A Finite Element Model of the Crash Test Dummy SET v0.2 50F for Low Severity Rear Impacts

Astrid Linder, Natsuki Omichi, Victor Alvarez, Shigeki Hayashi, Noritaka Takagi, Mats Svensson, Jobin D. John

Abstract Vehicle occupant safety assessments involving virtual models are gradually becoming more widely used by consumer testing organisations. For such assessments, validated virtual models of the dummies are needed as the first step towards the use of human body models (HBMs). Validation of a virtual dummy model requires virtual reproduction of test data from physical dummy tests at both component and whole-body levels. The aim of the present study was to further improve a finite element model of an average sized female crash test dummy (SET 50F v0.2) for low severity rear impact testing.

This was the first step towards a fully validated virtual dummy model (FE SET 50F), focusing on the performance of soft tissue neck injury assessment. The following physical tests of SET 50F v0.2 were performed: static spine bending tests (cervical, thoracic and lumbar), a dynamic drop test of the thorax and the abdomen rubber foam sections, and finally a rear impact sled test at 24 km/h delta-v. The finite element model (FE SET 50F 2.0.0) is a virtual analogue of the physical dummy SET v0.2 50F. It was calibrated by reproducing these component-tests and subsequently validated using the physical sled test results. Once fully validated, the FE SET 50F 2.0.0 can be used together with the physical SET v0.2 50F, to validate virtual seat models for virtual assessment of seat safety performance in rear impacts. The validated seat models may then be used together with validated Finite Element HBMs to virtually assess the protection provided by the seat in vehicle crashes.

Keywords Average female model, finite element, vehicle occupant safety, virtual testing, whiplash injury.

I. INTRODUCTION

Motor vehicle crashes resulting in soft tissue neck injuries, referred to as whiplash injuries, remain a major concern [1]. These injuries are the most common and costly disabling injuries for vehicle occupants. For the latest car year models (2010–2019) [1]), soft tissue neck injuries accounted for 43% of all injuries resulting in permanent medical impairments. Injury statistics from the late 1960s until today show that females have a 1.5 to 3 times higher risk of sustaining whiplash injuries than males [1–13]. Furthermore, some concepts for whiplash protection seats have proven to be more effective for males than females [14-15]. These injuries most often occur at low speed changes, between 10 km/h and 25 km/h [16–18], and the majority occurs in rear impacts [19–21]. Virtual model-based assessment of occupant protection in crash safety is increasingly being planned and adopted by consumer test organisations [22-23]. To perform such assessments, validated virtual models of both the vehicles and the occupants are needed. The SETs and their finite element (FE) counterparts could, once fully validated, be used to validate virtual seat models for usage in virtual assessment of the safety performance of vehicles in rear impacts.

To address this need, the aim of this study was to further improve a finite element (FE) model, FE SET 50F, to serve as the virtual analogue to the SET v0.2 50F crash test dummy [24]. Initially, component-level tests were performed to calibrate the FE model, followed by the validation of sled tests. This study focuses on the assessment of soft tissue neck injury risk in low severity rear impacts.

A. Linder (e-mail address: astrid.linder@vti.se; tel: +46 708 286468) is a Professor at Swedish National Road and Transport Research Institute, VTI, Sweden and adjunct Professor at the Department of Mechanical Engineering, Chalmers University of Technology, Sweden and at Monash University, Australia. N. Omichi is an Engineer, S. Hayashi is a Project Manager and N. Takagi is an Engineer at Toyota Motor Corporation, Japan. V. Alvarez is a Consultant at Lightness by Design, Sweden. M Svensson is a Professor at the Department of Mechanical Engineering, Chalmers University of Technology, Sweden. J. John is a Researcher at the Department of Mechanical Engineering, Chalmers University of Technology, Sweden.

II. METHODS

The FE SET 50F 2.0.0 was developed based on the beta-version of SET 50F v0.2 [24]. The preliminary model of FE-SET [25], in this study referred to as the Original CAE model, was further developed in this study to improve the torso mesh, spine joint stiffness and neck spring complex. Inconsistencies in the element lengths of the Original CAE model resulted in increased computational time. In addition, the need for improved agreement between the spine response and initial position of the neck of the Original CAE model compared to the dummy has been identified. Furthermore, the mass distribution has been updated to match that of the physical counterparts. The model was developed for the FE code LS-DYNA R11 (ANSYS Inc.).

The SETs constitute a pair consisting of an average female and an average male crash test dummy, developed for low severity rear impact testing. The geometries of the two SETs correspond to those of a 50 year-old average female and male, respectively, generated from the database HumanShape, humanshape.org. These are the same geometries as those used for the virtual human body models (HBMs) VIVA+ 50F and 50M [26]. Experience from the development of the BioRID II [27-28] and BioRID P50F [29] served as input for the development of the SETs. The first generation of the two SETs is described in [24], with the drawings available at OpenVT.eu.

The thoracic and lumbar spine segments of the SETs can bend in the frontal and sagittal planes and allow for axial rotation. The number of vertebrae has been reduced compared to the BioRID II. The SET neck design has muscle substitutes consisting of steel cables connecting between the head and the T1 level of the spine. The cables connect to springs and a rotational damper; all placed inside the head of each SET (as opposed to along the thoracic spine as in BioRID II). The chest and abdomen sections are moulded in rubber foam of different stiffness properties, consisting of the material PLIXXOPOL FI 4710W033. The chest consists of two left/right halves, and the lower part of the torso is casted in one piece. Metal pins, extending laterally from the spine, guide the chest and abdomen into their positions. The shoulders are pivoting around their clavicle joint attachment points at the sternum position, allowing for shoulder joint forward and rearward displacement relative to the torso.

In the construction of the SETs, some parts were sourced from other crash test dummies. For the SET 50F, the head and arms of the Hybrid III 5F were used. While the Hybrid III 5F head was used unaltered, the mass and size of the arms and legs were adjusted to that of the 50th percentile average female from HumanShape (https://humanshape.org/), and the upper arms were modified to fit on the shoulder of the SET 50F. The BioRID II pelvis was used with modifications to the soft tissue shape, i.e., increased width and rear side contour (described in more detail in [24]). For the SET 50M, the Hybrid III 50M head, arms and legs were used unaltered, except for the upper arms that were adjusted to attach to the shoulder of the SET 50M. The pelvis from the BioRID was used for the SET 50M.

Two alterations were implemented in SET v0.2 compared to SET v0.1. Firstly, the mass was increased to better match the equivalent sections of the VIVA+ 50F and 50M. Secondly, rubber blocks were placed between the vertebrae of the neck to provide improved stability of the neck in its initial position. The mass of the two SETs v0.2 used in this study, was increased compared to the two SETs v0.1 [24], to match the total mass and the distribution of the mass of the head, arms, torso, pelvis and legs of the VIVA+ models, see Table A1 in Appendix A.

Static Bending of the Spine

Bending tests of the thoracic and lumbar spine joints were performed in a test set-up in which the pelvis plate was placed vertically and gravitational force from weights, 3 kg and 6 kg, were applied at T1, as shown in Fig. 1. These tests were subsequently used to calibrate the stiffness of the FE thoracic and lumbar spine joints by scaling the moment-rotation characteristics. The cervical spine stiffness tests were carried out by placing the thoracic spine horizontally on a flat surface. Gravitational force from weights, 6 kg and 12 kg, was applied at the top of the neck as shown in Fig. 2. Comparison between the bending tests and the simulations of the same test set-up was done visually. The cervical spine section of the FE model was subsequently calibrated using these data, by tuning the initial forces in the spring and scaling the moment-rotation characteristics, of the joints.

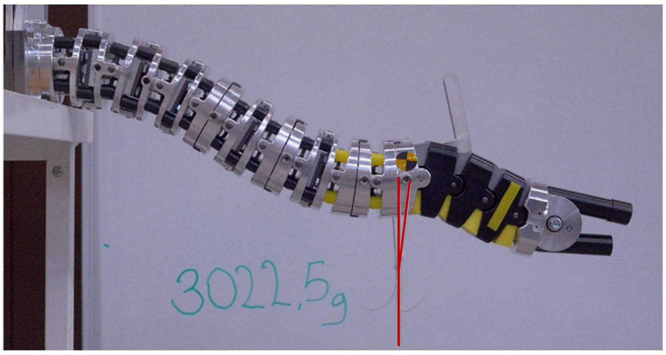

Fig. 1. Static bending of the thoracic and lumbar spine. The cord attached to the spine has been marked with red for clarity.

Fig. 2. Static bending of the cervical spine. The cord attached to the spine has been marked with red for clarity.

Drop Tests and Foam Material Model Calibration

Drop tests were performed on samples of the foam material used for the thorax and abdomen. To verify the properties of the foam, the test set-up used was the UNECE UN Regulation No. 129 test [30]. A semi-spherical impactor weighing 6 kg was dropped from the heights of 100 mm, 200 mm and 300 mm, resulting in impact velocities of 1.25 m/s, 1.90 m/s and 2.33 m/s (Table I). The impactor was dropped with the curved surface facing downwards on a foam sample with a thickness of 100 mm (Fig. 3). These drop tests were used to calibrate the material parameters of the foam material. The drop height of 300 mm was not applied to the foam of the abdomen as that foam was softer than the foam used for the thorax and would therefore be at risk of bottoming out (and potentially damaging the sphere). The results were analysed using ISO 18571.

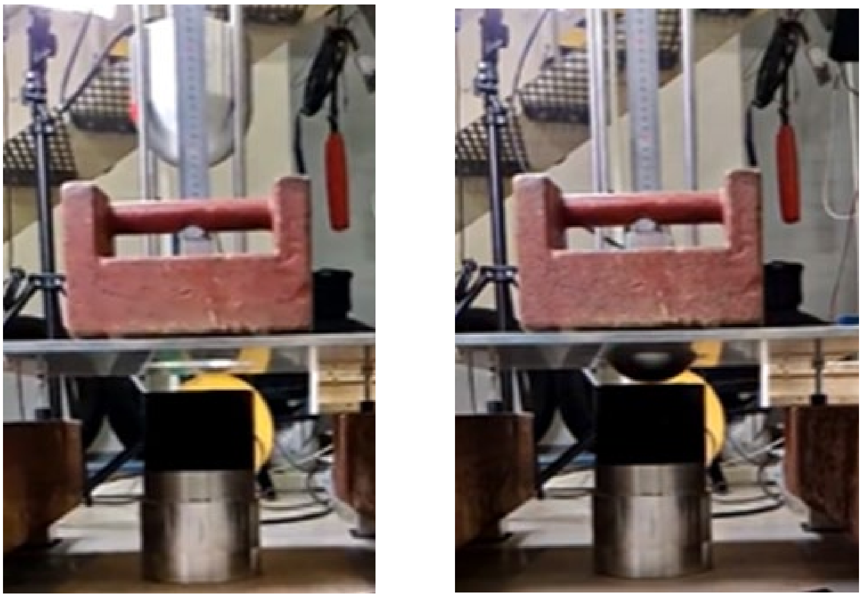

Fig. 3. The semi-sphere at initial position (*left*) and at impact (*right*) in the thorax and abdomen foam drop test.

TABLE I

DROP TEST HEIGHTS IN THE THORAX AND ABDOMEN FOAM DROP TEST

Drop Height (mm)	Abdomen Foam	Thorax Foam
100	○	○
200	○	○
300	none	○

Sled Test and Simulation

The SET v0.2 50F was run in a rear-impact sled test, in a seat of a commercially available vehicle model, year model 2024, using the high severity whiplash testing pulse described in the protocol for dynamic testing version 4.2 [31]. The head restraint position, seat back and height adjustment were positioned in accordance with this protocol. The sled test was run on the Inverse Crash System by Mannesmann-Rexroth, at Autoliv, Sweden. To position the SET v0.2 50M on the seat, it was lowered onto the seat from above and guided backwards into the seat back. The head-to-head restraint gaps were not predefined and corresponded to those of the SETs once positioned on the seat. When required, the head was adjusted to mimic a forward-viewing position. The seat was positioned in accordance with the European New Car Assessment Programme (Euro NCAP) procedure [31] and the SET was restrained with a conventional 3-point seat belt.

On-board high-speed video cameras recorded the tests at 1,000 fps, and video targets were fitted to the head of the SET, to the first thoracic vertebra (T1) and to the pelvis. Six degrees of freedom (6-DOF) sensors (TE Connectivity model 633), integrating gyros and accelerometers, were placed in the head and at T1, T8 and pelvis (described in more detail in [32]). The signals were sampled at 10 kHz and filtered according to the SAE J211 recommendations.

The sled test was simulated using an in-house FE model of the seat, validated by [33], and the FE SET 50F 2.0.0. For the positioning of the FE SET 50F 2.0.0, the angles of the dummy head, T1 and pelvis were obtained from the sled test results. The hip and heel points were estimated from the photographs prior to testing. The results were analysed using ISO 18571.

III. RESULTS

FE SET 50F 2.0.0 Model

A new mesh of the torso and abdomen was integrated into the FE SET 50F 2.0.0 model. It is available open source on OpenVT (https://openvt.eu/set/fe-set) and documentation of the model is published online (https://fe-set.readthedocs.io/). Due to inconsistent mesh sizes, the element length of the torso and lower leg was corrected to 8 mm. Hence, the added mass decreased from 8.2 g to 1.6 g, regions in the torso and legs with time steps ≤ 0.7 µs were eliminated and the computation time was reduced from 15 m 46 s to 12 m 56 s. By modifying the joint stiffness, the spine stiffness was adjusted to better match the physical dummy. In addition, the properties of the neck springs, and the neck stiffness were modified, and spring length were adjusted to match the physical dummy.

Static Bending of the Thoracic and Lumbar Spines

The spine bending tests were reproduced in the FE model for the same quasi-static loading condition and overlaid on the pictures from the physical tests (examples in Fig. 1 and 2) as shown in Fig. 4. The deflection of the thoracolumbar spine under the three different loading conditions and the simulations are shown in Fig. 4. In addition to updating the joint stiffness, to match the bending pattern observed in the physical tests, rotational angle range limits were defined for these joints.

Fig. 4. The loaded state for the three different loadings on the thoracolumbar spine, overlaid with the FE element model under the corresponding quasi-static loading. The cord attached to the spine has been marked with red for clarity.

Static Bending of the Neck

In addition to the segmental stiffness, the initial spring forces were set to 65.7 N in the anterior spring and 54.5 N in the posterior spring. In Fig 5, the simulation and physical test with the loading of solely gravity, and with 6 kg 12 kg, are shown.

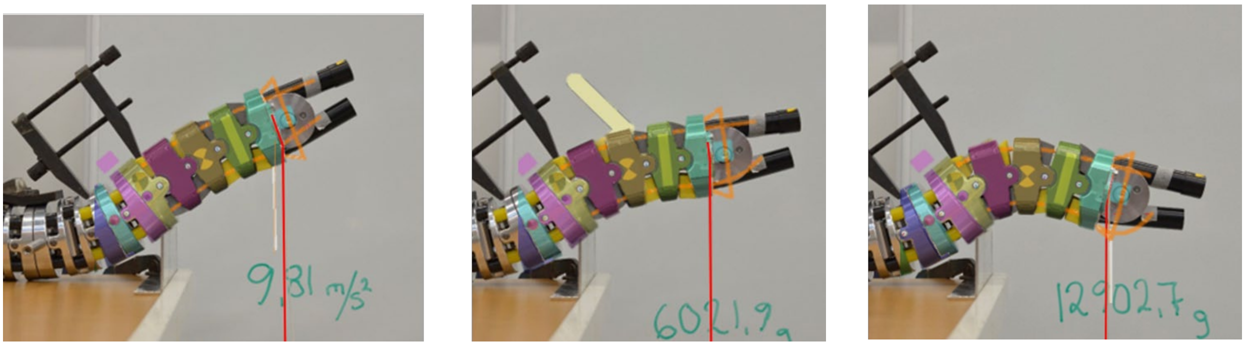

Fig. 5. The loaded state of the neck, overlaid with the FE element model being simulated under the corresponding quasi-static load condition with the loading of solely gravity, and with 6 kg 12 kg. The cord attached to the top of the neck has been marked with red for clarity.

Soft Component Drop Tests

The material model parameters were updated based on the results from the physical drop tests on the thorax and abdomen material specimens, Fig 3. The FE SET 50F 2.0.0 showed improved agreement with the test results, as shown in Fig. 6, for the 300 mm tests. The results were similar for all three drop heights for the thorax foam and for the two drop heights for the abdomen foam (Table I). The results from all the foam drop tests and the simulations are provided in Appendix A and the objective ISO rating scores are given in Appendix B. The overall rating scores for all the drop heights for abdomen and thorax test were rated good ($0.8 < R \leq 0.94$) for the modified material parameters.

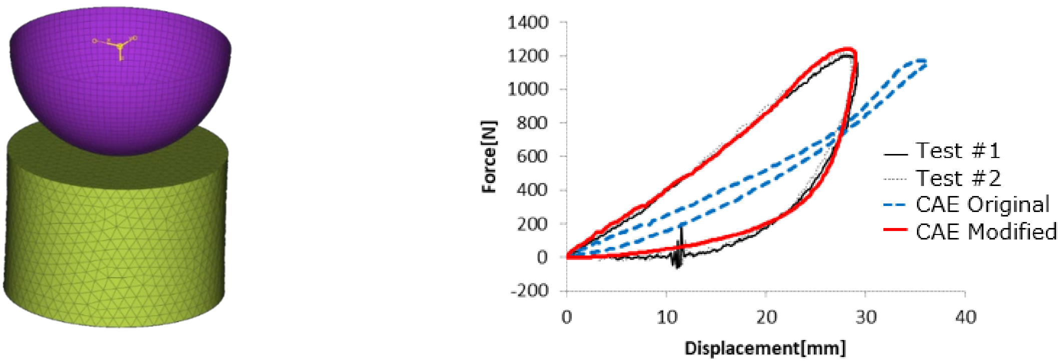

Fig. 6. FE simulation of the drop test of the foam (*left*). Force-displacement response of the drop test, comparing the foam simulation response with the physical tests (*right*). The original CAE model is represented by the blue dotted line, the FE SET 50F v0.2.0 (CAE Modified) is represented by the red line and the physical tests results are shown in grey and black.

Sled test

The comparison of the acceleration and angular velocity was made at four positions: the head, the 1st thoracic vertebrae (T1), the 8th thoracic vertebrae (T8) and the pelvis. The accelerations and angular velocities from the tests and simulations in all three directions-of-freedom are shown in Fig. 7 and Fig. 8. The X-acceleration has positive sign forward while positive y-rotational velocity of the head, represents backward rotation (extension motion). For the torso angle of 25 degrees, the initial positions of the SET 50F and the CAE models were: head angle -2.5 degrees/-2.6 degrees, T1 angle 26.8 degrees/26.2 degrees and pelvis angle 33 degrees/ 33 degrees. The objective ISO rating scores for the kinematics in the principal direction of loading, the sagittal plane, is given in Appendix C. The objective ISO rating scores for all the responses improved, with all the kinematics in x-direction getting either a good score (0.8 < R ≤ 0.94) or a fair score (0.58 < R ≤ 0.8) closer to 0.8. In the z-direction, all the responses had a fair score, except the T1 z-acceleration which had a score of 0.52. In the rotational responses, while scores had improved considerably from the previous version of the model, the scores were in the fair range or close to fair scores.

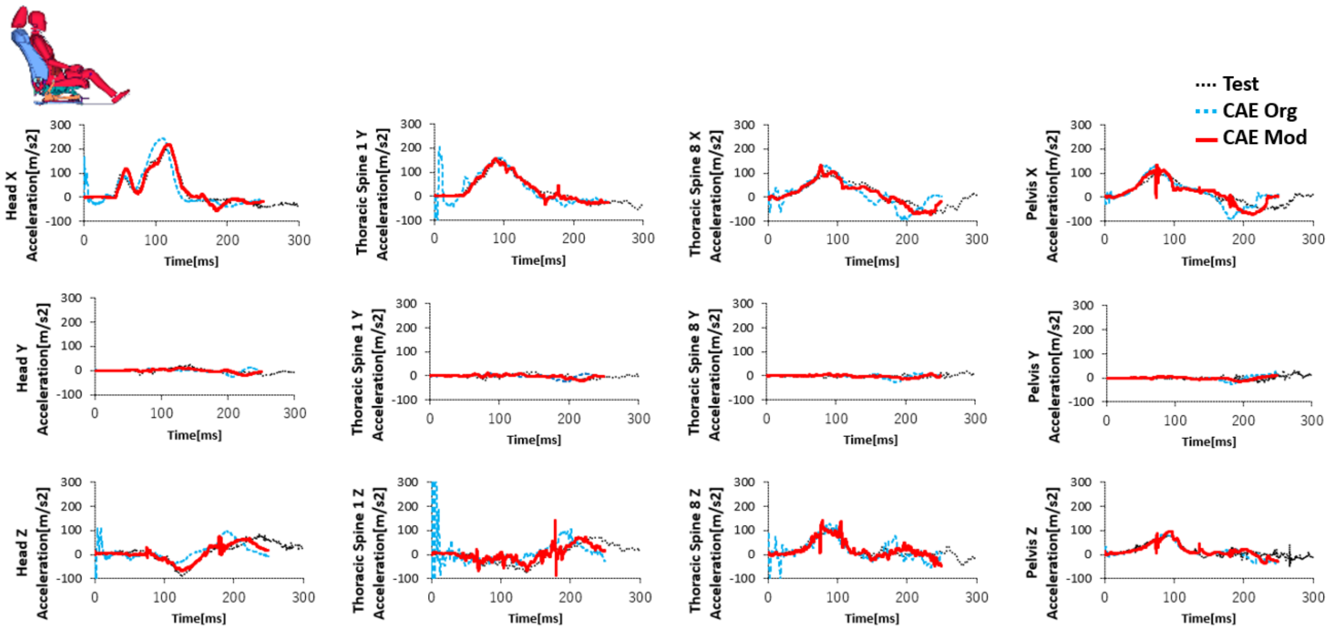

Fig. 7. Linear accelerations from the 24 km/h test with the SET v0.2 50F (Test) as well as the simulations with the FE SET 50F 2.0.0 (CAE Mod) and the CAE Org.

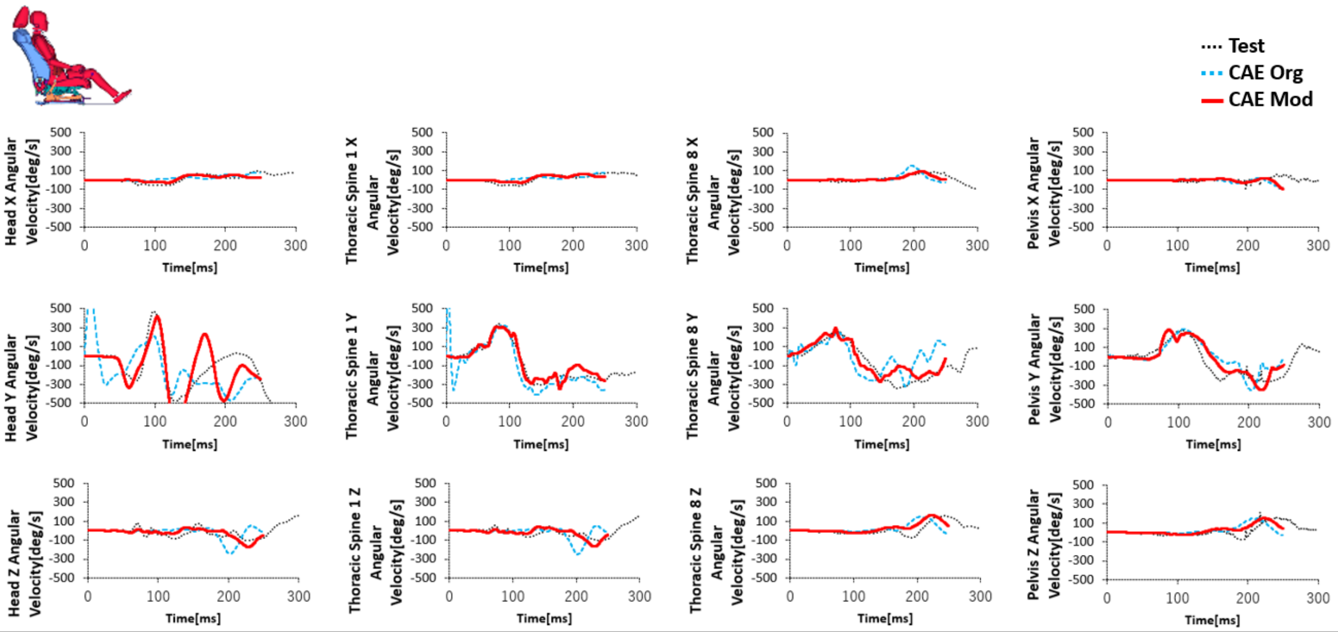

Fig. 8. Angular velocities from the 24 km/h test with the SET v0.2 50F (Test) as well as the simulations with the FE SET 50F 2.0.0 (CAE Mod) and the CAE Org.

IV. DISCUSSION

This study provides a first step in the process of attaining a fully validated FE model of a dummy for low severity rear impact testing. Once finalised, the physical SET and the corresponding virtual model could be used together for validation of virtual seat models, to be used in future virtual assessment of occupant protection in low severity rear impacts. The FE SET 50F 2.0.0 was developed to create a virtual representation of the hardware SET v0.2 50F.

The static spine bending tests were reproduced in the FE model for the same quasi-static loading condition and was overlaid on the pictures from the physical tests shown in Fig. 4 and 5. The visual comparison showed a similar bending pattern of both the lumbar and thoracic spine, as well as the neck, for all load cases. The dynamic response of the SET v0.2 was reproduced by the FE SET 50F 2.0.0, with improved accuracy after the current recalibrations. The calibrations of the material parameters resulted in improvement of the ISO scores in all the drop tests, with a marked improvement in the torso foam material (Appendix B). As a result of the calibration of the spine and the foam, the accelerations and rotational responses at head, T1, T8 and pelvis also improved with respect to the previous version of the model (Appendix C).

The calibration of the spine was done on a component level. Since the three spinal segments (lumbar, thoracic and cervical) are made of components that are either rigid or predominantly elastic, with little damping or friction, we assumed that quasi-static testing would be sufficient at this stage of the dummy development. The material properties of the rubber foam, on the other hand, were expected to have speed dependent deformation properties. Therefore, the impactor drop tests of Fig. 3, were included as they consist of a well-defined standardised test set-up, which is straight forward to reproduce in the virtual environment.

The validation of the seat model used in this study was presented in [33], in a rear-impact test study comparing the response between this seat model and the corresponding simulations. Those tests were run with the BioRID II dummy at delta-v 16 km/h and 24 km/h. The rear-impact sled experiments were then simulated using the BioRID II FE model (DYNAmore version 4.0.1). Two seat models were compared in [33]: an initial model created without any validation test data, and an improved model, validated and modified to match the seat kinematics observed during the sled tests. ISO waveform checks and injury-value estimation checks were carried out, in which the improved seat model demonstrated better ISO scores. Based on ISO scores, all estimated injury values had less than 20% deviation between the tests and simulations.

The physical sled test in this study did not include detailed measurements of the dummy prior to testing, such as faro-arm measurements of reference points on the dummy or the coordinates of the tracking targets. Instead, we relied on photo and video information to document the dummy positioning. Faro-arm measurements could be a better alternative for positioning of the virtual SET as well as for comparing the repeatability of the positioning in repeated physical tests. The lack thereof is a limitation of this study, and it is recommended for future studies comparing the response of physical and computer models.

In summary, the performance of the virtual SET was improved in terms of matching the physical tests results. This was achieved by modifications and recalibration at component level, comprising of remeshing and mass adjustments, and was verified in the virtual reconstruction of the sled test at 24 km/h. In addition to repeatability tests with the SET, further validations need to be undertaken for a range of impact velocities and vehicle seats. Furthermore, the FE SET 50F could be validated by running tests with the Chalmers LAB seat (of which a FE model is available open source [35]) and tests simulated with the FE SET 50F. Tests in the Chalmers LAB seat have also been performed with volunteers [36] and could provide an opportunity to compare the response of the virtual model to that of humans.

The SETs and the FE SETs, once fully validated, can be used in the virtual tests chain for virtual assessment of the safety performance of seats in rear impacts. Virtual seat models can be validated using a physical dummy and its virtual counterpart. What dummy model to use in the low severity rear impact tests is a question that has to be addressed in the planning of such tests. The ability of the high-speed crash test dummy, the Hybrid III, to provide a human-like response in low severity rear impact, was the focus of [37]. The following formulation can be found in the introduction of the Summary, "The poor biofidelity of the Hybrid III in low-speed rear impact conditions could send head restraint design in the wrong direction and reduce the level of whiplash protection offered to car occupants. The Hybrid III is therefore not appropriate for whiplash protection testing." The SETs have been specifically designed to provide human-like interaction with the seat in low severity rear impacts and provide the option of assessing the level of protection from soft tissue neck injuries in a crash. Inclusion of such assessments in virtual testing procedures are expected in the near future by Euro NCAP [23] and the Insurance Institute for Highway Safety (IIHS) [22], among others.

This study provides a first step in the process of a fully validated model of the SET 50F, to be used together with the physical dummy in the validation of virtual seat models. This will provide a basis for future virtual assessment of occupant protection in low severity rear impacts. In addition, simulations using more human like virtual occupant models such as the Total Human Model for Safety (THUMS), Global Human Body Model Consortium (GHBMC), SAFER HBM and VIVA+, are expected to provide extended insights into the safety performance of new cars.

V. CONCLUSION

A FE model, the FE SET 50F v2.0.0 of the crash test dummy SET v0.2 50F, was developed, calibrated on component level and validated in a sled test. The calibration tests included: dynamic drop tests of the soft part of the torso and abdomen as well as static spine-bending tests. The validation test was a sled test at 24 km/h. The FE SET 50F 2.0.0 showed improved responses that compared better with the physical tests as a result of the calibration performed on the component level. The FE SET 50F 2.0.0 is, together with its male counterpart, available open source at www.OpenVT.eu.

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VIII. APPENDIX A

TABLE AI
THE MASS OF THE SET v0.2 50F AND 50M AND THE VIVA+ 50F AND 50M.

	SET v0.2 50F mass (kg)	VIVA+ 50F mass (kg)	SET v0.2 50M mass (kg)	VIVA+ 50M mass (kg)
Head	3.9	3.8	4.4	4.4
Arms	5.2	6.0	9.5	7.7
Torso and Pelvis	37.6	32.5	39.9	40.6
Legs	16.0	19.9	23.5	23.5
Total	62.7	62.2	77.3	76.2

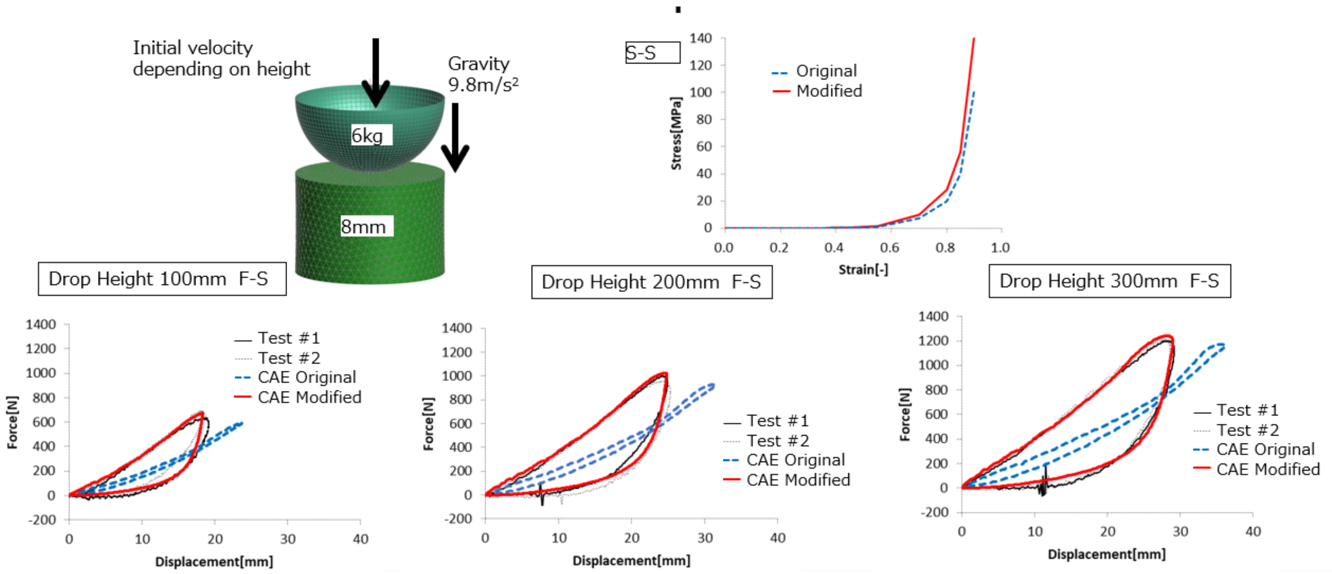


Fig. A1. The results from the thoracic foam drop tests and the simulations.

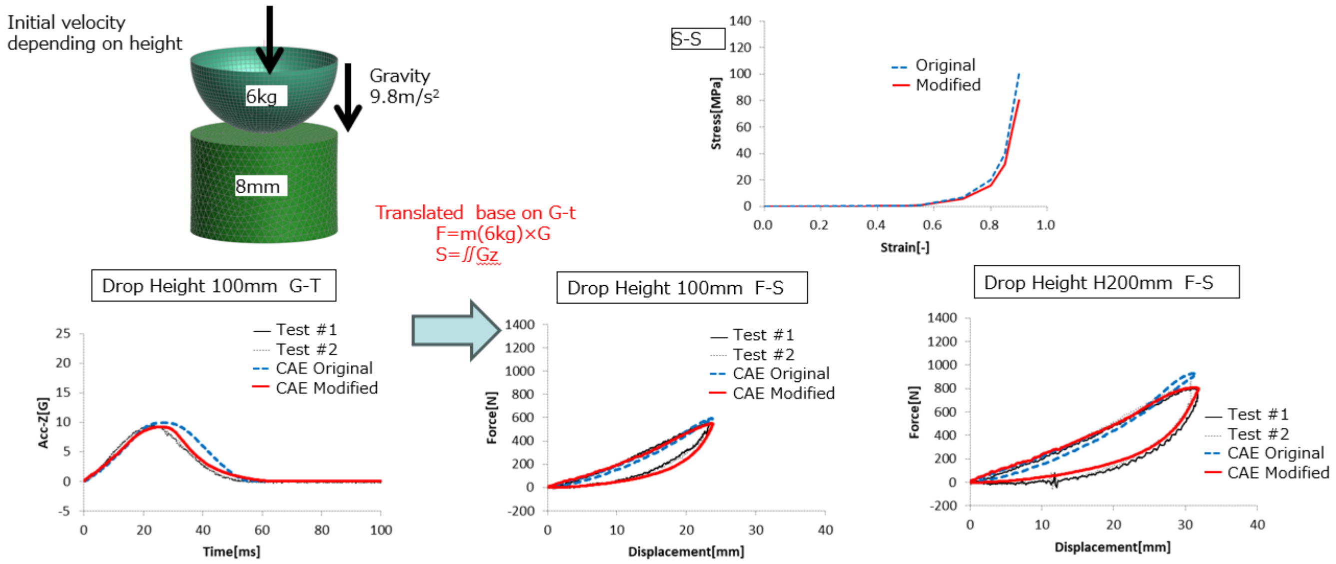
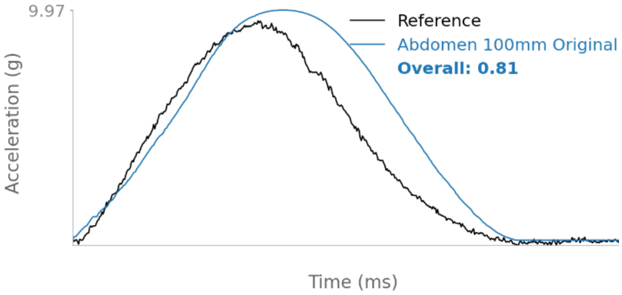


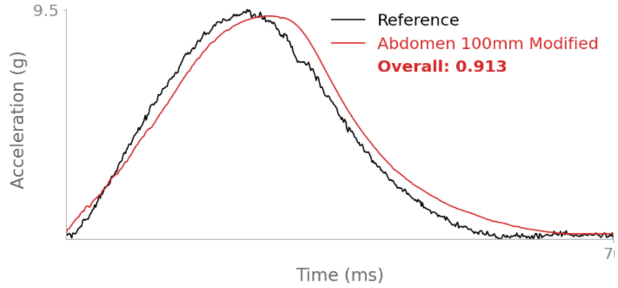
Fig. A2. The results from the abdomen foam drop tests and the simulations.

APPENDIX B: ISO 18571 Overall Rating

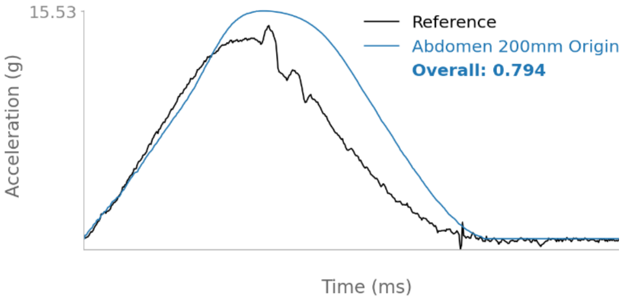
Abdomen Foam Drop Test

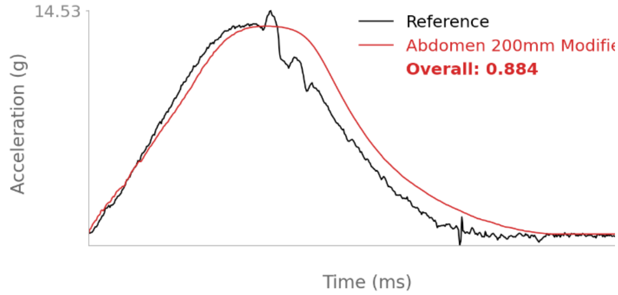
100 mm drop





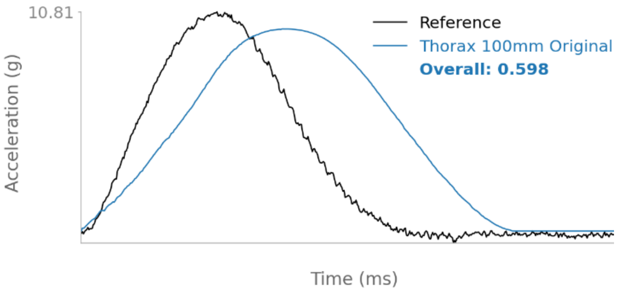
200 mm drop

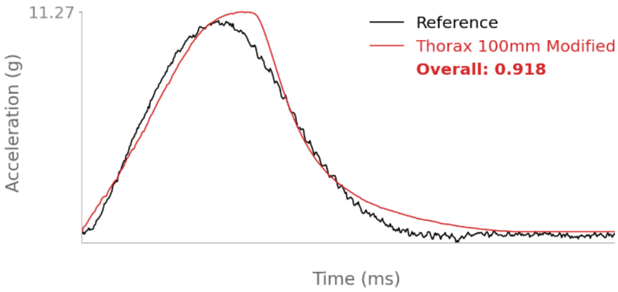




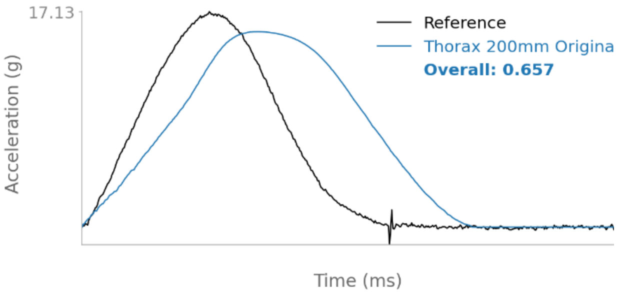
Thorax Foam Drop Test

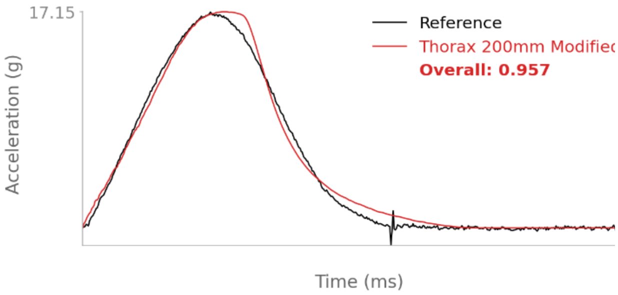
100 mm drop



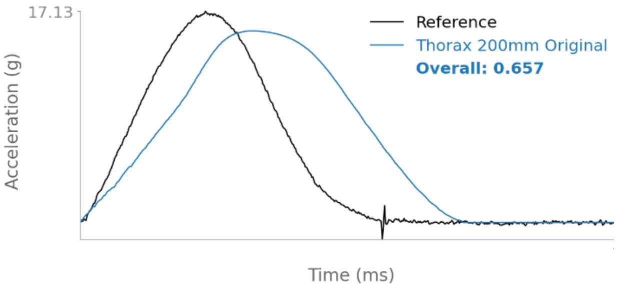


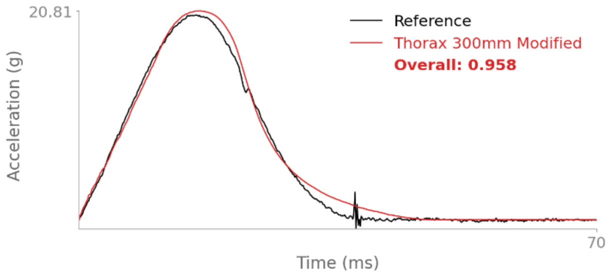
200 mm drop





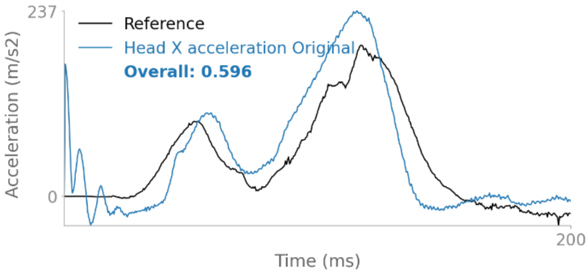
300 mm drop

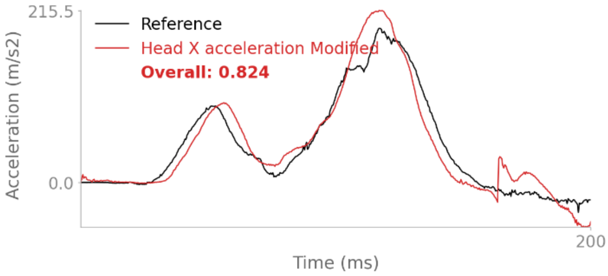


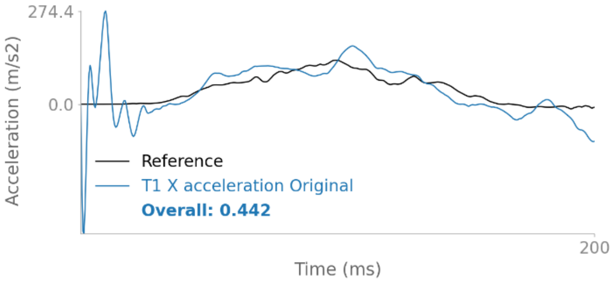


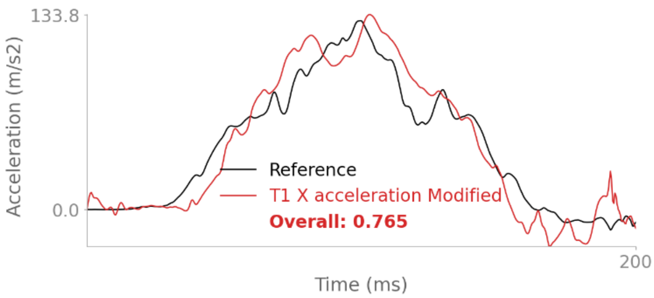
APPENDIX C: ISO 18571 Overall Rating of Sled Tests

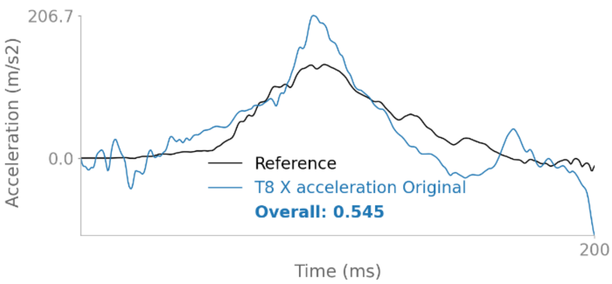
Linear Kinematics in X-direction

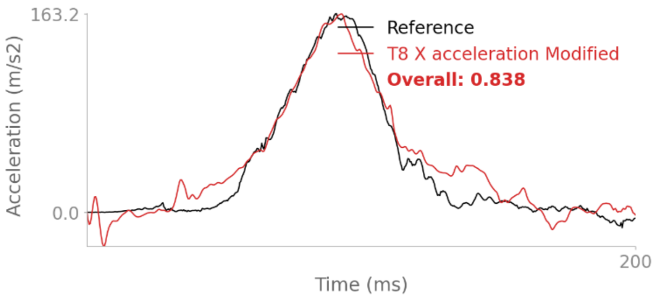


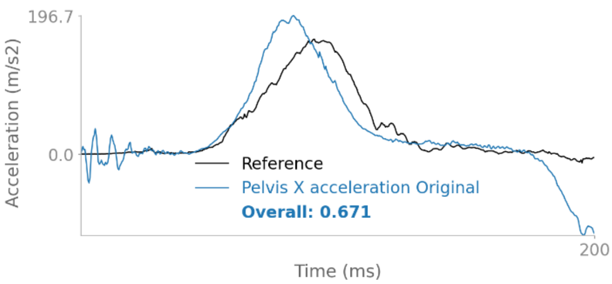


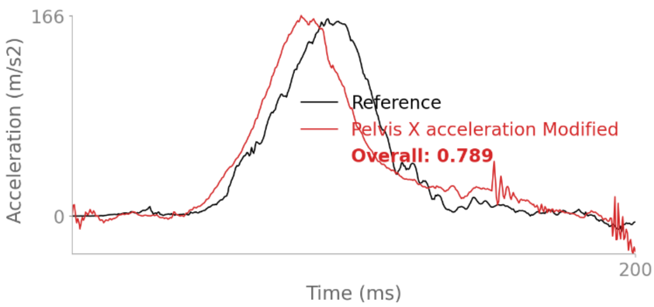




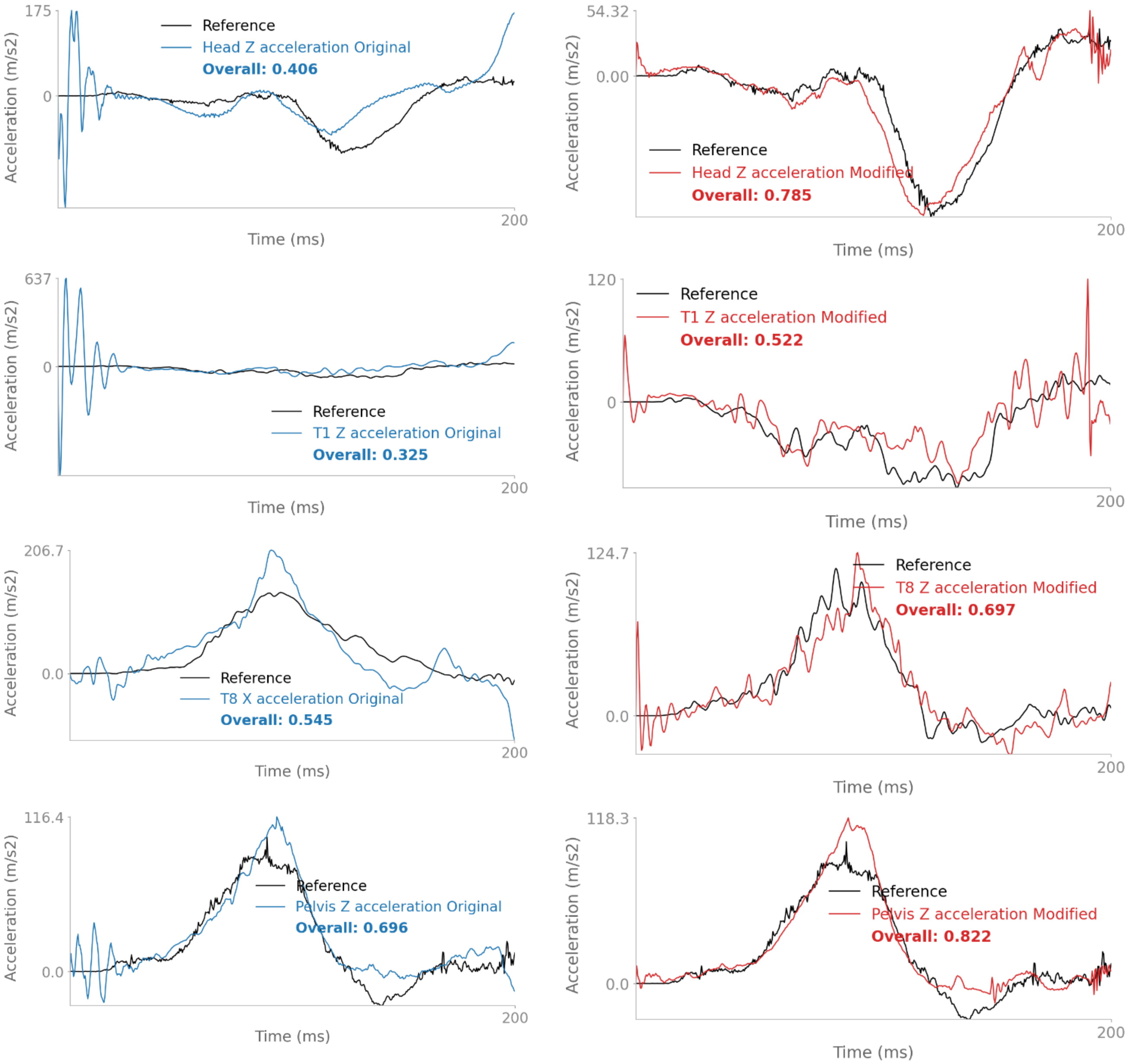




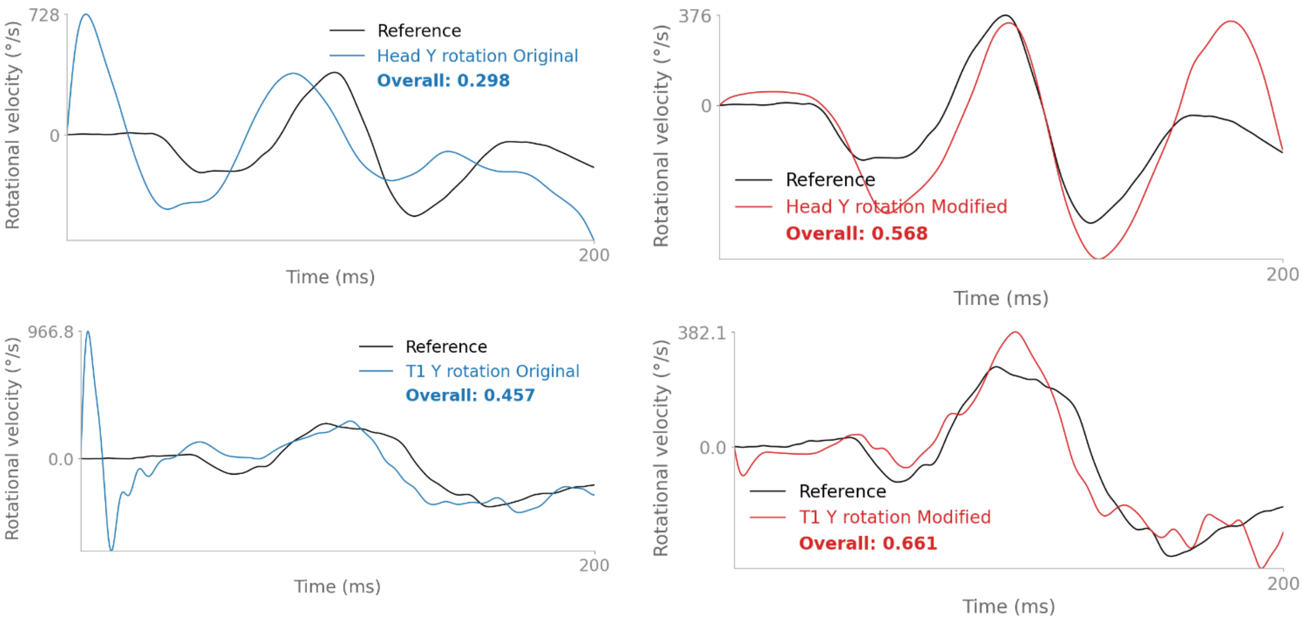


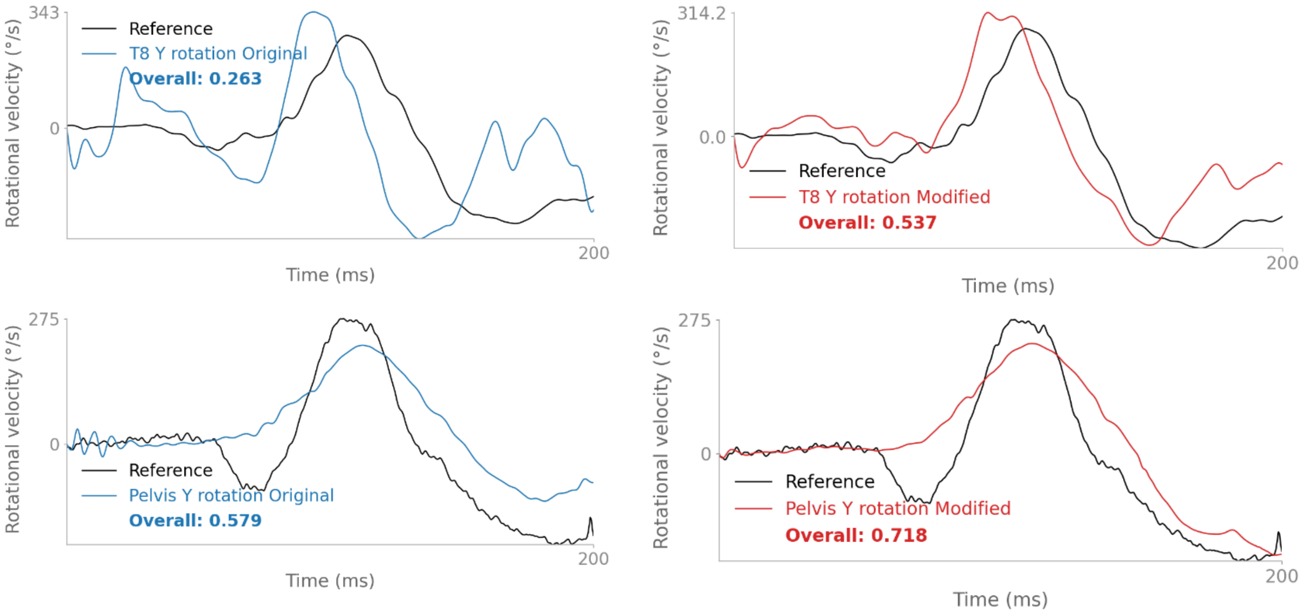


Linear Kinematics in Z-direction



Angular Kinematics in Y-direction




343
0
200
Rotational velocity (°/s)
Time (ms)
Reference
T8 Y rotation Original
Overall: 0.263
314.2
0.0
200
Rotational velocity (°/s)
Time (ms)
Reference
T8 Y rotation Modified
Overall: 0.537
275
0
200
Rotational velocity (°/s)
Time (ms)
Reference
Pelvis Y rotation Original
Overall: 0.579
275
0
200
Rotational velocity (°/s)
Time (ms)
Reference
Pelvis Y rotation Modified
Overall: 0.718