Chest injuries of vulnerable road users – application of the THOMO model to a frontal crash setup

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ABSTRACT

The research focuses on the application of the human body model in assessment of possible seat belt induced injuries in a frontal crash setup. The THOMO model is used as a reference (www.thomo.eu). Modifications applied to the model material data mimic aging or disease, leading to weakening of the thoracic structure of an occupant. A method of estimating chest injuries basing on rib fractures is used to verify the influence of seat belt settings on the occupant. The results show increased susceptibility of the aging thorax to the rib fractures caused by the seat belt loading. A reduction of forces exerted by the belt leads to reduction of the amount of the injuries and a different pattern of fractures. The results obtained are referred to other studies.

INTRODUCTION

The society is aging. It is assumed that until 2030, one fourth of the population will be age 65 or older (OECD, 2001). Weakening of the skeletal structure, both macro- and microscopic, results in increased vulnerability of the elderly occupants to fracture related injuries, likely to occur in automotive accidents (Schmidt, 1975; Zhou, 1996). The passive safety systems commonly used in cars are meant to couple the occupant to the vehicle, prevent excessive relative motion during the collision and reduce loads applied to the human body. The load thresholds, however, are set basing on the mechanical responses of the crash test dummies. Due to the limited biofidelity of the dummies, the designed load thresholds may lead to injuries in case of the vulnerable occupants, extending the recovery process or having fatal consequences.

Car accidents are the one of the major causes of fatalities in the motorized countries. The most frequent crash scenario is a frontal impact. Socio-economic costs of the car crashes and recovery of its victims is significant. In the European Union it exceeds the annual EU budget twice. It is yet another motivation to reduce the injuries, keeping in mind demographic changes.

Injuries to the thorax are responsible for one fourth of the fatalities, resulting from frontal car crashes, also when the passive restraints are used (Zhao, 2005). Fatalities caused by thoracic injuries result from pneumothorax or flail chest, occuring more frequently in case of elderly occupants (Borman, 2006). The increased frailty of aging thorax is a fact. Researchers give a wide spectrum of explanations to this phenomenon (Ito, 2009; Kent, 2005; Shimamura, 2003; Zhou, 1996).

To address these measures, the THOMO project was meant to develop a biofidelic model of the human thorax (Figure 1), aiming to improve the safety assessment. A human body model gives an opportunity to investigate the influence of decreasing the thorax mechanical endurance on the injury outcome of the occupant, which is a challenge in case of the crash test dummies. In the current research, a frontal car crash configuration, as the most frequently occurring type of the crash, was investigated.

Figure 1: Thoracic segment of the THOMO model. Skin, flesh, head and neck, part of the lower extremities removed for better visualisation.

METHODS

The approaches to determine age effect on thoracic injuries are usually divided to three: a structural change meaning deformation of the thoracic geometry, usually with increase of an angle between ribs and spine; a compositional change, meaning distribution of the cortical and trabecular bone along the ribs and constitution of the costal cartillage (i.e. develompent of collagen fibers and calcification); finally, the change of material properties with age (Kent, 2005; Kemper, 2007; Ito, 2009). Research by Kent et al. found that modification of the material properties has the strongest influence on the rib fracture pattern and count (Kent, 2005). Therefore, this approach has been used in the current research. The age related frailty of the chest was mimicked by modification of the rib failure plastic strain value.

The THOMO model of a 50^{th} percentile male was used as a reference of a healthy, young occupant. The model was seated in the simplified car seat and restrained with the standard three-point seat belts to the reference space (Figure 2). Dimensions of a typical middle-sized passenger car were used to determine anchorage points for the seat belt. A crash pulse of US-NCAP full frontal 56 kmh test was applied to the model (Rouhana, 2003). The simulations were performed using LS-Dyna code. Ribs endurance was modified by changing value of the failure plastic strain of the compact and trabecular bone to 0.8%, basing on the results obtained during the mechanical tests performed within the THOMO project on the elderly cadavers' rib material samples (Deliverable D2.3.2). The rib fractures were chosen as a risk measure (Ruan 2003; Shimamura, 2003; Zhou 1996). Location of the rib fractures was compared with cadaver tests performed at similar loading conditions (Shaw, 2009; Schmidt, 1975).

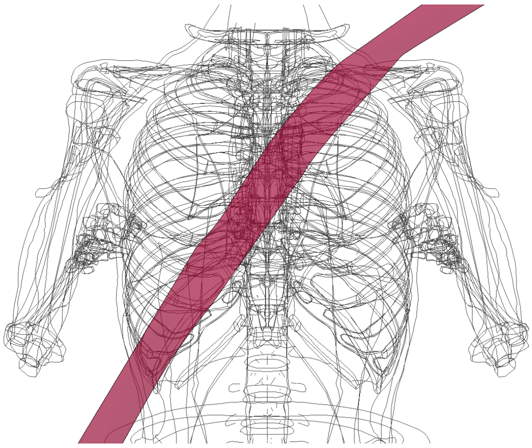


Figure 2: Location of the seat belt across the chest – front view.

The restraint parameters to modify were pre-tensioner performance (defined here as the belt length absorbed by the retractor within 10ms for 65mm and 90mm; within 12ms for 140mm) and the load limiter level, applied to the retractor. The load limiter was modeled with a force vs. belt payout function (Rouhana, 2003). The effectiveness of the buckle or anchor pre-tensioning was not considered.

Reduction of the rib material endurance mimicked an increased susceptibility of the bones to fracture, caused by deterioration and degeneration, resulting from aging or disease. Eight combinations of belt pre-tensioner and force limiter settings were applied to the model (Table 1), to check possible advantage of the reduction in the force thresholds.

Table 1: Settings of the seat belt

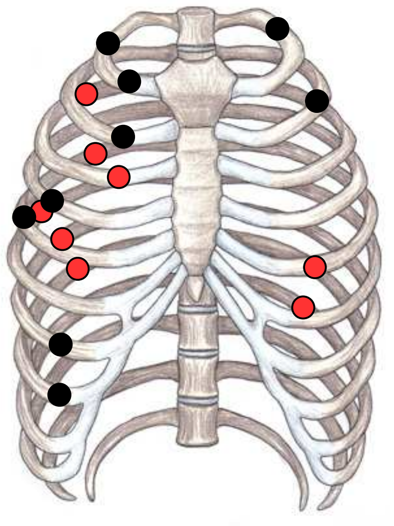
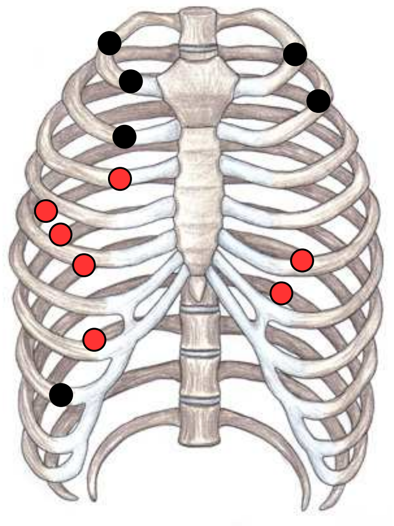
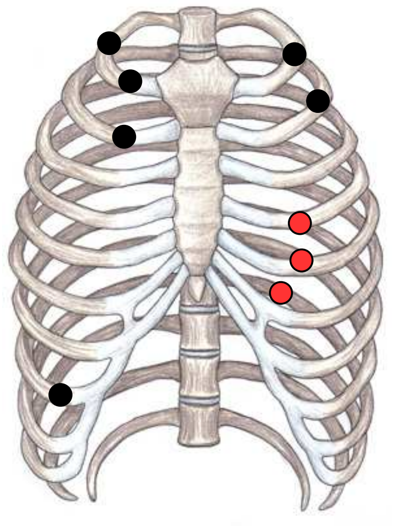
Combinations tested for 65mm, 90mm and 140mm pre-tensioner.			
Pre-tensioner \Force limiter	**No BFL**	**5 kN**	**3 kN**
65mm	x	x	x
90mm	x	x	x
140mm	x	x	

RESULTS

Numerous rib fractures have been observed in the models with a reduced failure plastic strain value. The count and location of the fractures were dependent on the settings of restraints used.

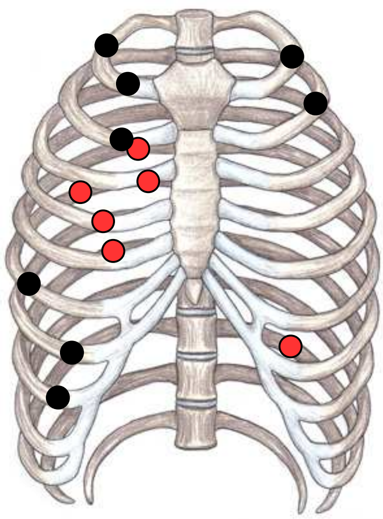
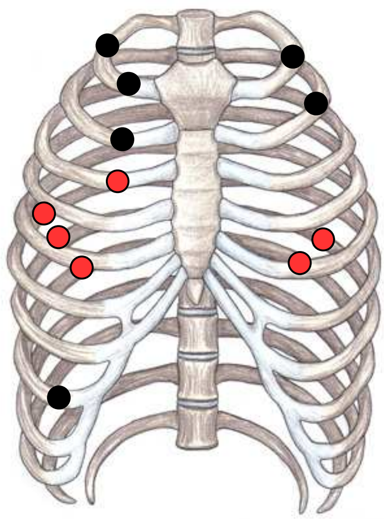
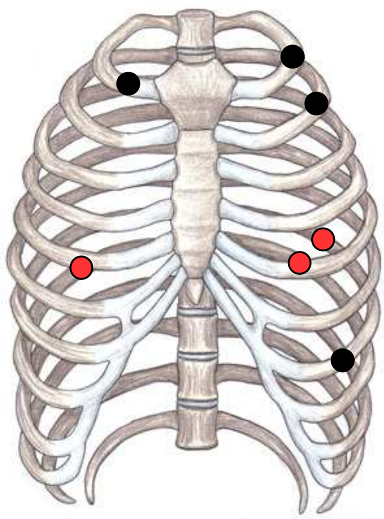
The amount of rib fractures decreased when the belt force limitation was applied to the retractor. Reducing the belt force limitation value from 5kN to 3kN brought further reduction of rib fractures. Regarding the 65mm pre-tensioner, for the case without the belt force limitation, the amount of fractures was 17, reducing to 13 with 5 kN belt force limitation and to 9 with the 3kN belf torce limiter (Table 2).

Table 2: Rib fracture for 65mm pre-tensioner and different force limitation values
Black dots mark rib fractures in the front of the ribcage, red dots – in the back
BFL stands for belt force limiter

No BFL	BFL 5kN	BFL 3kN
		

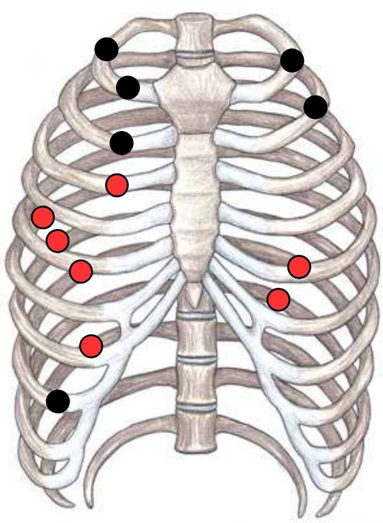
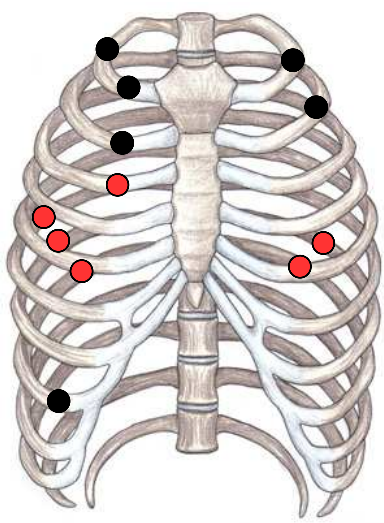
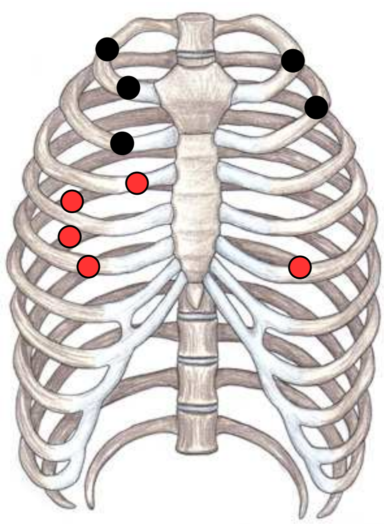
The same trend was observed for the 90mm pre-tensioner. For the case without the belt force limitation, the amount of fractures was 14, reducing to 12 with the 5kN belt force limiter and to 7 for the 3kN belt force limiter (Table 3). Pattern of the rib fractures corresponds to the 65mm pre-tensioner, for the same belt force limitation values.

Table 3: Rib fractures for 90mm pre-tensioner and different force limitation values
Black dots mark rib fractures in the front of the ribcage, red dots – in the back
BFL stands for belt force limiter

No BFL	BFL 5kN	BFL 3kN
		

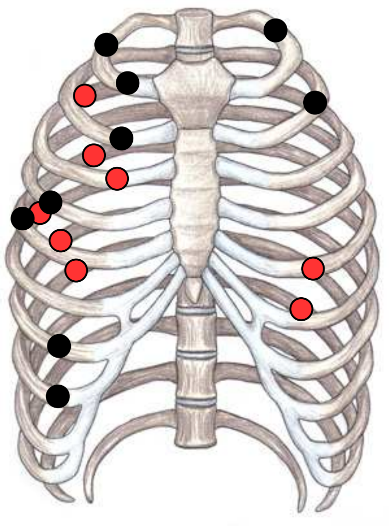
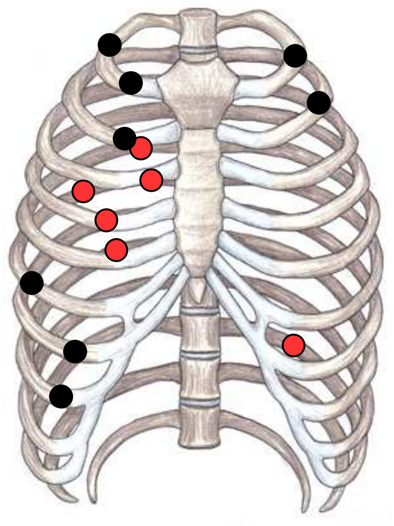
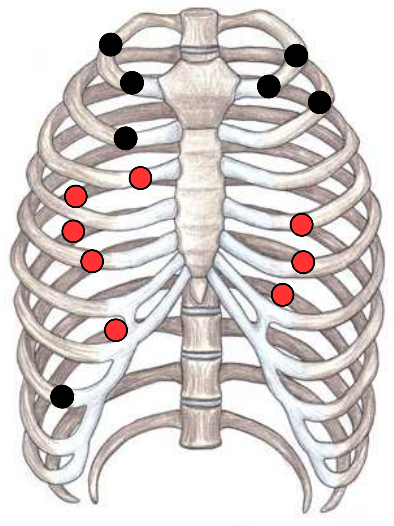
The difference in the count and location of rib fractures between different pre-tensioner settings for the same 5kN force limiter value was not significant (Table 4). It gives an impression, that a certain constant force applied is responsible for a certain amount of fractures. The belt force limiter seems to have influence on the amount of the rib fractures, but not on the pattern, when combined with a pre-tensioner.

Table 4: Rib fractures for 5kN belt force limiter and different settings of pre-tensioner
Black dots mark rib fractures in the front of the ribcage, red dots – in the back

65mm	90mm	140mm
		

However, when the same comparison was performed for different pre-tensioner settings without the belt force limiter, a difference in injury pattern could be observed. The 65mm pre-tensioner led to 17 fractures, 90mm and 140mm pre-tensioners to 14 and 15 fractures respectively, having different pattern of the injuries. Bilateral flail chest was more likely to occur in case of the 140mm pre-tensioner (fractures of ≥3 adjacent ribs on both sides, Table 5). It is assumed that the pre-tensioner characteristic could be responsible for the fractures pattern.

Table 5: Rib fractures for different settings of pre-tensioner, without belt force limitation
Black dots mark rib fractures in the front of the ribcage, red dots – in the back

65mm	**90mm**	**140mm**
		

DISCUSSION

Schmidt et al. ran sled tests at different speeds, with use of belted both male and female cadavers. For the 65+ age group at 50km/h, the number of rib fractures of the subjects was between 12 and 28. The highest count of rib fractures was observed for elderly females (Schmidt, 1975). The count of rib fractures (14-17) obtained during the simulations without the belt force limiter fits this range.

Shaw et al. performed the 40 km/h sled tests with a pulse mimicking a rigid barrier. Rib fractures resulting from the restraints were checked with use of eight male cadavers, fitting to a 50^{th} percentile male dimensions. Two of the subjects were 65+ years old (Shaw, 2009). The fractures pattern of the simulation with a 90mm pre-tensioner combined with a 3kN force limitation was closest to the results obtained with the cadaver tests. The count of rib fractures obtained with the 3kN belt force limiter regardless of the pre-tensioner setting fits to the results of Shaw et al. (7-10 in the simulations, 8 and 9 in the cadaver tests). It could be explained by lack of retractor at any belt segments in the cadaver experiments, allowing for the belt payout.

Location of the fractures also agrees with the findings of Tamura et al., performing the chest compression test with use of diagonal belt on a THUMS model, validated with use of cadaver data (Tamura, 2005). The most of the fractures appear on the right side of the thorax, along the belt, on the rib curvature approximately 1/3 and 2/3 of the distance from the sternum to the vertebrae.

The most popular setup to compare simulation results with the cadaver injuries is a Kroell type impact – a blunt hub dynamically loading the sternum (Kroell, 1971). This load type is not useful to evaluate age influence on the injury outcome, because the measured forces are dominated by mechanisms different than in case of restraint loading and they involve a wide range of impactor masses and velocities. Lack of relationship between chest deflection and age in Kroell type loading was shown by Kent et al. (Kent, 2005). Furthermore, due to obligatory seat belt use in most of the countries, loading from the restraints is more likely to occur in case of the automotive accident. Therefore, worth of investigation.

The thoracic segment was observed to show higher stiffness under the restraint-type loading, than under the hub-type loading, for both cadavers and numerical models (Murakami, 2004). This difference should be taken into account, when comparing the human body model responses under variable loading cases or refering to the crash test dummies measures.

The THOMO model is still under development, as most of the other human body models (Ito, 2009; Tamura, 2005; Zhao, 2005; Murakami, 2004; Ruan, 2003). The frontal crash setup is different from the validation impactor tests (Ruan, 2003; Kroell, 1971), therefore the results obtained should be regarded with a qualitative, not a quantitative approach. Mimicking the biomechanical response of the human body is a challenge, due to variability and complexity of the anthropometric measures.

CONCLUSIONS

The results show that belt force limiter reduced the number of rib fractures. The 3kN force level showed reduced count of rib fractures, compared to the 5kN force limiter. The trend was confirmed by both 65mm and 90mm pre-tensioner characteristics. It is assumed that the pre-tensioner settings are responsible for the rib fracture pattern and the belt force limiter value – for the rib fractures count.

Combination of the 90mm pre-tensioner and the 3kN belt force limiter showed the best performance, regarding the reduction of rib fractures count (Table 3, BFL 3kN). The combination of settings which is the closest to the current automotive applications is 90mm pre-tensioner and the 5kN belt force limiter. It is considered that the advanced passive safety systems should take into account the individual needs of an occupant.

Interaction with an airbag and car interior (steering wheel, etc.) was not considered in this study. It was observed that decreasing the belt force limiter values leads to an increased forward movement. Limitation of chest injuries should not bring more injury to the head and other body parts and it is an issue for a further investigation.

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