# THE FORCE ATTENUATION EFFECT OF FOAM MATTRESS IN SIMULATED SIDEWAYS FALL OF HIP ON LEVEL SURFACE

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## ABSTRACT

*While there have been studies on the impact attenuation of different floor coverings, the effectiveness of using foam mattress as protective floor covering against geriatric hip fracture is still unknown. The objective of current study is to compare the force attenuation of foam mattress with that of teak wooden block when subjected to an impact force that the human hipbone would experience in accidental fall. A porcine hip fall simulator which consisted of a 12-kg impactor and a surrogate pelvis made by 8 month old porcine hipbone and with effective stiffness of 75 kN/m was set up to simulate sideways fall of human hip. The porcine hip fall simulator was allowed to drop freely on the surrogate pelvis from a height starting from 10 cm to a final height of 50 cm. The results showed the use of one piece and two pieces of foam mattress provided significant force reduction ranging from 21% to 37% and from 38% to 61% respectively when compared to wooden impact, and the optimal force reduction occurred when impact energy approached 18 to 24 joules. We found the foam mattress worked best only in those falls where the impact load was of relatively low energy.*
*Relevance: Prevention of geriatric hip fracture is one of the major health issues in the foreseeable future. This study highlight the fact that the use of a protective floor covering may reduce the impact force on the hip in accidental fall and could be a relatively economical and practical way to reduce the risk of geriatric hip fracture.*

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## 1. INTRODUCTION

Foam mattress, a commercial product that is marketable in many supermarkets or chain stores, is often used as protective floor covering in kindergartens or kids' playgrounds to protect kids from injurious fall.

Although fall related injuries of the elderly population, especially geriatric hip fractures due to accidental fall are common, the effectiveness of foam mattress as protective floor covering for the elderly population has seldom been discussed. Conceivably, the biomechanics involved in the fall of the child and that of the elderly are different. Children are shorter and lighter in weight than an average adult. The impact force a child may encounter in accidental fall could be much smaller than that experienced by the adult. Viewed from the action and reaction perspectives, the reaction to the same impact force could also be different, given the fact that bone strength of the child and that of the elderly is different. Moreover, the bone strength of the elderly could show much variation. The more severe the osteoporosis, the weaker is the bone strength. Therefore, a protective floor covering works well for children may not be equally effective for the elderly.

It has been shown that the use of carpet as floor covering could significantly reduces the forces of impact on the hip in simulated falls, and would therefore be likely to reduce the incidence of hip fractures [1]. While carpet is often used as floor covering in the West, its use in the East and in countries where the climate is hot and humid is unpopular. Instead the floor coverings of most residential homes in these countries are simply concrete or wooden floor. There have been studies designed to investigate the impact attenuation properties of different floor coverings like pile carpet, loop carpet, wood tile, polyvinyl chloride, etc. [1-2]. However, the impact forces these studies used were constant and were much higher than that would experience by the human hipbone in accidental fall. The use of excessive impact force could result in local deformation and bottoming out of the materials under test. In actual fall, a wide range of impact forces can occur depending on the kinematics and dynamics of the fall. A sideways fall with direct impact on the greater trochanter of the proximal femur is the most likely situation that results in hip fracture as the thickness and therefore shock absorbing capacity of the subcutaneous tissues lateral to the greater trochanter is relatively much lesser than the soft tissues posterior to the greater trochanter [3-12]. According to the study of van den Kroonenberg et al, the peak impact force acting on the hip in sideways fall from standing height is 2.90 kN for a 5th percentile female and 4.26 kN for a 95th percentile female [13]. On the other hand, the study of Robinovitch et al predicted that an average individual falling from 0.7 m height would experience a peak hip impact forces ranging from 5.6 kN to 8.6 kN [14]. Therefore, in order to test the protective function of a floor covering in human falls, a wide range of impact forces similar to the impact load an average individual may experience on the hip in lateral fall should be used. A porcine hip fall simulator was set up to simulate sideways of human hip on level surface.

The purpose of this study was to compare the force attenuation function of two different floor coverings, namely foam mattress and teak wooden floor, when subjected to an impact force the human hip bone of an average individual may experience in falling accidents. Specifically the first part of this study was to set up a porcine hip fall simulator which simulated sideways fall of human hip from different heights against a level surface made of a piece of one centimeter thick wooden block. The height of the fall or the impact energy acting on the surrogate hip was adjustable so that the measured impact forces were within the range of 2 kN to 9 kN, which was the impact force range an average individual would experience on the hip in sideways fall. The second part of the study was to compare the force reduction provided by one piece of one centimeter thick foam mattress (Yi Yu Co. Ltd., Taiwan, composition: EVA 25%, PE 25%) with that of one centimeter thick teak wooden block when the porcine hip fall simulator was subjected to the same range of impact load and how did the force reduction affected by the addition of another piece of one centimeter thick foam mattress.

## 2. MATERIALS AND METHODS

The fall simulator consisted of an impactor, a surrogate pelvis made by 8 month-old porcine hipbone and a load cell, which recorded the impact forces (Fig. 1). The impactor was a rectangular metal frame of weight 12 kg. It was allowed to drop freely in a guillotine-like manner after manual elevation and release on two parallel cylindrical rails. The cylindrical rails were greased with oil during the impact experiment so as to allow the impactor a frictionless fall on gravity. The impactor dropped on the surrogate pelvis below by the release of a hook, which was electrically triggered. On release of the impactor, the same electric signal would activate the load cell to record the impact force throughout the course of the impact. The surrogate pelvis was made up of a porcine hipbone with soft tissues around the greater trochanteric region stripped off. The porcine hipbone was secured by potting the femoral head in a methylmethacryl mould, leaving the greater trochanter free and orientated horizontally with the posterolaterally aspect of the greater trochanter facing upward. A 6 mm thick silicon rubber was attached to the surface of the greater trochanter adhesive tape to simulate the soft tissue of human hip. The methylmethacryl mould with the secured porcine hip was bolted by two steel bars onto a steel platform to ensure the stability of the porcine hip on impact. Beneath the steel platform was mounted a load cell (Kistler KIS-9021, Kistler Instrumente AG Winterthur, Winterthur, Switzerland) to measure the impact force on the greater trochanter. Data were acquired at a rate of 10kHz and processed by computer. The entire surrogate pelvis was mounted on a steel springs (stiffness = 75 kN/m) to give the entire unit an effective stiffness comparable to that of a female pelvis as suggested by Kannus and Parkkari et al [15].

A prior test was conducted to determine the drop height of the naked impactor on the surrogate pelvis in order to give an impact force ranging from 2 kN to 9 kN. The test showed that a drop height of 10 to 50 cm, equivalent to an impact energy input of 12 to 59 joules would give an impact force ranging from around 2 kN to 9 kN.

The impactor was allowed to drop at a height starting from 10 cm with 5 cm increment to a maximum height of 50 cm or failure of porcine hipbone. For each impact height, the impact test was done first by padding the impactor with two pieces of foam mattress each of 1 cm thick. The porcine hipbone was inspected immediately after the impact to make sure that it remained intact. Otherwise, the impact force recorded would not be accepted as valid as the stiffness of the surrogate pelvis and therefore the impact force might be altered because of the fracture. If fracture of the porcine bone was noted, the porcine bone would be replaced and the experiment would start afresh. If the porcine hipbone appeared intact, the impact force would be accepted as valid and the impact experiment would proceed in the same way but with

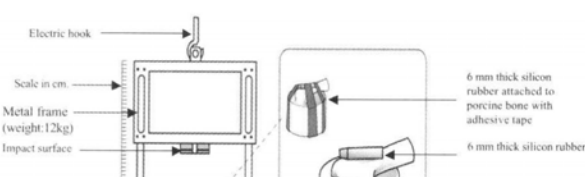


**Fig 1. The porcine hip fall simulator. The porcine hipbone embedded in methylmethacryl mould was placed in the drop-tower type impact testing apparatus. An impactor guided with two rods was dropped from the top of the tower. The surrogate pelvis was simulated by a spring with stiffness of 75kN/m. The reaction force was recorded during impact.**

the impactor wrapped at its undersurface one piece of one centimeter thick foam mattress. The height of the impactor was also lowered by one centimeter so that the impact distance measuring from the undersurface of the foam mattress to the surrogate pelvis remained unchanged. The porcine hipbone would be inspected again after the impact. If it was intact, the impact force recorded would be accepted as valid and the impact experiment would proceed in the same way but with the one centimeter thick foam mattress removed and replaced by one piece of one centimeter thick teak wooden block. As the thickness of the teak wooden block was the same as that of the foam mattress, no adjustment in the height of the impactor was needed. The porcine hipbone was again inspected after the impact. If it appeared intact, the experiment would proceed in the same way with the drop height increased by 5 cm and the impact tests were done in the same sequence first with the impactor padded with two pieces of foam mattress each of one centimeter thick, then with piece of one centimeter thick foam mattress and finally with one piece of one centimeter thick teak wooden block. The foam mattress was renewed to ensure that the shock absorbing capacity of the foam mattress under test would not be altered due to repeated impact. A total of 8 porcine hip specimens were used in this study.

# 3. RESULTS

All the 8 porcine hip specimens appeared grossly intact when the impact height was kept within the range of 10 cm to 50 cm. The impact forces recorded with two pieces of foam, one piece of foam and the teak wooden block were as shown in figure 2. The increase in mean impact forces recorded showed statistical significance as the drop height increased from 10 cm to 50 cm, irrespective of the type of impact surface used.

When the impactor was wrapped with teak wooden block, the mean impact forces recorded ranged from 2.57 kN at the lowest drop height of 10 cm or impact energy of 12 joules and increased steadily as the drop height was increased and reached a maximum of 7.57 kN at a height of 50 cm, which corresponded to an impact energy of 59 joules. When the impact surface was made of one piece of foam mattress, the mean impact forces recorded at the lowest drop height (10cm) and the highest drop height (50cm) were 1.69 kN and 5.88 kN respectively. ANOVA analysis showed that the mean impact force reduction in the presence of one piece of foam mattress at each impact energy level was statistically significant when compared to that of wooden impact ($p<0.001$).

When the impact surface was made up of two pieces of foam mattress, the mean impact forces recorded at the lowest drop height (10 cm) and the highest drop height (50cm) were 1.05 kN and 4.56 kN respectively. The mean impact forces recorded in the presence of two pieces of foam mattress at each impact energy level showed statistically significant reduction when compared to that of wooden impact (p<0.001). When compared with wooden impact, the percentage reduction of impact force by using one piece of foam mattress ranged from 21 % to 37 %, while two pieces of foam gave a force reduction ranging from 38% to 61% (Fig. 3). ANOVA analysis showed that the percentage of force reduction in both situations was statistically significant (p<0.001). The maximum percentage of force reduction occurred when the impact energy approached 18 to 24 joules, while the least percentage of force reduction occurred when the impact energy increased to 59 joules, which was the highest impact energy level in this study. As far as percentage of force reduction was concerned, the addition of another piece of foam mattress provided an increase in force reduction by about 20 %.

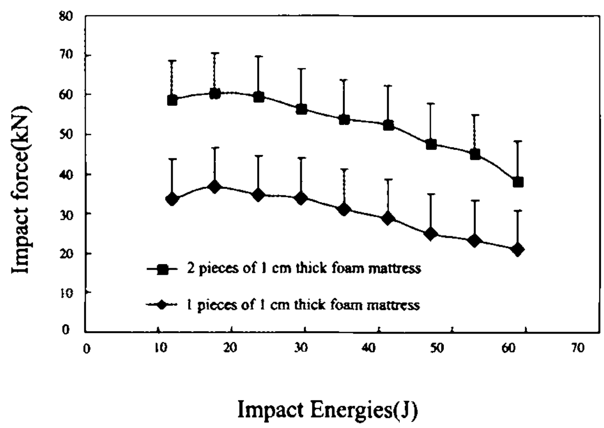


**Fig 3. Percentage of mean impact force reduction against teak wooden surface.**

## 4. DISCUSSION

The annual incidence of geriatric hip fracture due to fall reported annually in the United States is over 250,000 per year [16]. The medical expenditures associated with such mishaps are staggeringly high and would be on the rise given the fact that the elderly population is growing. Generally speaking, prevention of geriatric hip fracture can be approached by three different aspects. It can be avoided firstly by preventing falls and secondly by strengthening bone quality. The first strategy depends very much on the coordinative responses and the balancing power of the elderly, which are gradually declining with increasing age. It is not entirely feasible to rely solely on this strategy to reduce the risk of geriatric hip fractures. For the second strategy, as an increase in femoral neck bone density of more than 20% is required to raise the strength of the femur to the level of impact load in an average fall [17] and the use of drugs can only raise bone density for a few percent at best, it is a relatively uneconomical and impractical method for fracture prevention once osteoporosis has occurred. Prevention of hip fracture can also be achieved through the third strategy, that is reduction of impact force on the hip in fall accidents. The use of hip protector has been proved to be effective in reducing hip fracture [18]. However its effectiveness is plagued by the problem of patient compliance. As a certain proportion of fall accidents happen indoors, the search for a protective floor covering which can effectively reduce the impact force to a level below fracture threshold is an issue of major health concern.

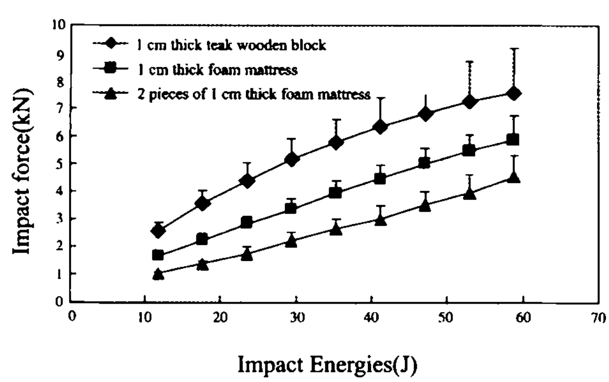


**Fig 2. Mean impact forces recorded (N) with various impact surfaces under different impact energy input (J).**

The fracture threshold of the cadaveric femur of the elderly was estimated to be around 3.44 $\pm$1.33 kN [19]. In those falls where the unattenuated impact forces are just large enough to fracture the hip, the impact attenuation provided by a floor covering will be most likely to prevent fractures. According to our experimental model, the mean unattenuated impact forces (impact with wooden block) associated with an impact energy of 18 and 24 joules were 3.58 $\pm$0.49 kN and 4.40 $\pm$0.65 kN respectively, which were just above the fracture threshold of the elderly. The presence of one piece of foam mattress would decrease the mean impact forces associated with impact energy of 18 and 24 joules to 2.25 $\pm$0.24 kN and 2.85 $\pm$0.28 kN respectively, which were below the mean fracture threshold of 3.44 kN. The presence of an additional piece of foam mattress at these corresponding impact energy levels further reduced the mean impact forces to 1.40 ±0.09 kN and 1.77 ±0.26 kN respectively, which were also well below the fracture threshold.

The impact energy input in this study ranged from 12 to 59 joules, which corresponded to an impact velocity range of 1.4 m/s to 3.13 m/s respectively. Our results showed that foam mattress, irrespective of whether we used one piece or two pieces of foam placed together, provided an optimal percentage of force reduction when subjected to an impact energy of about 18 and 24 joules. The corresponding impact velocities at these energy levels were 1.71 m/s and 1.98 m/s respectively, which were, however, less than the average impact velocity of the hip measured during kinematic studies of falling [20]. The percentage of force reduction demonstrated by foam mattress, one piece or two pieces alike, declined gradually as the impact energy increased beyond 24 joules or when the impact velocity was over 1.98 m/s. However, our experimental model showed that foam mattress could still provide a significant force attenuation effect over teak wooden block when subjected to a higher range of impact energy up to 59 joules, albeit at this energy level, the resultant attenuated mean impact forces exceeded the experimental mean hip fracture threshold of the elderly. Therefore, according to our experimental model, the impact attenuation property of foam mattress showed that it could work best as protective floor covering for the elderly in those falls where the impact energy acting on the hip was below 24 joules. Of course, the impact energy in actual falls could be much higher. The impact energy acting on the hip of an average adult in a direct fall from standing height estimated by free-fall physics could amount to several hundred joules with an impact velocity of about 4.2 m/s (given the subjects' average height was 165 cm). However, because of initiation of protective responses like energy absorption in the eccentrically contracting lower extremity muscles and initial ground contacts to the outstretched hands or knees, the impact energy of the body was attenuated by a mean of 62% [21]. Moreover the trochanteric soft tissues were found to absorb impact energy at a rate of approximately 1.7 joules per 1 mm change in thickness [22]. Therefore, the impact energy acting on the hip in actual falls could be much smaller than the value predicted by free-fall physics. The use of a suitable shock absorbing material as floor covering could significantly attenuates the impact on the hip and thus reduces the risk of hip fracture.

The design of the fall simulator in this study simulated the sideways fall of the human hip on level ground. However, instead of having the hip falling against the ground, it was the impactor that was padded with teak wooden block or foam mattress in our study falling against the hip. By adjusting the height of the impactor, the impact force acting on the surrogate pelvis could be adjusted to a level close to the impact force a human body would experience in real life situation. The use of a realistic range of impact force is important in the evaluation of shock attenuation effect of protective floor coverings, given the fact that potential non-linearalitis exit in all material behavior. The compliance of the subcutaneous tissues of the porcine hip specimen was a variable. By stripping off all the subcutaneous tissues and replacing with 6 mm thick silicon rubber, the impact force transmitted to the porcine hip would not be affected by this variable. As the purpose of this study was to compare the shock absorptive function of foam mattress with that of wooden block, the use of silicon rubber of standardized thickness in all porcine hip specimens could eliminate the variable.

The weakness of our experimental model was the assumption that stiffness of the surrogate pelvis, especially the porcine hipbone would remain constant as long as it appeared grossly intact on inspection. However, after repeated impact, the stiffness would be altered by the presence of micro-fracture of the porcine hip or any loosening of the bonding between the porcine hip bone and the methylmethacryl mould, which could not be revealed by gross inspection. In order to keep the possible damage to the surrogate pelvis due to repeated impact at a minimum, our impact protocol dictated that all impact tests started from the lowest impact energy first with two pieces of foam mattress, followed by one piece of foam and then by wooden or unattenuated impact. Our results showed that the impact forces in all specimen increased steadily as the impact energy increased except on three occasions in which the impact forces showed a paradoxical decrease despite an increase in impact energy. These paradoxical decreases in impact force were all noted when the impact energy reached 59 joules, the maximum impact load in our experimental model. Specifically, these decreases were noted in specimen 2 during impact with one piece of foam, in specimen 3 during wooden impact and in specimen 5 during impact with two pieces of foam. These paradoxical decreases might be attributed to alteration in stiffness of the surrogate pelvis caused by micro-fracture of the porcine hip or loosening of bonding between the porcine hip and the methylmethacryl mould.

As far as percentage of force reduction was concerned, this study showed that the use of an additional piece of foam mattress provided an improvement in force reduction by about 20 %. This increase in percentage of force reduction showed no significant variation with the magnitude of impact energy used. This could possibly be due to the fact that within the range of impact energy we used, the first piece of foam mattress had already undergone plastic deformation before the impact force was transmitted to the second piece of foam. This was in line with our observation that in our impact experiment, the first piece of foam always appeared permanently indented after the impact while the second piece of foam appeared grossly intact or relatively unscathed. That the optimal percentage of force reduction of using either two pieces or one piece of foam both fell within the low impact energy range of about 18 to 24 joules indicated that the overall viscoelastic response of either two pieces or one piece of foam subjected to impact by a relatively stiffer body was the same. When the foam is subjected to impact by a stiffer body, the first piece of foam will absorb part of the impact energy, resulting in deformation. The residual amount of energy will be transmitted to the second piece. The material behavior of the first piece of foam on impact would not be affected by the presence of another piece of foam beneath. However, the result could have been different if we had used a 2 cm thick foam mattress instead of wrapping together two pieces of foam, each of one cm thick or if we had attached the second piece of foam directly on the surface of the surrogate pelvis. In the latter situation, the impact occurred would be foam surface against foam surface.

This study showed that foam mattress, which has already been widely used in our community as protective floor covering for children, provided an optimal impact attenuation effect when subjected to an impact load of relatively low energy. Of course whether foam mattress could be used as protective floor covering to reduce the risk of geriatric hip fracture due to fall depends also on other properties of the foam mattress like stiffness, frictional forces on treading. These properties could affect energy consumption on walking and the frequency of slipping and tripping accidents, which could result in injurious falls. Moreover the choice of floor covering also depends on the indwellers' acceptance, maintenance, fire prevention, aesthetics, budget and etc. Further research is needed to attest its efficacy in reducing the incidence of geriatric hip fracture.

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