Effect of Femur Geometry on Hip Protectors Testing System

S A Yahaya1,2*, A A S Ahmad Iqbal1, Z M Ripin1 and M I Z Ridzwan1
1School of Mechanical Engineering, Universiti Sains Malaysia, Penang Malaysia
2Department of Biomedical Engineering, University of Ilorin, Ilorin, Nigeria.
*Corresponding author: yahaya.say@student.usm.my

Abstract. There have been different types of simplified femoral geometry incorporated into test systems for testing the biomechanical effectiveness of hip protectors. However, the effect of the simplification of femoral geometry in simulated sideways impact experiment has not been reported. In this study, an actual femoral geometry was fabricated and examined along with a simplified femoral geometry in a surrogate hip arrangement to mimic the fracture-causing situation in a sideways fall. A pendulum impact testing machine was used to evaluate the impact force response of both the femoral geometries at various velocity and constant residual impact energy for both geometries. The result showed that the peak impact force varied only 9% between actual and simplified geometries after normalizing the weight for both femurs in testing without a hip protector. However, a higher distinction of the impact force responses of both femurs was observed when testing with a hip protector. This findings at this moment suggest that the femur geometry affects the performance of a testing system. Therefore, the simplified femur geometry may not accurately substitute for the actual femur geometry in comparison of the impact attenuation of a hip protector in a simulated sideways fall.

1. Introduction
The response of a surrogate hip assembly is a critical factor in hip protector testing. The femur geometry represents a key component in the hip assembly. Its weight (effective mass) has been proven to affect the output force in a simulated impact experiment [1]. Though, this may include the anatomical features of such geometry. The surrogate femur, which is responsible for the dynamics of impact force response in vitro representation of real fall, has a considerable role to play in hip protector testing systems [2].

Drop tests are usually carried out to analyze energy dissipation of hip protectors in dynamic load setting with employed femoral geometry having the ability to produce loads that could be concentrated or distributed depending on the simulated model of the impact surface and/or simulated nature of the hip bone [3]. The need to simplify human anatomy in a test rig because of the difficulty in modelling irregular and complex geometry of biological system like the femur must not be used as a factor to compromise essential fracture causing events. Therefore, employed geometry must satisfy the condition to offer the expected response of a hip impact in a sideways fall.

Nevertheless, it has been argued that many parts of the anatomy of the hip structure, as demonstrated by the deformation of the soft organs and the articulation of the femur and pelvis, may not contribute to the magnitude of the impact force of the trochanter [4], the nature of impact site may have significant effect as demonstrated by disparities in reported values of hip protector performances using different test systems [2].
Building on the representation of trochanter with a semi-circled striker by Bulat et al. [5] and
the axially symmetrical ellipsoid on a pendulum contact surface used to represent the greater
trochanter by Parkkari et al. [1]. Haris et al. [3] had used a flat and a ball impactor to demonstrate
the effect of the roundness of the hip bone under impact configuration and showed distinction in the
forces transmitted against a case when the roundness was jettisoned, though Haris et al. [3] had slight
differences in the energies used in the evaluation of both configurations, the bare impact forces were
representative of earlier reported values by Wiener et al. [6]. Additionally, in a bid to represent
repeatable measuring method in a laboratory-controlled environment, Keenan and Evans [7] used
anatomic femur model that could also pass for a similar geometry of a semicircular feature with a
given radius to represent the greater trochanter but also having a distal part as though portion of the
femoral shaft had been modelled. This anatomic model could be seen as a build upon the rod used by
Mills [4] to represent the femur.

While there exist various impact test systems that do not incorporate the anatomical shape of the
femur; using mechanical anvil or a hip shaped anvil for testing as the representation of the pelvis [8],
a number of work incorporate the actual geometry of the femur in their surrogate hip model [9–12].
These differences in femur geometries may affect the hip protector testing system [2]. Towards, the
standardization of the test systems, it may be interesting to evaluate how a simplified femur geometry
response differs from that of the actual geometry.

In this study, we evaluated the impact response of the actual femur model against a simplified
model, in vitro, in simulated impact to the sideways.

2. Methodology Formatting the title, authors and affiliations

2.1. Experimental Setup
Two types of femur geometry were fabricated; simplified and actual bone geometry (Figure 1). The
simplified model of the femur bears the profile of the greater trochanter as traced from a Sawbones 4th
generation computer-aided design (CAD) model in SolidWorks 2016. The Aluminium block (195 x 40
x 50) mm was machined by using a 3-axis computer numerical control (CNC) milling machine
(Robodrill α-T21iFLb). The simplified femur geometry was based on the geometry employed by Keenan
and Evans [7]. Meanwhile, the actual geometry of femur bone was fabricated using a 5-axis CNC milling
machine (DMU 40 Monoblock). Aluminium was used to represent the bones because it has lightweight,
it can effectively transmit forces and it is resistant to high impact force usually employed in an impact
test.

![Figure 1. The actual and simplified femur geometry](image)

The femurs were incorporated into a surrogate pelvis that was attached to an impact pendulum
(Figure 2) which allowed impact from various inclined positions to hit a load cell (20kN capacity Kistler
Model CH-8408) that was connected to a Multichannel Charge Amplifier (Type 5070) and IMC device
data logger. The surrogate pelvis comprised of simulated human soft tissue made from polyethylene
foam [14] and proximal femur as earlier described. A pendulum impact machine 70 cm in length was fabricated for the experiment. It has a protractor that is attached to the pendulum holder to indicate the impact angle and incorporated adjustable slots for mass up to 30 kg. The study also investigated the biomechanical testing on soft hip protector (HipSaver) with a diameter of 19 cm and 1.8 cm thick. It is made of foam material and layered with a thin layer of plastic.

Figure 2. (a) The pendulum hip impact testing system (b) The Multichannel charge amplifier, IMC device and desktop used to record the data received from the Kistler load cell

2.2. The impact tests
The impact testing for this experiment was carried out under the following conditions:

- No hip protector on simplified and actual femur geometries without external load.
- No hip protector on simplified and actual femur geometries with 2.5kg load.
- No hip protector on simplified and actual femur geometries with 5kg load.
- Soft hip protector condition for the above-mentioned cases (1 -3)

Trials were performed at impact angles of 10°, 20°, 30°, 40°, 50°, 60°, 70°, and 80°. Twenty-four trials were carried out for each type of femur bones. T-test was further used to observe whether the impact force in each set of two test conditions differed significantly at a p-value of 0.05.

3. Results and discussion
Each figure should have a brief caption describing it and, if necessary, a key to interpret the various lines and symbols on the figure.

3.1. The effects of simplified and actual femur geometries on impact force
The result of the effect of femur geometry in terms of normalized impact force response is presented in Figure 3. As shown in the figure, there are two significant behaviours noticed; firstly between 1.13 – 2.53 kN simulated impact on actual geometry, the actual femur had a higher impact force response of 0.91 kN (±1.08) and secondly between 2.56 – 10.67 kN, the simplified femur had a higher impact response of 1.29 kN (±0.78). The second range is particularly of interest as most hip fracture studies examine impact above 2.5 kN and less than 10 kN. When the condition was adjusted to cause an increase in the impact force response of the actual geometry, an increase in the impact force response of the simplified geometry was also observed ($r^2= 0.962$), but the relationship is not linear. A nonlinear relationship exists between the two femurs, which suggest an unpredictable situation in using one to represent the other. All the impact forces show different response pattern though the peak forces increase with impact angle and load. As expected, the total impact time for both cases decrease as the height of impact increases. The result of t-test reveals that the impact force response of the two geometries significantly differs (p-value < 0.005).
3.2. Evaluation of the impact attenuation of the hip protector

The difference in the response of the femurs incorporated into the surrogate hip became more apparent by using both arrangements to test the impact attenuation of the soft hip protector (Figure 4). As the impact forces increase from low to high, the impact attenuation of the hip protector when the actual femur was used for the testing maintained a relatively linear curve while the response became parabolic when the simplified femur geometry was employed. Although the impact happening on the same kind of surface, since the hip protector overlaying the hip shaped soft tissue is the surface that comes in contact with the impact plate, the underlying femoral geometry plays a significant role in the force received by the hip in a simulated sideways fall thereby contributing to the debate on the effect of the test system on the performance of hip protectors. It is at this moment, suggested that care must be taken in implementing the simplification of this complex system to avoid simulation that may be unrealistic in actual fall condition.

Figure 3. The difference in impact force between the simplified and the actual geometry of the femur.
Figure 4. The impact attenuation provided by soft hip protectors with different types of femur geometry.

4. Conclusion
The impact force between the simplified and actual femur geometry, at the lower energy conditions, is slightly different, however as the conditions were varied to increase the impact force, the difference in impact forces between both femurs became apparent. After normalizing the weight for both femurs, there exist only 9% difference in the impact force response between the actual and simplified geometry. The difference between the reaction of the geometries in hip protector testing showed a distinctive effect in the evaluation of the same hip protector under the same test condition. In conclusion, the simplified geometry may not be suitable to replace the actual geometry of a femur in an impact test system for the evaluation of the performance of a hip protector. Thus, models must closely mimic the real femur in impact force evaluation of a simulated sideways fall.

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Acknowledgments
The authors would like to acknowledge technical assistance from Mr. Wan Mohd Amri Wan Mamat Ali, Mr. Faris Mohamed Zailan, Mr. Abdul Halim Che Aat, Mr. Baharom Awang, and Mr. Norijaz Abd. Aziz of the School of Mechanical Engineering, USM. The financial support provided under USM RUI grant (1001/PMEKANIK/8014070).