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Biomechanical comparison of hard and soft hip protectors, and the influence of soft tissue

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Abstract

Introduction: Hip protectors appear to be promising in preventing hip fractures. Currently, many different hip protectors exist, and it is not clear which hip protector has the best biomechanical properties. Therefore, the objective of this study was to compare the force attenuation capacity of 10 different hip protectors. Both hard hip protectors, which primarily shunt away energy, and soft hip protectors, which primarily absorb energy, were included.
Methods: Using a drop weight impact testing system and a surrogate femur, a weight of 25 kg was dropped from a height of 8 cm causing a force of almost 7806 N on the bare femur, which simulates a severe fall. After this calibration test, soft tissue and the different hip protectors in combination with the soft tissue were tested. Each test was repeated six times. To simulate normal-weight elderly people, a 1/2-inch-thick layer of foam was chosen, reducing the force by 18%. To examine the influence of soft tissue thickness, soft tissue was also simulated by a 1-inch-thick layer of foam, reducing the force by 49%.
Results: In the 1-inch soft tissue test, all hip protectors were capable in reducing the impact to below the average fracture threshold of elderly people (3100 N), although the hard types performed significantly better than the soft ones ($P < 0.001$). In the 1/2-inch soft tissue test, only the hard hip protectors were capable of attenuating the peak force to below the average fracture threshold of 3100 N (hard vs. soft hip protectors: $P < 0.001$).
Conclusions: This study showed that the hard, energy-shunting hip protectors were superior to the soft, energy-absorbing ones, especially in a simulation of normal-weight elderly people. With increased soft tissue thickness, soft hip protectors were also capable in reducing the impact to below the average fracture threshold of 3100 N.

Keywords: Elderly; Fall simulation; Hip fracture; Hip protector; Soft tissue

Introduction

More than 90% of all hip fractures are the consequence of a fall [1]. However, only 1–2% of all falls result in a hip fracture [2,3]. For a fall to result in a hip fracture, the force applied to the proximal femur must exceed its strength [2]. Three conditions influencing this outcome are: (a) the faller must land on or near the hip; (b) protective responses must fail; and (c) local soft tissues must absorb less energy than necessary to prevent fracture [2]. Because gait speed decreases with increasing age [4], frail elderly people are more likely to land on the hip. Furthermore, reaction time slows with age and therefore, protective responses may be delayed. Absorption of energy may be decreased due to weakness or atrophy of the muscles and reduced fat around the hip and buttocks. In addition, bone strength decreases with aging.

A preventive measure to reduce the impact of a fall on the hip is the hip protector [5]. Basically, two types of hip protectors exist: (1) hard, shell-shaped protectors, which primarily shunt away energy towards the surrounding tissues, including femoral shaft, iliac crest and soft tissues; and (2) soft protectors, which

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primarily absorb energy. Their effectiveness in practice depends on two issues: (1) the force attenuation capacity, which is in our study defined as the "the capability of a hip protector to decrease the peak force"; and (2) compliance, which is influenced by wearing comfort [6]. In the literature, two biomechanical studies suggest that the force attenuating capacity of the hard, energy-shunting hip protectors is superior to the soft, energy-absorbing ones [7,8]. However, compliance may be higher with soft hip protectors [9,10].

In our study, we examined the force attenuation capacity of hip protectors that are currently commercially available. After the above two biomechanical studies were carried out, several new hip protectors have been developed and the biomechanical properties of existing hip protectors have been improved. Therefore, the aim of this study was to compare the force attenuation capacity of all hip protectors that were commercially available at the start of our study. In addition, based on an earlier study that reported a high correlation between increased soft tissue thickness and decreased peak force, the influence of soft tissue thickness on the peak force of the different hip protectors was examined [11].

Our hypotheses were: (1) The force attenuation capacity of hard hip protectors, which primarily shunt away energy, will be higher than those of soft hip protectors, which primarily absorb energy. (2) The force exerted on the hip will be lower for hip protectors combined with thicker soft tissue than for hip protectors combined with thinner soft tissue, because part of the energy will be absorbed by the soft tissue.

Materials and methods

Hip protectors

All hip protectors were selected that could be identified by the literature or the Internet and were commercially available at the start of our study. Of the 11 manufacturers selected, nine different manufacturers were willing to participate. One manufacturer refused to participate, and one hip protector used in a previous patient study was no longer commercially available. Of each type, six underpants, including 12 protectors, were ordered. Of the Safehip hip protector, also the old model was tested, because this protector was used in a previous randomized controlled trial, which was performed by our department [12]. The characteristics of the different hip protectors are presented in Table 1. A photograph of the hip protectors is provided in Fig. 1.

Biomechanical tests

The tests were performed with a drop weight impact testing system and a surrogate femur (see Figs. 2A and B). From a height of 8 cm, a mass of 25 kg was dropped on the trochanter major. This caused an average force of 7806 ± 69 N (6378 ± 141 N in combination with a 1/2-inch-thick layer of soft tissue), which is clearly above the average impact of a fall in the muscle-relaxed (5050 N) and in the muscle-active state (6370 N) in women, and in the muscle relaxed state (6100 N) in men [13]. Therefore, this impact can be considered equivalent to a severe fall. Soft tissue was simulated by CF-45 Blue CONFOR foam (Safety devices Ltd., Great Britain), which is also used in dummies for crash tests (TNO, The Netherlands), and has a density of 6.0 kg/m^3, as assessed by the ASTM D3574 test method. To examine the influence of thickness of soft tissue, the tests were performed with a 1-inch- and a 1/2-inch-thick layer of simulated soft tissue, reducing the peak force by 49% and 18%, respectively. Earlier studies used soft tissue that absorbed 15–20% of energy, which simulates the soft tissue of normal-weight elderly people [7,8]. Using our device, we could not measure energy, while it was only designed to measure force. In one of the studies, it was shown that soft tissue reduced the impact force by 13.6–15.2% [7], which is comparable to the force reduction of 18% in our 1/2-inch soft tissue test. In addition, we doubled the soft tissue to examine the influence of soft tissue thickness. We attached the soft tissue directly around the femur in order to create the shape of the upper leg. This leg-shaped form was not an exact simulation of the anatomy of the human leg, but it was a standardized form created in such a way that the hip protectors were in contact with the surface on all sites, which is especially of importance for the shunting hip protectors. Also, the iliac crest, which was made of Acetal Copolymer, was positioned within reach of the protector so that it could be used for shunting.

Each test started with a calibration test to determine the exact value of the impact peak force on the bare femur. Subsequently, a soft tissue test and the different hip protectors in combination with the soft tissue were tested. As a surrogate femur, second generation composite bone was used, in which E-glass/Epoxy Composite simulates cortical bone, and Rigid Polyurethane Bone simulates cancellous bone (Sawbones Europe AB, Sweden). During the tests, the impact force on the proximal femur was measured under the femoral head (after shunting away and/or after absorption of the energy by the hip protector) using the C2 20 kN Force Transducer (Hottinger Baldwin Messtechnik GmbH, Germany), which has a sampling rate of 10 kHz, and a measurement resolution of 0.2%.

The force was compared with the average fracture threshold, defined as the average fracture force of elderly cadaveric proximal femora, of 3100 N [14]. For

Table 1
Properties of hip protectors

Hip protector (country)	Material of the protector	Suggested mechanism
Hard hip protectors		
Hornsby Healthy Hip (Hip Protector Studies Unit, Rehabilitation and Aged Care Service of the Hornsby Ku-ring-gai Health Service, Australia)	Hard PVC plastic; soft inner foam pad	Energy-shunting
KPH2 (Respecta Oy, Finland)	Outer shield of semiflexible high density polyethylene; inner shell of Plastazote	Energy-shunting/energy-absorbing
Safehip (Tytex Group, Denmark)	Polypropylene foam; inner core with higher density	Energy-shunting/energy-absorbing
Impactwear Hip Protective Garments (High Tech Bodywear Ltd., New Zealand)	Glass reinforced polypropylene polymer	Energy-shunting/energy-absorbing
Soft hip protectors		
Gerihip (Prevent Products, Inc., USA)	Crosslinked polyethylene pads	Energy-absorbing/energy-shunting
HipSaver (HipSaver, Inc., USA)	Urethane foam in a waterproof airtight pouch	Energy-shunting/energy-absorbing
Lyds Hip Protector (Lyds International BV, The Netherlands)	Microcellular polyurethane Sandsmaterial	Energy-absorbing
Safety Pants (Raunomo Oy, Finland)	Closed-cell polyethylene foam	Energy-absorbing
Safety Pants (Van Heek Medical, The Netherlands)	Polyurethane foam	Energy-absorbing

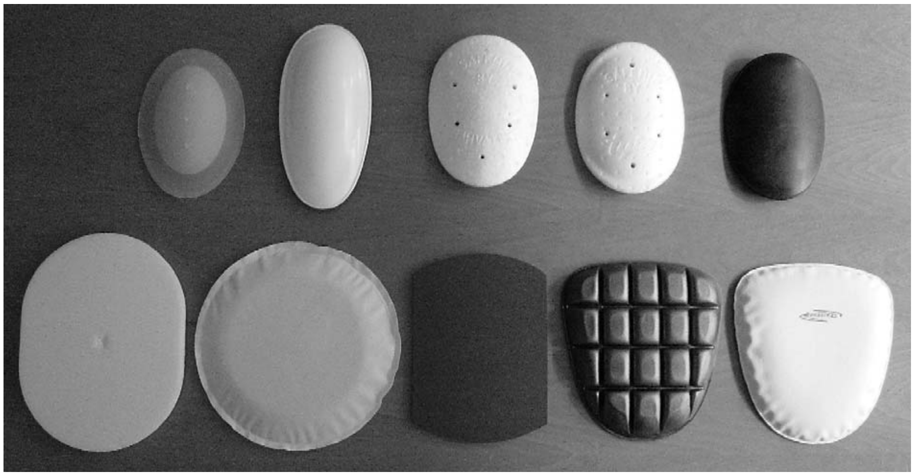

Fig. 1. Hip protectors. Top row (from left to right): Hornsby healthy hip; KPH2, Safehip (old); Safehip (new); Impactwear Hip Protective garments. Bottom row (from left to right): Gerihip; HipSaver; Lyds Hip Protector; Safety Pants (FI); Safety Pants (NL).

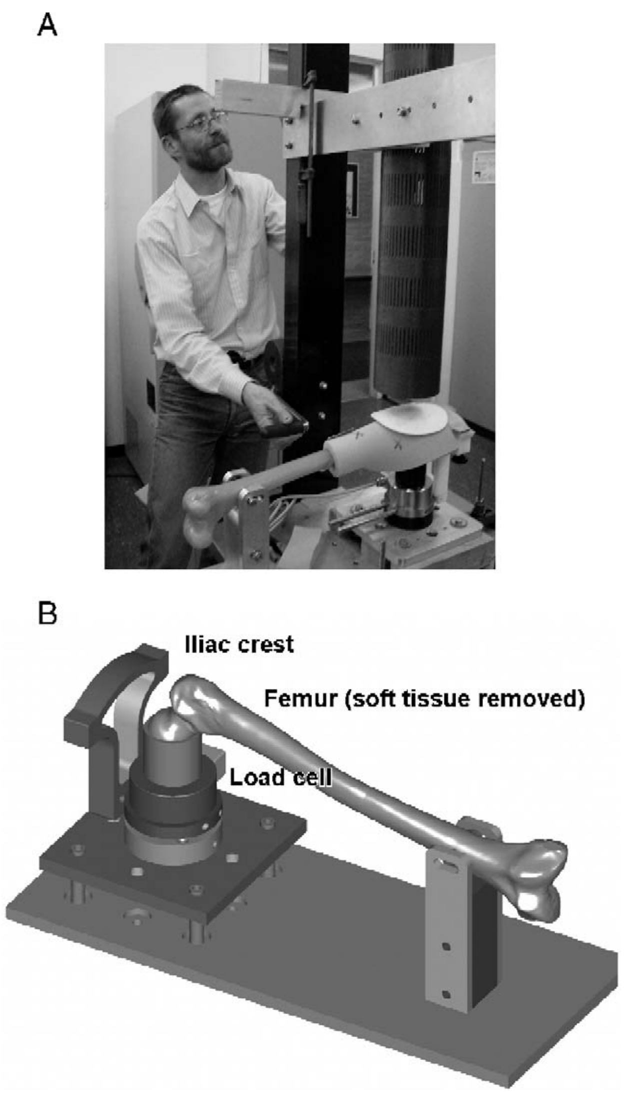

Fig. 2. (A) Drop weight impact testing system. (B) Schematic drawing of drop weight impact testing system.

each test, a new hip protector and new soft tissue were used, because these might be damaged during the test and this could influence the results of the following tests. Each test was repeated six times.

Statistical methods

First, the coefficients of variation were calculated for the calibration test, the soft tissue test and each hip protector by the following formula: standard deviation of six tests / average peak force of six tests. While we used a new hip protector and new soft tissue each test, the coefficient of variation does not only provide the variation of the testing device, but also the variation of the hip protector and soft tissue. Second, bar charts were used to present the average peak force of the calibration hit, the simulated soft tissue and the different hip protectors. The average peak force of the hip protectors was compared to the average fracture threshold of elderly cadaveric proximal femora (3100 N). Mann–Whitney *U* test was used to examine whether the peak force of hard hip protectors was significantly different from that of soft hip protectors at a *P* value of 0.05. In addition, multivariate regression analysis was used to examine whether there was an interaction between type of hip protector (hard/soft) and soft tissue thickness, in the association between type of hip protector and peak force (P value for the interaction term < 0.10). All analyses were performed using SPSS 12.0.1.

Results

In Table 2, the coefficients of variation for the different experiments are presented. In general, the coefficients of variation were very low (0.01–0.08), with two experiments having somewhat higher coefficients (0.18–0.19). In Fig. 3, two time-versus-force graphs are presented. The first graph represents the time-versus-force curves of the hard and soft hip protector with the lowest average peak force in the 1-inch soft tissue test. In the second graph, the results of the 1/2-inch soft tissue test are presented.

In Fig. 4, the results of the experiment with a soft tissue layer of 1 inch are presented. As can be seen, the average peak force on the femur was 7806 ± 69 N (see also Table 3). After adding the soft tissue, this force was reduced to 3998 ± 135 N, which is a reduction of 49%. When adding the different hip protectors, all hip protectors reduced the impact below the average fracture threshold of 3100 N. However, the hard hip protectors reduced

Table 2
Coefficients of variation of the calibration hit, soft tissue and hip protectors

Hip protector	1-inch soft tissue test	1/2-inch soft tissue test
Calibration hit	0.01	0.01
Soft tissue	0.03	0.02
Hard hip protectors		
Hornsby Healthy Hip	0.06	0.03
KPH2	0.03	0.05
Safehip		
Old model	0.06	0.08
New model	0.04	0.04
Impactwear Hip Protective Garments	0.06	0.19
Soft hip protectors		
Gerihip	0.07	0.05
HipSaver	0.03	0.18
Lyds Hip Protector	0.04	0.01
Safety Pants (Finland)	0.03	0.02
Safety Pants (The Netherlands)	0.08	0.06

The coefficients of variation were calculated for the calibration test, the soft tissue test and each hip protector by the following formula: standard deviation of six tests / average peak force of six tests.

the impact significantly more than the soft hip protectors (peak force: 968 N vs. 1897 N; $P < 0.001$). The KPH2 showed the largest decrease in average peak force (80% decrease vs. soft tissue hit). In the group of soft hip protectors, the Safety Pants (The Netherlands) showed the largest decrease (62% decrease vs. soft tissue hit).

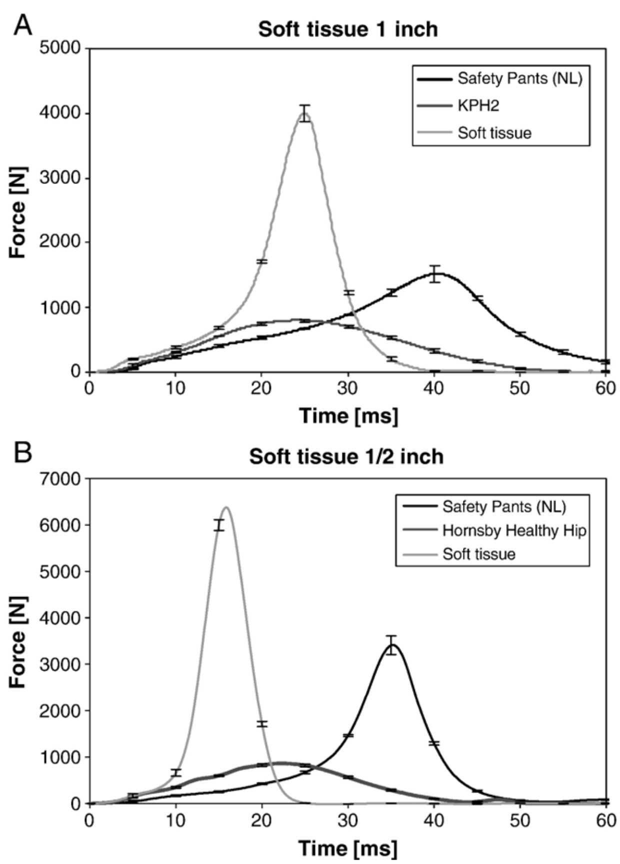

Fig. 3. Examples of time-versus-force graphs. The time-versus-force graphs of soft tissue and the hard and soft hip protector with the lowest average peak force are presented for the 1-inch soft tissue test and the 1/2-inch soft tissue test, respectively.

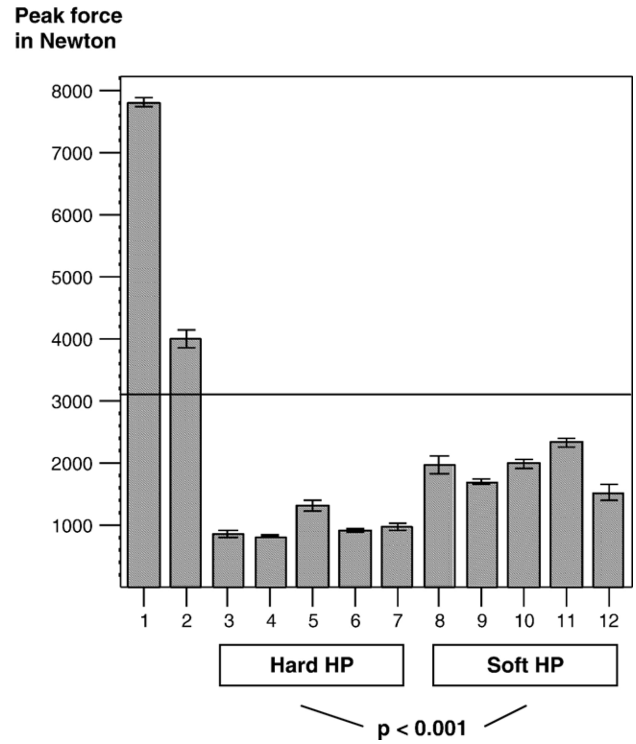

Fig. 4. Results of the 1-inch soft tissue experiment. The average peak force on the bare femur, soft tissue and hip protectors is presented. The horizontal line represents the average fracture threshold, which is defined as the average fracture force of elderly cadaveric proximal femora. 1 = bare femur; 2 = soft tissue; 3 = Hornsby Healthy Hip; 4 = KPH2; 5 = Safehip (old); 6 = Safehip (new); 7 = Impactwear Hip Protective Garments; 8 = Gerihip; 9 = HipSaver; 10 = Lyds Hip Protector; 11 = Safety Pants (FI); 12 = Safety Pants (NL).

Table 3
Force attenuation capacity of hip protectors

Hip protector	1-inch soft tissue test	1/2-inch soft tissue test
	Mean ± SD in Newton	Mean ± SD in Newton
Calibration hit	7806 ± 69	7806 ± 69
Soft tissue	3998 ± 135	6378 ± 141
Hard hip protectors		
Hornsby Healthy Hip	854 ± 50 (−79%)	862 ± 29 (−86%)
KPH2	804 ± 22 (−80%)	900 ± 50 (−86%)
Safehip		
Old model	1298 ± 81 (−68%)	2061 ± 156 (−68%)
New model	911 ± 33 (−77%)	1817 ± 71 (−72%)
Impactwear Hip Protective Garments	971 ± 57 (−76%)	2105 ± 405 (−67%)
Soft hip protectors		
Gerihip	1957 ± 133 (−51%)	4948 ± 235 (−22%)
HipSaver	1689 ± 44 (−58%)	3472 ± 624 (−46%)
Lyds Hip Protector	1984 ± 73 (−50%)	4423 ± 66 (−31%)
Safety Pants (Finland)	2330 ± 67 (−42%)	5186 ± 129 (−19%)
Safety Pants (The Netherlands)	1520 ± 128 (−62%)	3415 ± 201 (−46%)

The average peak force of six tests, the standard deviation and the percentage attenuation as compared with the soft tissue hit are presented.

In Fig. 5, the results of the experiment with a soft tissue layer of a 1/2-inch are presented (see also Table 3). Here, the soft tissue attenuated the force to 6378 ± 141, which is a reduction of 18%. Also here, hard hip protectors reduced the impact significantly more than soft hip protectors (peak force: 1549 N vs. 4266 N; $P < 0.001$), and only the hard hip protectors were able to attenuate the force to below the average fracture threshold of 3100 N. Based on Fig. 5, the Hornsby healthy Hip and the KPH2, which show similar results, were compared to the other hip protectors. The Hornsby Healthy Hip and KPH2 had a significantly lower peak force than the other hip protectors (peak force: 881 N for Hornsby Healthy Hip and KPH2 vs. 3396 N for other hip protectors; $P < 0.001$).

Finally, when combining hard and soft hip protectors in one analysis, an interaction term was found between type of hip protector (hard/soft) and soft tissue thickness ($P < 0.001$) in the association between type of hip protector and peak force. This indicates that the association between type of hip protector and peak force was significantly different when using a 1-inch soft tissue layer or a 1/2-inch soft tissue layer.

Discussion

In this study, a biomechanical comparison of 10 different hip protectors was made. It was shown that, in combination with a thicker soft tissue layer, all hip protectors were able to reduce the peak force below the average fracture threshold of 3100 N. However, in combination with thinner soft tissue, only the hard hip protectors were able to reduce the peak force of a severe fall below the average fracture threshold. In both experiments, the hard hip protectors reduced the impact on the proximal femur significantly more than the soft hip protectors ($P < 0.001$). This confirms our first hypothesis that the force attenuation capacity of the hard, energy-shunting hip protectors is higher than that of the soft, energy-absorbing ones. According to the manufacturers, most hard hip protectors do not only shunt away energy, but are also capable of absorbing energy. Another mechanism observed in Fig. 3 is that all hip protectors delay the force over time, thereby, decreasing the peak force.

The association between type of hip protector and peak force was significantly different when using the 1-inch soft tissue layer or the 1/2-inch soft tissue layer (P value for interaction <0.001). When combining this result with Figs. 4 and 5, it can be seen that the peak force was lowest in the 1-inch soft tissue test, largely confirming our second hypothesis (a lower peak force for hip protectors in combination with thicker soft tissue). However, two of the hard hip protectors, i.e. the Hornsby Healthy Hip and the KPH2, showed the lowest average peak force of all hip protectors, and more importantly, they showed very stable results in the 1-inch and 1/2-inch soft tissue test. Therefore, our second hypothesis is not true for these hip protectors.

Of the soft hip protectors, the HipSaver and the Safety Pants (The Netherlands) reduced the impact to a value similar to the average fracture threshold in combination with the thinner soft tissue. While all soft hip protectors performed better in combination with the thicker soft tissue layer than in combination with the thinner soft tissue, it is likely that the force attenuation capacity of the soft hip protectors could be improved by increasing their thickness. However, this may have a negative effect on compliance. It is unknown whether the compliance will be lower, equal or higher in comparison with hard hip protectors.

Our results confirm the study of Kannus et al. in which three hip protectors were included that were also used in our study, i.e. KPH2 (Finland), Safehip (Denmark) and Safety Pants (Finland) [7]. Also in that study, the hard hip protectors were superior to the soft one, and the KPH2 showed the best force attenuation capacity. The other hip protectors did reduce the impact force below the fracture threshold in the low and moderate impact force experiment, but not in the high impact force experiment. As compared to the study of Kannus et al., more hip protectors were included in our study (four vs. ten). As a consequence, it can be seen that there is not only a difference in performance between hard and soft hip protectors, but also a large variability within the two categories. The performance may depend on the chosen material, the shape of the protector and the working mechanism. In Table 1, the mechanism as suggested by the manufacturer was reported. However, our testing device was not able to measure the degree of shunting and the degree of absorption separately. Furthermore, in our study, the influence of soft tissue thickness was examined. Our results concerning the influence of soft tissue thickness agree

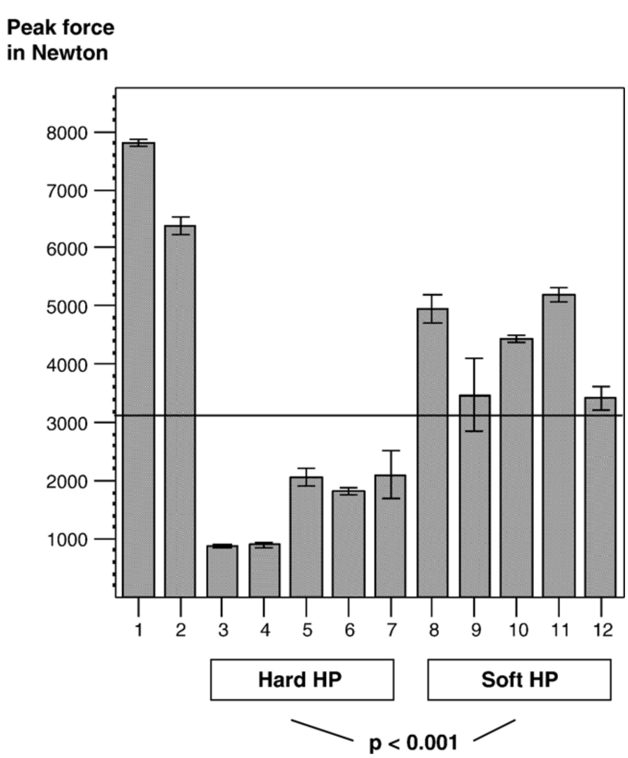

Fig. 5. Results of the 1/2-inch soft tissue. The average peak force on the bare femur, soft tissue and hip protectors is presented. The horizontal line represents the average fracture threshold, which is defined as the average fracture force of elderly cadaveric proximal femora. 1 = bare femur; 2 = soft tissue; 3 = Hornsby Healthy Hip; 4 = KPH2; 5 = Safehip (old); 6 = Safehip (new); 7 = Impactwear Hip Protective Garments; 8 = Gerihip; 9 = HipSaver; 10 = Lyds Hip Protector; 11 = Safety Pants (FI); 12 = Safety Pants (NL).

with an earlier study, reporting that a high correlation existed between increased tissue thickness and decreased peak force ($r^2 = 0.91$) [11].

The Safehip hip protector was capable in reducing the impact to below the average fracture threshold of 3100 N in our study. This result agrees with several patient studies with varying methodological quality [5]. However, in a randomized controlled trial, which was performed by our department, the Safehip hip protector was not effective in preventing hip fractures. This may be explained by low compliance or by the type of population. In our study, the compliance was 61% after 1 month, 45% after 6 months and 37% after 1 year ($n = 561$) [12]. These compliance rates are comparable to most other studies [6], indicating that the compliance should be improved before implementing hip protectors. A higher compliance may be reached by using a more extensive education program, and by making the hip protectors more comfortable. Another reason for the lack of effect may be that we not only included nursing home patients but also residents from homes for the elderly. The latter may have a somewhat lower risk on hip fractures, although only persons with a high risk on falls and fractures were included in our trial.

In contrast to Kannus et al. and Robinovitsch et al. [7,8], we did not use springs to explicitly represent the stiffness of the pelvic ring, because these springs cause secondary peaks in the femoral head loading. The damping of the springs is marginal compared to the damping of a body hitting the floor; consequently, the body mass bounces back immediately and creates a second impact. We considered it not physiological to place springs between the body mass and the earth without considerable damping. In the first pendulum set-up of Parkkari et al. [15], the stiffness had to be included explicitly because no femur was included in the testing set-up. In contrast, we used a Sawbone femur with physiological geometrical and mechanical properties and also explicitly modeled the soft tissues (skin and underlying muscles), so that the effective compliance was implicitly accounted for. This resulted in a smooth load response without secondary peak (Fig. 3). In line with others [16–18], we considered the stiffness of the pelvic ring to be infinitely stiff as compared to the femur and soft tissues. Our results compare well to that of others in terms of time to peak force [19], which suggests that the mechanical behavior of our set-up is comparable to that of the human hip.

We used an effective mass of 25 kg to introduce the impact load to the greater trochanter. In comparable studies in the literature, many different masses were used, varying from 5 kg [20] to 36.3 kg (effective mass = 40.3) [7]. By adjusting the height, the same impact can be exerted on the hip with any weight. However, for different masses, one cannot have the same impact (mass × velocity) and the same collision energy (0.5 × mass × velocity^2) at the same time. The energy of the collision is higher for lower masses at the same impact, because these have a higher velocity at the moment of impact and energy increases proportionally to velocity^2. There is no consensus on which combination of mass and height is most realistic for a fall. However, using our standardized testing system, it is possible to make a fair comparison of the force attenuation capacity of different hip protectors. Moreover, the absolute values of the peak forces were comparable to those of other studies [7,15,21].

A major strength of this study is that we compared 10 different hip protectors using a standard testing device. While it is impossible to simulate a fall and the human anatomy for 100% correctly, it is very important to use a standardized testing system in order to make a fair comparison of hip protectors possible. Because we were able to test 10 different hip protectors that are commercially available, the results may guide researchers in choosing between hip protectors when designing a new patient study. Another strength is that we were able to assess the influence of soft tissue thickness [7,8]. The experiment with thicker soft tissue is not a realistic representation of obese elderly people, because then the mass should also be increased. However, also in people having the same body mass index, differences in fat distribution exist, for example an abdominal vs. peripheral fat distribution. Limitations of our study include that we did not take into account differences in bone and muscle strength. In addition, we did not vary the direction, location and magnitude of the impact of a fall. By applying a large force straight down to the trochanter, we chose to simulate a worst-case scenario. Also, not all pelvic bones were simulated, i.e. the pubis and ischium. However, the iliac crest is the only pelvic bone that directly shunts the impact load; the rest is received by the femur and by the soft tissues. In addition, the leg-shaped form and the position of the iliac crest do not exactly represent the human anatomy. However, the hip protectors were in contact with the leg-shaped form on all sites of the hip protector, and also in contact with the iliac crest, which makes shunting possible. The decision to position the iliac crest within reach of the hip protector was based on the study of Kannus et al. [7]. Also, we investigated in one coauthor whether the Safehip hip protector was within reach of the iliac crest. Based on this result and based on the fact that the other hip protectors were of comparable size or longer, it was decided to locate the iliac crest within reach of the hip protector. Our tests showed that the energy-shunting hip protectors shunted an important part of the energy towards the iliac crest (data not shown). However, the results of the hard hip protectors may be overestimated for situations in which when the iliac crest is not reached, for example in tall people, or when the hip protector is not in the correct position. The iliac crest was not covered with soft tissue in our testing device because the soft tissue layer is very thin at this location in most people. This may have led to a small overestimation of the results.

Before implementing the hip protectors in daily practice, patient studies of good quality are needed to examine acceptance, adherence, effectiveness and costs in practice. When looking at the Cochrane review of Parker [5], it can be seen that 10 randomized controlled trials examined the effectiveness of the Safehip hip protector with varying results. In addition, one randomized controlled trial examined the Safety Pants (Finland) and one the KPH hip protector. Of these two studies, only the second one showed a statistically significant effect of the hip protector on hip fractures.

In conclusion, in this study, it was found that the hard, energy-shunting hip protectors were superior to the soft, energy-absorbing ones, especially in a simulation of normal-weight elderly persons. With increased soft tissue thickness, soft, energy-absorbing hip protectors were also capable in reducing the impact to below the average fracture threshold of 3100 N.

Acknowledgments

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