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Case Report

Hip Protectors to Prevent Pelvic and Hip Fractures While Riding a Bicycle

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Abstract
A previous study at an orthopedic rehabilitation clinic found that every eighth patient with a proximal femur or pelvic fracture had been injured in a bicycle accident: The most common cause of the registered cycling accidents was in 56 % a solo accident without external influence. This included falling when mounting or dismounting the bike (16 %) or slipping with one wheel on wet surfaces, ice, sand, leaves, gravel or clay (13 %) or getting caught on objects and obstacles on the road or on parts of the bike or brake or steering errors. During the healing phase, these patients asked us about a reliable protection for their hips while cycling. Because opinions in the literature about protectors are very inconsistent and commercial protectors specifically for cyclists are only occasionally available, we conducted a simple test of various protectors: A 3.1 kg bowling ball was dropped from different heights (25 cm, 45 cm, 65 cm, 85 cm and 100 cm) onto the protectors and the impact forces were recorded using a Kistler measuring plate (range 20 kN, measurement duration 2 s, measurement frequency 20 kHz). This measurement method is not suitable for accurately testing the impact on the trochanter major and pelvis, but due to our high measurement frequency, it provides good indications of the force reduction of different hip protectors. A trend was observed that thicker protectors - and those combined with a hard shell - achieved better impact force reduction. Finally, 5 participants regularly wore different protectors in cycling pants while cycling over 4 years and evaluated them for comfort and slippage. During this period, 4 of them fell onto their side while cycling: while the protectors showed minor scrapes and, in one case, a fracture of the hard shell, the hip and pelvic region of the participants remained unharmed, aside from minor bruises or scratches of their skin. Based on these clinical and biomechanical experiences, recommendations are made on how to design an optimal hip protector for cycling.

Keywords: Pelvic Fracture; Hip Fractures; Bicycle

Introduction
In the year 2024, in Germany 73,856 accidents involving cyclists and 27,450 accidents involving pedelec riders (e-bikers) with personal injury were recorded in the official accident statistics [1]. While the frequency of accidents among cyclists remained almost the same within the last four years, injuries among e-bike riders increased significantly: 9,491 more e-bike riders were injured in 2024, compared to 2021 [1]. Another retrospective data was collected from 700 German clinics (Trauma-Register DGU®) from the years 2010-2019 [2]. In this study a total of 14,651 severely injured cyclists were reported. The participants were divided into 3 age groups (60 to 69, 70 to 79 and ≥80 years) and a control group (20 to 59 years). Results: Skull injuries occurred overall most frequently by far, at 64.2%. There was a marked increase in severe head injuries in the group over 60 years old [2].
In Germany, there is no helmet requirement. But helmet use among cyclists in a crash was associated with reduced odds of head, serious head, face and fatal head injury. In particular, the magnitude of the reduction was greater for serious injury (serious head, OR = 0.31; fatal head, OR = 0.35) than those for any injury severity (head, OR = 0.49; face, OR = 0.67) [3]. Wearing a bicycle helmet is therefore an important protection in cycling accidents. In a biomechanical study the performance of moderne bicycle helmets in preventing diffuse brain injuries and skull fractures was examined, using impact conditions that represent a range of

real-world incidents [4].

On the other hand, fractures of the hip and pelvis from cycling only sporadically have been described in the literature [5]. Injuries of the acetabulum were reported even less frequently [5]. This low number of hip related injuries from cycling could be due to the fact that many statistics only mention accidents recorded by the police: For example, in Alaska's Strategic Highway Safety Plan, only police crash data were used to gain knowledge about the extent of the bicycle safety problem on the roads [6]. However, in many cases, cyclists who are seriously injured on the roads do not call the police, even if a car is involved. The result is a significant underreporting of the problem [6].

Nevertheless, in recent years, there have been occasional publications about hip and pelvic fractures in cycling. A study on e-bikers showed that 31.8% of the older cyclists suffered femoral neck and pelvic injuries [7]: A total of 360 patients using electric bicycles (E-bike) sustained orthopedic injuries, out of them 230 (63.8%) sustained limb/pelvis/spine fractures. Lower extremity fractures were more prevalent than upper extremity fractures [7]. The tibia was the most fractured bone (19.2%). Patients over the age of 50 years were at the highest risk for spine (20.5%), pelvis (15.9%) and femoral neck (15.9%) fractures relative to other age groups [7].

In 2018, we reported on a case study of 100 injured cyclists over a period of 12 years who were treated in a rehabilitation hospital in Germany [8]. Compared to a cohort of another 100 injured individuals in this hospital who had sustained hip fractures from other causes (tripping, falls from a height, osteoporosis, etc.), we found that one in eight patients - sent to our clinic with a femoral neck or hip fracture - had been involved in a bicycle accident [8]. This high injury rate was confirmed in 2023 by another study in the Netherlands [9]: The final study sample with proximal femur fractures (n = 875) consisted of 102 patients (11.7%) in which a bicycle accident was the cause of the hip fracture [9].

Hip-proximal fractures are indeed more common in older people than in younger ones. However, in our cohort [8], the cyclists affected by hip-proximal fractures were on average 12 years younger than our usual patient group with pelvic or femoral neck fractures (Table 1 "Comparison group") [8]. Moreover, it was not only inexperienced cyclists who were involved in cycling accidents, but also sporty and regular cyclists, including some competitive athletes [8].

In the general press, there have also been reports in recent years about professional cyclists with hip fractures, for example Ashleigh Moolman-Pasio in 2016 (collision with a parked motorcycle), Arnold Fiek in 2016 (fall 12 meters into Lake Lugano), Alexander Vinokourov in 2011 (9th stage of the Tour de France). In 2023, Eddy Merckx, at the age of 78, suffered a femoral neck fracture in a training accident on his bike.
The aim of our considerations was therefore to analyze the causes of these hip and pelvic fractures and to consider how these injuries can be prevented in cyclists. For this purpose, different commercially available hip protectors were also tested on a Kistler force plate for their reduction of impact forces. Finally, five regular cyclists tested the protectors for their use while cycling and four of these subjects also experienced accidental falls while using them over a period of four years.

Contemplation of Our Clinical Problem

In an orthopedic rehabilitation clinic, we collected data from 100 injured cyclists who were treated there after surgery between 2004 and 2016 [8]. Severe head injuries were not admitted to the orthopedic rehabilitation clinic but were treated in neurological clinics. The injured cyclists had a mean age of 59.4 years (16-85 years), including 52 men and 48 women. The youngest patient (16 years old) was a schoolgirl riding her bicycle who had been hit by a car traveling at about 80 km/h. She had suffered a femoral shaft fracture. The oldest patient (85 years old) sustained a fracture of the ankle when dismounting her bicycle.

Among the group of cyclists were some active and former competitive cyclists (1 participant of the amateur cycling league, 1 German triathlon champion with 800 km of cycling training per week, 1 triathlete in training, 1 participant in a mountain bike marathon, 1 racing cyclist training 12-14 hours per week, 1 participant who cycled up to 250 km per week) as well as other former competitive athletes (1 female competitive tennis player, 1 former participant in the German Cross-Country Skiing Championships, 1 marathon runner with a time of 2:45, 1 gymnast in the 3rd liga). But some accident victims, who used the bicycle as a means to get to work or as a form of exercise for health, also reported riding several thousand kilometers per year.

	Injured Cyclists (n)	Comparison Group (n)
Sub- and pertrochanteric femoral neck fracture	20	26
Medial femoral neck fracture	23	58
Lateral femoral neck fracture	1	2
Femoral neck fracture not precisely defined	8	14
(of which spontaneous femoral neck fractures)		(6)
Pelvic or acetabulum fracture	9	
Periprosthetic hip fracture	5	
Femoral shaft or supracondylar femur fracture	2	
Patella fracture	1	
Tibia or tibial head fracture	12	
Calcaneus multifragment fracture	1	
Ankle fracture	1	
Lumbar vertebra fracture	4	
Thoracic vertebra fracture	4	
Cervical spine: pain syndrome	1	
Clavicle fracture	1	
Acromio-clavicular dislocation	1	
Humerus fracture	5	
Elbow fracture	1	
Total	100	100
Mean Age	59,4 years (16-85 y.)	71.8 years (32-90 y.)

Table 1: 100 bicycle accidents treated at the orthopedic rehabilitation clinic and an additional 100 patients with proximal hip fractures for comparison.

In Table 1 is listed only the most severe injury from accidents of 100 injured cyclists treated at an orthopedic rehabilitation clinic. 20 of the cyclists were polytraumatized (11 were seriously injured) with additional fractures, which are not listed here. Some of the patients also had a additional mild head injury (for example, a scalp laceration) and the majority were wearing a helmet at the time of their fall. In the category "Femoral neck fracture not precisely defined" were patients listed who did not bring a detailed surgery report or X-ray. In the “Comparison group“ 100 patients from the rehabilitation clinic were randomly selected, who had suffered a pelvic or femoral neck fracture due to other causes. The patients in this comparison group had included 73 women and 27 men.

The most common cause of injury while cycling was reported 56 times as a solo accident without external influence. This included slipping with the front or rear wheel on wet surfaces, ice, sand, leaves, gravel or clay (13 accidents) or getting caught on objects and obstacles on the road or on parts of the bike or brake or steering errors or even falling when mounting or dismounting the bike (16 accidents). It should be emphasized that many bone fractures occurred at relatively slow riding speeds-sometimes almost while stationary. Example: A 50-year-old road cyclist got stuck in his clip pedals, tipped over with the bicycle and suffered a pertrochanteric femoral neck fracture. Collisions with another road user were the second most common cause of accidents, with 28 incidents (12 collisions with a car, 8 with another bicycle, 5 with a dog, 2 with a motorcycle, 1 with a child). In 8 of these 12 injuries, the cyclists suffered life-threatening multiple traumas. It should be noted that 5 patients with a hip endoprosthesis also suffered an accident with a periprosthetic fracture while cycling.

Fig. 1 shows two cyclists: A: The 60-year-old man was riding a road bike at 25 km/h in his lane slightly to the left when a rapidly passing car clipped the handlebars, causing them to twist and the cyclist fell to the left side. Accident consequences: left-sided acetabular comminuted fracture, scapula fracture, pubic bone fracture, as well as a small laceration on the skull. B: Helmet of this cyclist, who suffered a skull laceration on the head and mild concussion. The helmet had two external and internal three cracks. C and D: 57-year-old athlete (marathon personal best 2 h 45 min) on a bike tour from Zürich to Mühlheim (632 km). He was in a cycling group in the second position and collided with the rear wheel of the cyclist in front, causing him to fall onto the road on his side and suffered a severe pelvic fracture (Fig. 2).

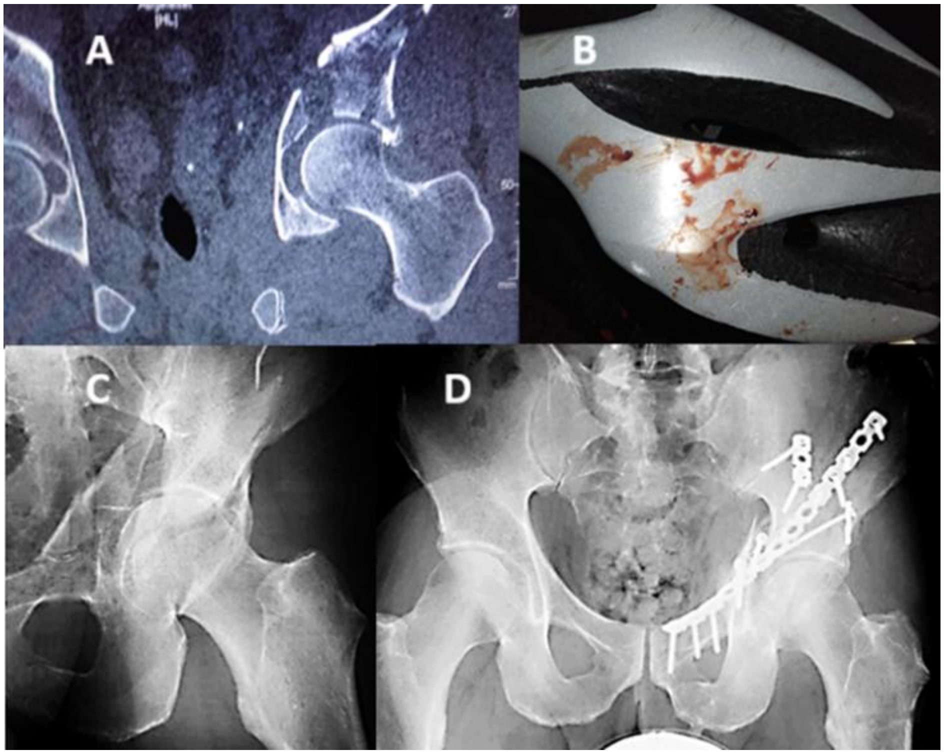

Figure 1: A-B: 60-year-old road cyclist who fell onto the road after a contact between his handlebars and a passing car; C-D: 57-year-old road cyclist who collided with the rear wheel of another cyclist in front.

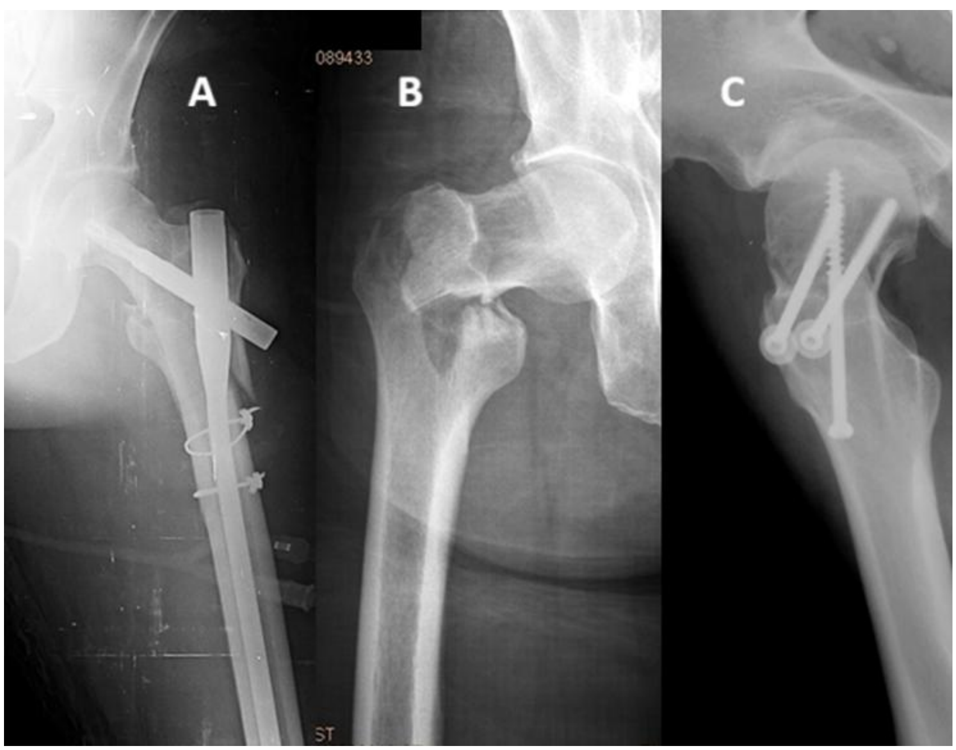

Figure 2: Three more cyclists who fell to the side while riding without external influence. A: 45-year-old road cyclist who slipped on a stream of water on the road with his bicycle and fell on his left side; B: This 43-year-old mountain biker fell on his side. The DXA bone density of the other hip showed a total bone mineral density of 0.992 g/cm²; however, Ward's triangle showed a value of 0.566, T-score -2.22, Z-score -0.99. He regularly used corticosteroid spray for bronchial asthma; C: 49-year-old road cyclist, 6th place in the Senior World Championship. He suffered a medial femoral neck fracture from a fall with his racing bike on ice.

To answer our patients' questions about the future protection of their hips while cycling, it is necessary to know the bone fracture threshold of the femur.

Fractures in the hip region primarily occur due to lateral impact on the greater trochanter. In older individuals with reduced bone density, both pelvic fractures and femoral neck fractures can occur even with lower levels of lateral force from the outside [10]. The force that leads to a pelvic or hip fracture ranges between 3.61 kN and 8 kN with reduced bone density further decreasing fracture resistance [11,12]. A literature review from 16 studies showed the "strength" of elderly cadaveric proximal femora - tested in a fall loading configuration defined as the compressive force (measured at either the greater trochanter or acetabulum) that produced fracture [13]. These data indicate a profound effect of both age and gender on femoral strength. For studies in which male and female data were combined, the median femoral strength averaged across all studies was 3,472 N (range, 2,110 to 4,354 N). The femoral strength was approximately 50% lower for specimens from older than from younger adults (3,770 N for specimens of mean age 74 years (SD=7 years) versus 7,550 N for specimens of mean age 33 years (SD=13 years) [13]. In specimens from older adults (median age=82 years for female and 78 years for male), the median femoral strength was approximately 30% lower for female than male specimens (2,966 versus 4,220 N) [13].

In addition, the characteristics of the soft tissue on the trochanter also affect the risk of fracture [14].

Test on the Mechanical Properties of Hip Protectors with a Kistler Plate

Lateral protectors that protect the greater trochanter are used by motorcyclists, skiers, ice hockey players and mountain bikers. However, hip protectors are also used for individuals at risk of falls in nursing homes. The question arises as to which of the hip protectors provide the best level of protection. For this reason, 21 hip protectors, 13 of them orthopedic for protecting people at risk from osteoporosis and 8 for protection in motorcycling or winter sports, were tested for their physical properties in reducing the forces applied [15]. A 60 mm thick Airex balance pad was used for comparison.

For this purpose, a simple but pragmatic experimental setup was chosen (Fig. 3). On the top of 1-5 Reebok steppers stacked on top of each other (effective height from 25 until 100 cm), a minimally inclined ramp was positioned. From a defined starting position, a bowling ball (3.1 kg) was allowed to roll. This fell onto a force plate positioned below (Kister Instruments CH/Switzerland, 900 x 600 mm, max. range 20 kN). The exact impact point on the force plate was marked with a crosshair. Various protectors were centered on this point but were deliberately not fixed to the force plate. The impact was recorded via an AD converter (National Instruments) using the Simi-Motion software (Simi Reality Motion Systems, V 7.3) (measurement frequency 20 kHz, measurement duration 2 s, trigger start 0.2 s before impact), stored and analyzed. The measurements were carried out a total of 3 times for each drop height. The room temperature was between 20°C and 22°C. In each of the three measurements for each protector, some protectors showed deviations of 5-10% from the peak force (Fig. 4). This was probably due to the fact that although the protectors were centered, they were not always hit exactly in the middle of the ball. Table 2 shows the mean value and standard deviation of the three measurements.

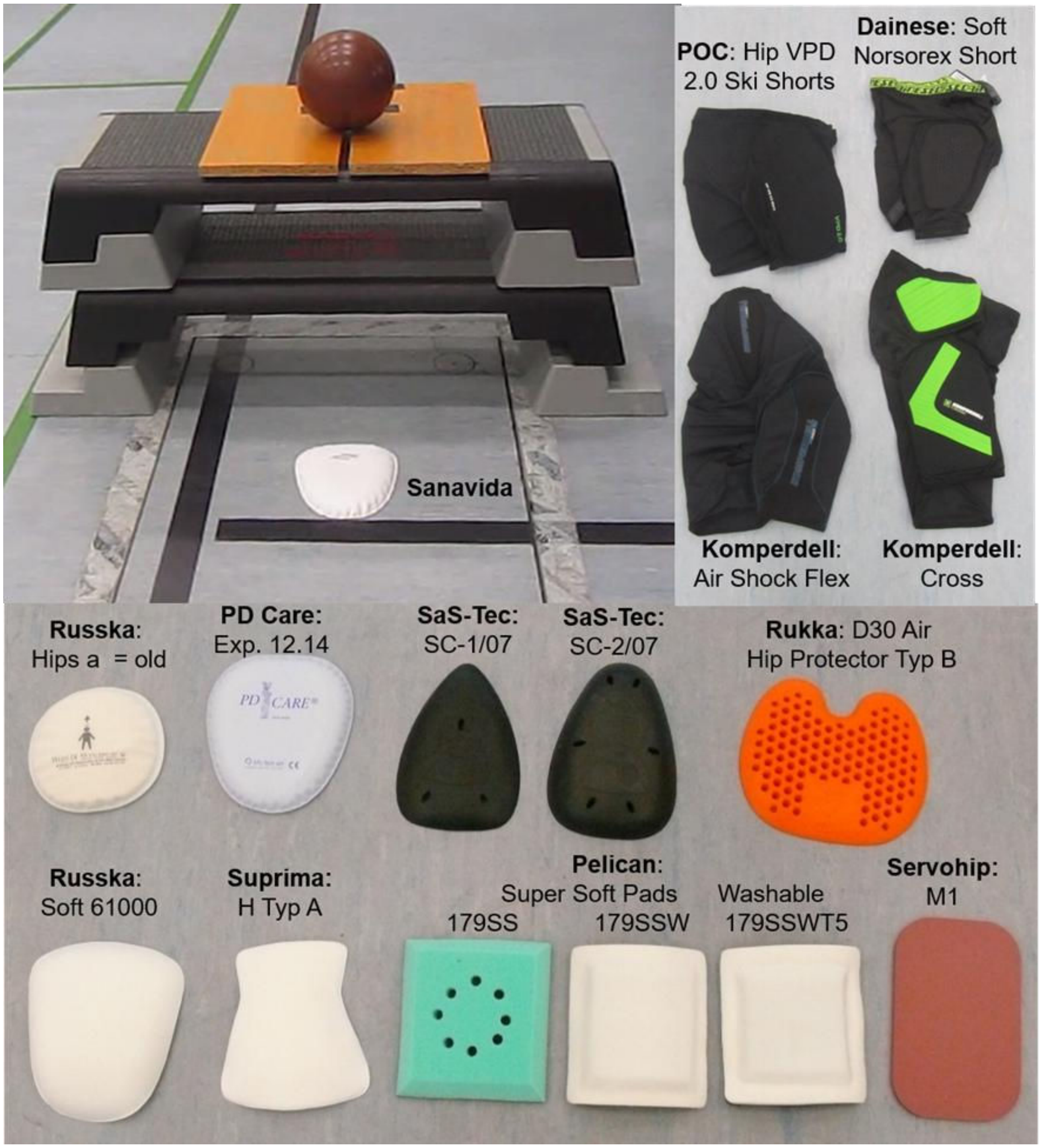

Figure 3: The hip protectors shown here (and also a 60 mm thick Airex mat, see Fig. 4) were placed on a Kistler measuring plate and a 3.1 kg bowling ball was dropped from heights of 25 cm, 45 cm, 65 cm, 85 cm and 100 cm.

Without padding, the impact forces of the bowling ball were already 9.2 kN at a drop height of 25 cm and even 16.8 kN at 45 cm. Therefore, further measurements were not conducted with the ball alone, but only with padding provided by the protectors. The following Table 2 shows the measured values for the drop of the 3.1 kg ball from a height of 100 cm, sorted by lowest impact force [kN].

Name	**Type**	**Material (use in sports)**	**Thick-ness [mm]**	**Impact force [kN] (± SD)**	**Impact time [ms] (± SD)**	**Impuls max [Ns] (± SD)**
Airex	Airex® Balance Pad	F (O)	60	1.84 (0.06)	12.16 (0.60)	11.94 (0.39)
Russka	Hips Kombi old	H+F (O)	21	3.24 (0.23)	9.90 (0.13)	13.16 (0.17)
Sanavida	Safety Protec-tors(HP) Comfort	V (O)	22	7.09 (0.82)	6.08 (0.03)	13.60 (0.32)
Pelican	179SSWT5 Super Soft	SG (O)	21	7.12 (1.07)	8.48 (0.20)	14.07 (0.50)

	Pads Washable					
POC VPD	Hip VPD 2.0 Ski Shorts	VP(WS)	13	7.33 (0.76)	2.18 (0.20)	4.62 (0.33)
Sas-Tec	SC-2/07	VS (M)	16	7.37 (0.16)	4.98 (0.08)	7.61 (0.34)
Russka	Hips Kombi new	H+F (O)	27	8.22 (0.47)	9.38 (0.13)	15.43 (0.52)
Suprima	H Typ A.. 2007 000	V (O)	12	8.33 (0.47)	6.33 (0.03)	14.13 (0.21)
Russka	Soft 61000 000	V (O)	20	8.62 (0.73)	9.08 (0.08)	14.61 (0.39)
Sas-Tec	SC-3/07	V (M)	11	8.78 (0.51)	6.03 (0.03)	14.61 (0.24)
Safehip	Kompakt old	H+F (O)	27	9.10 (0.41)	6.88 (0.53)	12.92 (0.78)
Rukka	d 30	(M)	13	10.06 (0.29)	1.73 (0.08)	8.69 (0.21)
PD CARE	Exp.12.14	V (O)	19	10.08 (0.87)	5.37 (0.08)	14.96 (0.52)
Pelican	179SSW Super Soft Pads Washable	SG (O)	21	11.09 (1.34)	8.90 (0.17)	15.64 (0.40)
Russka	Hips 2-peace	H (O)	27	12.65 (3.14)	8.22 (1.62)	14.59 (0.17)
Pelican	179SS Super Soft Pads	F (O)	21	12.73 (1.71)	6.15 (0.35)	14.85 (0.20)
Kom-perdell	Air Shock Flex	F (WS)	8	13.12 (1.58)	2.90 (0.25)	14.72 (2.84)
Dainese	Soft Norsorex Short	(WS)	7	13.28 (1.05)	2.55 (0.15)	13.34 (1.11)
Sas-Tec	SC-1/07	VS (M)	10	14.34 (0.31)	3.82 (0.03)	11.44 (0.11)
Servo-hip	M1	S (O)	6	14.76 (1.20)	2.17 (0.08)	14.19 (1.15)
Safehip	AirX	V (O)	16	16.58 (1.04)	4.25 (0.35)	15.71 (0.18)
Kom-perdell	Cross	F (WS)	9	21.18 (1.29)	3.62 (0.08)	16.45 (0.98)

Table 2: The hip protectors tested in the drop test with a 3.1 kg bowing ball, here dropped from a height of 100 cm. The values (mean value and stand deviation of three tests for each protector) are ranked according to the impact forces. In general, a greater material thickness results in lower impact values. However, the type of plastic used, as well as the shape of the protector (flat or dome-shaped), also seems to play a role. Material: F = Foam, H = Hard shell, H+F = Hard shell + foam, V = Viscoelastic foam, VP = Viscoelastic polymer foam, VS = Viscoelastic soft foam, P = Pro Shape and Crash Absorb®-Polsterung, S =Sands® Polsterung, SG = sealed green inner foam. Most protectors are available as orthopedic hip protectors (O), while sport protectors are indicated as: (WS) = winter sports, (M) = motorbiking.

In Fig. 4 the Airex balance pad with 60 mm material thickness works like a soft mattress, slowly absorbing the load. Thereby the best force reduction is achieved, which does not exceed 2.0 kN even in a fall from a height of 100 cm. This means that - even from this height - only 17 % of the impact forces occur compared to some other hip protectors.

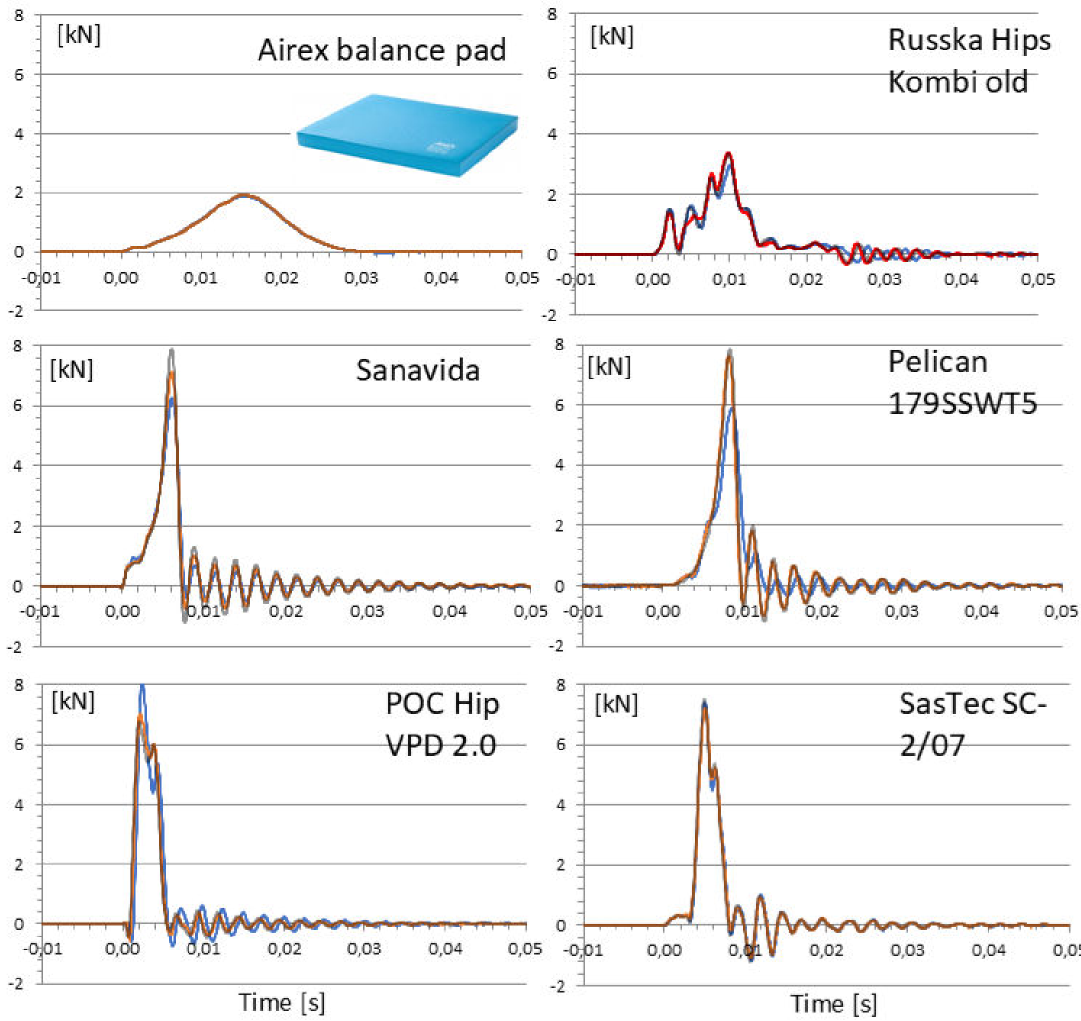

Figure 4: Curves of the impact forces of a 3.1 kg ball [kN] at a fall height of 100 cm on the five protectors showing the lowest impact values (Table 2), as well as on the Airex balance mat. Every protector was tested 3 times and all three curves were overlaid here (colors: red, blue and gray). The three curves almost always show identical patterns, but they look different from one to another protector. In some curves, the peak values differ, which is probably due to a slightly changed position of the protector on the measuring plate. The damped vibrations following the values for the protectors come from the natural frequency of the Kistler measuring plate.

The Russka Hip Kombi old version with hard shell (Fig. 3,6) shows a wavelike and significantly delayed increase in impact force, also resulting in a low maximum value. Unfortunately, this protector is no longer being produced, supposedly because it was too conspicuous for customers to wear. A very steep rise in force, but still low maximum values, is shown by the POC VPD ski protector pants.

The individual protectors all reduce the impact forces of the ball, but with different effectiveness. For example, the values for peak force at a low drop height of 25 cm are only 0.9 kN for the best protector, but 6.0 kN for the worst. At the maximum drop height of 100 cm, the values for the good protector are only 3.2 kN, while for the worst protector they reach 22.0 kN (Table 2). In general, thicker hip protectors (16 to 21 mm thick) perform better in reducing forces than thinner ones. However, the POC VPD ski protective pants and the protectors from SAS Tec and Suprima also provide good protection even with thin materials.

Most of the orthopedic protectors show greater protection at lower drop heights - but then a decreasing protective effect at higher drop heights compared to the sports protectors. This means that the orthopedic protectors become increasingly ineffective with increasing fall height. Regarding the impact times up to the peak force (another important protection criterion), the orthopedic protectors show at low drop heights the best results, which suggests the good damping properties of the viscoelastic materials used at least up to their full compression at higher drop heights. Because if the ball penetrates through the material, the protective effect diminishes significantly, which is reflected in smaller differences compared to the sports protectors at higher drop heights.

Some hip protectors for sports have the disadvantage that the padding used is thinner (about 10 mm): 4 of the 7 sports protectors commonly used for motorcycling or skiing significantly exceed the maximal impact values of orthopedic protectors. Here, either the viscoelastic material seems too thin, and/or the foam is unsuitable.

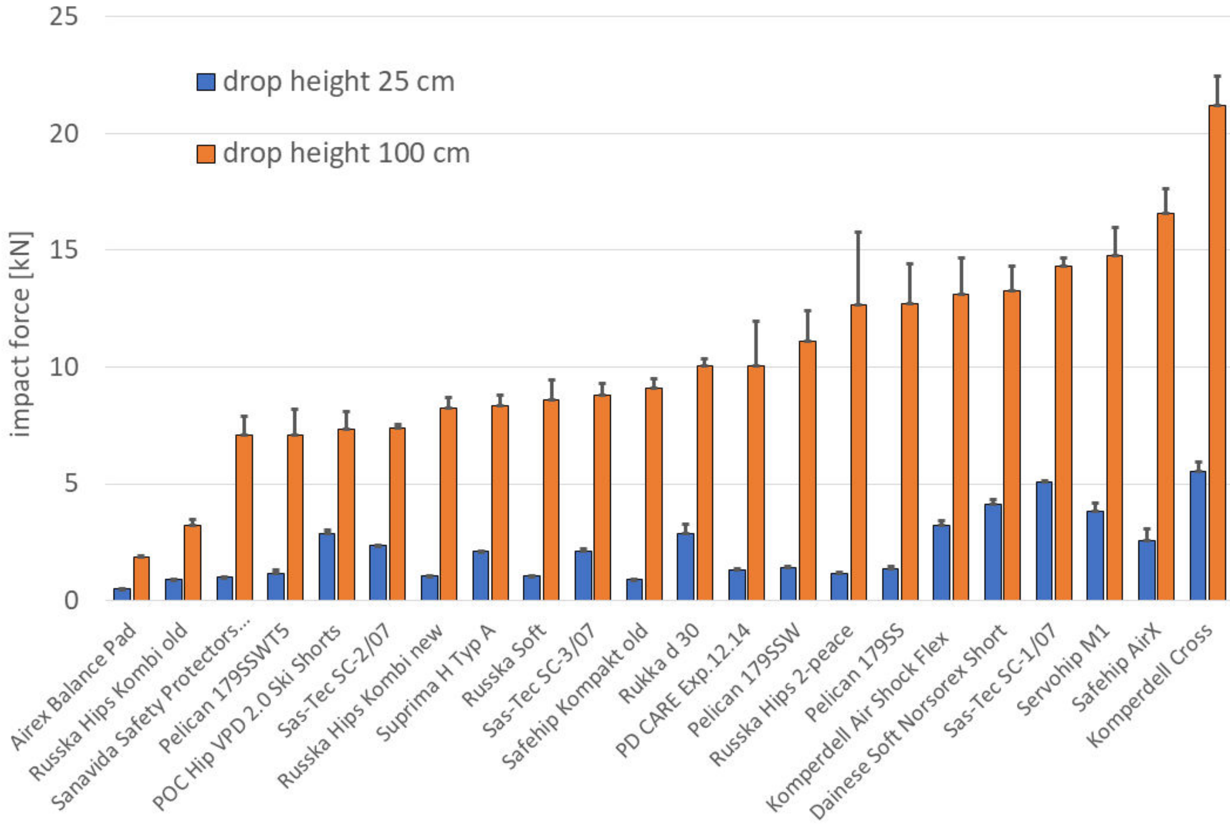

Figure 5: Impact Force [kN] and standard deviation of all tested hip protectors at a drop heigt of 25 cm and of 100 cm. The good protective effect at a 25 cm drop is no longer present with some protectors at a 100 cm drop. But 100 cm it is precisely the height that is crucial to ensure reliable protection while cycling. 5 protectors remain below or near the bone fracture treshold, while 16 exceed it.

Testing Some Protectors with Five Volunteer Subjects While Riding a Bicycle

Based on our results, 5 recreational cyclists (aged 50-77 years, cycling 1,500-8,000 km per year) decided to regularly use hip protectors while cycling. They chose the protectors from the geriatric/orthopedic range because these had shown the best results in our simple test. However, wearing them in the supplied underwear together with the padded cycling shorts could cause skin problems due to friction on the saddle after a few hours of sitting. Additionally, in these undergarments the protectors are sometimes not positioned exactly over the trochanter when the hip joint is bent. Therefore, over time, the 5 individuals decided for themselves to place the protectors between their elastic cycling shorts and the skin over the trochanter. At the beginning the protectors can shift while cycling, but if you sweat more they stick to the skin and do not move longer. Nevertheless, this is not an optimal solution. However, it is not possible to use other protective pants (skiing, motorcycling, etc.) while cycling, because it would also cause seating problems on the saddle.

Our method to fix the protectors in the cycling shorts, however, have protected the hips of 4 of these hobby cyclists in a fall to the side within four years (Fig. 6):

- In a 55-year-old cyclist wearing a Russka Hip Kombis old Protector (Table 2 and Fig. 4 or 5), the hard shell of the hip protector broke in the middle due to slipping on a wooden bridge and a subsequent side fall during mountain biking. A circular bruise appeared on the hip externally, but the hip itself remained uninjured. His bicycle helmet was cracked, but he suffered no brain damage

- A 77-year-old road cyclist moved left in a group, collided with a fellow cyclist and fell on his hip. He sustained an ankle sprain, but thanks to the protection of his protector (Sanavida), his hip was not injured
- The 64-year-old recreational mountain biker, who fell at about 10 km/h on a rocky forest trail (Fig. 6) and sustained a knee abrasion and a hip bruise, suffered a minor hematoma and scrapes on the hip, but no other serious injuries
- In the case of the 60-year-old recreational road cyclist, a young man suddenly stepped onto the street and collided with the cyclist (Fig. 6 Supplementary). The cyclist was going uphill at about 12 km/h. Consequences for him: dislocation of the middle joint of the left third finger and damage (arrow) to the protector

Discussion

Our study shows that people may be at risk of suffering a severe hip-proximal fracture while cycling from the age of about 45. Younger people are protected in the event of a normal sideways bicycle fall due to their high bone density. But on the other side, it is also known that professional cyclists (and swimmers too) have lower bone density than the general population and even significantly less than athletes in most other sports [18]. Younger people may also react even faster with defensive movements: When young persons are falling to the side, they often use hands or legs to prevent a high impact [16]. By this support the impact velocity of the pelvis decreased 3.6% for every 10 ms increase in the interval between hand and pelvis impact. As a result, the impact was reduced by an average of 22% [16].

However, the author's personal experiences with falling off the bike to the side (once he slipped on ice, twice because the clip pedals did not release - in one case due to a defect in the shoe plate, once because of contact with a pedestrian who stepped onto the street, Fig. 6) indicate that the fall happens very quickly, without the possibility to react. Other cyclists confirmed this experience.

A second protective factor, as previously mentioned, is the thickness of one's own soft tissue layer. Trochanteric soft tissue thickness is linearly correlated to the Body Mass Index (BMI). Experimental studies have shown that the soft tissue covering the hip improves energy absorption during a fall, and in this way, allows less energy to be transmitted to the proximal femur: To simulate normal-weight elderly people, a 1/2-inch-thick (1,27 cm) layer of foam was chosen, reducing the force by 18% [19]. To examine the influence of soft tissue thickness, soft tissue was also simulated by a 1-inch-thick (2,54 cm) layer of foam, reducing the force by 49% [19]. These findings may partly explain the reduced risk of hip fracture in elderly women who are overweight [17,19]. In a cadaver study, the thickness of soft tissues at the trochanteric bursa (measured by a needle probe) ranged between 8 and 45 mm and averaged 24 mm [13]. For a constant impact energy, peak force at the femoral neck decreased with tissue thickness at a rate of 71 N/mm [13].

Limitations of Our Study

Our method measuring the impact of the protectors on our Kistler plate does not meet the required standard for testing hip protectors [13,19]: the measurement criteria should take into account the surface geometry of the pelvic model, also the geometry and the mechanical properties of the proximal femur and also the trochanteric soft tissue stiffness [13]. For this, the following standardized measurement procedures would be necessary [19]: 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 [19]. After this calibration test, soft tissue and the different hip protectors in combination with the soft tissue can be tested [19].

Besides, to comply with the European testing standard for protectors, a falling weight of at least 5 kg (impact energy = 50 joules) is required. The joint protector standard EN1621-1:2012 states that for Level 1, the average residual force must not exceed 35 kN and a single impact must not exceed 50 kN. The average residual force for Level 2 protectors must be below 20 kN and no single impact may exceed 30 kN. In our study for example, all protectors of the SAS-TEC joint protectors presented here achieve the higher protection Level 2, whereas only the thinner variant of the hip protector, the SC-1/07, has Level 1.

Our study does not meet all of the test criteria, but it also has advantages: The Kistler force plate used here (Kistler Instruments AG, Winterthur, Switzerland) is one of the most precise biomechanical measuring instruments on the market and is internationally recognized as a standard. The force plates are highly precisely calibrated. The measurement frequency used here of 20 kHz is significantly higher than the typically used measurement frequency of 1 kHz or 5 kHz and allows a temporal resolution of the force peak of 0.05 ms. This an important factor in view of the short impact times of only a few milliseconds in some protectors, in order to capture even short force peaks. In addition, our simple method allows the physical properties of many protectors to be recorded and compared. Our measurements with the high-precision measuring instrument (Kistler) consistently show higher force values than those from other testing laboratories. The ball we used can correspond to an external impact object that is not completely flat, which makes the penetration depth slightly deeper and impact forces higher - perhaps comparable to a round stone on the street. However, the weight of the ball (3.1 kg) is much lower than the actual fall weight of the rider's hip region (25 kg) [19]. The fact that our measurements with only 3.1 kg fall weight (= 31 Joules) achieve such high force peaks of 14 - 21 kN despite the use of protectors is alarming. Nevertheless, a fall height of 100 cm is realistic when cycling. Purely mathematically, a cyclist falling sideways with a pelvic weight of 25 kg - 28 kg [13,19] and a fall height of 1 m would experience at least an impact energy of 245 Joules. This corresponds to 4-5 times more than the impact energy of a sledgehammer (50 joules). In fact, this should lead to severe fractures. Experiments involving young adults falling onto gym mats [literature see 13] indicate that, the impact velocity of the hip averages 3.01 m/s (SD=0.83 m/s) and the kinetic energy of the entire body at the moment of hip impact averages 307 J (SD=90 J). In this respect, our test setup presented here - as well as the European standard EN1621-1:2012 - is not realistically sufficient.

In this context, reference is made to a study on four young, voluntary subjects (27-35 years old) who were able to withstand an impact of up to 115 Joules or forces of 2.05 to 2.3 kN without injury during lateral pelvic compression against a wall, although they were wearing protectors on both sides [20]. In this experiment, the effects or material thicknesses of both protectors has to be added together, furthermore the soft tissue layer on both sides must also be included and the elasticity of the pelvic ligaments has to be considered [13,20]. Unfortunately, the consideration of protecting the hip and pelvic region in people of old age using protectors has been pushed into the background due to a few misleading publications. This includes, in particular, the study by Kiel [21]. There, the protector thickness of only 12.7 mm was far too thin to provide adequate protection. In addition, considering the advanced age (85 years) and the high proportion of female participants (79%) in their patient group, it can be assumed that the bone density of many participants was already very low. But in the meantime, many other studies on the effectiveness of protectors-taking individual circumstances into account and using the right protector material-have demonstrated a protective effect [22].

Requirements for a Hip Protector When Cycling

First of all, the individual factors of the cyclist need to be considered. This includes their age, ideally also knowledge about their bone density and the thickness - and also the stiffness - of their soft tissue layer in the hip area. However, one can anticipate that slender older adults at greatest risk of hip fracture will have greater effective stiffness resulting from decreased soft tissue over the hip and increased calcification and stiffness of the pelvic articulations and decreased effective mass [13]. They may have less effective protective responses when landing from a fall [13]. Furthermore, most active cyclists are quite thin. For most, increasing calorie intake will not succeed in thickening their soft tissue, because cycling burns those calories away. Therefore, it should be considered whether, in thin individuals, the missing soft tissue layer should be compensated by an additional protector thickness of 1.27 cm [19]. This would mean that the protector for them should have a minimum thickness of 1.27 + 1.5 cm = 2.77 cm. The protective effect of a protector, consisting of force reduction and time delay, also depends on its material properties, i.e., its construction and thickness, based on the principles of distribution (pressure distribution) and/or absorption (damping) [13,15,17,19]. Accordingly, in our experiment, the Airex pad shows by far the best values in this comparative test. Foams with a thickness of less than 15 mm, on the other hand, do not meet the safety criteria, but the combination with hard shells can improve the protective criteria [13,15,17,19]. In our study, thicker hip protectors perform better in force reduction-at least up to fall heights of 45 cm. This roughly corresponds with the literature, according to which protection increases with thickness and a minimum thickness of 15 mm for the viscoelastic material is considered reasonable [15]. Another crucial criterion, besides thickness and density, is also the material structure (honeycomb, tetrahedron, etc.). In addition, the shape of the protector, the extension, curvature, structure, the number and arrangement of layers, as well as the stiffness of a hard shell (pressure distribution) are important factors for force reduction [20]. In our study, a curved hip protector with a combination of hard shell and viscoelastic material achieved the best results (Russka Hips Kombi old). This was confirmed in other experiments [17]: The biomechanical test results showed that the padded, dome-shaped polyethylene shield of the KPH protector indeed provided an effective impact force attenuation in fall-to-the-side simulations in the elderly. Later, to further improve user compliance, the convexity of the shield was somewhat lowered and the new shield modification was named the KPH2 hip protector [17].

Thus, people's desire for the most unobtrusive wearing comfort must be taken into account [15]. Cyclists' compliance is the main problem why serious health impairments cannot be avoided in Germany. This applies the refusal to use bicycle helmets, but also to use hip protectors. And this false sense of shame is the reason why there are no effective hip protectors available for cycling. On the other hand, if you imagine that ice hockey players where similar forces act on their hips were wearing only thin leggings during a contest, the whole world would laugh at their naivety. So far, the sensible cyclists make do by wearing one of the hip protectors in their underwear and over it a padded cycling short. This way, a protector thickness of 20 to 25 mm can be achieved. However, it would be sensible and desirable if the industry could decide to develop good hip protectors for cycling. With regard to standardized test methods [13,19], we kindly ask researchers to develop and test protective gear that is safe for cyclists, taking into account vertical and also horizontal forces at high riding speeds.

Wishlist for hip protectors when cycling:

- Protector length: The bony outer side of the greater trochanter has a length along the skin of roughly 5 cm. Therefore, it would be sensible for the protector to be at least 20 cm long
- Width: The protector should completely cover the center and the outer side of the greater trochanter as well (for protection during falls at higher speeds), keeping in mind that the trochanter moves about 5 cm forward or backward under the skin with internal or external rotation of the hip. A width of at least 20 cm would therefore be sensible
- The width and length should be standardized so that standardized pockets could be mounted on the sides of cycling pants.
- The fixation of the protector is important. But when cycling, you cannot use just any underwear that has no or only poor saddle padding. Better would be integration into cycling shorts (sewn-in pocket or Velcro strips), where the appropriate pads can be positioned over the trochanter
- A hard surface can distribute pressure over a larger area to the side of the trochanter, this seems to enhance the protective effect. Perhaps, a construction of a protector would be useful that has a firm surface in the center (a little bit dome-shaped?) and more flexible areas toward the edges
- The protector must not shift while cycling
- The protector should be washable and, if possible, also breathable
- The protector should have an almost uniform surface without interruptions so that no sharp or pointed objects/stones can penetrate

Conflict of Interests

The authors declare that there is no conflict of interest related to this study.

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Supplementary File

Supplement Figure 6: Accident recordings of two cyclists wearing protectors after a side fall at low speed (10-12 km/h). Bone density was measured in both cyclists using the DXA method and was within the age-appropriate normal range. A-C: Mountain bike fall on a descent. She wore a protector "Leidel & Kracht - EN 1621-1-LK II A," material thickness 17 mm. Some scratches are visible on the protector`s surface; D-E: The protector "Russka Hips Kombi old" (21 mm thick, Table 2 and Fig. 4) showed only superficial damage after a side fall. Both protectors feature a hard shell with a soft padding material.