PERFORMANCE EVALUATION OF 3D PRINTED HIP PROTECTORS

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PERFORMANCE EVALUATION OF 3D PRINTED HIP PROTECTORS

by

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b	bias term
C	regularisation factor
A_r(exp)	experimental Attenuation rate
A'_r(exp)	mean experimental attenuation rate
A_r(est)	estimated Attenuation rate
A'_r(est)	mean estimated attenuation rate
g_i (x)	set of non-linear transformations
$K(x, x_i)$	kernel function
n	number of data points
R_{emp}	empirical risk
α	Lagrangian multiplier
α, α*	Lagrangian multiplier
ξ_i and ξ_i^*; i = 1,..., k	non-negative slack
$\|\|\omega\|\|^2$	Euclidian norm
F_{us}	Unprotected femoral neck force without soft tissue
F_{ps}	Protected femoral neck force with soft tissue
F_u	Femoral neck force unprotected with hip protector
F_p	Femoral neck force protected with hip protector
T_i	Initial temperature
T_{fe}	Final temperature external to the hip protector
T_{fint}	Final temperature internal to the hip protector
TC	Temperature conducted
TT	Temperature Trapped between the outer surface of the hip and the inner surface of the hip protector

LIST OF ABBREVIATIONS

3D	Three dimensions
ABS	Acrylonitrile butadiene styrene
ANN	Artificial Neural Network
FDM	Fused Deposition Modelling
GT	Greater trochanter
HP	Hip protector
RMSE	Root mean square error
RSM	Response surface methodology
SLA	Stereolithography
STL	Standard Tessellation Language
SVM	Support Vector Machine
SVR	Support Vector regression
TPU	Thermoplastic Polyurethane

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PENILAIAN TERHADAP PRESTASI PELINDUNG PINGGUL BERCETAK 3D

ABSTRAK

Jatuh ke arah sisi adalah merupakan ancaman besar kepada warga yang berusia yang mana kesannya boleh mengakibatkan kepatahan tulang pinggul. Oleh itu, sebagai strategi yang berkesan dalam menghalang berlakunya kepatahan tulang pinggul dalam kalangan warga yang berusia ini, pelindung pinggul perlu dinilai sebaiknya, memberikan kos yang efektif dan direka supaya mengikut bentuk pinggul pengguna bagi meningkatkan keberkesanannya. Kajian ini bertujuan untuk menilai keberkesanan pad pelindung pinggul bercetak 3D dalam mencegah kepatahan secara biomekanik apabila jatuh ke arah sisi dan melaksanakan strategi untuk memperbaiki prestasi pelindung pinggul tersebut. Hipotesisnya adalah bahawa teknik ini boleh dilaksanakan dan berkesan secara mekanikalnya. Oleh itu, menara hentaman biomekanik yang digabungkan bersama pengganti femoral proksimal pinggul dan pengganti tisu lembut berbentuk pinggul telah dihasilkan untuk mengakses keupayaan pelemahan hentaman bagi pelindung pinggul semasa simulasi jatuh ke arah sisi dilakukan. Pelindung pinggul bercetak 3 dimensi (3D) telah direkabentuk berdasarkan kepada geometri profil pinggul yang dikenakan pada permukaan model 3D. Alat ini dicetak melalui kaedah percetakan stereolitografi (SLA) menggunakan resin kopolimer putih vero, dan seterusnya dioptimumkan melalui metodologi permukaan tindak balas menggunakan empat jenis poliuretana termoplastik (TPU 75%, 85%, 95%, 98%) skala kekerasan A, pengisian yang berbeza ketumpatan (25%, 50%, 75% dan 100%) serta lapisan luar yang berbeza ketebalan (0.86 mm, 1.29mm dan 1.72mm) telah dicetak melalui pemodelan enapan fius (FDM). Kebolehlenturan dan kekuatan mampat bagi pelbagai

konfigurasi pelindung pinggul telah dijalankan. Akhirnya, model regresi vektor sokongan telah dihasilkan untuk meramalkan keupayaan pelemahan hentaman bagi pelindung pinggul pada tahap tenaga yang berbeza. Hasil dapatan menunjukkan bahawa daya yang dipindahkan kepada leher femur berada di bawah purata ambang patah bagi warga yang berusia (3472 N) apabila menggunakan pelindung pinggul bercetak 3D SLA, setanding dengan pelindung pinggul sedia ada. Seterusnya, keupayaan untuk memanipulasikan ketumpatan pengisian memberikan kesan yang penting kepada nilai pelemahan hentaman, diikuti dengan ketumpatan pengisian yang digabungkan dengan kekerasan skala bahan. Persamaan yang sangat baik didapati antara hasil model dan keputusan ujian. Kejituan dan ketepatan model yang dihasilkan ini menunjukkan keberkesanannya dalam meramal kapasiti hentaman optimum bagi rekabentuk pelindung pinggul. Kesimpulannya, dengan memaksimumkan kesemua parameter ini, menunjukkan bahawa penggunaan kaedah pembuatan bahan tambah dalam menghasilkan pelindung pinggul mampu menjadi strategi yang berkesan untuk memperbaiki prestasi pad berkenaan untuk mengatasi kepatahan tulang pinggul. Keberkesanan dan penerimaan rekabentuk pelindung pinggul yang baharu ini kepada warga berusia boleh diakses dengan melakukan ujian klinikal pada masa hadapan

PERFORMANCE EVALUATION OF 3D PRINTED HIP PROTECTORS

ABSTRACT

Fall to the sideways is a significant threat to the aged population with potentially severe hip fracture implications. Hence, being the most effective strategy for avoiding hip fractures among the vulnerable population, there is a need to ensure hip protectors are properly evaluated, cost-effective, and customized to the hip shape to improve adherence. This study aims to evaluate the feasibility of a proposed 3D printed hip protecting pad for biomechanical fracture prevention in sideways fall and undertakes strategies to improve such printed hip protectors' performance. It is hypothesized that this technique would be both feasible and mechanically effective. Therefore, a biomechanical impact tower incorporated with a surrogate anatomical proximal femoral and hip-shaped surrogate soft tissue was developed to access the impact attenuation capability of hip protectors in simulated sideways fall. A custom-fit three-dimensional (3D) printed hip protector was designed from an actual hip profile geometry imposed on the surface of a 3D modeled hip shield. It was printed by stereolithographic (SLA) printing method using verowhite copolymer resin and subsequently optimized by response surface methodology using four types of thermoplastic polyurethane (TPU 75%, 85%, 95%, 98%) shore A hardness, varied infill density (25%, 50%, 75% and 100%) and different shell thickness (0.86 mm, 1.29mm and 1.72mm) printed using fuse deposition modeling (FDM). Also, the flexibility and compressive strength of the various configurations of the hip protectors were investigated. Lastly, a support vector regression model was developed to predict the impact attenuation capability of the hip protectors at different energy levels. The results demonstrated that the force transmitted to the femoral neck was below the average fracture threshold of older adults (3472 N) using the 3D Printed SLA hip protector, and it competes favorably with an existing hip protector. Furthermore, the ability to manipulate the infill density has the most significant influence on the impact attenuation properties, followed by the infill density combined with the material shore hardness. Also, Good agreement was found between the model results and test results. The applied model's precision and accuracy show its applicability in predicting a hip protector design's optimum impact attenuation capacity. Conclusively, by maximizing all the parameters, it is demonstrated that using an additive manufacturing technique to print hip protectors could be an effective strategy in improving the performance of the pad and curbing hip fractures. The effectiveness and acceptability of this newly designed hip protector for older adults can be assessed further by conducting future clinical trials.

CHAPTER 1

INTRODUCTION

1.1 Preamble

A hip protector is a wearable used to protect a user's hip from the consequence of a severe impact in the case of a fall to the sideways. This research explores the viability of 3D printed hip protectors tested with a biomechanical drop tower impact simulator. The development of an effective hip protecting pad is a crucial prerequisite to providing assurance for a quality life in the advanced age population due to the predicted increase in associated medical cost in treating fractures due to sideways fall. Therefore, considerable exploitation and focusing of research efforts have been committed to developing novel hip protectors with better impact attenuation ability, lightweight, breathable, long cycle life, lower cost, custom fit, and high possibility of improving adherence and compliance. This chapter introduces the hip protector, the production, the protection mechanism, and the in-vitro testing methodology.

1.2 Curbing hip fracture with improved protective pads

A global annual number of 6.26 million hip fractures is projected to have a clinical and economic implication on the aged population by 2050 (Gandjour & Weyler, 2008; Melton, 1993; Melton et al., 2003; Stollenwerk et al., 2014). Hip fractures cause significant morbidity and are associated with increased mortality, loss of independence, and a financial burden (Empana et al., 2004; Grisso et al., 1991; Kumar & Parker, 2000). Figure 1.1 shows the various types of hip fracture, with the femoral neck fracture constituting about 90% of all fractures and results from a sideways impact to the greater trochanter in a fall. This impact on the greater trochanter accounts for the majority of all hip fractures.

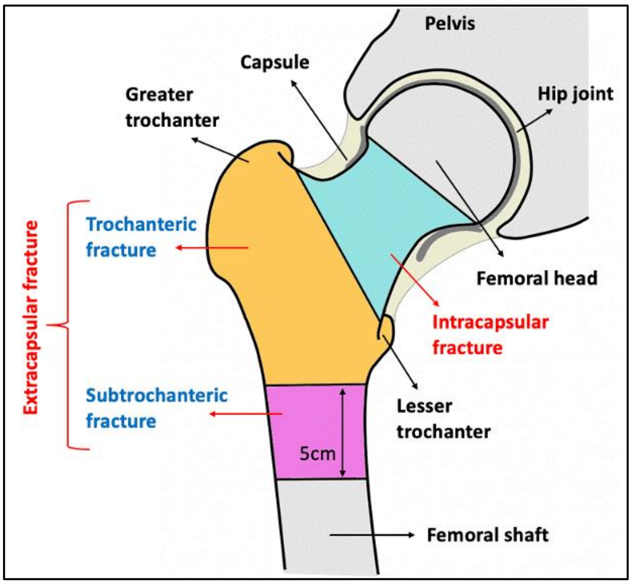
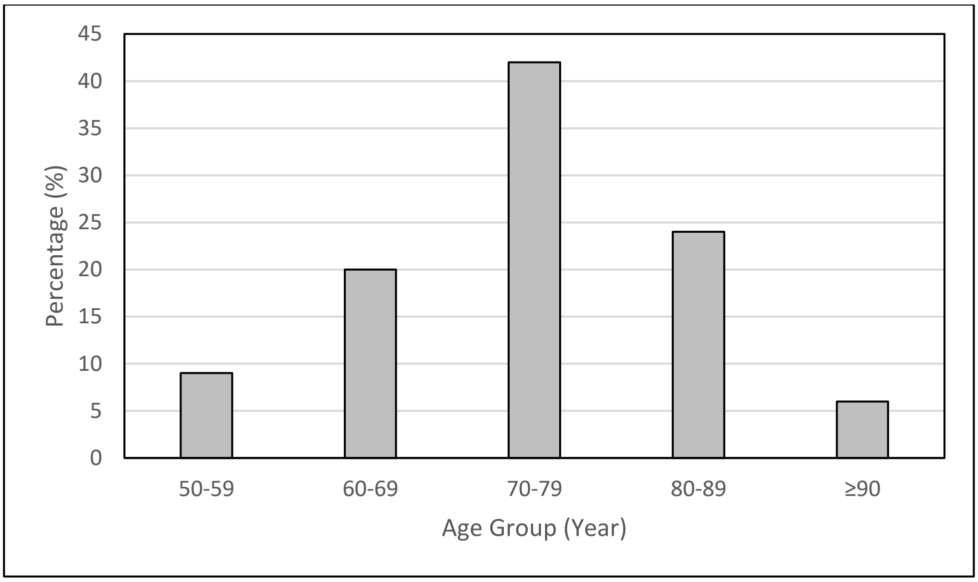
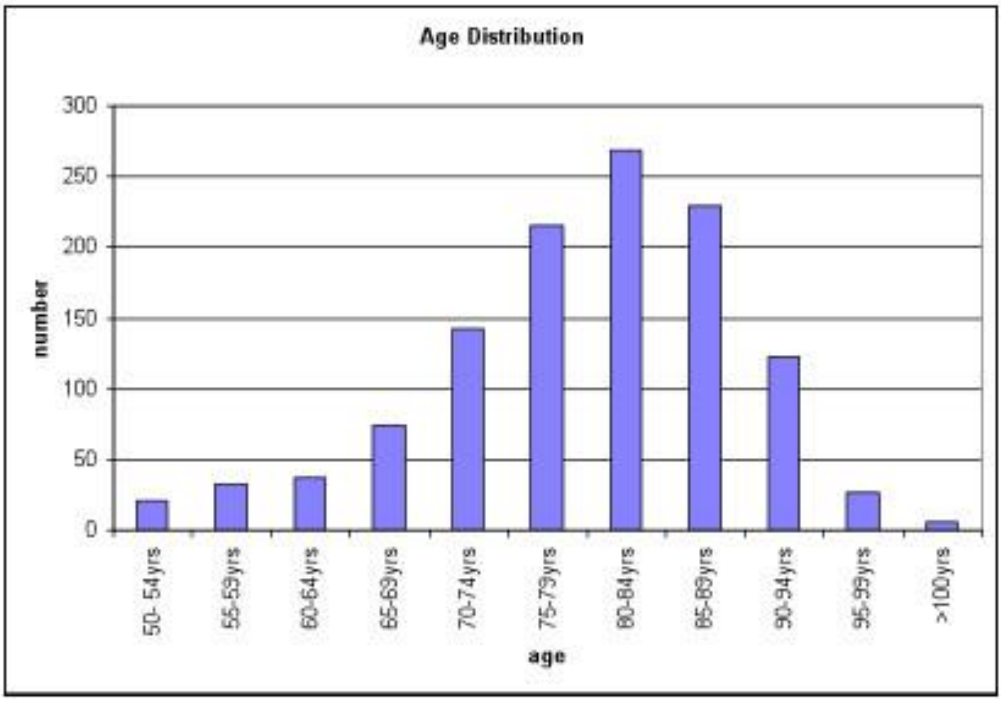


Figure 1.1: Various types of fractures of the femur that could result from sideways fall (Kyriacou & Khan, 2021)

Treating hip fractures is very expensive, costing a typical patient approximately USD 40,000 in direct medical cost in the first year following a hip fracture and roughly USD 5,000 in the years that follow (Leal et al., 2017). Approximately 20% of older adults hospitalized for a hip fracture die within a year, and about 50% will suffer a significant decline in independence (Milte & Crotty, 2014), and older adults are the most vulnerable population, as shown in Figure 1.2 (a) using the National Orthopedic Registry of Malaysia's Report of around 510 hip fracture cases in 2009 (Abdullah & Abdullah, 2010). Findings done in 2011 with data collected over five years for 1,177 patients in the United Kingdom show a similar trend of older adults and females more susceptible to hip fracture due to falls to the sideways, as shown in Figure 1.2 (b) (Pillai et al., 2011). A 2018 published study also correlated with the global trend of older adults' vulnerability (Barnea et al., 2018). Therefore, the mechanism of hip fracture and the choice of prevention strategy are of great interest (Lauritzen, 1996).



(a)



(b)

Figure 1.2: Distribution of hip fracture patients by age group (a) Malaysia 2009 (Abdullah & Abdullah, 2010), (b) the United Kingdom 2011 (Pillai et al., 2011)

Hip fractures may be prevented by utilizing three main strategies. The first strategy is to avoid falls by increasing coordinative responses and balancing power (Iaboni et al., 2018; Lam et al., 2004). The second strategy is to improve bone quality using medication and exercise (Benedetti et al., 2018). However, bone-strengthening results may take years to be effective (Courtney et al., 1994). The third strategy is to effectively attenuate the impact force to below the fracture threshold using external interventions like a hip protector and compliant floors (Laing & Robinovitch, 2009; Lam et al., 2004; Li et al., 2013; Minns et al., 2007; Nabhani & Bamford, 2004). This third strategy provides an immediate effect and could help curtail the menace of hip fracture. The ability of forces capable of fracturing human femur in a sideways fall to be attenuated using external intervention such as the hip protector is one of the most effective strategies in reducing morbidity and mortality in the aged population (Yum et al., 2020).

Figure 1.3: Conventional garment-based hip protectors

A hip protector is a specialized pad worn over the greater trochanter(GT) designed to prevent fall-related hip fractures among frail elderly individuals (G. Holzer & Holzer, 2007; Lauritzen, 1996). Hip protectors have been proven to be an effective strategy in reducing the impact force to the hip in a sideways fall (Cameron & Kurrle, 2002). Principally, there are two distinctive types of hip protectors, namely, “energy shunting type” or “energy-absorbing type” (Cameron & Kurrle, 2003), generally called the hard shell and soft shell hip protector, respectively. The impact force in a fall is distributed into the surrounding soft tissue by the “energy shunting type” of a hip protector. In contrast, the “energy-absorbing type” is usually made of compressible material and diminishes the force of impact by compression to densification (Haris et al., 2018).

Most hip protectors are traditionally made from molded foams and plastic, casting or cutting processes, making personalization very difficult to achieve. Therefore, the additive manufacturing (AM) technique offers various benefits and transformative potential over conventional manufacturing technologies to achieve effective and customised hip protectors that improve adherence (Attaran, 2017; Park et al., 2019; Wong & Hernandez, 2012). This process ensures proven energy absorbing and energy damping structures such as flexible honeycomb structures can be deployed for energy absorption (Bates et al., 2019) and, by extension, hip protection. When contact is made with the floor, an engineered hip protector with the right material and 3D printed auxetic structure (like the honeycomb) guarantees increased stiffness at the densification point without tearing, thereby absorbing the impact force and minimizing the trauma (Plant, 2014).

Mechanically, a hip protector is evaluated using a test system composed of a surrogate pelvis that strikes an impact surface, simulating the impact phase of a fall. A hip protector in place ensures only a fraction of the force is transferred to the vulnerable area that could have caused the hip to fracture. The data generated from these test systems are crucial in the design and development of hip protectors and for informing consumer purchase decisions (Cameron & Kurrle, 2003; Korall et al., 2015; Lauritzen & Askegaard, 1992; Minns et al., 2004; Parkkari et al., 1999; Robinovitch et al., 2009; Wiener et al., 2002). Therefore, it is essential to have a methodological study that develops impact testing system and illustrates the design's appropriate use to simulate hip anatomy and fall dynamics in evaluating hip protectors' effectiveness in preventing a hip fracture by subjecting hip protectors and surrogate femurs to higher impact forces, which are not feasible in in-vivo testing because of ethical and practical considerations (Mills, 2007).

1.3 Statement of the problem

Although improvements in hip protectors performance have been recorded, it still suffers poor compliance from the vulnerable population it is designed to cater for due largely to lack of fit and discomfort. It is increasingly difficult to get a hip protector that assures comfort and effectiveness at the same time. The inability to make user-specific hip protectors using traditional manufacturing techniques at a reasonable time and cost that could improve personalization and adherence persists. Also, improving performance has been on making new materials at greater expense and uncertainty and have resulted in bulky pads while reengineering current materials could make significant input on how impact protection is achieved with minima material and functional structure. The hip protectors' current manufacturing processes make it unbearably unaffordable as the production cost is so high that it makes it unendurably interesting for the vulnerable population (Hall et al., 2019). The need to procure expensive molds for manufacturing hip protectors, the inability to make user-specific hip protectors at a reasonable cost and the difficulty of modifying available hip protectors are among the general problems. Likewise, the potential of additive manufacturing techniques in hip protector manufacturing has mostly been unstudied.

Also, there is a lack of standardized test systems to test hip protectors' efficacy. Perhaps, the conflicting results of clinical trials are due, in part, to lack of agreement on techniques for measuring and optimizing the biomechanical performance of hip protectors as a prerequisite to clinical trials; as such, it continues to subject the effectiveness of the hip protector to debates (Cowling, 2004; Parker et al., 2006).

1.4 Objectives of the study

This research aims to evaluate an innovative 3D printed hip protector's biomechanical performance with the following objectives.

1. To develop the surrogate pelvis, femur geometry and soft tissue of the drop impact simulator, verify their performance and determine the best test parameters configuration for the experiment drop impact testing.
2. To assess the performance of custom-fit 3D printed hip protectors in a simulated sideways fall.
3. To determine the optimum design parameters of hip protectors using response surface methodology.
4. To predict the impact attenuation performance of 3D printed hip protectors using support vector regression.

1.5 Scope and limitation

This work examines the feasibility of using a 3D printed hip protector as a fracture prevention strategy using an experimental approach. Impact attenuation performance of a market hip protector with a known performance report was used to validate the test system in this work. Solid modeling was used to design the hip protector using a user's hip 3D mapping found in the literature. Investigations were carried out to develop 3D printed hip protectors using only commonly available 3D printing material such as verowhite resin® for SLA printed hip protectors and thermoplastic polyurethane (TPU) for FDM printed ones. Furthermore, important parameters that affect the performance of the hip protectors were screened using a full factorial design of the experiment. The hip protector was then optimized using response surface methodology. The various hip protectors were characterized appropriately by assessing the flexural and compression modulus of the 3D printed hip protectors and their thermal comfort evaluation. Finally, a predictive model that could predict the hip protector's performance was built using support vector regression. Only in-vitro investigations were carried out with surrogates' tissues, and the fracture threshold of 3.472 kN was used as the benchmark force for the hip protector performance.

1.6 Thesis structure

This thesis included five chapters, and the description of the following chapters is outlined in this section as follows:

Chapter 1 – Introduction: This introduction chapter includes the research background, research problems, objectives, scope, and limitation of this research work.

Chapter 2 - Literature review: In this chapter, various test systems for biomechanical performance evaluation of hip protectors were reviewed. Also are different hip fracture prevention techniques, methodological aspects of the investigation of the effectiveness of a hip protector and force attenuation provided by various hip protectors tested by different researchers. Finally, the theory behind drop impact systems, hip assembly, hip fracture, hip protector design and impact attenuation analysis of hip protectors were presented.

Chapter 3 - Methodology of the research: In this chapter, theories and methods employed during this research work were discussed. These include the design and construction of a drop impact tower with anatomical features for hip protector testing, the development of a hip joint simulator for synovial fluid analysis, fabrication and assembly of the system, and the performance analyses of hip protectors. Others include analysis of surrogate femur performance and soft tissue characterization, hip protector thickness on performance, and residual impact energy of the system.

Chapter 4 – Results and Discussions: In this chapter, the results obtained from this research are presented, analyzed and discussed. These include the influence of the synovial fluid in the surrogate pelvis characterization, evaluation of the effect of femur geometry on the test system, test condition optimization, characterization of the performance of custom-fit 3D printed hip protectors using the designed biomechanical hip protector testing system with anatomical femur geometry.

Chapter 5 – Conclusions and Recommendations: In this chapter, the design judgments and performance outcomes of the hip protector test system and hip protector performance were concluded with recommendations for further development.

CHAPTER 2

LITERATURE REVIEW

2.1 Chapter overview

There has been a surge in the global incidence of fall due to an increase in the aging population and has become a significant public health concern in developed and developing nations (Pekka Kannus et al., 2005). Epidemiological studies have estimated that there would be an exponential increase in the incidence of osteoporotic fractures in Asia. It is estimated that by 2050, 50% of all hip fractures would occur in this region (Dhanwal et al., 2011). A comparable trend has been registered in the Arabian Gulf region, with about 17.1 % increment recorded from 2009 to 2012, while there is a strong indication that this trend will continue (Azizieh, 2015).

Due to the limitations of other fall prevention strategies in recent years, the hip protector has gained a global interest in fracture prevention (Cameron & Kurrle, 2002) using two specific impact attenuation mechanisms. The hip protector is adaptable to meet the need of a wide range of individuals and reduce the risk factor and consequent impact of hip fracture (Minns et al., 2004).

Several processes make a hip protector, like fabricating and molding foam and plastics, including injection moulding, controlled shape cutting, polymerisation, polycondensation processes, composite materials, and additive manufacturing (Melo et al., 2010; Soh et al., 2020). Here, of particular interest is additive manufacturing, the process technologies for custom fit adaptive shape hip protectors were examined with the benefits of exploiting the fit of the intervention and human comfort for improved adherence (Park & Lee, 2019). Also, the recent progress in 3D printing techniques has opened essential routes for the production of hip protectors, like the achievement recorded in 3D printing of consequently having socio-economic impacts process design and integration and fracture prevention (Park et al., 2019).

Recent advances in the assurance of hip protectors' efficacy are to use biomechanically compliant test systems that replicate the human anatomy and effectively simulate impact activity in a typical fall to the sideways. These systems help to save costs and casualties that may arise from directly testing the intervention in a clinical trial and the limitation of testing with impact forces that are insufficient in a pelvis release experiment. One of the significant factors in the hip fracture prevention scheme with a significant contribution to reliability is the testing system. However, it is still lagging in standardization (Yahaya, Ripin, et al., 2019). The target of hip protector research, as opined by Robinovitch et al. (2009), for the critical parameter in the test system, is the peak force at the femoral neck or acetabulum with test systems that accurately simulate the anatomy, effective mass, effective stiffness, and impact velocity of the body during a fall on the hip. It has been experimentally established that most hip protectors can readily be tested in simple or slightly modified hip testing systems without significant problems if the testing condition is held constant (Li et al., 2013; Parkkari et al., 1994).

2.2 Curbing hip fracture with improved protective pads.

Due to falls in recent years, the susceptibility of frail elderly individuals to sustain hip fractures has encouraged many researchers to look into various strategies of preventing hip fractures resulting from falls. Strategies employed include improving coordinative response through exercise, the use of bone-strengthening vitamins/calcium supplements, health/environment hazard assessment and modification, multifactorial preventive programs, and the use of impact reduction interventions like protective compliant floor and the hip protector (Courtney et al., 1994; Iaboni et al., 2018; Laing & Robinovitch, 2009; Lam et al., 2004; Li et al., 2013; Minns et al., 2007; Nabhani & Bamford, 2004). The low possibility of achieving an increase in bone mineral density when osteoporosis has set in and the unassured improvement of coordinative responses to reduce the risk of hip fracture encourages the development of new interventions that would decrease hip fracture risk should a fall occur these processes.

These interventions employed to attenuate impact forces must maintain high efficacy and improve adherence and compliance without compromising the aesthetic. The significance of impact protection technology has helped reduce the economic strain arising from hip fracture, which can be devastating and could compromise the quality of life and eventual death within 24 months following a hip fracture (Buckinx et al., 2018). Besides, Santesso et al. (2014) suggest that with personal and design factors considered in the development of hip protectors that will improve adherence and compliance, the intervention will decrease hip fracture risk. The expectations are that hip protectors will provide decent protection against the estimated hip fracture of 4.5 million by the year 2050 (Veronese & Maggi, 2018).

Hip protectors represent a favorable solution in preventing fall-related hip fractures when coordination, speed and strength of upper body parts are not guaranteed to break a fall in order to avert higher force being incident on the hip or because of the inadequate protective response of the body due to age, sex and body mass index (Majumder et al., 2013). The two types of hip protectors are hard shell hip protectors and soft-shell hip protectors for the active prevention of hip fractures. Apart from the user’s compliance, the severity of fall influences hip protectors’ effectiveness (Laing & Robinovitch, 2008a; van Schoor et al., 2002).

The basic features of the hip protector that have enjoyed improvement over the years are the material properties, geometry and configuration of the protecting pad (O'Hearn, 2016). The materials are classified according to their energy shunting/absorbing mechanism (van Schoor et al., 2006). Soft hip pad materials can attenuate impact energy by energy absorption mechanism, while stiffer materials shunt impact by distributing energy to other tissues away from the greater trochanter. Though, each group of hips protecting materials have their drawbacks, such as bulkiness, aesthetic compromise, ineffectiveness in point load condition, need for constant monitoring to ensure the protection of the vulnerable site. Findings have shown that the impact attenuation performance of hip protecting pads can be enhanced by making combination pads based on the different types of impact attenuation mechanism and engineering new materials and techniques to obtain useful buffer characteristics like the incorporation of shear thickening polymer, incorporating a thin preformed shell within a softer layered material (Lauritzen et al., 1993), dispersion of polyethylene glycol in foam, use of composite materials and the implementation of airbag technology (Haris et al., 2018; Jeong et al., 2019; Lee et al., 2017; Q. Zhang et al., 2014). Conclusively, by taking cognizance of the stupendous resources spent examining and improving hip protectors' performance in the past, these interventions still present an opportunity in exploring modern ways to improve the performance of the hip protector cost-effectively.

A hip protector is generally regarded as a padded or plastic device incorporated into underwear to attenuate impact forces in the case of a fall to the sideways (Sellberg et al., 1992). Hip protecting materials are categorized into different types according to their mechanisms impact attenuation, including impact shunting (Hayes et al., 1997), impact absorptions and combined mechanism (Nabhani & Bamford, 2002). All hip protectors include some main features: material properties, pad geometry, attachment mechanism and pliability. Being the most reliable of the three strategies of preventing hip fractures, hip protectors are gaining significant attention in recent years. Hip protectors prevent fracture by absorbing/shunting away impact energies from vulnerable impact sites in a lateral fall depending on the structure and properties of the hip protecting materials.

Investigating fracture prevention using hip protectors showed that compliance with the device's use had been a significant obstacle in tackling the severity of the consequence of fall (Kannus & Parkkari, 2006). Similarly, adherence has been a ban on the result of most clinical trials seeking to classify the hip protector's efficacy. It has been reported in a study that most hip fractures occurred when the hip protector was not in use (Avenell et al., 2014; Cameron, 2001). Additionally, higher dropout or higher lack of compliance were noted in hip protectors that were seen not to fit well, too tight or awkward to wear (Hubacher & Wettstein, 2001; van Schoor et al., 2002; Villar et al., 1998).

Some studies have also used the finite element method (FEM) simulation to develop new designs of hip protectors and investigate the protective effect of novel materials and designs (Schmid Daners et al., 2008; Srewaradachpisal et al., 2011). By exploring various technological tools applied to design, optimization and production will expand the frontier of knowledge in the quest for impact force protection. The options available to reducing falling tendency in the aged are becoming slimmer, and the prevention of senile osteoporosis shows uncertain possibility. It is fascinating to influence the severity of impact and reduce the impact force when the greater trochanter hits the ground, yet not compromising the pad lightness and flexibility for a better appeal. To enhance compliance by the vulnerable population, researchers would have to evaluate novel materials, redesign, and optimize the current interventions while ensuring the devices' effectiveness.

2.2.1 Impact shunting hip protectors

Most hard-shell hip protectors are employed to bridge over the greater trochanter and redirects impact from it to the area surrounding the greater trochanter. This redistribution of impact force to area underlaying the greater trochanter can be viewed as a similar role played by the hard shell of a helmet. The hard-shell hip protector's effectiveness is proportional to the bending stiffness of the shell when loaded centrally (Lauritzen et al., 1993). Usually, the hard-shell hip protector is designed to bridge the greater trochanter to shunt away energies from the proximal femur (Pekka Kannus et al., 2000; Lauritzen et al., 1993). An example of a hard shell hip protector that bridges over the GT are the KPH hip protector, manufactured by Finnish Red Cross Orthopaedic Service, Helsinki, Finland, made of a dome-shaped polyethylene shield that shunts away forces from the greater trochanter in a typical impact due to a sideways fall by an elderly (Pekka Kannus et al., 2003).

2.2.2 Impact-absorbing hip protectors

The primary mechanism of impact-absorbing protectors is lowering the tissue's effective stiffness over the greater trochanter, typically by foam compression that prolongs the impact time (Choi et al., 2010a). A useful energy absorbing material will extend the duration of impact, lower the impact's bell curve, and translate to a lower peak impact force (Kannus et al., 1999). The soft-shell hip protector, which is seen as the impact-absorbing hip padding system, reduces the force applied to the proximal femur in the case of fall by absorption of energy through a "springs-in-series" mechanism by the material to reduce the local stiffness over the greater trochanter (Laing & Robinovitch, 2008b, 2008a). The soft-shell hip protector comes in different variants. Lauritzen & Askegaard (1992) found polystyrene foam with a density of 50 kg/m^3 to be quite an efficient energy absorber. Parkkari et al. (1994) had found Plastazote useful as a suitable energy attenuator because of its particular cross-linked polyethylene structure, but unreasonable thickness seems inadequate as a hip protector. Derler et al. (2005) proved that a well-formulated foam pad alone could provide good shock absorption and reduce impact forces even though Laing & Robinovitch (2008a) had opined that soft shell hip protectors alone could only substantially reduce the pressure over the greater trochanter, while only modestly reducing total impact force during simulated sideways falls.

2.2.3 Combination hip protector

Lauritzen et al. (1993) demonstrated that hip fractures in the elderly could be reduced by 50 percent if they wore a particular design of protector, which is a device that consists of a polypropylene shell with foam layers. The shell is thermoformed from a transparent glassy thermoplastic of density 1275 kg/m^3. It has a length of 135 mm, a width of 98 mm, and a thickness of 2.6 mm. The radii of curvature in the horizontal and vertical directions are 68 and 240 mm, respectively. It is covered on the inside with a 4.5 mm thickness of low-density polyethylene (LDPE) foam, density 64 kg/m^3. There is a 29 mm wide ring of 2.9 mm thick LDPE foam on the outside circumference with a density of 147 kg/m^3. The two foam layers are bonded together at the outside, acting as a pocket for the shell.

2.2.4 Fabrication of hip protector: various methods and materials

Since the inception of the hip protector, many materials have been used to make the hip protector. The materials are determined through a combination of physical property, material chemistry, and, most recently, alteration of material rheology (Cossa, 2019). However, due to the hip region's biomechanics, consideration for human comfort, compliance with external attachment to the human body and aesthetics, it is challenging to select materials for hip protection. Thus, there have been evolving studies on hip protector's material. Materials such as polyurethane, polypropylene, polystyrene, silicone, fur, sponge, fluid, and even air cushion have been explored to fabricate the hip protectors. Some materials are designed to crumple progressively, absorbing most of the kinetic energy that the material must dissipate when subjected to impact, while some strain hardens or expand to absorb or shunt away impact. The effect of using materials to alter the attenuation characteristic of foam has been detailed (Haris et al., 2018). However, the issue of bulkiness may still need to be addressed to improve adherence. Song et al. (2012) showed that the buffer rates of sponge materials with different hardness’s used as hip protectors are distinct when impacted under similar conditions. Their experimental results also showed that the thickness of the material also significantly impacted the buffer rate. They concluded that there are optimum thickness and hardness for buffer materials to absorb impact.

There are as many types of hip protectors as materials, and design ingenuity allows, with very many of them classified as either energy-absorbing pads made from foam or fabric due to their energy mechanism in impact attenuation and the ability of the protector to be easily formed around the body contour or the energy shunting pads, also known as the hard-shell, which can redistribute impact load from the greater trochanter to the surrounding tissue and usually form a bridge of sort over the greater trochanter (Laing & Robinovitch, 2009). The former may be more preferred because of its comfortability (Honkanen et al., 2006). Researchers also combine both kinds of materials to benefit from the soft material's energy absorption and the impact shunting capability of the hard one. While stiffer materials or materials that tend to exhibit higher stiffness are preferred for energy shunting hip protectors (Parkkari et al., 1995; Robinovitch et al., 1995a), protectors with lower stiffnesses are often desirable in energy-absorbing hip protectors (Laing & Robinovitch, 2009) and by the users (Honkanen et al., 2006). Various ways of fabricating hip protectors, such as flexible polyurethane or other types of foams, textiles, fiber-reinforced polymer composite and foams impregnated with dilatant materials, have been reported in literature. However, the fabricated hip protector's energy response depends on the specific characteristics of the materials used in the fabrication, the shape, structure, configuration, and the eventual stiffness of the pad.

Table 2.1 shows the various fabrication method of the hip protectors, their advantages and concerns.

Table 2.1: The various fabrication methods/materials of hip protector, their advantages and disadvantage

Fabrication Method/Material	**Advantages**	**Disadvantages**
molded foams	▪ Good cushioning ▪ Variety of shape and firmness ▪ Good energy absorption ▪ High porosity ▪ Light weight ▪ durable ▪ Good comfort	▪ Property depends on temperature and humidity ▪ 'Bottoming out' quickly ▪ Efficacy may require bulky pads that hinder compliance ▪ Low air permeability ▪ Low moisture transmission ▪ Shap distortion ▪ Special care is required
Thermoplastic polymer	▪ Good impact shunting ▪ Energy efficient ▪ Versatile	▪ High stiffness ▪ Less comfortable

Rigid Composite material	▪ Possibility of superior energy absorption ▪ Eco-friendly ▪ Shunting of relatively high impact force ▪ Can add strength in the critical area ▪ Could assist in the case of an oblique impact	▪ Not reusable after an incident ▪ Usually requires soft padding ▪ Discomfort to users in case of matrix fragmentation under impact ▪ High risk of fiber/matrix debonding under impact ▪ must be formed to shape
Gel-like hydrogel composite	▪ Possibility of longer duel time under the impact ▪ Possibility of controlling fiber morphology ▪ Simple and low-cost equipment ▪ Excellent mechanical properties ▪ Process scaling is possible	▪ Composite depends on many conditions ▪ Inhomogeneous energy dispersion at different parts of the hip protector
Rubber and elastomer	▪ Large stretch ratio ▪ High resilience ▪ Exceptionally waterproof ▪ Wide range of constancy of properties over wide range of temperature (-100 to 250 ^{o}C) for silicone elastomer ▪ Low thermal conductivity ▪ Low chemical reactivity ▪ Low toxicity	▪ Susceptible to vulcanisation ▪ Sensitive to ozone cracking
Shear thickening Fluid/dilatant	▪ Strain rate sensitive	▪ Need for STF to be contained within a foam and requiring

	▪ It could be modeled with a commercially available silicone-based product	complicated sealing processes ▪ reduced breathability due to the polymeric housing material ▪ very difficult to manufacture
Air cushioning	▪ Ultra-lightness ▪ Flexible ▪ Low cost	▪ High initial set up cost for manufacturing ▪ Comparatively lower efficacy
3D Spacer Fabrics	▪ High breathability, durability and washable ▪ Excellent recovery after impact ▪ Light in weight (especially 100% polyester ▪ Recyclable ▪ Environmentally friendly	▪ Higher production cost ▪ Risk of abrasion on body tissue by the loose edge ▪ Comparatively low efficacy
3D printed hip protector	▪ Offers customization opportunity ▪ Combine inherent material property with the ability to change internal structures ▪ Intricate structures and shapes can be printed	▪ Comparatively longer manufacturing time to print depending on the technology ▪ Requires modeling cost

2.2.4(a) Molded foams

Lewis (2006) opined that hip protectors or pads are often made from conventional foam materials, which have the following desirable property; good energy absorbing capacity, good durability, low weight, good recovery after compression, easy availability, and reasonable price (Lewis, 2006; Jari Parkkari et al., 1994). Different materials that have met these criteria have been employed in the fabrication of hip protectors, such as flexible cross-linked polyethylene foams with densities from 30 to 200 kg/m^3, Plastazote polyethylene foam, elastomeric foam, ethylene-vinyl acetate (EVA) copolymer (Parkkari et al., 1994), viscoelastic shock-absorbing foam (SAF) (Daners et al., 2008), among others. Foam performance is basically by compression. Very high load sends a foam beyond its densification point following a plateau from the elastic region when it is first compressed. Its performance may be affected by the failed foam's movement away from the protected site when subjected to unbearable load. Figure 2.1 shows a typical stress-strain curve of extruded low-density polyethylene foam material.

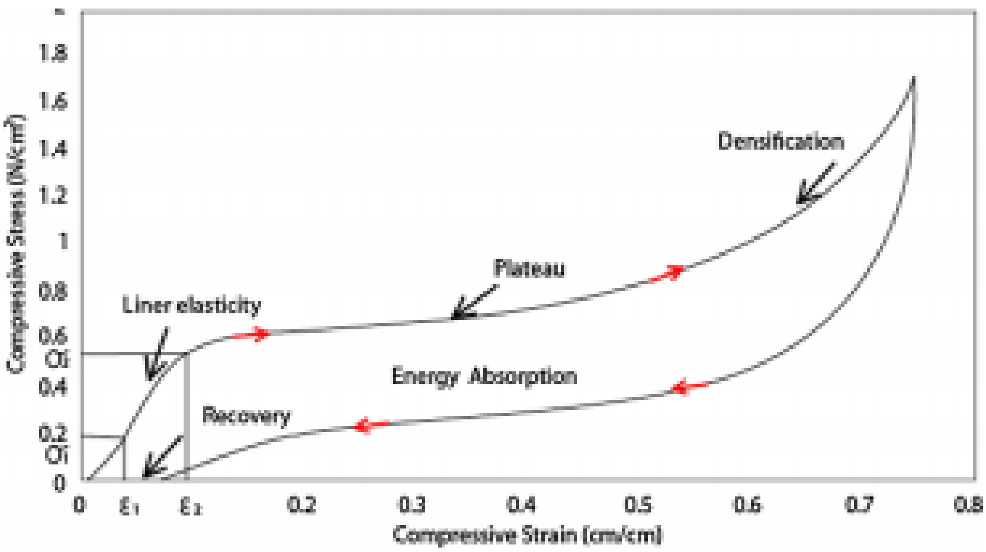


Figure 2.1: A typical stress-strain curve of extruded low-density polyethylene foam material (Ge & Huang, 2015)

Polyurethane (PU) is the most popular material by which softshell energy-absorbing hip protectors are made. Though, polyurethane resin (87–95 cm at the hip, 160 mm x 120 mm x 7 mm, 68.7 g) has also been used in the design of hard-shell hip protectors by Dermeister Corporation Tokyo, Japan (Li et al., 2013). It is easily molded into a hip protector by dispensing the liquid reaction mixture such as polyols, isocyanates, and other additives into the mold of the needed geometry for the hip pad.

The opportunity to manipulate the vast raw materials and other parameters involved in foam making enables the tuning of foam properties to meet specific property targets, including density, resilience, and hardness. The isocyanates and polyols are derived from crude oil; however, polyols may be derived from renewable sources. Polyurethanes are characterized by urethane linkage -NH- C (=O) - O – formed due to isocyanate with the hydroxyl group (Ashida, 2006) urethane with its characteristic structure presented in Figure 2.2. The full reactions of these base materials and other additives are responsible for the foam used as hip protectors. The quantity of each material and variation of other parameters determines the foam's property to be produced. Hence, higher energy-absorbing foams are more of interest in hip protection studies.

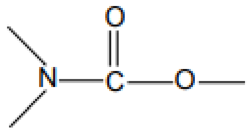


Figure 2.2: Structure of Polyurethane also known as urethane (Ashida, 2006)

Recently, a viscoelastic shock-absorbing foam (SAF) such as polyurethane is employed in the design of a soft-shell hip protector because of the strong dependency of its behavior on the rate of impact load. Another positive asset of SAF is that it absorbs energy upon impact, yet regular wearing adjusts its shape to the underlying tissue and is reported to provide adequate comfort. One of the most widespread impact-absorbing hip protector is the Hipsaver hip protector, made by Hipsaver Inc., Canton, MA, USA, which is made of viscoelastic open-cell foam known as Urethane foam encapsulated in a waterproof, airtight pouch, and has a thickness of 16 mm, sewn into cotton underwear to have a center point coincide directly over the GT when worn (Choi et al., 2010a; Laing & Robinovitch, 2008b).

Another popular foam used as a hip protector is EVA, with its elastomeric property impressive for improving the impact resistance of the hip protector in a sideways fall. Even the addition of EVA particle to polymer matrix has been reported to improve such a hip protector (Melo & Dos Santos, 2009). Chan et al. (2000) also developed a Tai Kwan Do matting inspired hip protector made from EVA foam shaped into 2×3 rows of a cube with dimensions 6 (width) × 7 (length) × 2.5 (depth) cm in each cube, made to be waterproof and demonstrate shock absorbency. Though this protector was not mechanically tested, a clinical trial suggests appreciable acceptability and relative risk of fractures in the hip protector group compared with the control group, given as 0.264 (95% CI=0.073–0.959). Similarly, the SafeHip Soft protector is another type of softshell hip protector made of closed-cell ethylene vinyl acetate (EVA) foam, sewn into cotton underwear having a horseshoe-shaped pad with maximum width and height of 170 mm each and thickness of 14 mm. The protector has a gap that makes the foam padding surrounds but does not directly cover the GT, earning it the nickname of the "horseshoe" hip protector (Laing & Robinovitch, 2008a) and comprehensively tested by Choi et al. (2010b).

Some hip protectors might not be custom molded but fabricated from a block of foam cut to the desired shape. The AHF hip protector is made of viscoelastic polyurethane (PUR) foam (Holzer et al., 2009). It has a roundish shape but narrower on the sides. The pad is constructed using two layers of foam in different shores that are connected (van Schoor et al., 2006). Other popular ones include the Safetypants (Van Heek Medical, The Netherlands) made from polyurethane foam (Park et al., 2019; van Schoor et al., 2006), Lyds Hip Protector (Lyds International BV, The Netherlands) made from microcellular polyurethane Sandsmaterial (van Schoor et al., 2006), Safety Pants (Raunomo Oy, Finland) made from closed-cell polyethylene foam

(Holzer et al., 2009)(van Schoor et al., 2006), Gerihip (Prevent Products, Inc., USA) made of cross-linked polyethylene pads (van Schoor et al., 2006), Posey Hipsters™, 4 Pelican and many more.

Additionally, Song et al. (2018) studied sponge materials used as a hip protector and showed that the buffer rates of materials with different hardness and density are distinct when impacted under similar conditions. Their experimental results also showed that the thickness of the material significantly impacted the buffer rate. They concluded that there exist optimum thickness and hardness for buffer materials to attenuate impact. Other foam polymers that have been demonstrated as hip protectors include polystyrene (PS), polyethylene (PE), polypropylene (PP), phenolic, and olefinic.

2.2.4(b) Thermoplastic polymer

Most hard hip protectors have been fabricated from different thermoplastic polymer types produced via chain-growth polymerization from the monomer. Under impact, the hard plastic serves as a uniform pressure distributor over the area it covers, thereby shunting away impact forces that could be traumatic (Nicotra et al., 2014). KPH hip protector manufactured by Finnish Red Cross Orthopaedic Service, Helsinki, Finland, is made of dome-shaped polyethylene, produced from the polymerization of ethylene (Kannus et al., 2003). Hornsby Healthy Hip is also made from rigid PVC plastic with a soft inner foam pad produced by the Hip Protector Studies Unit, Rehabilitation and Aged Care Service of the Hornsby Ku-ring-gai Health Service, Australia and is suggested to shut impact away from the GT strictly. Nabhani & Bamford (2002) also made a hip protector of rigid oval shell from acrylonitrile-butadiene-styrene (ABS) with a soft lining made of closed-cell polyurethane with a length of 119 mm, a width of 80 mm and thickness of 14 mm, aimed at using the rigid