A Novel Hip Protector Material With High Impact Force Attenuation: Leak-Allowed Air Cushion*

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Abstract
Hip protectors can reduce the incidence of hip fractures. However, low user acceptance and compliance in use remain a major obstacle in the effective use of hip protectors, due to its discomfort and extra effort needed to wear it, etc. A leak-allowed air cushion is an air-bubble cushion designed to have one or some orifices on the side. In this cushion, an impact load is shunted to open air with airflow through orifice(s), and the energy is dissipated by the friction of the airflow. With the lightness, the flexibility, and the inexpensiveness, this cushion has a potential to be accepted by the target users at high levels of compliance. The purpose of this study was to evaluate a potential of the cushion as a hip-protector material by comparing with other three commercially-variable impact attenuation materials: polyethylene elastmer; silicon gel; and porous polyurethane. To this end, we performed impact tests for pads made of the materials using a falling-mass impact loader. The pad made of leak-allowed air cushions reduced the peak impact force from 7700N (recorded with no pad) to 1213 N, which was 38 – 64 % lower than the attenuated peak forces recorded in the other material pads. We concluded that the leak-allowed air cushion could be a novel hip protector material with high capacity of impact-force attenuation.

Key words: Hip Protector, Air Cushion, Impact Attenuation, Hip Fracture, Osteoporosis

1. Introduction
Falls among the elderly living in either general communities (1-5) or nursing homes (6, 7) are unfortunately very common. Stalenhoef et al (5) reported that 25 - 31% of residents aged 55 years and over living in a community fall once or more in a year, and of these 9% have some serious injuries including 4% fractures. Even in nursing homes, the incidence of falls is about 1.5 falls per person per year, and the risk of hip fracture is quite high (annual rate of 5-6%) (7). One of the most serious consequences of falling is bone fracture, in particular femoral neck fracture (hip fracture). For the elderly, hip fracture reduces life expectancy. Hip fracture leads to a reduction of 15% in survival rate at 5 years after the fracture, and the majority of the deaths occur within the first 6 months following the fracture (8). For the
survivors, functional disability is significant. There was a sustained decline in function at 6 weeks after the fracture with little improvement by 6 months (9). Percentages of recovery differ by area of function, ranging from as low as 20.3% for putting on pants to as high as 89.9% for climbing five stairs (10). A hip fracture brings a financial problem too. Dolan and Torgerson (11) estimated that the cost of a hip fracture is about £12000 during the first year after the fracture in UK, although other fractures were less expensive, at £467, £479 and £1338 for wrist, vertebral and other fractures, respectively. Hip fracture in the elderly is a worldwide problem that indiscriminately affects both sexes, all ethnic groups, and all geographic areas (12), and is increasing exponentially (13, 14).

The strongest determinant of hip fractures is direct impact on and around the hip (15-18). Parkkari et al (17) reported that the majority of the hip patients (76%) had fallen directly to the side. The potential energy associated with the falls was an order of magnitude greater (about 450 J) than the energy required to fracture elderly proximal femurs (5 to 51 J), suggesting the falling energy is more than enough to raise a peak force at a hip beyond the fracture load of the bone (778 to 4040 N) (19). Many types of hip protectors (20-27) have been developed to prevent hip fractures in the elderly at high risk of falling, which are devices that reduce the force transmitted to the proximal part of the femur through the greater trochanter in a fall. It has been proven in clinical trials that wearing a hip protector dramatically reduces the likelihood of hip fracture from falling (7, 22, 28).

Since the 1980s, many types of hip protectors have been designed and marketed around the world (20-27). The hip protection systems can attenuate the impact force delivered to the proximal femur in a fall by absorbing the impact energy with an energy absorbing material such as silicon rubber (20) or polyethylene plastic (21) (Energy-absorbing type), by shunting the energy away from the greater trochanter into the surrounding soft tissue of the thigh using a rigid plastic shield (Energy-shunting type) (22, 23, 29), or by both of these two mechanisms (Combination type) (24-27). However, low user acceptance and compliance in use remain major obstacles in the effective use of the hip protector systems (22, 30-34). Villar et al (30) reported that approximately 50% of elderly rest home residents would wear hip protectors in order to prevent hip fractures, but long-term compliance drops to about 30%. The reasons are discomfort (too tight/ poor fit); the extra effort (and time) needed to wear the device; urinary incontinence; and physical difficulties/ illnesses (34). Meyer and Mühlhauser (35) pointed out that the low acceptance and compliance in use of hip protectors could be one of the reasons for the ineffectiveness of hip protector concluded by the systematic reviews with meta-analysis of randomized controlled trials (36-39). In this study, to develop a hip protector with high acceptance and compliance as well as high impact-force attenuation, we focused on a ‘leak-allowed air cushion’ as a novel hip protector material. A leak-allowed air cushion is an air-bubble cushion with one or some orifices on the side. An air-bubble cushion with no orifices behaves somewhat like a spring because impact energy can be mostly recovered on the rebound except a little turned into heat. With the orifices there is a mechanism to shunt impact load to open air with airflow through the orifice(s) and to dissipate the energy by the friction of the air moving, thus a much reduced rebound effect (Fig.1a, b). Therefore, a leak-allowed air cushion could be categorized to the combination type. Air-bubble cushions have been used commonly as packing material for fragile items. In the hip-protecting application it is expected that they can be lighter, more flexible and cheaper than existing products, and that their unique qualities will be conducive to higher levels of protector wearing compliance.

In this study we investigate the impact-attenuation ability of a leak-allowed air cushion and discuss its efficacy as a hip protector material. To this end, impact tests using a falling-mass impact loader were performed: (1) to determine the orifice to produce the maximum impact-force attenuation; and (2) to compare the impact-attenuation ability of the leak-allowed air cushion with existing materials.
2. Materials and Methods

2.1 Leak-allowed air cushion

The leak-allowed air cushions used in this study were made by piercing the wall of a commercial air-bubble cushion (Puti Puti®, Kawakami Sangyo, Nagoya, Japan, φ32 mm×h13 mm) with a hot needle. The air bubble cushions were made of polyethylene film with a thickness of 40 μm. Figure 1c shows the side view of the leak-allowed air cushion with a single orifice on the sidewall. The weight of the single leak-allowed air cushion was 0.1 gf, giving a bulk density of 0.001 g/cm³.

![Figure 1](image)

Figure 1 Mechanism of impact-force attenuation in a leak-allowed air cushion. The leak-allowed cushion is an air-bubble cushion with one or some orifices to release internal air out when it is impact-loaded. The orifice(s) allow the impact load be shunted to open air with airflow through the orifice(s) and the energy be dissipated by the friction of the air moving. (a) Closed-air cushion. (b) Leak-allowed air cushion. (c) Side view of a single leak-allowed air cushion.

2.2 Effect of orifice size and number

It was reasoned that the size and number of orifices would probably affect the impact-force attenuation characteristic of the cushion. To find the adequate design of orifice for effective impact attenuation, a series of impact tests were performed on cushions with various numbers and diameters of orifices (Table 1). In the case of a single-orifice cushion, the diameter of the orifice was varied from φ0.5 to φ3.0 mm. In the case of a multiple-orifice cushion, the orifice size was fixed at φ0.5 mm and the number of orifices was varied from one to thirty six. In all cases the orifices were made in the same location on the side of the cushion.
2.3 Impact loading test

An impact load was applied to a sample by dropping a striker of 1630 g mass onto the sample placed on a silicon sheet with a thickness of 5 mm, simulating skin tissue, from a height of 3 cm, giving a contact velocity of 0.7 m/s (Fig.2). The striker was composed of a steel weight, a reflection plate for detection of sample deformation, and two linear guides. The flat bottom surface of the striker has square area of 10 cm x 10 cm. In this study, the peak force measured without a sample was defined as “input impact force”, which was 1580 N in the above loading condition. The input impact force attenuated by a sample was detected by a piezoelectric load cell (208C05, PCB Piezoelectric, New York, USA) underneath the silicon sheet at a sampling rate of 50 kHz. Simultaneously, the displacement of the sample was monitored using a laser displacement sensor (ZX-LD40, Omron, Kyoto, Japan) installed beside the sample stage by measuring the distance between the reflection plate and the sensor. The detected signals were transferred to a windows-based computer and analyzed to obtain waveforms and force-displacement curves. From the analyzed data, the optimal orifice was determined. Ten samples of the same orifice design were tested, but each sample was tested only once.

2.4 Comparison with the other impact-attenuation materials

To evaluate the efficacy of a pad made of leak-allowed air cushions with the optimal orifice determined, impact tests were performed using the same apparatus under the actual level of impact load to cause hip fracture. By dropping the striker from 42 cm height with no sample, input impact peak force of 7700 N was obtained at 2.3 m/s. This peak force was above the peak-hip impact force of 5600 N predicted by Robinovitch et al (40) corresponding to a situation of falling from a 0.7-m height in the muscle-relaxed state. This peak force was also clearly above the mean fracture loads of an elderly femur reported in previous studies(19, 41-43), ranging from 2100 to 4600 N. To bear the high impact loading, seven leak-allowed air cushions were arranged to form a pad as shown in Fig.3a. The hexagonal arrangement of leak-allowed air cushions was designed to have an area larger enough to cover the greater trochanter of a human proximal femur. Additionally, a recoverable leak-allowed air pad was designed in the same arrangement and tested. In order to recover the original shape after impact loading, this pad has open-cell porous polyurethane forms with a low-bulk density (EZQ-S®, bulk density: 0.013 g/cm³, INOAC, Nagoya, Japan) inserted into each leak-allowed air cushion (Fig.3b), of which elasticity helps the pad regain the original shape after impact loading, taking about one second in the case of the φ1.5-mm single orifice. In this experiment, pads made of other impact-attenuation materials: polyethylene elastomer

Table 1  Orifice conditions. Condition 1: a single orifice with a diameter varied from φ0.5 mm to φ3.0 mm. Condition 2: a multiple orifice with a varied number from 1 to 36 of holes. Each hole had the same diameter of φ0.5 mm. The total area of a multiple orifice corresponds to the area of a single orifice in the same column.

<table>
<thead>
<tr>
<th>Condition 1: single orifice diameter</th>
<th>0.5</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition 2: multiple orifice Number of φ 0.5-mm holes</td>
<td>1</td>
<td>4</td>
<td>9</td>
<td>16</td>
<td>25</td>
<td>36</td>
</tr>
<tr>
<td>Total area</td>
<td>0.20</td>
<td>0.79</td>
<td>1.77</td>
<td>3.14</td>
<td>4.91</td>
<td>7.07 mm²</td>
</tr>
</tbody>
</table>
used for the commercial-hip protector (bulk density: 0.61 g/cm³, Gunze, Kyoto, Japan); silicon gel (αGEL®, bulk density: 0.36 g/cm³, GELTECH, Tokyo, Japan); porous polyurethane (EGR-2®, bulk density: 0.09 g/cm³, INOAC, Nagoya, Japan) were compared with the leak-allowed air pads. These pads were also prepared to have the same dimension and pad-arrangement as the leak-allowed air pads. Ten samples of the same pad design were tested in this high impact loading condition, but each sample was not reused.

![Figure 2](image)

Figure 2  Schematic diagram of impact loading system. A steel of 1630-g mass was dropped from 3 cm or 42 cm height onto a sample. Force applied to the sample was measured using a piezoelectric load cell underneath the sample and the displacement of the sample was monitored by a laser displacement sensor simultaneously.

![Figure 3](image)

Figure 3  (a) Top view of a leak-allowed air pad for higher impact force, which was made of seven leak-allowed air cushions. (b) A recoverable pad consisting of seven leak-allowed cushions and low-density porous polyurethane forms inserted into each cushion. Arrows show the site of an orifice of φ1.5 mm on the side wall of the cushions.
3. Results

3.1 Effect of orifice size and number

The smallest peak force was recorded with the $\varphi 1.5$-mm single orifice, only 58% of that observed for a closed-air cushion (Fig.4a). In a closed-air cushion with no orifice, the repeated rebound of the striker from the cushion was observed after the impact loading (Fig.5a). The hysteresis of force-displacement curve during this rebounding was relatively small, meaning that the given impact energy was not being absorbed effectively by the closed-air cushion. On the other hand, a leak-allowed air cushion with a single orifice attenuated the input impact force well with much less rebound after the impact loading (Fig.5b-d). The hysteresis of force-displacement curve increased as the orifice size increased, suggesting that the applied impact energy was consumed by being converted to airflow ejected from the orifice during the impact loading. With the $\varphi 1.5$-mm single orifice, the applied impact load was damped with no rebound (Fig.5c). Larger orifices with a diameter of $\varphi 2.0$, $\varphi 2.5$, or $\varphi 3.0$ mm meant that the striker could bottom out during the impact (Fig.5d shows the case of the $\varphi 2.0$-mm orifice), which made the peak force rise, suggesting the air was being blown out of the cushion too quickly. Compared with the no-orifice cushion, the peak force was 24% larger for the $\varphi 2.5$-mm orifice and 54% larger for the $\varphi 3.0$-mm orifice (Fig.4a).

Among the tested multiple orifices, the twenty-five multiple orifice version resulted in the minimum peak force, which was 40% smaller compared with the peak force of a no-orifice air cushion (Fig.4b). With the multiple orifices, leak-allowed air cushions showed the similar responses (Fig.6). Increased number of orifices decreased the peak force as well as the number of rebounds. The twenty-five multiple orifice demonstrated a small rebound of the striker without bottoming-out (Fig.6c). In the case of a thirty six-multiple orifice, having therefore a larger total orifice area, a higher peak force was observed because of bottoming-out (Fig.6d). However, the peak force for the thirty six-orifice cushion was still 27% smaller than that of a no-orifice air cushion (Fig.4b).

The best of all the cushions tested, from the point of view of the attenuation of the peak force, was the single orifice type with orifice diameter of 1.5 mm, which was used as pad material.

![Figure 4](image_url) Comparison of attenuated peak forces measured under impact of the 1580-N input among the closed-air cushion and the leak-allowed air cushions. (a) Closed-air cushion vs. leak-allowed air cushions with a single orifice with a varied orifice diameter. (b) Closed-air cushion vs. leak-allowed air cushions with varied number of orifices. The value shows the average ± 1SD of ten samples. Each sample was tested only once.
Figure 5 Typical force and displacement waveforms in leak-allowed air cushions with a single orifice under impact of the 1580-N input. A force-displacement curve is superimposed on each waveform graph. Orifice diameter: (a) closed-air cushion; (b) 0.5 mm; (c) 1.5 mm; and (d) 2.0 mm

Figure 6 Typical force and displacement waveforms in leak-allowed air cushions with a multiple orifice under impact of the 1580-N input. A force-displacement curve is superimposed on each waveform graph. Number of orifice: (a) four; (b) nine; (c) twenty five; or (d) thirty six.
3.2 Comparison with the other impact-attenuation materials

The pad of leak-allowed air cushions showed the lowest attenuated peak force of 1213 N (± 238 SD) among the tested materials in a response to a high input impact force of 7700 N (Fig.7). Even in the recoverable type, the peak force was lower (1484 N ± 191 SD) than the other three impact-attenuation materials. Compared with the peak force observed in the leak-allowed air pad, peak forces were 1.6-, 1.8-, and 2.6-fold larger in the polyethylene elastomer pad (1969 N ± 23 SD), in the silicon gel pad (2162 N ± 30 SD), and in the porous polyurethane pad (3358 N ± 109 SD), respectively. Only the leak-allowed air pad and the recoverable leak-allowed air pad attenuated the input impact load of 7700 N below the range of hip fracture, which is the mean fracture load of the proximal femur of elderly women ± 1 SD (3100 ± 1200 N) (42).

The leak-allowed air pad showed the lowest stiffness (91 N/mm) under the high impact loading (Fig.8a), which was 22%, 29%, and 8% of those of the polyethylene elastomer pad (412 N/mm), the silicon gel pad (318 N/mm), and the porous polyurethane pad (1079 N/mm), respectively. The recoverable leak-allowed pad had a biphasic response, in which a low stiffness (98 N/mm) comparable with that of the leak-allowed pad within about 9-mm deformation and a higher stiffness (303 N/mm) beyond that were observed (Fig.8b). The three impact-attenuation material pads showed a rapid increasing of force just after the first contact followed by a large rebound of the striker (Fig.8c, d, and e). The porous polyurethane also had a biphasic response (Fig.8e).

Figure 7  Comparison of attenuated-peak forces seen during impact loading of the 7700-N input among the closed-air pad, the leak-allowed air pad, the recoverable leak-allowed air pad, the polyethylene elastomer pad, the silicon gel pad, and the porous polyurethane pad. The value shows the average ± 1SD of ten samples. Each sample was tested only once. The shaded area shows a mean fracture load of the proximal femur of elderly women ± 1 SD (42).
4. Discussion

The selection of orifice size is critical to the performance of a leak-allowed air cushion. The range of proper orifice size seems to be narrow and will also depend on the overall size and the material of the air cushion. Our impact loading tests demonstrated that too small or too large orifice area allowed rebounds or “bottoming out” of the striker on the sample stage, which caused unacceptable large peak forces (Figs. 5 and 6). A leak-allowed air cushion with a single orifice of a diameter of 1.5 mm showed the greatest impact-attenuation capacity compared with the other orifice designs. With this optimal orifice, the pad of leak-allowed air cushions damped the input impact peak force of 7700 N to 1213 N (± 238 N SD), which was 40 – 60 % lower than those recorded in the other impact-attenuation materials (Fig.7). The recoverable-type pad showed the comparable attenuation capacity to that of the leak-allowed air pad. Even in the recoverable-type pad, basically, a leak-allowed air cushion takes charge of impact-attenuation effect. Therefore, the optimal orifice design should be common to both the types of air pad and the same impact-attenuation effect is expected for them. However, inserting the low bulk-density sponge into an leak-allowed air cushion increased the peak force by 24% compared with the non-recoverable type (Fig.7), because the sponge compressed by impact could disturb the air cushion flatten completely, spoiling the optimized impact-attenuation effect of leak-allowed air cushion. To give higher capacity to a recoverable-type pad, lower bulk-density of sponge is desirable, but a longer time would be taken for the recovery.

Our pads of leak-allowed air cushions showed 81% - 84% reduction in peak force in the 7700-N input impact loading. These impact-attenuation capacities were comparable with the best capacity shown among the existing types. Kannus et al. (44) reported that
combination types (KPH1, KPH2, and SAFEHIP) show a higher capacity of impact attenuation (87%-, 88%-, and 63%-reduction in peak force, respectively) than the energy-absorbing type (Safetypants) (55%-reduction in peak force) during 6130-N impact loading simulating a sideways-fall in the elderly. Only KPH1 and KPH2 showed attenuated peak forces below the fracture range of the proximal femur of elderly women. While, energy-shunting pads may have a less capacity of impact attenuation than the combination types, which was reported to attenuate an applied impact force of 5800 N by 68% (23). Although it is difficult to make direct comparisons between our pads and those reported in the previous literature, because each experimental design was not exactly the same as the others, the performance of the leak-allowed air pads seems to be better than those of the energy-absorbing and energy-shunting types, but comparable with that of the combination types.

The lightness and flexibility give potentially high user acceptance and wearing compliance to the leak-allowed air pads. Although all the three types of hip protectors could reduce effectively the risk of hip fracture, however, the acceptance and compliance of these hip protectors are current major problems. For the elderly at high risk of falling, hip protectors should be used at all times. This requires strong commitment from the user or the person providing care for them. In community setting, since adherence will be dependent on the users themselves, it may be more problematic (32). In the elderly who were issued with hip protectors, compliance with use of the hip protectors was reported to be only 20-30% (22, 30, 33). The reasons are large thickness and bulky shape to absorb sufficiently impact energy in energy-absorbing pads, or uncomfortable hard shell to shunt energy away from the trochanter region in energy-shunting pads (27). Combination-type protectors would be essentially more comfortable due to less hardness and thickness to attenuate impact force than the other two types, but still bulky. Additionally, the design of previous hip protectors requires the wearer to fix the pad or insert it into specially-designed underwear. Any innovation to reduce the discomfort of use will tend to increase wearing compliance. Our pads made of leak-allowed air cushions, which has a hexagonal shape with a width of 95 mm, a thickness of 13 mm and an extremely-light weight of 0.75 gf (3.0 gf for the recoverable type), is smaller, thinner, and much lighter than the previous combination types. With the lightness and flexibility, the leak-allowed air pads could be fitted in a detachable way to any kind of underwear or pants using a hook-and-loop tape such as Velcro™. We believe that these features of the leak-allowed air cushion have the potential to greatly improve user acceptance and wearing compliance. For practical usage, in particular, the recoverable type is more favorable than the non-recoverable type, because the latter would suffer undesirable flattening of the pad by daily physical activities.

Main criteria of good hip protector material have been defined by Parkkari et al as follows: 1) good energy absorbing capacity; 2) good durability; 3) low weight; 4) good recovery after compression; 5) easy availability; and 6) reasonable price (45). Our leak-allowed air pads seem to be superior to previous materials according to almost all the criteria. One major limitation of our leak-allowed air pads is durability. In this study, after an impact loading at 7700 N peak, a small crack on the periphery of an orifice was observed in several cases, because the air cushion material is quite thin polyethylene film. For clinical use a tougher cushion material, but light and flexible, is desirable. According to criterion 6) (cost), our leak-allowed air cushion has a distinct advantage over the previous materials. Actually, it is unclear whether hip protectors is being provided in reasonable prices, because the cost effectiveness of a hip protector is unclear (51). Nevertheless, since the leak-allowed air cushion is made from a common and inexpensive packing material, we think the manufacturing cost could be very low and in principle this benefit can be passed on to patients.

In this study, a striker of 1630 g mass was used to evaluate the impact attenuation
capacities of the air cushions or the pads by falling it from 3- or 42-cm height. However, as an actual case, the human hip with larger mass falls from higher height, consequently, higher impact energy should be given to a hip protector. To decrease peak force to the safety level after that impact, the design of leak-allowed air pad should be improved, e.g. simply, by making it larger and thicker, and optimized for orifice. Nevertheless, the leak-allowed air pad could provide necessary impact attenuation capacity with lighter weight and smaller size compared with pads made of other impact attenuation materials, resulting in higher user acceptance and compliance.

In this study, the leak-allowed air cushion was designed and tested as a novel hip-protector material, which proposes a new mechanism of impact-force attenuation. The results obtained from impact tests showed that the optimized leak-allowed air pads had higher impact-attenuation abilities than the other attenuation materials selected in this study. With the high capacity of impact attenuation, the ultra-lightness, the flexibility, and the potential for low cost, we concluded that our designed leak-allowed air pads could be technically effective and also well accepted by patients.

Acknowledgements

The authors thank Masato Sugitani and Yousuke Sawashima for their assistances for the sample preparation and the impact loading tests, and Dr. Nathan Scott for valuable discussions.

References


