























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 GHBMC [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.

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