a protrusion that projects from the shaft of the femur and receives insertion at the ilopsoas muscle
Shore Hardness	a measure of resistance to indentation of elastomeric or soft plastic materials based on the level of deflection of an indentor head. Values range from 0 (full deflection) to 100 (no deflection).

1. CHAPTER 1 INTRODUCTION AND OBJECTIVES

According to a demographic research survey completed by the United Nations Population Division, from 2010 to 2050, while the entire population of this world will grow just by 39%, the oldest old population (those aged 85 and over) will grow more than 350% (Grammich, 2011). With global demographic trends of increased life expectancy giving way to a rising number of older adults in the community, a considerable increase in fall related injuries can also be expected. It is for this reason that fall and injury prevention efforts have been brought to the forefront of research in recent years.

1.1. Occurrence of falls in the elderly

Falls are the number one cause of injury related hospitalization and deaths in older adults, where approximately 33% of adults over the age of 65 and 50% of those over age 80 fall at least once per year (Lord, Sherrington & Menz, 2001). Moreover, 50% of those that have experienced a fall previously are likely to fall repeatedly (Lord, Sherrington & Menz, 2001). A widely used definition of a fall, as derived by the Kellogg International Work Group on the Prevention of Falls by the Elderly, is “an event which results in a person coming to rest inadvertently on the ground or other lower level…” (World Health Organization, 2013). A fall may occur due to a variety of reasons, for example, slipping, tripping, incorrect weight shifting during a transfer, loss of support or even loss of consciousness (Gibson, Andres, Kennedy & Coppard, 1987) (Robinovitch, Feldman, Yang & Schonnop, 2013).

The incidence of falls varies based on different conditions. For example, gender plays an important role. In the younger old, fall rates for both genders are similar, however among the older old, women tend to fall more frequently than men (Scott, 2004), (Skelton, 2004). Fall incidence also varies across different living situations. For instance, falls occur twice as frequently in nursing homes as opposed to in the community setting (Rubenstein, Josephson & Robbins, 1994).

1.2. Impact of fall related injuries

About 10-15% of falls in older adults cause serious injury (Kerse, 2010). These include joint strains and sprains, soft tissue injuries, muscle contusions, cuts and abrasions and bone fractures (Bourke, O'Brien & Lyons, 2007). In particular, falls are the cause of over 90% of hip fractures (Tideiksaar, 2002). In Canada alone, there are over 25,000 hip fractures annually (Papadimitropoulos, Coyte, Josse & Greenwood, 1997). Other serious consequences of falls include injuries to the head and spine, wrist and shoulder.

Fall-related injuries are directly responsible for a decrease in physical function, significant disability and loss of independence. About 20% of hip fracture patients die within one year after the fracture, and 50% will have a major decline in independence (Oliver, Griffiths, Roche & Sahota, 2010). Moreover, falls can instigate adverse psychological effects such as a fear of falling, decreased social interaction and depression (Skelton, 2004). Falls not only cause pain and suffering to the individual who experienced the injury, but also impose significant pressure on the family as well as the health care system (Lord, 2001). The Canadian government spends an upwards of $3 billion each year in direct care costs associated with fall-related hip fractures ("Fall prevention," 2012).

The increased risk of falls in older adults can be classified under intrinsic and extrinsic risk factors. Intrinsic factors generally include: gender (where women are seen to fall more frequently than men, and are more likely to incur a hip fracture during the fall), medical conditions, impaired mobility, loss in visual acuity, and impaired cognition (Skelton, 2004). Risk for injury also depends on strength, reaction time and psychological factors such as anxiety (Nordin, 2008). Extrinsic risk factors can include environmental hazards (poor lighting, slippery floor conditions, uneven surfaces and clutter), footwear and clothing, living situation (where living alone can imply better functional ability, fall outcomes may be worse due to lack of assistance), and inappropriate assistive devices (Skelton, 2004).

1.3. Hip anatomy and hip fractures

The human hip (Figure 1-1) is a ball-and-socket joint where the spherical femoral head fits into the socket in the pelvis known as the acetabulum. Distal to the femoral head is the femoral neck oriented at a typical angle of 135 degrees to the diaphysis, which allows for a wide range of motion at the hip joint. The greater trochanter (GT) is a bony landmark that extends laterally just distal to the femoral neck, and the lesser trochanter extends medially (Skill Builders Physiotherapy & Rehabilitation Center, 2009). Both are sites for muscle attachment.

The incidence and cause of hip fractures vary with age. In young individuals, hip fractures are typically due to high-energy impacts such as motor vehicle accidents or falls from an elevated height (Thuan & Swiontkowski, 2008). In contrast, 90% of hip fractures in older adults are caused by falls from standing height or lower and while performing day-to-day activities (Grisso, Kelsey, Strom & Chiu, 1991). There are two primary sites for hip fracture that are similar in frequency (Figure 1-2). A femoral neck fracture consists of a fracture line that transects the ‘neck’ region of the proximal femur. An intertrochanteric fracture involves a fracture line connecting the greater and less trochanters.

Surgery is commonly used in the treatment of hip fractures and various rehabilitation interventions are employed to assist in the recovery process. Despite these efforts however, 15-25% of patients experience a decline in physical ability to perform daily activities and have a 5-to-8 fold increased risk for all-cause mortality during the first 3 months after a hip fracture (Haentjens, Magaziner, Colón-Emeric, et al., 2010) (Oliver, Griffiths, Roche & Sahota, 2010).

1.4. Factors influencing impact force during a fall

An individual's fracture risk is defined by the ratio (Φ) of the applied load divided by the failure load, where if $\Phi \geq 1$, failure is predicted to occur:

$$\Phi = \text{Fracture Risk} = \frac{\text{Applied Load}}{\text{Failure Load}}$$

While the applied load depends on the impact configuration, impact energy (e.g. fall height) and stiffness of the contact site, failure load depends on bone density and rate of loading, for example.

As previously mentioned, hip fracture incidence increases exponentially with age. This is due to a combination of age-related declines in bone strength, increases in the frequency of falls, and changes in mechanics of falling. In order to accurately predict fracture risk, the applied force must be estimated accurately. Since it is difficult to safely obtain such measures from real-life falls, researchers have addressed this issue by combining safe experiments with young adults with mathematical modelling of the measured impact dynamics. A simple but useful mathematical representation of the impact stage of a fall (Robinovitch, Hayes & McMahon, 1997) is a single-degree-of-freedom model consisting of mass (*m*), connected to a spring (of stiffness *k*), falling from a height (*h*) (Figure 1-3). Damping is neglected since the response is governed by elastic rather than viscous behaviour. The mass and stiffness are "effective" parameters specific to the hip impact site. At the instant of fall initiation, the system contains potential energy, which is subsequently converted into kinetic energy during descent and finally elastic strain energy during impact. The following equations govern these energy exchanges, where *x* is the deflection of the spring, *F* is peak force, and $g = 9.81\ \text{m/s}^2$:

$$Energy = mgh = \frac{1}{2}mv^2 = \frac{1}{2}kx^2 = \frac{1}{2}\frac{F^2}{k}.$$

This suggests that peak force (F) generated during impact is:

$$F = \sqrt{2mghk} = \sqrt{mk} \bullet v.$$

Peak impact (compressive) force at the proximal femur (greater trochanter or the femoral neck) is the most accepted measure of hip fracture risk during a fall (Robinovitch, Evans, Minns & Laing, 2009). A major reason for this is that applied forces can be compared to reported measures of the force required to fracture cadaveric femurs, in a simulated fall loading configuration. Predicted values of peak force applied to the proximal femur during a fall from standing range from 1145 to 5288N (Robinovitch, Hayes & McMahon, 1997).

The velocity of the pelvis at the moment of impact during a sideways fall from standing height is described in literature to be average 3.0m/s, with a standard deviation of 1.0m/s (Feldman & Robinovitch, 2007). These values were determined from experiments where participants were unexpectedly perturbed by a sudden sideways translation of the surface upon which they stood. This resulted in a loss of balance and a sideways fall onto the hip (on thick compliant mats). Using a motion capture system, pelvis impact velocity was calculated as the vertical velocity of the hip marker at the moment of impact.

In order to construct a testing system that accurately simulates a fall, in addition to the velocity and the applied force to the pelvis, reasonable estimates for the mass and stiffness of the artificial hip must also be known. Pelvis release experiments provide the best available estimates for these variables and reveal that the effective mass of the body during a fall is approximately one-half of the total body mass and the effective stiffness of the body is about 40 kN/m (Robinovitch, Evans, Minns & Laing, 2009). These experiments consist of drop tests which measure the dynamic response of healthy young adults to low-velocity impacts on the hip. The participant was horizontally suspended using a cloth sling (straps at the thigh and above the iliac crest) above a force plate. The sling was attached to 2 overhead pulleys via a steel cable. During the experiment, the participant was lifted to a height of 5cm above the force plate and released. The effective mass is a function of all body segments having a non-zero vertical velocity during hip impact. The effective stiffness of the hip is dependent on the stiffness of the pelvic bone itself, stiffness of the soft tissues overlying the hip and stiffness of the tendons and ligaments connecting the pelvis to the lower and upper limbs. While these experiments provide valuable estimates of the above mentioned parameters, they are derived from young participants and impact velocities much lower than those occurring during falls from standing (Robinovitch, Hayes & McMahon, 1997) (Feldman & Robinovitch, 2007).

Hip protectors and compliant flooring represent two engineering interventions developed to reduce the peak impact force transferred to the proximal femur during a fall and thus prevent injury to the hip. These devices act as a secondary spring (k_2) acting in series with the stiffness of the body (k_1) during a sideways fall on the hip (Figure 1-4). The total effective stiffness k', peak estimated force, and percent reduction in force provided by k_2 depends on the stiffness of the body k_1:

$$k' = \frac{k_1 \times k_2}{k_1 + k_2} \quad , \quad F = v\sqrt{m\left(\frac{k_1 \times k_2}{k_1 + k_2}\right)}$$

$$\%\,Force\ Attenuation = 100 \times \left(1 - \sqrt{\frac{k_2}{k_1 + k_2}}\right)$$

The force attenuation provided by a specific hip protector can be estimated through various approaches. One option is experiments with humans (such as pelvis release tests and unexpected lateral translations). While this method has the merit of involving living humans, peak impact energies and forces are limited by safety concerns. A second approach is to use a mathematical model to predict force attenuation. While this method allows the systematic control of parameters to observe the effect on the outcome variables of interest, the results are theoretical and depend on the accuracy of the mode in describing real-life falls in humans. A balance between the above mentioned approaches is to simulate falls with an instrumented mechanical system that includes realistic anatomy of the femur and pelvis, and matches the effective mass and stiffness of the body during a fall. This allows for systematic control and modification of the impact conditions and measurement of high forces applied to the proximal femur during realistic falling conditions.

1.5. Hip fracture prevention efforts

1.5.1. Hip protectors

Since the early 1990's, external hip protectors have been advocated as a method to prevent hip fractures, by reducing the impact force and the stress applied to the proximal femur during a fall. Hip protector pads are commonly secured inside specially crafted pockets on the lateral aspect of undergarments, or (less commonly) secured to the body through attachment straps (Figure 1-5). This padding worn around the hip is designed in the form of foam pads (known as soft-shell) or plastic shields (known as hard-shell) that provide a barrier between the hip and the ground. While the two types of hip protectors function through different mechanisms, both types serve to reduce the energy transferred to the proximal femur in order to prevent a hip fracture.

Soft-shell hip protectors (Figure 1-6) are comprised of compliant foam or rubber-type materials that directly contact with the skin surface over the greater trochanter. During a fall, the material deforms and in so doing absorbs energy (energy-absorbing mechanism). A hard-shell hip protector (Figure 1-7) is typically designed in the form of a dome that does not directly contact the skin surface over the greater trochanter, but instead forms a bridge over it. During a fall, the energy is diverted away from the bone into the surrounding soft tissue where it can be more safely absorbed (energy-shunting mechanism).

A third category of hip protectors, still in its infancy, is inflatable hip protectors. Based on the principle of pre-impact fall detection, an inflatable hip protector pad is set to deploy after a fall is detected, a few milliseconds prior to impact of the body with the ground (Nyan, Tay & Murugasu, 2008). The advantage of this approach, in comparison to passive designs is that, while dormant the pad is 'invisible' (i.e. has minimal thickness) and can inflate to a large volume during a fall, to absorb or disperse the impact force. This quality is attractive as it addresses the issues related to poor user compliance, such as lack of comfort and poor aesthetics, and therefore may be more effective is the prevention of hip fractures. Similar concepts have already achieved wide recognition and success in other industries. Examples include inflatable airbags which have become a standard safety feature in motor vehicles to prevent crash injuries, and have lately also been implemented as a protective motorcycle suit, head and cervical protector in sport helmets, and an avalanche life-preserving suit (Wu & Shuwan, 2008).

Despite their promise, there are significant barriers to the clinical effectiveness of hip protectors. As an active form of injury prevention, they require commitment from the user to wear them on a regular basis. Moreover there is lack of regulation regarding the biomechanical performance of hip protectors. These are discussed in greater detail in Section 1.5.

1.5.2. Compliant flooring

Compliant flooring represents an alternative or complement to hip protectors in preventing fall-related injuries in high risk environments (hospitals, nursing homes, care facilities and senior centers). Similar to soft shell hip protectors, the objective is to reduce the impact force transferred to the body through energy absorption in the floor material (Casalena, Cavanagh, Streit, Badre-Alam & Ovaert, 1998). Once the floor is installed, this passive form of injury prevention eliminates the user's requirement to comply with the intervention strategy, thereby providing perfect compliance. Moreover, since compliant flooring does not target a specific area of the body, protection is theoretically offered to any region that contacts its surface (including the head).

On the other hand, cost effectiveness data are not yet available to support the costs associated with materials and installation of compliant floor over individual cost per unit of hip protectors. Additionally, compliant flooring provides no protection to the individual in outdoor spaces, a limitation that does not exist with wearable hip protectors.

1.6. Literature review

1.6.1. Hip protector efficacy

While hip protectors represent a promising strategy to prevent fall-related hip fractures, their clinical effectiveness is still under debate (Kiel, Magaziner, Zimmerman & Ball, et al., 2007). Hip protector efficacy trials have yielded conflicting results. Initial cluster-randomized studies (where participants were grouped according to their living arrangement) prior to 2001 indicated that hip protectors significantly reduce the incidence of hip fractures (Gillespie, Gillespie & Parker, 2011). This led to the wide application of hip protectors in institutional settings.

Recent results have challenged this view. Pooled data from cluster randomized trials in nursing homes showed a statistically significant reduction in hip fracture rates in groups allocated to receive the hip protectors (Kiel, Magaziner, Zimmerman & Ball, et al., 2007). However, when data were pooled on an individual participant basis, statistical significance was no longer evident (Kiel, Magaziner, Zimmerman & Ball, et al., 2007). A possible explanation for this difference may stem from the fact that randomization according to facility may introduce methodological bias. The site where the intervention is implemented may vary significantly from the control unit, with respect to initial hip fracture rates, awareness of falls and aggressiveness of fall prevention programs (Kiel, Magaziner, Zimmerman & Ball, et al., 2007). Additional studies have cast doubt on the effectiveness of hip protectors in the home and institutional settings (Parker, Gillespie & Gillespie, 2006). For example, the largest randomized controlled trial in the United Kingdom provided no evidence that use of hip protectors among women living independently in the community affected the incidence of hip fractures (Birks, Porthouse, Addie, et al., 2004). In addition to the potential methodological bias of the studies, results may also vary due to the type of hip protectors employed in the interventions (Kiel, Magaziner, Zimmerman & Ball, et al., 2007).

Researchers generally agree that two primary factors limit the clinical effectiveness of hip protectors. First there is low to moderate compliance among users in their initial acceptance and long-term adherence to wearing these devices. Secondly, there are currently over 30 different types of external hip protectors available on the market (Laing, Feldman, Jalili, Tsai & Robinovitch, 2011) and the biomechanical performance of the devices varies widely (Laing, Feldman, Jalili, Tsai & Robinovitch, 2011) as measured by the ability to attenuate impact force during a fall. These issues are explored in detail below.

1.6.2. Compliance associated with hip protectors

Issues related to user compliance are a major barrier to the effectiveness of hip protectors. User compliance is comprised of initial acceptance to wearing a hip protector, and long-term adherence to continue its usage. A literature review on studies on PubMed, Embase and the Cochrane Library revealed that initial acceptance of hip protectors ranged from 37% to 72% (median of 68%), while long-term adherence varied between 20% to 92% (median of 56%) (Schoor, Deville, Bouter & Lips, 2002).

One reason for the wide range in acceptance and adherence between studies is lack of a consistent definition of compliance and methods of measuring it. Definitions of compliance include, average wearing time on active days and waking hours, percentage falls with hip protector and percentage participants wearing hip protectors. Another potential reason for inconsistency in compliance rates is variability in the types of hip protectors used in interventions (soft versus hard shell). Furthermore, the duration of follow-up varied across studies, and in some cases, participants who dropped out of the trials were replaced by others.

Hip protector compliance is a multifaceted issue. It is not only dependent on the hip protector pad itself, but also on the accompanying undergarment that encloses the protector pad. Significant determinants of acceptance and adherence in literature include characteristics of the undergarment, level of comfort, aesthetics and personal appearance, protective value, cost, laundry, and ease of don/doff. Cameron et al (Cameron & Quine, 1994) reported a disinterest in the use of hip protectors due to residents not indentifying themselves to be at risk for falls, concerns over comfort, accuracy of fit, and unfamiliarity with the product. Hubacher et al (Hubacher & Wettstein, 2001) reported a 68% initial acceptance rate, and adherence rates of 36% after 10 months (the reason for stopping use was not medical in 88% of users and 12% medical (pain when wearing protector) (Hubacher & Wettstein, 2001). Determinants of compliance are not only user-specific, but can also be influenced by caregivers and health administrators. Butler et al (Butler, Coggan & Norton, 1998) reported concerns from nurses and managers over the extra time/effort needed to don/doff the hip protector when toileting and dressing. Staff identified issues pertaining to incontinence and laundering. Effective compliance was a result of education and motivation on behalf of the staff, in believing the intervention's effectiveness in preventing fractures.

1.6.3. Biomechanical performance of hip protectors

Studies have yielded a conflicting view on the level of reduction in femoral impact force offered by various hip protectors. This is partially due to the lack of consistent techniques employed to measure biomechanical performance. In response the International Hip Protector Research Group (IHPRG) recently published recommendations to standardize the biomechanical testing of hip protectors. These describe that the biomechanical performance or protective value of hip protectors during falls should be expressed by the percent reduction (from baseline unpadded conditions) in the peak force applied to the proximal femur (Robinovitch, Evans, Minns & Laing, 2009). These guidelines describe values of impact velocity, effective mass, and stiffness for the testing system, which we were adhered to for all components of the research in this thesis.

1.7. Goals and objectives

Improved knowledge is required of how the design features of hip protectors influence both biomechanical performance and user compliance. With this additional knowledge, both performance and compliance can be optimized to construct a hip protector superior in its overall effectiveness in preventing hip fractures. Hence, the goal of this thesis is to systematically investigate the relationship between design features, performance and user compliance to improve the design and therefore the overall effectiveness of hip protectors for fall-related injury prevention.

I address this goal through three objectives:

a) To determine the effect of pad geometry and material properties on the force attenuation capacity of hip protectors;

b) To determine how pad geometry and material properties influence user preferences in the selection of hip protectors;

c) To determine whether knowledge of biomechanical performance influences user preferences in selecting hip protectors.

To address the above objectives, custom hip protector pads were created with varying degrees of thickness, hardness and surface area. The structural properties and force attenuation capacity of each were determined through dynamic indentation and fall impact simulation tests, respectively. Factors influencing user preference were derived based on incorporating Likert scales questionnaires to assess how various characteristics of the pad affect preferences in selection of hip protectors.

1.8. Figures

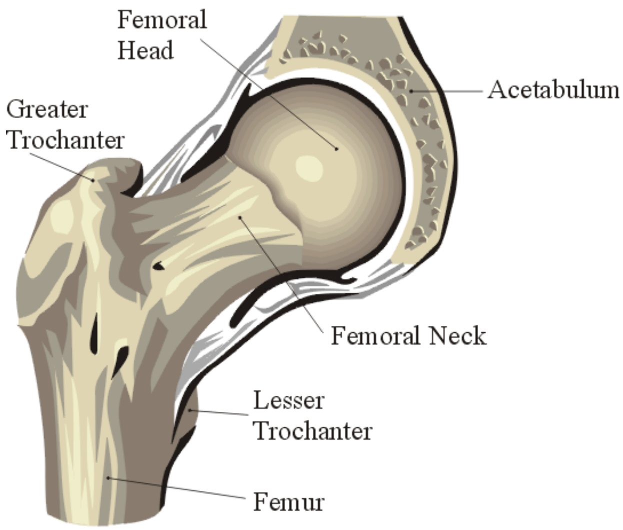


Figure 1-1. ***Anatomy of the Human Hip Joint ("Hip anatomy," 2013). Downloaded on July 28, 2013 from http://www.fpnotebook.com/_media/ThighAnatomyHipJointAnterior.gif (modified from Corel draw 9)***

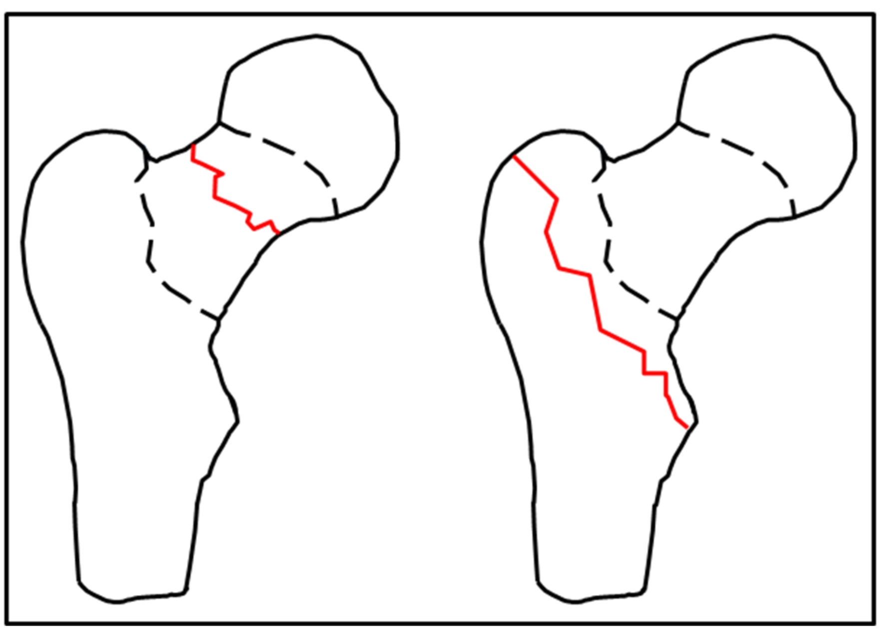


Figure 1-2. ***Types of Hip Fractures: Femoral neck fracture (left) and Intertrochanteric fracture (right)***

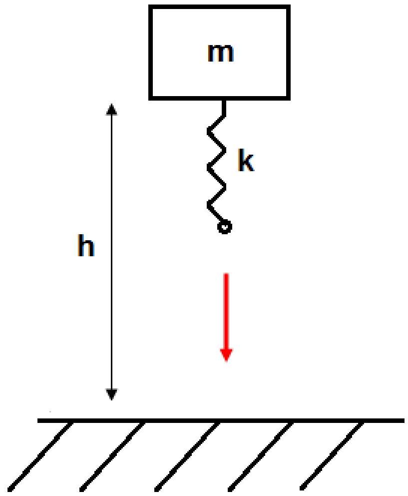


Figure 1-3. ***Mathematical model of a fall – object with mass (m), stiffness (k) falling from a height (h)***

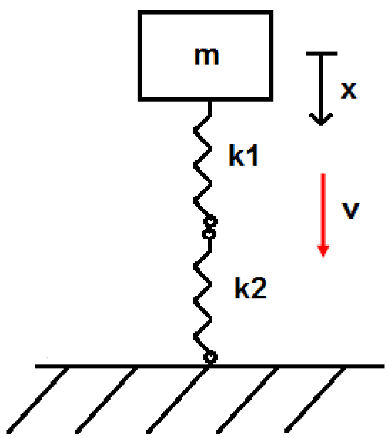


Figure 1-4. ***Modelling of a hip protector or compliant flooring as a spring that is in-series with the body during impact***

Figure 1-5. Placement of hip protectors inside specially crafted undergarments ("Kph hip protector," 2013). Downloaded on July 28, 2013 from http://www.livingmadeeasy.org.uk/clothing and footwear/hip-protectors-p/kph-hip-protector-0108335-2545-information.htm

Figure 1-6. Example of a soft shell hip protector pad (Hip Ease)

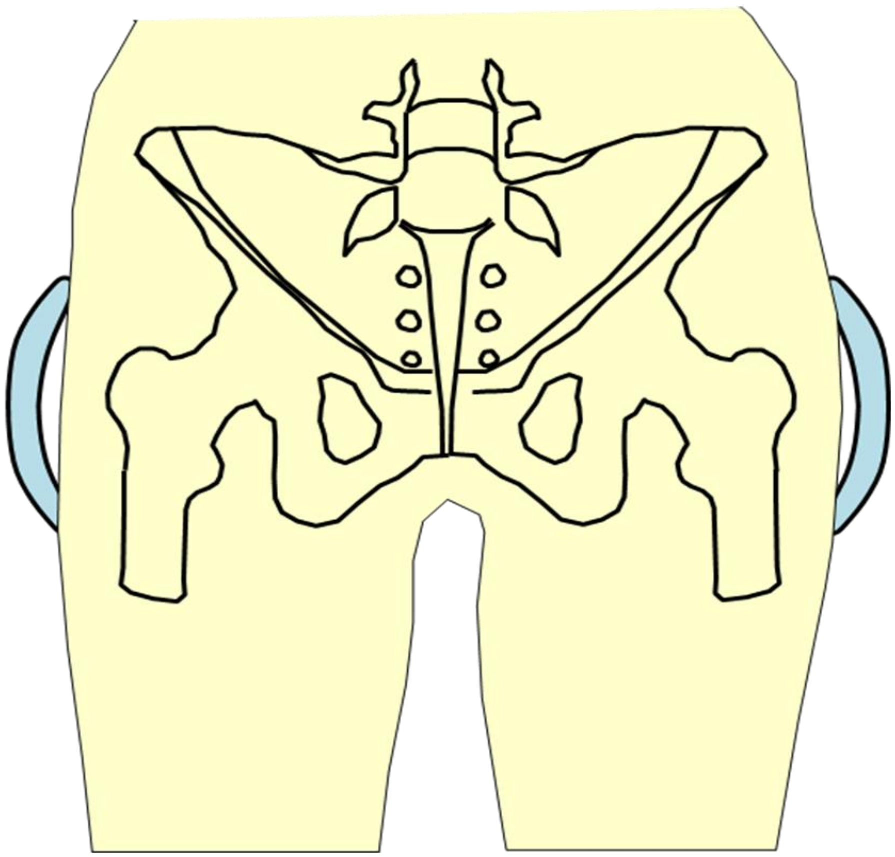


Figure 1-7. Example of a hard-shell hip protector pad and its placement over the greater trochanter.

2. Effects of Pad Geometry and Material Properties on the Biomechanical Effectiveness of Wearable Hip Protectors

2.1. Introduction

The biomechanical effectiveness of hip protectors is gauged primarily through the percentage of force attenuation i.e. reduction in the amount of impact force transferred to the proximal femur when compared to the unpadded condition. Due to safety concerns, it is not reasonable to perform participant testing when determining force reduction provided by a hip protector. Therefore, impact is simulated using a mechanical testing system to measure a variety of outcomes of interest.

As previously mentioned, researchers have employed a multitude of testing systems to determine the biomechanical performance of hip protectors. A typical testing arrangement however, would consist of an artificially created version of the human hip, a mechanism to reproduce the fall, and a sensor system to record the outcome of the impact. Figure 2-1 illustrates such a hip impact simulator used during a fall impact study (Laing, Feldman, Jalili, Tsai & Robinovitch, 2011). To ensure accuracy of the testing conditions, it is essential that the characteristics of the artificial hip mirror the properties of an average human hip, including appropriate bone structure, musculature and other soft tissues. A fall is simulated by the release of the artificial hip from an elevated height, which can be modified to reflect falls from standing or lower/higher than standing height. The sensor system typically consists of a force plate at the impact site on the ground and a load cell located inside the artificial hip at the proximal femur. The force plate serves to indicate the actual force of the impact, while the load cell conveys the proportion of the impact force that is transmitted to the proximal femur in the efforts of detecting whether it is sufficient to cause a hip fracture. Biomechanical effectiveness is the typical outcome measure and is defined as the percentage of force attenuation provided by the hip protector compared to the unpadded condition. The higher the force attenuation, the greater the biomechanical effectiveness.

Hip protectors differ in their degree of biomechanical effectiveness due to the variation in their design features, particularly the geometry and material properties. There are currently over 30 different hip protectors on the market, a combination of hard and soft shell. Literature has revealed some to be more effective than others. For the scope of this thesis however, custom hip protectors were created and tested in order determine how geometric and material properties affect the force attenuation capacity of a hip protector. The three main hip protector pad characteristics investigated included pad thickness, hardness of the material and surface area. This process will be explained in greater detail in the subsequent section.

It is important to note the distinctions between material hardness (as measured in durometer), elastic modulus (measured in Pascals or Nm/s^2), and stiffness (measured in N/m). Elastic modulus is an inherent property of a material, while stiffness is a structural parameters that depends on geometry as well as elastic modulus. Shore hardness – a parameter most often used in the foam rubber industry - is measured through an indentation test, and tends to vary linearly with elastic modulus. Under axial loading, the theoretical stiffness k of a structure is directly proportional to elastic modulus (E) and cross-sectional area (A), and inversely proportional to the length (L):

$$k = \frac{AE}{L}.$$

2.2. Methods

2.2.1. Custom-made hip protectors

Previous studies have conducted tests on commercially available hip protectors to determine their biomechanical effectiveness, which has varied between 2.5% to 40% (Laing, Feldman, Jalili, Tsai & Robinovitch, 2011). To further the investigation of how intrinsic pad characteristics affect performance, this thesis focuses on three distinct factors (of soft-shell hip protectors) which have previously demonstrated biomechanical significance.

The area under the force-deflection curve determines the amount of energy absorbed by a hip protector. Thickness and hardness of a material both contribute to the amount of energy absorbed. The higher the energy absorbed, the greater the biomechanical effectiveness. In terms of conservation of energy, the energy absorbed at impact is a function of the distance (i.e. thickness) that the pad provides before bottoming out. The hardness of a hip protector pad is dependent on its material composition. A hip protector with a low hardness value would collapse easily and thus would be unable to absorb energy upon impact, while one with a high stiffness value would be unable to deform thus creating the same problem. The third factor is the surface area of the hip protector pad. The larger the surface area of the protector pad, the larger the region over which the impact force can be distributed (given that the entire surface of the hip protector contacts the ground during impact), thereby decreasing the likelihood of an injury as a result of a concentrated impact.

Taking the above characteristics into consideration, an array of custom-made hip protector pad prototypes were created with varying levels of thickness, hardness and surface area. Four values were chosen for each of the variables to provide enough variation in biomechanical performance, while maintaining a reasonable scope of the study. Thickness values were 5mm, 15mm, 25mm and 35mm. Hardness values were 43, 50, 60, and 81 durometer. Surface area was varied based on circles of diameter 5.5in, 6.5in, 7.5in and 8.5in. These values were comparable to current protectors available on the market. For example, LYDS and HipEase are at the opposite ends of the spectrum with thickness values of 6.5mm and 32 mm, respectively. Sizes of commercial hip protectors vary from e.g. 160x110 for HIPS to 220x200 for HipSaver (Laing, Feldman, Jalili, Tsai & Robinovitch, 2011). The material types were chosen across the range of Shore Hardness (SH) values the manufacturer had available. A hip protector was created for each combination of thickness, hardness and surface area, for a total of 64 different hip protector prototypes (Figure 2-2). Three samples of each prototype were purchased and cut into a circular shape (Figure 2-3), i.e. the form most commercially available hip protectors take (Figure 2-4). The geometric and material properties of all 64 hip protectors are illustrated in Appendix A.

2.2.2. *Impact pendulum testing*

To measure the force attenuation capacity of the custom made hip protector prototypes, the Simon Fraser University hip impact simulator system was used. This system simulates the impact energy of a typical fall, and the effective mass and stiffness of the body measured from pelvis release experiments. It is compatible with published guidelines for measuring the biomechanical performance of hip protectors (Robinovitch et al., 2009). The system consists of an artificial surrogate pelvis attached to a metal arm that acts as a pendulum (Figure 2-5). This arm is released to impact the ground horizontally through the aid of an electromagnet. The impact velocity of the pelvis is varied by adjusting the angle from which the pendulum is dropped, to simulate falls from different heights. The surrogate pelvis was designed to match the surface geometry and variation in soft tissue properties of an average older woman (ave. age 77.5 years) to within one standard deviation (Laing & Robinovitch, 2008). It is composed of materials varying in stiffness that simulate the soft tissues of the human body (e.g. polyethylene foams), as well as an artificial version of the proximal femur mounted onto a base plate. A 1.6mm layer of gum rubber was secured over the entire surface of the artificial pelvis to simulate the skin. The total effective stiffness of the system is 42 kN/m (Laing and Robinovitch, 2010; Robinovitch et al., 1997), while the effective mass is 28 kg, within one standard deviation of the mean measured from women during lateral falls on the hip (Robinovitch et al., 1997).

The surrogate pelvis was attached to the metal pendulum arm through leaf-springs, to help account for the compressive stiffness of the pelvis itself (distinct from the stiffness of the peripheral soft tissue). On the ground at the impact site is a force plate that measures the force applied to the skin surface during a fall. In addition, at the junction of the femoral neck of the surrogate pelvis is a uni-axial load cell which captures the amount of impact force transmitted to the joint during the fall.

To test the force attenuation capacity of the custom hip protector prototypes, falls were simulated with the impact pendulum in the padded and unpadded conditions. The unpadded conditions consisted of a set of 3 trials of the surrogate pelvis directly impacting the floor-mounted force plate. The initial angle of the pendulum arm was fixed to 33.5° relative to the ground to maintain an impact velocity of 3.4 ms^{-1} (to reflect a fall from standing height; Robinovitch, Hayes & McMahon, 1991). In the padded trials, each hip protector prototype was secured to the lateral portion of the surrogate pelvis, immediately above the Greater Trochanter, through the use of adhesive tapes. Once again, three trials were conducted for each type of hip protector; however different samples were used in each trial to eliminate the possibility of structural damage in effecting the results. All 192 padded trials were randomized and unpadded trials were executed at the very beginning of the experiment, every 32 padded impacts, and at the very end of the experiment. Every 30 trials, the surrogate pelvis was allowed to rest in order to allow the materials within to decompress and return to their original form. To maintain the impact velocity constant over variations in pad thickness, the angle of the pendulum arm was adjusted.

2.2.3. Materials testing system

We quantified the force-deflection properties of each hip protector prototype, with an Instron servohydraulics materials testing system (FastTrack™ 8874, Canton, MA, USA) (Figure 2-6). This device consists of a double-acting servohydraulic actuator, with a force capacity of up to ±25 kN in the upper crosshead and an axial stroke length 100mm. It also consists of a lower t-slot table that can be used to place the item to be tested. A fatigue-rated load cell (biaxial Dynacell™) is embedded in the actuator arm which was used to compresses and decompresses the samples. The 8874 works in conjunction with a two-axis digital controller (Labtronic 8800™, Novi, MI, USA) that provides full system control to enable various test conditions. Waverunner© testing software was used to generate test conditions and waveforms.

During the measures, a rigid hip shaped indenter (Laing, Feldman, Jalili, Tsai & Robinovitch, 2011) was used to compress and decompress the protector pad. Ramp loading and unloading rates were $35mms^{-1}$ similar to previous experiments (Laing, Feldman, Jalili, Tsai & Robinovitch, 2011). The pad was compressed until one of two conditions was met. Either the distance between the indenter and base plate on which the pad was placed was equal or less than 2mm, or until a force of 4000 ± 100N (typical peak load for a sideways fall) was detected by the testing system, at which point the trial was stopped (to prevent damage to the protector and indenter head).

2.2.4. Data collection – Impact Pendulum Tests

To obtain force attenuation data, each combination of hip protector pad prototypes (n=64) was tested using the Hip Impact Simulator system. Three trials were conducted in each case, again on three separate samples, done to eliminate the effect of structural damage on the results. A total of 192 padded trials were collected with thickness, hardness and surface area varying randomly. During each trial, the hip protector was affixed to the surrogate pelvis with the use of double-sided adhesive tape at the center of the pad. Unpadded trials were also conducted, to determine baseline values of force transferred to the femoral neck. Force plate and load cell data were acquired at a rate of 1000 Hz, and was filtered with a dual-pass fourth-order Butterworth low pass filter with a 35 Hz cut-off frequency. For the purposes of this study, the peak force at the load cell was utilized to determine percentage of force attenuation provided by the hip protectors.

2.2.5. Data collection – Dynamic Indentation Tests

To acquire force deflection data, each of the 64 combinations of the hip protector pad prototypes were tested using the Instron Materials Testing System. Prior to commencement of testing, warm up procedures were first conducted on the system (which consisted of 100 cycles lowering and lifting the indenter arm. The system was also calibrated to ensure accuracy of the level of indentation. Displacement and load limits were set to 40mm and 4500N respectively, to alert the tester of conditions resulting in damage to the system or the hip protector pad due to an excess application of force by the indenter head. Should such a condition arise, the test was set to be automatically suspended. Following the start-up procedures, a pad prototype was selected from a randomized group, and placed on the t-slot table, where the indenter arm was adjusted to an appropriate height (one that would compress the foam down to 2mm from the base plate. A data acquisition rate of 1000 Hz was used. Each pad was set to undergo a single trial, to ensure damage to the structural properties of the pad from the previous trial was not reflected in data from the subsequent trial (especially true in the case of the pads with high stiffness). The exception was, if a force of 4000 ± 100N was not obtained, the trial was repeated until the condition was met (or force exceeded the maximum allowed limit). Data was saved in a CSV file format.

2.2.6. Data analysis

Data from the impact pendulum experiment focused on determining the level of force attenuation provided by the various combinations of hip protector pad prototypes. Load cell data was averaged across the 3 padded impact trials for each combination of hip protectors. In addition, load cell data for all unpadded trials was also averaged. Force attenuation was used as a measure of biomechanical effectiveness in this study. It was obtained from the following expression, where Loadcell_unpadded and Loadcell_padded represent the peak average force value observed at the loadcell during unpadded and padded trials, respectively:

$$\%\,Force\ Attenuation = \left(\frac{Loadcell_{unpadded}\ -\ Loadcell_{padded}}{Loadcell_{unpadded}}\right) * 100$$

Position and Load data from the dynamic indentation test was filtered using a 4th order low-pass Butterworth filter, with a 35Hz cut-off frequency. A MATLAB routine was created to determine the starting point of the compression phase of the pad. This was determined based on the instance at which the force increased 3 standard deviations above the mean of the constant phase preceding the compression of the pad. In addition, the peak force at the load cell and the end of the decompression phase was also determined through the MATLAB routine. Outcome variables of interest were stiffness, energy absorbed, absolute energy dissipated and relative energy dissipated. A sample force-deflection curve is shown in Figure 2-7. Stiffness (k) was measured as the tangent of the force-deflection curve during the compression phase at 200N, 2000N, and at 3000N. The energy absorbed (E_abs) was calculated as the area under the force-deflection curve during the compression phase. Absolute energy dissipated (E_dis) was calculated by subtracting the area under the decompression phase portion of the curve, from E_abs. Relative energy dissipation, E_rel (%) was defined as per the following expression:

$$Energy_{relative} = \left(\frac{E\_dissipated}{E\_absorbed}\right) * 100$$

In terms of statistical examination, a preliminary bivariate analysis was performed to determine the correlation between geometric/material properties of the hip protectors and their force attenuation capacity. More importantly, multiple regression analysis was performed to determine the general form of the equation to predict force attenuation (dependent variable) from the independent variables of geometric (thickness and surface area) and material (hardness) properties, and outcome variables of the dynamic indentation test (k_200, k_2000, k_3000, E_abs, E_dis, E_rel). All analyses were performed using statistical analysis software SPSS and a significance level of $\alpha = 0.05$.

2.3. Results

In simulated falls with the hip impact pendulum, the peak force measured at the femoral neck during baseline unpadded conditions averaged 2534 N (Appendix B). During the padded conditions, peak forces at the femoral neck ranged from 1374 N to 2449 N (Appendix C). The corresponding minimum and maximum force attenuations ranged from 3.3% to 45.8%, respectively (Appendix D).

Force attenuation increased with increasing thickness and surface area, however for hardness, increased only until SH=60 (corresponding to the material LD45). Beyond this (SH=81 (HD80)), force attenuation dropped rapidly. This is evidenced by the fact that the lowest force attenuation, as seen in Figure 2-8, was 3.3% observed for a pad of the material HD80. Additionally, an increase in thickness at a constant surface area produced a greater rise in force attenuation than an increase in surface area at the same thickness value. Furthermore, as hardness was increased till SH=60 at a constant thickness, force attenuation too increased, although to only a small degree. However, at the level of SH=80, the material performed poorly, and force attenuation shows a sharp decline. Reversing the situation, a change in thickness at a constant hardness value once again produced a greater increase in force attenuation (Appendix E).

From indentation testing, the range of stiffnesses (Figure 2-9) observed were 46.5 kN/m to 646.8 kN/m for k_200, 154.7 kN/m to 985.1 kN/m for k_2000 and 213.8 kN/m to 1020.4 kN/m for k_3000. The range of observed energy absorption was 0.26 J to 42.6 J, energy dissipated was 0.1 J to 26.5 J, and relative energy dissipated was

17.2% to 89.7% (Figure 2-10). We were able to calculate k_200 for all 64 samples, but k_2000 for only 52 samples and k_3000 for only 40 samples. This was due to limitations in being able to safely exceed forces of over 2000 N with very thin or very stiff pads.

In bivariate correlations each of thickness, hardness, surface area, k_200, k_2000, k_3000, E_abs, E_dis and E_rel significantly associated (at $p<0.01$) with force attenuation. Thickness, surface area, E_abs, E_dis correlated positively with force attenuation, with correlation coefficients of 0.630, 0.362, 0.884 and 0.633, respectively. Hardness, k_200, k_2000, k_3000, E_rel correlated negatively with force attenuation, with coefficients of -0.433, -0.530, -0.887, -0.863 and -0.507, respectively. In univariate linear regressions (Table 2-1), k_2000 and k_3000 and E_abs had the largest R^2 values, explaining 78.7%, 74.5% and 78.2% of the variability in force attenuation, respectively. The remaining variables explained between 13% and 40% of the variability.

Multiple regression analysis (Table 2-2) was performed to identify the combined contributions of thickness, hardness and surface area, on force attenuation. The multiple correlation coefficient, R = 0.846, indicates a good level of prediction for the dependent variable. The Coefficient of Determination, $R^2 = 0.716$, indicates that the independent variables explain 71.6% in force attenuation (ANOVA indicates that the overall regression model was a good fit for the data. Results $F(3,60) = 50.371$, $p < .0005$). Estimated model coefficients reveal that the general form of the equation to predict Force Attenuation from thickness, hardness and surface area is as follows:

$$\begin{aligned} Predicted\ \%\ Force\ Attenuation \\ &= 12.766 + (0.722 \times Thickness) - (0.387 \times Hardness) \\ &+ (0.058 \times SurfaceArea) \end{aligned}$$

The above equation indicates how the dependent variable (force attenuation) varies with each independent variable, when all other variables are held constant. Therefore, for each 1mm increase in thickness, force attenuation increases 0.722%; for each 1 level increase in shore hardness, force attenuation decreases 0.387%; and for each 1cm^2 increase in surface area, force attenuation increases 0.058%.

2.4. Discussion

This study examined how the geometric and material properties of hip protectors influence their force attenuation capacity during simulated falling experiments. Thickness and surface area displayed a positive linear relationship with force attenuation i.e., the thicker and larger hip protector prototypes provided greater protection (Figure 2-11). A non-linear trend was observed between force attenuation and material hardness. Force attenuation was seen to increase with increasing hardness up to the point of SH = 60, and then decreased for SH=81. A potential reason for this non-linear behaviour is differences in the “bottoming out” process of the various pads. In particular, under the high impact energy of our simulated falls, pads of low hardness (LD15, LD24 and LD45) will likely experience a high degree of compaction, at which point their stiffness increases rapidly. In this “bottomed out” state, they are capable of little additional energy absorption. Force attenuation will depend on their ability to absorb energy before bottoming out, which increases with increasing hardness. In the case of a very high hardness (HD80), the pad may not bottom out, but deforms little and absorbs limited energy throughout impact, and thus provides little force attenuation. A second possible explanation for non-linear trends is differences in energy dissipation (damping) between the various materials, and conversion of kinetic and strain energy into heat. In our compression experiments, the percent energy dissipation was greatest for HD80, and negligible for LD15, LD24 and LD45 (especially at the lowest thickness value). An optimal value of damping may lie between these extremes.

Over the range we examined, variations in thickness had the largest effect on force attenuation followed by variations in surface area, and finally hardness. This result agrees with the study by Laing et al. where biomechanical effectiveness was seen to depend more on geometry type than material type (Laing, 2011). The difference in mean force attenuation between the lowest and highest thickness was 21.7%, between the lowest and highest surface area was 12.7% and the lowest and highest hardness was -13.8%. This observation is also evident in Figure 2-12, where estimated marginal mean curves are seen to change the greatest for thickness, followed by surface area, and lastly hardness.

Stiffness variables k_200, k_2000 and k_3000 negatively correlated to force attenuation (Figure 2-13). At 200N, the relationship was non-linear, however at higher loads (2000N and 3000N) the relationship was linear. At all load conditions, thicker hip protectors (at low stiffness values) generated greater force attenuation (indicated by the red circles in Figure 2-13 a,c,e). This observation agrees with Laing et al. (Laing, 2011) who also observed that hip protectors with a lower initial stiffness attenuated greater force at all load conditions. On the other hand, hip protectors with a larger surface area provided higher force attenuation than their counterparts (indicated by the lines drawn on Figure 2-13 b,d,f).

Under axial loading, the structural stiffness *k* is directly proportional to the cross-sectional area (*A*) and Young's modulus (*E*), and inversely proportional to the length (*L*) of the structure. The peak force (*F*) at the impact site depends on the mass (*m*), stiffness (*k*) and velocity (*v*). Thus, the peak force scales linearly with the impact velocity, and with the square root of the material and geometric properties of the hip protector pad:

$$k = \frac{AE}{L} \quad and \quad F = \sqrt{mk} \bullet v, \quad therefore \quad F = \sqrt{\frac{mAE}{L}}\, v$$

In order to understand the relationship of the energy-based variables, it is first important to recognize the energy conservation process that takes place in the impact pendulum experiment. At the "standing height" position, the surrogate hip contains gravitational potential energy (dependent on height and weight). During the falling stage, the energy is transformed into kinetic energy due to its motion. As the hip continues to fall, it gains momentum and the kinetic energy continues to rise. Upon collision with the ground, the kinetic energy is transformed into many different forms (such as sound and heat), as well as elastic potential energy resulting from the instantaneous deformation of the hip protector pad as it collides with the ground. Throughout this process, the total amount of energy remains the same.

Energy absorbed had a positive relationship with force attenuation due to the ability of the protector to deflect the material and conform to the hip-shaped indenter head applying the load (Figure 2-14). Thinner hip protectors absorbed the least amount of energy while also providing the least amount of force reduction (as indicated by the different circles in Figure 2-14 a). The thicker hip protectors were on the opposite end of the spectrum, absorbing the most energy and attenuating the greatest force (Figure 2-14 a). Pads with a larger surface area were seen to provide higher force attenuation despite absorbing the same amount of energy (Figure 2-14 b, where the lines provide an approximation for constant surface area values).

The general consensus in literature for a threshold of force required for hip fracture is based off of elderly females and set at 3100 N (Kannus, Parkkari, Poutala, 1999). The force required to produce a hip fracture is approximately 2830N in older women and 4380N in older men (Kanus et al., 2006). Many studies have reported that a varying amount of force occurs during a fall due to the varying mechanisms and heights from which a fall may take place. One study broke down falls into three categories measuring joules, force and force attenuated by soft tissue alone into three categories of low impact (41J, 4330 N, 3740 N), moderate impact (74 J, 7230 N, 6130 N) and high impact (110 J, 10840 N, 9190 N). This leads to required force attenuation, after factoring in a soft tissue barrier, of 17%, 49% and 66% for low, moderate and high impact respectively (Kannus, Parkkari, Poutala, 1999). For all 64 hip protectors, force measured at the load cell during impact did not exceed this value. In light of this, it is challenging to agree on a single % force attenuation value that would be sufficient to prevent a hip fracture. The greater the attenuation capacity, the more protected the hip is, not only from a fracture point of view, but also in efforts to prevent general injury to the hip.

The results of this study are important for several reasons. Most importantly, this study is first of its kind in systematically examining the impact of hip protector characteristics on its biomechanical performance. Previous studies have been conducted where only commercial hip protectors were used. The current study documents important and non-obvious trends between force attenuation, and hip protector thickness, hardness and surface area. The advantage of custom creating and testing these hip protectors was that even subtle relationships between hip protector characteristics and force attenuation were seen (Figure 2-8). Our results allow users to select the desired level of force attenuation, and “mix and match” characteristics such as thickness, stiffness and surface area, to meet their personalizing needs.

There are also notable limitations to this portion of the study. Firstly, the 64 hip protector pads created as part of this study were all of soft-shell type. Future research can be conducted where hard-shell hip protectors are custom created and their biomechanical effectiveness tested. Second, we used “average” values of body mass and stiffness in simulated falls with our impact pendulum, which does not allow a personalized approach. A personalized approach (i.e. using an individual's mass and stiffness of the pelvis) could perhaps be more desirable as it would provide a more accurate picture of the impact force applied to the femur during a fall. However, this approach is not practical due to feasibility issues surrounding the creation of a surrogate pelvis with multiple effective mass and stiffness values. Experiments were conducted at only a single impact velocity of 3.4ms^{-1} (i.e. simulating a typical fall from standing). It would be valuable to know the effect of impact velocity on the force attenuation provided by each pad. Third, while our system was state-of-the-art, it is difficult to compare our results to previous studies using different types of test systems. For example, a 2009 study by Holzer et al. mechanically tested a variety of commercial hip protectors using the European standard for motorcycle clothing, involving an impact energy of 50 J (Holzer, Skrbensky & Holzer, 2009). Parkkari et al conducted a study where an impact force of 8.2 kN was used to test the various hip protectors (Parkkari, Kannus, Poutala & Vuori, 1994). Future research should focus on systematically modifying additional geometric (e.g. shape) and material properties (e.g. constructing a hip protector from a combination of materials) to determine its effect on force attenuation. Finally, our statistical modelling techniques assumed linear relations, which while valid for thickness and surface area, could not describe the observed non-linear relationship between force attenuation and hardness. Future work should involve non-linear modeling techniques to account for these trends.

Overall, each of thickness, hardness and surface area influence the biomechanical performance of hip protectors. Thicker hip protectors not only have a lower stiffness (especially at higher loads), but also absorb a greater amount of energy as they are able to deflect to a higher degree while being indented. Moderate stiffness is necessary to provide support during impact, and to simultaneously ensure sufficient compliance. Hip protectors with a larger surface area are able to more effectively distribute the applied force away from the proximal femur, in addition to being able to physically cover and protect a greater surrounding area during hip impact. Therefore, creating hip protector pads with a high thickness, moderate stiffness and large surface area is a promising strategy to increase the effectiveness of this type of intervention.

While the benefits of implementing this strategy are clear, its effect on user compliance needs to be investigated, as typically larger hip protectors are thought of to be undesirable. The next chapter in this thesis serves to explore this exact point, and determine whether such implementation is not only biomechanically effective but also practical.

2.5. Figures

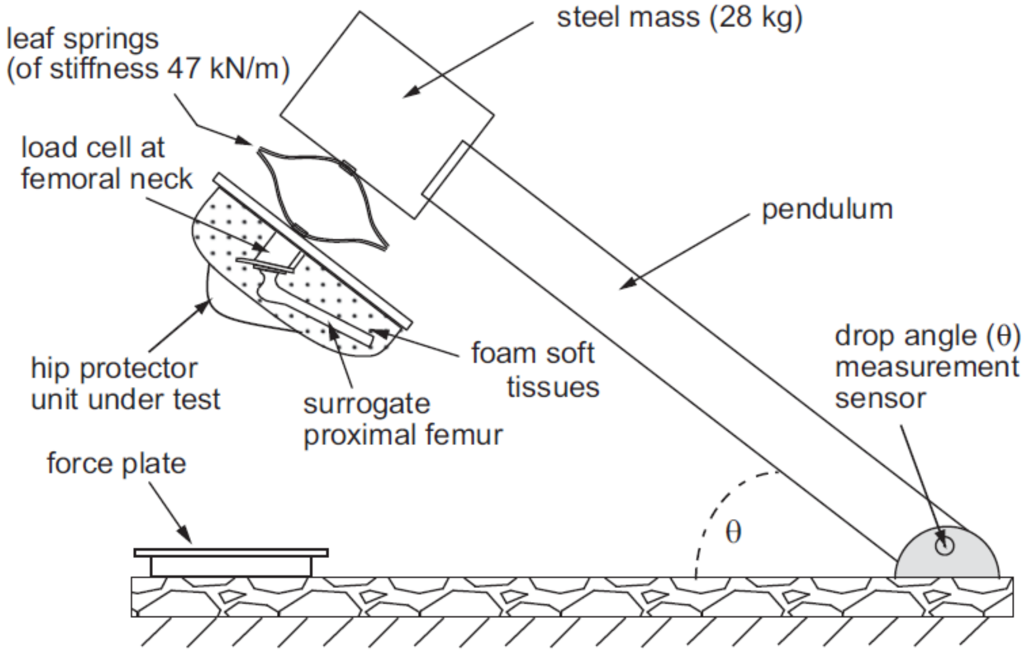


Figure 2-1. Simon Fraser University hip impact simulator. The surrogate pelvis is connected to the impact pendulum arm. A load cell located by the femoral neck measures force transferred to the bone. The force plate measures force applied to the surface of impact (Laing, Feldman, Jalili, Tsai & Robinovitch, 2011).

Figure 2-2. 64 Hip Protector Prototypes (5 samples of each) – Prior to Shaping

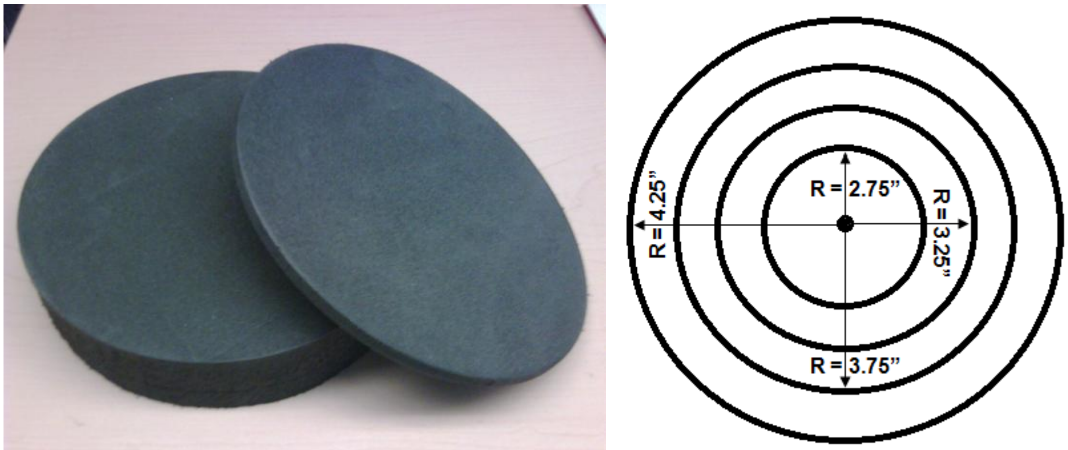


Figure 2-3. ***Sample Hip Protector pad prototypes (left) and dimensions (radius, inches) of the 4 surface area values.***

Figure 2-4. ***Photographs showing a selection of commercially available hip protectors (Laing, Feldman, Jalili, Tsai & Robinovitch, 2011)***

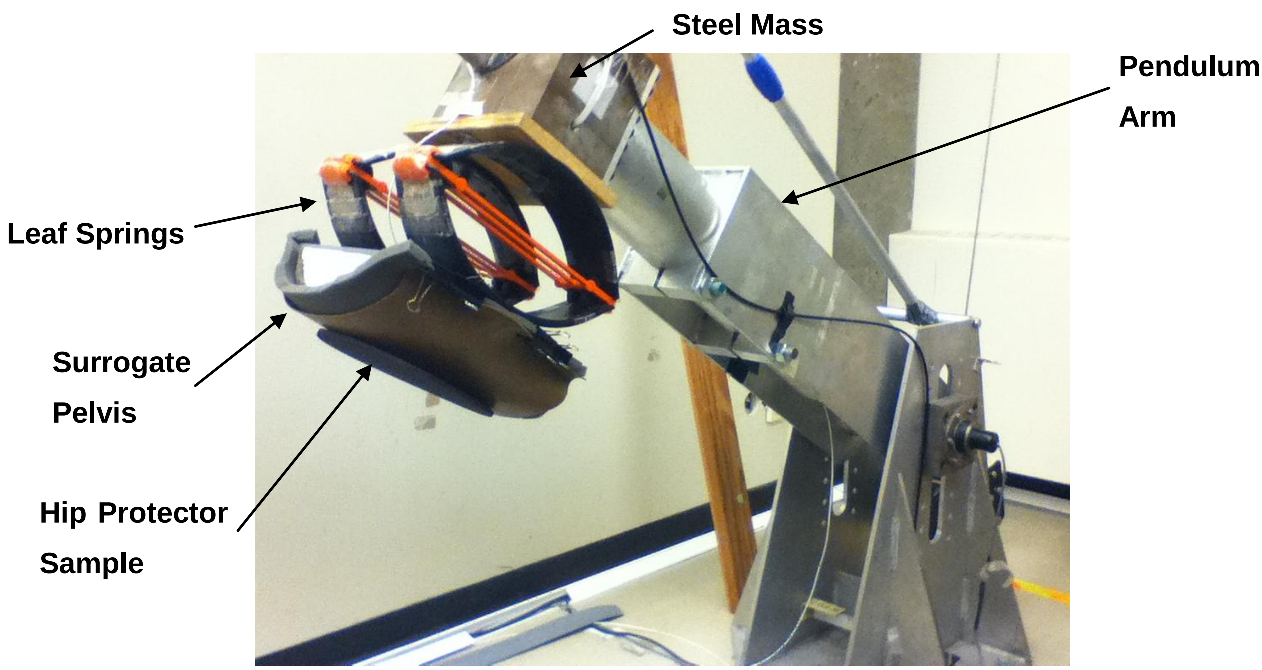


Figure 2-5. The Simon Fraser University Hip Impact Simulator.

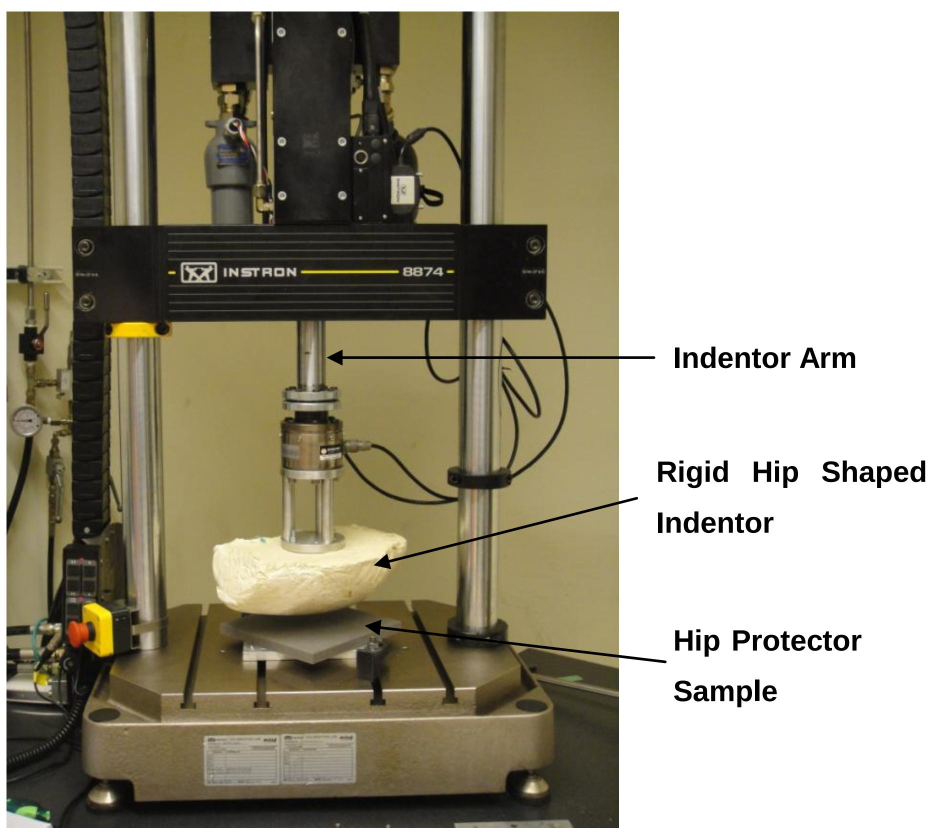


Figure 2-6. INSTRON Materials Testing System for dynamic indentation testing

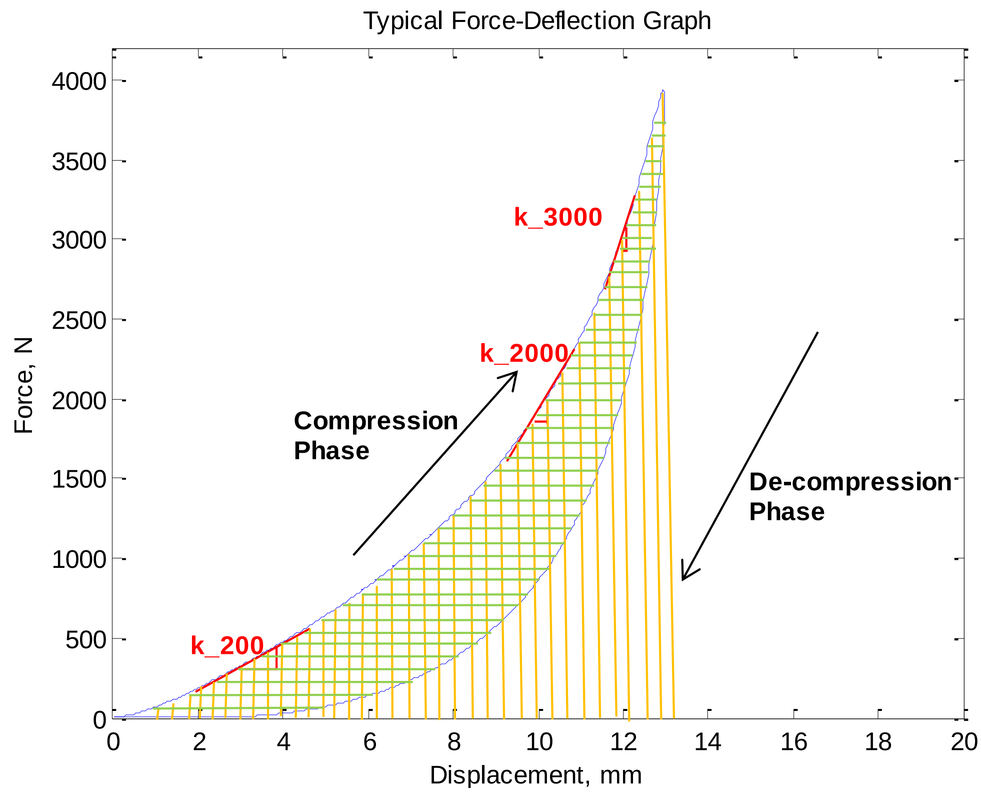


Figure 2-7. Sample Force-Deflection curve (Thickness = 15mm, Hardness = 60, and Surface Area = 214.1cm^2) illustrating stiffness at 200N, 2000N and 3000N as well as E_abs (yellow) and E_dis (green).

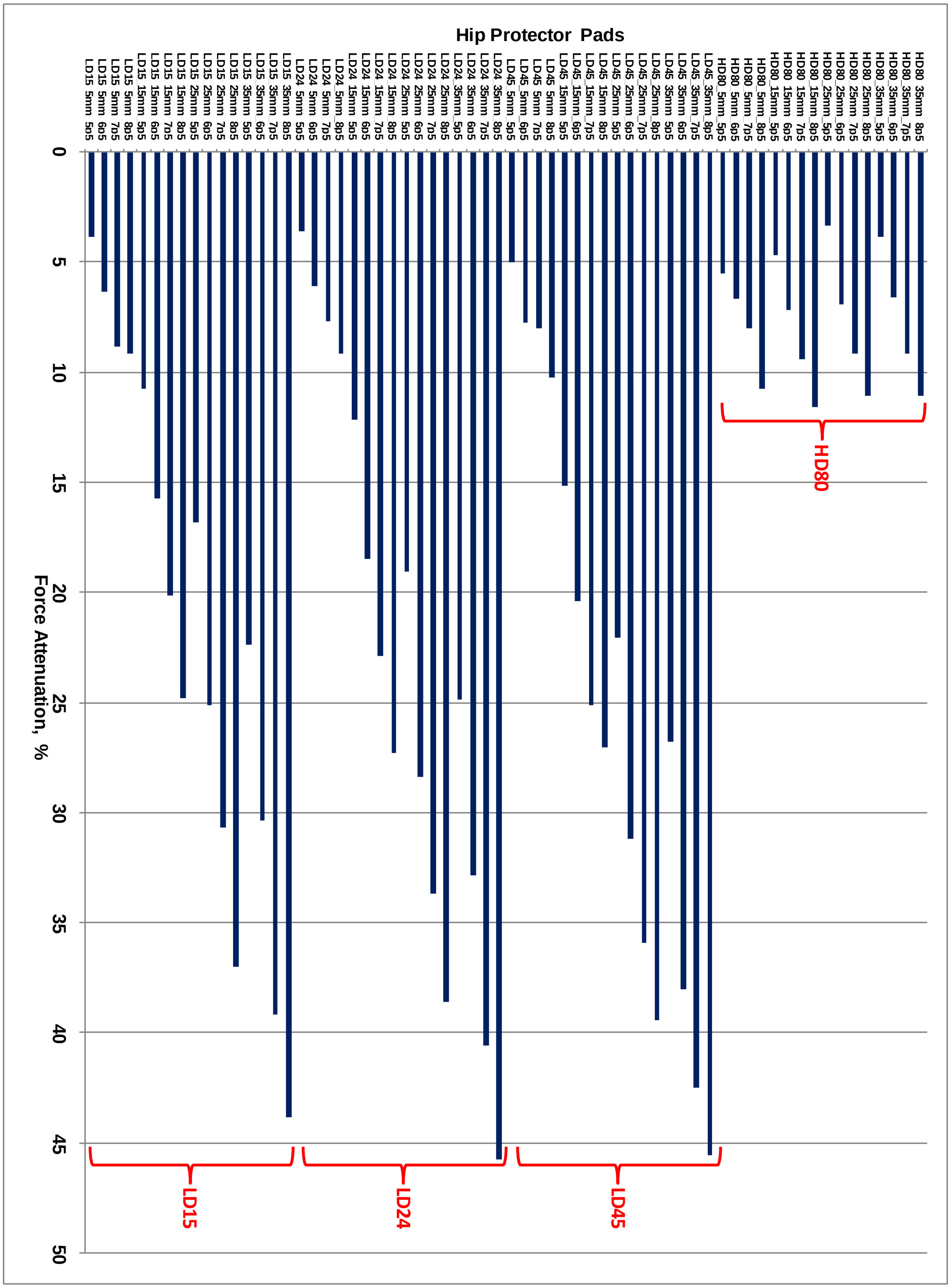
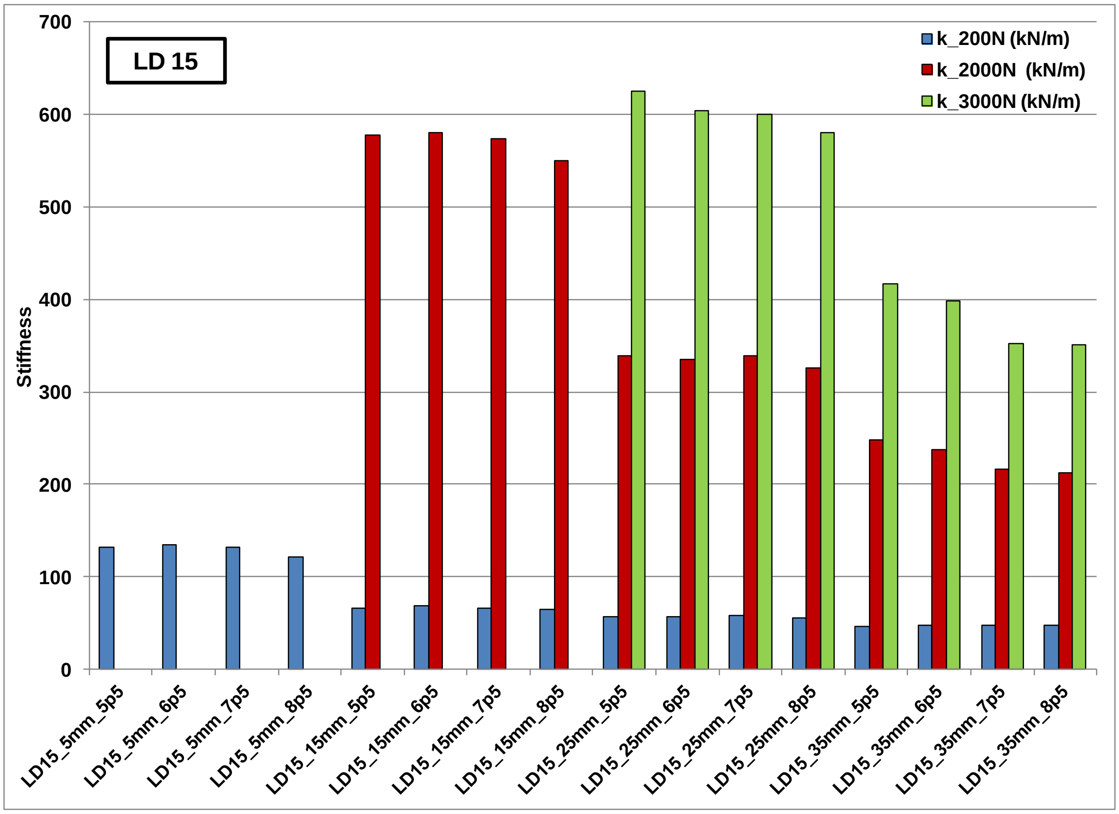
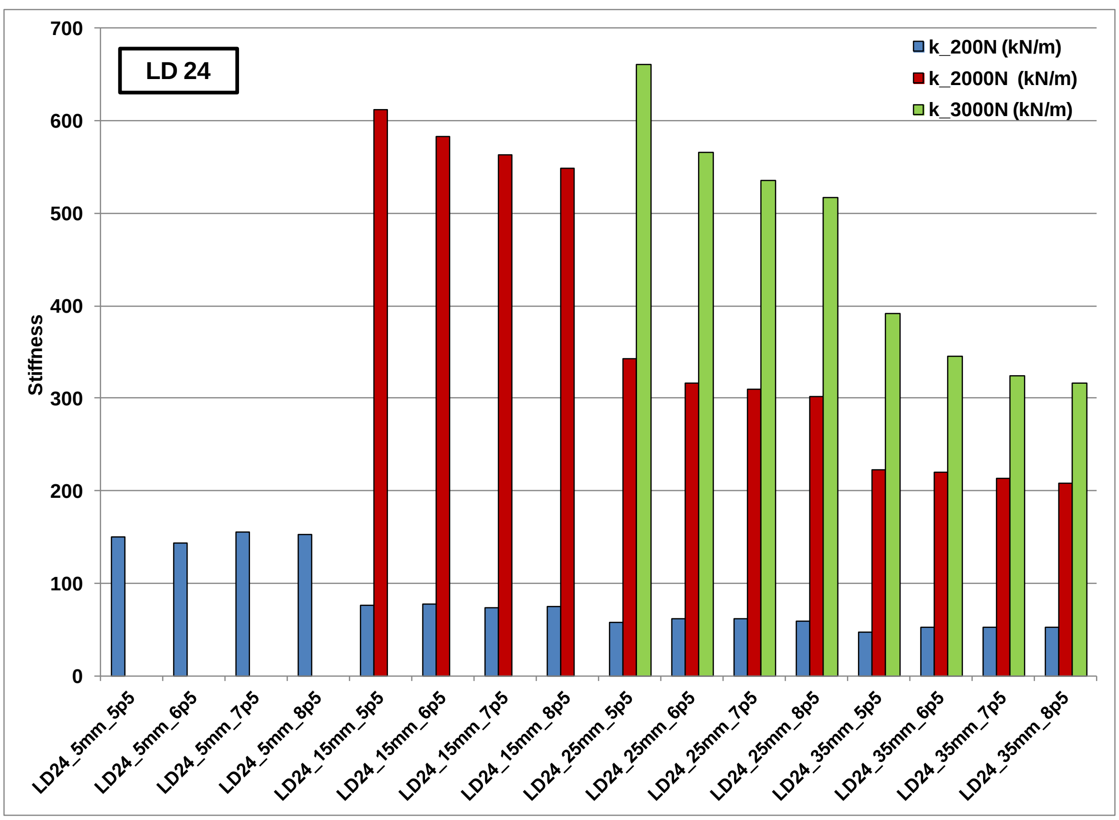


Figure 2-8. Percentage of Force Attenuation for all 64 hip protector prototypes, with groupings of material type represented in red.


LD 15
k_200N (kN/m)
k_2000N (kN/m)
k_3000N (kN/m)
Stiffness
700
600
500
400
300
200
100
0
LD15_5mm_5p5
LD15_5mm_6p5
LD15_5mm_7p5
LD15_5mm_8p5
LD15_15mm_5p5
LD15_15mm_6p5
LD15_15mm_7p5
LD15_15mm_8p5
LD15_25mm_5p5
LD15_25mm_6p5
LD15_25mm_7p5
LD15_25mm_8p5
LD15_35mm_5p5
LD15_35mm_6p5
LD15_35mm_7p5
LD15_35mm_8p5


LD 24
k_200N (kN/m)
k_2000N (kN/m)
k_3000N (kN/m)
Stiffness
700
600
500
400
300
200
100
0
LD24_5mm_5p5
LD24_5mm_6p5
LD24_5mm_7p5
LD24_5mm_8p5
LD24_15mm_5p5
LD24_15mm_6p5
LD24_15mm_7p5
LD24_15mm_8p5
LD24_25mm_5p5
LD24_25mm_6p5
LD24_25mm_7p5
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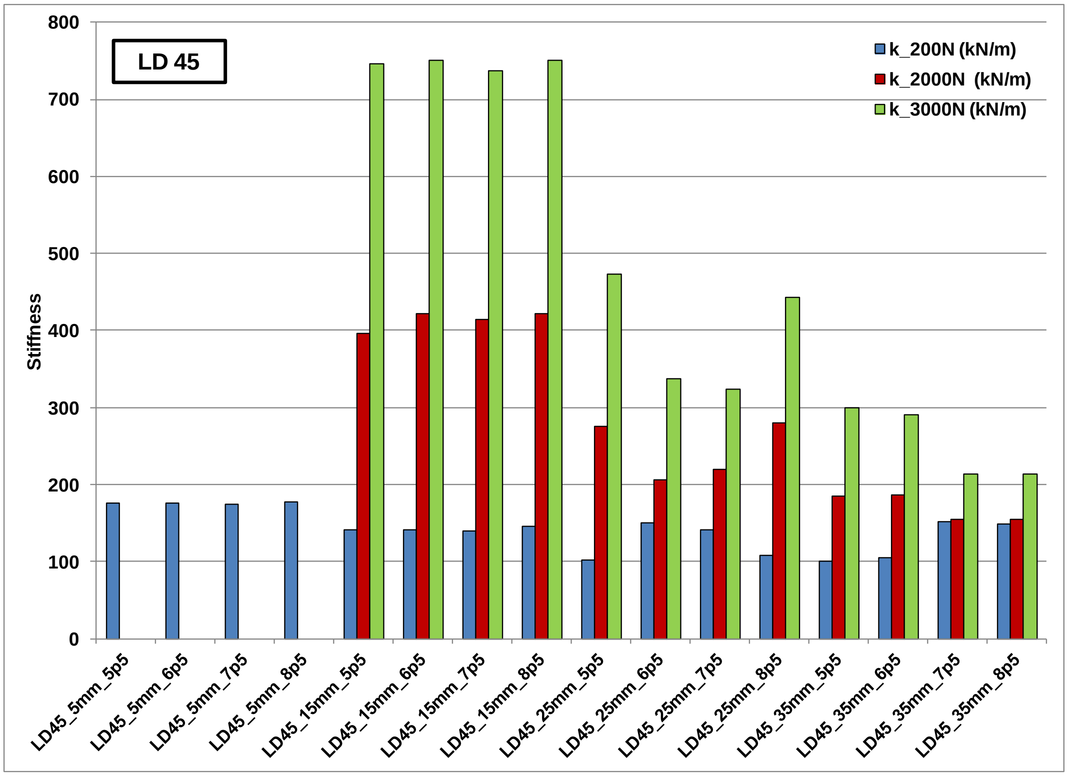
LD24_35mm_7p5
LD24_35mm_8p5



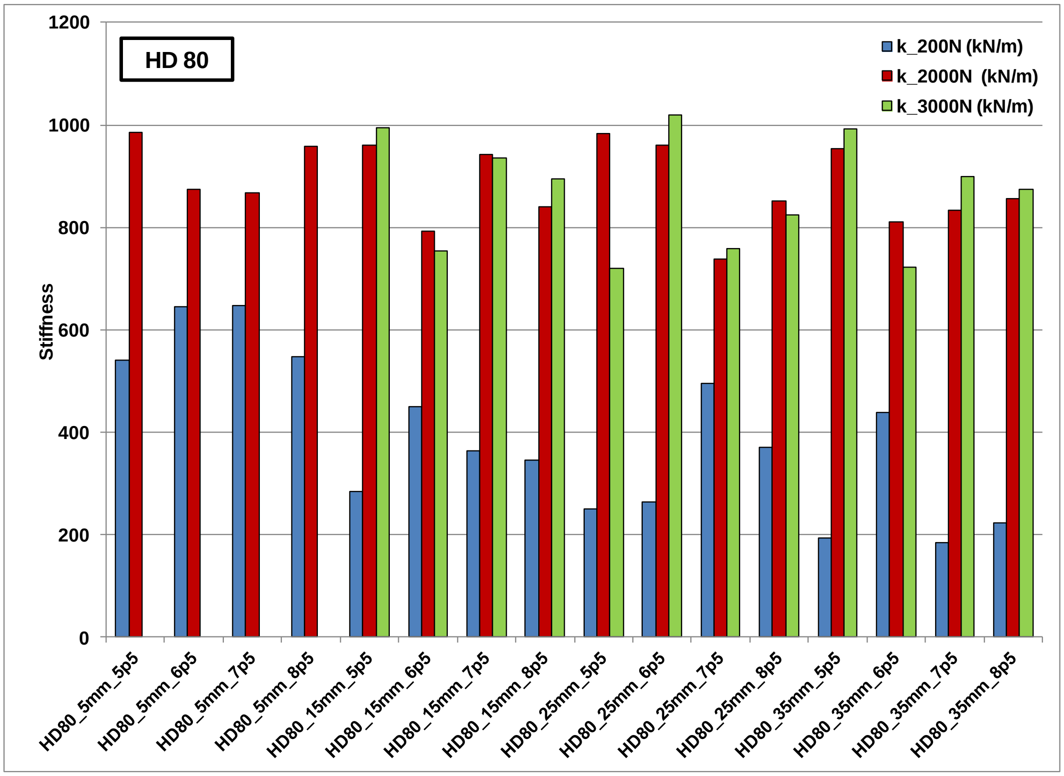
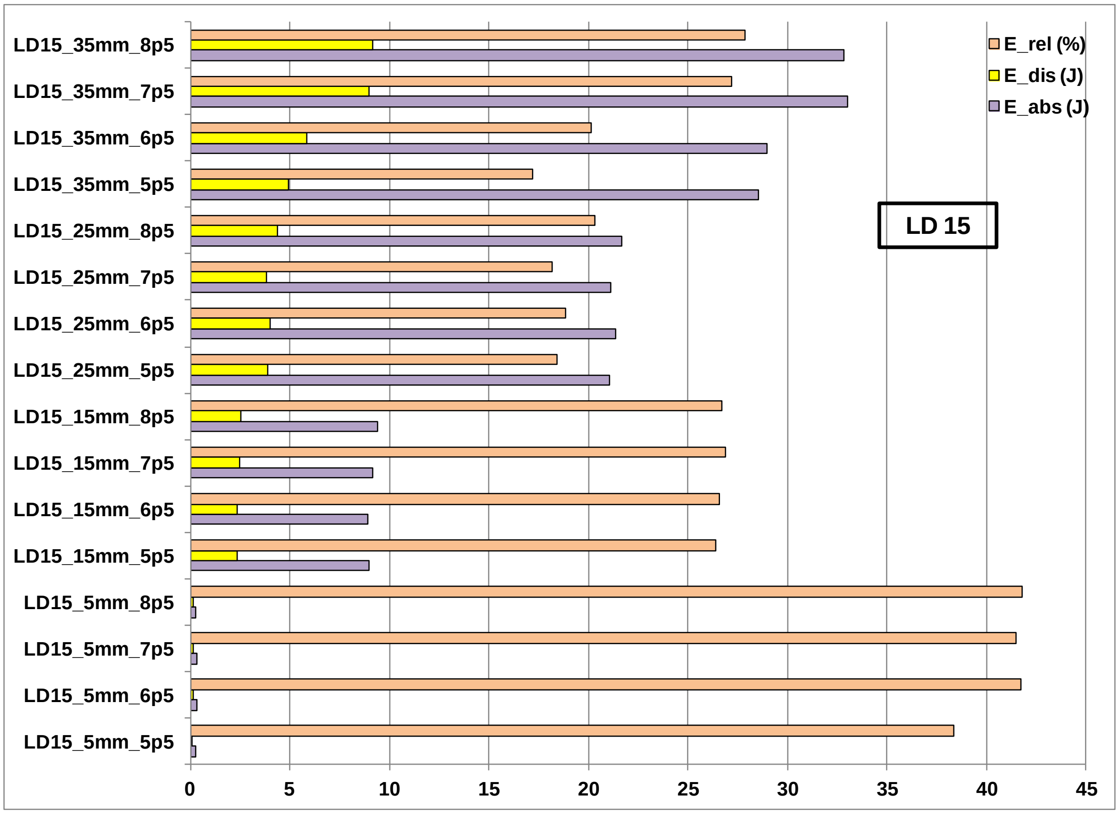
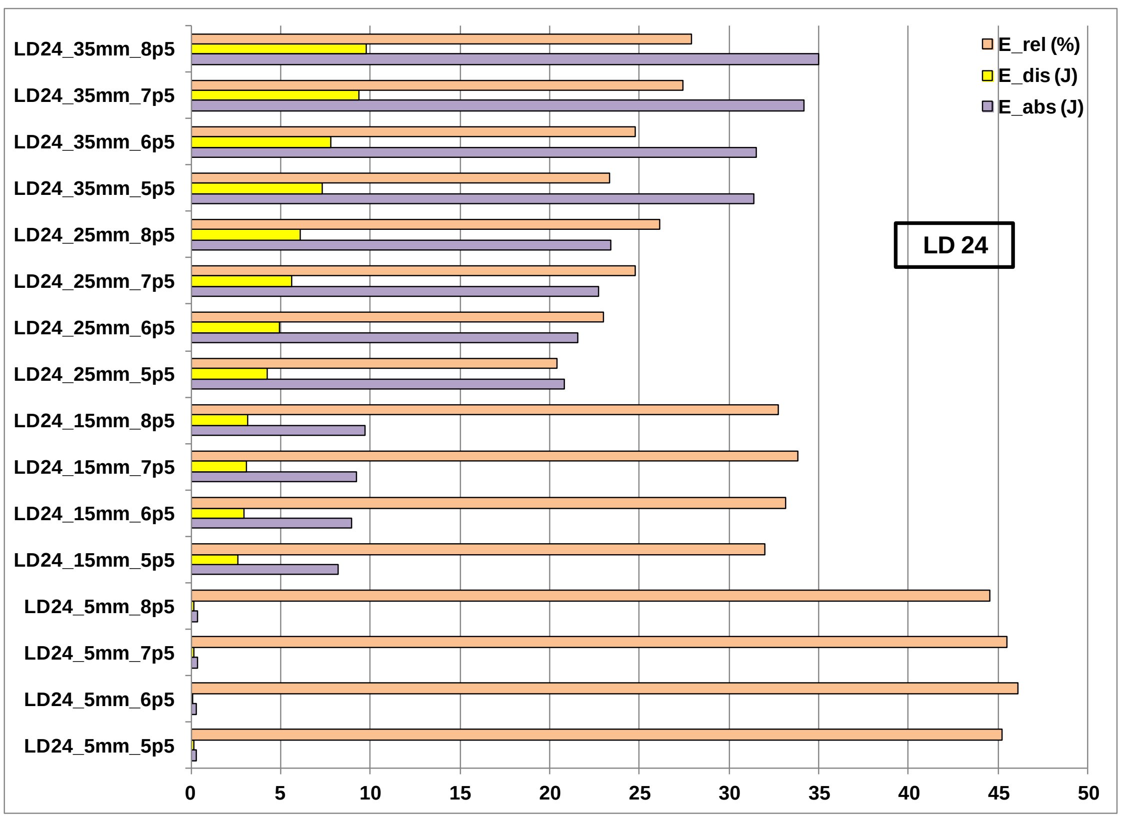
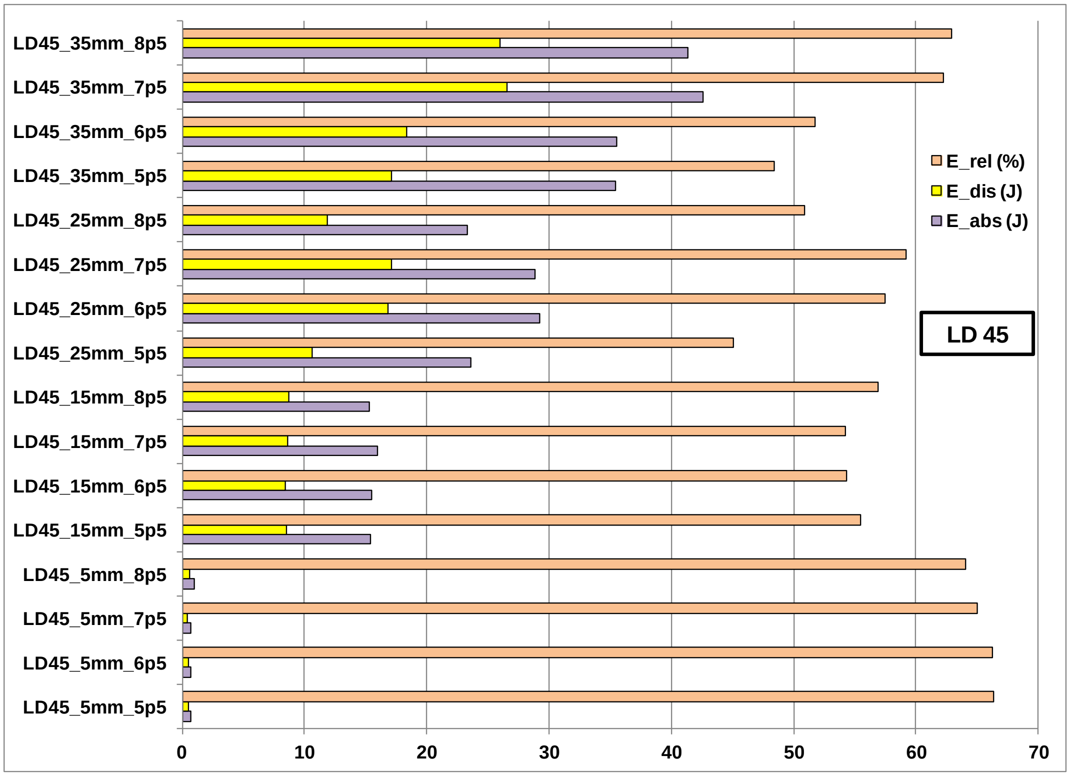


Figure 2-9 Stiffness (k_200, k_2000 and k_3000) plotted for all 64 hip protector pad combinations


LD 15
E_rel (%)
E_dis (J)
E_abs (J)
LD15_35mm_8p5
LD15_35mm_7p5
LD15_35mm_6p5
LD15_35mm_5p5
LD15_25mm_8p5
LD15_25mm_7p5
LD15_25mm_6p5
LD15_25mm_5p5
LD15_15mm_8p5
LD15_15mm_7p5
LD15_15mm_6p5
LD15_15mm_5p5
LD15_5mm_8p5
LD15_5mm_7p5
LD15_5mm_6p5
LD15_5mm_5p5
0 5 10 15 20 25 30 35 40 45


LD 24
E_rel (%)
E_dis (J)
E_abs (J)
LD24_35mm_8p5
LD24_35mm_7p5
LD24_35mm_6p5
LD24_35mm_5p5
LD24_25mm_8p5
LD24_25mm_7p5
LD24_25mm_6p5
LD24_25mm_5p5
LD24_15mm_8p5
LD24_15mm_7p5
LD24_15mm_6p5
LD24_15mm_5p5
LD24_5mm_8p5
LD24_5mm_7p5
LD24_5mm_6p5
LD24_5mm_5p5
0 5 10 15 20 25 30 35 40 45 50



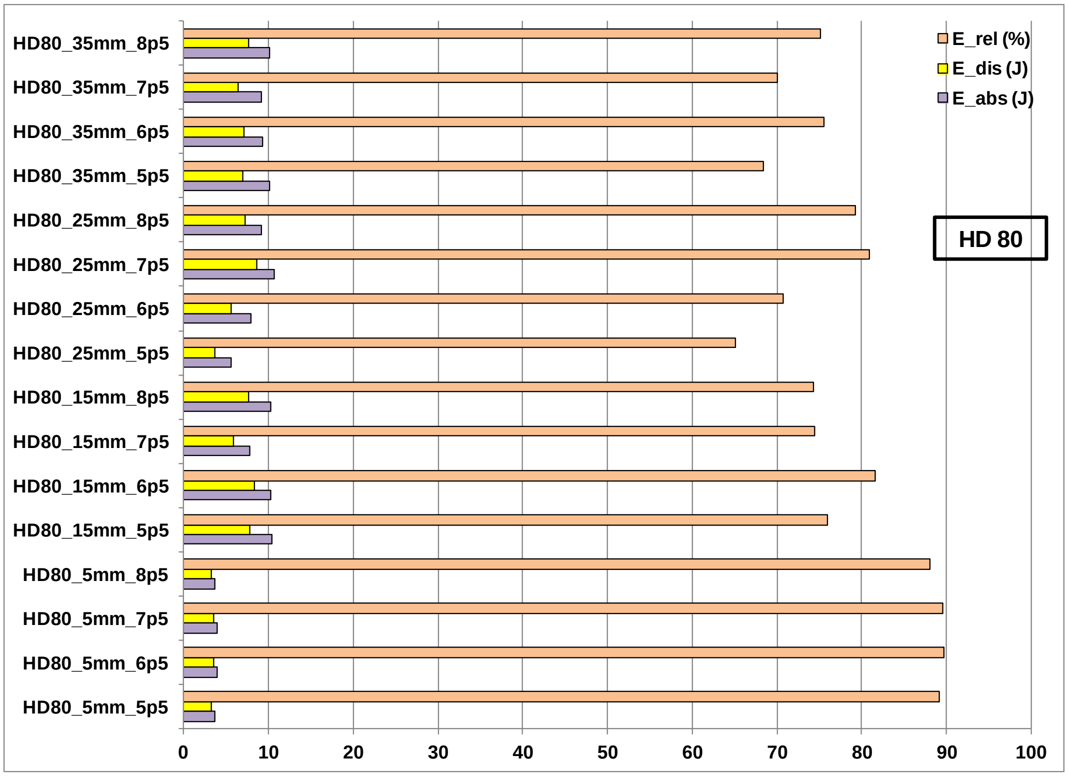


Figure 2-10. Energy Absorbed, Energy Dissipated and Relative Energy Dissipated plotted for all 64 hip protector pad combinations

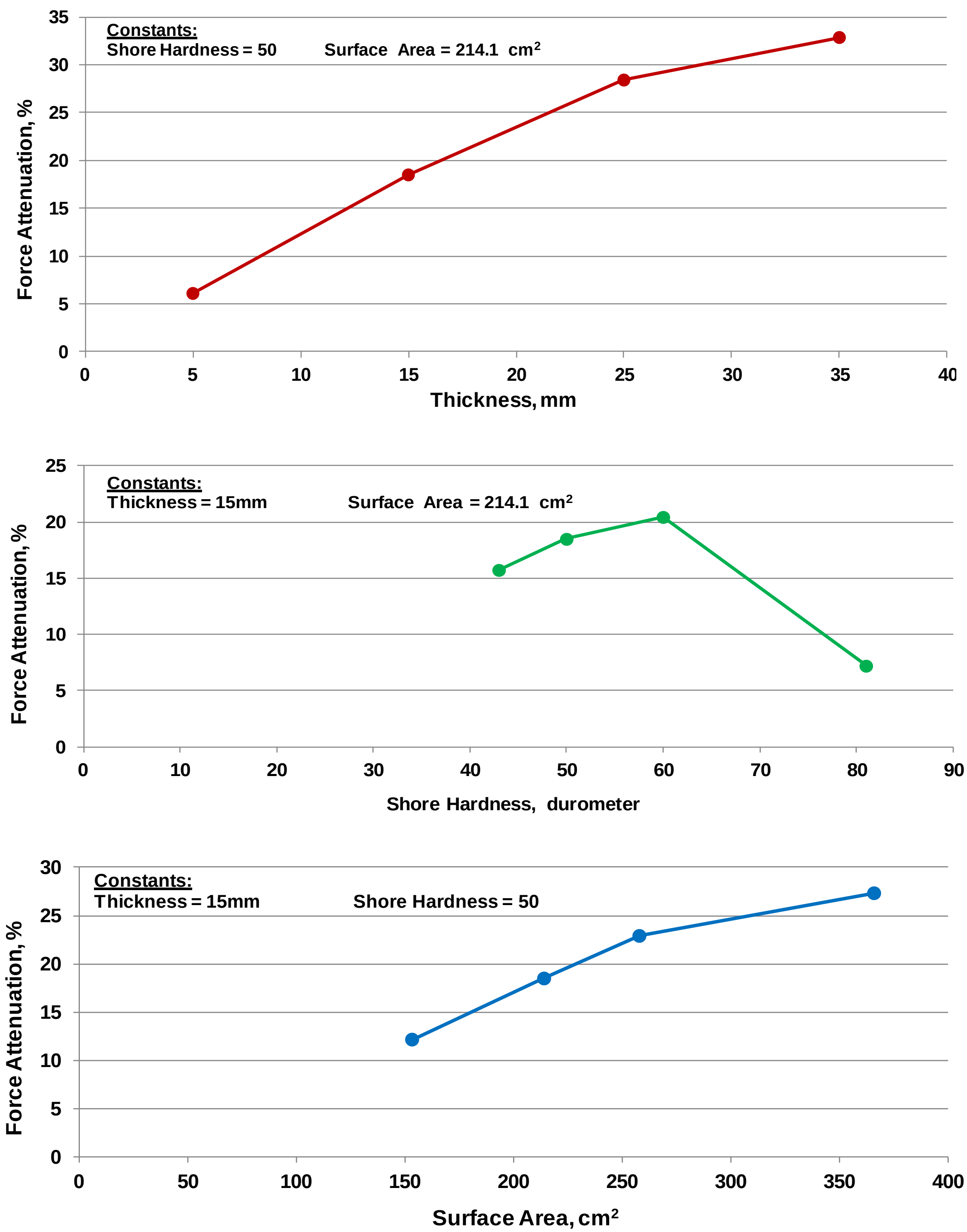


Figure 2-11. Graph illustrating the relationship between % Force Attenuation and Thickness (top), Hardness (middle), and Surface Area (bottom), with the remaining two variables constant at the second lowest level for each plot.

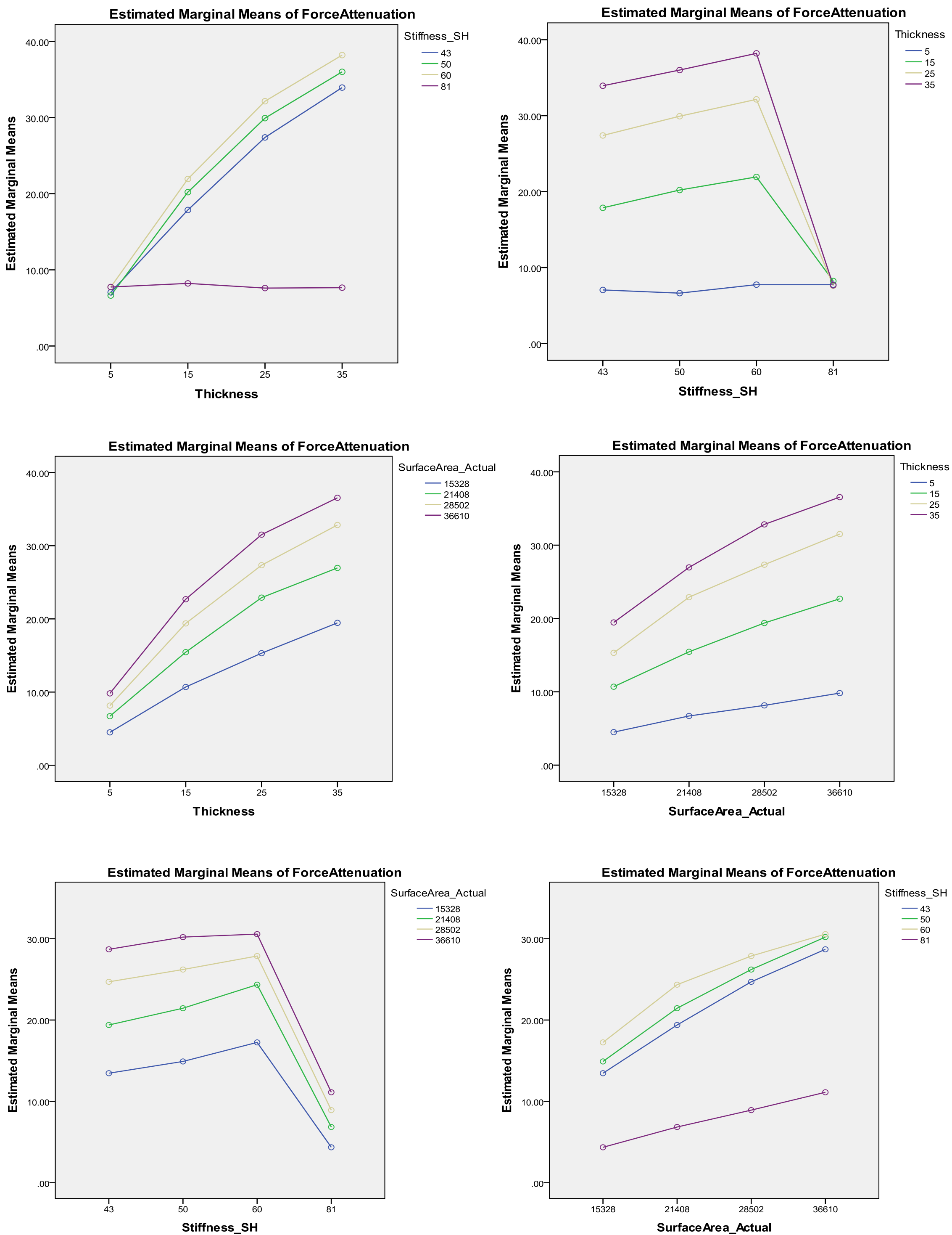


Figure 2-12 Estimated Marginal Means of Force Attenuation – Plots of Interactions between Thickness, Hardness and Surface Area demonstrating the trend in each variable.

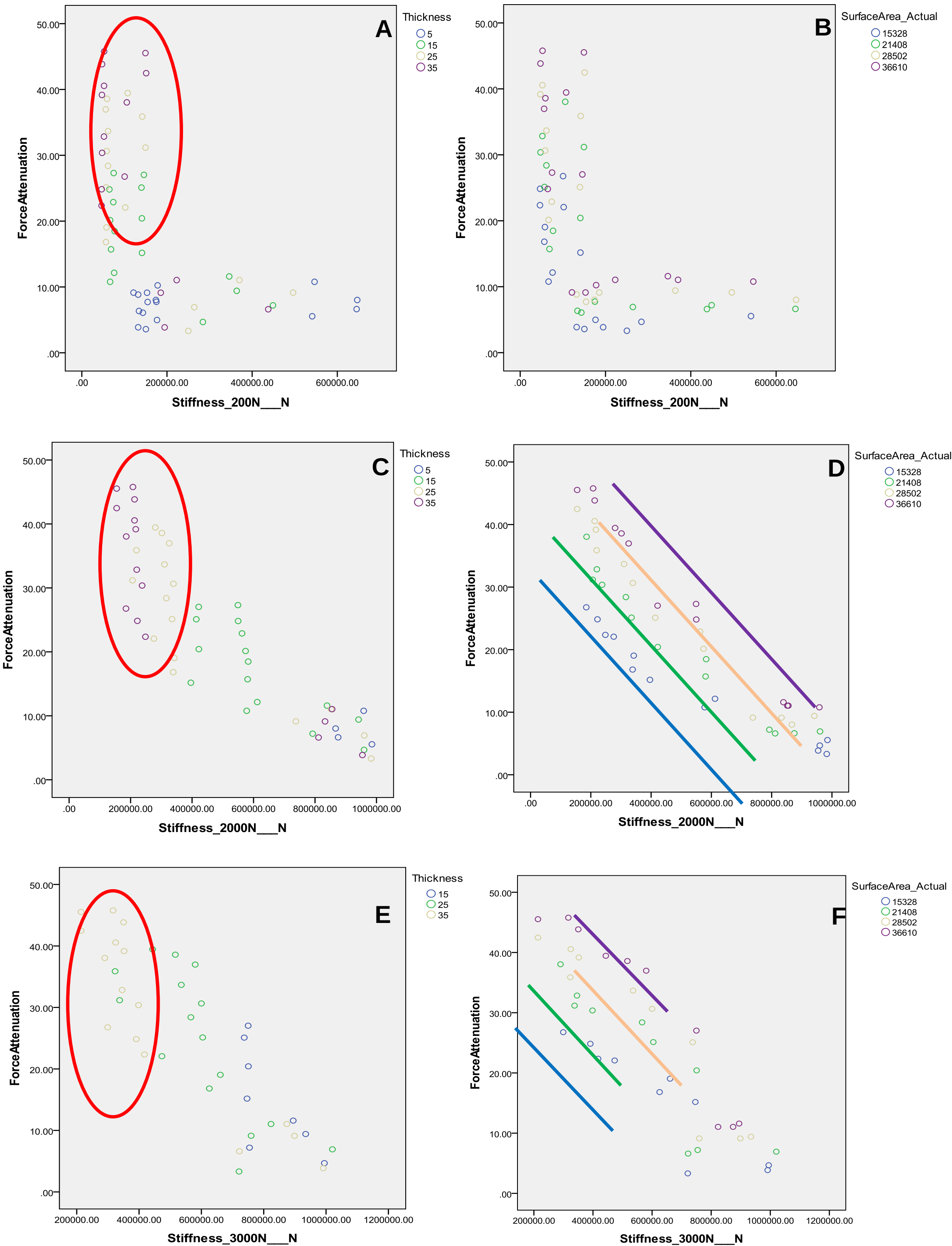


Figure 2-13. Scatter plots of Force Attenuation versus Stiffness_200N (A, B), Stiffness_2000N (C, D), Stiffness_3000N (E, F) . The red circles symbolize groupings of pads with high thickness values. The 4 sequential lines represent different levels of surface area.

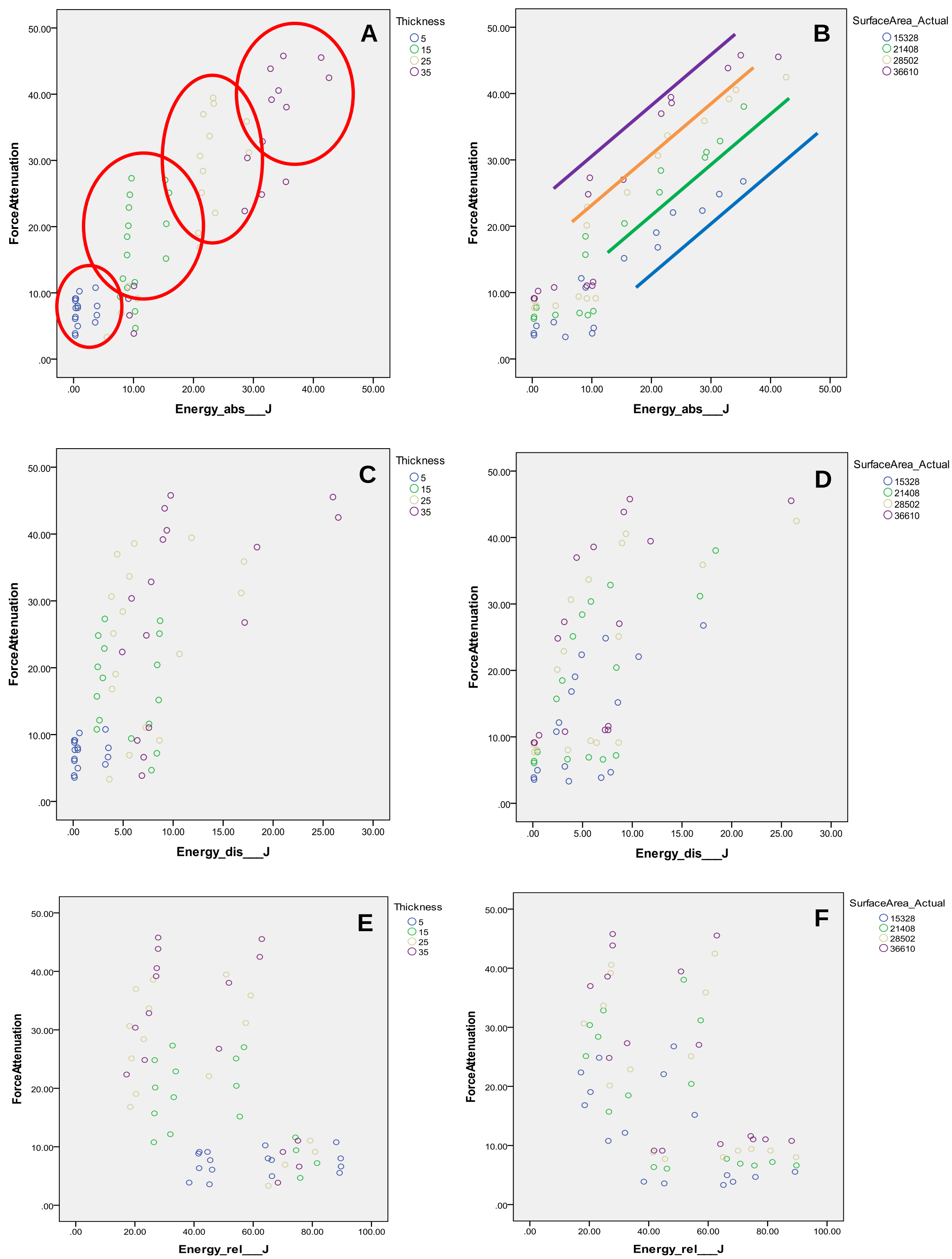


Figure 2-14. Scatter plots of Force Attenuation versus Energy Absorbed (A,B), Energy Dissipated (C,D), Relative Energy Dissipated (E,F). The red circles indicate groupings thickness. The 4 sequential lines in plot B represent different levels of surface area.

2.6. Tables

Table 2-1. Univariate Regression for the Dependent Variable Force Attenuation

Variables	R	R^2	Adjusted R^2	F	Sig.	B	t	Sig.
Thickness	0.630	0.397	0.387	40.828	<0.001	0.722	6.390	<0.001
Hardness	0.433	0.188	0.175	14.335	<0.001	-0.387	-3.786	<0.001
Surface Area (cm^2)	0.362	0.131	0.117	9.342	0.003	0.058	3.056	0.003
k_200	0.530	0.280	0.269	24.167	<0.001	< - 0.001	-4.916	<0.001
k_2000	0.887	0.787	0.782	184.208	<0.001	< - 0.001	-13.572	<0.001
k_3000	0.863	0.745	0.738	110.747	<0.001	< - 0.001	-10.524	<0.001
E_abs	0.884	0.782	0.779	222.571	<0.001	0.941	14.919	<0.001
E_dis	0.633	0.400	0.390	41.348	<0.001	1.439	6.430	<0.001
E_rel	0.507	0.257	0.245	21.407	<0.001	-0.296	-4.627	<0.001

Table 2-2. Multiple Regression Analysis for the Dependent Variable Force Attenuation and the variables Thickness, Hardness, Surface Area

Variables	R	R^2	Adjusted R^2	F	Sig.	B	t	Sig.
Thickness (mm)						0.722	9.156	0.000
Hardness	0.846	0.716	0.702	50.370	0.000	-0.387	-6.296	0.000
Surface Area (cm^2)						0.058	5.258	0.000

3. Determinants of User Preference in the Selection of Wearable Hip Protectors

3.1. Introduction

Hip Protectors have been proposed as a promising strategy for the prevention of fall related hip injuries including hip fractures. Their effectiveness is primarily dominated by their ability to reduce impact force transmitted to the greater trochanter and femoral neck region of the hip joint and user compliance in wearing the device. While the issue of biomechanical performance is central to the quality of the hip protector pad, lack of user compliance with hip protectors has been one of the major barriers to the effectiveness of this type of intervention. Chapter 2 systematically investigated how material and geometric properties of hip protectors influence their biomechanical performance. However, even the top performing hip protectors are of little value if the target user group does not wish to wear them. It is for this reason that I am investigating the issue of user compliance associated with hip protector usage, in order to gain a deeper understanding of the factors that influence preference. The topic of compliance is divided into initial acceptance of the hip protector pad, and the long term adherence to wearing the device. The focus of this chapter will be on the former, where I will examine determinants of user preference in the selection of wearable hip protectors. Research indicates hip protector compliance to be a multi-faceted issue. Some of the factors that lead to increased hip protector usage are indicated in Table 3-1 (Schoor, Deville, Bouter & Lips, 2002).

Adherence to hip protectors is often measured using the help of caregivers making daily measurements in a diary or charts/cards to record hours of hip protector usage by residents (Parkkari, Heikkila & Kannus, 1998) (Cryer, Knox, Martin, Barlow, 2002). However, multiple choice questionnaires have also been used in literature to gather user perception on factors such comfort and acceptability of hip protectors. Madrecka et. al. conducted a compliance survey to establish factors that influence low user compliance. two questionnaires were designed, one for older adults, the other for medical staff. The older adult survey was comprised of 26 multiple choice questions relating to the individual's medical condition and perception of acceptability (Appendix F). The medical staff survey included 20 multiple choice questions relating to their professional experience and perception of patient responsiveness (Appendix G). The main findings demonstrated that 51% of users found the hip protectors valuable, 41% reported discomfort, and 29% found it difficult to don/doff (Madrecka, Lyons, O'Connor, Ryan, O'Hara, Real, Collins, McGloughlin, 2009).

Hip protectors are frequently sold at medical supply stores and a doctor's prescription is not needed ("Hip protectors: Taking," 2012). Therefore, either the older adult themselves or their family member is primarily responsible for the purchase of the product. While care staff are not directly responsible for the purchase of hip protectors, they play a key role in ensure long-term adherence. Occasionally, hip protectors are also provided free of charge through governmental health programs.

Figure 3-1 shows a hypothetical model created to illustrate the 3 different levels of user preference investigated in this thesis. Tier 1 of the model addresses an individual's overall preference in selecting a given hip protector. During the initial acceptance phase, overall preference towards a hip protector is what drives the decision to start wearing the device. This type of preference is influenced by a combination of secondary factors, such as comfort, cost and style of garment to just name a few. These secondary factors are subconsciously weighted against one another to form an opinion about the hip protector's overall preference. Tier 2 of the model addressed three of the most prominent secondary preference factors, according to literature. These include preference according to the perceived comfort level associated with the hip protector, attractiveness in appearance once the hip protector is worn, and the protective value provided by the hip protector in order to prevent fall related hip injuries. Similar to how the perceived factors in tier 2 influence overall preference in tier 1, tertiary factors relating to the intrinsic characteristics of the hip protectors exist that influence comfort, appearance and protection (tier 2), and in turn influence the overall preference (tier 1). These tier 3 factors include the thickness of the hip protector pad, the hardness of the material with which it is constructed, and its surface area. For example, research has shown hip protectors that have too high of a thickness/ hardness/surface area value, rate poorly with users due to their inability to conform to the shape of the hip, therefore resulting in lack of comfort and a poor body image. This thesis will systematically investigate the relationship between each of the three levels of user preference in order to provide a full picture of initial acceptance of hip protectors, to eventually aid in the design of these devices that is not only biomechanically superior, but also elicits high compliance rates from its users.

3.2. Methods

3.2.1. Participants

Eighteen older adults (2 male and 16 female) participated as part of the resident group of this study with ages ranging from 58 to 102 years (mean = 79.7 yrs, SD = 11.1 yrs). In addition, fourteen young individuals (1 male and 13 female) participated as part of the care staff group of this study with ages ranging from 22 to 60 years (mean = 41.6 yrs, SD = 12.8 yrs). The group of elderly participants were residents at one of the following five Assisted Living (AL) sites of the Fraser Health Authority in British Columbia, Canada: Belvedere, Dania Manor, Seton Villa, Hawthorne and Courtyard Terrace. The other group of participants were care staff at one of the following three Assisted Living Sites (ALS) of the Fraser Health Authority in British Columbia, Canada: Dania Manor, Seton Villa and Courtyard Terrace.

Participants were recruited through advertisements and flyers posted on notice boards at various AL sites, as well as through word-of-mouth promotion. To aid in the process of participant recruitment and to elicit interest about the study, older adults and care staff were encouraged to attend a presentation conducted at their respective AL sites. The presentation provided a background on the nature, cause and consequences of hip fractures, preventative efforts, and participation guidelines of the study being conducted.

The experiment protocol was approved by the Research Ethics Board at the Fraser Health Authority and at Simon Fraser University (Appendix H). All participants provided separate informed written consent for both above mentioned parties.

3.2.2. Experimental protocol

The experimental protocol for the hip protector preference study was based on a series of questions that were answered by the participants. Instructions provided to participants as part of the questionnaire were based on a predetermined script, so as to ensure consistency of the information delivered. The questionnaires were slightly modified to correspond with the two different participant groups. In the case of care staff, the initial questions asked were pertaining to previous health care related role, length of employment at the current AL site, number of falls at the site in the past year, percentage of residents they believe to be at high risk for falls, number of residents wearing/inquiring about hip protectors, and many more (Appendix I). For older adults, the initial section of the questionnaire contained questions that were used to gather participant information, such as their physical characteristics (age, gender, height, weight), fall history, use of mobility aid, length of stay at AL site, etc. In addition, older adults were asked to identify from a list provided to them any chronic conditions they may have (Appendix J).

The subsequent portion of the questionnaire consisted of six questions, and was aimed at assessing the participant's current knowledge of hip protectors (Appendix K). Participants were asked to provide binary responses of yes or no to the first five questions, which consisted of whether they had heard about, seen, used/know anyone who used a wearable hip protector, as well as whether they could understand the difference between a soft-shell versus a hard-shell hip protector. The last question asked participants to circle on the diagram of a pelvis one of the three highlighted locations that showed the most appropriate placement of the hip protector on the body. The above set of questions helped determine the level of familiarity each participant had with wearable hip protectors. This information could serve to be useful when determining whether prior knowledge of the intervention influenced the preference ratings provided in the subsequent sections of the questionnaire.

Next, each participant was provided with a brief education session on wearable hip protectors. The purpose of this activity was to ensure that all participants were equipped with at least the basic knowledge of hip protectors prior to answering questions indicating their preference of one over another. The education session consisted of an explanation of what hip protectors are, why they have been proposed as a strategy for reducing hip fracture risk, the difference between hard-shell and soft-shell hip protectors and lastly the correct placement on the body.

For the main portion of the questionnaire (Appendix L), twelve specially-built hip protector pads were constructed using different configurations of thickness, hardness, and surface area. Specifically, pads A, B, C, and D each had different thicknesses (5, 15, 25, and 35 mm) while the remaining eight pads had the same thickness as pad B. Pads E, F, G, and H each had different hardness (SH = 43, 50, 60 and 81 (or LD 15, 24, 45, and 80)), while the remaining eight pads had the same hardness as pad F. Pads I, J, K, and L each had different surface areas (5.5, 6.5, 7.5 and 8.5 inch diameter circles), while the other eight pads had the same surface area as pad J. Hence pads B, F, and J were identical with respect to thickness, hardness, and surface area. Participants were shown these 12 pads in groups of four (depending on the hip protector variable in question), and were asked their preference based on 5 criteria.

The older adults were asked their preference in selecting a hip protector for everyday wear, whereas care staff was asked their preference for recommending a hip protector to older adults at their site of employment. The five preference criteria were based on the three-tier study model described previously. They involved overall preference of the hip protector, preference according to perceived comfort, preference according to perceived attractiveness in appearance, preference according to perceived protective value and lastly overall preference with knowledge of the biomechanical performance of the hip protectors. For this last criterion, participants were shown a bar graph of the force attenuation capacity of each hip protector prototype based on results of the impact pendulum tests.

Due to feasibility reasons participants were not required to wear the hip protectors prior to making their preference selections, since such a task would require the hip protectors to be enclosed inside garments of many different sizes and styles. Therefore only the hip protector pads were shown, and participants were conveyed that these products were simply prototypes. Participants were only allowed to manipulate the hip protector prototypes in their hands, apply an impact force to the pad by tapping the hip protector, or superficially place the protector on their hip to get a sense for its fit.

In the final section of the questionnaire participants were asked to verify whether the preferences selected separately for thickness, hardness and surface area for each of the five criteria, put together would form the hip protector they would prefer to wear / recommend (for each respective criteria). Participants were shown a specific hip protector for each criteria (from the 64 combinations of prototypes available) that matched their selections for thickness, hardness and surface area. A binary response of yes or no was required as to whether that is the hip protector which they find the most preferable or not. If the latter choice was the response, participants were allowed one chance for a revision to change a single or multiple values of the three variables.

3.2.3. Data collection

Hip protector preference under the five main criteria was measured on a Likert scale. Each criterion contained three subsections, for the variables thickness, hardness and surface area, and each subsection contained four values for that particular variable (e.g. thickness) while maintaining the remaining two variables constant (e.g. hardness and surface area) at the second lowest of the four values. The process outlined in Figure 3-2 was followed to answer the questionnaire. For each criteria, participants were asked to rate the 12 hip protector pads by circling a number from 0 (least preferred) to 10 (most preferred) on the scale provided. Questions for the criteria were first randomized at the level of preference criteria and subsequently at the level of the three hip protector variables. The exception to this was the first evaluation was always for overall preference prior to biomechanical performance knowledge) and the last evaluation was for overall preference post biomechanical performance knowledge. Furthermore, participants were not allowed to refer to ratings provided for any previous criteria.

3.2.4. Data analysis

Data analysis primarily focused on addressing three distinct aims brought up in this section. Firstly, whether a relationship exists between preferences indicated for Level 2 variables (comfort, appearance and protection) and Level 1 (overall preference). Secondly, the relationship between preferences indicated for Level 3 variables (thickness, hardness and surface area) and Level 2 (comfort, appearance and protection). Lastly, whether knowledge of actual protection offered influences an individual's overall preference (i.e. comparison between the responses of criteria 1 and 5 in the questionnaire). For all three aims, linear regression models were generated using generalized linear models. Since each participant (older adult or care staff) contributed twelve observations (i.e. one observation for each of the twelve hip protector pads), the models are fitted with a random effect for the participant. For the purpose of analysis, comfort, appearance, and protection ratings were treated as continuous variables.

For the first of the primary aims, overall preference (Q1) was included as the response variable in a general linear models regression analysis. The explanatory variables were comfort (Q2), appearance (Q3), protection (Q4), and subject group (older adult versus care staff). Three interaction terms for Q2, Q3, and Q4 versus subject group were also included in the model. Subject ID nested within subject group was included as a random effect because the ratings of each of the twelve pads occurred within subjects. For the second of the primary aims, three analyses were performed with comfort, appearance, and protection as the response variables in analysis of variance. For all three models, the explanatory variables were pad, subject group, and the pad by subject group interaction. Subject ID nested within subject group was included as a random effect. For each response variable, pairwise comparisons were performed to compare mean ratings for pads with respect to different levels of thickness, hardness, and surface area. Because pads B, F, and J were identical with respect to all three qualities, the average across those three pads was used to represent their respective levels in the pairwise comparisons instead of the individual means for B, F, and J. For the last primary aim, a “change” factor was calculated for the change observed in overall preference after knowledge of actual biomechanical performance. Change was equal to ratings for the first criteria subtracted from the last criteria. This variable for change was subsequently included as a response variable in a generalized linear models regression analysis. Explanatory variables included the ‘pad’, ‘subject group’ (subject ID nested within as a random effect), as well as an interaction term for ‘pad by subject group’.

Since the levels of thickness, hardness, and surface area have numerical interpretations, contrasts were included to test for the presence of linear relationships between these variables and ratings for each of the three response variables. In addition to the above tests for thickness, hardness, and surface area, comparisons between subject groups for each pad are also provided. However, these comparisons were only of interest if the pad by subject group interaction was significant in the model. Kenward-Rogers degrees of freedom were used for all pairwise comparisons.

A secondary aim of this section of the study was to assess differences in preferences between the two subject groups (older adults and care staff). It is important to note that the two groups answered different questions when they completed the questionnaire: The older adults respond with their personal preferences, whereas the care staff indicates their recommendations for the *average* resident at their respective AL site. Therefore, the primary aims were fitted to include terms for participant role (older adult versus care staff). This enabled a comparison between the two groups to answer the question, "Do residents' personal preferences differ from staff recommendations for the *average* resident?".

3.3. Results

With regards to aim 1, there was a significant positive association between overall preference and each of perceived comfort (F value = 38.96, $p<0.0001$) and protection (F value = 136.53, $p<0.0001$). There was no evidence of a significant association between overall preference and appearance (F value = 0.12, $p = 0.7251$). Furthermore, no evidence was found between overall preference and subject group, or among the interaction terms between the subject group and the three Level 2 explanatory variables. F-test results of regression (Table 3-2) for the response variable overall preference and explanatory variables comfort and protection indicate a significant relationship. Furthermore, the 'estimate' coefficients from the general linear models regression analysis (Table 3-3) reflect how a unit change in the significant predictor variables (comfort and protection in this case) affects the dependent variable (overall preference). These indicate that protection is more strongly related to overall preference than comfort, as indicated by the 'estimate' values of 0.3013 for comfort and 0.5727 for protection. Appearance on the other hand did not display a significant relationship with overall preference.

With regards to aim 2, we found a significant relationship ($p < 0.0001$) between all Level 3 variables and each response variable in Level 2. As seen in Table 3-4, for the response variable comfort, F tests indicate a significant relationship with both explanatory variables ‘pad’ ($p<0.0001$) and ‘subject group’ ($p=0.0413$). ‘Pad by subject group interaction’ did not produce a significant relationship. Specifically, F test results that tested separate pad features indicated that each of thickness, hardness and surface area showed significant associations ($p<0.0001$) with comfort (Table 3-5). Figure 3-3 indicates the estimated means, and standard errors for the 12 hip protector pad prototypes, averaged across both participant groups for comfort, appearance and protection. The combination that received the highest average rating for comfort was the lowest thickness (5mm), lowest hardness (SH = 43) and second smallest surface area (pad with diameter of 6.5in). The combination with the lowest rating was the highest thickness (35mm), highest hardness (SH = 81) and largest surface area (pad with diameter of 8.5in). In terms of the response variable appearance, the model indicates a significant relationship for the variable ‘pad’ ($p<0.0001$) as well as for the ‘pad by subject group interaction’ ($p=0.0165$). Furthermore, each of thickness, hardness and surface area showed significant associations ($p<0.0001$) with appearance. The combination that received the highest and the lowest average ratings for appearance were the same combinations found previously in comfort i.e. highest appearance ratings for lowest thickness (5mm), lowest hardness (SH = 43) and second smallest surface area (pad with diameter of 6.5in), and lowest appearance ratings for highest thickness (35mm), highest hardness (SH = 81) and largest surface area (pad with diameter of 8.5in). As per Table 3-6, since ‘pad by subject group interaction’ was significant in the case of appearance, difference between subject groups for each pad was determined. However, in this latter analysis, none of the Bonferroni adjusted p-values obtained were significant in nature (Table 3-7). Lastly, in the case of protection (Table 3-8), a significant relationship for the variable ‘pad’ ($p<0.0001$) as well as for ‘pad by subject group interaction’ ($p<0.0001$) was found, with each thickness, hardness and surface area showing significant associations ($p<0.0001$) with protection (Table 3-9). The combination that received the highest average rating for protection was the second greatest thickness (25mm), second lowest hardness (SH = 50) and second largest surface area (pad with diameter of 7.5in). The combination that received the lowest average rating for protection was the thinnest (5mm), hardest (SH = 81) and smallest surface area (pad with diameter of 5.5in). Once again, since 'pad by subject group interaction' was significant in this case, tests for difference between subject groups for each pad were conducted. Analysis revealed only two items obtained significant Bonferroni adjusted p-values; difference in ratings between older adult and staff was significant for the lowest hardness (SH=43, p=0.0459) and the highest hardness (SH=81, p=0.0108).

Lastly, the analysis for aim 3, whether overall preference ratings changed after responders are provided knowledge of actual protection offered, revealed a significant change (Table 3-10). As seen in Figure 3-4, change in thickness was the most striking (preference changed for the top 2 performing hip protectors). Averaged over all participant responses and hip protector pads, the overall least squares mean Change, with the standard error, t-test and 95% confidence limits was calculated. The estimated mean change in ratings was found to be 0.96 (Table 3-11). Furthermore, a change in overall preference ratings was seen to differ between subject groups, as illustrated by the significant p value (p=0.0247) observed for the term 'subject group'. Results illustrate the Change to be significantly different from zero in the case of staff members (p<0.0001) but not for older adults (p=0.00524) (Table 3-12). A significant value for the explanatory variable 'pad' (p<0.0001) was obtained, with results for t-tests indicating several hip protector pads for which the change in ratings was significantly different from zero. The change was positive for some pads (pads C, D, G, K and L) and negative for others (pad A), as indicated by positive or negative values for "Estimated Mean Change" (Table 3-13). The significant p-value for the 'pad by subject group' interaction indicates a significant difference in mean Change among combinations of pads and subject groups. Table 3-14 includes the least squares means and standard errors for each of the two subject groups for each of the twelve pads and the corresponding standard error, t-test, and 95% confidence limits. Again, significances were found for both positive and negative Changes. Lastly, as pads B, F and J were identical with respect to their inherent characteristics (thickness, hardness and surface area), a standard average was calculated across the three pads to provide a more precise image of their ratings, as opposed to simply calculating the average for each pad individually. This average was used instead of the mean rating for each of the three pads when making pairwise comparisons. As seen from Table 3-15, the only significant outcome for 'Diff between Subj Grps for Standard Pad' (estimated mean change of -1.7011, p=0.0095). Table 3-15 provides the Multiple Regression Analysis for Overall Preference with each thickness, hardness and surface area. Only the variable hardness displayed significance.

3.4. Discussion

In this chapter of the study, through the administration of questionnaires, I examined factors influencing an individual's preference when selecting a hip protector. It was found that an individual's overall preference in selecting a hip protector is predominantly influenced by the level of comfort and protection against injury, where the latter displayed a slightly greater strength of association. Attractiveness in appearance was also examined, and while individual participant's comments suggested preference one way or another, results across participants did not yield a significant relationship with overall preference. These results suggest a level of forethought and practicality on the part of the user where selection is made based on whether the devise will fulfil the purpose it was designed for. Furthermore, the close relationship of overall preference with comfort indicated that individuals were considering the long-term implications of using such a devise on a daily basis.

The minimal thickness also ensures the profile of the hips is not extended when the protector is worn with the garment, therefore maintaining the physical appearance of the user. The primary advantage of a hip protector with minimal stiffness (i.e. high flexibility) is that it conforms to the shape of the body therefore preserving its external appearance, but also mimics the soft tissue present around the hip region to provide users with comfort (especially if they are lying on their side). The hip protector with minimal surface area (diameter=5.5in) was not chosen as having high comfort or appearance, potentially due to the size of the pad not matching the size of the average human hip. Comments by participants during the rating process suggested a hip protector with such a small surface area would not stay at a constant location on the hip, and could instead migrate upwards especially while seated. The most preferred size (diameter=6.5mm) seemed to more closely resemble the area at the side of the hip. Participants believed this size would seamlessly integrate with the general shape of their hip (i.e. not protrude), and the pad would not shift around. The hip protector combination of second greatest thickness (25mm), second lowest hardness (SH = 50) and second largest surface area (pad with diameter of 7.5in) was perceived by participants as possessing the greatest protective value. In contrast to preferences provided for comfort and appearance, in the case of protection, participants selected the generally thicker, stiffer and hip protectors with a large surface area. However, the hip protectors with the greatest thickness, hardness and surface area did not receive the highest ratings. Participants feared a hip protector that was highly thick and stiff would in fact cause injury to the hip due to low compliance. Additionally, the largest hip protector (8.5in diameter) was rated low by participants and viewed as excessive, as they did not believe it provided any more protection than the hip protector with 7.5in diameter (rated highest).

Participant's overall preference underwent a significant change once knowledge of biomechanical performance of each hip protector was provided (care staff and older adults). Generally, the ratings for overall preference shifted in favor of the hip protectors that illustrated a higher force attenuation capacity than their counterparts. This indicates the participant's desire for greater protective value in a hip protector, even if it is at the expense of other factors such as comfort and appearance.

This result further supports the finding of the primary objective where protection produced the greatest strength with overall preference than comfort or appearance. Specifically, the greatest change in ratings was positive and was observed for pads D (thickness: 35mm), G (hardness: SH=60) and L (surface area: diameter 8.5in), which in fact demonstrated the highest force attenuation in their respective categories (33%, 20% and 27%, respectively). Furthermore, a significant different was noticed between the ratings for the two subject groups. Staff members preferred the hip protectors with the greatest biomechanical performance. Older adults on the other hand, were ready to forego the hip protector with the highest force attenuation to select one with a slightly lower performance but with higher comfort and appearance attributes.

The preference ratings for comfort, appearance and protection also produced a significant association with the hip protector's geometric and material properties. Results suggested a hip protector with low thickness (5mm), low hardness (SH=43) and second smallest surface area (diameter=6.5in) was most preferable not only in terms of comfort but also in terms of attractiveness in appearance when worn. It is not surprising that a hip protector with minimal thickness provides a high degree of comfort, since the lack of ‘bulkiness’ enables users to move about with ease as well as stay seating for extended period of time without the pad exerting pressure on the soft tissue at the hip. This result agrees with a study by Honkanen et. al, where soft and flexible pads were chosen over their counterparts as they provided the greatest level of comfort when worn (Honkanen, Dehner, Lachs & , 2006). Additionally, Honkanen et. al. studied the garment based features of hip protectors in a nursing home setting, and found that light colored, heavier weight cotton blend fabric with the ability to be a “pull up” style as well as “wrap around” demonstrated the greatest acceptance in staff as well as the elderly (Honkanen, Dehner, Lachs & , 2006). Therefore, in addition to knowing user preferences for changes in pad characteristics, it would have also been valuable to include a garment variable in the current study to observe its effect on preference.

Despite the result that comfort and protection influence the user’s overall preference, cost of the hip protector is also observed as a significant factor in literature (Cameron, Kurrle, Quine, Sambrook, Chan, Lockwood, Cook & Schaafsma, 2011). The typical cost for a pair of hip protectors is $80-$100 ("Hip protectors: Taking," 2012). Cameron et. al. conducted a cluster randomized controlled trial of 234 elderly residents and studied the impact of hip protector cost in relation to compliance. They created 3 cohorts, with the first group receiving hard shell hip protectors without cost, the second group an educational session and hip protectors without cost, and the third group was the control group who received a brochure about hip protectors. These cohorts were followed for both compliance and secondary outcomes (falls, injuries and fractures). No one in the third group purchased hip protectors, indicating that providing free hip protectors was necessary for initial acceptance. But once provided with a free hip protector there was no difference in adherence in the other 2 groups or in secondary outcomes (Cameron, Kurrle, Quine, Sambrook, Chan, Lockwood, Cook & Schaafsma, 2011).

The result that overall preference is influenced primarily by perceived comfort and perceived protective value is important in itself, as it allows hip protector manufacturers to identify the preference area most valuable to the user during the initial acceptance phase. Additionally, one of the most important yet non-obvious results of this study is that knowledge of biomechanical performance affects the user’s overall preference, in favor of high performing hip protectors. This conveys the highly important fact that user opinions are subject to change should proper education be provided. The impact of this finding can be widespread, where it would be beneficial for biomechanical performance measures to be made available to potential buyers to help them make an educated purchasing decision.

There are notable limitations to this portion of the study. Firstly, the 64 custom made hip protector pads were only prototypes, and therefore did not have the same polished nature to them as protectors available on the market. There were not enclosed within an undergarment, as most traditional hip protectors are marketed. Additionally, as they were prototypes, the pads did not have a tapered edge. These factors above could have potentially affected the score provided by users in the various preference criteria. A second limitation is that only 4 values for each of thickness, hardness and surface area were used in this study. It would have been valuable to obtain preference scores for smaller increments for each of the three to more clearly understand how preference varies with minor changes in pad characteristics. Furthermore, only a subset of compliance related factors were considered as part of this study. While perceived comfort, attractiveness in appearance and protective value are at the core of overall preference, additional research must be conducted to account for factors such as cost, garment type, ease of don/doff, launderability, etc. Limitations also exist on the participant level, where only residents cognitively intact to make their own decisions and staff of AL sites were sampled. Lastly, long term adherence to use was not examined as part of this study, and should be included as part of future research.

While these limitations have influenced the interpretation of the results, these points were decided upon to ensure feasibility of the study. Future research should focus on systematically modifying additional geometric (e.g. shape) and material properties (e.g. constructing a hip protector from a combination of materials to create a hard shell hip protector) to determine its effect on user preference. Furthermore, a preference study can be conducted using commercial hip protectors to understand whether findings of this study translate to those available on the market.

In conclusion, the findings of this study further our current knowledge of user preference in the selection of hip protectors. In order to construct an effective hip protector, it must not only possess high biomechanically performance, but also generates high user compliance. Manufacturers must understand that comfort plays an imperative role in the type of hip protector that users select for everyday wear. Therefore, it is not sufficient to solely focus on producing hip protector that are thick and of a large profile to absorb the maximum amount of impact force, as these will seldom be worn. One may think that high performance and high comfort are mutually exclusive requirements, however through advancement in materials technology, I believe it will be possible to design hip protectors with a low profile that are able to absorb a significant amount of impact energy.

3.5. Figures

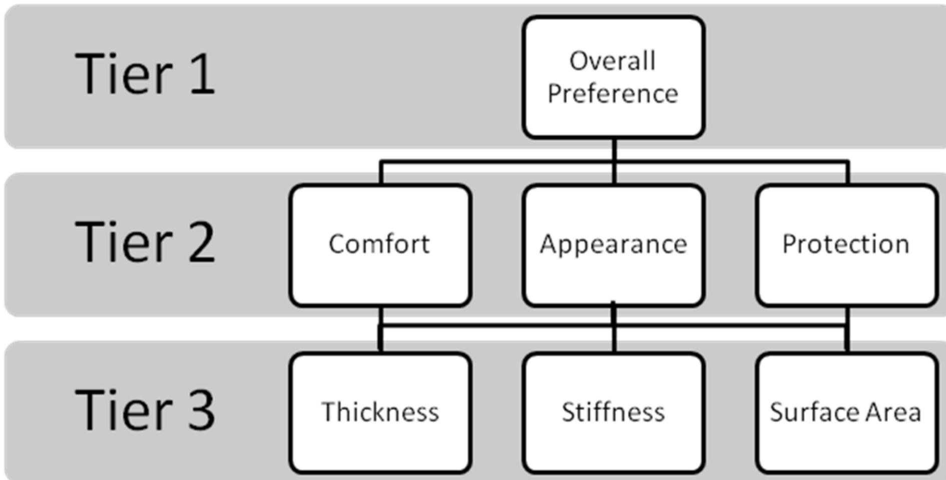


Figure 3-1. User Preference Model of Hip Protector Acceptance: Divided into Tiers

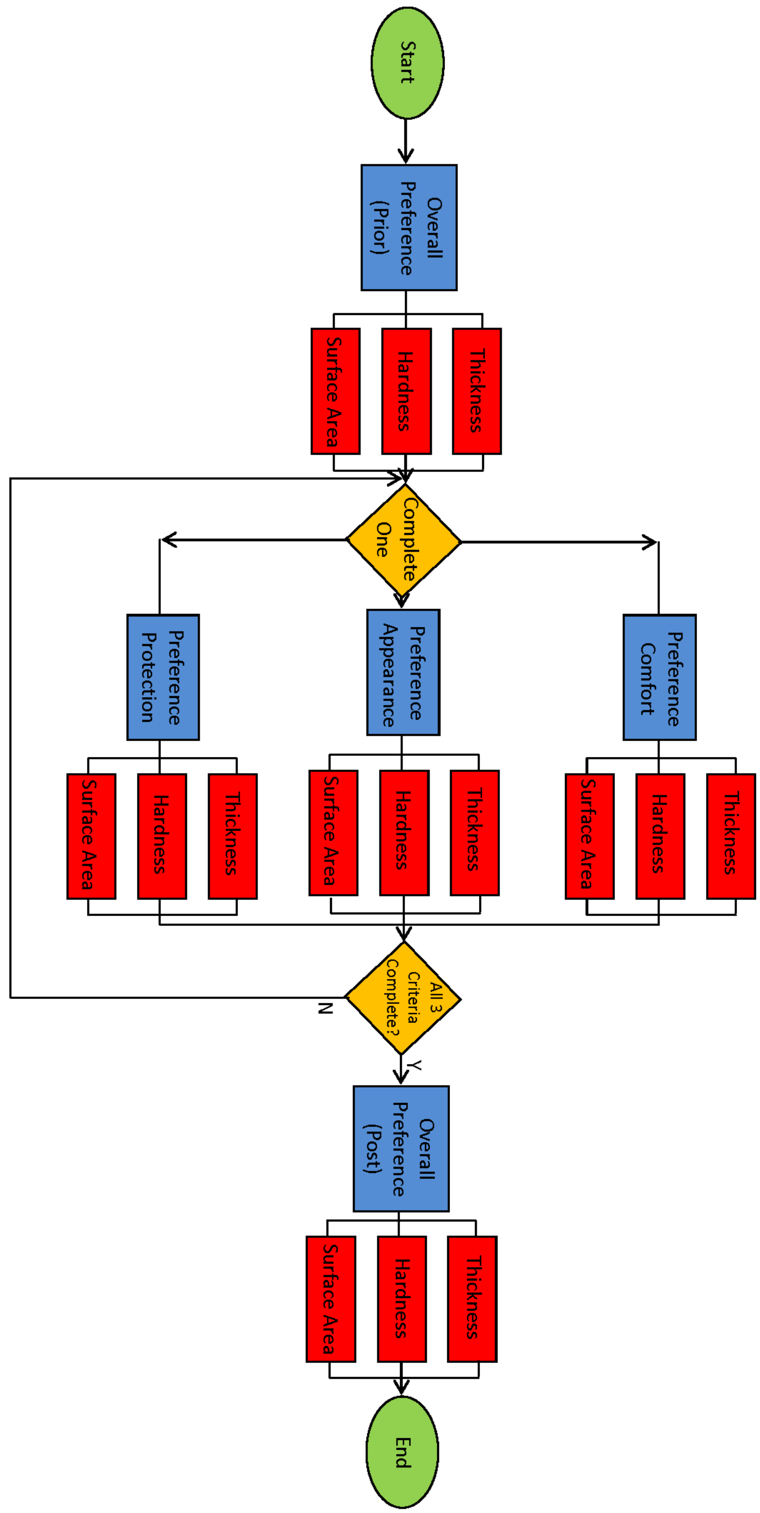


Figure 3-2. ***Flowchart illustrating the steps followed by responders to complete the main preference questionnaire***

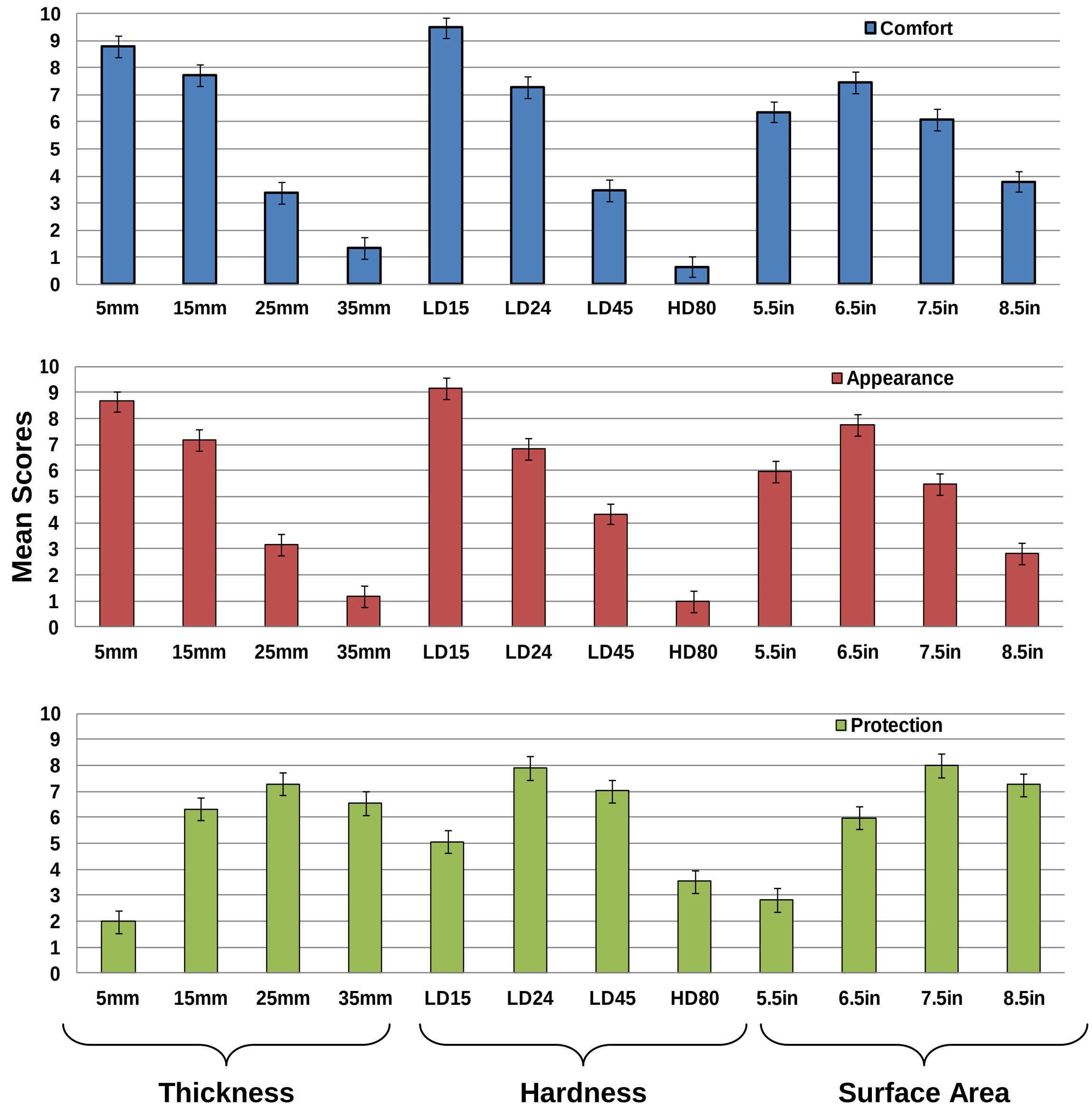


Figure 3-3. Estimated Means for Comfort, Appearance and Protection as they relate to Thickness, Hardness and Surface Area.

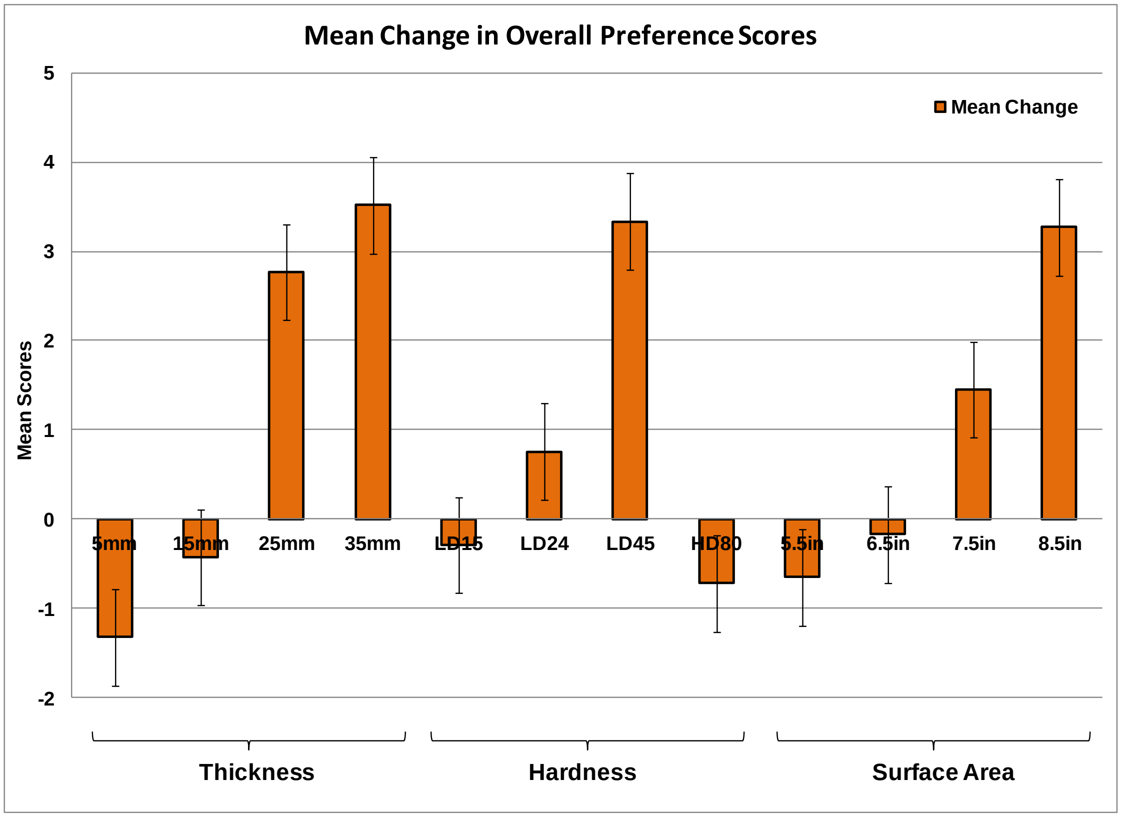


Figure 3-4. ***Estimated means for Change in Preference as they relate to Thickness, Hardness and Surface Area.***

3.6. Tables

Table 3-1. ***Explanation of Factors leading to Increased Hip Protector Usage (Schoor, Deville, Bouter & Lips, 2002)***

Usage Factor	Explanation
Comfort	Whether the hip protector is comfortable has been an important factor when considering the use of hip protectors. Discomfort can lead to aches, pains and bruising, and therefore result in non-compliance of the device.
Appearance	The shape of the human figure when the hip protector is worn must be aesthetically pleasing to the user. Studies have cited that hip protectors which give the illusion of wider hips are seldom worn by individuals.

Protection	The perception of the amount of protective value offered by a particular hip protector would highly influence the initial adoption of the device.
Cost	High cost of hip protectors often times deters an individual from purchasing the product.
Laundry	Concerns pertaining to washing and drying of the hip protectors is particularly of importance to the care staff that are at many times responsible for laundry practices.
Garment	The fit, style, color and quality of the undergarment that encloses a hip protector pad are all factors in an individual's decision of wearing a hip protector.
Ease of Don/Doff	Physical limitations and issues pertaining to urinary incontinence are some of the concerns which that make it difficult for wearing and removing of the hip protector.
Fall Risk	A disagreement on the risk of falling can definitely influence an individual's decision of whether to wear a hip protector.
Recommendation by a Doctor	Studies have demonstrated that if a hip protector has been recommended by a medical professional (similar to prescription medications), the older adult is more likely to wear it.
Support from Care Staff	Education and motivation on the part of the care staff influences the uptake and continued use of hip protectors, as the staff encourage residents to use the device by informing them of the benefits.

Table 3-2. F-test Results of Regression of Overall Preference

Type 3 Tests of Fixed Effects				
Effect	Num. DF	Den. DF	F Value	Pr > F
Comfort	1	374	38.96	< 0.0001
Appearance	1	373	0.12	0.7251
Protection	1	376	136.53	< 0.0001
Subject Group	1	243	0.96	0.3285
Comfort * Subject Group	1	374	2.53	0.1126
Appearance * Subject Group	1	373	0.46	0.4970
Protection * Subject Group	1	376	1.84	0.1752

Table 3-3. Coefficients from the Regression of Overall Preference (based on General Linear Models Regression Analysis)

Solution for Fixed Effects						
Effect	Subject Group	Estimate	Standard Error	DF	t value	Pr > |t|
Intercept		-0.7077	0.5671	227	-1.25	0.2133
Comfort		0.3013	0.09387	376	3.21	0.0014
Appearance		0.06738	0.09551	348	0.71	0.4809
Protection		0.5727	0.06145	373	9.32	<0.0001
Subject Group	Elder	0.7236	0.7391	243	0.98	0.3285
Subject Group	Staff	0	-	-	-	-
Comfort * Subject Group	Elder	0.2060	0.1296	374	1.59	0.1126
Comfort * Subject Group	Staff	0	-	-	-	-
Appearance * Subject Group	Elder	-0.08881	0.1306	373	-0.68	0.4970
Appearance * Subject Group	Staff	0	-	-	-	-
Protection * Subject Group	Elder	-0.1193	0.08781	376	-1.36	0.1752
Protection * Subject Group	Staff	0	-	-	-	-

Table 3-4. COMFORT: F-test results for Explanatory Variables in the Model

Effect	Num. DF	Den. DF	F Value	Prob. F
pad	11	330	60.34	<.0001
subject_grp	1	30	4.55	0.0413
pad*subject_grp	11	330	1.10	0.3636

Table 3-5. COMFORT: F-test results for Testing Separate Pad Features

Effect	Num. DF	Den. DF	F Value	Prob. F
Thickness	3	330	103.40	<.0001
Hardness	3	330	129.16	<.0001
Surface Area	3	330	25.03	<.0001
Linear Thickness	1	330	261.45	<.0001

Effect	Num. DF	Den. DF	F Value	Prob. F
Linear Hardness (SH)	1	330	339.50	<.0001
Linear Hardness (LD)	1	330	349.43	<.0001
Linear Surface Area	1	330	30.89	<.0001

Table 3-6. APPEARANCE: F-test results for Explanatory Variables in the Model

Effect	Number DF	Den. DF	F Value	Prob. F
pad	11	330	56.32	<.0001
Subject Group	1	30	2.17	0.1508
Pad* Subject Group	11	330	2.16	0.0165

Table 3-7. APPEARANCE: F-test results for Testing Separate Pad Features

effect	Number DF	Den. DF	F Value	Prob. F
Thickness	3	330	103.30	<.0001
Hardness	3	330	102.50	<.0001
Surface Area	3	330	36.02	<.0001
Linear Thickness	1	330	263.54	<.0001
Linear Hardness (SH)	1	330	286.20	<.0001
Linear Hardness (LD)	1	330	292.35	<.0001
Linear Surface Area	1	330	46.13	<.0001

Table 3-8. PROTECTION: F-test results for Explanatory Variables in the Model

Effect	Num. DF	Den. DF	F Value	Prob. F
Pad	11	330	22.29	<.0001
Subject Group	1	30	0.15	0.7056
pad* Subject Group	11	330	4.32	<.0001

Table 3-9. PROTECTION: F-test results for Testing Separate Pad Features

Effect	Number DF	Den. DF	F Value	Prob. F
Thickness	3	330	35.83	<.0001
Hardness	3	330	17.50	<.0001
Surface Area	3	330	29.69	<.0001
Linear Thickness	1	330	57.23	<.0001
Linear Hardness (SH)	1	330	14.77	0.0001
Linear Hardness (LD)	1	330	15.25	0.0001
Linear Surface Area	1	330	59.42	<.0001

Table 3-10. Change in Preference: F-test Results for Subject Group

Effect	NumDF	DenDF	FValue	ProbF
pad	11	330	12.01	<.0001
subject_grp	1	30	5.59	0.0247
pad*subject_grp	11	330	2.25	0.0118

Table 3-11. Change in Preference: Least Squares Mean Change in Overall Preference, Over All Subjects and Pads

Estimated Mean Change	Standard Error	DF	t-value	P-value	Lower 95% Limit	Upper 95% Limit
0.9600	0.1906	30	5.04	<.0001	0.5708	1.3492

Table 3-12. Change in Preference: Least Squares Mean Change in Overall Preference By Subject Group

Subject Group	Estimated Mean Change	Standard Error	DF	t-value	P-value	Lower 95% Limit	Upper 95% Limit
Elder	0.5093	0.2521	30	2.02	0.0524	-0.00563	1.0242
Staff	1.4107	0.2859	30	4.93	<.0001	0.8269	1.9945

Table 3-13. Change in Preference: Least Squares Mean Change in Overall Preference By Pad

Pad	Estimated Mean Change	Standard Error	DF	t-value	P-value	Lower 95% Limit	Upper 95% Limit
A: Thick 5	-1.3214	0.5376	352	-2.46	0.0145	-2.3787	-0.2641
B: Thick 15	-0.4246	0.5376	352	-0.79	0.4302	-1.4819	0.6327
C: Thick 25	2.7698	0.5376	352	5.15	<.0001	1.7125	3.8272
D: Thick 35	3.5159	0.5376	352	6.54	<.0001	2.4586	4.5732
E: Stiff 43	-0.2897	0.5376	352	-0.54	0.5903	-1.3470	0.7676
F: Stiff 50	0.7579	0.5376	352	1.41	0.1595	-0.2994	1.8153
G: Stiff 60	3.3333	0.5376	352	6.20	<.0001	2.2760	4.3906
H: Stiff 81	-0.7183	0.5376	352	-1.34	0.1824	-1.7756	0.3391
I: Surface 5.5	-0.6508	0.5376	352	-1.21	0.2269	-1.7081	0.4065
J: Surface 6.5	-0.1706	0.5376	352	-0.32	0.7511	-1.2280	0.8867
K: Surface 7.5	1.4484	0.5376	352	2.69	0.0074	0.3911	2.5057
L: Surface 8.5	3.2698	0.5376	352	6.08	<.0001	2.2125	4.3272

Table 3-14. Change in Preference: Least Squares Mean Change in Overall Preference By Subject Group within Pad

Pad	Subject Group	Estimated Mean Change	Standard Error	DF	t-value	P-value	Lower 95% Limit	Upper 95% Limit
A: Thick 5	Elder	-2.5000	0.7112	352	-3.52	0.0005	-3.8987	-1.1013
A: Thick 5	Staff	-0.1429	0.8064	352	-0.18	0.8595	-1.7288	1.4431
B: Thick 15	Elder	-0.7778	0.7112	352	-1.09	0.2749	-2.1765	0.6209
B: Thick 15	Staff	-0.07143	0.8064	352	-0.09	0.9295	-1.6574	1.5145
C: Thick 25	Elder	3.1111	0.7112	352	4.37	<.0001	1.7124	4.5098
C: Thick 25	Staff	2.4286	0.8064	352	3.01	0.0028	0.8426	4.0145
D: Thick 35	Elder	2.3889	0.7112	352	3.36	0.0009	0.9902	3.7876
D: Thick 35	Staff	4.6429	0.8064	352	5.76	<.0001	3.0569	6.2288
E: Stiff 43	Elder	-1.7222	0.7112	352	-2.42	0.0160	-3.1209	-0.3235
E: Stiff 43	Staff	1.1429	0.8064	352	1.42	0.1573	-0.4431	2.7288
F: Stiff 50	Elder	0.4444	0.7112	352	0.62	0.5324	-0.9543	1.8431

Pad	Subject Group	Estimated Mean Change	Standard Error	DF	t-value	P-value	Lower 95% Limit	Upper 95% Limit
F: Stiff 50	Staff	1.0714	0.8064	352	1.33	0.1848	-0.5145	2.6574
G: Stiff 60	Elder	3.1667	0.7112	352	4.45	<.0001	1.7680	4.5654
G: Stiff 60	Staff	3.5000	0.8064	352	4.34	<.0001	1.9140	5.0860
H: Stiff 81	Elder	-0.7222	0.7112	352	-1.02	0.3106	-2.1209	0.6765
H: Stiff 81	Staff	-0.7143	0.8064	352	-0.89	0.3763	-2.3003	0.8717
I: Surface 5.5	Elder	-0.9444	0.7112	352	-1.33	0.1850	-2.3431	0.4543
I: Surface 5.5	Staff	-0.3571	0.8064	352	-0.44	0.6581	-1.9431	1.2288
J: Surface 6.5	Elder	-2.0556	0.7112	352	-2.89	0.0041	-3.4543	-0.6569
J: Surface 6.5	Staff	1.7143	0.8064	352	2.13	0.0342	0.1283	3.3003
K: Surface 7.5	Elder	2.1111	0.7112	352	2.97	0.0032	0.7124	3.5098
K: Surface 7.5	Staff	0.7857	0.8064	352	0.97	0.3306	-0.8003	2.3717
L: Surface 8.5	Elder	3.6111	0.7112	352	5.08	<.0001	2.2124	5.0098
L: Surface 8.5	Staff	2.9286	0.8064	352	3.63	0.0003	1.3426	4.5145

Table 3-15. Change in Preference: Results for Standard Pad (Pads B, F, and J)

Label	Estimated Mean Change	Standard Error	DF	t-value	P-value	Lower 95% Limit	Upper 95% Limit
Standard Pad Avg	0.05423	0.3244	190	0.17	0.8674	-0.5857	0.6941
Standard Pad*Elder Avg	-0.7963	0.4291	190	-1.86	0.0651	-1.6428	0.05021
Standard Pad*Staff Avg	0.9048	0.4866	190	1.86	0.0645	-0.05509	1.8646
Diff between Subj Grps for Standard Pad	-1.7011	0.6488	190	-2.62	0.0095	-2.9809	-0.4213

Table 3-16. Multiple Regression Analysis for the Dependent Variable Overall Preference and the variables Thickness, Hardness, Surface Area

Variables	R	R^2	Adjusted R^2	F	Sig.	B	t	Sig.
Thickness (mm)						-0.035	-1.406	0.161
Hardness	0.311	0.096	0.089	13.522	0.000	-0.114	-6.116	0.000
Surface Area (cm^2)						0.003	0.911	0.363

4. Conclusion

The primary objective of my master's thesis was to further our understanding of how geometric and material properties of hip protectors not only influence their biomechanical performance, but also user preference in product selection. I also examined how knowledge regarding the force attenuation capacity of a hip protector influenced the likelihood of its acceptance among users. In this chapter, I synthesize results and consider how hip protectors might be designed to optimize both biomechanical performance and user acceptance.

In my first study, discussed in Chapter 2, I constructed 64 distinct (soft-shell type) hip protector prototypes, with different combinations of thickness, hardness, and surface area. I considered 4 levels for each variable. I conducted dynamic indentation tests on each hip protector using a materials testing system, to determine force deflection properties and energy absorption properties. Furthermore, I tested each pad with a hip impact simulator to determine the force attenuation it provided in a simulated fall from standing. I observed a wide range of force attenuation between the various designs, from 3.3% to 45.8%. I also found that force attenuation was influenced more strongly by the geometric properties than the material properties I explored. Increases in thickness produced the greatest increase in force attenuation, followed by an increase in surface area, and lastly an increase in stiffness of the material (to a certain degree).

In my second study, detailed in Chapter 3, I examined how the same pad characteristics (hardness, thickness and surface area) influenced user preferences in the selection of wearable hip protectors. In particular, I examined how these parameters influence perceived comfort, attractiveness in appearance and protective value, through detailed questionnaires administered to older adults and care staff at Assisted Living sites. I found that overall preference independently associated with both perceived comfort and protection. Furthermore, each of thickness, hardness, and surface area associated with perceived comfort, appearance and protection. The hip protector with the smallest thickness, least hardness and second smallest surface area was perceived to be the most comfortable and most attractive when worn. Hip protectors with intermediate values of thickness, hardness, and surface area were perceived to possess the greatest protective value. Accordingly, a thicker and larger surface area and moderate hardness provides improved biomechanical performance. However, thinner, smaller and less stiff hip protectors promote greater acceptability.

Participant preferences changed substantially after knowledge was provided of each hip protector's biomechanical performance, shifting to higher thickness and hardness. This indicates the importance of clear documentation of valid results from mechanical testing, as a key towards user acceptance of more biomechanically sound designs.

In an effort to amalgamate the findings from both the biomechanical performance and user preference studies, an objective function is constructed to identify optimal values of parameters that seek to maximize or minimize this function. As established previously, the overall hip protector effectiveness depends on two factors: its biomechanical performance and user compliance. From this, I construct the following equation to provide an overall score for a given hip protector.

*Overall_Score = [a_pref * (Preference_Score)] + [a_biomech * (Biomechanical_Score)],*

where a_pref and a_biomech are weighting factors (ranging from 0 to 1), subject to the constraint:

a_pref + a_biomech = 1.

Note that the above equation of weighting factors is not meant to imply dependency between the quantities of a_pref and b_biomech. Instead, the equation is only used to compare optimal designs for a range of relative weighting of preference versus biomechanical performance.

Next, equations for each of the biomechanical performance and user preference components are created, based on their relationship with pad characteristics of thickness (in mm), hardness (in durometer) and surface area (in cm^2).

$$Preference\_Score = (p\_thick * Thickness) + (p\_hard * Hardness) + (p\_area * Surface\_Area) + p\_Constant \quad ,$$

$$Biomechanical\_Score = (b\_thick * Thickness) + (b\_hard * Hardness) + (b\_area * Surface\_Area) + b\_Constant \quad ,$$

where p_thick, p_hard, p_area represent the weighting factors for preference, and are the Unstandardized coefficients "B" from the multiple regression analysis of overall preference versus thickness, hardness, and surface area. Similarly, b_thick, b_hard, b_area represent the weighting factors for biomechanical performance, and are the Unstandardized coefficients "B" from the multiple regression analysis of force attenuation versus thickness, hardness, and surface area. A note, however, that the coefficients need to be adjusted/scaled uniformly so that the range in values for both scores is equal. Prior to scaling, the range in Preference_Score was found to be 6.0 and 48.7 for Biomechanical_Score. The adjustment was performed by scaling the preference weightings by a value of 8.1 (48.7/6.0), to provide a revised range of 48.7. The values of the y-intercepts (i.e. p_Constant and b_Constant) are also derived from the respective multiple regression analyses. Therefore, the revised equations are,

$$Preference\_Score = (-0.035*8.1 * Thickness) + (-0.114*8.1 * Hardness) + (0.003*8.1 * Surface\_Area) + 10.945 \quad ,$$

$$Biomechanical\_Score = (0.722* Thickness) + (-0.387 * Hardness) + (0.058 * Surface\_Area) + 12.766 \quad .$$

Increments of 0.1 were used in generating combinations of weighting factors for a_pref and a_biomech (Table 4-1). As thickness, hardness and surface area are continuous variables, the optimization analysis was executed using incremental values of each within the range used in the study. i.e.:

Thickness: from 5mm; increment of 2mm; to 35mm; (16 values)

Hardness: from 43; increment of 2; to 81; (20 values)

Surface Area: from 155.3cm^2; increment of 10cm^2; to 365.3cm^2; (22 values)

The maximum and minimum Overall_Scores are provided in Table 4-2 for each of the 11 groupings of a_pref and a_biomech. Based on the maximum Overall_Score, the optimal pad combination is maximum thickness (35mm), minimum hardness (43 durometer), and maximum surface area (365.3 cm^2) for groupings 1 to 8. For the remaining 3 groupings, optimal characteristics for hardness and surface area remain the same, however optimal value for thickness reduced to the minimum (5mm).

Our predicted optimal surface area (of 8.5in diameter) is similar in magnitude to several commercial protectors, including HipSaver. However, our predicted optimal thickness of 35 mm is considerably higher than values observed in marketed products (Laing et al., 2011). Indeed, we are aware of only one commercial product with a comparable value - HipEase, a soft shell hip protector with a pad thickness of 32mm, product produced by Patterson Medical/Sammons Preston. Most commercial hip protectors have a pad thickness ranging from 10 to 20mm, and despite our results, this may introduce challenges for market adoption of thicker products. Furthermore, our optimal stiffness (of approximately 350kn/m at a force level of 3000N) is lower than the smallest value observed in commercially available hip protectors (438kN/m for KPH, by Qvortrup Medical A/S). This may be explained by the low thickness of commercial hip protectors, and the need to utilize materials of higher stiffness to ensure sufficient energy is absorbed prior to bottoming-out. Our optimal design combines a larger thickness with a low stiffness material to provide greater biomechanical performance (44% force attenuation versus 20% (SD=9) observed among 26 commercially available devices).

Clearly additional research is required to determine user acceptance and adherence in using the thicker, lower stiffness products suggested by our optimization. The willingness of users to accept such products may relate to associating thickness with protective value, and low stiffness with ability to conform to the shape of the body.

Overall, this analysis illustrates one such technique to optimizing the biomechanical performance coupled with the overall preference of hip protectors. Utilizing the values for pad characteristics mentioned above, manufacturers can optimize their products to yield a higher degree of overall effectiveness. All in all, this work demonstrates that soft shell hip protectors are successfully able to reduce the impact force transmitted to the proximal femur during a sideways fall. Furthermore, it also illustrates the need for research to combine the effects of not only biomechanical performance but also user preference when devising new hip protector designs. This is imperative in order to ensure an enhanced quality of future generations of hip protectors, thereby reducing the occurrence of hip fractures and providing a higher quality of living for older adults.

4.1. Limitations

There are some important limitations to the current study. I used prototype, in-house designs of protectors which were similar in nature to devices on the market, but which likely require refinements prior to marketing. For example, a tapered edge (a common feature of the commercial hip protectors) was not present, which may affect both force attenuation capacity and acceptance.

In addition, due to the nature of the study, my data represents only the initial acceptance of the protectors, meaning we did not examine the short or long term adherence to hip protector use. For this study, a single geometry (circular) was used in the construction of the 64 protector prototypes. However, the market does contain a variety of hip protector geometrical shapes which may demonstrate differences in user preference and biomechanical testing. Finally, although the stiffness of the materials used to construct the prototype was varied, the actual material composition could be altered. We could demonstrate difference, for example, between elastic vs. viscoelastic materials (e.g. viscoelastic materials for hip protectors provide an intelligent damping system that can adapt to different strains). Compliance studies with viscoelastic hip protectors have already found high compliance rates (76.8%) ("Hip protector systems:," 2008). Furthermore, we did not examine the effect of garment design on preferences. Color, fit and cost could also be examined to determine its extent on user acceptance of hip protectors. Lastly, our statistical models assumed linear trends between independent and dependant variables and were unable to capture the observed non-linear trends between (e.g., between stiffness and force attenuation).

4.2. Future directions

Future studies should explore the effects of hip protector shape on both preference and force attenuation capacity. Variables such as cost, ease of don/doff and laundering should also be taken into consideration. Additionally non-linear modelling techniques should be employed during statistical analysis to account for the non-linear behaviour of the variables influencing preference as well as performance.

Based on an investigation of how product design affects both biomechanical performance and user preference, the results of this thesis inform not only the development and selection of more effective hip protectors, but also facilitate human-centered design. Hopefully our results will lead to improvements in the number of older adults who choose to wear hip protectors and to family and staff commitment to assisting individuals in the use of hip protectors. Higher compliance rates should lead to a decrease in fall-related injuries (specifically hip fractures), and alleviate related demands and costs to the health care system.

Future research should investigate how hip protector design features influence long-term adherence to obtain a more comprehensive view of user compliance with hip protectors and integrate these data with current results in the design of the next generation of clinically effective, comfortable, stylish and cost effective hip protectors; ones that do not hinder the user, but rather enhance their quality of life.

4.3. Tables

Table 4-1. Combinations of a_pref and a_biomech used during Optimization

Combinations	a_pref	a_biomech
# 1	0	1
# 2	0.1	0.9
# 3	0.2	0.8
# 4	0.3	0.7
# 5	0.4	0.6
# 6	0.5	0.5

# 7	0.6	0.4
# 8	0.7	0.3
# 9	0.8	0.2
# 10	0.9	0.1
# 11	1	0

Table 4-2. Results of the Optimization

	Overall_Score							
Comb.	Max.	Thick-ness (mm)	Hardness (durometer)	Surface Area (cm^2)	Min.	Thick-ness (mm)	Hardness (durometer)	Surface Area (cm^2)
# 1	42.6	35	43	365.3	-6.0	5	81	155.3
# 2	35.3	35	43	365.3	-11.5	5	81	155.3
# 3	28.1	35	43	365.3	-17.1	5	81	155.3
# 4	20.9	35	43	365.3	-22.6	5	81	155.3
# 5	13.6	35	43	365.3	-28.2	5	81	155.3
# 6	6.4	35	43	365.3	-33.7	5	81	155.3
# 7	-0.9	35	43	365.3	-39.3	5	81	155.3
# 8	-8.1	35	43	365.3	-44.8	5	81	155.3
# 9	-12.9	5	43	365.3	-52.9	35	81	155.3
# 10	-17.1	5	43	365.3	-61.4	35	81	155.3
# 11	-21.3	5	43	365.3	-70.0	35	81	155.3

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Appendices

Appendix A.

Geometric and Material Properties of 64 Custom Made Hip Protector Prototypes

Hip Protector Name	Thickness (mm)	Hardness (material)	Hardness (SH)	Surface Area (diameter, in)	Surface Area (cm^2)
LD15_5mm_5p5	5	LD15	43	5.5	153.3
LD15_5mm_6p5	5	LD15	43	6.5	214.1
LD15_5mm_7p5	5	LD15	43	7.5	285.0
LD15_5mm_8p5	5	LD15	43	8.5	366.1
LD15_15mm_5p5	15	LD15	43	5.5	153.3
LD15_15mm_6p5	15	LD15	43	6.5	214.1
LD15_15mm_7p5	15	LD15	43	7.5	285.0
LD15_15mm_8p5	15	LD15	43	8.5	366.1
LD15_25mm_5p5	25	LD15	43	5.5	153.3
LD15_25mm_6p5	25	LD15	43	6.5	214.1
LD15_25mm_7p5	25	LD15	43	7.5	285.0
LD15_25mm_8p5	25	LD15	43	8.5	366.1
LD15_35mm_5p5	35	LD15	43	5.5	153.3
LD15_35mm_6p5	35	LD15	43	6.5	214.1
LD15_35mm_7p5	35	LD15	43	7.5	285.0
LD15_35mm_8p5	35	LD15	43	8.5	366.1
LD24_5mm_5p5	5	LD24	50	5.5	153.3
LD24_5mm_6p5	5	LD24	50	6.5	214.1
LD24_5mm_7p5	5	LD24	50	7.5	285.0
LD24_5mm_8p5	5	LD24	50	8.5	366.1
LD24_15mm_5p5	15	LD24	50	5.5	153.3
LD24_15mm_6p5	15	LD24	50	6.5	214.1
LD24_15mm_7p5	15	LD24	50	7.5	285.0
LD24_15mm_8p5	15	LD24	50	8.5	366.1
LD24_25mm_5p5	25	LD24	50	5.5	153.3
LD24_25mm_6p5	25	LD24	50	6.5	214.1

Hip Protector Name	Thickness (mm)	Hardness (material)	Hardness (SH)	Surface Area (diameter, in)	Surface Area (cm^2)
LD24_25mm_7p5	25	LD24	50	7.5	285.0
LD24_25mm_8p5	25	LD24	50	8.5	366.1
LD24_35mm_5p5	35	LD24	50	5.5	153.3
LD24_35mm_6p5	35	LD24	50	6.5	214.1
LD24_35mm_7p5	35	LD24	50	7.5	285.0
LD24_35mm_8p5	35	LD24	50	8.5	366.1
LD45_5mm_5p5	5	LD45	60	5.5	153.3
LD45_5mm_6p5	5	LD45	60	6.5	214.1
LD45_5mm_7p5	5	LD45	60	7.5	285.0
LD45_5mm_8p5	5	LD45	60	8.5	366.1
LD45_15mm_5p5	15	LD45	60	5.5	153.3
LD45_15mm_6p5	15	LD45	60	6.5	214.1
LD45_15mm_7p5	15	LD45	60	7.5	285.0
LD45_15mm_8p5	15	LD45	60	8.5	366.1
LD45_25mm_5p5	25	LD45	60	5.5	153.3
LD45_25mm_6p5	25	LD45	60	6.5	214.1
LD45_25mm_7p5	25	LD45	60	7.5	285.0
LD45_25mm_8p5	25	LD45	60	8.5	366.1
LD45_35mm_5p5	35	LD45	60	5.5	153.3
LD45_35mm_6p5	35	LD45	60	6.5	214.1
LD45_35mm_7p5	35	LD45	60	7.5	285.0
LD45_35mm_8p5	35	LD45	60	8.5	366.1
HD80_5mm_5p5	5	HD80	81	5.5	153.3
HD80_5mm_6p5	5	HD80	81	6.5	214.1
HD80_5mm_7p5	5	HD80	81	7.5	285.0
HD80_5mm_8p5	5	HD80	81	8.5	366.1
HD80_15mm_5p5	15	HD80	81	5.5	153.3
HD80_15mm_6p5	15	HD80	81	6.5	214.1
HD80_15mm_7p5	15	HD80	81	7.5	285.0
HD80_15mm_8p5	15	HD80	81	8.5	366.1
HD80_25mm_5p5	25	HD80	81	5.5	153.3

Hip Protector Name	Thickness (mm)	Hardness (material)	Hardness (SH)	Surface Area (diameter, in)	Surface Area (cm^2)
HD80_25mm_6p5	25	HD80	81	6.5	214.1
HD80_25mm_7p5	25	HD80	81	7.5	285.0
HD80_25mm_8p5	25	HD80	81	8.5	366.1
HD80_35mm_5p5	35	HD80	81	5.5	153.3
HD80_35mm_6p5	35	HD80	81	6.5	214.1
HD80_35mm_7p5	35	HD80	81	7.5	285.0
HD80_35mm_8p5	35	HD80	81	8.5	366.1

Appendix B.

Load Cell Data of Unpadded Conditions during Impact Pendulum testing

Unpadded - Hip Protector ID	Force at Load Cell, N
250N__Unpadded_1_Raw_1.txt	2505
250N__Unpadded_1_Raw_2.txt	2548
250N__Unpadded_1_Raw_3.txt	2548
250N__Unpadded_10_Raw_1.txt	2506
250N__Unpadded_10_Raw_2.txt	2527
250N__Unpadded_10_Raw_3.txt	2526
250N__Unpadded_11_Raw_1.txt	2610
250N__Unpadded_11_Raw_2.txt	2611
250N__Unpadded_11_Raw_3.txt	2631
250N__Unpadded_2_Raw_1.txt	2463
250N__Unpadded_2_Raw_2.txt	2505
250N__Unpadded_2_Raw_3.txt	2506
250N__Unpadded_3_Raw_1.txt	2526
250N__Unpadded_3_Raw_2.txt	2547
250N__Unpadded_3_Raw_3.txt	2547
250N__Unpadded_4_Raw_1.txt	2505
250N__Unpadded_4_Raw_2.txt	2506
250N__Unpadded_4_Raw_3.txt	2548
250N__Unpadded_5_Raw_1.txt	2547
250N__Unpadded_5_Raw_2.txt	2548
250N__Unpadded_5_Raw_3.txt	2548
250N__Unpadded_6_Raw_1.txt	2484
250N__Unpadded_6_Raw_2.txt	2527
250N__Unpadded_6_Raw_3.txt	2527
250N__Unpadded_7_Raw_1.txt	2547
250N__Unpadded_7_Raw_2.txt	2548
250N__Unpadded_7_Raw_3.txt	2547

Unpadded - Hip Protector ID	Force at Load Cell, N
250N__Unpadded_8_Raw_1.txt	2505
250N__Unpadded_8_Raw_2.txt	2527
250N__Unpadded_8_Raw_3.txt	2547
250N__Unpadded_9_Raw_1.txt	2548
250N__Unpadded_9_Raw_2.txt	2569
250N__Unpadded_9_Raw_3.txt	2548
250N__Unpadded_Raw_1.txt	2463
250N__Unpadded_Raw_2.txt	2505
250N__Unpadded_Raw_3.txt	2505

Appendix C.

Force measured at Load Cell during Impact Pendulum Testing

Hip Protector Name	Force at Load Cell, N
LD15_5mm_5p5	2435.3
LD15_5mm_6p5	2372.7
LD15_5mm_7p5	2309.7
LD15_5mm_8p5	2302
LD15_15mm_5p5	2260.3
LD15_15mm_6p5	2135.3
LD15_15mm_7p5	2023.3
LD15_15mm_8p5	1904.7
LD15_25mm_5p5	2107.3
LD15_25mm_6p5	1897.0
LD15_25mm_7p5	1757.0
LD15_25mm_8p5	1596.7
LD15_35mm_5p5	1967.0
LD15_35mm_6p5	1764.0
LD15_35mm_7p5	1541.0
LD15_35mm_8p5	1422.7
LD24_5mm_5p5	2442.7
LD24_5mm_6p5	2379.3
LD24_5mm_7p5	2338.0
LD24_5mm_8p5	2302.3
LD24_15mm_5p5	2225.7
LD24_15mm_6p5	2065.3
LD24_15mm_7p5	1953.7
LD24_15mm_8p5	1841.7

Hip Protector Name	Force at Load Cell, N
LD24_25mm_5p5	2051.0
LD24_25mm_6p5	1814.0
LD24_25mm_7p5	1680.3
LD24_25mm_8p5	1556.0
LD24_35mm_5p5	1904.0
LD24_35mm_6p5	1701.3
LD24_35mm_7p5	1506.0
LD24_35mm_8p5	1373.7
LD45_5mm_5p5	2407.3
LD45_5mm_6p5	2337.3
LD45_5mm_7p5	2330.3
LD45_5mm_8p5	2274.0
LD45_15mm_5p5	2149.0
LD45_15mm_6p5	2016.0
LD45_15mm_7p5	1897.7
LD45_15mm_8p5	1848.7
LD45_25mm_5p5	1974.3
LD45_25mm_6p5	1743.7
LD45_25mm_7p5	1624.3
LD45_25mm_8p5	1534.0
LD45_35mm_5p5	1855.3
LD45_35mm_6p5	1569.7
LD45_35mm_7p5	1457.3
LD45_35mm_8p5	1380.0
HD80_5mm_5p5	2393.0
HD80_5mm_6p5	2365.3
HD80_5mm_7p5	2330.3
HD80_5mm_8p5	2260.3
HD80_15mm_5p5	2415.0
HD80_15mm_6p5	2351.0
HD80_15mm_7p5	2295.0

Hip Protector Name	Force at Load Cell, N
HD80_15mm_8p5	2239.7
HD80_25mm_5p5	2449.3
HD80_25mm_6p5	2358.0
HD80_25mm_7p5	2302.0
HD80_25mm_8p5	2253.7
HD80_35mm_5p5	2435.7
HD80_35mm_6p5	2366.0
HD80_35mm_7p5	2302.3
HD80_35mm_8p5	2253.7

Appendix D.

Results of Impact Pendulum and Dynamic Indentation Tests

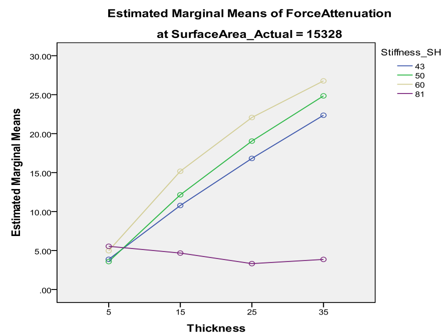
Hip Protector Name	Force Attenuation (%)	k_200N (kN/m)	k_2000N (kN/m)	k_3000N (kN/m)	E_abs (J)	E_dis (J)	E_rel (%)
LD15_5mm_5p5	3.87	132.37	-	-	0.26	0.1	38.35
LD15_5mm_6p5	6.35	134.24	-	-	0.31	0.13	41.72
LD15_5mm_7p5	8.83	132.32	-	-	0.3	0.12	41.52
LD15_5mm_8p5	9.14	121.35	-	-	0.28	0.12	41.8
LD15_15mm_5p5	10.78	66.48	577.71	-	8.96	2.37	26.41
LD15_15mm_6p5	15.72	68.64	580.79	-	8.93	2.38	26.6
LD15_15mm_7p5	20.14	66.52	574.05	-	9.14	2.46	26.86
LD15_15mm_8p5	24.82	64.72	549.90	-	9.39	2.51	26.7
LD15_25mm_5p5	16.82	56.59	338.71	625.52	21.07	3.89	18.45
LD15_25mm_6p5	25.12	56.92	334.94	604.24	21.37	4.03	18.86
LD15_25mm_7p5	30.65	58.50	339.34	600.08	21.1	3.83	18.17
LD15_25mm_8p5	36.98	56.11	325.47	580.11	21.65	4.4	20.34
LD15_35mm_5p5	22.36	46.38	248.33	417.31	28.56	4.91	17.19
LD15_35mm_6p5	30.37	47.64	237.51	398.30	29	5.84	20.15
LD15_35mm_7p5	39.17	47.25	216.84	352.03	33.03	8.98	27.18
LD15_35mm_8p5	43.85	47.53	212.89	350.32	32.85	9.15	27.85
LD24_5mm_5p5	3.58	150.47	-	-	0.29	0.13	45.23
LD24_5mm_6p5	6.08	143.39	-	-	0.27	0.12	46.11
LD24_5mm_7p5	7.72	154.57	-	-	0.36	0.16	45.47
LD24_5mm_8p5	9.12	153.18	-	-	0.39	0.17	44.56
LD24_15mm_5p5	12.15	75.91	612.08	-	8.23	2.63	31.99
LD24_15mm_6p5	18.48	77.03	582.71	-	8.94	2.96	33.14
LD24_15mm_7p5	22.89	73.91	562.52	-	9.23	3.12	33.81
LD24_15mm_8p5	27.31	74.77	549.18	-	9.67	3.16	32.73
LD24_25mm_5p5	19.04	57.97	342.36	660.77	20.82	4.25	20.39

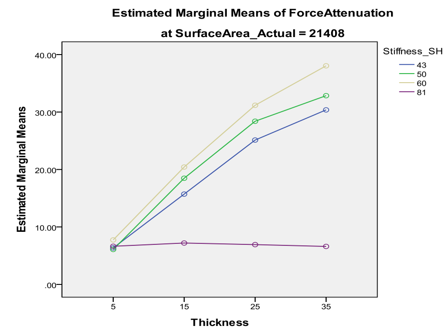
Hip Protector Name	Force Attenuation (%)	k_200N (kN/m)	k_2000N (kN/m)	k_3000N (kN/m)	E_abs (J)	E_dis (J)	E_rel (%)
LD24_25mm_6p5	28.40	61.45	316.36	566.25	21.59	4.96	22.99
LD24_25mm_7p5	33.67	61.57	310.18	535.64	22.69	5.62	24.77
LD24_25mm_8p5	38.58	59.13	301.76	516.40	23.39	6.11	26.14
LD24_35mm_5p5	24.85	46.64	222.05	391.10	31.4	7.32	23.32
LD24_35mm_6p5	32.85	52.00	219.99	345.84	31.53	7.8	24.74
LD24_35mm_7p5	40.56	52.18	212.79	324.84	34.19	9.37	27.39
LD24_35mm_8p5	45.78	52.41	207.59	316.59	35	9.75	27.87
LD45_5mm_5p5	4.98	176.59	-	-	0.7	0.46	66.36
LD45_5mm_6p5	7.74	175.12	-	-	0.7	0.46	66.26
LD45_5mm_7p5	8.02	173.93	-	-	0.69	0.45	65
LD45_5mm_8p5	10.24	178.05	-	-	0.98	0.63	64.1
LD45_15mm_5p5	15.18	141.25	396.09	746.46	15.42	8.55	55.47
LD45_15mm_6p5	20.43	141.06	422.05	750.81	15.48	8.41	54.32
LD45_15mm_7p5	25.10	140.09	413.79	737.47	15.92	8.63	54.23
LD45_15mm_8p5	27.03	145.81	421.53	750.07	15.28	8.69	56.89
LD45_25mm_5p5	22.07	101.98	275.93	473.34	23.63	10.64	45.03
LD45_25mm_6p5	31.17	149.46	206.35	337.66	29.25	16.81	57.49
LD45_25mm_7p5	35.89	141.88	219.17	323.18	28.88	17.09	59.16
LD45_25mm_8p5	39.45	107.78	280.56	443.45	23.28	11.84	50.86
LD45_35mm_5p5	26.77	100.55	184.98	299.31	35.42	17.15	48.42
LD45_35mm_6p5	38.04	105.67	185.87	290.03	35.51	18.39	51.78
LD45_35mm_7p5	42.48	151.15	154.74	213.86	42.61	26.52	62.23
LD45_35mm_8p5	45.53	149.44	154.68	213.80	41.31	25.98	62.91
HD80_5mm_5p5	5.54	541.07	985.15	-	3.61	3.22	89.23
HD80_5mm_6p5	6.64	645.34	875.23	-	3.89	3.49	89.69
HD80_5mm_7p5	8.02	646.80	867.05	-	3.94	3.53	89.6
HD80_5mm_8p5	10.78	546.55	958.32	-	3.67	3.23	88.09
HD80_15mm_5p5	4.68	284.27	959.66	994.64	10.32	7.83	75.91
HD80_15mm_6p5	7.20	448.89	792.35	754.34	10.26	8.37	81.61
HD80_15mm_7p5	9.41	363.72	941.63	934.62	7.8	5.81	74.52
HD80_15mm_8p5	11.60	346.22	839.05	894.58	10.21	7.59	74.3

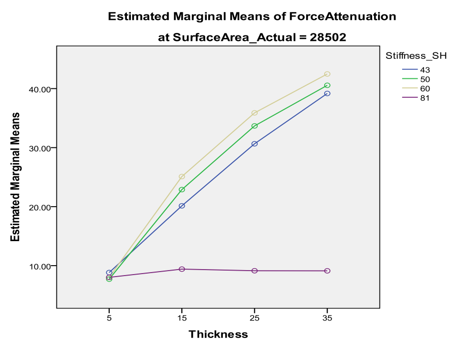
Hip Protector Name	Force Attenuation (%)	k_200N (kN/m)	k_2000N (kN/m)	k_3000N (kN/m)	E_abs (J)	E_dis (J)	E_rel (%)
HD80_25mm_5p5	3.32	250.17	982.70	720.79	5.56	3.62	65.13
HD80_25mm_6p5	6.93	264.14	960.46	1020.35	7.94	5.62	70.8
HD80_25mm_7p5	9.14	496.13	737.69	759.64	10.65	8.62	80.97
HD80_25mm_8p5	11.04	370.09	851.94	823.43	9.16	7.26	79.29
HD80_35mm_5p5	3.86	194.52	954.21	991.09	10.06	6.88	68.36
HD80_35mm_6p5	6.61	437.84	811.51	721.94	9.33	7.05	75.56
HD80_35mm_7p5	9.12	185.41	832.63	898.78	9.16	6.41	70.04
HD80_35mm_8p5	11.04	222.75	855.51	874.15	10.08	7.57	75.13

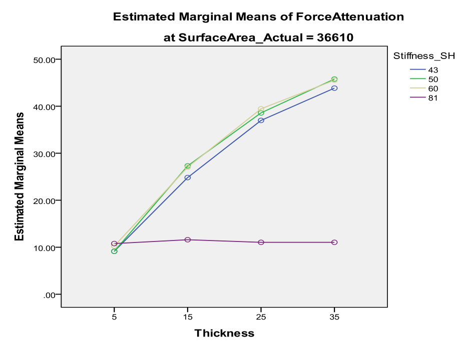
Appendix E.

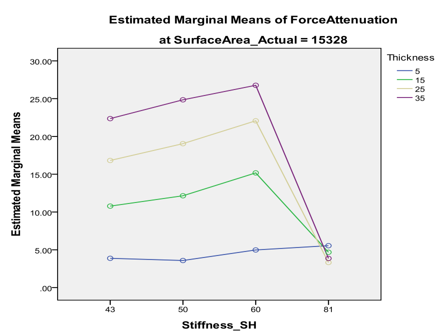
Estimated Marginal Means of Force Attenuation

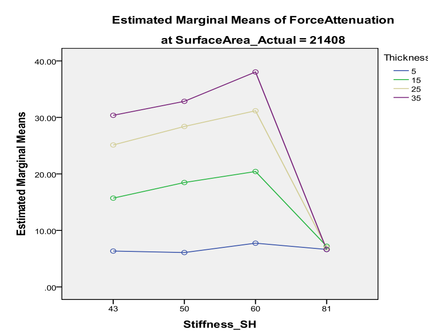


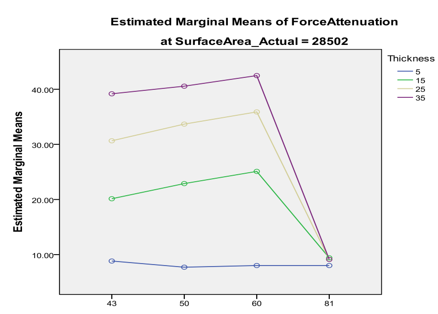


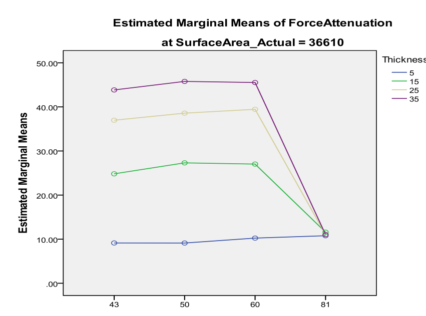


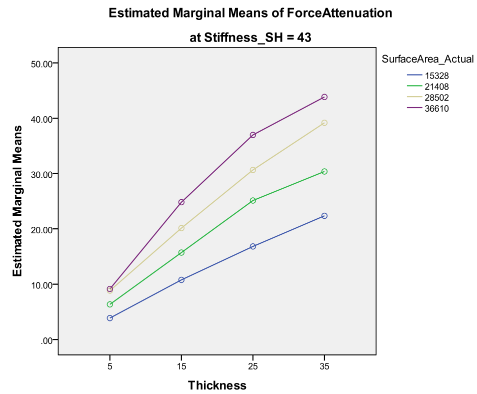











Estimated Marginal Means of ForceAttenuation
at Stiffness_SH = 43
SurfaceArea_Actual
15328
21408
28502
36610
Estimated Marginal Means
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30.00
20.00
10.00
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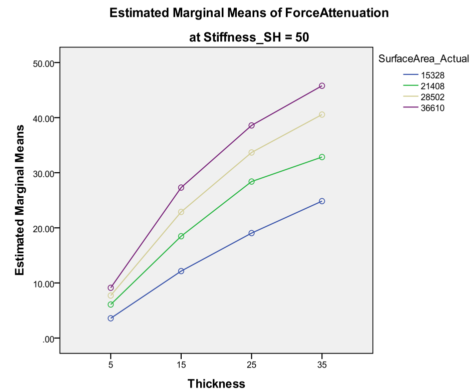
5
15
25
35
Thickness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at Stiffness_SH = 50
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21408
28502
36610
Estimated Marginal Means
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10.00
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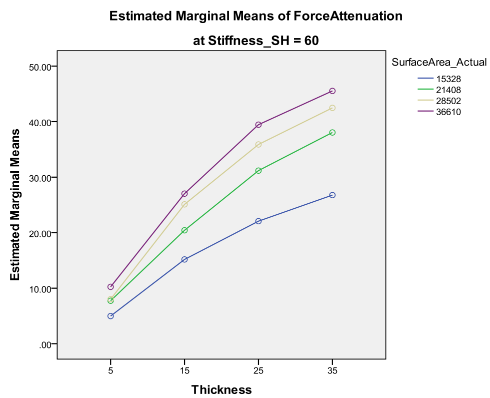
5
15
25
35
Thickness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at Stiffness_SH = 60
SurfaceArea_Actual
15328
21408
28502
36610
Estimated Marginal Means
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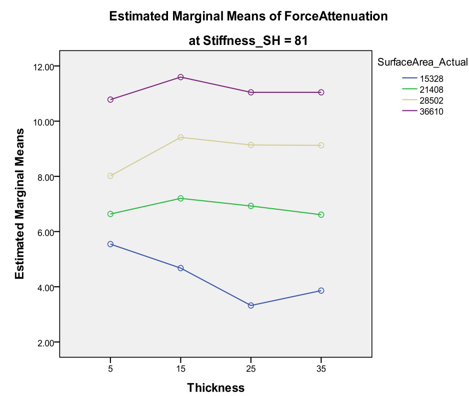
5
15
25
35
Thickness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at Stiffness_SH = 81
SurfaceArea_Actual
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21408
28502
36610
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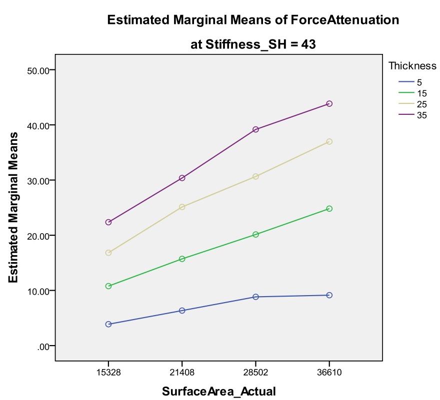
10.00
8.00
6.00
4.00
2.00
5
15
25
35
Thickness


Estimated Marginal Means of ForceAttenuation
at Stiffness_SH = 43
Thickness
5
15
25
35
Estimated Marginal Means
50.00
40.00
30.00
20.00
10.00
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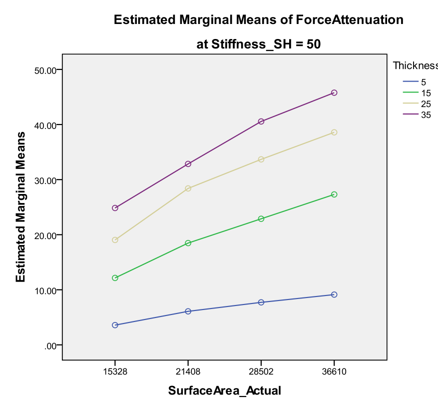
21408
28502
36610
SurfaceArea_Actual


Estimated Marginal Means of ForceAttenuation
at Stiffness_SH = 50
Thickness
5
15
25
35
Estimated Marginal Means
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40.00
30.00
20.00
10.00
.00
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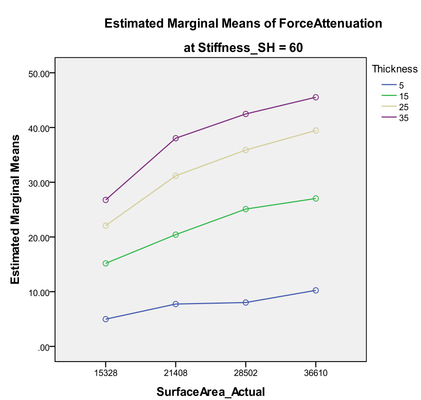
28502
36610
SurfaceArea_Actual


Estimated Marginal Means of ForceAttenuation
at Stiffness_SH = 60
Thickness
5
15
25
35
Estimated Marginal Means
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40.00
30.00
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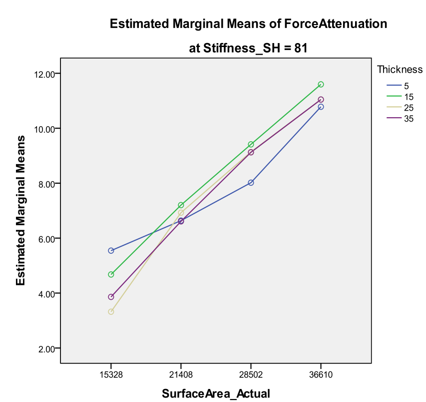
28502
36610
SurfaceArea_Actual


Estimated Marginal Means of ForceAttenuation
at Stiffness_SH = 81
Thickness
5
15
25
35
Estimated Marginal Means
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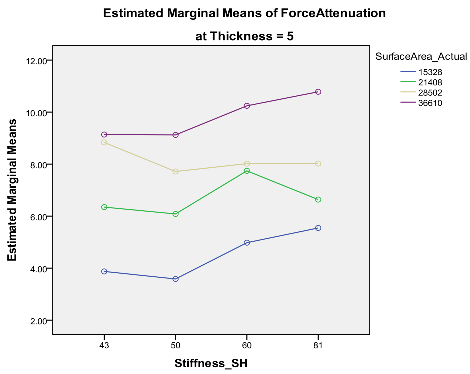
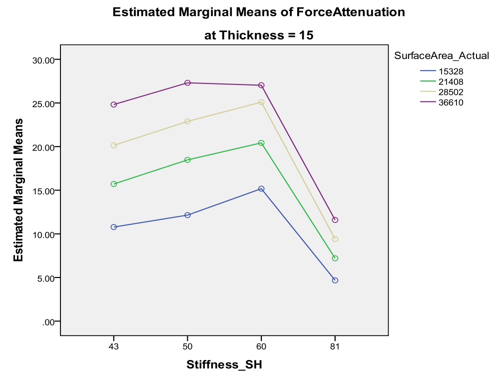
10.00
8.00
6.00
4.00
2.00
15328
21408
28502
36610
SurfaceArea_Actual


Estimated Marginal Means of ForceAttenuation
at Thickness = 5
SurfaceArea_Actual
15328
21408
28502
36610
Estimated Marginal Means
Stiffness_SH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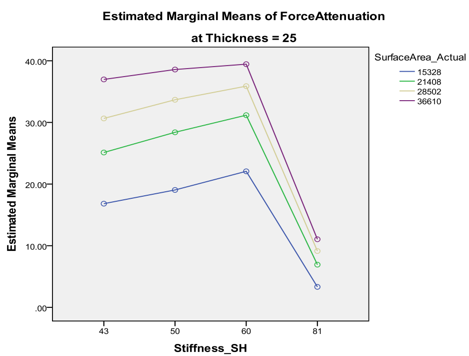
21408
28502
36610
Estimated Marginal Means
Stiffness_SH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SurfaceArea_Actual
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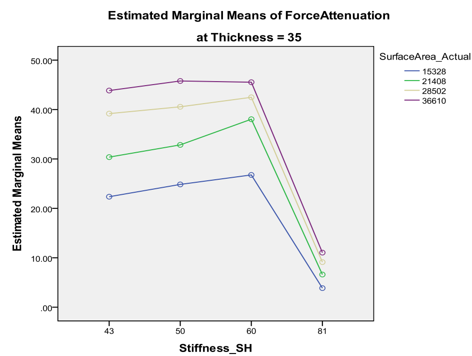
21408
28502
36610
Estimated Marginal Means
Stiffness_SH


Estimated Marginal Means of ForceAttenuation
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SurfaceArea_Actual
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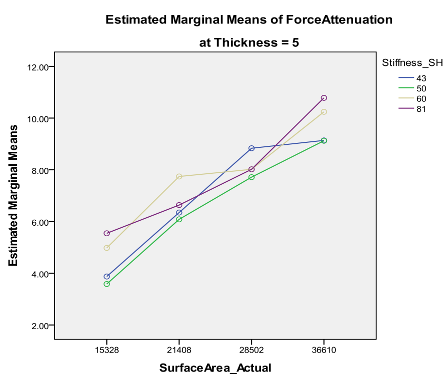
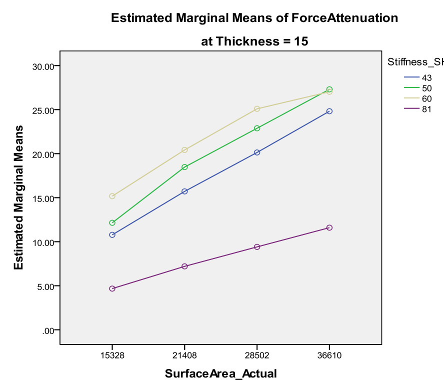
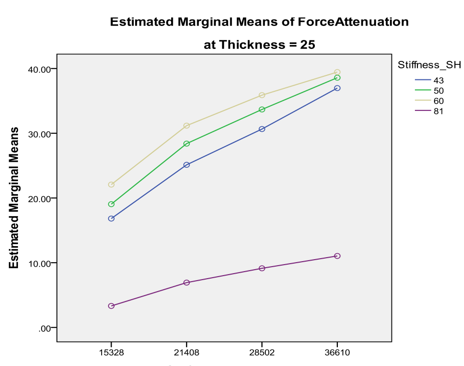
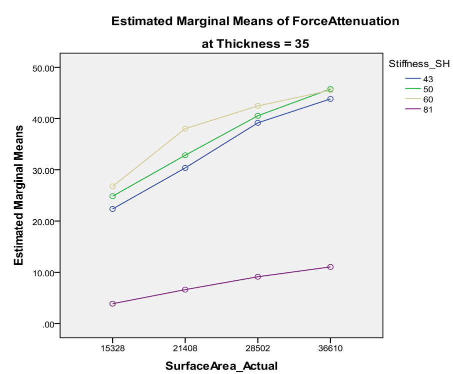
21408
28502
36610
Estimated Marginal Means
Stiffness_SH


Estimated Marginal Means of ForceAttenuation
at Thickness = 5
Stiffness_SH
43
50
60
81
Estimated Marginal Means
SurfaceArea_Actual


Estimated Marginal Means of ForceAttenuation
at Thickness = 15
Stiffness_SH
43
50
60
81
Estimated Marginal Means
SurfaceArea_Actual


Estimated Marginal Means of ForceAttenuation
at Thickness = 25
Stiffness_SH
43
50
60
81
Estimated Marginal Means
SurfaceArea_Actual


Estimated Marginal Means of ForceAttenuation
at Thickness = 35
Stiffness_SH
43
50
60
81
Estimated Marginal Means
SurfaceArea_Actual

Appendix F.

Patient Questionnaire

Patient Questionnaire	
Demographic Information	1. Gender 2. Age group (by half decade)
Fall & Fracture Risk	3. Risk factors for falls, including fear of falling 4. Previous falls history and frequency 5. Fall related injury (yes/no) 6. Fall related hip fracture 7. Other hip fractures
Hip Protector Use	8. Awareness of hip protector 9. Hip protector use (yes/no) 10. If no: reasons for non-use 11. Who recommended hip protector? 12. Duration of use (months) 13. Timing and frequency of use 14. How many hip protectors owned? 15. Name of hip protector being worn
Additional Factors	16. Use of incontinence pads (yes/no) 17. Difficulty using both pads and hip protectors? 18. Difficulty donning hip protectors? 19. Need for assistance with dressing 20. Need for assistance with daily activities 21. Does hip protector provide confidence for activity? 22. Does hip protector limit activity? 23. Any medical problems from hip protector use? 24. Falls while wearing hip protector? 25. Hip fracture while wearing hip protector? 26. Dislikes about hip protector use.

Appendix G.

Health Professional Questionnaire

Health Professional Questionnaire	
Demographic Information	1. Health Care Discipline 2. Length of employment in current setting 3. Number of designated beds for aging adults in facility
Falls and Fractures	4. Number of falls among patients seen in previous 2 weeks 5. Number of hip fractures in patients seen in previous 2 weeks 6. Number of these hip fractures associated with a fall
Hip Protector Awareness & Prescription	7. Awareness of hip protectors 8. Recommend use of hip protectors to patients 9. Number of hip protectors recommended for persons with incontinence 10. Number of hip protectors recommended for persons without incontinence 11. Which brand most likely to recommend? 12. Reasons for this recommendation
Perception of patient compliance	13. Do patients refuse hip protectors? 14. Reasons given for non-use (cost, difficulty donning, discomfort, other) 15. Reports of greater confidence in activity with hip protector use? Why? 16. Reports that hip protectors limit activity? Why? 17. Reports of medical problems from hip protector use?
Other Factors	18. Reports of falls during hip protector use? 19. Reports of fracture during fall while wearing hip protector? 20. Health Professional's perception of reasons for low patient compliance with hip protectors

Appendix H.

Simon Fraser University and Fraser Health Authority Ethics Approval

Minimal Risk Expedited Approval

SFU ENGAGING THE WORLD

OFFICE OF RESEARCH ETHICS

8888 University Drive
Multi-Tenant Facility
Burnaby, BC Canada, V4A 1S6
[redacted]
Email: [redacted]
http://www.sfu.ca/research/ethics

Date	File	Approval	Principal Investigator
21 June 2012	[2011s0540]	Approved	Deshmukh, Priyanka

Title	Start Date	End Date
Designing for Compliance in the Use of Wearable Hip Protectors: User Preferences in Product Selection	21 June 2012	21 June 2015

SFU Position	Department / School	Supervisor
Graduate Student	Engineering Science	Robinovitch, Stephen

Hello Priyanka,

Your application has been categorized as 'Minimal Risk' and approved by the Director, Office of Research Ethics on behalf of the Research Ethics Board, in accordance with University Policy r20.01 (http://www.sfu.ca/policies/research/r20.01.htm)

The Research Ethics Board reviews and may amend decisions made independently by the Director, Chair or Deputy Chair at the regular monthly meeting of the Board.

Please acknowledge receipt of this Notification of Status by email to [redacted] and Include the file number as shown above as the first item in the Subject Line.

You should get a letter shortly. Note: All letters are sent to the PI addressed to the Department, School or Faculty for Faculty and Graduate Students. Letters to Undergraduate Students are sent to their Faculty Supervisor.

Good luck with the project,

Hal Weinberg, Director

[redacted]

fraserhealth
Better health. Best in health care.

Fraser Health Research Ethics Board
FHA, Evaluation and Research Services
#400, 13450 102nd Avenue, Surrey, BC V3T 0H1
Phone: [redacted] Fax: [redacted]

CERTIFICATE OF FHREB APPROVALS

Official Notification - FHREB Number *(to be used on all future correspondence):* **FHREB 2012-038**	
Principal Investigator: FELDMAN, Fabio	**Hospital/Facility & Department:** Central City, Seniors Fall and Injury Prevention
Institution(s) or Geographical Areas where research will be carried out: Community Sites	
Co-Investigator(s): ROBINOVITCH, Stephen, SIMS-GOULD, Joanie, DESHMUKH, Priyanka	
Funding Agencies and/or Corporate Sponsor: Canadian Institutes of Health Research	
Title: Designing for compliance in the use of wearable hip protectors: user preferences in product selection.	

Documents Included in this Approval	Date of Approval	Date of Expiry	Type of Approval	Approval of the FHREB
• Application for Initial Ethical Review, dated 2012 May 14 • Research Protocol, version 2, 2012 May 20 • Hip Protector – Initial Education Program, undated • Consent Form (care provider), version 2, dated 2012 May 27 • Consent Form (family member), version 2, dated 2012 May 27 • Consent Form (older adult), version 2, dated 2012 May 27 • Script to Participants, undated • Advertisement, version 1	2012 May 31	2013 May 31	Initial Approval; Delegated Review	[redacted]

CERTIFICATION:

With respect to clinical trials:

1. The membership of the Fraser Health Research Ethics Board complies with the membership requirements for research ethics boards as defined in Part C Division 5 of the Food and Drug Regulations and the Tri-Council Policy Statement.
2. The Fraser Health Research Ethics Board carries out its functions in a manner consistent with Good Clinical Practices.
3. The Fraser Health Research Ethics Board has reviewed and approved the clinical trial protocol and the informed consent form for the trial which is to be conducted by a qualified investigator named at the specified clinical trial site. This approval of the documentation listed above and the views of the Fraser Health Research Ethics Board have been documented in writing.

With respect to delegated review:

A co-chair of the FHREB has reviewed and approved the documentation listed above for the forenamed research study in accordance with the FHREB Policy on "Ethical Conduct of Research and Other Studies Involving Human Subject", the Tri-council Policy Statement: Ethical Conduct for Research Involving Human", and the "International Conference on Harmonisation Guidance E6: Good Clinical Practice E6: Consolidated Guidelines".

With respect to full board review:

Full FHREB review and approval of the documentation listed above was completed for non-expedited review in accordance with the FHREB Policy on "Ethical Conduct of Research and Other Studies Involving Human Subjects", the Tri-council Policy Statement: Ethical Conduct for Research Involving Human" and the "International Conference on Harmonisation Guidance E6: Good Clinical Practice E6: Consolidated Guidelines".

The FHREB approval for this study expires ONE year from the approval date of this certificate. Researchers must submit a Request for Annual Renewal for ongoing research studies prior to the expiry date in order to receive annual re-approval.

Appendix I.

Participant Information (Care Staff)

1. **Name: _________________________**
2. **Age: _____**
3. **Gender (circle): Male / Female**
4. **Education Level: ___________________**
5. **Length of employment in the health care sector: _______________**
6. **Length of employment at the current site: _______**
7. **Previous job titles and description: _______________**
8. **Current job title and description: _______________**
9. **How many falls have occurred at the AL site in the last 12 months?:**
10. **What percent of residents at the site do you think are at a high risk for falls? __________________**
11. **Have any of the residents previously incurred a hip fracture? How many?**
    Yes / No ______________
12. **To your knowledge, how many residents are currently wearing a hip protector on a daily basis? ______________**
13. **Have residents previously asked you about hip protectors?**
    Yes / No
14. **What are some of the problems or issues you foresee with the use of hip protectors?**

Appendix J.

Participant Information (Older Adults)

1) **Name:** ________________________
2) **Age:** _____
3) **Gender (circle): Male / Female**
4) **Height:** ______
5) **Weight:** ______
6) **Education Level:** ___________________
7) **Length of stay at AL site: ____ years ____ months**
8) **When walking around, do you usually use a mobility aid (circle 1 option).**
    i. None   Cane   Walker   Wheelchair
9) **Number of falls in the past 12 months:** _______
10) **Do you think you are at a high risk for falls? Yes / No**
11) **Have you previously incurred a hip fracture? Yes / No**
12) **Do you have any chronic diseases? (Circle)**
    i. Adult onset diabetes
    ii. Arthritis
    iii. Kidney and bladder problems
    iv. Dementia
    v. Parkinson's disease
    vi. Glaucoma
    vii. Lung disease
    viii. Cataracts
    ix. Macular degeneration
    x. Osteoporosis
    xi. Enlarged prostate
    xii. Alzheimer's disease
    xiii. Depression
    xiv. Cardiovascular disease

Others: __________________

Appendix K.

Current Knowledge of Hip Protectors

Current Knowledge of Hip Protectors

This brief questionnaire aims to assess your current knowledge and level of familiarity with hip protectors. Please circle either Yes or No, for questions 1 to 5.

1. Have you ever heard about wearable hip protectors? Yes / No

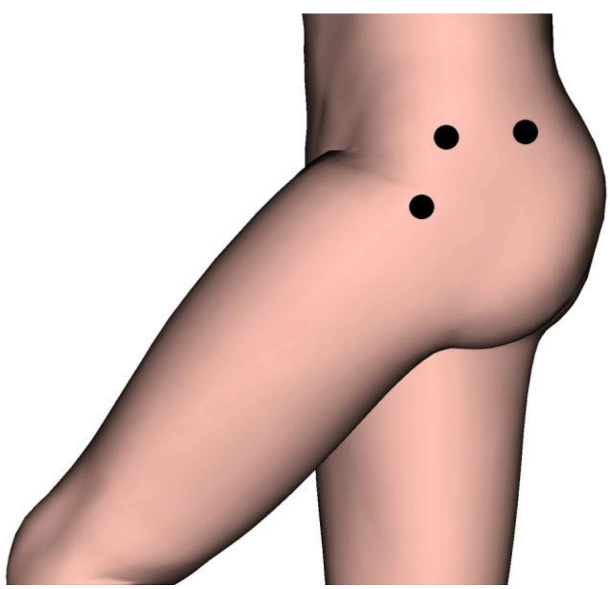
2. Have you ever seen a hip protector? Yes / No

3. Have you ever used a hip protector? Yes / No

4. Do you know anyone who has used a hip protector? Yes / No

5. Do you understand the differences between soft-shell and hard-shell hip protectors? Yes / No

6. Circle on the diagram below one of three locations (black dots) that is most appropriate for centering the location of a hip protector pad.



Appendix L.

Likert Scale Questions based on 5 Preference Criteria

1) OVERALL PREFERENCE OF HIP PROTECTOR

Score (circle) the following hip protectors on a scale of 0 (Least Preferred) to 10 (Most Preferred) based on your overall preferences in selecting a hip protector for everyday wear.

2) PREFERENCE OF HIP PROTECTOR ACCORDING TO COMFORT

Score (circle) the following hip protectors on a scale of 0 (Least Preferred) to 10 (Most Preferred) based on your perceived comfort in selecting a hip protector for everyday wear.

3) PREFERENCE OF HIP PROTECTOR ACCORDING TO APPEARANCE

Score (circle) the following hip protectors on a scale of 0 (Least Preferred) to 10 (Most Preferred) based on your perceived attractiveness in appearance in selecting a hip protector for everyday wear.

4) PREFERENCE OF HIP PROTECTOR ACCORDING TO PROTECTION AGAINST INJURIES FROM FALLS

Score (circle) the following hip protectors on a scale of 0 (Least Preferred) to 10 (Most Preferred) based on your perceived protective value in selecting a hip protector for everyday wear.

5) OVERALL PREFERENCE OF HIP PROTECTOR – BASED ON ACTUAL PROTECTIVE VALUE OF HIP PROTECTORS

According to the Biomechanical Performance bar chart, score (circle) the following hip protectors on a scale of 0 (Least Preferred) to 10 (Most Preferred) based on your overall preferences in selecting a hip protector for everyday wear.