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Virtual Assessment of a Representative Torso Airbag under the Fall from Height Impact Conditions

Raúl Aranda-Marco * and Steffen Peldschus

Biomechanics and Accident Analysis, Institute of Legal Medicine, Ludwig-Maximilian Universität München, 80336 Munich, Germany; steffen.peldschus@med.uni-muenchen.de
* Correspondence: raul.aranda@med.uni-muenchen.de; Tel.: +49-89-2180-73364

Abstract: A fall from height is the main cause of serious injuries and fatalities in occupational and work-related accidents, especially construction. Falls from scaffolds, ladders, or roofs are very frequent accident scenarios. Especially for those falls from a height of 1 m to 6 m, the use of wearable smart airbags has been proposed to mitigate possible torso injuries. In this study, a virtual assessment of such an inflatable protector was conducted using numerical simulations and finite element human body models in order to determine its impact-protection performance under realistic impact conditions and identify its possible limitations. The findings obtained from the simulation study showed a significant protective effect provided by the airbag, mitigating a multiple rib fracture scenario and reducing the risk of internal organ injuries for those falling from four meters of height or less. The use case analyzed in this research demonstrates the suitability of using a virtual environment not only to evaluate current protectors but also to develop new protector devices, which could improve occupational safety.

Keywords: occupational safety; fall from height; virtual assessment; airbag protector; human body models; finite elements

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1. Introduction

Occupational injuries are a public health issue and lead to huge medical and social costs [1,2]. Among all unintentional injuries, work-related falls represent the second leading cause of death worldwide after traffic accidents [3,4]. Frequently, occupational accidents that lead to permanent disabilities and a high rate of fatalities occur within the construction industry [5]. Among different construction accidents, falls are the leading cause of serious injuries (48%) and fatalities (30%) [6]. In particular, a fall from height (FFH) is the main cause of serious injuries and fatalities [7]. A fall from height represented 13% and 23.5% of all occupational fatalities in 2021 in the USA and UK, respectively [8,9].

Previous studies found that falls from scaffolding [10], from ladders [11], and from roofs are the most frequent causes of workplace injuries related to falls from height [12]. Regarding height, falls from 1 to 6 m in height were identified as one of the most common accident scenarios [13,14]. According to the statistics published by the German Federal Institute of Occupational Safety and Medicine (BAUA), between 2006 and 2015, 50% of all fatalities reported due to a fall from height occurred from a fall between 2 and 5 m of height [15]. In order to improve the safety of work conditions, many technologies and countermeasures have been developed that could help predict, prevent, and mitigate the risk of falls from height [16]. Some authors proposed the use of safety rule checking systems to provide mechanisms to identify and analyze fall risks [17]. To prevent fall accidents, some authors noted the necessity of specific training for workers [18,19]. The use of new technologies such as augmented reality and virtual reality has already been suggested to perform hazard simulations and visualizations, helping workers prepare better for potential risks [20]. Prevention through design has already been proposed, avoiding fall risks by eliminating their causes in the early design and planning stages [21]. Other studies insisted on the implementation of on-site precautionary measures such as reducing unguarded openings and the use of personal fall arrest systems (PFAS) [22,23]. Additionally, modern technologies, including sensors and alarm technologies, have been integrated into wearable devices to enhance the effectiveness of traditional equipment [24]. However, despite the known risk of severe injuries, many workers still do not use personal arrest systems [25]. Although skin and soft tissue injuries, as well as upper or lower extremity fractures, are the most frequent injuries, the majority of severe injuries are located in the head and thorax body regions [26].

The use of a safety helmet to protect the head has been associated with the prevention of intracranial injury resulting from work-related falls from a height up to 4 m [27]. Analogically to the helmet, wearable smart airbag protectors that are available on the market have arisen as a possible solution to protect the thorax, providing impact absorption in case of falls from 2 to 5 m in height [28,29]. A wearable smart airbag could be defined as an inflatable protector covering the thorax and the back, which would be worn by the worker and would be automatically activated when a fall from height was detected. The use of this kind of protection system by motorcyclists to mitigate thorax injuries such as rib fractures has been analyzed in previous works, showing limited protection [30–32]. However, the possible benefit of the use of thorax protectors to prevent work-related thorax injuries due to a fall has not been investigated. We propose to use numerical simulations in combination with finite element human body models to evaluate this kind of protector, especially for those situations that cannot be physically tested due to a high risk of injury. Numerical models of the human body have been used previously for the assessment of other personal protective equipment, such as motorcycle helmets [33,34], bicycle helmets [35,36], and neck braces [37]. The objective of this study is to obtain, based on biomechanical criteria, a preliminary estimation of the potential impact protection of a torso airbag under the impact conditions of a fall from a height. More specifically, the study is meant to support estimations of the fall heights at which protection can be expected when using an airbag system with current technology.

2. Materials and Methods

2.1. Finite Element Models

The evaluation of the protection potential of an airbag for the torso was conducted using finite-element numerical simulations. All simulations were conducted using the human body model GHBMC M50 Detailed Pedestrian Version 1.6 [38], which is a current state-of-the-art, finite element human body model formed of 1.25 million nodes and 2.35 million elements, comprising its 1005 parts. The model represents the anthropometry of a 50th percentile male with a height of 1.75 m and a weight of 77.5 kg. The geometry of this model was developed based on MRI and CT scans obtained from a male volunteer. This human body model was equipped with a self-modeled generic airbag protector covering the anterior and posterior sides of the torso (Figure 1). The generic airbag finite element model, with a total of almost 29,000 elements, was modeled to imitate the geometry, shape, and characteristics of the currently available commercial airbags. Once inflated, the airbag reaches a thickness of 8 cm with a relative pressure of 0.6 bars for a total gas volume of 32 L.

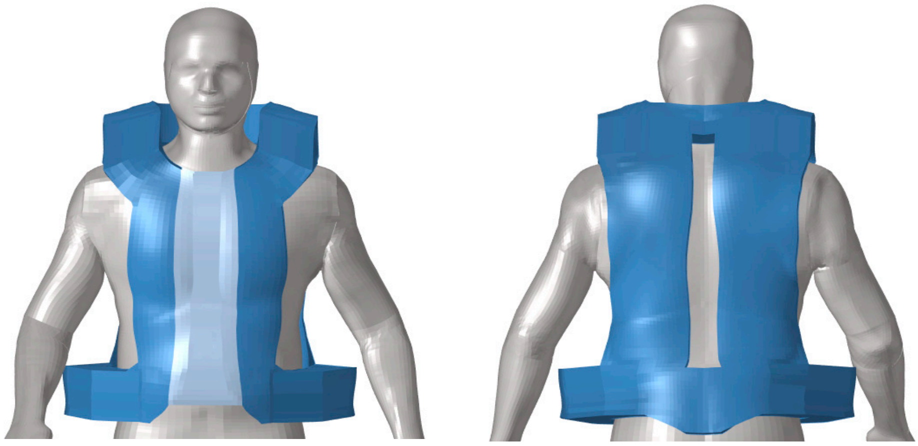

Figure 1. Anterior and posterior views of the GHMBC model equipped with the FE airbag model.

2.2. Simulation Study

The load case selected for this evaluation was the impact of the posterior side of the human body against the ground due to a fall from a height. The human body model was positioned at five degrees' inclination to the ground to implement direct impact with the ground. Six different fall heights (from 1 m to 6 m) were simulated, which, in terms of impact conditions, means an impact was simulated at six different impact velocities (Table 1).

Table 1. Simulated fall heights and their corresponding impact velocities.

Fall Height (m)	Impact Velocity (m/s)
1	4.42
2	6.26
3	7.66
4	8.85
5	9.89
6	10.84

Each of those fall scenarios was simulated with and without an airbag in order to obtain a direct comparison between the protected and the non-protected states. As the focus of this study was to estimate the impact protection performance of a torso airbag, the impact velocity was prescribed, and only the last milliseconds before the impact and the impact phase itself were calculated. A total of 12 finite element numerical simulations were implemented to determine the protection performance of a torso airbag under the impact conditions of a fall-from-height impact situation. All simulations were conducted using the LS-Dyna solver code.

2.3. Evaluation Criteria

Non-protected and protected impact situations were compared, focusing on three biomechanical criteria: a strain-based analysis of the rib cage, the thorax deflection, and the Viscous Response. A strain-based analysis was conducted to determine the possible number of rib fractures. The ultimate strain values of 1.8% and 13% were set for the cortical and trabecular bone rib materials, respectively [39]. The thorax deflection was also measured, which allowed for the severity of skeletal injuries to be determined according to the Abbreviated Injury Scale (AIS) through the application of the Compression Criterion [40,41]. The measurement of the thorax deflection also allowed for the maximal Viscous Response to be calculated, as well as the following application of the Viscous Criterion to assess the probability of a severe or more (AIS 4+) soft-tissue injury [42,43]. In addition to these biomechanical criteria, the acceleration at the vertebrae C7, T8, and T12 was measured to estimate the possible reduction in the loads supported by the spine.

3. Results

The findings obtained from the simulation of a fall from 1 to 6 m height resulting in a direct impact to the back without and with the airbag protector are reported in Tables 2 and 3, respectively. It was possible to simulate the complete impact phase for all fall scenarios except for the case of a fall from a height of 6 m without an airbag. In this case, a numerical error interrupted the calculation due to some nodes having out-of-range forces in some soft-tissue shoulder parts.

Table 2. Simulation results for six different fall heights without an airbag.

Fall Height (m)	Deflection (mm)	Viscous Response (m/s)	Max Acc C7 (g)	Max Acc T8 (g)	Max Acc T12 (g)	Number of Rib Fractures
1	37	0.51	174	200	196	0
2	46	0.87	237	359	373	2
3	50	1.1	258	474	534	4
4	55	1.46	361	575	694	6
5	57	1.72	533	475	603	7
6 *	38 *	1.75 *	370 *	2046 **	739 *	6 *

* The simulation was interrupted due to a numerical error. Last calculated state. ** Low plausible value, probably generated by a numerical error during calculation.

Table 3. Simulation results for six different fall heights with an airbag.

Fall Height (m)	Deflection (mm)	Viscous Response (m/s)	Max Acc C7 (g)	Max Acc T8 (g)	Max Acc T12 (g)	Number of Rib Fractures
1	27	0.16	107	50	46	0
2	33	0.25	122	67	53	0
3	39	0.4	156	133	100	1
4	48	0.87	249	220	206	2
5	49	1.15	542	446	393	4
6	50	1.48	691	648	612	6

The values of deflection without an airbag show low compression of the rib cage. According to the Compression Criterion, an injury severity of AIS 1 would be reported for those cases with a deflection above 55 mm. Therefore, for a fall from 1 m to 3 m, no injury would be expected. For a fall between 4 and 5 m, the airbag would be able to reduce enough the thorax compression obtained without the airbag (55 mm and 57 mm deflection, respectively), reducing the injury severity from AIS 1 to AIS 0.

The maximal Viscous Response obtained from the fall scenarios without an airbag tends to increase with the impact velocity, which means that it also increases with the fall height. This tendency remains for simulations with airbags. However, in comparison, the inflatable protector would be able to reduce all maximal Viscous Response values. The possible benefit of the airbag according to this parameter is more evident after the translation of the obtained maximal Viscous Responses into the probability of suffering an AIS 4+ soft-tissue injury by applying the Viscous Criterion. For the case of a fall from 1 to 3 m, the maximal Viscous Response varies from 0.16 m/s to 0.4 m/s, all of which, according to this criterion, could translate into a 0% risk of AIS 4+ injury. A positive effect of the airbag is also observed by the reduction in the Viscous Response from 1.46 m/s to 0.87 m/s in a fall from a height of 4 m. This effect would be translated into a reduction in the probability of severe injury, limiting this risk to 20% from an initial 95% probability. In a fall from a height of 5 m, the Viscous Response would also be reduced from 1.72 m/s to 1.15 m/s; however, despite the airbag, a high risk of AIS 4+ still exists (65%). Although the simulation from a 6 m height without an airbag was not totally completed, the preliminary value of 1.75 m/s would be reduced by the performance of the airbag, obtaining a 1.48 m/s maximal Viscous Response. However, despite this improvement, the risk of a severe injury would decrease by only 1% (from 100% to 99%) and, as a consequence, no significant protection effect from the airbag is expected.

The effect of an airbag protector could also be observed at the maximal acceleration values, measured at three different vertebrae (C7, T8, and T12). The airbag would be able to considerably reduce the maximal acceleration measured at T8. Reductions of 75%, 81%, 71%, and 61% were observed for the cases of a fall from 1 m to 4 m, respectively. Similarly, considerable reductions varying between 70% and 85% would be expected in the maximal acceleration values measured at T12. However, the maximal acceleration mitigation would not be as significant in a fall from a 5 m height at both vertebrae, where variations of 6% and 34%, respectively, were reported. For a 6 m fall height, a reduction of at least 17% would be expected at vertebra T12. The accelerations measured at C7 do not suggest such a remarkable positive effect of the airbag when compared with the measurements carried out at the thoracic vertebrae. For a fall from a height of up to 4 m, the reduction in the acceleration values would be between 31% and 48%. In the case of a fall from a height of 5 m, the results with the airbag show a slight increase in the acceleration values.

Finally, the strain-based analysis of the rib cage from the simulations without an airbag shows that a minimum of zero rib fractures would be expected in a fall from 1 m and a maximum of 7 rib fractures would be expected in the case of falling from 5 m. As previously mentioned, the simulation of a fall from a height of 6 m was interrupted due to a numerical error. Considering the calculated time, at least six rib fractures would occur. The airbag could reduce the number of rib fractures expected in a fall from a 2 m height from 2 to 0. The inflatable protector could also prevent the fracture of 3 and 4 ribs in the case of a fall from 3 m and 4 m, respectively. A light mitigation effect could also be expected when falling from a height of 5 m, where the number of rib fractures could be reduced from 7 to 4 ribs. Figures 2 and 3 show the strain contour plot of the rib cage corresponding to a fall from a 4 m height without and with an airbag, respectively, as an example.

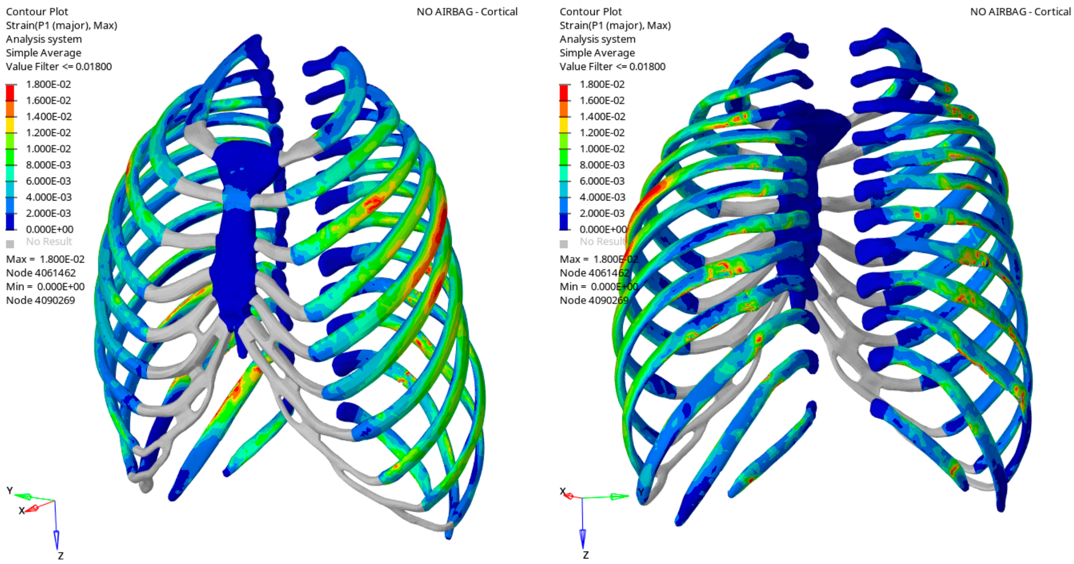

Figure 2. Strain values corresponding to the cortical bone of the human body model rib cage for a fall without airbag from 4 m height.

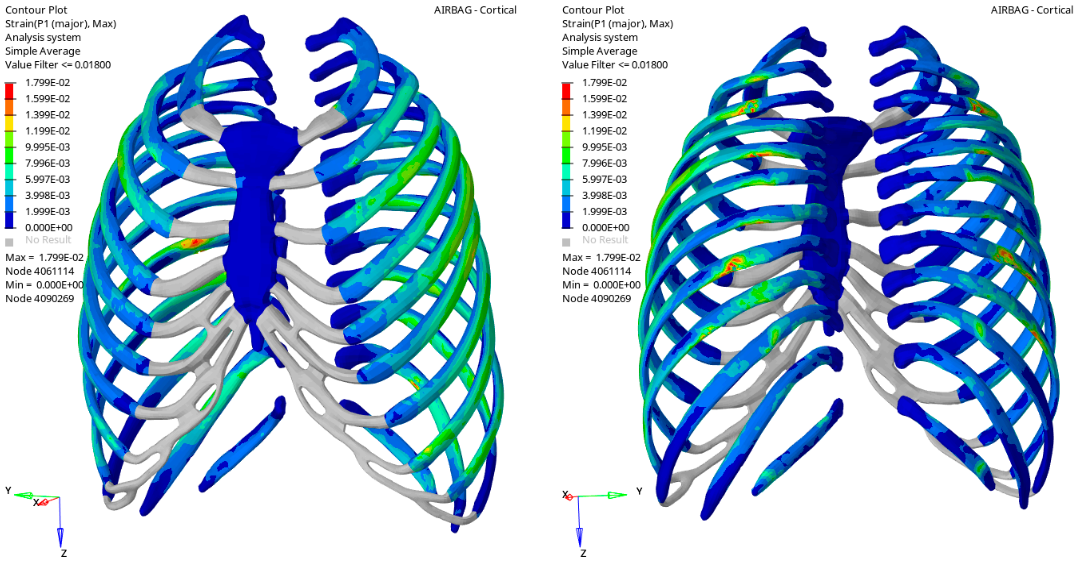

Figure 3. Strain values corresponding to the cortical bone of the human body model rib cage for a fall with an airbag from 4 m height.

4. Discussion

In this research, a first evaluation of the impact protection performance of a torso airbag under the impact conditions derived from a fall from height was performed. In a numerical study, in combination with a finite element human body model, six different fall heights were simulated to assess the possible benefit of wearing an inflatable protector. The protection effect of the airbag was analyzed by comparing the non-protective and protective impact situations according to three biomechanical criteria: thorax deflection, Viscous Response, and number of rib fractures. In addition, the peaks in acceleration at vertebrae C7, T8, and T12 were compared.

The results indicate that the effectiveness of the airbag in mitigating injury severity varies depending on the fall height. A very positive effect of the airbag is observed in the case of a fall between 1 and 3 m. For these fall heights, the airbag would be able to reduce the Viscous Response, simultaneously eliminating the risk of severe soft-tissue injury according to the Viscous Criterion. The airbag would prevent any rib fracture caused by a two-meter fall, and only one fracture would be expected in the case of a three-meter fall. The positive effect of the airbag can also be observed through the considerable reduction in the acceleration peak at the spine, especially at T8 and T12. The significant influence of the protection effect of the airbag was also observed in a fall from a height of 4 m. The risk of AIS4+ soft-tissue injury, according to the Viscous Criterion, would be limited to 20%, and the airbag would reduce the number of rib fractures from 6 to 2. The acceleration peaks would be decreased, varying from the 31% reduction found at vertebra C7 to the 70% reduction observed at T12. In a fall from a height of 5 m, the airbag would be able to mitigate the impact's severity but not significantly. Despite the airbag mitigation, the value of the Viscous Response would mean a 65% risk of severe soft-tissue injury, and the fracture of four ribs would still occur. In addition, a remarkable reduction in acceleration (34%) was only observed at T12. As previously mentioned, the simulation of a fall from a 6 m height without an airbag was only partially calculated; therefore, it was not possible to conduct a direct comparison with the airbag simulation. Regarding the results obtained for the other no-airbag simulations, the observed increasing trend of the considered parameters with the increase in fall height suggests that, for a 6 m fall, these parameters would also increase. Regarding the airbag simulation, six ribs would be fractured, and a 99% risk of an AIS 4+ injury was calculated; therefore, initially, a significant influence on injury mitigation caused by the airbag would not be expected.

The values of thorax deflection were low in all cases, and, according to the Compression Criterion, the highest values would not imply an injury severity level higher than AIS 1. Thorax deflection measures the compression of the anterior part of the rib cage with regard to the posterior part of the body, and the Compression Criterion was mainly developed for injury severity assessments of frontal impacts. The low values obtained for this kind of impact indicate a low deformation of the rib cage and suggest the low importance of this parameter for posterior impacts when evaluating the airbag's performance. However, thorax deflection should be considered in the evaluation of the airbag under other load conditions, especially during frontal impact. The low deflection values also indicate that little energy was dissipated during the impact, caused by the deformation of the rib cage. This state was confirmed during the strain-based analysis of the rib cage. Most of the rib fractures were found at the posterior part of the rib cage and not at the anterior part or the sides, suggesting a direct dissipation of the impact energy caused by breaking the bone material. In addition, the acceleration peak values were found to be generally high for all the impact situations. An explanation for these values could rely on the material of the vertebrae in the model. The vertebrae are implemented with a rigid material, preventing a break in this bone material; therefore, the absorption of impact energy is considerably reduced and, in consequence, higher acceleration peaks are generated.

The findings presented in this research should be considered carefully because there are some existing limitations. Firstly, in this study, only one impact scenario (a direct back impact at an almost horizontal position) was considered in the evaluation of the protection performance of the airbag. This scenario was selected first because the back was reported as the part of the body that most frequently touches the ground in the case of a fall from height [44]. However, for a deeper evaluation of the airbag's protection performance, other impact scenarios, such as side impact or frontal impact, should also be considered in further studies. In addition, as the objective of this study was to evaluate the impact protection of a torso airbag, only the impact phase was simulated, and a direct impact was assumed to be the worst-case scenario without considering the fall kinematics or other possible secondary impacts during the fall.

Another limitation of this study is that the airbag finite element model used for the evaluation of the protection performance could not be fully validated. The finite element airbag model used in this research is a generic model that was modeled by adopting possible realistic parameters such as the pressure, thickness, and volume of currently available commercial airbags, but it does not exactly reproduce a model that is available on the market. Other factors, such as airbag ergonomics and the adjustments to fit the human body, were not contemplated; therefore, its impact response might slightly differ from its real behavior. In addition, this work was focused on the impact protection performance of the airbag, and other important characteristics of smart personal protective equipment, such as correct accident detection and the logarithm that manages the airbag activation, were not considered. The impact situation was always calculated assuming full inflation of the airbag at a prescribed pressure value, and possible alterations in the inflation process were not considered. Nevertheless, taking these limitations to the airbag modeling into account, it was possible to complete a realistic preliminary estimation of the impact protection performance of such a protector, which could be representative of some of the products that are available at present.

Some limitations of the human body model, GHBMC, should also be considered. The model used for this study is derived from the occupant version and developed for pedestrian accident scenarios. This means that the model is more oriented toward the calculation of computational injury mechanics and the prediction of possible injuries in body regions such as the head, neck, thorax, and low extremities than in the thoracic part of the spine. Therefore, more efforts are needed to implement injuries to this body region, especially regarding the modeling of bone material, the vertebral interaction, and the kinematics of this part of the spine. In addition, the model that was used is what is called a passive model. This means that no muscle activation was implemented in the finite element human body model during the simulation, and its possible effects on the results were not analyzed. However, despite these limitations, the use of finite element human body models and numerical simulations for the virtual assessment of personal protective equipment or the simulation of different accident scenarios and loading conditions should be considered a powerful tool for further development. The higher biofidelity, as well as the more realistic kinematics of the human body models in comparison with anthropometric testing devices, have already been demonstrated under diverse impact conditions [45,46].

5. Conclusions

The study presented in this paper showed the suitability of numerical simulations and finite element human body models for the evaluation of personal protective equipment for work-related activities. The virtual assessment of protectors enables the performance of such a device to be analyzed in realistic scenarios that could not be performed with volunteers due to the high risk of injury. In addition, the use of finite human body models provides more biofidelity than any other kind of human body representation, such as anthropometric test devices. To demonstrate the suitability of this method, the evaluation of a torso airbag, which could mitigate the injuries derived from the impact produced by a fall from height, was chosen as the use case in this study. After the simulation of a back impact produced by falls from different heights, it was found that such an airbag could provide significant protection for a fall from 4 m of height, mitigating the fracture of multiple ribs and reducing the risk of severe injuries to the internal organs. Under the conditions considered in this analysis, such an airbag system constitutes a form of potential personal protective equipment.

The benefit of the virtual assessment of protectors using human models lies not only in the determination of the performance limits of a protector but also in the implementation of different parametric studies, which makes the development of more effective protective equipment feasible.

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References

1. Baron, S.L.; Steege, A.L.; Marsh, S.M.; Menéndez, C.C.; Myers, J.R. Nonfatal work-related injuries and illnesses—United States, 2010. *CDC Health Disparities Inequalities Rep. USA* **2013**, *62*, 35.
2. Dembe, A.E. The social consequences of occupational injuries and illnesses. *Am. J. Ind. Med.* **2001**, *40*, 403–417. [CrossRef]
3. Mangharam, J.; Moorin, R.; Straker, L. A comparison of the burden and resultant risk associated with occupational falls from a height and on the same level in Australia. *Ergonomics* **2016**, *59*, 1646–1660. [CrossRef]
4. World Health Organization. Available online: https://www.who.int/news-room/fact-sheets/detail/falls (accessed on 8 May 2023).
5. Chan, A.P.; Wong, F.K.; Chan, D.W.; Yam, M.C.; Kwok, A.W.; Lam, E.W.; Cheung, E. Work at height fatalities in the repair, maintenance, alteration, and addition works. *J. Constr. Eng. Manag.* **2008**, *134*, 527–535. [CrossRef]
6. Hu, K.; Rahmandad, H.; Smith-Jackson, T.; Winchester, W. Factors influencing the risk of falls in the construction industry: A review of the evidence. *Constr. Manag. Econ.* **2011**, *29*, 397–416. [CrossRef]
7. Zhang, M.; Fang, D. A cognitive analysis of why Chinese scaffolders do not use safety harnesses in construction. *Constr. Manag. Econ.* **2013**, *31*, 207–222. [CrossRef]
8. BLS. Fatal Occupational Injuries by Event or Exposure. Available online: https://www.bls.gov/charts/census-of-fatal-occupational-injuries/fatal-occupational-injuries-by-event-drilldown.htm (accessed on 28 April 2023).

9. HSE. Health and Safety Executive, Work-Related Fatal Injuries in Great Britain. Available online: https://www.hse.gov.uk/statistics/fatals.htm (accessed on 28 April 2023).
10. Nadhim, E.A.; Hon, C.; Xia, B.; Stewart, I.; Fang, D. Falls from Height in the Construction Industry: A Critical Review of the Scientific Literature. *Int. J. Environ. Res. Public Health* **2016**, *13*, 638. [CrossRef] [PubMed]
11. DiDomenico, A.T.; Lesch, M.F.; Blair, M.F.; Huang, Y.-H. Reaching on ladders: Do motivation & acclimation affect risk taking? *Prof. Saf.* **2013**, *58*, 50–53.
12. Dong, X.S.; Wang, X.; Largay, J.A.; Platner, J.W.; Stafford, E.; Cain, C.T.; Choi, S.D. Fatal falls in the U.S. residential construction industry. *Am. J. Ind. Med.* **2014**, *57*, 992–1000. [CrossRef]
13. Huang, X.; Hinze, J. Analysis of construction worker fall accidents. *J. Constr. Eng. Manag.* **2003**, *129*, 262–271. [CrossRef]
14. Zlatar, T.; Lago, E.M.G.; Soares, W.D.A.; Baptista, J.d.S.; Barkokébas Junior, B. Falls from height: Analysis of 114 cases. *Production* **2019**, *29*, e20180091. [CrossRef]
15. Bleyer, T.; Bentz, I.; Fähnrich, R. *Tödliche Arbeitsunfälle: Absturzunfälle*; Bundesanstalt für Arbeitsschutz und Arbeitsmedizin: Dortmund, Germany, 2017.
16. Newaz, M.T.; Ershadi, M.; Carothers, L.; Jefferies, M.; Davis, P. A review and assessment of technologies for addressing the risk of falling from height on construction sites. *Saf. Sci.* **2022**, *147*, 105618. [CrossRef]
17. Takim, R.; Zulkifli, M.H.; Nawawi, A.H. Integration of automated safety rule checking (ASRC) system for safety planning BIM-based projects in Malaysia. *Procedia-Soc. Behav. Sci.* **2016**, *222*, 103–110. [CrossRef]
18. Camino Lopez, M.A.; Ritzel, D.O.; Fontaneda, I.; Gonzalez Alcantara, O.J. Construction industry accidents in Spain. *J. Saf. Res.* **2008**, *39*, 497–507. [CrossRef]
19. Kaskutas, V.; Dale, A.M.; Lipscomb, H.; Evanoff, B. Fall prevention and safety communication training for foremen: Report of a pilot project designed to improve residential construction safety. *J. Saf. Res.* **2013**, *44*, 111–118. [CrossRef]
20. Zhang, Z.; Pan, W. Virtual reality supported interactive tower crane layout planning for high-rise modular integrated construction. *Autom. Constr.* **2021**, *130*, 103854. [CrossRef]
21. Zhang, S.; Sulankivi, K.; Kiviniemi, M.; Romo, I.; Eastman, C.M.; Teizer, J. BIM-based fall hazard identification and prevention in construction safety planning. *Saf. Sci.* **2015**, *72*, 31–45. [CrossRef]
22. Chi, C.F.; Chang, T.C.; Ting, H.I. Accident patterns and prevention measures for fatal occupational falls in the construction industry. *Appl. Ergon.* **2005**, *36*, 391–400. [CrossRef]
23. Cakan, H.; Kazan, E.; Usmen, M. Investigation of factors contributing to fatal and nonfatal roofer fall accidents. *Int. J. Constr. Educ. Res.* **2014**, *10*, 300–317. [CrossRef]
24. Choo, H.; Lee, B.; Kim, H.; Choi, B. Automated detection of construction work at heights and deployment of safety hooks using IMU with a barometer. *Autom. Constr.* **2023**, *147*, 104714. [CrossRef]
25. Dong, X.S.; Largay, J.A.; Choi, S.D.; Wang, X.; Cain, C.T.; Romano, N. Fatal falls and PFAS use in the construction industry: Findings from the NIOSH FACE reports. *Accid. Anal. Prev.* **2017**, *102*, 136–143. [CrossRef]
26. Turgut, K.; Sarihan, M.E.; Colak, C.; Guven, T.; Gur, A.; Gurbuz, S. Falls from height: A retrospective analysis. *World J. Emerg. Med.* **2018**, *9*, 46–50. [CrossRef] [PubMed]
27. Kim, S.C.; Ro, Y.S.; Shin, S.D.; Kim, J.Y. Preventive Effects of Safety Helmets on Traumatic Brain Injury after Work-Related Falls. *Int. J. Environ. Res. Public Health* **2016**, *13*, 1063. [CrossRef] [PubMed]
28. Köppe, G.J.J.; Gloy, Y.-S.; Gries, T.; Lehnert, M.; Kim, H.-D.; Min, M. *Entwicklung Einer Tragbaren Persönlichen Schutzausrüstung Gegen Absturz—"Scaffbag"*; BG Bau: Berlin, Germany, 2016.
29. Minerva Airbag Systems. Available online: https://www.minerva-as.com/opus-2-0/ (accessed on 3 May 2023).
30. Aranda Marco, R. *Biomechanical Effectiveness Assessment of Motorcyclist Airbags in Realistic Impact Scenarios Using Human Body Models*; Ludwig-Maximilian Universität München (LMU): Munich, Germany, 2022.
31. Serre, T.; Masson, C.; Llari, M.; Canu, B.; Py, M.; Perrin, C. Airbag jacket for motorcyclists: Evaluation of real effectiveness. In Proceedings of the IRCOBI 2019, International Conference on the Biomechanics of Injury, Florence, Italy, 11–13 September 2019; pp. 533–547.
32. Cherta Ballester, O.; Llari, M.; Honoré, V.; Masson, C.; Arnoux, P.-J. An evaluation methodology for motorcyclists' wearable airbag protectors based on finite element simulations. *Int. J. Crashworthiness* **2021**, *26*, 99–108. [CrossRef]
33. Fernandes, F.A.; De Sousa, R.A. Finite element analysis of helmeted oblique impacts and head injury evaluation with a commercial road helmet. *Struct. Eng. Mech.* **2013**, *48*, 661–679. [CrossRef]
34. Yu, X.; Logan, I.; de Pedro Sarasola, I.; Dasaratha, A.; Ghajari, M. The protective performance of modern motorcycle helmets under oblique impacts. *Ann. Biomed. Eng.* **2022**, *50*, 1674–1688. [CrossRef] [PubMed]
35. Milne, G.; Deck, C.; Bourdet, N.; Carreira, R.; Allinne, Q.; Gallego, A.; Willinger, R. Bicycle helmet modelling and validation under linear and tangential impacts. *Int. J. Crashworthiness* **2014**, *19*, 323–333. [CrossRef]
36. Posirisuk, P.; Baker, C.; Ghajari, M. Computational prediction of head-ground impact kinematics in e-scooter falls. *Accid. Anal. Prev.* **2022**, *167*, 106567. [CrossRef]
37. Meyer, F.; Deck, C.; Willinger, R. Protection from motorcycle neck–braces using FE modelling. *Sports Eng.* **2018**, *21*, 267–276. [CrossRef]

38. Untaroiu, C.D.; Putnam, J.B.; Schap, J.; Davis, M.L.; Gayzik, F.S. Development and preliminary validation of a 50th percentile pedestrian finite element model. In Proceedings of the International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Boston, MA, USA, 2–5 August 2015; p. V003T001A004.
39. Poulard, D.; Kent, R.W.; Kindig, M.; Li, Z.; Subit, D. Thoracic response targets for a computational model: A hierarchical approach to assess the biofidelity of a 50th-percentile occupant male finite element model. *J. Mech. Behav. Biomed. Mater.* **2015**, *45*, 45–64. [CrossRef]
40. Lobdell, T.E.; Kroell, C.K.; Schneider, D.C.; Hering, W.E.; Nahum, A.M. Impact Response of the Human Thorax. In *Human Impact Response: Measurement and Simulation*; King, W.F., Mertz, H.J., Eds.; Springer: Boston, MA, USA, 1973; pp. 201–245. [CrossRef]
41. Kroell, C.K.; Schneider, D.C.; Nahum, A.M. Impact tolerance and response of the human thorax II. *SAE Trans.* **1974**, *83*, 3724–3762. [CrossRef]
42. Lau, I.V.; Viano, D.C. The viscous criterion—Bases and applications of an injury severity index for soft tissues. *SAE Trans.* **1986**, *95*, 672–691. [CrossRef]
43. Viano, D.C.; Lau, I.V. A viscous tolerance criterion for soft tissue injury assessment. *J. Biomech.* **1988**, *21*, 387–399. [CrossRef] [PubMed]
44. Xia, P.; Chang, H.-F.; Yu, Y.-M.; Dai, G.-X.; Li, H.-W.; Jiang, Q.-G.; Yin, Z.-Y. Morphologic studies of high fall injuries. *Chin. J. Traumatol.* **2012**, *15*, 334–337.
45. Beeman, S.M.; Kemper, A.R.; Madigan, M.L.; Franck, C.T.; Loftus, S.C. Occupant kinematics in low-speed frontal sled tests: Human volunteers, Hybrid III ATD, and PMHS. *Accid. Anal. Prev.* **2012**, *47*, 128–139. [CrossRef] [PubMed]
46. Yaguchi, M.; Ono, K.; Kubota, M.; Matsuoka, F. Comparison of biofidelic responses to rear impact of the head/neck/torso among human volunteers, PMHS, and dummies. In Proceedings of the 2006 International IRCOBI Conference on the Biomechanics of Impacts, Madrid, Spain, 20–22 September 2006; pp. 20–22.