Description of Equestrian Accidents and Implications on Testing of Equestrian Safety Vests

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Abstract Equestrians sports have a high injury rate and many athletes use chest protective equipment, i.e., the safety vest. Safety vest certification includes impact attenuation tests, but it is not known how relevant these tests are compared to real-world accidents. We categorised 902 equestrian accidents with suspected torso injury that occurred during competitions in the United States, 2020-2023. Falls from horses accounted for 68-92% of all cases with torso injury. The remaining cases were kicked, stepped on, or struck by a horse, and other scenarios. Most torso injuries were caused by forward or sideway falls from a horse in connection to a jump, with the first impact to the head or shoulder. We simulated two representative accident scenarios and compared to simulations of the impact tests in EN 13157 and ASTM F1937 standards. Simulations suggest that the impact tests defined in standards loaded the safety vest similar to hoof kicks but that they did not represent the slower loading seen in the simulated fall accidents. Hence, additional impact test methods are needed to assess safety vest performance in falls from horses.

Keywords body protectors, certification test, equestrian accidents, finite element simulations, torso injury

I. INTRODUCTION

Equestrians are at high risk of severe injuries due to the nature of the sport, with high speeds astride horses with potentially unpredictable behaviour [1]. Horse riding has been reported to cause more injuries per hour riding than motorcycle riding in the US [2] and caused more insurance claims than mountain biking in New Zealand [3]. The frequency of chest, thorax or torso injuries in equestrians varies from 9% to 58% [4-42], depending on the discipline, country, method of data collection, study population, definitions of injured body area, and injury severity. Torso injuries were most frequent among severely injured riders [7][20-21][27][32-33][35][37][41], less than 10% for children [8][24][28][30][36][40], and higher for adults [6][26][28][30]. A US study showed that older adults (over 54 years of age) had 55% torso injuries as compared to approximately 20% for adults 20-54 years of age and 10% for children [6]. According to a recent study of insurance data from equestrian accidents, the risk for permanent medical impairment was 11% for torso injuries [43].

Injury preventive measures can either be accident avoidance, i.e., educating the rider to better understand the horse and its behaviour, increasing trainer awareness of risky situations and to design obstacles and the course such that the risk for horse falls is minimised, or to mitigate injuries when accidents occur, i.e., riders wearing personal protective equipment when competing, training, and handling horses. Most riders today wear helmets when competing and increasingly in training and handling of the horse. Available protection equipment for chest injury are the equestrian safety vests (also called body protector, chest guard, protective jacket, and protective waistcoat) and air vests (also called inflatable vest or air jacket). Equestrian safety vests typically cover the ribcage and upper back and are made from a foam material that will absorb some of the energy in an impact. The air vest is typically connected to the saddle by a tether and inflates when the rider separates from the horse.

There is a scarcity of studies on equestrian safety vests and air vests, of the reviewed literature on equestrian injuries [4-44], only five studies included information on chest protection usage [16][22][34][42][44] and four studies analysed their effectiveness [20][31][42][44]. One study found an increased odds of serious or fatal injury for riders with air vests [44], discussing that it could be because riders may be more likely to wear air vests during high-risk activities but that more research was required to understand the reasons. No study found that wearing a safety vest increases the risk of injuries in accidents, although concern was raised in [45] that some safety vest designs cause interaction with the helmet, thereby limiting neck extension and the field of

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view for jockeys, potentially increasing the risk for accidents, and may prevent medical personnel to start treatment immediately at the scene of accident. In eventing, wearing a safety vest in the cross-country phase reduced the relative risk of injury by 56% [42]. A Swiss study found that wearing a safety vest was a statistically significant protective factor for riders from different equestrian disciplines [20]. In a retrospective survey, there were fewer injuries per hour ridden and on average for equestrians who claimed that they often or always used a safety vest compared to others [31]. These three studies indicate that safety vests may provide a protective benefit; however, more research is warranted on this topic, e.g., with case control studies or accident reconstructions.

Certification testing of personal protective equipment should represent loading in real-life injury producing accidents, to assess the protective performance and ensure that a minimum level of protection is maintained. In Europe, impact energy transmission is tested by drop tests at 25, 30, and 35 J using a 2.5 kg impactor and requiring that the resultant force be equal to or less than 4 kN (EN 13158, Fig. 1a). The British Equestrian Trade Association has its own standard, BETA Body Protector Standard, with the same impact testing as EN 13158. The Australian certification testing is similar to EN 13158 but testing only at 25 J and with a 5 kg impactor (ASB 1:1998). Several governing bodies in the US require safety vests certified to ASTM F1937, ASTM F1937 includes drop tests at 25 J with a 5 kg impactor, requiring that the impactor acceleration be less than 300 g. The stiffness is also evaluated by impacting the vest while placed on a deformable material (Fig. 1b). The impact tests in standards are rapid events with durations around 10 ms, up to 20 ms in test with a softer anvil (Fig. 1c). It is not known how relevant this loading is to real-life accidents.

Previous research on injury producing events show that the majority of injuries were caused by falls from horses (60-83%) and to a much lesser extent by kicks, bites, being trodden on, or struck by a horse body [4-7][10][12-16][18-20][23-24][26][28-29][33-35][38-41][43]. Only one study separately presented the type of events that resulted in chest injuries, 93% were caused by falls from or simultaneously with a horse [6]. None of the studies provided details on types of falls or other circumstances that are needed to reconstruct the accidents with simulations. Therefore, the primary aim of this paper was to categorise equestrian accidents. The secondary aim was to compare safety vest loading and deformation between falls from horse and impact tests prescribed in certification standards, using finite element simulations as further described in Appendix B.

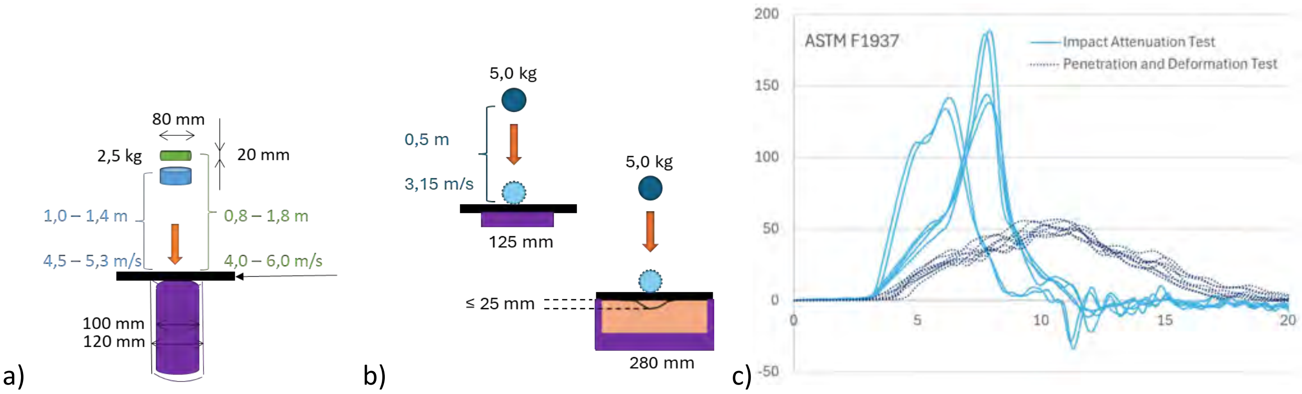

Fig. 1 a) Schematic illustration of the EN 13158 impact energy transmission test. The vest is represented by the black bar, the anvil (purple) is placed inside a hollow cylinder and a disc (blue) or bar (green) impact the vest surface. b) Schematic illustration of the ASTM F1937 impact attenuation test and penetration and deformation test. The vest is represented by the black line and a spherical impactor is dropped onto the surface. The anvil is represented as purple and deformable surface orange (right). c) Example measurements from testing of a vest at different temperatures according to ASTM F1937.

II. METHODS

Anonymised data from January 2020 through December 2023 were provided by the US Equestrian Federation (USEF). The database tabulates standardised reports from licensed officials regarding incidents and accidents that occurred during USEF competitions. Included were cases with suspected injury to the torso in the event types; hunter, jumper, hunter/jumper, eventing, and dressage. Hunter, jumper, and hunter/jumper have been combined and hereafter referred to as hunter/jumper. Excluded were cases where horses were not directly involved (such as medical incidents, fires, fall from ladders, bicycle accidents, and dog bites) and cases lacking free text descriptions of the accidents. Data was processed using Microsoft Excel version 2402 (Microsoft Corp., Redmond, Washington, United States).

A torso injury was defined based on the reported injured body part, which was from a free text entry in the database with varying levels of details. Therefore, torso injury cases were grouped into the following categories: shoulder, chest, abdomen, side, and back. Cases could include multiple injury categories. Clavicle fractures were included in shoulder injury, rib fractures in chest injury, and spinal injuries (lumbar and thoracic spine) in back injuries. No distinction was made between upper and lower back and side injuries since it was not always evident which region was involved. In addition, any cases involving treatment described as *spine-immobilization*, *back precautions*, or *back boarded* was included in back injuries, except if it was explicitly identified as involving only the cervical spine.

Free text descriptions of the accidents were analysed and classified into types of accidents; fall from horse, dragged by horse, kicked by horse, stepped on by horse, struck by horse, hit horse, i.e., the rider impacted the horse, and other scenarios, e.g., cart, slip, trip, and bicycle accidents. For fall from horse, we classified the following; rider's direction of fall in relation to the horse, horse's gait, rider's area of body in first contact, type of impacted surface, if the fall was in connection to a jump, horse behaviour prior to the fall, if the horse fell or not, if the horse fell on or rolled over the rider, and if the rider was unbalanced, out of tack or holding on to the horse prior to the fall. Appendix A describes how different phrases were consistently interpreted to determine the rider's fall direction. The horse's gait was either provided or interpreted based on the text description. For example, a fall that occurred between fences while jumping a course was interpreted as happening while the horse was cantering.

Lastly, two representative accidents were simulated with the explicit finite element (FE) method using a Human Body Model (HBM) representing an average size female wearing a generic safety vest. The results were compared to simulations of the impact test prescribed in the two certification standards EN 13158:2018 and ASTM F1937. The methods are further described in Appendix B.

III. RESULTS

The USEF accident data contained 3347 cases for the four-year period 2020- 2023, of these, 384 were from dressage, 355 from eventing and 2396 from hunter/jumper. Fig. 2 illustrates the number of cases per year and the ratio of torso injuries. For dressage, torso injuries decreased from 27% to 15% during the period, possibly due to few cases in 2020. For eventing and hunter/jumper there was no clear trend and cases with torso injury were on average 27% and 31%, respectively. There were nine reported fatalities, most related to medical conditions or other circumstances. Fatalities related to accidents with horses were non-existent in dressage, one in eventing and two in hunter/jumper disciplines. There were 50 reported horse-related serious injuries; none in dressage, 11 in eventing and 39 in hunter/jumper. In eventing, the majority (91%) of severe horse-related injuries involved the torso and 46% for hunter/jumper.

Table I lists all results for the included cases with torso injury. The percentage of cases with junior participants was 15%, 23%, and 39% for dressage, eventing, and hunter/jumper respectively. Most of the cases involved female riders (90-100% for junior participants and 86-93% for senior riders). The use of torso protection increased from 2020 to 2023 but was still low for hunter/jumper and dressage (Fig. 3). In eventing, both chest guard and air vest were used in 34% of the cases, only chest guard in 39% and only air vest in 2% of the cases. It is worth noting that safety vests were required for the cross-country phase of eventing, but not for dressage or jumping disciplines. Fig. 4 illustrates the distribution of torso injuries per the categories of body areas. In dressage, most injuries were to the back, while in eventing and hunter/jumper the shoulder was most frequently injured.

Most torso injuries were related to falling from a horse (68%, 91% and 94% for dressage, eventing, and hunter/jumper respectively), as illustrated in Fig. 5. In dressage, 30% of cases were other accident scenarios than fall from horse, e.g., kicked by horse (12%) and struck by horse (6%). For approximately 5% of all cases, a fall from horse was combined with another scenario (multiple accidents in Table I), e.g., *"… she lost her balance and fell sideways, and the horse stepped on her chest and/or shoulder".*

Fig. 2. Total number of cases (bars, left axis) and ratio of torso injury (markers, right axis) per event type and year.

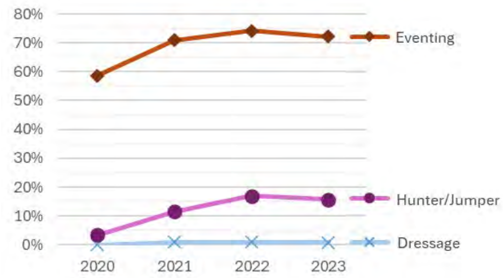

Fig. 3. Chest guard and/or air vest usage.

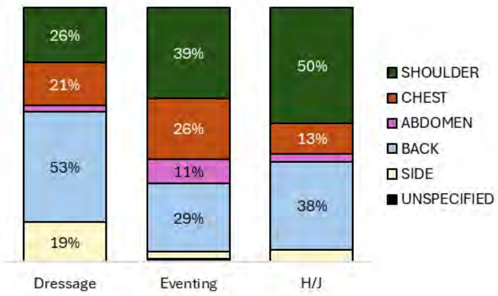

Fig. 4. Body region injured. H/J: hunter/jumper.

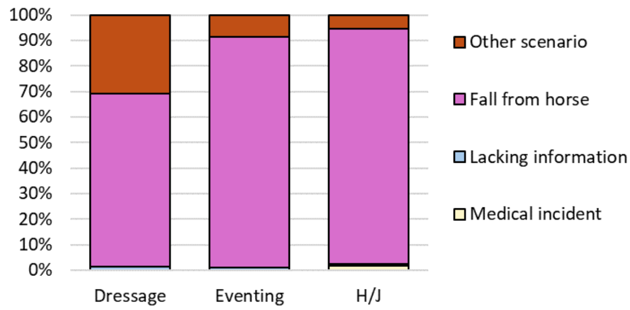

Fig. 5. Distribution of accident types. H/J: hunter/jumper.

TABLE I

ALL CASES WITH TORSO INJURY

	Dressage		Eventing		Hunter/jumper	
Number of cases	68		95		739	
	n	%	n	%	n	%
Junior	10	*14.7*	22	*23.2*	291	*39.4*
Senior	57	*83.8*	73	*76.8*	449	*60.8*
Female	62	*91.2*	85	*89.5*	685	*92.7*
Male	6	*8.8*	10	*10.5*	55	*7.4*
Shoulder	18	*26.5*	37	*38.9*	367	*49.7*
Chest	14	*20.6*	25	*26.3*	96	*13.0*
Abdomen	2	*2.9*	10	*10.5*	25	*3.4*
Back	36	*52.9*	28	*29.5*	279	*37.8*
Side	13	*19.1*	3	*3.2*	37	*5.0*
Chest guard & air vest	0	*0.0*	32	*33.7*	25	*3.4*
Chest guard only	0	*0.0*	37	*38.9*	24	*3.2*
Air vest only	0	*0.0*	2	*2.1*	32	*4.3*
No chest protection	68	*100.0*	24	*25.3*	659	*89.2*
Medical incident	0	*0.0*	0	*0.0*	12	*1.6*
Lacking information	1	*1.5*	1	*1.1*	6	*0.8*
Fall from horse	46	*67.6*	86	*90.5*	680	*92.0*
Other scenario	21	*30.9*	8	*8.4*	41	*5.5*
Dragged by horse	2	*2.9*	0	*0.0*	1	*0.1*
Kicked by horse	8	*11.8*	5	*5.3*	25	*3.4*
Stepped on by horse	0	*0.0*	3	*3.2*	24	*3.2*
Struck by horse	4	*5.9*	3	*3.2*	5	*0.7*
Hit horse	1	*1.5*	1	*1.1*	5	*0.7*
Other	9	*13.2*	2	*2.1*	17	*2.3*
Multiple accidents	3	4.4	6	6.3	36	4.9

Cases involving fall from a horse were further categorised (Table II). Dressage had only 46 cases and is therefore only briefly presented. The majority of dressage riders landed on the ground (91%) and the surface was mostly sand or artificial (84%). Horse speed was high (canter, gallop, or bolt) for the majority of cases (Fig. 6a). The horses' movements were often reported, and almost half of the falls were preceded by bucking (Fig. 6b). Most falls were sideways (note low reporting rate) (Fig. 6c), and the rider often landed on the side and/or back (45% each) (Fig. 6d).

There were 86 fall cases in eventing and 680 in hunter/jumper. Most riders landed on the ground (approx. 90%) and less often on the rails or standards in jumps (8%). In eventing falls, the ground surface was often dirt or grass (82%) and in hunter/jumper it was sand or artificial arena footing (91%). For both disciplines, the horse's gait was canter for most cases (95-96%) and most falls were in close connection to a jump (75-78%) (Fig. 7a, 8a). Many of these falls were because the horse stopped suddenly or did a rapid movement in front of the obstacle (21% eventing, 17% hunter/jumper) or because the horse stumbled or tripped while landing (11% eventing, 4% hunter/jumper) (Fig. 7b, 8b).

Riders frequently fell forwards (62% eventing, 57% hunter/jumper) or sideways (32% eventing, 39% hunter/jumper), but rarely fell backwards or were thrown upwards (Fig. 7c, 8c). Forward falls were categorised into fell off, with a mostly vertical component in the fall (often over the horse's head when it was lowered), and projected forward, with a significant horizontal component of the rider's speed. It was not always possible to determine the type of forward fall from the descriptive texts, see Appendix A for more details on the methodology. Riders were projected forward 2.75 and 1.64 times more often than fell forward, for eventing and hunter/jumper respectively. This is in line with the result that the superior area of the body most frequently made the first impact with the ground or object (head, neck and shoulders in 60-61% of cases) (Fig. 7d, 8d). In hunter/jumper, shoulder impacts occur in 40% of cases, followed by back (26%) and side (22%), Fig. 7d. In eventing, shoulder impacts occur in 30% of cases, followed by side and head and face (27%), Fig. 8d. In very few cases, it was noted that the rider had time to brace for landing with arms or hands (3%).

All simulation results are presented in Appendix B.

TABLE II
CASES WITH TORSO INJURY DUE TO FALL FROM A HORSE
CATEGORIES IN BOLD WITH PERCENTAGE OF ALL CASES, WHILE THE SUBCATEGORIES ARE PRESENTED AS PERCENTAGES PER CASES WITH INFORMATION FOR THAT CATEGORY.

	Dressage		Eventing		Hunter/jumper	
Number of cases	46		86		680	
	n	*%*	n	*%*	n	*%*
Gait information	**18**	***39.1***	**73**	***84.9***	**590**	***86.8***
Backing	0	*0.0*	1	*1.4*	1	*0.2*
Still	0	*0.0*	0	*0.0*	5	*0.8*
Walk	2	*11.1*	0	*0.0*	7	*1.2*
Trot	2	*11.1*	0	*0.0*	7	*1.2*
Canter	6	*33.3*	70	*95.9*	559	*94.7*
Gallop	2	*11.1*	0	*0.0*	1	*0.2*
Bolt	6	*33.3*	2	*2.7*	10	*1.7*
Footing information	**44**	***95.7***	**84**	***97.7***	**672**	***98.8***
Sand / artificial	37	*84.1*	15	*17.9*	612	*91.1*
Dirt / grass	7	*15.9*	69	*82.1*	60	*8.9*
Weather information	**44**	***95.7***	**84**	***97.7***	**665**	***97.8***
Sunny	29	*65.9*	60	*71.4*	453	*68.1*
Artificial light	2	*4.5*	0	*0.0*	84	*12.6*
Cloudy / rainy	13	*29.5*	24	*28.6*	128	*19.2*

TABLE II – CONTINUED

	Dressage		Eventing		Hunter/jumper	
	n	%	n	%	n	%
Horse fell	**3**	***6.5***	**31**	***36.0***	**173**	***25.4***
… on knees			1	*3.2*	15	*8.7*
… on / rolled over rider			14	*45.2*	36	*20.8*
Fall in connection to jump	**0**	***0.0***	**67**	***77.9***	**508**	***74.7***
Before			19	*28.4*	119	*23.4*
Takeoff			0	*0.0*	11	*2.2*
Mid-air			7	*10.4*	68	*13.4*
Ran into / crashed through			2	*3.0*	22	*4.3*
Rotational fall			8	*11.9*	7	*1.4*
Landing			20	*29.9*	153	*30.1*
Right after			9	*13.4*	78	*15.4*
Horse's behaviour information	**38**	***82.6***	**39**	***45.3***	**285**	***41.9***
Bucked	16	*42.1*	3	*7.7*	53	*18.6*
Jumped straight up	1	*2.6*	0	*0.0*	18	*6.3*
Rapid movement or turn	6	*15.8*	4	*10.3*	38	*13.3*
Reared	4	*10.5*	3	*7.7*	5	*1.8*
Spooked or spun	7	*18.4*	2	*5.1*	27	*9.5*
Stopped	1	*2.6*	15	*38.5*	94	*33.0*
Stumbled/tripped/slipped	**3**	***7.9***	**12**	***30.8***	**50**	***17.5***
Rider unbalanced	7	*15.2*	9	*10.5*	107	*15.7*
Rider in contact with horse	5	*10.9*	2	*2.3*	19	*2.8*
Rider's fall direction info.	**13**	***28.3***	**34**	***39.5***	**293**	***43.1***
Forward, fell off	2	*15.4*	4	*11.8*	44	*15.0*
Forward, projected	0	*0.0*	11	*32.4*	72	*24.6*
Forward, unspec.	0	*0.0*	6	*17.6*	50	*17.1*
Sideway	10	*76.9*	11	*32.4*	113	*38.6*
Backward	1	*7.7*	1	*2.9*	6	*2.0*
Upward	0	*0.0*	1	*2.9*	8	*2.7*
Impacting surface information	**44**	***95.7***	**82**	***95.3***	**659**	***96.9***
Ground	40	*90.9*	73	*89.0*	591	*89.7*
Jump	0	*0.0*	7	*8.5*	55	*8.3*
Other object or wall	4	*9.1*	2	*2.4*	13	*2.0*
First contact information	**29**	***63.0***	**33**	***38.4***	**296**	***43.5***
head & face	3	*10.3*	9	*27.3*	52	*17.6*
neck	0	*0.0*	1	*3.0*	9	*3.0*
shoulder	5	*17.2*	10	*30.3*	117	*39.5*
arms & hands	0	*0.0*	1	*3.0*	9	*3.0*
chest & abdomen / prone	1	*3.4*	4	*12.1*	18	*6.1*
back	13	*44.8*	2	*6.1*	78	*26.4*
side	13	*44.8*	9	*27.3*	66	*22.3*
hip	6	*20.7*	1	*3.0*	18	*6.1*
buttocks	2	*6.9*	2	*6.1*	8	*2.7*
legs & feet	0	*0.0*	1	*3.0*	7	*2.4*

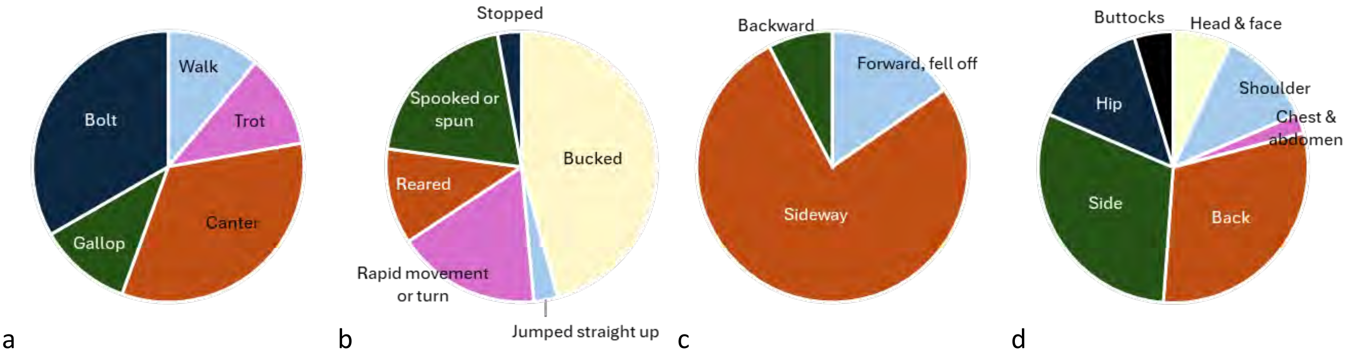

Fig. 6. Dressage, fall from horse; a) Horse's gait reported in 40% of cases. b) Horse's behaviour reported in 83% of cases. c) Rider's fall direction reported in 28% of cases. d) Body area in first impact reported for 63% of cases. For d, multiple body areas could be provided for each case, so the sum is larger than 100%.

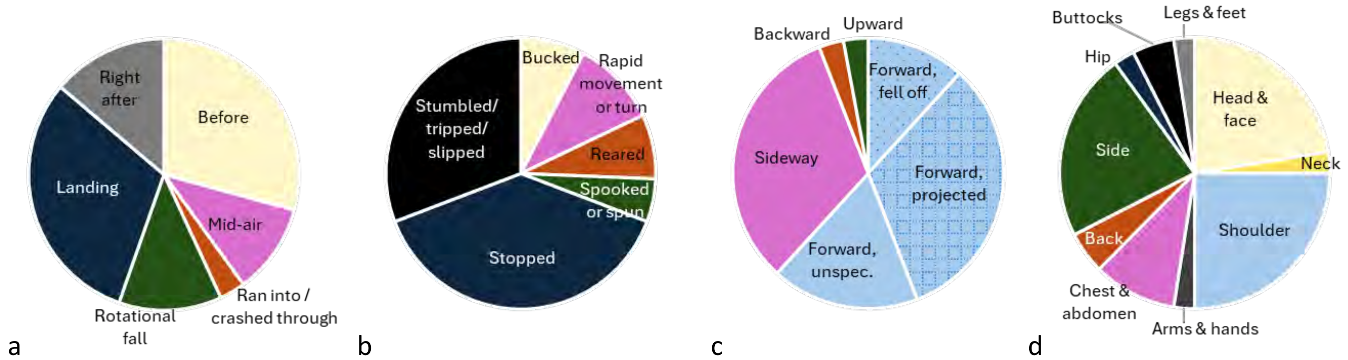

Fig. 7. Eventing, fall from horse; a) Information on connection to a jump was reported in 78% of cases. b) Horse's behaviour reported in 45% of cases. c) Rider's fall direction reported in 40% of cases. d) Body area in first impact reported for 38% of cases. Plots present percentages out of the total number of cases with available information. For d, multiple body areas could be provided for each case, so the sum is larger than 100%.

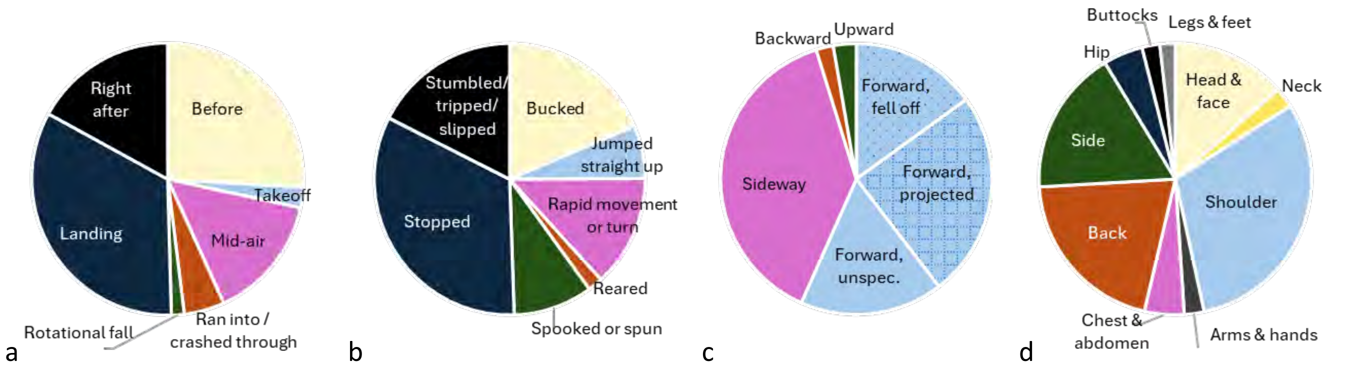

Fig. 8. Hunter/jumper, fall from horse; a) Information on connection to a jump was reported in 75% of cases. b) Horse's behaviour reported in 42% of cases. c) Rider's fall direction reported in 43% of cases. d) Body area in first impact reported for 44% of cases. Plots present percentages out of the total number of cases with available information. For d, multiple body areas could be provided for each case, so the sum is larger than 100%.

IV. DISCUSSION

Equestrian Accidents

We have characterised four years of equestrian incidents and accidents with suspected torso injuries, using anonymised data from the USEF, for three disciplines: dressage, eventing, and hunter/jumper. The majority of accidents were falls from horses. For eventing and hunter/jumper disciplines, more than 90% of torso injuries were the result of a fall from a horse, which is in line with a US trauma centre study that found that 93% of severe chest injuries were caused by falls from horses [6]. In dressage, 68% of torso injuries were caused by falls from horses and the remaining cases mainly by horse kicks and other accidents. To the best of our knowledge, no study has previously presented data separately for dressage. The percentage of torso injuries resulting from a fall from horse is within the range of 60-83% reported in studies that describe horse-related accidents without specifying the discipline [4-7][10][12-16][18-20][23-24][26][28-29][33-35][38-41][43].

Implications on Certification Impact Tests

To evaluate the relevance of impact tests in certification standards, EN 13158 and ASTM F1937 were simulated. In the simulations, the FE safety vests were compressed for 10-25 ms with peak reaction forces of 3 kN and 10 kN, for EN 13158 and ASTM F1937. These rapid events represent severe hoof kicks regarding both peak forces and force duration, as hoof kicks are rapid events with impact durations less than 30 ms and peak forces typically below 2 kN and occasionally up to 9 kN [46]. Frontal impact tolerance for minor injury to the sternum is 4 kN and 9 kN to the chest [47] and lateral impact chest impact tolerances are 10 kN for AIS 3+ [47] and 5.5 kN for 25% risk of AIS 4+ [48]. Therefore, the acceptance criteria of EN 13158 and ASTM F1937 impact testing seem relevant to assess safety vest protection against horse kicks.

The USEF data indicate that riders' fall directions were mostly forwards or sideways. Therefore, we chose to simulate one sideways fall and one forward fall scenario. The horizontal speed component was estimated as 4.5 m/s, within the range of a horse's typical canter speed in jumping [49] and above the typical speed for transitioning from trot to canter of 4 m/s [50]. At international jumping competitions the average horse speed should be between 5.4 - 6.7 m/s, according to FEI Jumping Rules [51]. Horses may reduce their speed if they feel that the rider is coming off and when approaching obstacles. Hence, 4.5 m/s is a relevant horizontal speed. The vertical speed was calculated based on a fall height of 1.5 meters, the approximate height of the centre of gravity for an average female seated on a horse. We chose to simulate a rail impact because riders often fell in connection with jumps (75%), although only 9% of riders were noted to impact the jump rails or standards. A rail impact will result in larger local chest deformations, as compared to landing on flat ground. Results show that wearing a vest was beneficial in frontal chest compression, but not when the chest was compressed laterally in the sideways fall. The rail impact was simulated with an impact velocity of 4.5 m/s, to represent a rider continuing forward when the horse stops, and at 9.0 m/s, to represent speeds during the cross-country phase of eventing (6.7-9.5 m/s according to FEI rules [52]). For the more severe rail impacts, AIS 3+ rib fractures were predicted for all ages, except 25-year-olds with safety vests, indicating that this impact may be at the upper end beyond which safety vests reduce rather than prevent injuries.

Falls have a much longer impact duration than hoof kicks, since the vest material is loaded by the inertia of the decelerating body. Vest compression in the simulated fall accidents had a duration of 60-100 ms, as compared to 10-25 ms for the certification impacts. Neither certification test evaluates the safety vests' impact energy attenuation for the slower compression velocities seen in falls at typical canter speeds. This is important because many modern energy absorbing foams have material properties that are rate dependent, typically with increasing stiffness at higher load rates. Our simulations of certification testing had compression speeds of 3 m/s or higher, whereas the fall accidents had vest compression speeds as low as 0.4 m/s. If the stiffness is too low compared to the thickness of the vest, there is a risk that the vest foam is fully compressed, i.e., bottoms out, before the impacting body mass has stopped decelerating. When the vest bottoms out, the stiffness of the compressed material becomes higher than the chest stiffness and the remaining impact energy will be attenuated by chest deformation. Therefore, we recommend that certification testing is complemented with impact tests at lower velocities, which would require a higher impactor mass to maintain the same impact energy. It should be noted that certification impact tests are done for 25 and 35 J, while the energy is much higher (400 J) when a female torso of 28 kg impacts ground at 4.5 m/s. Further work is needed to design a test setup that represents vest loading seen in falls from horses at different speeds. Results from improved impact test have the potential to guide riders in choosing the safety vest that provides the best protection, for their intended riding activities.

Limitations

The main limitation in our chosen method for characterising the accident data was the quality of free text descriptions and lack videos of the falls. The accidents were characterised based on free text descriptions submitted by licensed officials at USEF competitions. It is evident that these officials have varying backgrounds which is reflected by texts focusing on either medical information, human factors leading up to the events, the accident circumstances, or the welfare of the horse (omitting details on the rider). Therefore, information is not complete for all cases. Information on the type of accident was lacking for less than 2% of cases. However, for the further analysis of cases with fall from horse, the information was less complete. The gait information was available for 85% of cases in eventing and 87% for hunter/jumper, but only for 39% of dressage cases. For eventing and hunter/jumper, around 40% of the cases had information on the rider's fall direction, the horse's behaviour, and the body part in first contact during the impact. There were no significant differences between cases with and without information. Therefore, cases with information seem to be representative of all accidents, but we cannot rule out an unknown bias. Also, there is an inherent subjectivity in the choice of words for the free text descriptions. In an effort to obtain some level of objectivity, the authors jointly agreed on interpretations of different phrases which was then used to characterise accidents, as exemplified in Appendix A for the rider's fall direction.

Another limitation was the inclusion of cases with suspected torso injury only. Therefore, we cannot account for accidents where the protective equipment, namely the safety or air vests, prevented an injury. In dressage and hunter/jumper, chest protection usage was low (1% and 13% respectively) and it seems reasonable that the selection criteria will provide a representative overview of accidents producing torso injury. However, safety vest use is mandatory for eventing in the cross-country phase and therefore the overall usage was 70%, with the remain cases occurring during the dressage or jumping phases where safety vests are not required or in other situations, such as in the stabling area. Hence, our study does not capture cases in cross-country where the vest protected the rider from a torso injury. However, the goal of our study was to provide results that can enhance vest protection by suggesting improvements to the certification tests and not to study how well current safety vests prevent injuries.

It has been outside the scope of this study to simulate the certification with impact testing for shoulder pads. However, we found that riders often landed on their shoulder and had a high percentage of shoulder injury in the USEF data for the eventing and hunter/jumper disciplines. Therefore, it is recommended to assess shoulder pads with a similar method as used herein, which has previously been done for cyclist shoulder injuries [53].

V. CONCLUSION

Most torso injuries involved forward or sideway falls from a horse in connection to a jump, landing on sand or grass and with the first impact to the head or shoulder. Equestrian safety vest certification testing has requirements for impact energy attenuation; however, current impact tests are short duration events, similar to the force and impact duration from severe hoof kicks. They do not represent the loading in fall scenarios, despite that the majority of injuries occurred after falling from a horse. As energy absorbing materials often have rate dependent material properties, further development of impact test methods, by adding test cases that capture the larger span of loading seen in real-life accidents, is warranted.

VI. ACKNOWLEDGEMENTS

We thank USEF for kindly preparing and providing anonymised data on equestrian accidents, Victor Alvarez (Lightness by Design, Sweden) for help with material models for energy absorbing foams, and Folksams Forskningsstiftelse, Sweden, for funding this work.

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VIII. APPENDIX A - INTERPRETATION OF RIDER'S FALL DIRECTION IN USEF ACCIDENT DATA

TABLE III
INTERPRETATION OF FREE TEXT DESCRIPTIONS IN USEF ACCIDENT DATA

Phrase	Interpretation	Phrase	Interpretation
bouncing rider up … and over ...		came (off) over ...	
falling forward		coming over ...	
falling over ...		go over ...	
fell forward ...		rolled over …	Forward, unspecified
fell off over...		tumbled over …	
fell over ... landing on face	Forward, fell off	went forward ...	
fell over neck...		went off...	
fell quickly over ...		went over ...	
fell straight over …		come off … side …	
go down over ...		fell off to side/left/right …	
rider slid down/over/off neck...		fell sideways …	
up and over ...		horse zigged … rider zagged …	Sideway
… kept going ...		rider went right/left	
both did face plant ...		rolled off to … side/left/right …	
catapulted forward ...		slid off …	
continued forward...		slid off (to) side ….	
dartlawned ...		(horse) fall back on rider…	
dislodged over ...		came off backside of horse	
ejected ...		falling backwards …	Backward
fell straight over...		fell behind horse …	
flew off …		fell off backwards …	
flipped over ...		horse reared up and went over …	
front flip		popped off/up/out ...	
horse stopped, but … did not		sending rider up in air	Upward
jarring rider ...		went up …	
jumped forward ... dived	Forward, projected		
launching ...			
pitched ...			
propelled forward ...			
propelled over ...			
rotational fall of rider			
sailed over ...			
sending … over ...			
sent forward ...			
somersaulted …			
thrown ...			
thrown forward …			
thrust forward ...			
went out over ...			
went straight forward ...			

IX. APPENDIX B – SIMULATIONS OF FALL ACCIDENTS AND CERTIFICATION TESTING

Method

Representative accidents were simulated with the explicit FE method using a previously developed and validated HBM representing an average female, the VIVA+ HBM [54]. A generic FE equestrian safety vest model was developed, and its loading pattern in the accident simulations was compared to simulations of the European and US standard impact tests. All simulations were performed in LS-Dyna smp single precision revision R13 (ANSYS/LS-DYNA), meshing, preprocessing and postprocessed was done using LS-Prepost version 4.9 (ANSYS/LS-DYNA), Notepad++ version 8.4, and GNU Octave version 7.1.0 (https://octave.org/).

The VIVA+ 50th percentile female standing model version 0.3.2 (Fig. B1), downloaded from the OpenVT platform [54], was used to simulate representative falls from horses. We chose two fall scenarios that were represented in the USEF data; sideways to the ground and forward into rail. Videos were not available, so we estimated impact speeds based on knowledge of the likely rider height from the ground and typical canter speeds. The sideways fall, where the rider impacts the ground with the shoulder and side first, was simulated with a vertical speed representing a fall from 1.5 meters (5.4 m/s) and a horizontal speed of 4.5 m/s, typical for canter speeds in jumping [49]. A forward fall, where the rider's chest impacts a wooden rail in a fixed jump or fence, was simulated with the two impact velocities of 4.5 and 9.0 m/s.

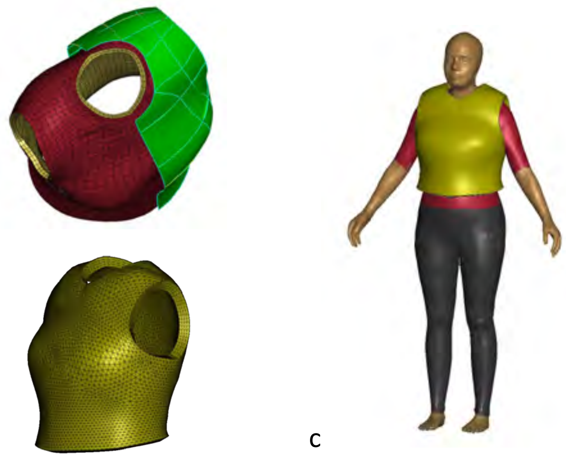
a
b
c

Fig. B1. Simplified safety vest FE model. a) The inside surface geometry in relation to VIVA+ torso skin mesh. b) FE safety vest mesh, c) VIVA+ 50F with safety vest.

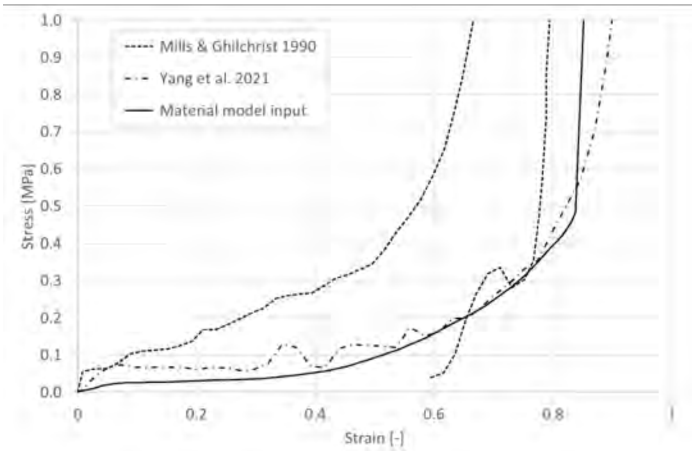

Fig. B2. Stress-strain curve for the energy absorbing foam in the FE safety vest model (solid line) compared to [56] (dash-dotted line) and corridor from [57] (dashed lines).

A simplified equestrian FE safety vest (Fig. B1) was developed for the HBM chest by copying the external skin mesh and projecting it 5 mm outwards. Then, a simplified surface geometry was created from splines, defined by nodes on the projected skin mesh. The new geometry (Fig. B1a) was meshed with shell elements (ELFORM=16) to become the inside of the vest, the outside was created by projecting the shell elements 25 mm outward. The vest thickness was taken from measurements on commercially available equestrian safety vests. The foam material was modelled with tetrahedral elements (ELFORM=13) between the inside and outside surface meshes (Fig. B1b). The material model chosen was a non-linear stress-strain curve, developed for modelling highly compressible low-density foams (MAT_057: LCID according to Fig. B2, HU=1E-7, SHAPE=20). Stress-strain data was taken from [55] and, for relevance, compared to experimental data from [56-57], Fig. B2. The inside and outside surfaces were given linear elastic material properties relevant for nylon (MAT_001: E= 500 MPa, PR=0.32). Total mass of the vest model was 922 grams.

The ground model had solid elements (ELFORM=1) and linear elastic material properties (MAT_001: E=80 MPa, PR=0.3) representing loose to medium well-graded sand [58]. The fence rail was 80 cm in diameter, 2.4 m long and rigidly fixed at both ends. It was modelled with solid elements (ELFORM=1) and a linear elastic material (MAT_001: E=10 GPa, PR=0.3, RO=500 kg/m3) representative of pine wood, e.g., [59]. Sliding contacts were defined between the safety vest model and the VIVA+ skin (CONTACT_AUTOMATIC_SURFACE_TO_SURFACE:

FS=0.3, FD=0.3), and between the ground or wooden rail and the VIVA+ skin and the safety vest model (CONTACT_AUTOMATIC_SURFACE_TO_SURFACE: FS=0.7, FD=0.7).

In all HBM accident simulations (Fig. B3), rib strain was output and processed according to [60] to provide the risk of rib fractures for riders of 25, 45 and 65 years of age and resultant chest compression was output to calculate the Chest Compression (C), defined as the chest deformation divided by initial chest depth, and the Viscous criteria (VC), defined as the chest compression multiplied with the chest deformation velocity. These criteria were developed for crash test dummies in frontal impacts. The VIVA+ HBM does not have instrumentation to measure chest compression. Therefore, three set of nodes were used to calculate the anterior-posterior chest compression (red arrows illustrated in Fig. B4). The maximum C and VC were used to predict injury. C_{max} = 30% predicts an AIS2+ injury according to [61]. VC_{max} should be less than 1 m/s and has been shown to correlate well with injury risk [62].

Lastly, models were created to simulate EN 13158:2018 and ASTM 1937. The anvil and impactors were modelled with solid elements (ELFORM=1) and linear elastic materials properties (MAT_001: E=210, PR=0.28, RO=7.85E+04) representing steel. The superior part of the impactor was modelled as rigid locked in all degrees of freedom except for Z-motion. According to the standards, the impactors had masses of 2.5 and 5.0 kg and initial Z-velocities of 5.3 and 3.15 m/s for EN 13158 and ASTM 1937, respectively. The test material was modelled as a cylinder with 40 cm in diameter and the same thickness, element formulation and material model as described above for the safety vest (Fig. B5-6). Contact was defined between the test material and impactor/anvil (CONTACT_AUTOMATIC_SURFACE_TO_SURFACE: FS=0.15, FD=0.1).

a

b

Fig. B3. HBM simulations of equestrian falls from horse, a) sideways fall on ground, and b) frontal fall with chest impact into wooden rail.

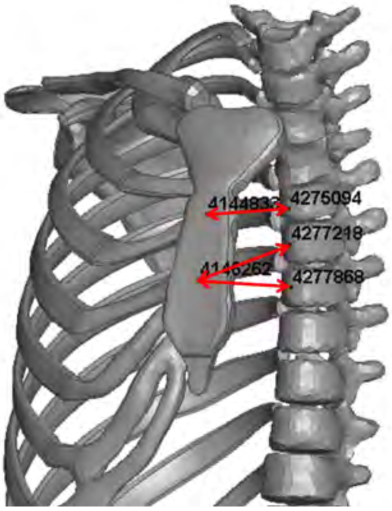

Fig. B4. Illustration of three pairs of nodes (arrows) used to measure chest deformation.

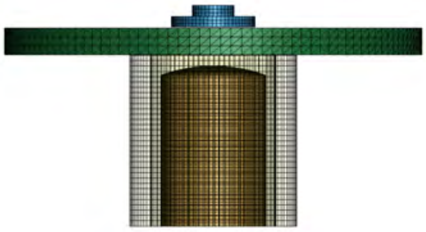

Fig. B5. Model of EN 13158 with part of safety vest (green), impactor (blue) and anvil (yellow) inside a cylinder (transparent mesh).

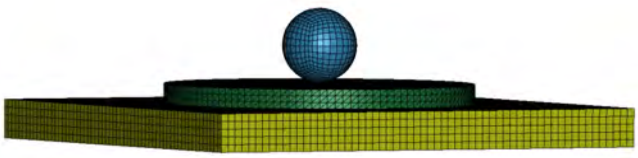

Fig. B6. Model of ASTM F1937 with part of safety vest (green), impactor (blue) and flat anvil (yellow).

Results

All accident simulations successfully finished, and results are presented in Table IV. The only severe accident scenario was the 9 m/s chest impact into a wooden rail. The safety vest reduced the average number of predicted fractures from 3 to 1 for a 25-year-old and reduced the values of the compression and the viscous criteria, although still above injury thresholds. The sideways fall to ground predicted 20%, 50% & 100% risk of sustaining one rib fracture for the 25-, 45-, and 65-year-olds, respectively. It was the first rib on the impacted side that had the highest risk of fracture (21-82%). The safety vest did not reduce the risk of rib fractures, and in fact it increased the risk for 65-year-olds because of a changed rib cage deformation that increased the risk for the 9th rib from 3% without to 32% with the safety vest (Fig. B7). The viscous criterion was reduced below the injury threshold, indicating a protection benefit for soft tissue injury at the later stage of the impact when the rider rolls over into a prone position and the chest compresses in the anterior-posterior direction.

In the simulations of EN 13158 and ASTM F1937 impact tests, the FE safety vests were compressed for 10 - 25 ms with peak reaction forces of 3 kN and 10 kN, respectively, which are below the allowable thresholds of 4 kN for EN 13158 and 300 g for ASTM F1937 (equivalent to a reaction force of about 15 kN). The ASTM F1937 peak acceleration (218 g) and impact duration (10 ms) compared well to the experimental test data in Fig. 1, verifying that our safety vest FE model had a similar response to a commercially available safety vest.

Table V compares deformation of the FE safety vest model in the accident scenarios to the European and US certification impact tests. The impact duration during standard impact tests were much shorter than during the falls. The maximum compression in EN 13158 was similar to the 4.5 m/s chest impact into a wooden rail, but the compression velocity was much higher. The ASTM F1937 maximum compression and compression velocity was similar to the 9 m/s rail impact. Both standards had higher maximum compression and much higher compression velocity than the sideways fall to ground. Hence, the FE vest deformation in the simulated falls was not captured well by either standard test method.

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TABLE IV
RESULTING INJURY PREDICTION WITH VIVA+ IN ACCIDENT SIMULATIONS

Simulation		Sideways fall to ground		Forward fall into wooden rail, 4.5 m/s		Forward fall into wooden rail, 9 m/s	
Safety vest		no	yes	no	yes	no	yes
Predicted average number of fractured ribs	25 yo.	0.2	0.2	0	0	3.9	1.0
	45 yo.	0.5	0.5	0	0	5.6	3.2
	65 yo.	1.0	1.2	0.2	0	8.4	6.7
Compression criterion	%	17 - 18	4 – 5	14 – 22	11 – 17	57 – 67	51 – 61
Viscous criterion	[m/s]	1.6 – 1.9	0.3 – 0.4	0.9 – 1.8	0.5 – 1.0	6.3 – 7.9	5.1 – 6.2

TABLE V
MEASUREMENTS ON FE SAFETY VEST. *AT LOCATION OF MAXIMUM COMPRESSION

		Sideways fall to ground	Forward fall into wooden rail, 4.5 m/s	Forward fall into wooden rail, 9 m/s	EN 13158	ASTM F1937
*Max. compression**	%	52	54	85	60	82
*Duration of compression**	[ms]	100	90	60	25	10
*Max. compression velocity**	[m/s]	0.9	1.2	3.0	3.8	3.0
Max. internal energy	[J]	166	58	183	28	20

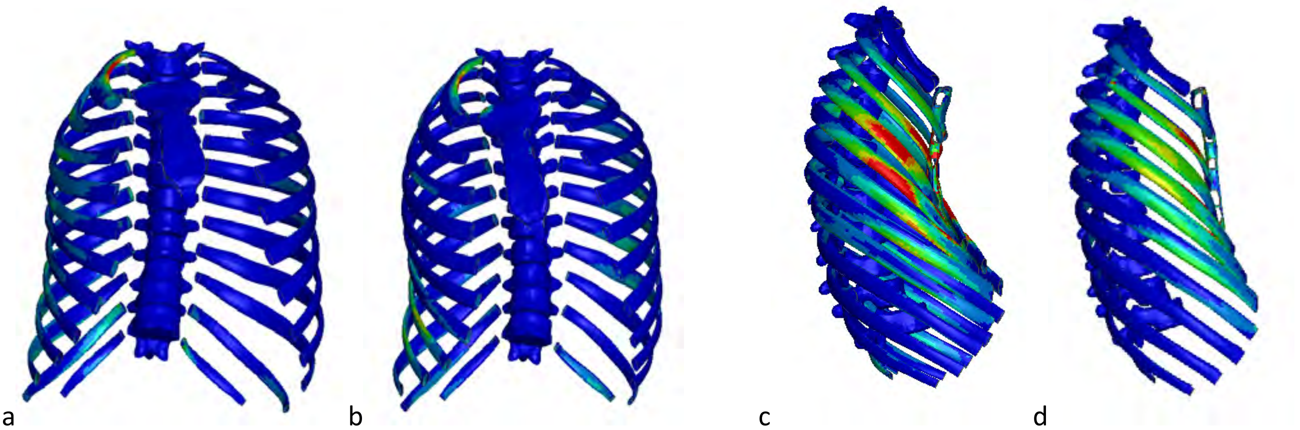

Fig. B7. Maximum principal strain in the ribs for the sideways fall to ground without (a) and with safety vest (b), and for the forward fall into wooden rail at 9 m/s without (c) and with safety vest (d). Fringe scale from blue = 0 to red = 0.15 strain.