

change in posture (Fig. 3): in other words, this suggests that a unique individual impacted in several slightly different postures could experience different strain level in the ribcage. Although the first subject (test 1413) sustained a large number of rib fractures while the other subjects did not sustain any, the strain values predicted by THUMS - P1 are similar to those obtained with the THUMS - P2. Conversely, the strain predicted with THUMS - P3 were very close to those measured in the experiment. It is interesting to note that the biofidelity of THUMS rib strain prediction would be given significantly different ranking depending on which posture is considered or if the default THUMS posture is used. Similarly, the angle of the arm was found to play an important role in the predicted strain levels (Fig. 9a). It is consistent with [17][32], and it is interesting to note that the THUMS model used in the current study mimics this sensitivity. The simulation run without the arm interaction showed that the strain level was lower than in the simulations where the arm was present. This indicates that the direct interaction of the wall with the ribcage does not generate enough deformation of the ribcage to generate strain levels commensurate with the level observed in the experiments, at least in the upper ribcage (ribs higher than rib 6, Figs. 9a and 10a).

The influence of posture and arm interaction with the impacting wall and the ribcage is a major challenge for the development of a reliable biofidelity assessment method, as there is not enough information about the arm pre-impact position and kinematics throughout the impact (the full kinematics (translation and rotation) of the struck arm was not measured during the tests) to include this information in the simulation. What is more, the predicted strain was found to be very sensitive to the location of the strain measurement location on the rib (Fig. 13a). This result is in line with [15], where corridors were created from the strain along the rib in side impact: it was shown that the position of the peak value was dependent on the type of loading (impactor or unfolded airbag). Therefore, the location of the strain measurement, either in experiments or simulations, has to be carefully decided based on the expected type of deformation. A particularity of side impact loading is that it can generate both compressive and tensile strains on the outer surface along the rib [15], while in frontal loading the outer surface of the ribs experience almost exclusively tension [16].

In the simulation results with THUMS v1.4, the principal strains exhibited good correlations with the longitudinal strains, and therefore both strains can be used to estimate the strain level in the cortical ribs. Principal strains is commonly used in FE analysis as it is a default output of any simulation software package, while estimating the longitudinal strain requires to compute this measurement. However, this result should not be interpreted as a proof that longitudinal strains are sufficient to predict fracture. It would rather suggest that the THUMS rib models are not very sensitive to more complex (non-tensile) loadings, which is consistent with the impossibility to properly predict the location of rib fractures. This limitation is not specific to THUMS and has been reported in other computational models such as the GHBM [33][34]. Yet, the modification of the posture and of the arm angle is not sufficient to fully characterize the differences between PMHS and the model. In particular, the geometry of the ribcage was shown to vary between people as a function of age, sex and body mass index [35] and the impact response of the thorax was found to greatly depend of the geometric properties while being less sensitive to variation in material properties [3]. The next step for the current study will be to assess how changes in the thorax geometry influence the predicted Impact response. Another topic of interest is to improve rib fracture prediction in side impact by the development of a methodology to test ribs at the component level in a configuration that is consistent with what the ribs are subjected to in side impact [37]. The initial attempt reported on in [38] showed that the rib boundary conditions in side impact had to be better understood to define a relevant test methodology.

Finally, the contribution of the scapula was not analyzed in the current study, although [20] reported large variations between the three PMHS included in the test series (position and orientation relative to the thorax). Because of the large inter-individual variations inherent to PMHS, a parametric analysis based on a computational model is a coherent approach to further investigate how the load is transmitted through the scapula and the thorax in side impact.

V. CONCLUSIONS

The THUMS computational model was used to simulate side impact tests performed with three PMHS. The spine posture and arm position measured in the experiment were used to set-up THUMS pre-impact

configurations similar to that of the PMHS. The effect of the interaction of the arm with the ribcage on the predicted strain was investigated, along with the influence of the strain measurement location in the rib FE models. It was shown that the posture and arm angle greatly influence the strain level predicted in the simulation, and therefore, the assessment of the model biofidelity requires to test several pre-impact configurations. In THUMS, the longitudinal and principal strains could be interchangeably used to assess the strain level in the ribs. This study did not include the contribution of the thorax geometry or scapula position and orientation to the impact response predicted with the computational model, but it is the next logical step.

VI. ACKNOWLEDGEMENT

The analysis performed in this study has been funded by and carried out in association with SAFER - Vehicle and Traffic Safety Centre at Chalmers University of Technology, Sweden. D. Subit thanks the European Union for its financial support through the Marie Curie International Incoming Fellowship (FP7-PEOPLE-2013-IIF, project BioAge # 622905). F. Möhler gratefully acknowledges the financial support from the Franco-German University through the Franco-German double degree program between Arts et Metiers - ParisTech and Karlsruhe Institute of Technology. The views expressed in this article are those of the authors and do not necessarily represent the views of the funding bodies.

VII. REFERENCES

- [1] Ito O, Dokko Y, Ohashi K. Development of adult and elderly FE thorax skeletal models. *SAE International*, 2009.
- [2] Jacobo, A, Yamamoto Y, Kato R, Sato F, Ejima S, Dokko Y, Yasuki T. Influence of age specific parameters on the thoracic response under controlled belt loading conditions, *International Journal of Automotive Engineering*, 6(3):83-90, 2015, 10.20485/jsaeijae.6.3_83
- [3] Schoell SL, Weaver AA, Vavalle NA, Stitzel JD. Age- and sex-specific thorax finite element model development and simulation. *Traffic Inj Prev.*, 2015;16 Suppl 1:S57-65
- [4] Beillas P, Berthet F. Performance of a 50th percentile abdominal model for impact: effect of size and mass. *European Society of Biomechanics Conference*, 2012.
- [5] Poulard D, Subit D, Donlon JP, Lessley DJ, Kim T, Park G, Kent RW. The contribution of pre-impact spine posture on human body model response in whole-body side impact. *Stapp Car Crash J.*, 2014, 58:385-422.
- [6] Poulard D, Subit D, Nie B, Donlon JP, Kent RW. The contribution of pre-impact posture on restrained occupant finite element model response in frontal impact. *Traffic Inj Prev.*, 2015;16 Suppl 2:S87-95
- [7] Al-Hassani A, Abdulrahman H, Afifi I, Almadani A, Al-Den A, Al-Kuwari A, Recicar J, Nabir S, Maull KI. Rib fracture patterns predict thoracic chest wall and abdominal solid organ injury. *Am Surg.*, 2010 Aug;76(8):888-91.
- [8] Shweiki E, Klena J, Wood GC, Indeck M. Assessing the true risk of abdominal solid organ injury in hospitalized rib fracture patients. *J Trauma.*, 2001 Apr;50(4):684-8.
- [9] Liman ST, Kuzucu A, Tastepe AI, Ulasan GN, Topcu S. Chest injury due to blunt trauma. *Eur J Cardiothorac Surg.*, 2003 Mar;23(3):374-8.
- [10] Song E, Trosseille X, Baudrit P. Evaluation of thoracic deflection as an injury criterion for side impact using a finite elements thorax model. *Stapp Car Crash J.*, 2009, 53:155-91.
- [11] Forman JL, Kent RW, Mroz K, Pipkorn B, Bostrom O, Segui-Gomez M. Predicting rib fracture risk with whole-body finite element models: development and preliminary evaluation of a probabilistic analytical framework. *Annals of Advances in Automotive Medicine / Annual Scientific Conference*, 2012;56:109-124.
- [12] Li Z, Kindig MW, Kerrigan JR, Untaroiu CD, Subit D, Crandall JR, Kent RW. Rib fractures under anterior-posterior dynamic loads: experimental and finite-element study. *J Biomech.*, 2010;43(2):228-34. doi: 10.1016/j.jbiomech.2009.08.040.

- [13] Mendoza-Vazquez M, Brodin K, Davidsson J, Wismans J. Human rib response to different restraint systems in frontal impacts: a study using a human body model. *International Journal of Crashworthiness*, 2013, 18(5).
- [14] Watanabe R, Katsuhara R, Miyazaki H, Kitagawa Y, Yasuki T. Research of the relationship of pedestrian injury to collision speed, car-type, impact location and pedestrian sizes using human FE model (THUMS Version 4), *Stapp Car Crash Journal*, 2012, 56:269-321.
- [15] Leport T, Baudrit P, Potier P, Trosseille X, Lecuyer E, Vallancien G. Study of rib fracture mechanisms based on the rib strain profiles in side and forward oblique impact. *Stapp Car Crash J.*, 2011, 55:199-250.
- [16] Trosseille X, Baudrit P, Leport T, Vallancien G. Rib cage strain pattern as a function of chest loading configuration. *Stapp Car Crash J.*, 2008, 52:205-231
- [17] Kemper AR, McNally C, Kennedy EA, Manoogian SJ, Duma SM. The influence of arm position on thoracic response in side impacts. *Stapp Car Crash J.*, 2008, 52:379-420.
- [18] Subit, D, Boruah, S, Forman, J, Salzar, R, Crandall, J. Strain distribution in the human ribs during antero-posterior loading, *Japanese Society of Automotive Engineers*, 2013.
- [19] Lessley D, Shaw G, et al. Whole-body response to pure lateral impact. *Stapp Car Crash J.*, 2010;54:289-336.
- [20] Donlon JP, Poulard D, Lessley D, Riley P, Subit D. Understanding how pre-impact posture can affect injury outcome in side impact sled tests using a new tool for visualization of cadaver kinematics. *J Biomech.*, 2015, 48(3):529-33
- [21] LS-DYNA Keyword User's Manual, Volume I & II, LS-Dyna R7.1.2, Lawrence Livermore Software Technology Corporation (LSTC), 2014.
- [22] Pipkorn B, Mroz K. Validation of a Human Body Model for Frontal Crash and its Use for Chest Injury Prediction. *SAE Digital Human Modeling for Design and Engineering Conference, Pittsburgh, PA*, 2008.
- [23] Pipkorn B, Subit D, Donlon J-P, Sunnevang C. A computational biomechanical analysis to assess the trade-off between chest deflection and spine translation in side impact. *Ann Assoc Adv Aut Med*, 2014.
- [24] Pipkorn B, Kent R. Validation of a human body thorax model and its use for force, energy and strain analysis in various loading conditions. *International Research Council on Biomechanics of Injury (IRCOBI) Conference*, 2011.
- [25] Pipkorn B, Lopez-Valdes F, Lundgren C, Bråse D, Sunnevang C. Innovative seat belt system for reduced chest deflection. *Proc 24th Technical Conference on Enhanced Safety of Vehicles*. 2015, Paper Number 15-0371.
- [26] Engelbrektsson, K. Evaluation of material models in LS-DYNA for impact simulation of white adipose tissue. Göteborg : Chalmers University of Technology, Department of Applied Mechanics, Göteborg, Sweden, 2011, no: 2011:46
- [27] Poulard D, Subit D, Donlon JP, Kent RW. Development of a computational framework to adjust the pre-impact spine posture of a whole-body model based on cadaver tests data. *J Biomech.*, 2015, 48(4):636-43.
- [28] Viano DC, Lau IV, Asbury C, King AI, Begeman P. Biomechanics of the human chest, abdomen, and pelvis in lateral impact. *Accid Anal Prev.*, 1989, 21(6):553-74
- [29] Golman AJ, Danelson KA, Miller LE, Stitzel JD. Injury prediction in a side impact crash using human body model simulation. *Accid Anal Prev.*, 2014 Mar;64:1-8. doi: 10.1016/j.aap.2013.10.026.
- [30] Golman AJ, Danelson KA, Stitzel JD. Robust human body model injury prediction in simulated side impact crashes. *Comput Methods Biomech Biomed Engin.*, 2016;19(7):717-32.
- [31] Stalnaker, R.L., Tarriere, C., Fayon, A., Walfisch, G., Balthazard, M., Masset, J., Got, C., and Patel, A. Modification of part 572 dummy for lateral impact according to biomechanical data. *Proc. 23rd Stapp Car Crash Conference*, 1979, pp: 843-872. Society of Automotive Engineers, Warrendale, PA.
- [32] Cesari, D., Ramet, M., and Bloch, J. Influence of arm position on thoracic injuries in side impact. *Proc. 25th Stapp Car Crash Conference*, 1981, pp:270-297. Society of Automotive Engineers, Warrendale, PA.

- [33] Li Z, Kindig MW, Kerrigan JR, Untaroiu CD, Subit D, Crandall JR, Kent RW. Rib fractures under anterior-posterior dynamic loads: experimental and finite-element study. *J Biomech.*, 2010;43(2):228-34.
- [34] Poulard D, Kent RW, 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 May;45:45-64. doi: 10.1016/j.jmbbm.2015.01.017. Epub 2015 Jan 31.
- [35] Shi X, Cao L, Reed MP, Rupp JD, Hoff CN, Hu J. A statistical human rib cage geometry model accounting for variations by age, sex, stature and body mass index. *J Biomech.*, 2014;47(10):2277-85.
- [36] D Subit, B Sandoz, J Choisine, C Amabile, C Vergari, W Skalli, S Laporte. Rib Length Variation with Age and Sex-Measurements from High-Resolution Low-Radiation X-Ray Images of Volunteer Subjects. *24th International Technical Conference on the Enhanced Safety of Vehicles (ESV)*, 2015.
- [37] Subit D, Möhler F, Pipkorn B. Biofidelity corridors for sternum kinematics in low-speed side impacts. *Traffic Inj Prev.*, 2015;16 Suppl 2:S168-75
- [38] del Pozo de Dios E, Kindig MW; Arregui-Dalmases C; Crandall J; Takayama S; Ejima S; Kamiji K; Yasuki T. Structural response and strain patterns of isolated ribs under lateral loading. *International Journal of Crashworthiness*, 2011, 16(2): 169-180.