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Side impact applications of the PIPER scalable child human body model

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Abstract

The PIPER scalable child Human Body Model was recently released. It is scalable as a function of stature/age within the PIPER software. While several applications have been performed in frontal impact as new versions of the model were developed, no side impact applications have been reported up to now. The objectives of the current study were to investigate the usability of the PIPER child model and software for side impact through two applications related to the effect of anthropometric variations.

In the first application, the pelvic region validation setup from Ouyang et al. (2003) was investigated using five subject specific models. The anthropometric variations were found to partially explain the experimental variability. In the second application, the extreme anthropometric range possibly represented by the Q3 dummy in the regulation R129 was studied. A large effect was also observed on the response in simplified side impact simulations. The results should be considered as preliminary considering some of the statistical and setup assumptions made to build the extreme models. However, the methodology that was developed could be used with different assumptions to refine the extreme models, and these could be used in the future to check the CRS dynamic behaviour not only for dummy dimensions but for the complete range of anthropometry a dummy is covering.

Introduction

The regulation UNECE R129 on Child Restraint Systems (CRS) introduced many changes over the regulation R44. In particular, in order to specify which children can use a CRS, it moved away from a weight based to a stature based classification that is expected to be easier to use by the parents. More specifically, CRS manufacturers can now specify a continuous range of statures usable with a CRS. Then the regulation defines the dummies from the Q family that must be used for the frontal, the rear and the new side impact tests.

As dummies are defined for discrete ages and are not continuously scalable, each dummy is associated with a range of statures in R129. For example, while the Q3 has a nominal stature of 985mm, it can be used to certify CRS for statures between 870 and 1050 mm (Article 7.1.3.6 of the regulation). In addition, geometrical requirements at the 5th or the 95th percentile level are defined to ensure that children of extreme dimensions for a stature in the range can use the CRS. For example, children with a 95th percentile shoulder breadth (for any stature in the range) should fit in the CRS. Other requirements include the pelvic breadth, sitting height, and the shoulder height for now. When combining the two geometrical specification, a CRS certified with a Q3 may be used with a 95th percentile shoulder and pelvic breadth 1050mm stature child but also with a 5th percentile shoulder and pelvic breadth 870mm stature child. These two extremes could correspond to large shoulder and pelvic variations, which may affect the response and performance in side impact in particular as the shoulder and pelvis are loading paths for that configuration.

However, the CRS dynamic performance cannot directly be assessed for such extreme dimensions as the dummies correspond to an average anthropometry for a given age (e.g. average 3 years old (YO) anthropometry for the Q3). Furthermore, for the side impact tests, the frontal version of the Q dummy

is used even when a side impact version exists (e.g. Q3 and not Q3s). These versions may carry significant limitations in terms of biofidelity for side impact.

Because (1) they can be scaled to different dimensions and (2) they have the potential to be more omnidirectional than dummies as they are not subjected to the same physical constraints, Human Body Models could be used to study such phenomena. The PIPER child scalable model (Beillas et al, 2016 PoCC) was publicly released in April 2017 (www.piper-project.org) along with frontal and side impact validation conditions. It is scalable as a function of stature/age within the PIPER software (www.piper-project.org). While several applications had been performed in frontal impact with a previous (Beillas et al., 2013, 2014a, 2014b) and the current version of the model (Giordano et al., 2017), the side impact validation is recent and no side applications have been reported.

Therefore, the objectives of the current study are to investigate the usability of the PIPER child model in side impact through two related applications:

- A study of the sensitivity of the PIPER model to variations of anthropometry within the context of the side impact validation for the pelvic region using the Ouyang et al. (2003) dataset. For this, the model will be scaled to the characteristics of Post Mortem Human Surrogates (PMHS) used in the test series with the PIPER software.
- A study of the side impact response of the PIPER model after scaling it to describe the extreme range of stature and anthropometry for which the Q3 can be used to assess a CRS in R129.

Methods

PIPER Scalable Child HBM

The PIPER child HBM version 1.0.0 was used for all simulations. Its geometry is identical to the version 0.3 presented in Beillas et al. (2016). The baseline model describes a 6 YO child whose main anthropometric dimensions were normalised by nonlinear scaling (kriging interpolation) using GEBOD (Cheng et al., 1994) regressions as a reference. It is continuously scalable by anthropometry from 1.5 to 6 YO also using the GEBOD regressions implemented in the child scaling module of the PIPER software (version 1.0.1 used for this study).

The model is mostly deformable. It includes descriptions of the head (deformable skull and brain), neck (deformable vertebrae, discs, ligaments, muscles), trunk (including simplified representations of the internal organs of the thorax and abdomen, deformable ribcage and pelvis, rigid thoracic and lumbar vertebrae articulated by 6 d.o.f. beams), and extremities (deformable shoulder and hip, deformable lower extremities diaphysis, rigid foot, 6 d.o.f. beams for the elbow, wrist, knee and ankle). With regards to the current application in side impact, the model includes growth cartilage on the pelvis and shoulder bones. The model is composed of approximately 546,000 elements of which 52,000 are rigid, distributed in 407 parts. The material properties are derived from the literature. The time step is 0.32 μ s (with 15 grams added). The model is available in Ls-Dyna. An illustration is provided in *Figure 1*.

The model performance was checked against over 20 validation setups, mostly derived from PMHS tests. These include regional (e.g. isolated head drop) and full body setups (e.g. sled), in frontal or side impact. The side impact validation setups for the trunk region include mainly a pendulum shoulder impact (3 and 6 YO, scaled corridors from Irwin et al., 2002) and a pelvis impact (Ouyang et al., 2003). For the pelvic impact, significant discrepancies had been observed between the tests and the response of the baseline model but none of the parameters tested in a sensitivity analysis (e.g. reduced soft tissue thickness on the impacted side, increased abdominal bag mass, increased pelvic cartilage stiffness) had an effect that could explain these discrepancies (Beillas et al, 2016). The baseline responses of the 3 and 6 YO models in these two test setups are provided in *Figure 2*.

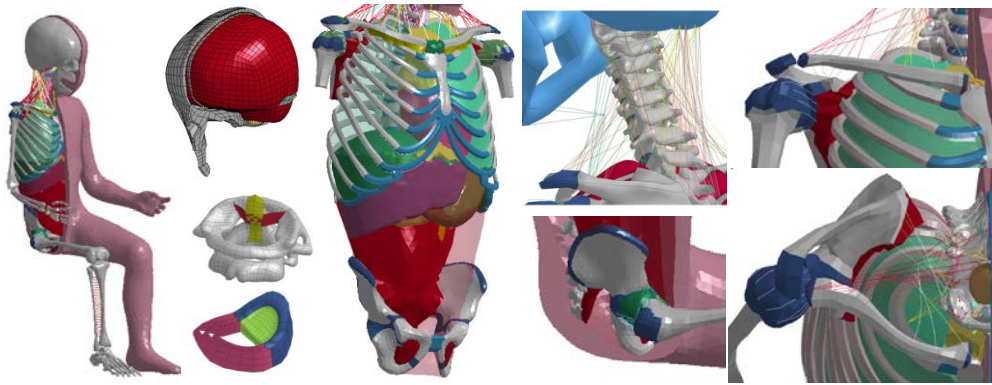


Figure 1. Overview of the PIPER Child model components

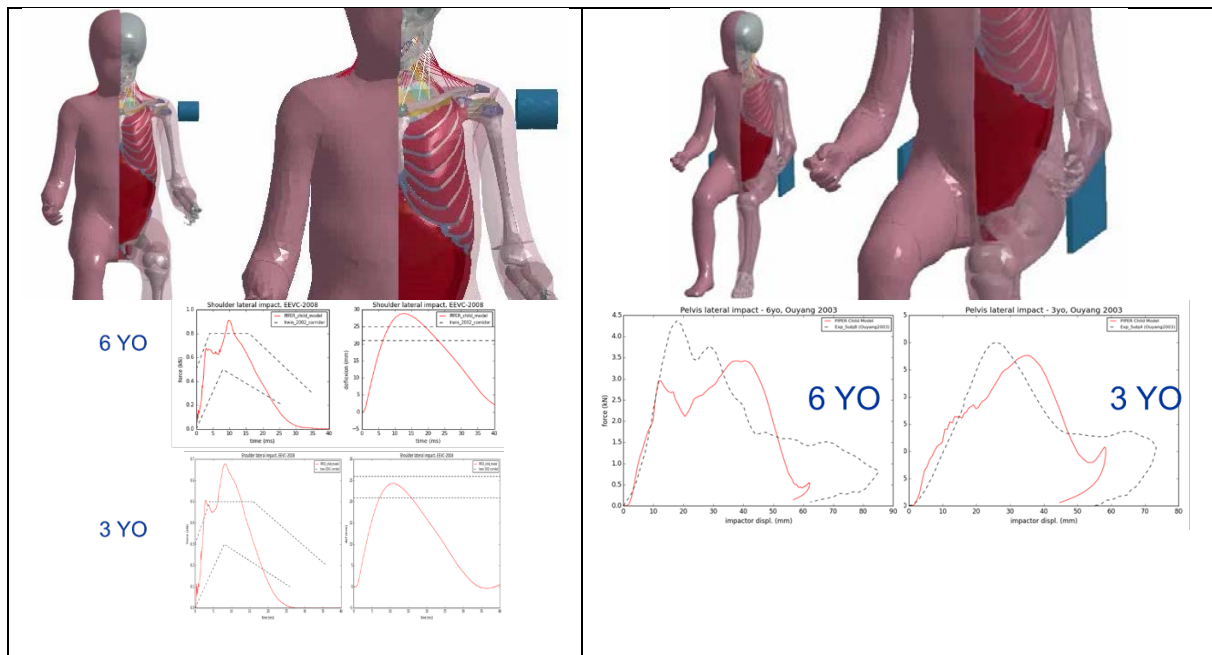


Figure 2. Response of the baseline model in side impact: shoulder (left, corridors from Irwin et al., 2002) and pelvic regions (right, example of response from Ouyang et al., 2003).

Sensitivity in the side pelvic validation setup

Differences of anthropometry had been listed as one of the other possible reasons for some of the mismatches observed in the Ouyang et al. (2003) setup. It was observed in particular that the PMHS used in the experiments were much lighter than the model. For the current study the model was scaled to match the stature and weight of five individual test subjects using the PIPER software.

The anthropometry of the PMHS was approximated by scaling the model in two steps:

- First the stature and weight were reduced using the regression computed from the Snyder database (Snyder et al., 1977) in the anthropometric module and a corresponding simplified scalable model in the scaling constraint module (all provided with PIPER). In this step, both skeleton and skin were scaled using no intermediate target in the kriging module.
- Then the weight was reduced by adjusting the external circumferences in regions with large flesh thickness while keeping the bones fixed (use of intermediate target in the kriging module). This also required adjusting the simplified scalable model.

The illustration in Figure 3 shows sections and segments dimensions defined in the “Scaling Constraints” PIPER module to reduce the weight of the model. The final target models are represented in Figure 4, with a summary of the weights obtained in Table 1.

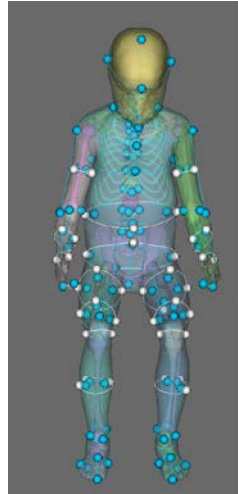


Figure 3. Source (white) and target (blue) sections and segments with control points defined in the PIPER application (“Scaling Constraints” module)

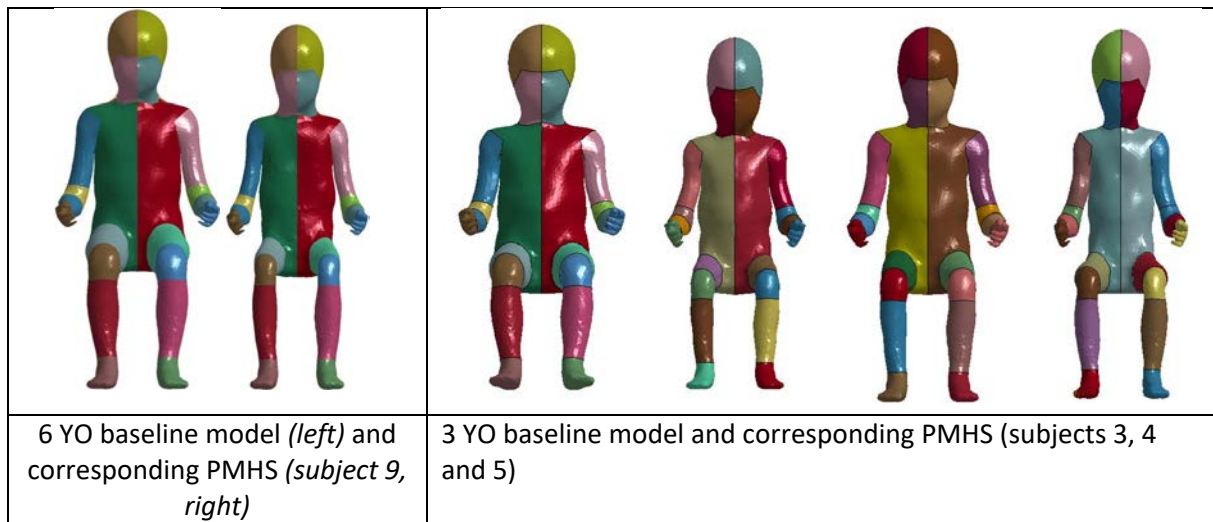


Figure 4. Scaling to Ouyang’s subject anthropometry. See Table 1 for the subject characteristics.

Table 1. Summary of statures and masses for the PMHS and corresponding scaled models

	Subject	Age (years)	height (mm)	weight (kg)	Scaled model	
					height (mm)	weight (kg)
Ouyang PMHS	3	3	850	10.5	850	11.35
	4	3	930	13.5	930	13.7
	5	3	910	10	910	10.9
	8	6	1090	20	1080	19.8
	9	6	1080	16.5	1080	16.1
Baseline models	3 YO	3	952	16	-	
	6 YO	6	1127	23		

For the impact setup, support and impactor were simulated by a rigid flat plate covered with Neoprene (for the support) and Sorbothane (for the impactor). The LS-Dyna viscoelastic law was used to represent the behavior of these materials with properties taken in the literature. The loading conditions were simulated by applying the initial velocity to an impactor of the same mass as the one used in the tests. As this velocity varied between PMHS, the exact value was used for the paired comparisons between baseline and scaled models. Impactor displacement and contact force between pelvis and impactor were saved as outputs of the simulations.

Sensitivity for the Q3 range: scaling methodology

As the Q3 can be used to certify CRS for children between a stature of 870mm and 1050mm, the current study aimed to generate three models with the following characteristics:

- the stature of the Q3 dummy (985mm) with 50th percentile dimensions (“Q3 size”)
- a 870mm stature with 5th percentile characteristics (small model) for anthropometric dimensions specified by R129 (e.g. shoulder width, hip breadth)
- a 1050mm stature with 95th percentile characteristics (large model) for anthropometric dimensions specified by R129 (e.g. shoulder width, hip breadth)

In the current R129, a number of dimensions are specified and must be verified independently for a given stature, typically at the 95th percentile level (sitting height, shoulder and hip breadth, shoulder height) or at the 5th (shoulder height). However, values are typically not provided for both 5th and 95th percentiles, and these dimensions would not be sufficient to drive the scaling by anthropometry.

The Candat database used for the definition of the Q dummies is not publicly available. Only limited values were published, and these are not sufficient to calculate percentile for anthropometric dimensions. Therefore, the Snyder public database (from Snyder et al., 1977) included with the PIPER software was used for the current effort. The anthropometric module provided with the PIPER software does not allow computing percentile values directly. However, since it allows sampling a virtual population as an output (using the methodology described by Parkinson and Reed, 2010), a large number of predictions can be made and percentiles can be estimated based on this population.

Virtual populations corresponding to the three models model statures were generated (1000 subjects each) to estimate the 5th (for the 870mm stature), the 50th (for the 985mm stature) and the 95th (for the 1050mm stature) percentiles for four Snyder measurements available in the database. The first three (sitting Height, maximum Hip Breadth Seated, Shoulder Breadth) are similar as the R129 requirements. For the fourth, as the shoulder height of R129 was not available in Snyder, the Suprasternale Height (standing) was selected as the measurement location is close to the location of the shoulder height (seated). Then, as an approximation, the shoulder height was estimated indirectly by removing from the sitting height the difference between stature and suprasternale height (i.e. corresponding to the head and neck). This can be considered as an indicator but not an accurate measurement.

The results for Snyder, along with the available Candat, R129 and Q3 dummy dimensions, are summarized in *Table 2*. Some discrepancies can be observed between the predictions and the 95th dimensions provided with R129 for a stature of 1050mm, especially for the shoulder height which is computed indirectly.

Table 2. Percentiles computed using the Snyder database (see text for methodology) and comparison with the Q3 dummy and values provided in the R129 text. Italicized values are computed indirectly and may not be reliable. The shoulder height value was not directly used for scaling.

	Snyder 5th	Q3	Snyder 50th	CANDAT 50th	Snyder 95th	R129 95th
Stature (mm)	870	985	985	950	1050	1050
Age (Year)	-	3	-	3	-	-
Sitting height (mm)	466	544	559	548	630	618
Shoulder height (mm)	234	329	334	-	418	391
Suprasternale height (standing, mm)	638				823	
Shoulder width (mm)	188	259	245	-	293	301
Hip width (sitting) (mm)	132	200	186	-	231	249

Then, a full set of anthropometric characteristics available in Snyder was generated using the PIPER anthropometric module with the following metrics and values as predictors:

- for the Q3 like model: the Q3 measurements were used (stature, sitting height, hip and shoulder breadth)
- for the small model (5th percentile 870 mm stature): stature and predictions at the 5th percentile level were used
- for the marge model (95th percentile 1050 mm stature): stature and predictions at the 95th percentile level were also used. The R129 values were not used (despite being available) to ensure consistency with the Snyder database.

Finally, the predicted anthropometries were used in scaling constraint module (as in *Figure 2*) and then in the kriging module to generate the three models.

Sensitivity for the Q3 range: Simplified side impact setup

For the simulation, a generic Group 1 CRS model developed by VFSB in the CASPER EC project and available under an Open Source license was used (www.piper-project.org). This CRS was not designed for regulation R129. It includes a deformable shell and a rigid base. The child models were positioned in the generic CRS model using the PIPER software. They were settled using a gravity run, and a harness was added. The three models were finally subjected to two impact conditions:

- (1) A simplification of the R129 side impact setup in which the door was simulated as rigid and the intrusion was applied to accelerate the CRS. No rebound was allowed for the base.
- (2) A far side impact condition using a harder pulse proposed by Holtz et al. (Ircobi, 2016).

Results

Sensitivity in the side pelvic validation setup

An illustration of the kinematics response for the pelvic impact is provided in *Figure 5*. The impactor engaged the pelvic region, resulting in a compression of the soft tissues, followed by a pelvic translation (with some spine lateral flexion), and a compression of the soft tissues on the fixed side.

Corresponding impactor force vs displacement responses are shown on *Figure 6* for all five subjects. Overall, the simulations performed with the scaled models reduced the discrepancies between the baseline model and the experiment. The changes improved the peak force values in the three cases with the highest discrepancies (PMHS 5, 8, 9), and improved the timing of the peak force in all cases. The shape of the curve and the timing of the peak may be more affected by the change of anthropometry than the amplitude. The scaling had limited effect on the peak displacement however, which remained consistently smaller than the reported experimental results.

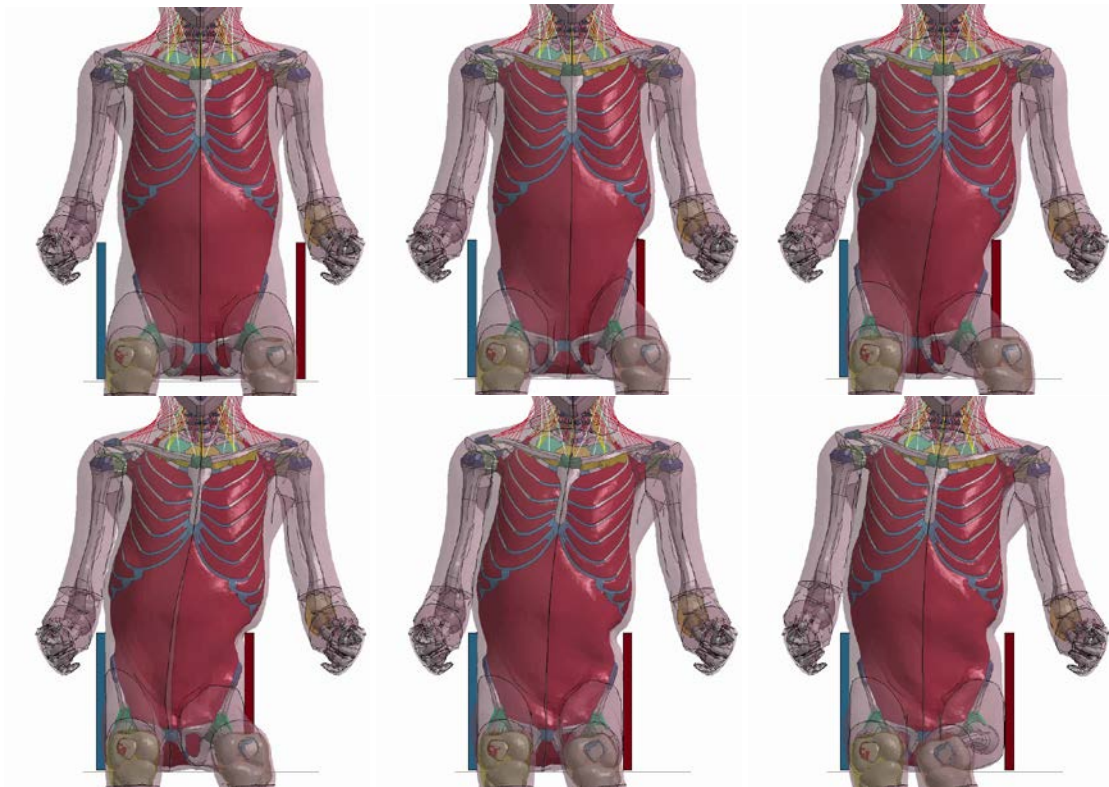


Figure 5. Illustration of kinematics response for Ouyang's lateral impact (scaled model matching the Subject 9, impactor velocity of 7.1 m/s). At 0, 5, 10, 15, 20 and 25 ms after contact.

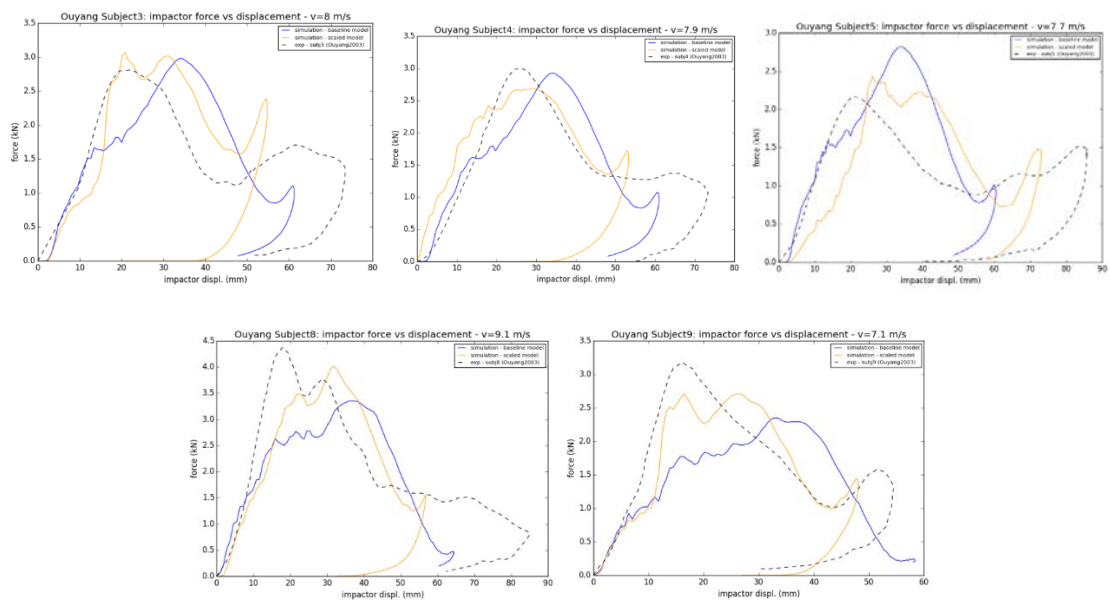


Figure 6. Response comparison between the baseline (purple), scaled (orange) and test subject (dashed) for five PMHS tested in Ouyang et al. (2003). The 3 YO model is used as the baseline for the first three subjects (top) and the 6 YO is used for the last two (bottom)

Sensitivity for the Q3 range

The combinations of range of stature with the anthropometric percentiles resulted in very different anthropometries and human models, with masses ranging from 10.4 kg (for the 870mm stature) to 23.1 kg (for the 1050mm). The Q3 stature model mass was 17.1 kg, which is higher than the Q3 dummy mass (14.6 kg). Corresponding ages in the anthropometric prediction (using the stature and 5th or 95th values as predictors) were less than 1 YO to almost 6 YO.

Despite these difference, all models fitted in the CRS after small postural adjustments to the lower and upper extremities in the PIPER positioning modles. The three models in the CRS are shown in *Figure 7*. The legs of the smallest model were moved to allow for the belt fitting. The three models interacted very differently with the CRS.

In the R129 impact (*Figure 8*), the smallest model slid on the CRS and the shoulder was engaged late (around 40ms) when the head was already close to the contact surface. Conversely, the shoulder of the largest model was engaged early (around 25ms), and the head barely contacted the CRS. This resulted in different load path (e.g. head vs. shoulder) between the models, and in the end, very different loading to the head.

In far side setup (*Figure 9*), the CRS shell had a tendency to deform as it is not supported by a door and the head of the tallest model had a tendency to protrude from the CRS. The time of shoulder engagement also differed between models (as in the near side setup). Head contact forces also differed between models.

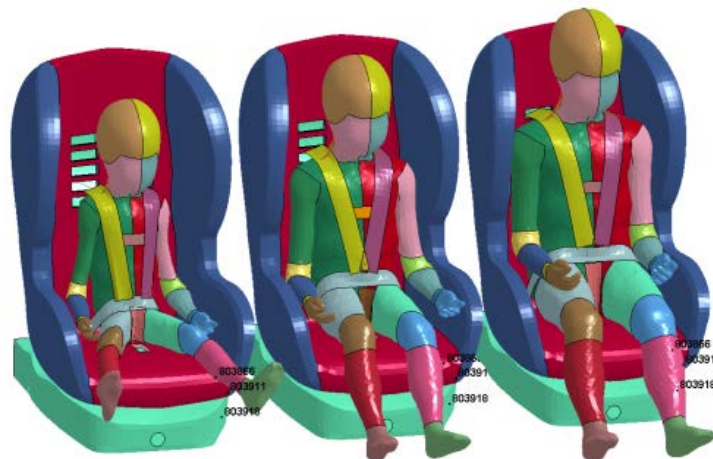


Figure 7. Range of models positioned in the CRS and belted. Left: 870 mm stature with 5th percentile characteristics. Center, 985mm with 50th percentile characteristics (similar to a Q3). Right: 1050mm stature with 95th percentile characteristics. See text for exact definitions. For the smallest model, the legs were moved

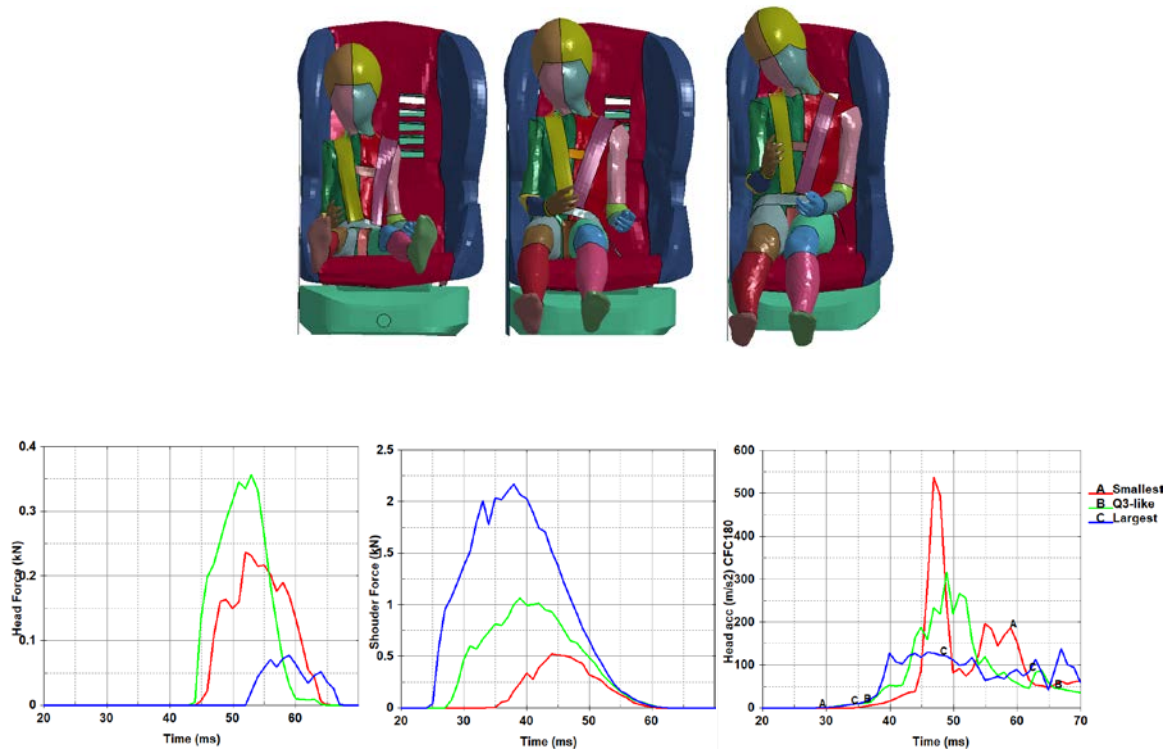


Figure 8. Responses of the three models in the R129 simplified near side impact conditions. The kinematics and response curves illustrate the difference of shoulder engagement and corresponding head loading. The illustrations on top are taken near head contact time.

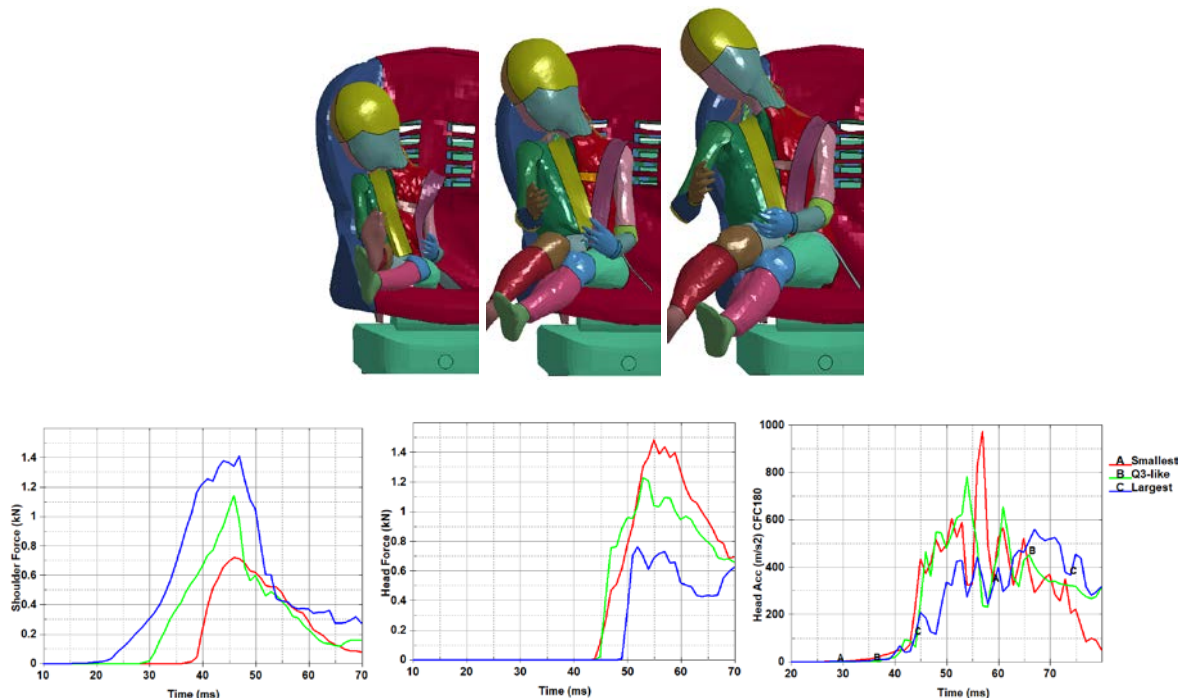


Figure 9. Responses of the three models in the simplified far side condition. The kinematics and response curves illustrate the difference of shoulder engagement and head loading. The illustrations are taken at 65ms.

Discussion

For the pelvic impact validation setup, the anthropometric scaling allowed approaching the stature and the mass of the PMHS used in the tests. Several observations can be made based on the responses. Anthropometry and/or mass seem important for the configuration (more than all other parameters studied in Beillas et al., 2016) as they affected (and improved) significantly the shape of the response curve and the timing of the peak when compared to the baseline model. This suggests that efforts to scale the response curves to define corridors should account for such parameters. The effect on the peak force was more limited, and the effect on the peak displacement almost negligible. The mismatch on the peak displacement may be at least partially related to the fact that the initial kinetic energy of the impactor is lower than the area under the curve in the tests. This may suggest a measurement issue or that the pneumatic device was not completely decoupled after contact and continued to transfer some energy to the impact during the compression. The main limitation of the scaling is the fact that, as the complete anthropometry or skeletal dimensions from the PMHS are unknown, predictions had to be made using average external dimensions derived from the Snyder database. This does not account for changes of soft tissues thickness or skeletal dimension. Regressions regarding pelvic anthropometry in particular could be used in the future to better constraint the skeleton.

The Q3 range application in side impact shares the same limitations on scaling driven by external dimensions. Furthermore, many assumptions were made when building the models. For availability and consistency reasons, the Snyder database was used (rather than the Candat database or the R129 95th values) and discrepancies were observed on some of the measurements when available. This means that the larger model does not exactly fit the R129 requirements on 95th anthropometry. Also, the shoulder height could not be used as it is not present in the Snyder database. However, in the future, it could be estimated independently for each of the subject of the Snyder database based on other dimensions, and then used in the statistical analysis. A more important assumption was the fact that all variables related to R129 requirements were assumed to be concurrently at the 5th or the 95th percentile. While it is expected that some variables may be correlated (e.g. shoulder and hip breadth), the likelihood for all value to be extreme at the same time is unknown. A more in-depth analysis of the Snyder database (outside the PIPER software) could provide some insight into these assumptions. Otherwise, dimensions could be set at the 5th or 95th one at a time, and the most likely models could be generated using the anthropometric module in PIPER.

These assumptions led to models which are very different in terms of weight (from 10.4 to 23.1 kg) and ages in the anthropometric prediction (from less than 1 YO to almost 6 YO). While large, these variations are not inconsistent with those observed on the PMHS tested by Ouyang and reported in *Table 1* (with weights between 10.5 and 20 kg for five subjects of 3 or 6 years old, with statures between 850 and 1080 mm).

In the two simplified side impact setups, the three models generated led to different engagement of the shoulder, loading of the head, and head containment in far side. This suggests that such variations could play a role in the CRS protection provided in side impact but this should be further evaluated in more realistic setups (as the CRS was not designed for R129 and the boundary conditions were idealized). In the end, the scaling assumptions should be further refined to investigate if the range of statures associated with a dummy in R129 coupled with wide anthropometric variations without constraints on the weight or age could lead to such board differences.

Conclusions

The PIPER child model was successfully scaled using the PIPER software and used in two side impact applications related to the possible relationships between anthropometry and side impact response.

Overall, these results are considered as encouraging considering the recent availability of these tools, and they suggest that other side impact applications may be possible.

Results from both application results suggested a sensitivity of the model response to anthropometric variations. This sensitivity may partially explain the experimental variability of the pelvic impact response in the Ouyang et al. (2003) tests. For the application on the extreme range of children covered by a Q3 dummy in R129, the results should be considered as preliminary considering some of the statistical assumptions. However, the methodology could be used with different assumptions to refine the extreme models, and these could be used in the future to check the CRS dynamic behaviour not only for dummy dimensions but for the complete range of anthropometry a dummy is covering.

Acknowledgements

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