Assessment of the force attenuation capability of 3D printed hip protector in simulated sideways fall

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Abstract

An innovative 3D printed hip protector has been designed and tested to decrease the possibility of hip fracture in a sideways fall to a hard surface. The main design purpose was to create custom fit hip protector, reduce the manufacturing period and make the protector comfortable to wear. This work compares the new energy shunting 3D printed hip protector design with an existing energy absorbing hip protector. A drop tower mechanical test rig was designed and developed to simulate a sideways fall with sufficient impact energy to fracture an unprotected greater trochanter (GT). The test rig incorporates the actual geometry of a femur made from steel and uses a foam to simulate trochanteric soft tissue over the greater trochanter. Similar impact energy was used for the testing of each hip protector. The weight of the striker mass was maintained, and the height was adjusted to obtain an impact energy of 21–43J to produce femoral neck force of 3–9 kN. Results illustrate that the 3D hip protector compares favorably in attenuating impact force capable of causing hip fracture to a value below the fracture threshold of 3.472 kN. The influence of the 3D hip protector on peak transmitted forces to the vulnerable site of the greater trochanter is shown to be positive. It is anticipated that future protectors can be 3D printed after optimizations to end the bundling of same hip protector for different body geometry.

1. Introduction

The menace of hip fracture has become a global concern as it constitutes a barrier to quality life to the world growing aged population. As aged population continue to surge so is the hazard of hip fracture resulting from fall to the sideways. Hip fracture has become the third cause of immobility to adult population[1]. When falls cannot be prevented and the coordinative response of the body is too slow to break the fall, more force will be applied to the hip and it is susceptible to cause fracture most especially in osteoporotic bones[2].

Hip fractures due to sideways falls are caused by the peak forces applied to the greater trochanter (GT) at the instance of impact. Though, this impact force is difficult to predict, they are determined by the velocity, effective mass, hardness of the impact surface, and the body’s natural dampening effect on impact [3].

Biomechanical test and clinical trials have proven that hip fracture can be drastically reduced by wearing a hip protector [4–8]. Researchers have, therefore, designed various types of hip protectors to prevent hip fracture in a sideways fall [7]. Applicable results that authenticate the ability of the hip protector to prevent fracture have been reported by various research groups.

Common hip protectors uses energy shunting and energy absorption principles or a combination of both [9]. Most hip protectors are made from off the shelf foam, plastic, sponge material or specially manufactured materials such as shear thickening polymers, PEG impregnated foam [10] and most recently, hydrogel and fibres composite [11]. These protectors have come in different shapes like oval, circular, square, dome and particularly, some hard shell emerging shunting hip protectors have been made to overlay the GT and some are designed to
Lack of comfort (too tight or poor fit) ranks topmost in the reason given for why so many people do not comply to the usage of the hip protector [13]. However, avoidable incidents are still being recorded because of the low adherence to the use of the hip protector. It is, therefore, pertinent to examine the possibility of creating a custom fit hip protector using additive manufacturing technique (3D printing) for the unique geometry of every individual. This is indeed a leap from traditional material to 3D printing and ends the bundling of same hip protector for different body geometry. In this research, a hip protector is designed according to the user’s hip 3D mapping similar to the protective pad made by Park et al [14] but hereby tested with a biomechanical test system which incorporates a surrogate soft tissue and steel femur. It is envisaged that with a better fit, the hip protector will remain in position during falls and better attenuate the impact force from the fall.

2. Methods and materials

An actual femur surrogate made from aluminum was used to represent the musculoskeletal impact site to provide realistic biomechanics of the impact situation as reported in previous research. It was created from the 5 axes CNC machine (DMU 40 Monoblock) using a Sawbones® femur geometry (figure 1).

The trochanteric soft tissue overlaying the greater trochanter was simulated using polyethylene foam of 8 mm thickness and 25 Nm stiffness. This reduced the impact force transmitted to the femoral neck by 11% during the evaluation that closely mimic a typical representation of human soft tissue [15].

A 3D printed hard-hip protector was designed to specifically complement the hip surface geometry of the user. With the intent of carrying out dynamic simulation, faster design development and detailing, and auto generated manufacturing data, the 3D modeling was done using the solid modelling method in Solidworks® as against non-uniform rational basis spline (NURBS) method or the polygon method that is based on triangles with mesh structures. This method ensured high relative accuracy and options for more detailed calculations such as knowing the weight of the actual material and ability to incorporate the properties of the material in dynamic modelling. According to the contours of the curved surface of the human hip geometry reported for women with a mean age of 77.5 years, mean body mass of 61.2 kg, mean height of 1.61 m, and mean body mass index of 23.6 kg m$^{-2}$ [16], the three-dimensional (3D) coordinates describing the average surface geometry of the hip, buttock and anterior thigh region coordinates were plotted in SolidWorks 2016 to create the surface geometry that formed the interior surface of the hard-hip protector making contact with the skin surface.
Other features were added to get the geometry to the desired configuration. The 3D modeled structure of the hip protector was printed using Objet 30 Scholar 3D Printer, which uses a printing method that gives a very high accuracy and smooth surface finishing known as Stereolithography (SLA). The estimated mass of the hard-hip protector is 448 g. The estimated amount of time to print the hip protector was 10 h and 50 min. The dimension of the hard hip protector is 164 mm in width, 153 mm in length and 20.4 mm thickness directly above the greater trochanter (figure 2(b)) modelled similar to the Caresse hip protector of 230 × 140 × 22 mm [12].

The protective pad was made by selectively curing a VeroWhite resin layer-by-layer using an ultraviolet (UV) laser beam to give a highly rigid detailed 3D print. The material properties of the VeroWhite is shown in table 1. The Model and support were prepared using Object Studio Software and Object Studio Manager was used for cueing the job for the printer. The printing is done at about 16-micron layer and the rigid shell which closely follow the contour of the hip surface was supported using supports that matched the curved surface. The pad was cleaned, and all supporting materials were removed after the printing. The chemical composition of the material of the 3D printed hip protector was determined by Fourier Transform Infrared Spectroscopy (FT-IR) with a NICOLET iS10 Thermo Scientific instrument, using Attenuated Total Reflectance (ATR) detector. The wavelength range varies between 650 cm⁻¹ and 4000 cm⁻¹ and each spectrum is achieved by a resolution of 4 cm⁻¹ of 32 scan. Also, the internal morphology, chemical composition and crystalline structure of the 3D printed hip protector were characterised using NanoSEM S-3400 scanning electron microscope.

The HipSaver hip protector was used as a comparative benchmark for the performance of the fabricated 3D hard hip protector. The HipSaver soft hip protector has a smaller thickness but a larger surface area. It is typically placed in a pocket of a special undergarment right above the greater trochanter.

![Figure 2. (a) The hard hip protector modelled according to hip surface geometry, (b) Top and (c) Side views of the hip protector.](image)

Table 1. Material property of Verowhite rigid opaque resin used as hip protector [17].

| Property                  | ASTM     | UNITS | Value  |
|---------------------------|----------|-------|--------|
| Tensile strength          | D-638-03 | MPa   | 50–65  |
| Elongation at break       | D-638-05 | %     | 10–25  |
| Modulus of elasticity     | D-638-04 | MPa   | 2000–3000 |
| Flexural strength         | D-790-03 | MPa   | 75–110 |
| Flexural modulus          | D-790-04 | MPa   | 2200–3200 |
| Shore Hardness (D)        | Scale D  | Scale D | 83–86 |

(figure 2(a)).
The choice of the HipSaver was made because of its prominence as an effective hip protector across many research groups using different testing systems [12, 16, 18, 19].

The test rig closely follows the recommendation of the general consensus from the International Hip Protector Research Group for biomechanical testing at the Copenhagen conference [20] on the design of hip protector test rigs but with adoption of lower effective mass as Mills [21]. No spring fixture was incorporated to simulate the pelvis to avoid damping the energy since the articulation of the hip of an elderly person may lack the elastic properties represented by a spring constant. The experimental set up represents the condition of sideways fall capable of causing hip fractures. The test rig is an impact tower designed to accommodate loads up to 30 kg and could allow adjustment for impact height of 2 m (figure 4).

A fabricated mild steel load carrying assembly with slots to increase the load capacity of the impactor was employed, which had a 100 mm diameter and 3 mm thick flat plate to act as the impact plate (floor). Mild steel was used due to its ability to maintain its shape (not deflect) during impact. A frictionless bearing and rail mechanism were used to adjust the height of the load carrier and a stopper was used to hang and release the load carrier allowing it to fall onto the hip assembly. The force received at the neck of the femur was recorded with a 20 kN capacity load cell (Kistler Model CH-8408) which is connected to a Multichannel Charge Amplifier (Type 5070) and IMC device data acquisition system (IMC STUDIO). The data acquisition system was adjusted to supply 5 V to the load cell and the data was recorded at a frequency of 50 KHz. This data acquisition system (IMC STUDIO) was

Figure 3. (a) The HipSaver hip protector pad (b) interior view of the 3D printed hip pad.
used to capture the impact force from the load cell to give instantaneous visualization and output graphical plot of the impact data.

The aluminium femur and polyethylene foam constitute the component of the hip assembly to evaluate the performance of the 3D printed hard hip protector (figure 4) versus a current hip protector which efficacy had been tested by other researchers—the HipSaver hip protector [18, 22, 23].

This test rig enables the attenuation properties of hip protectors to be tested and provides the advantage of a steal surrogate femur that allows sufficient amount of impact force to be transmitted to the femoral neck.

Hence, to test the impact attenuation ability of the 3D printed hip protector, the percentage impact attenuation rate is defined as follows [19].

\[
\% \text{Impact Attenuation} = \left(1 - \frac{F_u}{F_p}\right) \times 100\%
\]

Where \( F_u \) is the impact force recorded by the load cell at the femoral neck when the hip geometry is unprotected and \( F_p \) is the impact recorded at the same point when the hip geometry is protected by the hip protector. The unprotected force \( F_u \) is the femoral neck force when the soft tissue is in place, but the hip protector is not.

The threshold force to cause a hip fracture varies according to different individuals. The value taken as the threshold force was 3.472 kN because it lies within the lower range of threshold forces for a hip fracture to occur. If the hip protectors were able to attenuate the impact force below 3.472 kN [9], the hip protectors will most certainly be able to prevent the occurrence of hip fractures. A soft lining made of Polyurethane foam sponge was also incorporated with the 3D printed hip protector and its effect was also evaluated.

Conclusively, the ratio of the standard deviation of three measurements to the mean of the three measurements was used to determine the variation coefficient for each test condition. The impact forces where examined using One-way Anova for significant difference at a P-value of 0.05 for the two test conditions with or without the hip protector. The impact forces and consequence percentage impact force attenuation were presented using box plots and scatter plots. The average impact force at the femoral neck was compared with average hip fracture threshold of elderly people (3472N) [9]. Regression analysis was conducted by fitting a linear model for the peak impact femoral neck force over the impact velocity.

3. Results

3.1. Microstructure and chemical composition

The microstructure of the 3D printed hip protector was determined from the analysis of the SEM image which reveals a hydrophilic plate-like and flaky morphology of the fractured polymer surface with cleavage appearance, which is a common feature of a brittle material [24] as shown in figure 5.

The chemical structure of the Vero white photopolymer 3D printed hip protector was confirmed by FT-IR through the characteristic vibrational energies of the various groups present in the molecule. The combination of monomers in the Vero white photopolymer shows a material that is strong, stiff and have notable capacity for abrasion.
and Impact resistance as many well defined bands similar to that of native ABS [25] and treated ABS [26] were identified (Figure 6); namely: at 3695–3064 cm⁻¹ range, a broad peak was observed indicating the presence of hydrogen bond (O–H stretch), confirming the existence of hydrate. A huge and sharp bond slightly before 3000 cm⁻¹ responding to C–C bond. At 1715 cm⁻¹, the C=O bond indicating carbonyl double is present [25]. Signal at 1637 cm⁻¹ informs the presence of aromatic compound like the C=C stretching mode of poly(butadiene). Also, Signal about CH₂ groups is given at 1456 cm⁻¹ and the fingerprint region, 1000–600 cm⁻¹, show strong signal informing aromatic ring [27].

Though, the broad peak that appears at 3355 cm⁻¹ is not present in native ABS but similar peaks appearance around this wavenumber has been reported by previous authors [26] and has been presumed to be due to the addition of toughening and anti-static additives by the manufacturer [25].

3.2. Determination of optimised test condition

To simulate a sideways fall on the hip to determine the best test condition for the hip pads, an effective mass of 5.52 kg was used as the impact mass with a velocity of 3.71 m s⁻¹ from a drop height of 0.7 m just as reported in a previous study [15]. This velocity gives a typical representation of velocity in a sideways fall as demonstrated by van Den Kroonenberg et al [28]. Hence, the kinetic energy value of the impact mass is 37 J and able to produce effective force capable of producing fracture in the instance of a free fall to the side way. Through the aforementioned procedure, the optimized arrangement for carrying out the impact attenuation test of the 3D
The protector was at the impact load of 5.52 kg at a height of 0.7 m that produced an impact force within the range of 9.29 kN.

Despite the lower impact energy when using impact mass of 5.52 kg at this height, representative impact force in a sideways fall and characteristic percentage of attenuated force similar to that of human soft tissues were achieved. Figure 7 shows the trend of the attenuated force against the impact energy of the surrogate soft tissue and as the impact energy decreases below beyond 37.91 J, the amount of force attenuated by the polyethylene foam increases to values uncharacteristic of the reported trochanteric soft tissue of the average human subject. Below 37.96 J of initial impact energy, the femoral neck force falls below 4 kN and the performance of the soft tissue is not representative of actual human tissue as it depicts performance above 30%. Also, when the impact energy increases, the compression force experienced by the foam increases, thereby increasing the stiffness of the foam and consequently reducing its ability to absorb the impact force.

### 3.3. Performance of hip protectors

To evaluate the performance of the hip protectors, a mass of 5.52 was dropped from a height of 100–800 mm, at an interval of 100 mm, with corresponding velocity of 1.4 m s\(^{-1}\), 1.98 m s\(^{-1}\), 2.43 m s\(^{-1}\), 2.80 m s\(^{-1}\), 3.13 m s\(^{-1}\), 3.43 m s\(^{-1}\), 3.71 and 3.96 m s\(^{-1}\) respectively to generate impact forces at various energy levels representing a mild to intense fall. So, the impact energies were about 5.42 J, 10.83 J, 16.24 J, 21.66 J, 27.08 J, 32.49 J, 37.91 J and 43.32 J, respectively.

A total number of 70 tests were conducted. All trials were completely processed except that the peak force for the unpadded condition was not repeated 3 times in the 700 mm falling height (n = 2) as done in all cases. While testing was done from height of 100 mm to 800 mm, the measured forces similar in range to the forces observed to fracture isolated femoral were observed from the impact height of 400 mm upward.

As expected, the falling speed becomes higher as the drop height of impact become higher with peak force ranging from 990 N to 9214 N in the unprotected hip assembly. Also, the linear dependency of the peak impact force of the unprotected hip to the falling speed was \(R^2_{\text{unprotected}} = 0.86\) as well as \(R^2_{3\text{D pad}} = 0.99\) and \(R^2_{\text{HipSaver}} = 0.97\) for the 3D pad and Soft hip protector protected hip assembly respectively shown in figure 8.

The impact attenuation rates of both the 3D hard protector and the soft hip protector at a simulated sideways impact condition using the optimized test condition (drop impact height of 800 mm and impact mass of 5.52 kg and energy of 43 J) are presented in figure 9. The hardness and viscoelasticity of both materials play vital roles in accounting for the difference in the impact attenuation provided by both hip protectors. The hip geometry received the force of 9,217 ± 100 N when unprotected and 2,955 ± 56 N when protected with the 3D printed hard hip protector and 2,784 ± 81 N when protected with the HipSaver soft hip protector (figure 9).

The attenuation rate was determined by comparing impact force transmitted to the femoral neck of an unprotected surrogate hip with that of a protected one. The difference between both would mean the attenuation rate of the material, signalling the ability of the material to resist the incident impact. Maintaining the same impact condition, the impact protection ability of the 3D hip protector was evaluated vis-à-vis a soft hip protector which has been examined by different researchers and found effective. The 3D protector was
equally very effective in shunting away force from being transmitted to the femoral neck. It demonstrates an effective impact force attenuation characteristic as it was able to ensure 68% of the impact force is not transmitted to the critical area that can cause the bone to fracture. Conversely, the attenuation rate of the HipSaver in this respect is found to be 70% (figure 10).

Figure 10 shows the effect of varying the magnitude of the force by varying the impact energies, it could be seen that the capacity of the hip protectors remains high and proves to be effective at forces that are capable of causing hip fractures.

Also, the effect of a soft lining made of Polyurethane foam with a total thickness of 1.5 mm when compressed is seen in figure 11. The impact attenuation slightly increases with about 5% thereby reducing the recorded impact force when the 3D printed hip protector is lined with a soft spongy foam which is intended to serve as an interface between the pad and the body tissue directly underlying the hip pad.

4. Discussion

The objective of this study was to examine the ability of 3D printed hip protector to reduce the magnitude of impact force in an in vitro examination simulating sideways impact. This is essential towards employing rapid prototyping techniques in optimising the performance of hip protectors that will be clinically effective and
improve adherence owing to the ability to make custom-fit hip pads. It was hypothesised that the 3D printed hip protector would attenuate total impact force within the most vulnerable area of the hip—the GT. The impact to the femoral neck was reduced by 68% using the 3D protector while total force reduction by the Hip Saver hip protector was 70%. These were found to be statistically similar for both protectors. Indicating the 3D printed hip protector is a viable alternative and probably the expected direction to focus research for femoral fracture prevention.

As expected the impact force to the GT increases as the residual impact energy increases but the attenuation properties of the hip protector showed statistical improvement even as the residual energies were increased though the total impact forces were getting closer to the fracture threshold. This correlate with previous findings that the higher the severity of the fall, the more susceptible is the bone to fracture [10].

While the hip protector was designed with the exact profile of the soft tissue it covers, our result shows that the perfect fit will be an incentive for adherence by the user and there will be minimal case of misalignment of the hip protector as the protector seamlessly slip into position and ensure impact is shunted away from the GT to the surrounding tissue effectively. Impact to the GT is presumably less owing to the behaviour of the rigid material to act like a spring with sufficient stiffness ensuring a very high resistance to the impact force and ultimately prolonging the duration of the impact. Though the difference in impulse of the unprotected hip assembly scenario and the protected one were found to be statistically insignificant, the forces were. The differences in the magnitude of forces were compensated for by the increased time of the impact.
When impacts which were not sufficient to fracture the femur were simulated at very low impact energy, unexpected results were found. The 3D hip protector increases the impact force found without hip protector therefore having a $-7\%$ and $-10\%$ impact attenuation rate at 5.4 J and 10.8 J of residual impact energy, respectively. At this simulated energy level, the peak impact forces recorded were 1009 N and 1418 N for the unprotected hip assembly and 1078 N and 1565 N for the 3D printed hip protected assembly at the aforementioned energy level respectively. This might be due to the protector representing extra load on the tissue and increasing the local stiffness of the trochanteric soft tissue at such energy level. This is however reversed in the test that actually represents the fracture causing situations.

The result of the impact attenuation of the 3D printed hip protectors favourably compares to the result of other hard hip protectors reported in literature. Comparing the performance of this 3D printed hard hip protector with a soft hip protector (HipSaver) drawing from the evaluation done on various hip protectors by Laing et al.\textsuperscript{[12]} and comparing the performance of some hard hip protectors and the HipSaver, at an impact velocity of $3 \text{ m s}^{-1}$, the HipSaver soft hip protector performs better than the Caresse, Hip Guard and Safehip Classic hard hip protectors with the percentage of force attenuation of these hard hip protectors within $6\%$ compared with the soft hip protector. Taking the percentage difference of force attenuated by the HipSaver hip protector and the Caresse, Hip Guard and Safehip Classic hard hip protectors which differ within $6\%$ and comparing it to the difference between the force attenuated by the 3D printed hard hip protector and the HipSaver hip protector which is $4\%$, it can be concluded that the 3D printing of hip protector in this experiment is valid option to build on the gains of researchers to find effective means of preventing hip fracture.

Though the energy of 120 J was recommended by the Copenhagen Conference, the suitable drop height to achieve an impact force of 120 J with a load of say 5.52 kg is 2.2 m. However, at this height, using our impact test system, the resulted impact force will be far above the recommended range of 4,050 to 6,420 needed to simulate the fracture causing event. Our test rig demonstrates that fracture causing force can be simulated by a far less impact energy in an isolated femur like that of Mills\textsuperscript{[21]} and Bulat\textsuperscript{[29]} among others. At this energy level, the average force attenuated by the hip model made of aluminium femur and polyethylene soft tissue is about 27% which is close to the amount of force that is attenuated by the human soft tissue overlaying the GT\textsuperscript{[30]}. While further studies are ongoing to optimize the performance of the 3D printed hip protector to drastically reduce the weight of the 3D printed hip protector, its advantage of customization to fit a user’s hip geometry provides additional incentive for adherence. It is also hypothesized that at a very high impact energy that may render the soft hip protector ineffective, chances are that, the 3D hard-hip protector would be helpful in shunting away the force from the vulnerable position especially when combined with a soft material to have a combined hip protector. The current 3D printed hip protector competes favourably with other hip protectors in terms of volume. It has a total volume of 465,120 mm$^3$, which is about 41% smaller than the HipSaver, 34% smaller than Caresse and 11% smaller than Hipguard.

Concern about a printed hard hip protector inducing pressure in situ has also been addressed by combining the hip protector with a soft padding foam as a liner which becomes an interface between the hip protector and the human body, thereby improving comfort, avoiding body to protector friction or pressure and also contributing to cushioning the impact force with a little but a not insignificant amount of impact attenuation.

5. Conclusions

The study highlighted the statistical significance of printed hip protectors using verowhite photopolymer as compared to the conventional foam made hip protector. The 3D printed hip protector is a high-quality plastic which offers good impact resistance when subjected to impact force experienced in a sideways fall. The hip protector was able to reduce the impact force to below the hip fracture threshold force of 3.472 kN. The advantage of 3D printing is the possibility of creating intricate shapes which may be otherwise impossible in the traditional manufacturing method. It gives an opportunity to explore complex structure that may be difficult to achieve using subtractive manufacturing technique. The current hip protector comparatively withstands shocks due to a sideways fall and compete favourably with a hip protector currently in use and adjudged to be effective by so many research group as well as shown the possibility of custom-fit hip protector for the unique geometry of every individual.

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