Seat Evaluation Tools (SETs)

Development of prototype concepts of the SETs of an average female and male for low severity rear impact crash testing

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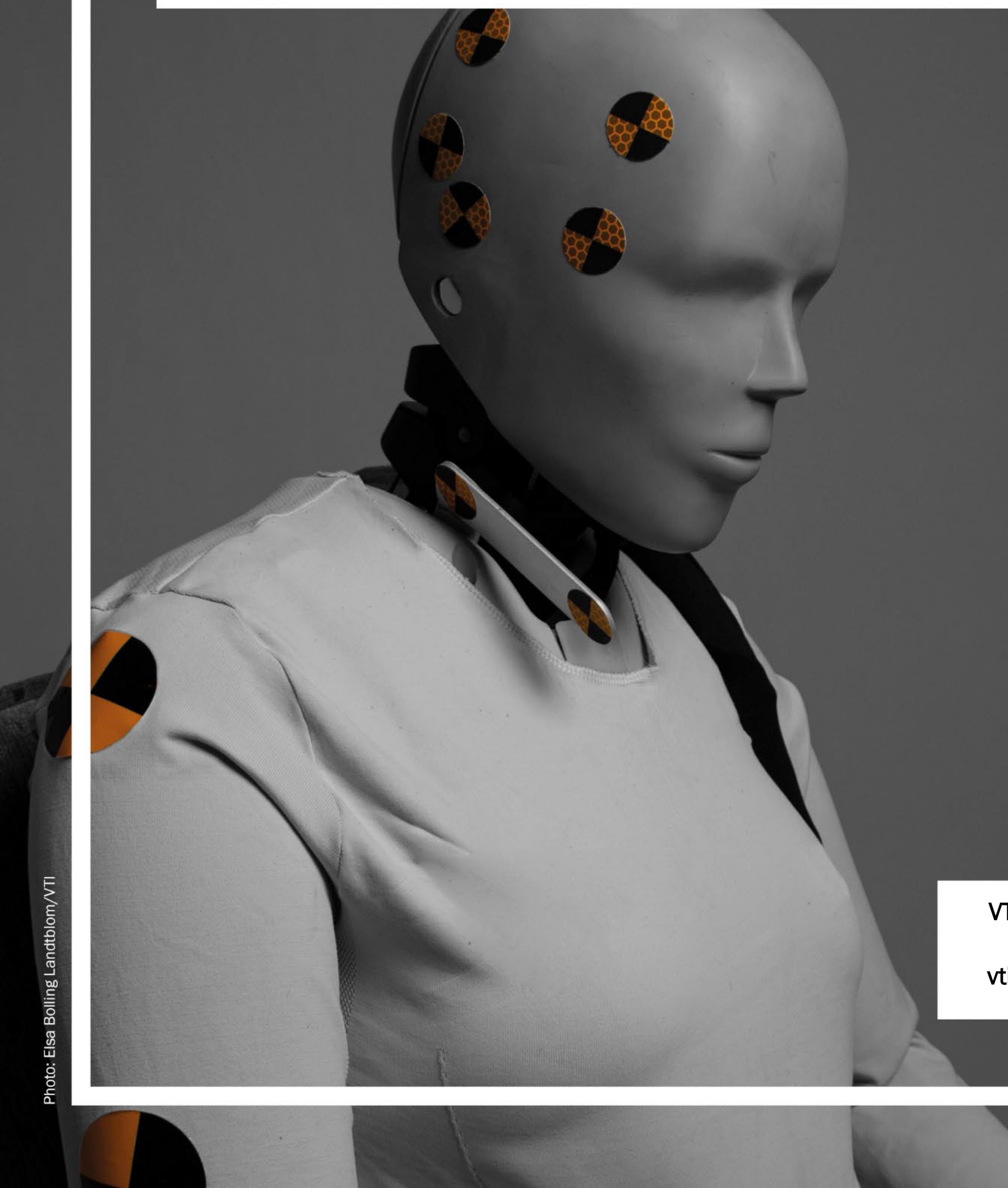

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Kort sammanfattning

Syftet med denna studie har varit att utveckla nya sätesutvärderingsverktyg, Seat Evaluation Tools (SET), med geometrierna för en genomsnittlig kvinna (50F) och man (50M) som sittande fordonspassagerare, baserade på data från humanshape.org. SET har utformats för att utvärdera fordonssätets skyddsprestanda vid en upphinnandekollision i låg hastighet.

Fokusområden har varit rörelsen i ryggrad, nacke och skuldror för att ge en människolik interaktion med fordonssätet. Förbättringar har gjorts utifrån tidigare lösningar för dämpning av nacken och ett nytt koncept för skuldrans rörlighet har implementerats. Mjuka material har använts för att underlätta torsons rörlighet och en bröst- och ländrygg med rörlighet i tre dimensioner har utvecklats.

Två fysiska prototyper, SET v0.1 50F och 50M, har utvecklats och samtliga ritningar och CAD-modeller finns tillgängliga genom OpenVT-plattformen (https://openvt.eu/). Prototyperna har testats i krockprov och resultaten har jämförts med tidigare voluntärtester.

Arbetet har varit en del av det EU-finansierade projektet VIRTUAL.

Nyckelord

Fordonssäkerhet, Krockprovning, Modell av genomsnittlig kvinna och man, Personskadeprevention, Sätesutvärderingsverktyg, Upphinnandekollision.

Abstract

The aim of this study has been to develop new Seat Evaluation Tools (SET)s with the geometries of an average female (50F) and male (50M) as seated car occupants, based on data from humanshape.org. The SETs have been designed to evaluate the occupant protection performances of car seats in a low severity rear impact.

Focus areas have been the motion of the spine, neck and shoulders to enable a human-like interaction with the car seat. Improvements have been made to previous designs of the neck spring and damper system, and a new solution for shoulder flexibility has been implemented. Soft body materials have been used to facilitate the motion of the torso, and a 3D thoracic and lumbar spine design has been developed.

Two physical prototypes, SET v0.1 50F and 50M, have been developed and all drawings and CAD models have been made available under open-source license on the OpenVT platform (https://openvt.eu/). The prototypes have been run in initial dynamic tests and the results have been compared to previous volunteer tests.

This work was carried out within the EU-funded project, VIRTUAL.

Keywords

Average female and male models, Crash testing, Low severity rear impact, Occupant protection, Seat evaluation tools, Vehicle safety.

Summary

This report describes the development of the Seat Evaluation Tools (SETs) of an average female and male seated vehicle occupant, the SET 50F and SET 50M, a task within the EU-funded project VIRTUAL. The SETs are models of the human and have a geometry based on data from humanshape.org, also used for the VIVA+ models. In the report, the reader is guided through the development process by 81 figures, 28 tables, 15 exploded views and resulting details and specifications.

Purpose

The aim of this study has been to develop a new set of evaluation tools for the analysis of occupant protection in low velocity rear collisions and to enable comparison between the protection of the female and male part of the population. The SETs have been made specifically for evaluation of the protective performance of vehicle seats in the event of a low severity rear impact, up to 24 km/h, and are designed to create a human-like interaction with the vehicle seat.

Engineering

Experience from the development of the BioRID has been an important information source and many ideas from this project have been reused and further developed. The concepts for the spine and neck are a continuation of ideas developed within the ViVA II project. The spine is a system of aluminum vertebrae with joints providing motion in both sagittal and lateral directions, and rotation around the vertical axis. The neck has three plastic vertebrae with similar damping as the BioRID but with the springs and damper now located inside the head. Both neck and spine vertebrae have rubber bumpers to avoid the risk of metal-to-metal clashes giving unwanted peaks in the sensor readings. A new concept for shoulder motion has been implemented, allowing the shoulders to move in the sagittal direction. This way, the torso is able to “sink in” into the car seat at a rear impact. The soft body parts are moulded in polyurethane foam to facilitate body motion in a better way than the previously used silicone rubber, and they are connected to the aluminum core via steel pins mounted to the vertebrae and shoulder mechanisms. The pelvis of the 50F is a modified (male) BioRID pelvis with added pads to cohere with the geometry of an average female.

The SETs are equipped with four sets of three-axial accelerometers with integrated gyros located at pelvis, chest, neck and head. The sensor models have been chosen to be able to provide high precision measurements of angular displacement and motion in all directions.

Design and engineering work has been made in the CAD tool Creo Parametric, version 7.0. The choice of CAD system was based on stability and availability. A total of 105 drawings and 113 3D models have been made available at the OpenVT platform, (https://openvt.eu/) in neutral file formats, along with the native Creo files, consisting of 1.7 GB of CAD data.

Production

Production and assembly of the SETs were carried out at the VTI workshop with support of providers of specific machined and moulded details.

Testing

The SETs were run on the same seat as used in previous volunteer tests, with an impact pulse of 7 km/h. A comparison of the test results shows that for the horizontal displacement, the response of the head of the SETs were similar to the corridors of the volunteers. The motion of the T1 of the SETs, had the same shape as the volunteers although the maximum horizontal displacement was lower. The same trend was observed for the angular displacement.

Sammanfattning

Denna rapport beskriver utvecklingen av sätesutvärderingsverktyg, Seat Evaluation Tools (SETs), för en genomsnittlig kvinna och man som sittande fordonspassagerare, SET 50F och SET 50M, ett arbete inom det EU-finansierade projektet VIRTUAL. SET:arna är modeller av människan och har en geometri baserad på data från humanshape.org som också används för VIVA+-modellerna. I rapporten leds läsaren genom utvecklingsprocessen av 81 figurer, 28 tabeller, 15 sprängskisser och resulterande detaljer och specifikationer.

Syfte

Syftet med denna studie har varit att utveckla en ny uppsättning utvärderingsverktyg för analys av passagerarskydd vid lågfartskollisioner bakifrån och att möjliggöra jämförelse mellan skyddet av den kvinnliga och manliga delen av befolkningen. SET:arna är gjorda speciellt för utvärdering av fordonssätes skyddsprestanda vid en upphinnandekollision i låg hastighet, upp till 24 km/h, och är designade för att skapa en människolik interaktion med fordonssätet.

Teknik

Erfarenheter från utvecklingen av BioRID har varit en viktig informationskälla och många idéer från detta projekt har återanvänts och vidareutvecklats. Koncepten för ryggrad och nacke är en fortsättning på idéer som utvecklats inom ViVA II-projektet. Ryggraden är ett system av aluminiumkotor med leder som ger rörelse i både sagittala och laterala riktningar och en rotation runt den vertikala axeln. Halsen har tre plastkotor med en dämpning liknande BioRID men med fjädrar och dämpare nu placerade inne i huvudet. Både nack- och ryggkotorna har gummidämpare för att undvika risken att metalldelar slår ihop och ger oönskade störningar i sensoravläsningarna. Ett nytt koncept för skuldran har implementerats, som låter skuldran röra sig i sagittal riktning. På så sätt kan torson "sjunka in" i ryggstödet vid upphinnandekollision. De mjuka kroppsdelarna är gjutna i polyuretanskum, med ambitionen att underlätta kroppens rörelser på ett bättre sätt än silikongummi som tidigare använts, och de är länkade till aluminiumskelettet via stålstift monterade på ryggkotor och skuldror. Pelvis för 50F är ett modifierat BioRID-pelvis med adderade putor för att ge en överensstämmelse med geometrin för en femtiopercentil kvinna.

SET:arna är utrustade med fyra treaxliga accelerometrar med integrerade gyron, placerade vid pelvis, bröstkorg, nacke och huvud. Sensormodellen har valts för att ge hög mätprecision av vinkelförändring och rörelse i alla riktningar.

Design och konstruktion har gjorts i CAD-verktyget Creo Parametric, version 7.0. Valet av CAD-system baseras på stabilitet och tillgänglighet. Totalt 105 Ritningar och 113 3D-modeller har gjorts tillgängliga på OpenVT-plattformen (https://openvt.eu/) i neutrala filformat, tillsammans med de ursprungliga Creo-filerna, bestående av 1,7 GB CAD-data.

Produktion

Produktion och montering utfördes på VTI-verkstaden, med stöd från leverantörer av specifika bearbetade och gjutna detaljer.

Provning

Prototyperna har provats med samma säten som används i tidigare voluntärprov vid en krockpuls om 7 km/h. En jämförelse av testresultaten visar att horisontalrörelsen för huvudet liknade korridoren för voluntärproverna. Rörelsen för T1 hos SET:arna hade samma form som vid voluntärproven men den maximala horisontalförskjutningen var mindre. Samma trend observerades för vinkelförändringen.

Preface

This report is part of the outcome of the VIRTUAL project, namely the design and construction of the Seat Evaluation Tools (SET) of an average female (50F) and male (50M), for use in the assessment of injury protection of the seat occupant in a low severity rear impact. This study forms part of the VIRTUAL (Open Access Virtual Testing Protocols for Enhanced Road User Safety) project, funded within the European Union Horizon 2020 Research and Innovation Programme. The project has been coordinated by VTI who has been in charge of the development of the SET 50F and 50M within the project.

I would like to acknowledge, in addition to the authors of this report, the contribution from

Mr Gustav Danielsson and Mr Johan Pettersson, who made the components consisting of metal and plastic.

Mr Jia Cheng Xu for compiling the data from the SET sled tests and the volunteer tests from previous studies.

Ms Elisabet Agar for her thorough language review.

The staff at the VTI crash laboratory for their efforts in ensuring the high quality of all tests.

In addition, this work would not have been finalised at this high standard without the fruitful interaction of the companies producing the different parts of the SETs; the Vollsjö Industri AB and Finspångs Allmekano AB.

Gothenburg, October 2022

Astrid Linder
Coordinator of the VIRTUAL project

Granskare/Reviewer

Dr Victor Alvarez, Lightness by Design.

Table of content

1. The design and performance of the SET prototypes

This chapter describes the context of the development process with experience from previous projects leading to the resulting Version 0.1 of the Seat Evaluation Tools (SETs).

1.1. Introduction

The term Seat Evaluation can be found in (LINDER, 2002) where differences of the protection performance of different car seat models were studied. The higher risk of soft tissue neck injuries for female occupants was also highlighted in this thesis, as a focus area for future work. The world's first crash test dummy for low severity rear impact occupant safety assessment, the BioRID (Davisson, 1999) is a model of an average male. A prototype of an average female, based on the design of the BioRID, the BioRID P50F (CARLSSON, DAVIDSSON, LINDER, & SVENSSON, 2021), was designed as a first step in addressing the need for a model representing the female part of the population in the assessment of crash safety.

In the ViVA and ViVA II[1] projects, funded by the Swedish Innovation Agency, Vinnova, a virtual Human Body Model (HBM) of a female with the stature and mass close to that of a 50th percentile female (ViVA F50 v2), was developed. Part of ViVA II also included the development of CAD designs for a physical model resembling an average sized woman, based on the ViVA F50 v2, to be used for evaluation of whiplash protection solutions based on virtual simulations. These CAD designs were developed to be used in a future project, i.e., the VIRTUAL project (See APPENDIX D).

The aim of this study has been to develop and prototype physical Seat Evaluation Tools (SET)s, of an average female and male in a vehicle seated occupant, the SET 50F and SET 50M. The SETs have the geometry of an average female and male corresponding to those defined by humanshape.org, also used for the VIVA+ models (JOHN ET AL. 2022). The SETs are designed to evaluate the safety performance of car seats in a low severity rear impact and also to be able to show how these scenarios affect the female and male body differently. Experience from the development of the BioRID, especially BioRID II and BioRID P50F, has served as input to the development, and the engineering work has involved the reuse and further development of many ideas from these projects.

So, what is a SET? This is the story of the Seat Evaluation Tool – a human-like evaluation tool, designed to assess the injury protective properties of car seats in a low severity rear impact. As a physical tool in an otherwise virtual project, the SET provide an additional path to simulation of the human in a crash scenario. The SETs are model concepts designed to interact with the seat in a rear impact in a human-like manner and are in the version described in this report, v0.1 prototypes.

1.2. Focus areas

The SETs are designed for analysis of the human body and car seat interaction at low-speed rear impact, which leads to the following focus areas in the development work:

- A spine mechanism resembling the movement of the human spine:
    - A thoracic and lumbar spine with a degree of rotational capacity around the vertical axis (outlined in the ViVA II project and further developed in this project).
- A torso providing human-like interaction with the car seat:
    - Geometry as VIVA+ 50F and 50M

[1] For more info about ViVA II, see the Vinnova website at https://www.vinnova.se/p/viva-ii--virtual-vehicle-safety-assessment-step-2-open-source-human-body-models-and-crash-testing/

- "Body-like" material softness
- Movable shoulders.

- A simplified neck:
  - Muscle resembling damping mechanism
  - Facilitate flexion, retraction, and extension.

1.3. The concepts of SET v0.1 50F and 50M

The different properties of the chest and abdomen give a splitting point of the torso. A soft abdomen combined with a more rigid, but flexible, chest would resemble the properties of the human torso. The chest part has been split in left/right halves for better producibility, and the abdomen part reaches all the way from front to back, to make better use of the material softness.

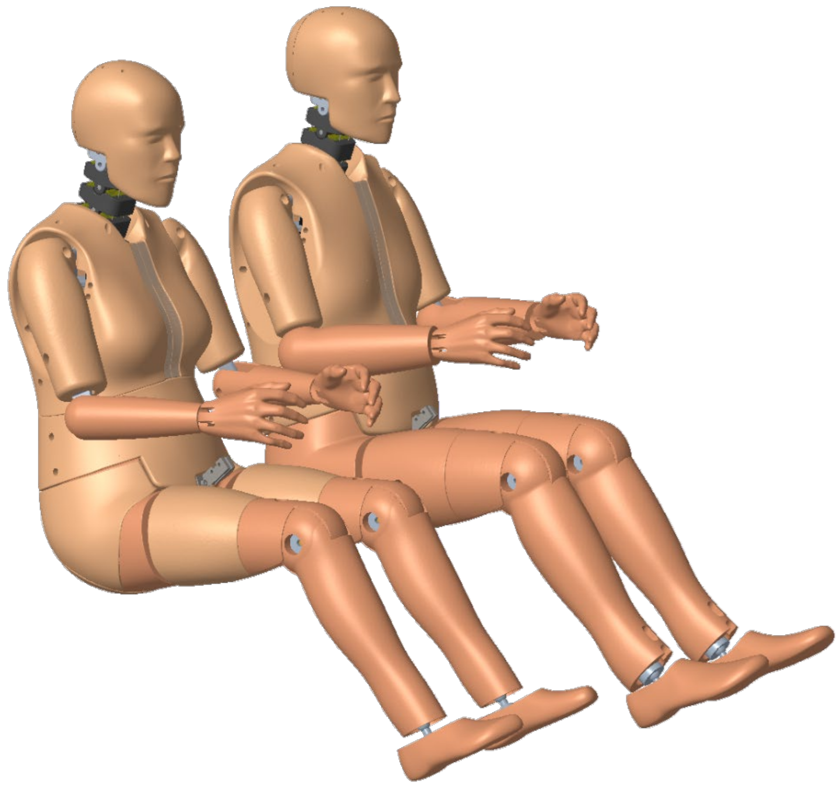

Figure 1. The SET v0.1 50F and 50M.

In SET v0.1, solutions from Hybrid III/BioRID II have been used, with minor customisations, for the lower arms, lower legs, pelvis and head (see TABLE 1).

Table 1. Common parts used in the SET v0.1.

Name	SET 50F	SET 50M
Head	Hybrid III 5F (customised)	Hybrid III 50M (customised)
Pelvis	BioRID II (customised)	BioRID II
Lower arm	Hybrid III 5F	Hybrid III 50M
Upper leg	Custom	Hybrid III 50M
Lower leg	Hybrid III 5F	Hybrid III 50M

Similar to the VIVA+, the SET 50F was developed first. Based on the experience from this work, the same engineering solution was applied in the development of the SET 50M.

1.3.1. The soft body

Previous experience from the BioRID established that the silicone material used for the soft body was found too stiff (Davidsson, 1999), and attempts to enable more freedom of movement were made by partly cutting through the torso.

Moulded polyurethane (PUR) foam has been used as the material of the parts surrounding the metal parts of the construction. PUR foam is commonly used in the car manufacturing industry, e.g., dashboards. The method gives a soft foam core covered with a more solid skin. By tweaking the production parameters, softness and density of the foam and stiffness of the skin can be controlled, making it possible to create a more human-like body, i.e. allowing more flexible movement and seat interaction. Material samples were discussed in dialogue with the chosen supplier to confirm that this was the way forward.

1.3.2. A 3D moving spine

The spine has been designed to facilitate a human-like movement of the torso. It consists of 15 aluminium vertebrae, designed to determine the range of motion in the sagittal and coronal planes and the amount of rotation along the z-axis. Between the vertebrae there are steel springs and soft bumpers to define the bending force and range for each vertebra joint. The spine is connected to the soft torso via connecting pins, which transfer the movement of the spine to the torso. The length and location of the connecting pins have been chosen to not interfere with other moving parts. The spines of SET 50F and SET 50M share the majority of parts, with a few parts defining the difference in length of the torso between the average female and the average male (see 3.1 Spine for details).

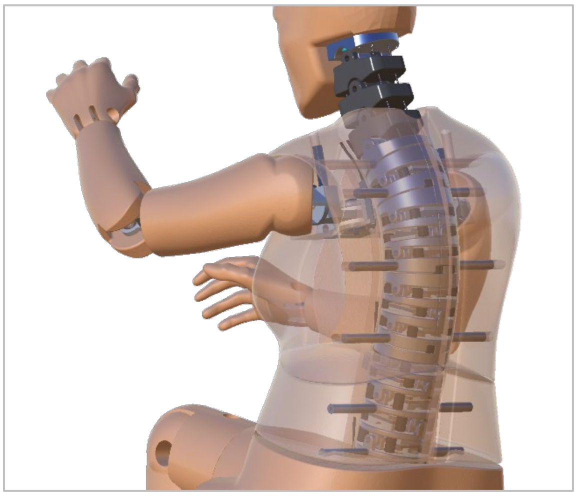

Figure 2. The spine, chest and abdomen.

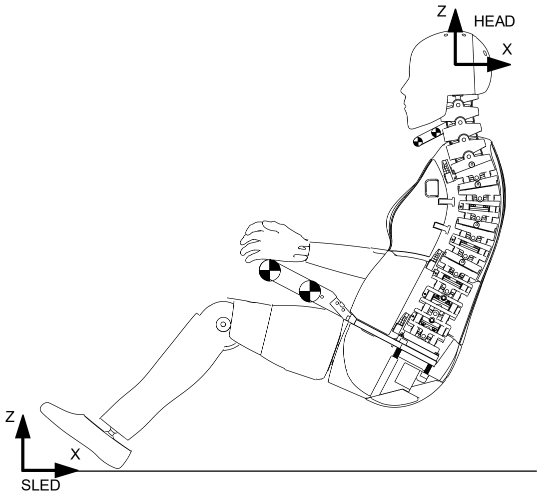

Figure 3. SET coordinate system.

The vertebrae of the spine follow a design principle where every second vertebra joint has been rotated 90° to allow for movement in the coronal and sagittal planes. Each vertebra joint has an angular range of motion of ±4°. The vertebra joint geometry has two variants with different heights and the vertebrae vary in thickness and angle between the interface surfaces. This way the spine assembly has been engineered to match the curvature of the VIVA+ torso. Three rotating vertebrae have been placed in the thoracic spine section, adding the option of twisting the torso about the Z axis (Figure 3). Each rotator vertebra rotates ±8°, giving a total twist angle of ±24° for the entire torso. All vertebrae have a flat steel spring (1) and soft bumpers (2) to control the range of motion and resistance. The rotating vertebrae accommodate an axial bearing solution and rotational bumpers (3) to enable the rotational motion (FIGURE 4, FIGURE 5).

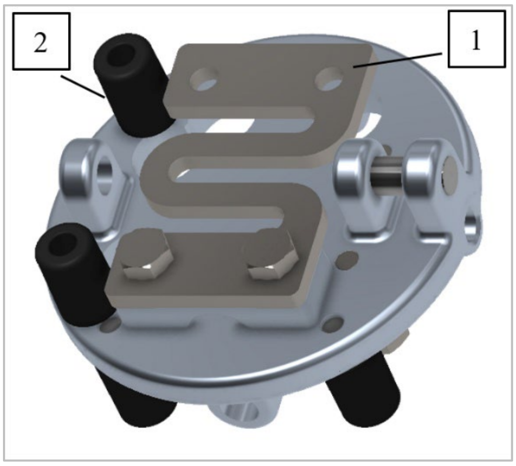

Figure 4. *Bending vertebra.*

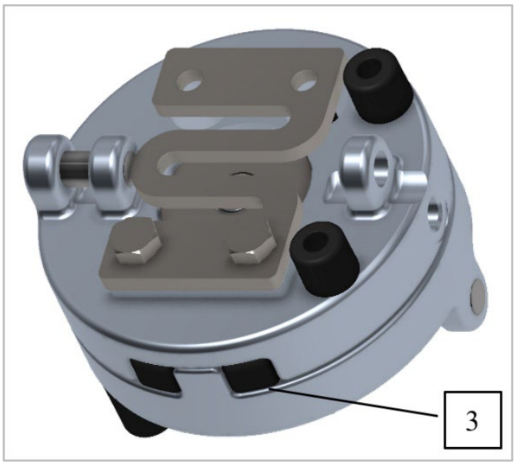

Figure 5. Rotating vertebra.

The soft bumpers (2) were originally intended to dampen the end positions of the bend movement. During the build process, the steel springs (1) were found too weak, giving the spine a tendency to “fall forward”. Hence, the soft bumpers were made longer and stiffer to contribute to the spine stability by adding more stiffness to each joint.

1.3.3. The neck

The neck concept is a two-dimensional system based on the mechanisms developed for BioRID, simplified by using three vertebrae, instead of seven. For the neck vertebrae, polyoxymethylene (POM) was used to dampen and to give minimum friction for the wires of the neck muscle substitutes, while elastomer dampers have been used between vertebrae.

The same principle of muscle resembling wires, connected to springs and a rotational oil damper, has been used for the neck but has been made more compact. The damper and springs are located inside the head, allowing the muscle resembling wires to be as short as possible (compared to the BioRID), and hence, wire tension at a minimum. The damper has been further developed with improved precision, simplifying the oil filling process (see section 1.3.3.1 for more info). There is a simple mounting interface between the spine and neck at T1 to facilitate further development of neck concepts.

The angular range of motion of the cervical spine vertebrae has been based on anatomic studies (KAPANDJI, 1974). Analysis of the vertebral motion in CAD during retraction to extension determined the angular range of motion of each vertebra. It was concluded that for proper retraction of the neck, the upper vertebrae must allow for more flexion than the lower vertebrae. The flexion limit between the two lower vertebrae is 4°, while the flexion limit between the two upper vertebrae is 15°. Thus, the head can move horizontally rearwards in the initial phase of a rear impact (FIGURE 6).

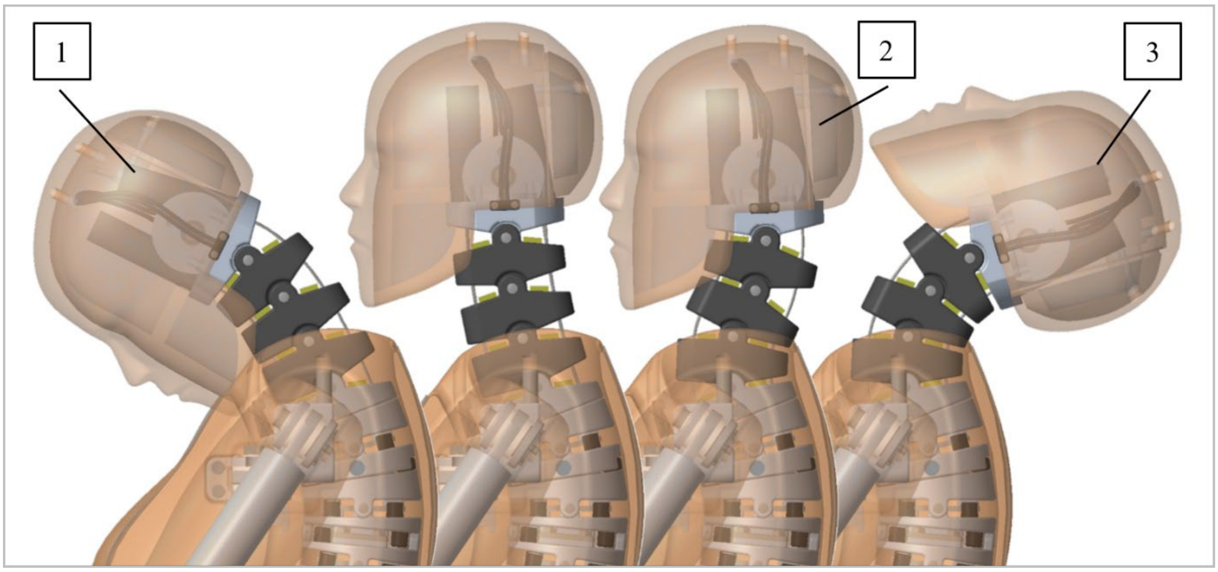

Figure 6. Neck flexion (1), retraction (2), and extension (3).

Oil filled damper

The damper is an oil filled housing with an internal paddle wheel. When the housing is rotated by the damper wire, the paddle wheel pushes the oil through a small adjustable aperture hole (FIGURE 7). This mechanism was created for BioRID and has been further developed to better suit the SETs. The damper wire of the SETs is led from the T1 vertebra through the neck to the damper and back again (FIGURE 8). To control the performance of the damper, machining tolerances have been sharpened and the bearing quality has been improved. A two-way system for oil filling has been added for easier evacuation of air. The design has also been modified to enable through-axis mount.

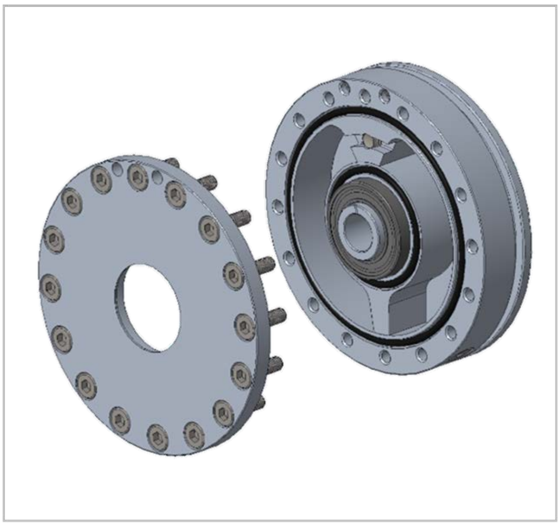

Figure 7. The damper; opened.

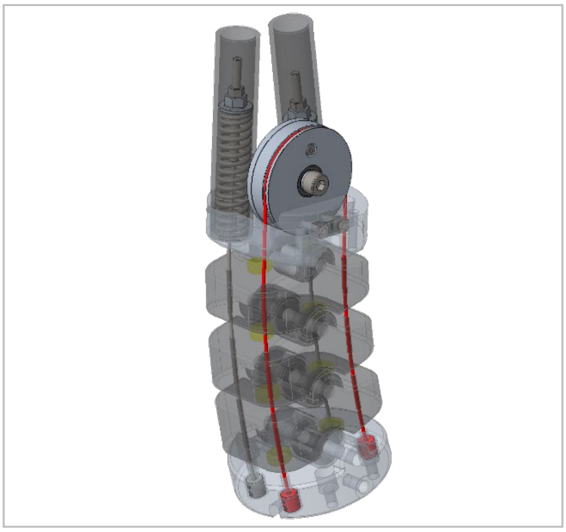

Figure 8. The damper wire (red).

Muscle resembling springs

The muscle resembling springs are led from the T1 vertebra through holes in the three neck vertebrae to the adjustable spring assemblies mounted on the C1 vertebra inside the head. The spring constants (TABLE 2) have been chosen based on the results of the BioRID II study (DAVIDSSON, 1999). For the SET 50F, the spring constants have been set 20% lower than for SET 50M. The springs run through

POM tubes, to prevent them folding under pressure. The posterior spring is in an angled position due to the limited space available inside the head (FIGURE 10).

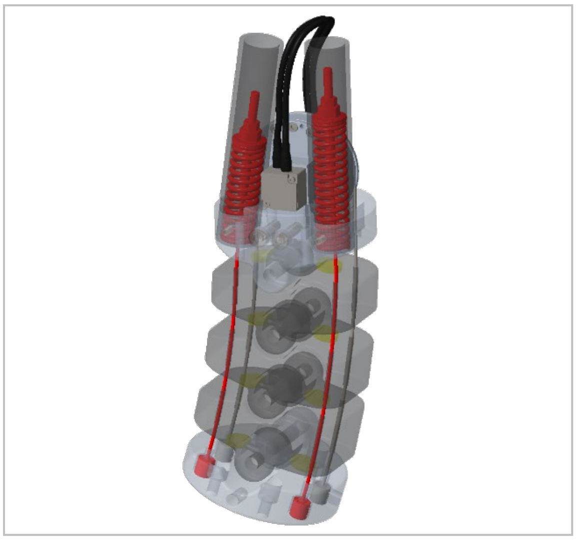

Figure 9. Muscle resembling springs and wires (red).

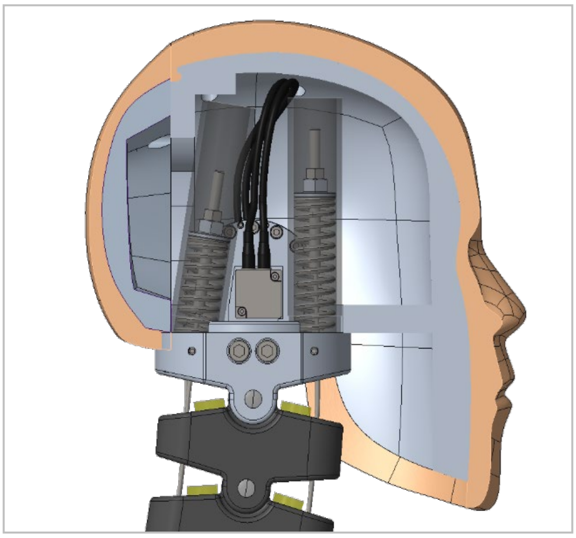

Figure 10. Muscle resembling springs.

Table 2. Muscle resembling spring properties.

	SET 50F		SET 50M	
	Spring constant (N/mm)	**Length (mm)**	**Spring constant (N/mm)**	**Length (mm)**
Anterior Spring	7,8	84	9,8	81,2
Posterior Spring	13,4	63,6	16,8	65,6

1.3.4. Customisation of the BioRID pelvis

The pelvis of the BioRID II was used for the SET 50F. To match the 50th percentile female geometry of the VIVA+, the pelvis must be wider and rounder (FIGURE 11).

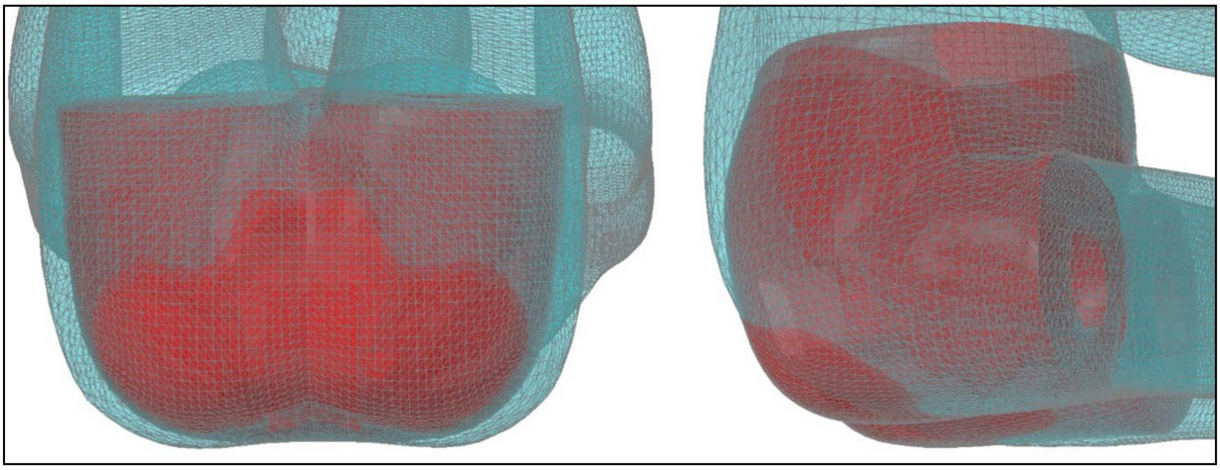

Figure 11. The BioRID II pelvis (red) vs VIVA+ 50F (blue).

The SET 50F pelvis is a modified BioRID II pelvis from which the sitting bone area has been removed, and a new outer geometry has been created by glued on PUR foam addons (FIGURE 12).

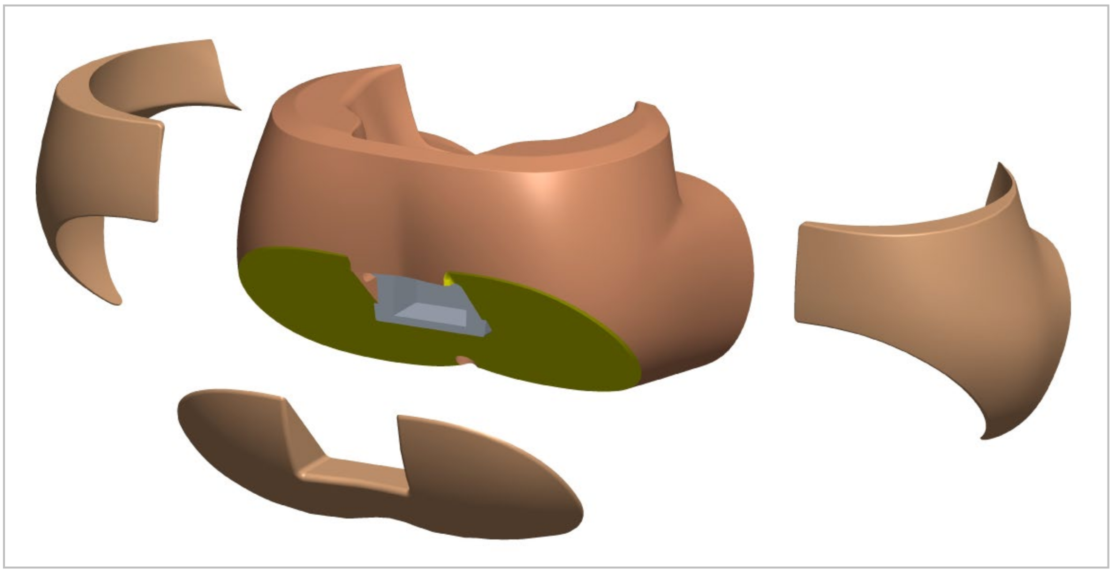

Figure 12. SET 50F pelvis; exploded view.

1.3.5. Modified Hybrid III Head

The Hybrid III 5F head matches the size of the VIVA+ 50F head sufficiently (FIGURE 13) and has been used for the SET 50F. A Hybrid III 50M head will be used for the SET 50M. Modification has been made to the occipital interface (FIGURE 15) to make space for the neck muscle substitute springs and damper. Four holes have been added on top of the head to enable tool access to the four head mounting screws of the occipital interface (FIGURE 14). The threaded hole for the traditional lifting system has been plugged to avoid risk of damaging the neck (see Section 2 HANDLING AND STORAGE).

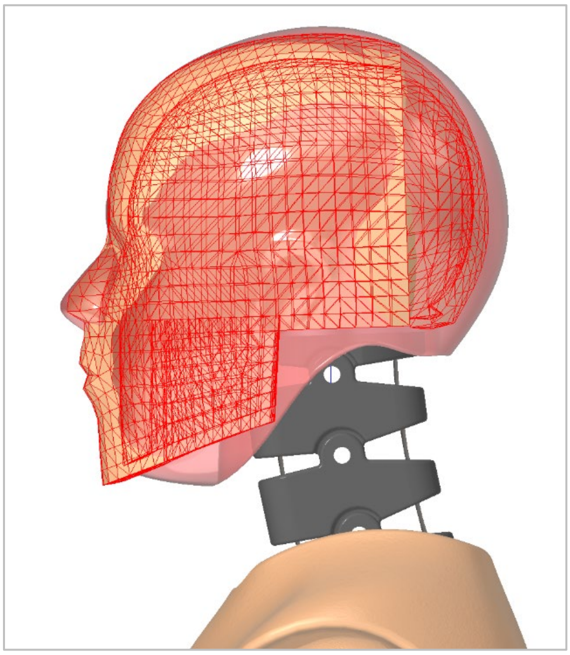

Figure 13. Head; The Hybrid III 5F (red) vs VIVA+ 50F.

Figure 14. Head; New holes, plugged lifting thread.

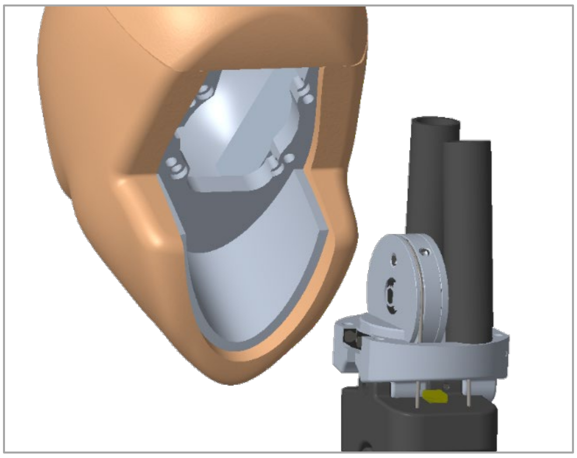

Figure 15. The occipital interface.

1.3.6. A soft torso

The soft torso is based on the geometry of the VIVA+ models and has been designed to interact with the spine. It consists of two chest halves and an abdomen part, all three moulded in soft PUR foam. The movement of the spine is transferred to the torso via connecting pins.

The chest has been split in two parts for production and assembly reasons. Metal cylinders have been inserted into the chest parts to adjust their weight. To ensure flexibility and facilitate the movement of the spine and torso, the abdomen has been produced in as soft PUR as possible. The weight of the abdomen has not been corrected and is at this stage approximately 2.7 kg less than the abdomen of the VIVA+ 50F model.

The torso parts are secured in place by Velcro strips.

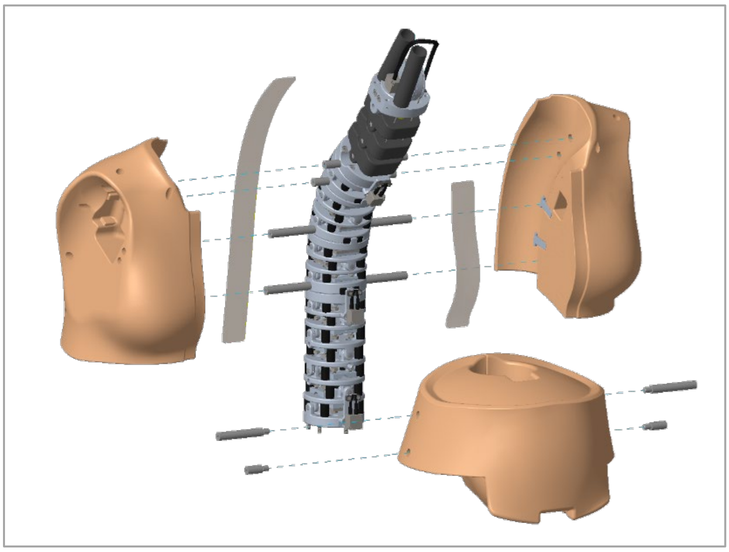

Figure 16. The chest halves, abdomen and Velcro strips; exploded view.

1.3.7. Shoulder mechanism

In this study, the aim was to create a simple and robust solution to make the torso "sink into" the bucket shape of the seat at rear impact, letting the shoulders fold forward.

A movable shoulder has been implemented in the Test Device for Human Occupant Restraint (THOR) dummy. Further improvements to this solution have been studied (TÖRNVALL, 2008). The movement of the scapula and its interaction with the clavicula is an intricate system to reproduce, hence proper simplification is required to create a robust and producible solution. However, the THOR dummy is intended for frontal impact and consequently its shoulder mechanism is not designed for the intricate interaction with the car seat backrest, which is the target for the SETs.

To simplify the shoulder mechanism, the following considerations were made: Since the scapula is essentially floating freely on the surface of the thorax, the clavicula is the main component in the positioning of the shoulder. As the SET is solely suitable for low-speed rear impact, it was natural to limit the shoulder movement to the horizontal plane, and thus creating a more simple and robust mechanism, where the clavicula has been reduced to a moving fixation point for the arm.

The shoulders assembly is kept in place by the geometry of the soft chest where the sternum has been reduced to a connector between the left and right shoulder mechanism. The shoulder movement is transferred to the chest via connecting pins.

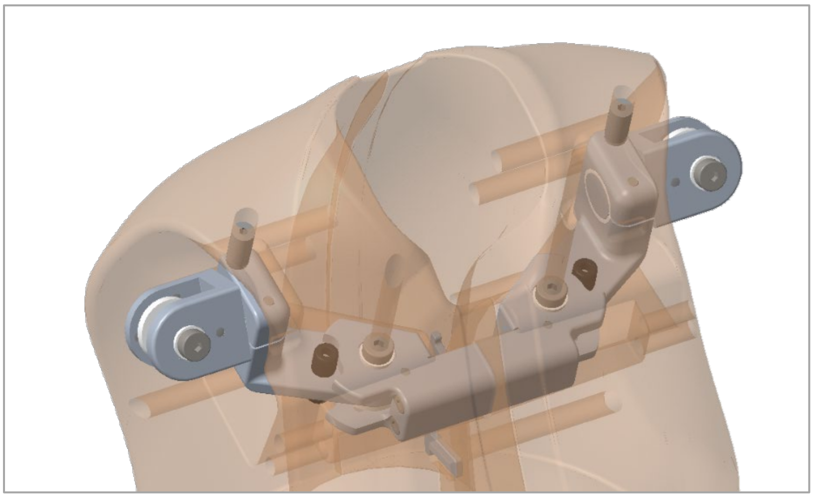

Figure 17. The shoulder mechanism.

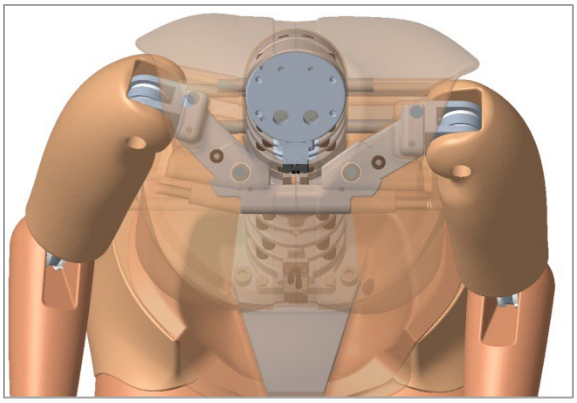

Figure 18. Shoulder movement; retracted.

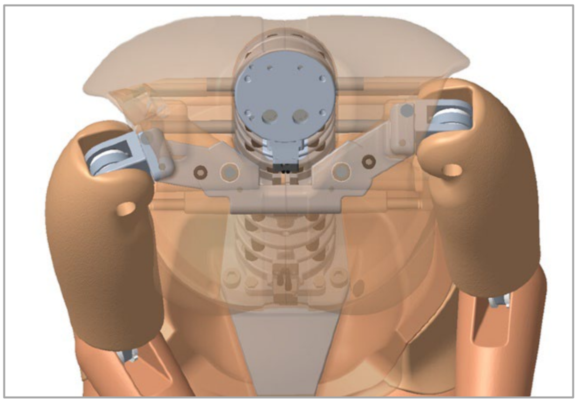

Figure 19. Shoulder movement; extended.

1.3.8. Arms and legs

The upper arms are custom made to match the new shoulder mechanism. The same upper arm foam parts have been used in both SET 50F and SET 50M. To provide the correct weight, the skeleton of SET 50F has been made in aluminium while the SET 50M skeleton has been made in steel. The SET 50M upper arm assembly has been extended by making the elbow joint longer than the 50F version.

Hybrid III 5F lower arms have been used for the SET 50F, and for the SET 50M the lower arms from Hybrid III 50M have been used. All joints have POM bushings to give better friction control.

The PUR foam is symmetric for the left and right upper arms, except the location of holes for mounting screws at the shoulder and elbow.

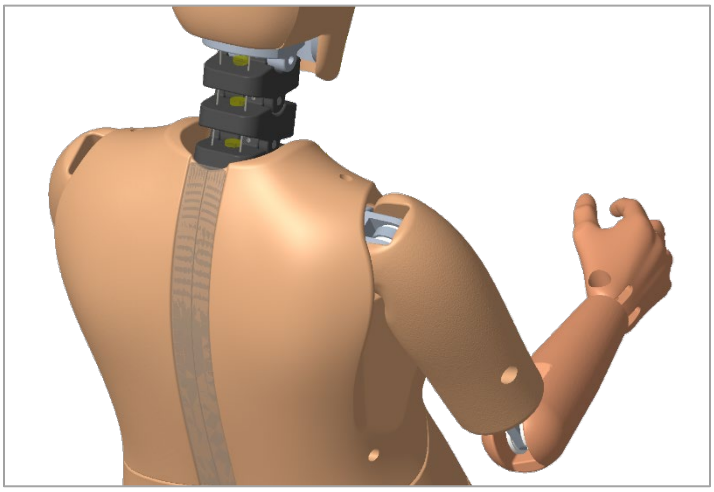

Figure 20. The upper arm and shoulder geometry.

The upper leg of SET 50F (FIGURE 21) is based on a reused femur skeleton (1) from the BioRID P50F prototype. The custom load cell replacement (2) has also been re-used from the BioRID P50F prototype. See the following report for measurement details (CARLSSON, DAVIDSSON, LINDER, & SVENSSON, 2021). The assembled femur skeleton has been fixated in the moulding tool with the PUR foam moulded onto it, in a symmetric design to be used on both the left and right leg.

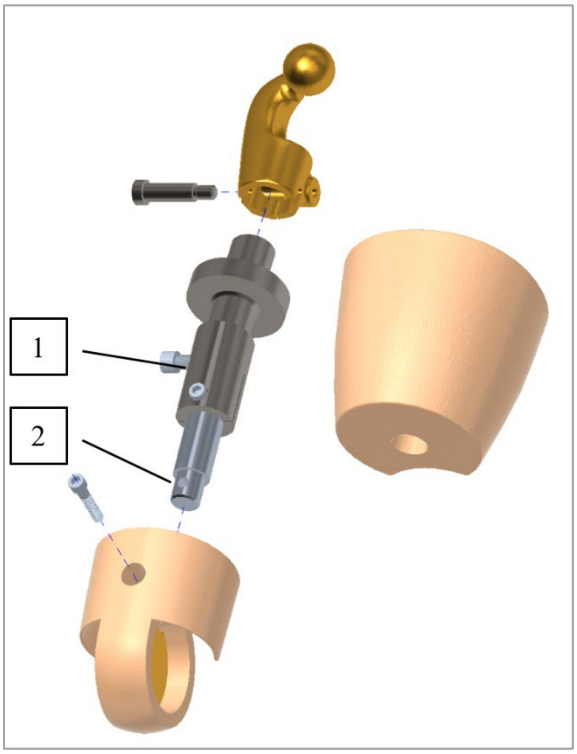

Figure 21. SET 50F upper leg; exploded view.

1.4. Engineering methods

Design and engineering work has been made in the CAD tool Creo Parametric, version 7.0 at VTI, Gothenburg, Sweden. The choice of CAD system is based on stability and availability. Drawings and 3D geometry have been made available on the OpenVT Gitlab platform (https://openvt.eu), in neutral file formats, along with the native Creo files.

1.4.1. Workarounds

To be able to work with such complex geometry and assembly structures within a basic Creo license, a few workarounds have been made:

- The torso parts *chest*, *abdomen*, and the *pelvis add-ons* (SET 50F) have all been created within the parts F50_TORSO and M50_TORSO and extracted as family table instances.
- The common geometry between the *pelvis* and *abdomen* has been created by copying surfaces within the assembly TORSO_SURFACES. The geometry of the pelvis is not entirely correct, due to being based on simple control measurements of an old BioRID pelvis.
- The SET 50F and SET 50M variants of the *neck* and *spine* have been created as family table instances of NECK_GENERIC and SPINE_GENERIC.
- All vertebrae parts and assemblies have been created as family table instances of VERTEBRA_GENERIC, ROTATOR_GENERIC and NECK_VERTEBRA_GENERIC.
- All symmetrically mirrored parts have been created as the “right” version and their “left” counterpart has been created as a mirrored part in a temporary assembly.

1.4.2. Movement

The entire SET (except the neck) has been assembled with mechanism connections to be able to drag the SET body into various positions. A regeneration will reset the body into the default position.

The neck assembly is controlled by parametric relations. The BEND parameter values, 1/0/1 to represent flexion/normal/extension and the PUSH parameter values 0/14.5, represent normal/full retraction. For conveniency, all appropriate neck parameter combinations have been represented as family table instances, all shown in the study assembly NECK_BEND.

1.4.3. Common parts

The CAD models representing Hybrid III/BioRID II parts are not exact and are only intended to be used for visualisation. The weight of the Hybrid III/BioRID II parts has been set manually based on available supplier information.

2. Handling and storage

This chapter describes how to handle the SETs. The SETs are delicate measurement devices and should be handled with care. Follow these recommendations in order not to damage the SETs.

2.1. Lifting the SETs

The SETs may not be lifted by the head or arms. A single-point lifting system has been created by mounting a lifting string at the pelvis flag (shackle through designated hole) and a sling under the armpits around the chest. These strings are connected to a common steel ring serving as the lifting point. Hence, the SETs will balance close to the seated position (see FIGURE 22) and can easily be moved and put into the test setup (for string lengths, see TABLE 3). Handled this way, the stresses induced on the SETs will not change its performance.

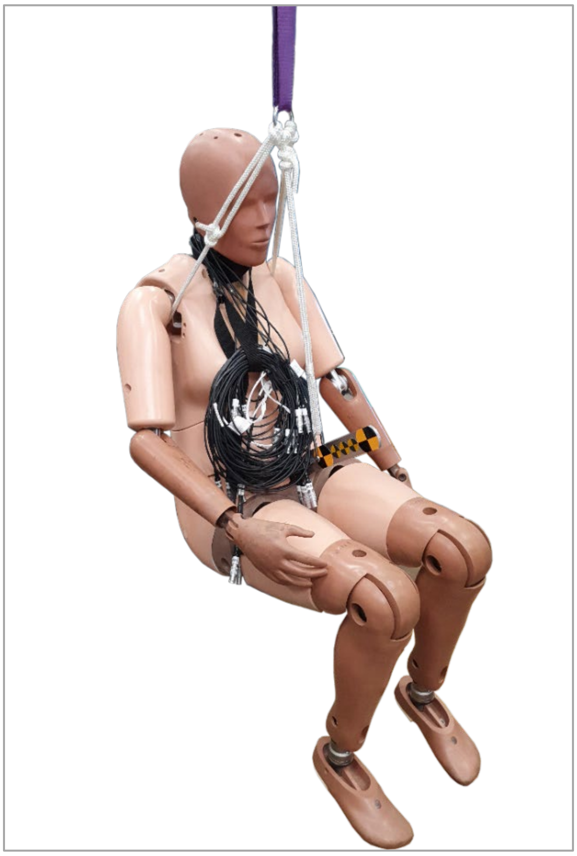

Figure 22. Lifting the SET.

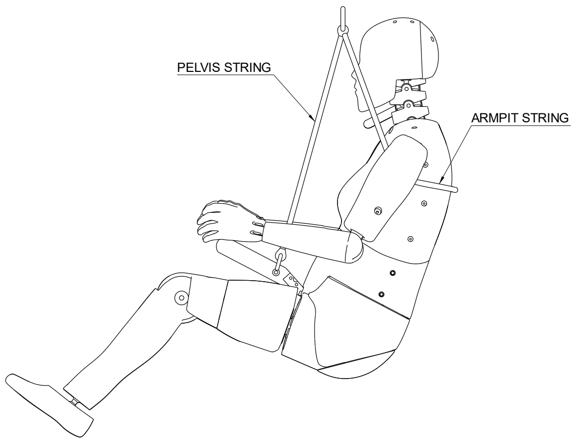

Figure 23. Lifting strings arrangement.

Table 3. Lifting string lengths.

Name	Length (mm)
Pelvis string	600
Armpit string	1300

2.2. Handling the SETs

Do not move or position the SET by pulling the arms. Due to the design of the arm attachments, risk of damage may ensue.

The spine has been made of durable aluminium vertebrae, steel pin joints, polyurethane rubber bumpers, steel cables and springs. Handling is unlikely to damage the design or change the material properties. The SETs should be stored in a reclined seated position, i.e., in a chair.

3. Assembly of the SET

This chapter describes the parts of the SETs 0.1, including assembly instructions.

The SET components are described in the suggested assembly order, starting with subcomponents followed by the complete body assembly. Each section starts with a description of the inherent parts followed by assembly instructions.

Parts numbering follow the pattern ###-###-##, whereby the mid three figures indicate the location of a particular part. The last two figures, numbers 01–10, are generally reserved for generic drawings, e.g., LX vertebra 815-102-11, part of LX assembly 815-102-00, part of spine assembly 815-100-00, part of SET 50F 815-000-00.

SET 50F has part number series 815-###-## and SET 50M part number series 816-###-##.

Approximately two thirds of the part numbers are common between SET 50F and SET 50M, they follow the SET 50F numbering pattern 815-###-##.

A complete list of drawings can be found in APPENDIX A.

Moulded PUR foam parts must be cleaned properly with acetone to remove the silicone oil release agent. The silicone oil may otherwise contaminate not only the SETs, but also the entire test environment.

3.1. Spine

The spine (FIGURE 24) is the core mechanism of the SET, connected to the torso via connecting pins which are short at the pelvis and shoulders to facilitate rotational movement of the torso.

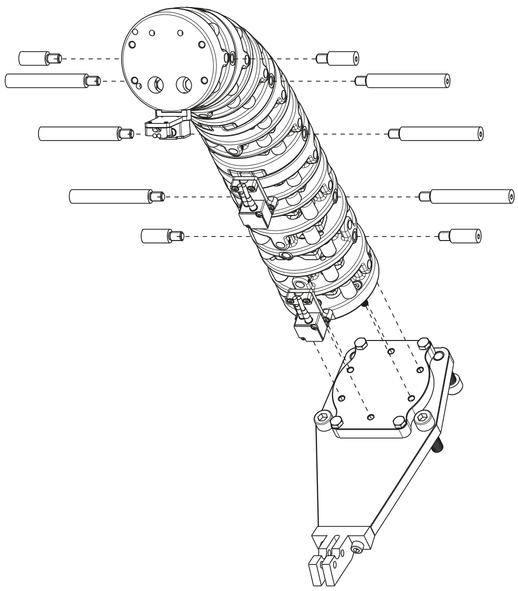

Figure 24. The spine, spine base and connecting pins; exploded view.

The spines of SET 50F and SET 50M share the majority of parts, with a few significant parts defining the difference in geometry. The difference between the spines is recognised by vertebrae (15), (16), (17), (18) and (19), being thicker and (15) adding an angle to the thoracic spine section (FIGURE 25).

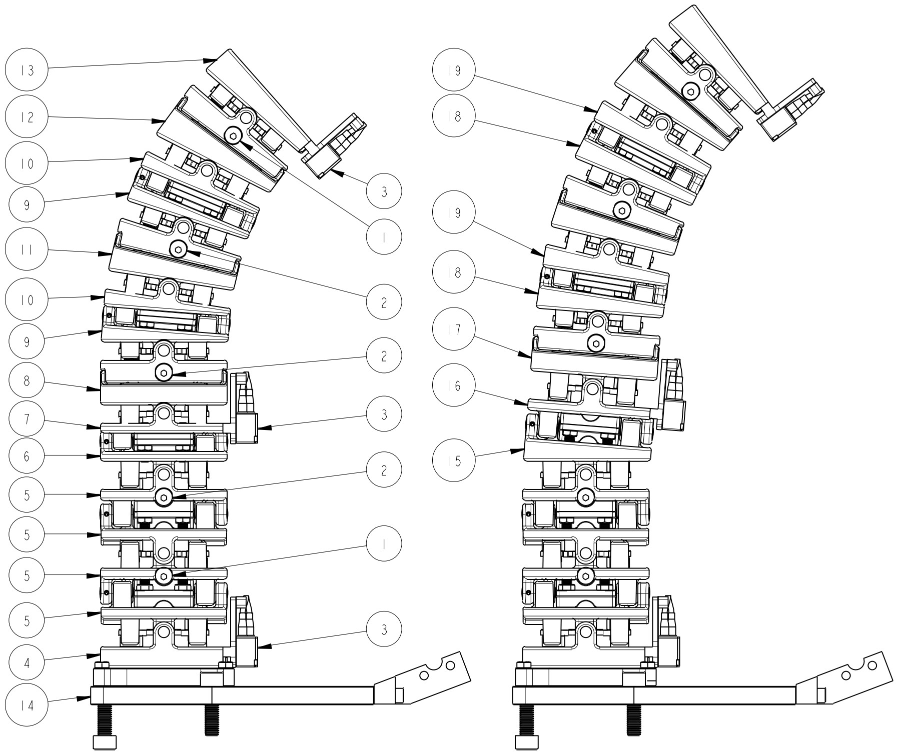

Figure 25. Spine assembly; SET 50F (left), SET 50M (right).

Table 4. Spine subcomponents; SET 50F & SET 50M.

Item	Name	SET 50F	SET 50M	Part No	Drawing No	Quantity (per spine)
	Spine Assembly	X		815-100-00	815-100-00	
	Spine Assembly		X	816-100-00	816-100-00	
1	**Chest Pin 25mm**	X	X	815-100-19	815-100-19	4
2	**Chest Pin 75mm**	X	X	815-100-21	815-100-19	6
3	**Sensor Assembly**	X	X	815-100-30	815-100-30	3
4	**L5 Assembly**	X	X	815-101-00	815-100-01	1
5	**LX Assembly**	X	X	815-102-00	815-100-01	4
6	**T12-L1S Assembly**	X		815-103-00	815-100-01	1
7	**T10-T11S Assembly**	X		815-104-00	815-100-01	1
8	**T10 Rotator Assembly**	X		815-105-00	815-100-02	1
9	**T4-T5S Assembly**	X		815-106-00	815-100-01	2
10	**T3-T4S Assembly**	X		815-107-00	815-100-01	2
11	**T6 Rotator Assembly**	X	X	815-108-00	815-100-02	1
12	**T1 Rotator Assembly**	X	X	815-109-00	815-100-02	1
13	**T1 Assembly**	X	X	815-110-00	815-100-01	1
14	**Spine Base Assembly**	X	X	815-302-00	815-302-00	1
15	**T12-L1S Assembly**		X	816-103-00	816-100-01	1
16	**T10-T11S Assembly**		X	816-104-00	816-100-01	1
17	**T10 Rotator Assembly**		X	816-105-00	816-100-02	1
18	**T4-T5S Assembly**		X	816-106-00	816-100-01	2
19	**T3-T4S Assembly**		X	816-107-00	816-100-01	2

Table 5. Spine vertebrae: SET 50F & SET 50M.

Item	Name	SET 50F	SET 50M	Part No/Drawing No	Quantity (per spine)
4	**L5 Vertebra**	X	X	815-101-11	1
5	**LX Vertebra**	X	X	815-102-11	4
6	**T12-L1S Vertebra**	X		815-103-11	1
7	**T10-T11S Vertebra**	X		815-104-11	1
8	**T11-T12S Vertebra (rotator lower)**	X		815-105-11	1
8	**T9-T10S Vertebra (rotator upper)**	X	X	815-105-21	1
9	**T4-T5S Vertebra**	X		815-106-11	2
10	**T3-T4S Vertebra**	X		815-107-11	2
11	**T6-T7S Vertebra (rotator lower)**	X	X	815-108-11	1
11/12	**T1-T2S Vertebra (rotator upper)**	X	X	815-108-21	2
12	**T2-T3S Vertebra (rotator lower)**	X	X	815-109-11	1
13	**T1 Vertebra**	X	X	815-110-11	1
15	**T12-L1S Vertebra**		X	816-103-11	1
16	**T10-T11S Vertebra**		X	816-104-11	1
17	**T11-T12S Vertebra (rotator lower)**		X	816-105-11	1
18	**T4-T5S Vertebra**		X	816-106-11	2
19	**T3-T4S Vertebra**		X	816-107-11	2

3.1.1. Spine Base

The spine base (FIGURE 26) acts as an adapter between the spine and pelvis. The pelvis can be mounted with three M10 screws from below, or a combination of two M10 screws from below, and two 3/8 screws from above. The pelvis position indicator (7) is mounted at the front surface of the spine base and acts both as a positioning tool and a lifting point for the SET. See also sections 5.2 POSITION INDICATORS and 2.1 LIFTING THE SET.

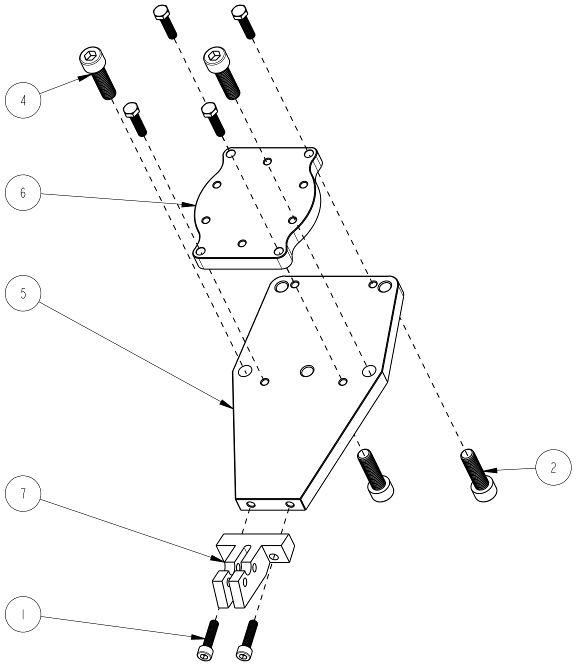

Figure 26. The spine base assembly; exploded view.

Table 6. The spin base assembly, inherent parts.

Item	Name	Part No	Drawing No	Quantity
	Spine Base Assembly	815-302-00	815-302-00	
1	**Insex Screw M6x25**	815-000-22		2
2	**Insex Screw M10x35**	815-000-23		2
3	**Hexagon Screw M6x25**	815-000-34		4
4	**Insex Screw 3/8x1 1/4**	815-000-40		2
5	**Pelvis Plate**	815-302-11	815-302-11	1
6	**Spine Adapter**	815-302-12	815-302-12	1
7	**Pelvis Position Indicator**	815-302-13	815-302-13	1

3.1.2. Linear vertebrae

The LX vertebra is shown in FIGURE 27, see drawings 815-100-01 and 816-100-01 for the linear vertebrae variants.

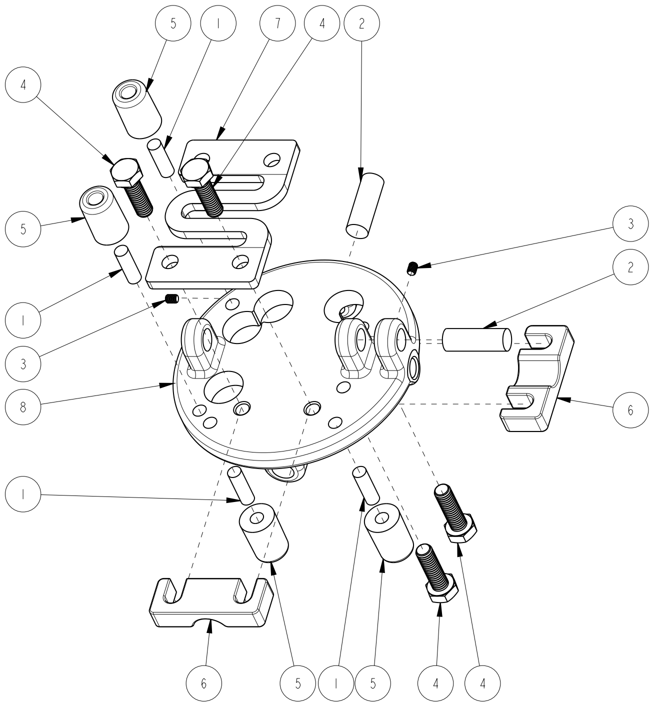

Figure 27. Linear vertebra assembly; exploded view.

Table 7. Linear vertebra assembly, inherent parts.

Item	Name	Part No	Drawing No	Quantity
	Vertebra Assembly		815-100-01/816-100-01	
1	**CP Pin 5x16**	815-000-13		4
2	**CP Pin 8x24**	815-000-16		2
3	**Stop Screw M3x4**	815-000-29		2
4	**Hexagon Screw M6x16/M6x20**	815-000-32/33		4
5	**Bumper 13,5mm/20,5mm**	815-000-51/52	815-000-51/52	4
6	**Spring Block 4,5mm/8mm**	815-100-11/12	815-100-11	2
7	**Vertebra Spring**	815-100-13	815-100-13	1
8	**Vertebra**	See drawing		1

3.1.3. Assembly instructions

Numbers refer to FIGURE 27.

1. Press fit bumper cylindrical pins (CP) (1).
2. Mount the vertebra spring (7) with the appropriate spring block (6) and hexagon screws (4).
3. The joint CP pin (2) and stop screw (3), the two lower hexagon screws (4) and spring block (6), are all mounted when the vertebra assembly is connected to the next vertebra of the spine.
4. The bumpers (5) are, due to their oversize, mounted following assembly of the spine. They tend to “pop out” and must therefore be glued in place. Clean them with acetone, roughen the bottom surface and glue in place with TEC 7 industrial adhesive.

3.1.4. Rotating vertebrae

The rotator vertebrae enable a twist angle of about ±8° each. T10 rotator vertebra is shown in FIGURE 28, see drawings 815-100-02 and 816-100-02 for the rotator vertebrae variants.

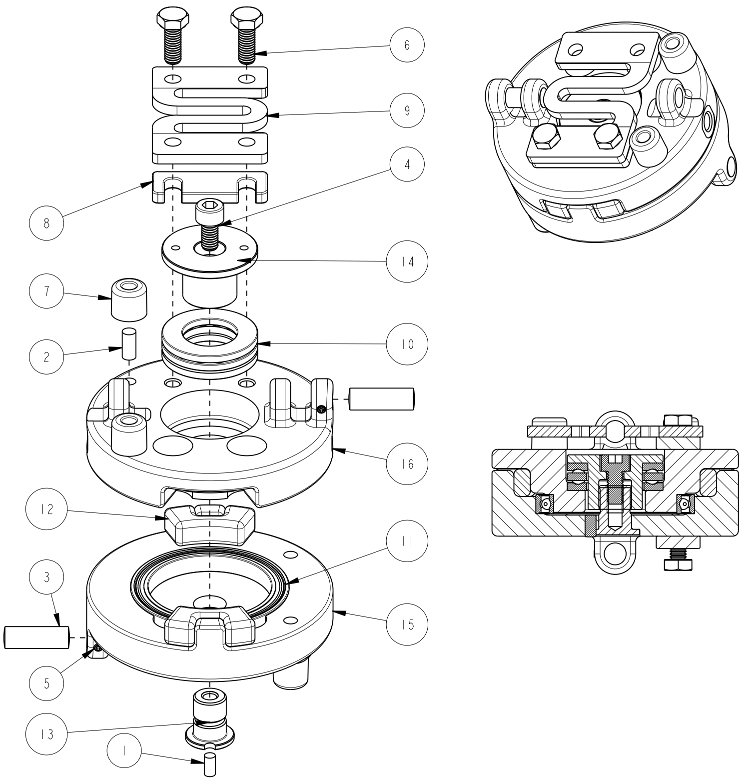

Figure 28. Rotating vertebra assembly; exploded, section and ISO views.

Table 8. Rotating vertebra assembly; inherent parts.

Item	Name	Part No	Drawing No	Quantity
	Rotator Assembly		815-100-02/816-100-02	
1	**CP Pin 4x8**	815-000-10		1
2	**CP Pin 5x11**	815-000-12		4
3	**CP Pin 8x24**	815-000-16		2
4	**Insex Screw M6x12**	815-000-20		1
5	**Stop Screw M3x4**	815-000-29		2
6	**Hexagon Screw M6x16/M6x20**	815-000-32/33		4
7	**Bumper 13,5mm/20,5mm**	815-000-51/52	815-000-51/52	4
8	**Spring Block 4,5mm/8mm**	815-100-11/12	815-100-11	2
9	**Vertebra Spring**	815-100-13	815-100-13	1
10	**SKF 51104**	815-100-14		1
11	**SKF 61809-2RS1**	815-100-15		1
12	**Twist Element**	815-100-16	815-100-16	2
13	**Rotator Centre**	815-100-17	815-100-17	1
14	**Rotator Nut**	815-100-18	815-100-18	1
15	**Lower Rotator Vertebra**	See drawing		1
16	**Upper Rotator Vertebra**	See drawing		1

3.1.5. Assembly instructions

Numbers reference FIGURE 28.

1. Place rotator centre (13) in the lower vertebra, put rotation lock CP pin (1) in place (press fit).
2. Press fit bumper CP pins (2).
3. Put radial bearing (11) and twist elements (12) in place.
4. Assemble upper and lower vertebra sub-assemblies by inserting the upper vertebra into the radial bearing (11).
5. Put the axial bearing (10), rotator nut (14) and the insex screw (4) in place.
6. Adjust the total bearing play with the rotator nut (14) and lock its position with the insex screw (4).
7. Mount the vertebra spring (9) with the appropriate spring block (8) and hexagon screws (6).
8. The joint CP pin (3) and stop screw (5), the two lower hexagon screws (6) and the spring block (8), will all be mounted when the vertebra assembly is connected to the next vertebra of the spine.
9. The bumpers (7) are, due to their oversize, mounted afterwards when the spine has been assembled. They tend to "pop out" and must therefore be glued in place. Clean them with acetone, roughen the bottom surface and glue in place with TEC 7 industrial adhesive.

3.1.6. Spine assembly instructions

1. Fixate the assembled spine base to a work bench with e.g., a screw clamp.
2. Mount the L5 assembly (six screws).
3. Mount the vertebrae by putting the CP pins 8x24 into position, lock them with stop screws M3x4.
4. Connect the vertebra springs with the hexagon screw M6x16/M6x20 and the spring block 4,5mm/8mm (variant depending on the vertebra mounting "ear" height).
5. Mount the bumpers as stated above.
6. Mount the upper three pairs of connecting pins (to be used for mounting the chest halves).

3.2. Neck

The neck is assembled as a separate unit to be fitted onto the spine. Three similar vertebrae are positioned between the C1 and C7 vertebrae, defining the bending limits of the neck. The C1 vertebra is a platform for the muscle resembling springs and damper, a sensor, and the occipital interface for the head.

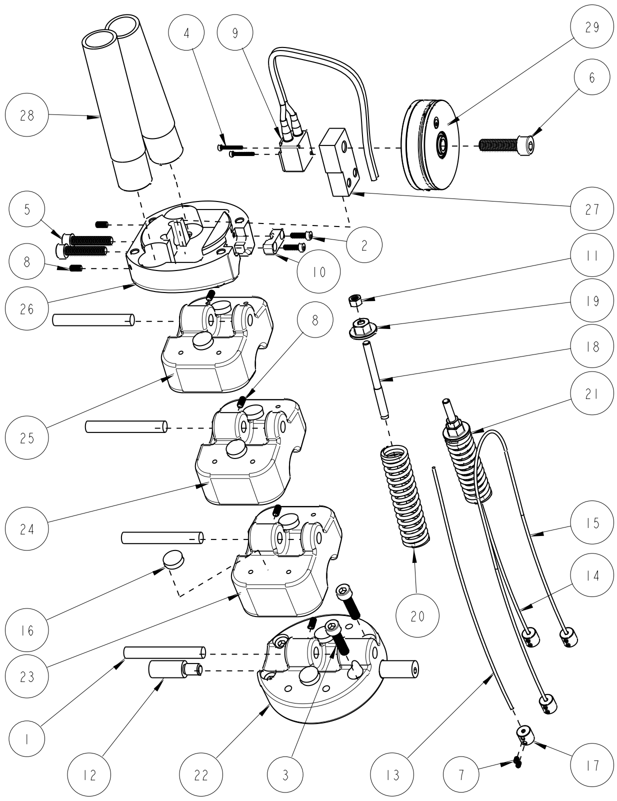

Figure 29. Neck assembly; exploded view.

Table 9. Neck assembly; inherent parts.

Item	Name	SET 50F	SET 50M	Part No	Drawing No	Quantity (per spine)
	Neck Assembly	X		815-200-00	815-200-00	
	Neck Assembly		X	816-200-00	816-200-00	
1	**CP Pin 8x60**	X	X	815-000-17		4
2	**Insex Screw M3x12**	X	X	815-000-21		2
3	**Insex Screw M6x25**	X	X	815-000-22		4
4	**Insex Screw M2x16**	X	X	815-000-24		2
5	**Insex Screw M6x30**	X	X	815-000-27		2
6	**Insex Screw M8x30**	X	X	815-000-28		1
7	**Stop Screw M3x4**	X	X	815-000-29		12
8	**Stop Screw M4x8**	X	X	815-000-31		6
9	**TE 633 Sensor**	X	X	815-000-61		1
10	**Cable Clamp**	X	X	815-000-62	815-000-62	1
11	**Nut M5**	X	X	815-000-64		2
12	**Chest Pin 25mm**	X	X	815-100-19	815-100-19	2
13	**Anterior Wire**	X		815-200-11		1
13	**Anterior Wire**		X	816-200-11		1
14	**Posterior Wire**	X		815-200-12		1
14	**Posterior Wire**		X	816-200-12		1
15	**Damper Wire**	X		815-200-13		1
15	**Damper Wire**		X	816-200-13		1
16	**Neck Shock Absorber**	X	X	815-200-14	815-200-14	8
17	**Wire Stopper**	X	X	815-200-21	815-200-20	4
18	**Wire Terminal**	X	X	815-200-31	815-200-30	2
19	**Spring Adjustment Nut**	X	X	815-200-32	815-200-30	2
20	**Spring Anterior**	X		815-200-42		1
20	**Spring Anterior**		X	816-200-42		1
21	**Spring Posterior**	X		815-200-52		1
21	**Spring Posterior**		X	816-200-52		1
22	**C7 Vertebra**	X	X	815-201-11	815-201-11	1
23	**C5-C6 Vertebra**	X		815-202-11	815-200-01	1
23	**C5-C6 Vertebra**		X	816-202-11	816-200-01	1
24	**C4 Vertebra**	X		815-203-11	815-200-01	1
24	**C4 Vertebra**		X	816-203-11	816-200-01	1
25	**C2-C3 Vertebra**	X		815-204-11	815-200-01	1
25	**C2-C3 Vertebra**		X	816-204-11	816-200-01	1
26	**C1 Vertebra**	X	X	815-205-11	815-205-11	1
27	**C1 Damper Bracket**	X	X	815-205-12	815-205-12	1
28	**Spring Tube**	X	X	815-205-13	815-205-13	2
29	**Damper Assembly**	X	X	815-205-30	815-205-30	1

3.2.1. Damper

The damper is an oil filled housing with an internal paddle wheel. When the housing is rotated, the paddle wheel pushes the oil through a small adjustable aperture hole.

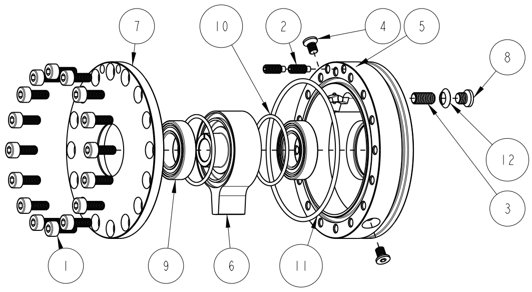

Figure 30. Damper; exploded view.

Table 10. Damper; inherent parts.

Item	Name	Part No	Drawing No	Quantity
	Damper Assembly	815-205-30	815-205-30	
1	**Insex Screw M3x8**	815-000-25		16
2	**Stop Screw M3x8**	815-000-30		2
3	**Stop Screw M4x8**	815-000-31		1
4	**Oil Plug (Insex CS Screw M3x6)**	815-000-39		2
5	**Damper Body**	815-205-31	815-205-31	1
6	**Damper Paddle Wheel**	815-205-32	815-205-32	1
7	**Damper Cover**	815-205-33	815-205-33	1
8	**Damper Adjustment Cover**	815-205-34	815-205-34	1
9	**SKF 61801-2RS1**	815-205-35		2
10	**O-Ring 23x1,2**	815-205-36		2
11	**O-Ring 48x1,5**	815-205-37		1
12	**Damper Adjustment Gasket**	815-205-38	815-205-38	1

3.2.2. Assembly instructions

The oil used in the damper is Omicron Transmission Super EP 690 (ISO VG 680).

Assembly of the rotational damper (FIGURE 30):

1. Press the two lateral roller bearings (9), SKF 61801-2RS1, onto the shafts of the damper paddle wheel (6).
2. Apply Super EP 690 oil onto the two O-rings (10) and position them into their grooves in the damper paddle wheel (6).
3. Position the assembled damper paddle wheel into the damper body (5).
4. Apply Super EP 690 oil onto the O-ring (11) and put it into its groove in the damper body (5).
5. Put the damper on a flat surface, fill the oil compartment with Super EP 690 oil.
6. Mount the damper cover (7) and the 16 insex screws (1).
7. Mount the friction adjustment screw (3) and the damper adjustment cover (8).

8. Top up with Super EP 690 oil. The holes for the oil plugs (4) act as a filling point on one side and air evacuation on the other side. Rotate the paddle wheel and cycle through the filling process until the damper is completely filled. It is vital that there is no air captured inside the damper.
9. Mount the two oil plugs (4).
10. Mount the cable attachment screws (2).

For calibration of the damper, see Section 4.1DAMPER.

3.2.3. Neck assembly instructions

Numbers reference FIGURE 29.

1. Glue the neck shock absorbers (16) to the vertebrae close to the vertebra joints in accordance with FIGURE 31. Double-sided adhesive tape was found to be the best solution.
2. Assemble the C1 damper bracket (27) to the C1 vertebra (26) with the two insex screws (5).
3. Mount the damper (30) to the C1 damper bracket (27) with the damper mounting screw (6). Position the damper so that the marking on the paddle wheel and the adjustment cover are both pointing upwards (see FIGURE 32). Fully tighten the damper mounting screw (6).
4. Assemble the vertebrae C7 (22), C5-C6 (23), C4 (24), C2-C3 (25) and C1 (26) with their respective CP pins 8x60 (1), and lock pin positions with the stop screws (8).

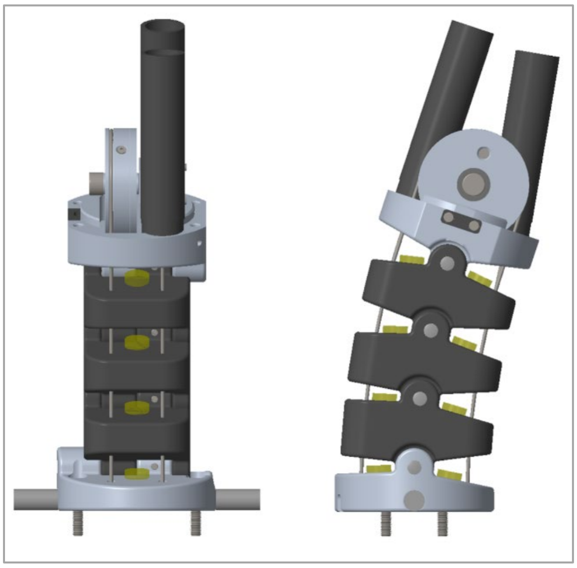

Figure 31. Neck neutral position; Shock absorber locations (yellow).

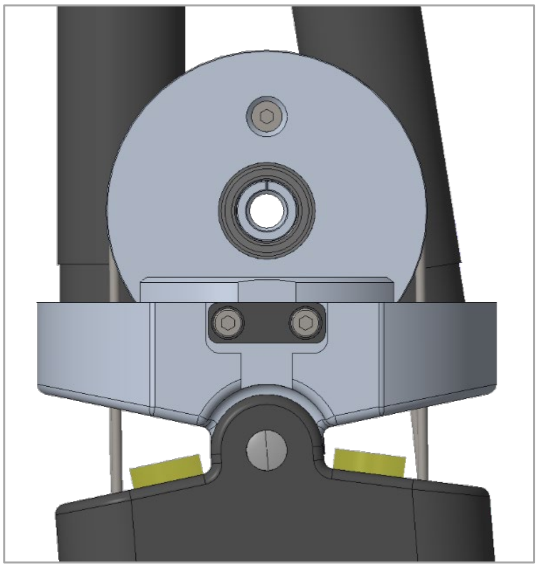

Figure 32. Damper positioning (mounting screw hidden for clarity).

3.2.4. Damper wire

An effect of the movement geometry of the neck is that the length of the damper wire will not be constant. With the neck bent fully rearward, the wire path will be approximately 1 mm shorter compared to the vertical position (FIGURE 33).

Numbers reference FIGURE 29.

1. Thread the (uncut) wire through the posterior vertebrae holes, through the groove in the damper, and through the anterior vertebrae holes.
2. Mount the cable stopper (17) at the posterior end of the cable, tighten the two stop screws (7).

3. Mount the cable stopper (17) loosely at the anterior end of the cable, do not tighten the two stop screws (7).
4. Position the neck vertebrae with the joints in a straight line in accordance with FIGURE 33. In this position, the wire path is at its longest state. NB. Assembling the damper wire with the neck in a bent state could damage the damper due to high wire tension force. Check that the damper is positioned in accordance with FIGURE 32.
5. Fully tighten the wire with a pair of pliers, tighten the two stop screws (7) (FIGURE 34)
6. Position the neck vertebrae with the joints in the neutral position in accordance with FIGURE 31. Position the damper in accordance with FIGURE 32.
7. Tighten the wire mounting screws (2, FIGURE 30) on the damper.
8. Cut the wire close to the wire stopper.

To disassemble the damper and/or wire, bend the neck rearwards to give the most wire slack. At this point it is easy to remove/remount the damper without having to release the wire stoppers. Keep in mind that the damper must not rotate to its end positions, as mentioned before.

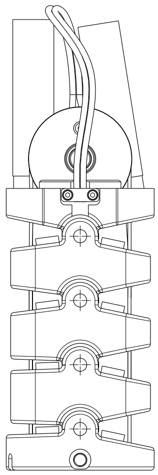

Figure 33. Neck; initial vertical position.

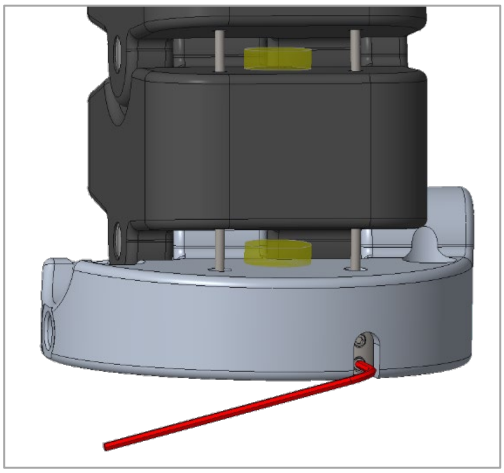

Figure 34. Tightening of damper wire.

3.2.5. Spring assembly

Numbers reference FIGURE 29.

1. Cut wire to length in accordance with
2. Table 11.
3. Solder the wire to the wire terminal (18).
4. Thread the wire through C1, through the three neck vertebrae and out through C7.
5. Mount the wire stopper (17) at the wire end. Use four stop screws in each wire stopper.
6. Position the neck in accordance with FIGURE 31.
7. Assemble the anterior and posterior springs, adjust the spring adjustment nuts to touch the relaxed springs. Mark these positions with a pen on the wires.
8. Bend neck forward to give slack in the anterior spring, adjust the spring adjustment nut down 8.5 mm to pre-tension the spring (use the pen marking as a reference).
9. Bend the neck rearward to give slack in the posterior spring, adjust the spring adjustment nut down 4 mm.

Table 11. Spring wire lengths.

	Name	Part No	Wire Length (mm)
SET 50F	**Anterior wire**	815-200-11	216
	Posterior wire	815-200-12	186
SET 50M	**Anterior wire**	816-200-11	232
	Posterior wire	816-200-12	193

3.3. Head

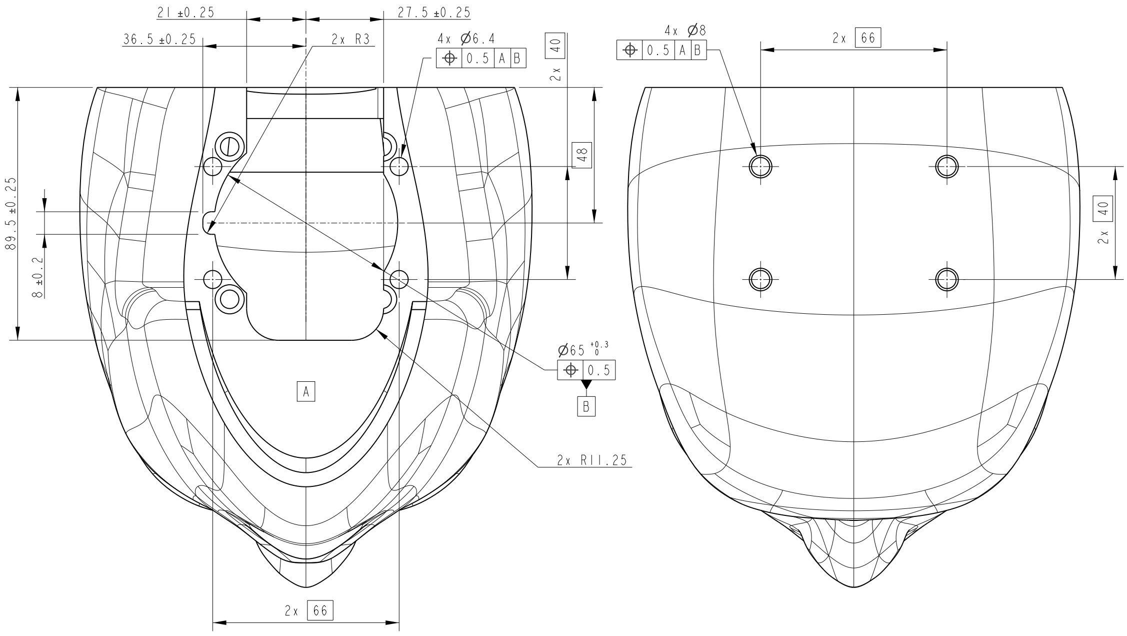

Figure 35. Head modifications (SET 50M).

The occipital interface has been modified to make space for the muscle resembling springs and damper. New holes have been made through the skull and skin to access the four mounting screws. This way, the springs, sensor and damper are easily accessible (FIGURE 35).

The threaded hole for lifting the eye mount is plugged to avoid the risk of lifting the SET by its head (see FIGURE 14).

3.4. Pelvis

The SET 50F uses a modified BioRID pelvis with soft PUR patches to conform with VIVA+ female geometry. The sitting bone area has been machined off (FIGURE 36) and soft PUR patches have been glued on to create a geometry coherent with the VIVA+ female HBM (FIGURE 37).

SET 50M has a standard BioRID pelvis.

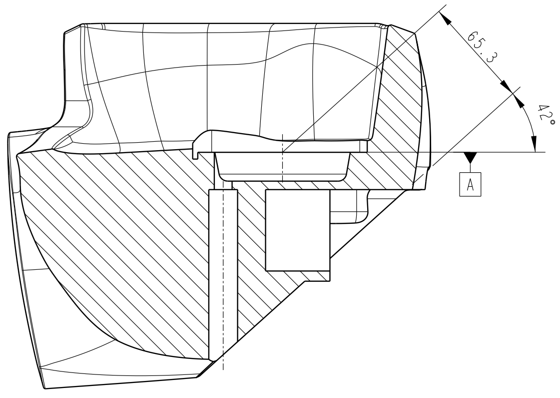

Figure 36. SET 50F; Machining of BioRID II pelvis.

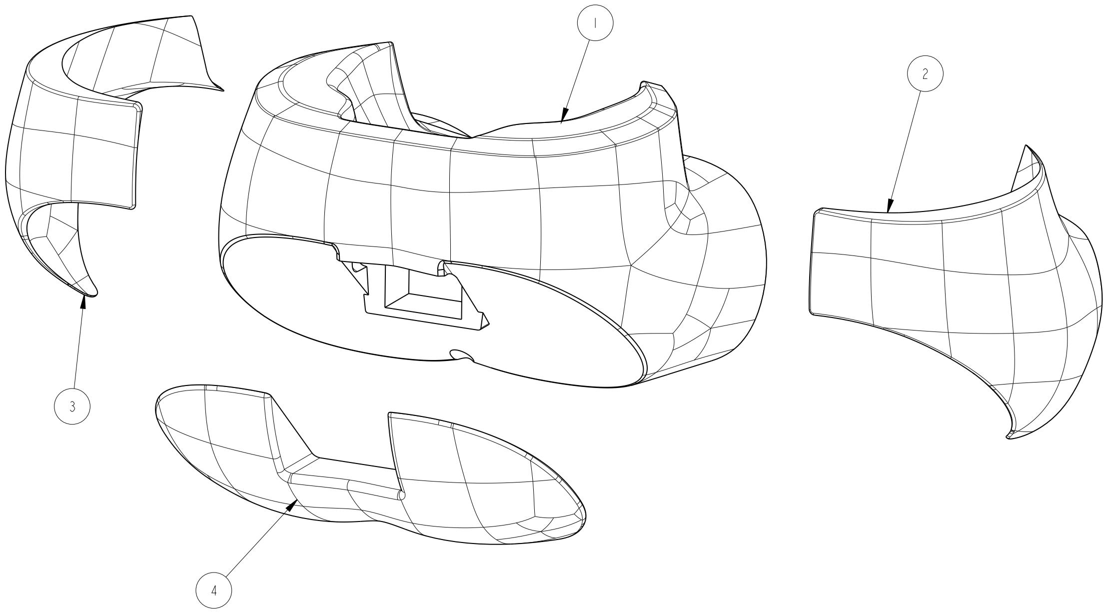

Figure 37. SET 50F Pelvis; exploded view.

Table 12. SET 50F Pelvis; inherent parts.

Item	Name	Part No/ Drawing No
	Pelvis Assembly	815-300-00
1	**Hybrid III M50 Pelvis (Machined)**	815-301-11
2	**Pelvis Add-on Right**	815-301-12
3	**Pelvis Add-on Left**	815-301-13
4	**Pelvis Add-on Bottom**	815-301-14

3.4.1. Assembly instructions

Clean the parts with acetone, it is important to remove all silicone release agent for the adhesive to adhere properly. Use TEC 7 industrial adhesive, secure with straps while hardening.

3.5. Abdomen

The abdomen foam is a single part wrapped around the spine and secured by a Velcro strip covering the split line at the rear centre, connected to the spine via connecting pins.

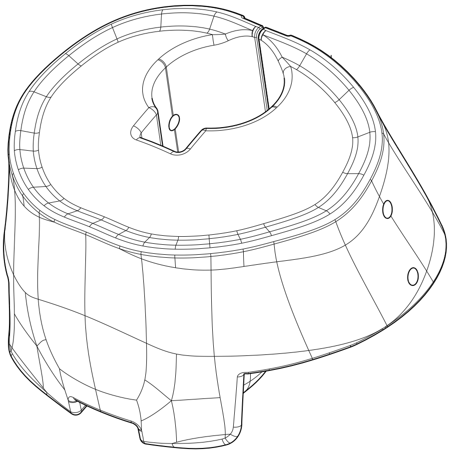

Figure 38. The abdomen.

Table 13. Abdomen; inherent parts.

Name	SET 50F	SET 50M	Part No/Drawing No	Note
Abdomen Foam	X		815-500-11	
Abdomen Foam		X	816-500-11	
(Velcro Strip Back)	X		(815-400-15)	Co-used with Chest
(Velcro Strip Back)		X	(816-400-15)	Co-used with Chest

3.5.1. Assembly instructions

Since the abdomen foam is partly covered by both the pelvis and the chest, it must be put in place before the chest.

1. Position the abdomen foam in front of the spine.
2. Pull the rear split open (with both hands), pull the abdomen foam rearwards around the spine.
3. Mount the connecting pins (On the SET 50F prototype, the lower connecting pins were left out because geometrical mismatch between the pelvis and abdomen misaligned the holes for the connecting pins).

The rear split will be closed and covered when the chest has been assembled.

3.6. Chest

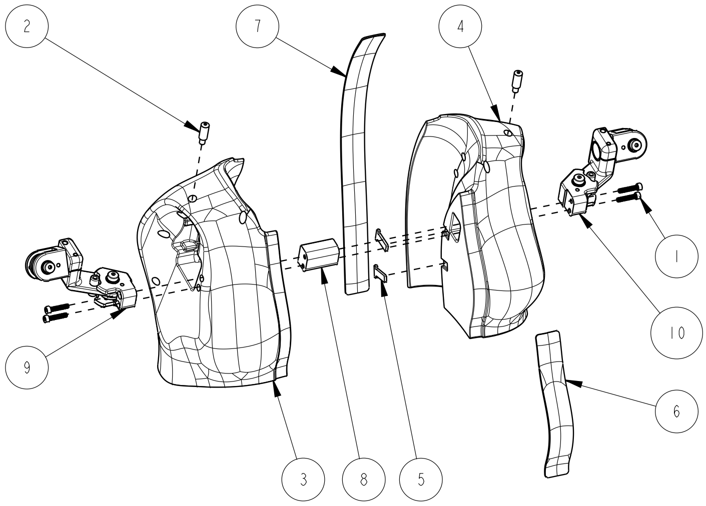

Figure 39. Chest; exploded view.

Table 14. Chest; inherent parts.

Item	Name	SET 50F	SET 50M	Part No	Drawing No	Quantity
	Chest Assembly	X		815-400-00	815-400-00	
	Chest Assembly		X	816-400-00	816-400-00	
1	**Insex Screw M6x30**					See Figure 40
2	**Chest Pin 25mm**					See Figure 40
3	**Chest Foam Right**	X		815-400-11	815-400-11	
3	**Chest Foam Right**		X	816-400-11	816-400-11	
4	**Chest Foam Left**	X		815-400-12	815-400-11	
4	**Chest Foam Left**		X	816-400-12	816-400-11	
5	**Chest Cable Clamp**	X	X	815-400-13	815-400-13	2
6	**Velcro Strip Front**	X		815-400-14	815-400-14	
6	**Velcro Strip Front**		X	816-400-14	816-400-14	
7	**Velcro Strip Back**	X		815-400-15	815-400-15	
7	**Velcro Strip Back**		X	816-400-15	816-400-15	
8	**Sternum**					See Figure 40
9	**Shoulder Assembly Right**					See Figure 40
10	**Shoulder Assembly Left**					See Figure 40

3.6.1. Assembly instructions

Numbers reference FIGURE 39.

Glue the two chest cable clamps (5) to the chest foam left (4) (see Section 5 INSTRUMENTATION for usage).

Push the two chest halves (3) and (4) onto the connecting pins of the spine. Give the chest a proper hug to squeeze it together, secure and close the gaps with the Velcro strips (6) and (7). The back of the Velcro strip (7) also secures the abdomen.

3.7. Shoulders

The same shoulder mechanism (FIGURE 41) has been used both in the SET 50F and SET 50M, but with different lengths of the sternum (3) defining the shoulder width (FIGURE 40).

The joint solution used for the sternum joint (12) and shoulder yoke (11) is based on a fitted bolt (4) and an axially movable hub nut (8). The controlled friction of the joint is created by the POM bushings (5) and (6) in combination with the compression of the hub gasket (7). The fitted bolts (4) used for mounting the shoulder yoke (11) into the clavicula (13) have an additional POM bearing surface for controlled friction.

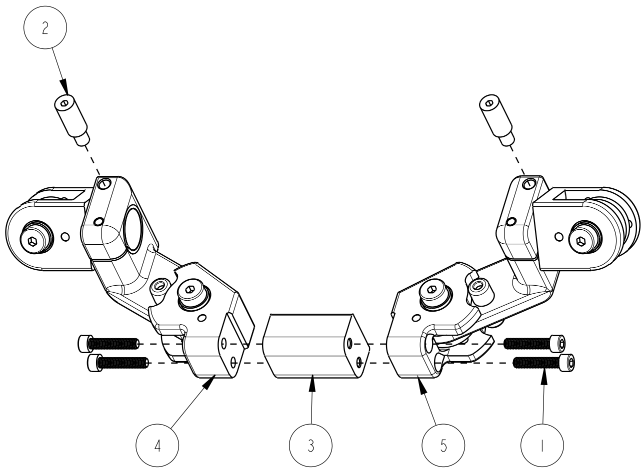

Figure 40. Shoulder mechanism.

Table 15. Shoulder mechanism; inherent parts.

Item	Name	SET 50F	SET 50M	Part No	Drawing No	Quantity
	Shoulders Assembly	X		815-410-00	815-410-00	
	Shoulders Assembly		X	816-410-00	816-410-00	
1	**Insex Screw M6x30**	X	X	815-000-27		4
2	**Chest Pin 25mm**	X	X	815-100-19	815-100-19	2
3	**Sternum**	X		815-700-11	815-700-11	1
3	**Sternum**		X	816-700-11	816-700-11	1
4	**Shoulder Assembly Right**	X	X	815-411-00	815-411-00	1
5	**Shoulder Assembly Left**	X	X	815-412-00	815-411-00	1

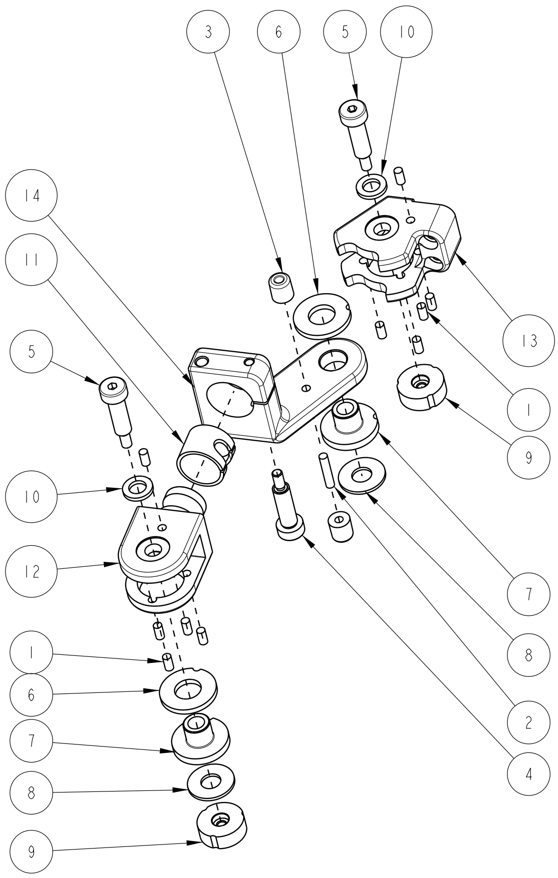

Figure 41. Shoulder (right); exploded view.

Table 16. Shoulder assembly; inherent parts.

Item	Name	Part No	Drawing No	Quantity (per shoulder)
	Shoulder Assembly (right/left)	815-411-00/815-412-00	815-411-00	
1	**CP Pin 5x10**	815-000-11		10
2	**CP Pin 5x25**	815-000-14		1
3	**Bumper 13,5**	815-000-51		2
4	**Fitted Bolt M6x30 w Sleeve**	815-000-63	815-000-63	1
5	**Fitted Bolt M6x30**	815-000-65	815-000-63	2
6	**Hub Cover**	815-410-12	815-410-12	2
7	**Hub Bushing**	815-410-13	815-410-13	2
8	**Hub Gasket**	815-410-14	815-410-14	2
9	**Hub Nut**	815-410-15	815-410-15	2
10	**Hub Bolt Washer**	815-410-16	815-410-16	2
11	**Shoulder Bushing**	815-410-17	815-410-17	1
12	**Shoulder Yoke**	815-410-18	815-410-18	1
13	**Sternum Joint (right/left)**	815-411-11/815-412-11	815-411-11	1
14	**Clavicula (right/left)**	815-411-12/815-412-12	815-411-12	1

3.7.1. Assembly instructions

The same joint design has been used for both the sternum joint (12) and the shoulder yoke (11). The group of three CP pins acts as rotation lock for the hub nut (8). Note that the hub nut (9) should be able to move freely in the axial direction and that at least one CP pin is required for rotation locking (should tolerances be too sharp, the other CP pins can be left) (FIGURE 41).

The group of two CP pins acts as rotation lock for hub cover (5) and hub bushing (6).

1. Mount CP pins (1) flush to the outside of the sternum joint (12) and shoulder yoke (11).
2. Mount CP pin (2) into clavicula (13) centric so that the same length is visible on both sides.
3. Position the hub bushing (6), hub cover (5) and hub gasket (7) through the clavicula (13). Keep them together and position into the sternum joint (12). The slots in (5) and (6) must match the CP pins.
4. Insert the hub nut (8) and put the fitted bolt (4) with hub bolt washer (9) through the joint.
5. Insert the shoulder yoke (11) and shoulder bushing (10), with the slot of (10) slightly rotated downward so that the fitted bolt (4) can enter the slot easily. Insert the fitted bolt (4).

3.8. Arms

The upper arm foam (5) (FIGURE 42) is moulded onto the brachium (4) at production (shown separated for clarity). The elbow joint (3) is inserted into the brachium (4) along with the POM bushing (2), which has a slot for the fitted bolt (1). The fitted bolt (1) is equipped with a layer of POM to provide adequate friction.

Rotation of the elbow joint (3) is achieved with the same parts (1) and (2) used in the shoulder joint.

For details of the shoulder joint, see FIGURE 41.

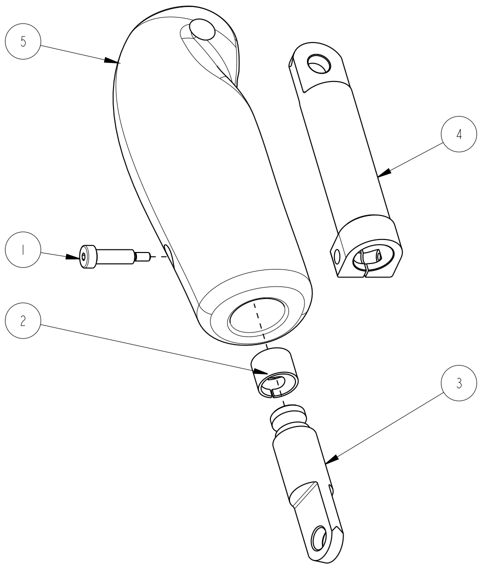

Figure 42. Upper arm; exploded view.

Table 17. Upper arm; inherent parts.

Item	Name	SET 50F	SET 50M	Part No	Drawing No
	Arm Upper Assembly	X		815-710-00	815-710-00
	Arm Upper Assembly		X	816-710-00	816-710-00
1	**Fitted Bolt M6x30**	X	X	815-000-63	815-000-63
2	**Shoulder Bushing**	X	X	815-410-17	815-410-17
3	**Elbow Joint**	X		815-700-11	815-700-11
3	**Elbow Joint**		X	816-700-11	816-700-11
4	**Brachium (right/left)**	X		815-710-11/815-711-11	815-710-11
4	**Brachium (right/left)**		X	816-710-11/816-711-11	815-710-11
5	**Arm Upper Foam (right/left)**	X	X	815-710-12/815-711-12	815-710-12

3.8.1. Assembly instructions

The elbow joint (3) is inserted into the brachium (4) along with the POM bushing (2). Note that the POM bushing (2) needs to be correctly oriented when inserting the fitted bolt (1). For adjustment of the joint, see section 4.5.

3.9. Legs

The SET F50 legs (FIGURE 43) are a combination of the Hybrid III 5F lower legs and knee, a Hybrid III 50M Femur skeleton (6) and a custom femur extension (4) replacing the load cell. For considerations regarding the load cell replacement, see BioRID P50F report (CARLSSON, DAVIDSSON, LINDER, & SVENSSON, 2021).

Complete Hybrid III legs have been used for the SET 50M.

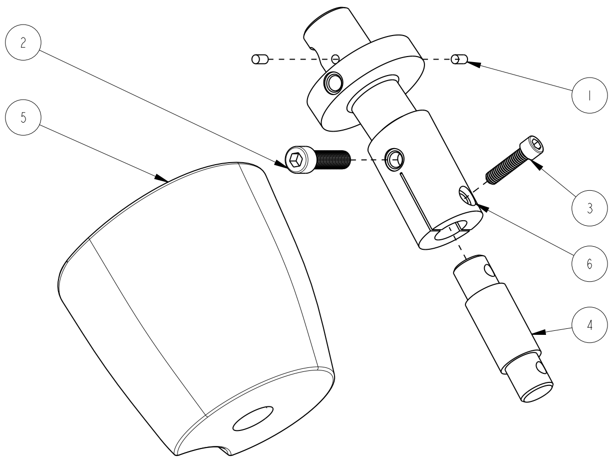

Figure 43. SET 50F Upper leg; exploded view.

Table 18. SET 50F Upper leg; inherent parts.

Item	Name	Part No	Drawing No	Comment
	Leg Upper Assembly	815-820-00	815-820-00	
1	**CP Pin 6,3x12**	815-000-15		Not used
2	**Screw Insex UNC 1/2x51**	815-000-36		
3	**Screw Insex UNC 3/8x38**	815-000-37		
4	**Femur Extension**	815-800-12	815-820-00	
5	**Leg Upper Foam**	815-800-13	815-820-00	
6	**Hybrid III Femur (right/left)**	815-820-11/815-821-11	815-820-00	

The assembled femur skeleton is fixated in the moulding tool and the PUR foam (5) is moulded onto it. Screw (2) and (3) act as a rotation lock.

As the femur is already rotation locked by the fitted bolt of the hip joint, it was decided not to use the CP Pins (1).

3.9.1. Assembly instructions

The leg assembly procedure is the same as for the legs of the standard Hybrid III dummy.

4. Adjustment and calibration

This chapter describes the initial calibration of the SET. Adjustments can be made to modify the seated position/spine bend, although adjustability is very limited.

Since the SET is in a prototype state, calibration and adjustment have been studied in an "investigate-as-you-go" manner. Methods and measurements are recommendations based on these studies.

4.1. Damper

This calibration test should only be carried out in special situations, i.e., when a new damper unit is being assembled or when the results of the spine and torso evaluation test do not fulfil the requirements.

The damper calibration test is carried out by loading the damper with a weight. A polyester rope (Ø2 mm) should be attached to the damper (FIGURE 44). The polyester rope winding angle should be approximately 360°. One end should be attached to a drop weight while the other end should be attached to a release mechanism. At test start, the release mechanism releases the rope and the weight drops 125 mm due to gravity and rotates the damper. The drop weight velocity should be calculated from video; drop weight displacement data obtained by recording with high-speed video and plotted versus time. The tests were recorded with a high-speed camera at 500 frames per second and a resolution of 1920x1280.

Two calibration marks were attached to the weight, with a known distance, to be used as a dynamic scale for the measurements. The tests were analysed in a tracking software, in this case with the software TEMA by Image Systems. The positions of the calibration marks were tracked to obtain the velocity in each frame (and then exported to excel to create the graphs).

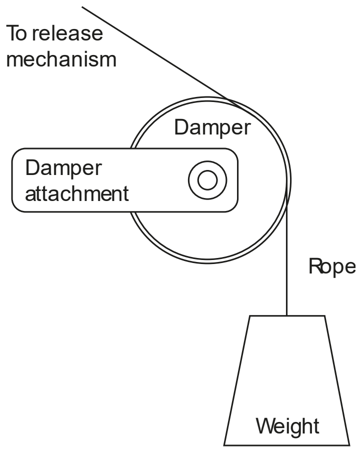

Figure 44. Damper calibration test arrangement.

In order to perform satisfactorily, the damper velocity shall be within the limits defined in TABLE 19 and TABLE 20. If the damper does not perform within the specified range, the damper may be broken, manufactured with too large tolerances, contamination of damper oil, or the valve screw may not be in the proper position.

Table 19. SET 50F damper calibration test requirement limits.

Drop mass 9.0 kg			Drop mass 16.8 kg		
Time (ms)	**Lower value (m/s)**	**Upper value (m/s)**	**Time (ms)**	**Lower value (m/s)**	**Upper value (m/s)**
0	0.00	0.00	0	0.00	0.00
100	0.20	0.30	125	0.35	0.50
450	0.25	0.35	225	0.5	0.70
-	-	-	250	0.5	0.70

Table 20. SET 50M damper calibration test requirement limits.

Drop mass 9.0 kg			Drop mass 16.8 kg		
Time (ms)	**Lower value (m/s)**	**Upper value (m/s)**	**Time (ms)**	**Lower value (m/s)**	**Upper value (m/s)**
0	0.00	0.00	0	0.00	0.00
100			125		
450			225		
-	-	-	250		

4.2. Neck

At prototype assembly, there was an unforeseen issue with the initial positioning of the neck. Due to the simplification with fewer vertebrae, each vertebra becomes an instable rocking board, reaching for its end position. Desired and repeatable positions for the vertebrae must be established (see Section 6.4 INITIAL HEAD POSITION).

For adjustment methods of the neck springs, see assembly Section 3.2.5 SPRING ASSEMBLY and 6.4 INITIAL HEAD POSITION.

4.3. Spine curvature

There are no actual adjustments available for the spine. Modifications can be made by simply replacing existing parts with other parts featuring different dimensions or properties (FIGURE 45).

- The spring block (1) located between the vertebra and the vertebra spring is replaceable. By modifying the height of the spring block, the neutral position of the vertebra will be altered. This way the overall spine curvature can be modified. Note that a custom sized spring block will affect the safety distance between adjacent vertebrae. Please check for colliding parts when assembling the customised vertebra.
- The vertebra spring (2) is replaceable. By switching to thicker/thinner material, the bending force of the vertebra will be altered. Note that a custom vertebra spring also requires custom spring blocks for correct assembly distance.

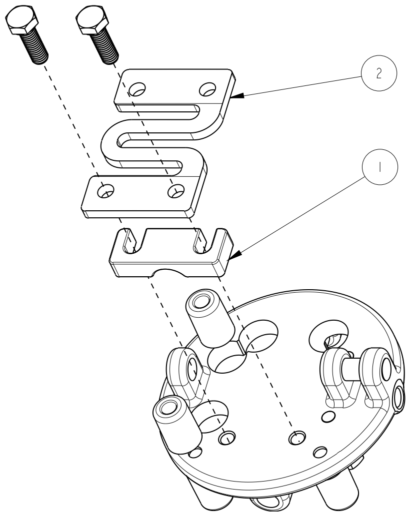

Figure 45. Spine curvature; replaceable vertebra components.

4.4. Shoulder mechanism

A simple calibration rig is created using a vise and a dynamometer (FIGURE 46):

- Fasten the shoulders assembly in a vice by the sternum.
- Put a M8 screw in the threaded hole of the clavicula.
- Attach a string between the M8 screw and the dynamometer.
- Adjust the fitted bolt torque to achieve a pull force of approximately 20N for SET 50F and 26N for SET 50M.

The torque adjustment screw is also accessible through the chest (FIGURE 47).

Figure 46. Calibration of the shoulder mechanism.

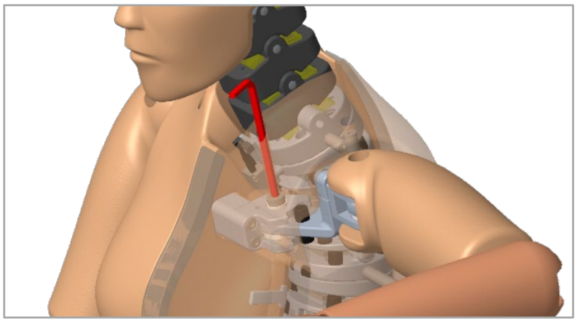

Figure 47. Clavicula torque adjustment.

4.5. Arm adjustment

Adjust the default joint torque to approximately 8 Nm as follows:

- Position the SET in the erect seated posture.
- Set the elbow angle to 90°.
- Keep the arm so that the upper arm is vertical, and the lower arm is pointing forward.
- Tighten the lower arm attachment screw so that the lower arm is slowly pulled downwards by gravity (Figure 48).
- Keep the arm so that the upper arm is horizontal and the lower arm is pointing forward (note the rotation of the upper arm to make the joint axis horizontal).
- Tighten the arm attachment screw so that the arm is slowly pulled downwards by gravity (Figure 49).
- Keep the arm horizontally. The upper arm should point forward and the lower arm should point inward.
- Tighten the shoulder yoke attachment screw so that the is slowly pulled downwards by gravity (Figure 50).

Tighten the elbow attachment screw so that the lower arm is slowly pulled downwards by gravity (Figure 51).

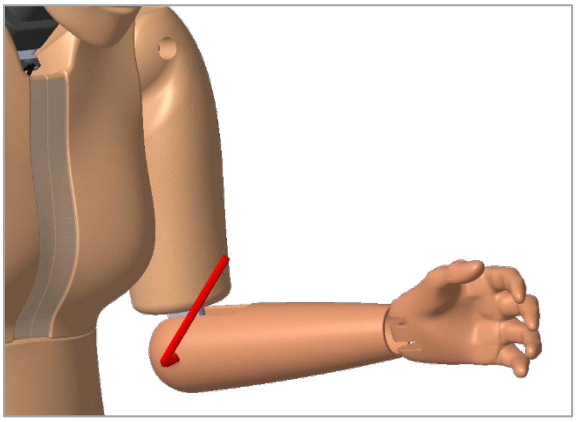

Figure 48. Lower arm adjustment.

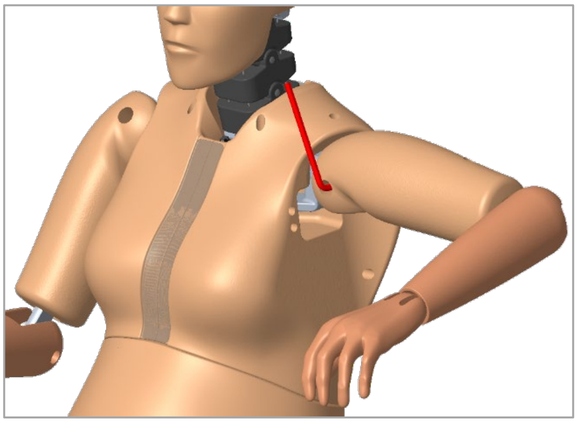

Figure 49. Upper arm to shoulder yoke adjustmen.

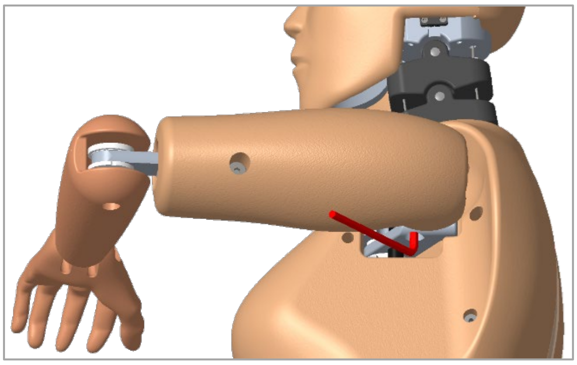

Figure 50. Shoulder yoke adjustment.

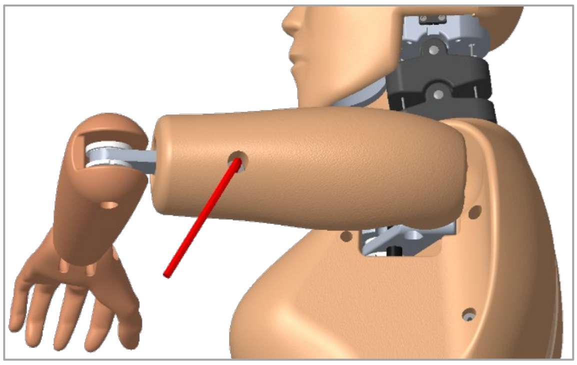

Figure 51. Upper arm to elbow adjustment.

4.6. Leg adjustment

To conform with the BioRID II validation, a femur joint torque of approximately 30 Nm in flexion and extension is appropriate. To adjust the initial femur joint torque to approximately 30 Nm:

- Dismount the abdomen from the spine (the chest halves must also be dismounted).
- Position the SET in the erect seated posture (on its posterior part of the pelvis on a table).
- Remove lower leg and foot.
- Keep the upper legs horizontal.
- Tighten the femur joint adjustment screw so that the upper leg is slowly pulled downwards by gravity (FIGURE 52).
- Assemble the lower legs. Keep each leg so that both the upper and lower leg are horizontal. Tighten the knee adjustment screw so that the lower leg is slowly pulled downwards by gravity (FIGURE 53).

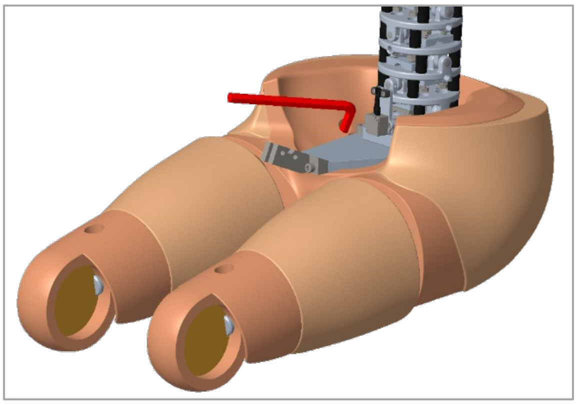

Figure 52. Femur joint adjustment.

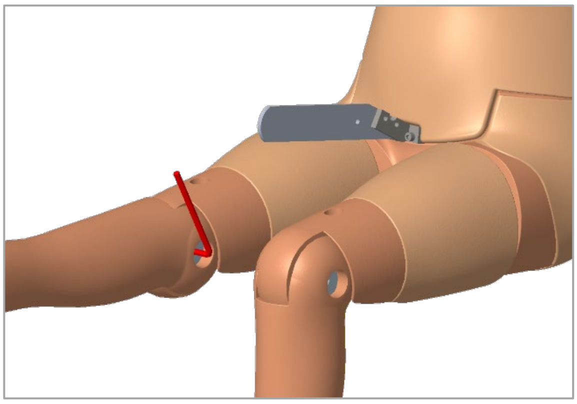

Figure 53. Knee adjustment

5. Instrumentation

This chapter describes the sensorial equipment of the SETs.

Focus for the sensor equipment is the relative movement from the pelvis through the spine and neck to the head. To monitor this movement adequately, each SET has been equipped with four combination sensors containing three-axial accelerometers and gyros.

5.1. Sensors

The SET is equipped with four sets of three-axial accelerometers with integrated gyro, TE Connectivity Model 633 6-DOF, at the following locations, where a mounting interface is located on the vertebrae:

- L5 vertebra (fixed to Pelvis)
- L1 vertebra (lower chest)
- T1 vertebra (at neck mount)
- C1 (head).

See FIGURE 54 and FIGURE 55 for detailed locations of the sensors.

Table 21. Sensor positions; related drawings.

Item	Name	Drawing No
SET 50F	**Sensor Positions**	815-000-01
SET 50M	**Sensor Positions**	816-000-01

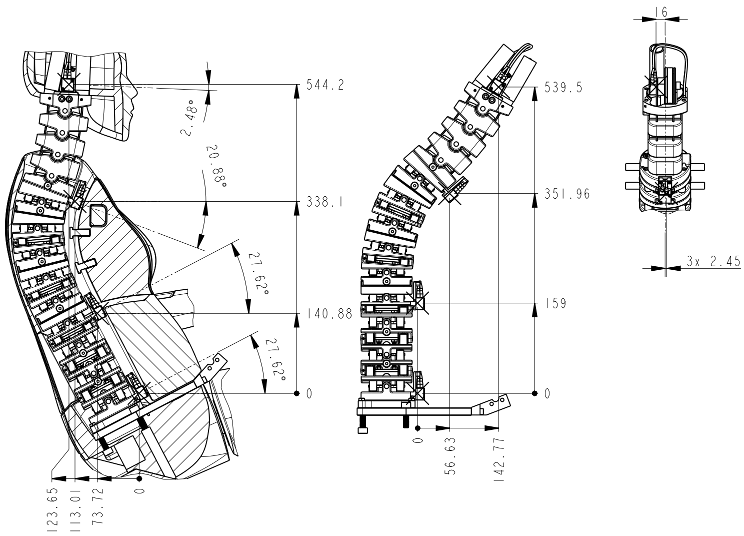

Figure 54. SET 50F sensor positions.

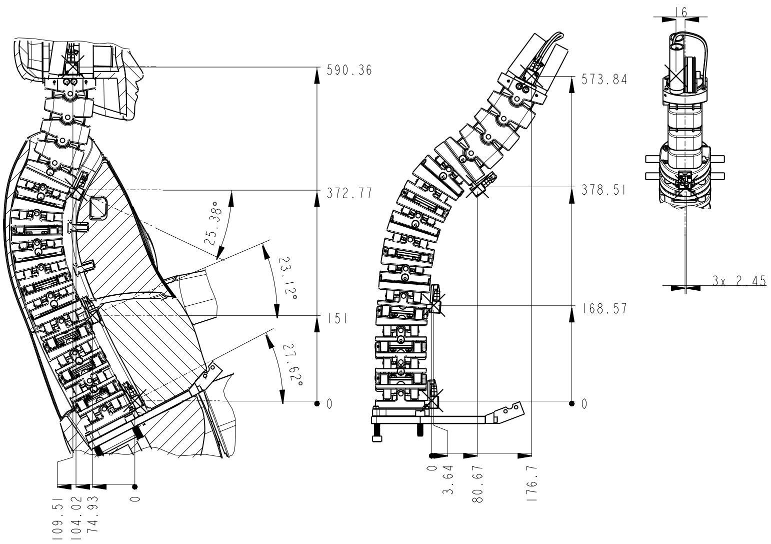

Figure 55. SET 50M sensor positions.

5.2. Position indicators

Position indicator flags have been mounted with rigid connections to the pelvis and T1 vertebra to facilitate tracking their movement. The flags have been equipped with markers for film tracking.

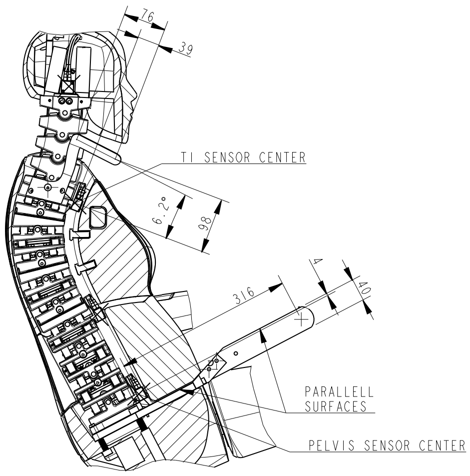

Figure 56. SET 50F marker flag positions (the same relative positions apply to SET 50M).

Table 22. Marker flag positions; related drawings.

Item	Name	Drawing No
SET 50F	**Marker Flag Positions**	815-000-03
SET 50M	**Marker Flag Positions**	816-000-03
	Pelvis Flag	815-100-23
	T1 Flag	815-100-24

6. Sled testing

This chapter describes the positioning of the SET in the test sled seat, along with the initial sled test evaluation. The SET is intended to be used in a pure rear impact (180°) in normal seated postures, using conventional car seats with head restraints or equivalent laboratory seat systems.

The geometry of the SET is based on the initial posture of the VIVA+ HBM and this is also the default posture.

6.1. Initial pelvis position and pelvis angle

The default pelvis angle is 27.6° and the head base should then be horizontal (if the spine curvature is in default position). This angle is indicated by the pelvis flag (see Section 5.2).

6.2. Initial torso shape

The SET back shape and spine curvature is based on the initial posture of the VIVA+ HBM. However, it is possible to change the spine curvature and back surface shape slightly by adjusting the angles between the vertebrae in the thoracic and lumbar spine, but it is not the intention for the SET to be an adjustable device (see Section 4.3).

6.3. Positioning on test sled seat

The SET is positioned with the single-point lifting system (see 2.1 LIFTING THE SET)

- Centre the SET on the seat.
- Position the back of SET very close to the seatback (almost touching the seat back).
- Lower the SET very gently until the SET touches the seat cushion, push the SET rearwards by the legs until the SET touches the seat back.

6.3.1. Positioning on LAB seat

- While lowering, hold up the lower leg until the thighs are parallel to the seat cushion.
- Lower the SET until a slack appears in the single-point lifting system, release the single-point system by unscrewing the two shackles.

Figure 57. Positioning; LAB seat.

6.3.2. Feet and legs

- Position the heels on the bottom plate.
- Rest the feet on the foot support.
- Keep the distance between the ankles at approx. 95 mm (at the larger diameter of the ankles).
- Keep the distance between the knees at approx. 60 mm.

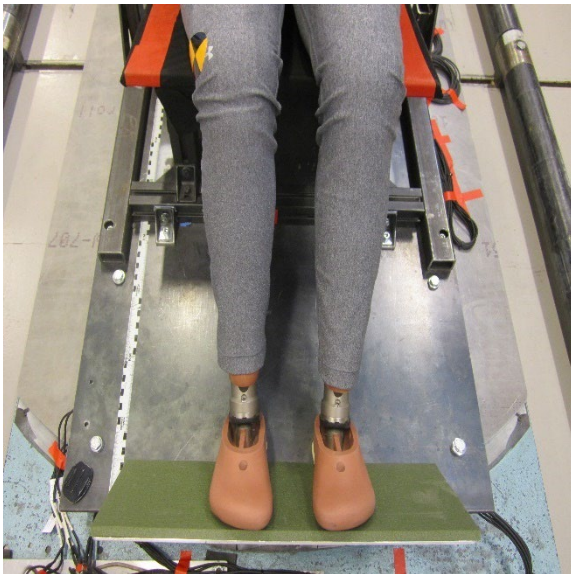

Figure 58. Positioning; feet and legs.

6.3.3. Arms and hands

- Keep the upper arms parallel to the line of the back.
- Keep the palms resting on the thighs.
- Keep the distance between the thumbs at approx. 75 mm.
- Keep the elbow as close as possible to the torso.

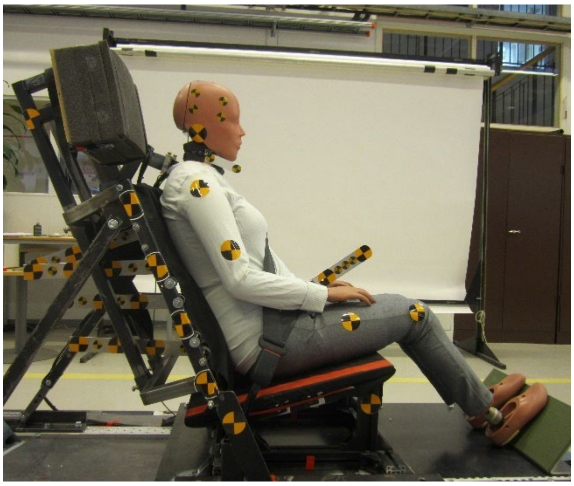

Figure 59. Positioning; arms and hands.

6.4. Initial head position

Adjusting the cable pair on the right side of the dummy changes the neck curvature and the head angle. The anterior and the posterior cables are shortened and lengthened, respectively. The cable pretension affects the friction and the resistance to flexion/extension of the neck, which influences the response of the dummy. Be sure to keep proper pretension on the springs, see further details in section 4.2.

As mentioned in section 4.2, there are no neutral positions for the neck vertebrae. For adequate and repeatable setup, the neck vertebrae must be positioned in accordance with FIGURE 60.

Keep the distance between the head support and the head at approx. 100 mm, when using 130 mm padding on the LAB seat (FIGURE 61).

Figure 60. Positioning; neck configuration.

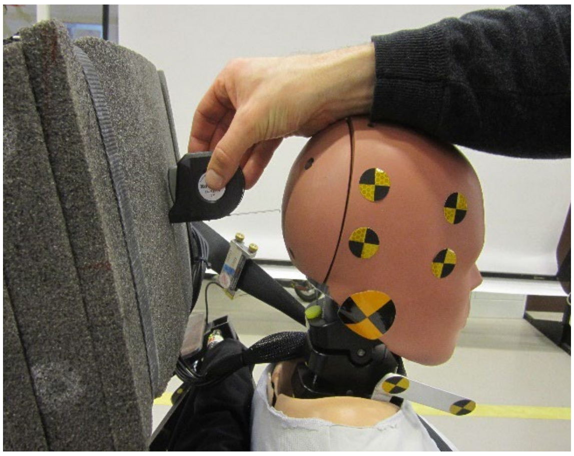

Figure 61. Positioning; head distance.

6.5. Sled test evaluation

Sled tests were conducted to perform an initial evaluation of the dynamic responses of the SETs and can be found in APPENDIX F. Test scenarios and seat equipment were chosen to enable a comparison with previous volunteer tests described in LINDER ET AL. (2013).

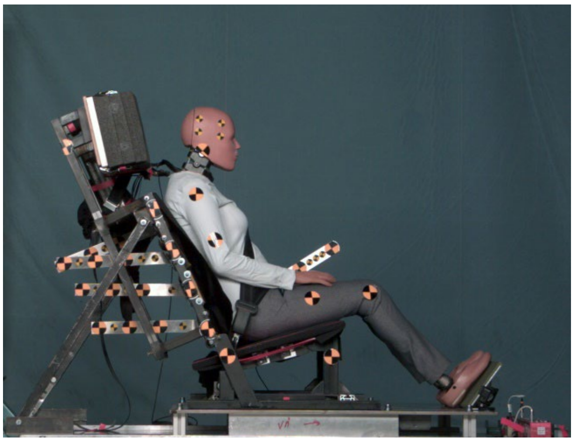

Figure 62. Sled evaluation test, SET 50F

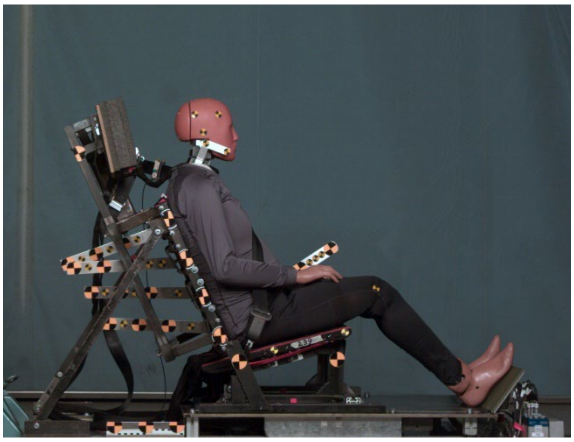

Figure 63. Sled evaluation test, SET 50M

7. Discussion and future work

Prototyping new ideas is a learning process. Shown here is a list of insights and improvement areas discovered during the development of the SET v0.1 prototypes and possible improvements to be considered in a future continuum of this project.

7.1. Neck positioning

At prototype assembly, there was an unforeseen issue with the initial positioning of the neck. The simplified design with fewer vertebrae than the human neck in combination with the lack of the dampers between vertebrae found in BioRID, caused each vertebra to become an instable rocking board, reaching for its end positions. The fact that the wire tension is strongest in the neutral upright position contributes to this issue. Hence, how to create repeatable initial positions for the vertebrae should be further investigated. In addition, future improvements to the neck of the SET could be created by adding springs or polymer cushions between the neck vertebrae to create a neutral neck position.

7.2. Adjustable damper wire

The damper wire begins and ends with a wire lock. However, this solution does not offer the option of adjusting the wire tension. If this is desired, an eccentric rotatable mount for the damper could be added.

7.3. Damper O-rings

The O-rings located on the damper wing are rotating by the damper movement and have been found to be a leakage risk (one of two produced dampers showed initial leakage). Mechanic precision and selection of O-ring type need to be investigated. There are also commercially available rotational dampers at sizes suitable for integration within each neck vertebra, a solution worth investigating.

7.4. Neck wire routing improvement

The current wire routing of the neck vertebrae with straight holes through the vertebrae in combination with the free passage in between, causes the wire routing path to vary in length during neck motion. The main drawback is inconsistent wire tension in the damper connection. Ideally, the wire lengths during movement of the neck geometry would be constant. A way to solve this issue would be to connect a tension damper to the wires.

The current wire routing solution requires cutting the wires close to the wire lock due to lack of space. This solution would be improved by adding holes in the T1 vertebra to make space for the wire endings. Alternatively, the wire lock could be fitted inside the body of the T1 to lead excessive wire out on the side to safeguard accessibility for pliers.

7.5. Neck design improvement

The project has resulted in a thoracic and lumbar spine with a capacity to move around the vertical axis (compared to the design of the BioRID). The next step could also involve creating this capability of the neck. This possibility has been studied previously, but due to the complexity of the mechanism no products have reached beyond prototype level (SARALE, 2004). Some of the complexity issues have been related to the use of wire driven springs and damper, implemented in BioRID. These issues might be solved by using micro-sized rotational dampers integrated within the vertebrae for controlled damping of X and Y motion and Z rotation (see also 7.3). Such a solution could also be of interest for future development of the current SET neck design.

7.6. Additional load cells

There is a simple mounting interface between the spine and neck assemblies to facilitate further development of neck concepts. The possibility to place a load cell at this position was discussed, but not implemented in the v0.1. of the SETs.

7.7. Pelvis softness

The material of the Hybrid III pelvis currently used in both SET 50F and SET 50M is stiffer than the human interaction with the seat. SET 50M use a stiff BioRID pelvis and SET 50M is a mixture with softer add-on patches. A new pelvis for both SET 50F and 50M with soft PUR foam would be an improvement and would give the same properties for the male and female pelvises.

7.8. Chest softness and spine motion

The bumpers between the vertebrae were modified to stiffen the spine, and the intended behaviour of the chest foam was that it would follow the movement of the spine. Test results (i.e., the T1 rotation and displacement) indicate that the chest foam might be limiting the bending of the spine.

7.9. Abdomen softness and geometry

The aim was to create a soft abdominal volume with the same functionality as the liquid compartment of the BioRID. Material samples from the supplier showed potential, but the actual moulded parts were significantly stiffer. Further extensive material research is required to pinpoint the possibilities and limitations of soft bodies with the capacity of both compression and extension.

7.10. Connection between soft bodies

The flexibility of the PUR foam parts cannot fully cover the range of motion of the torso. When bent rearwards, gaps will appear between the pelvis and abdomen, and between the abdomen and chest. A possible improvement may involve slightly compressing the PUR foam to utilise material relaxation. Another solution may involve connecting the torso parts along the mating surfaces. Both solutions would require a more flexible PUR foam material than currently used.

7.11. Modified tools for the upper legs and upper arms

The upper legs and arms were moulded onto the metal core. This method could cause leakage in the moulding tool, since the tool is dependent on the precision of the core part. Adding a hollow geometry in the moulded part would solve this issue and would also create a leg/arm with replaceable foam.

The left and right upper arm PUR foam are were made as mirrored parts in the prototypes. In a future version, the same part could be used for left and right arm (giving asymmetric locations of mounting screws for left/right).

The upper leg of the SET 50F prototype is moulded onto the re-used assembled femur from a previous prototype. For future productions, a custom femur (the same for left/right) needs to be produced.

8. Acknowledgements

I was thrown into the exciting VIRTUAL project to continue the works of Anders Flogård, who sadly couldn’t finalise what he started. I never had the chance to meet him, but I hope that our creations are something he would be proud of.

Building prototypes is impossible without a good workshop, my deepest gratitude to Gustav Danielsson at the VTI workshop for making reality out of the impossible and to Tommy Pettersson for brilliant discussions and for pushing quality beyond limits. Last but not least, thanks for good ideation, inspiration and a never-ending source of competence and experience, Mats Svensson and Astrid Linder without whom this never would have happened.

Gothenburg, September 2022

Magnus Karemyr
Puppet master

Magnus Karemyr is a research engineer at VTI since 2020 and has during the last two years been involved in the VIRTUAL project. Being an industrial designer, he enjoys prototyping projects both virtually and physically in the workshop. Magnus is also working with bicycle related research projects.

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List of figures

List of tables

Appendix A. SET v0.1 Drawings

Design and engineering work has been made in the CAD tool Creo Parametric, version 7.0 at VTI, Gothenburg, Sweden. The choice of CAD system was based on stability and availability. Drawings and 3D geometry have been made available at the OpenVT platform (https://openvt.eu/) in the neutral file formats PDF and STEP, along with the native Creo files.

Parts numbering follow the pattern ###-###-##, whereby the mid three figures indicate the location of a particular part. The last two figures, numbers 01–10, are generally reserved for generic drawings, e.g., LX vertebra 815-102-11, part of LX assembly 815-102-00, part of Spine assembly 815-100-00, part of SET 50F 815-000-00.

SET 50F has part number series 815-###-## and SET 50M part number series 816-###-##.

Approximately two thirds of the part numbers are common between SET 50F and SET 50M, they follow the SET 50F numbering pattern 815-###-##.

A list of the engineering drawings for SET v0.1 50F and 50M can be found in TABLE 23, TABLE 24 and TABLE 25.

Table 23. SET 50F and 50M common drawings.

Name	Drawing No
PACKAGING DIMENSIONS	815-000-03
BUMPER 13.5	815-000-51
BUMPER 20.5	815-000-52
CABLE CLAMP	815-000-62
FITTED BOLT M6X30	815-000-63
SPRING BLOCK	815-100-11
VERTEBRA SPRING	815-100-13
TWIST ELEMENT	815-100-16
ROTATOR CENTRE	815-100-17
ROTATOR NUT	815-100-18
CHEST PIN	815-100-19
PELVIS FLAG	815-100-23
T1 FLAG	815-100-24
SENSOR ASSEMBLY	815-100-30
SENSOR BRACKET	815-100-31
L5 VERTEBRA	815-101-11
LX VERTEBRA	815-102-11
T9-T10S VERTEBRA	815-105-21
T6-T7S VERTEBRA	815-108-11
T1-T2S VERTEBRA	815-108-21
T2-T3S VERTEBRA	815-109-11
T1 VERTEBRA	815-110-11
NECK SHOCK ABSORBER	815-200-14
CABLE STOPPER ASSEMBLY	815-200-20
CABLE ADJUSTMENT ASSEMBLY	815-200-30

Name	Drawing No
C7 VERTEBRA	815-201-11
C1 VERTEBRA	815-205-11
C1 DAMPER BRACKET	815-205-12
SPRING TUBE	815-205-13
DAMPER ASSEMBLY	815-205-30
DAMPER BODY	815-205-31
DAMPER PADDLE WHEEL	815-205-32
DAMPER COVER	815-205-33
DAMPER ADJUSTMENT COVER	815-205-34
SPINE BASE ASSEMBLY	815-302-00
PELVIS PLATE	815-302-11
SPINE ADAPTER	815-302-12
PELVIS POSITION INDICATOR	815-302-13
CHEST CABLE CLAMP	815-400-13
HUB COVER	815-410-12
HUB BUSHING	815-410-13
HUB GASKET	815-410-14
HUB NUT	815-410-15
HUB BOLT WASHER	815-410-16
SHOULDER BUSHING	815-410-17
SHOULDER YOKE	815-410-18
SHOULDER ASSEMBLY RIGHT & LEFT	815-411-00
STERNUM JOINT LEFT & RIGHT	815-411-11
CLAVICULA LEFT & RIGHT	815-411-12
ARM UPPER FOAM RIGHT & LEFT	815-710-12

Table 24. SET 50F drawings.

Name	Drawing No
SET 50F	815-000-00
SENSOR POSITIONS	815-000-01
SPINE ASSEMBLY	815-100-00
VERTEBRAE ASSEMBLY	815-100-01
ROTATOR ASSEMBLY	815-100-02
T12-L1S VERTEBRA	815-103-11
T10-T11S VERTEBRA	815-104-11
T11-T12S VERTEBRA	815-105-11
T4-T5S VERTEBRA	815-106-11
T3-T4S VERTEBRA	815-107-11
NECK ASSEMBLY	815-200-00
NECK VERTEBRAE	815-200-01
NECK WIRES	815-200-02
NECK SPRINGS	815-200-03
PELVIS ASSEMBLY	815-300-00
H3 M50 PELVIS MACHINED	815-301-11

Name	Drawing No
PELVIS ADDON RIGHT & LEFT	815-301-12
PELVIS ADDON BOTTOM	815-301-14
CHEST ASSEMBLY	815-400-00
CHEST FOAM RIGHT & LEFT	815-400-11
CHEST STRIP FRONT	815-400-14
CHEST STRIP REAR	815-400-15
SHOULDERS ASSEMBLY	815-410-00
STERNUM	815-410-11
ABDOMEN FOAM	815-500-11
HEAD MODIFICATIONS	815-600-01
ELBOW JOINT	815-700-11
ARM UPPER ASSEMBLY RIGHT & LEFT	815-710-00
BRACHIUM RIGHT & LEFT	815-710-11
LEG UPPER FOAM	815-800-13
LEG UPPER RIGHT & LEFT	815-820-00

Table 25. SET 50M drawings.

Name	Drawing No
SET 50M	816-000-00
SENSOR POSITIONS	816-000-01
SPINE ASSEMBLY	816-100-00
VERTEBRAE ASSEMBLY	816-100-01
ROTATOR ASSEMBLY	816-100-02
T12-L1S VERTEBRA	816-103-11
T10-T11S VERTEBRA	816-104-11
T11-T12S VERTEBRA	816-105-11
T4-T5S VERTEBRA	816-106-11
T3-T4S VERTEBRA	816-107-11
NECK ASSEMBLY	816-200-00
NECK VERTEBRAE	816-200-01
NECK WIRES	816-200-02
NECK SPRINGS	816-200-03
CHEST ASSEMBLY	816-400-00
CHEST FOAM RIGHT & LEFT	816-400-11
CHEST STRIP FRONT	816-400-14
CHEST STRIP REAR	815-400-15
SHOULDERS ASSEMBLY	816-410-00
STERNUM	816-410-11

Name	Drawing No
ABDOMEN FOAM	816-500-11
HEAD MODIFICATIONS	816-600-01
ELBOW JOINT	816-700-11
ARM UPPER ASSEMBLY RIGHT & LEFT	816-710-00
BRACHIUM RIGHT & LEFT	816-710-11

Appendix B. Weights of SET v0.1 50F and 50M

The total weight of SET 50F is 58 Kg and of SET 50M is 72 Kg. Due to lower weight than expected of the PUR foam parts, additional weight inserts were necessary. This was not fully implemented in the SET prototypes.

Table 26. Mass properties of SET 50F.

Body segment	SET 50F weight from CAD (Kg)	SET 50F actual weight (Kg)	VIVA+ 50F weight (Kg)
Complete body	63.0	58.0	62.7
Head	2.7	2.9	3.9
Arms	4.5	4,7	6.5
Chest	11.2	11.2	12.8
Torso (Thorax+Abdomen+Pelvis)	32.7	33,4	31.9
Legs	19.0	17,0	19.8

Table 27. Mass properties of SET 50M.

Body segment	SET 50M weight from CAD (Kg)	SET 50F actual weight (Kg)	VIVA+ 50M weight (Kg)
Complete body	72.9	71.7	76.75
Head	4.5	3.5	4.4
Arms	8.4	8.1	8.2
Chest	13.2	13.1	15.9
Torso (Thorax+Abdomen+Pelvis)	35.8	34.5	38.9
Legs	22.9	25.6	24.2

Appendix C. Suppliers

The SET prototypes were produced at the VTI workshop, Linköping, Sweden, with much appreciated help and expertise from the following suppliers:

PUR foam parts

Vållsjö Industri, Olofström, Sweden

Precision mechanics

Finspångs Allmekano, Lotorp, Sweden

Springs

Lesjöfors Spring and Pressings, Vällingby, Sweden

Appendix D. Design concepts from the ViVA II project

The text in this section is a translated extract from the work by A. Flogård in the ViVA II project[2], describing the ideas leading to the spine and neck solutions used in the SET 50F and SET 50M. References have been added to the text.

A simplified human-like spine

The spine curvature of the ViVA OpenHBM F50 formed the basis for ideas created for various possible simplifications, a perception of the project was that the previously built BioRID II had more joints than was probably necessary. BioRID was also only mobile in one plane, which the ViVA II project wanted to expand to resemble a more human-like mobility for improved seat interaction. The limited distance between the spine joints and their movement requirements in combination with the fact that they must be able to withstand loads for a longer period of time without fatigue, significantly limited the construction possibilities. In BioRID II, all springs were linked together outside the joints as it could only move in one plane. This solution simplified the force situation considerably as the entire spring structure was connected as an external unit.

In this new proposal for a F50, each joint and "vertebral body" must support its own load, which places significant demands on the attachment between the spring and the "vertebral body". The mobility of the joint must also be twice as extensive, with half the number of joints to ensure the total range of motion. The advantage, however, is that greater distance between the joints in one plane provides an opportunity to create mobility in the other planes. However, it also creates conditions placing high demands from a packing and strength point of view, as the space is severely limited along the spine. The distribution of mobility was tested in several different configurations. TABLE 28 shows a working configuration from a packing point of view.

In this configuration, the cervical spine is limited to one plane, similar to the BioRID II, but with fewer joints. According to previous studies (SARALE, 2004), a working 3D cervical spine would require five individually controlled wires, which technically is outside the scope of the ViVA II project.

[2] The ViVA II project was funded by the Swedish Innovation Agency, Vinnova. For more info about the project, see the Vinnova website at https://www.vinnova.se/p/viva-ii--virtual-vehicle-safety-assessment-step-2-open-source-human-body-models-and-crash-testing/

Table 28. Comparison of overall spine movement for BioRID, ViVA II and the Kapandji study.

	BioRID	ViVA II 3D			Kapandji (standing)[3]		
	Ext/FLex	Ext/Flex	Lat Flexion	Rotation	Ext/Flex	Lat Flexion	Rotation
Lumbar							
Vertebra joints	5	3	2	0			
Angle / joint	10° / 5°	±12.5°					
Angle total	50° / 25°	±37.5°			25° / 60°	20°	5°
Thoracic							
Vertebra joints	12	6	3	3			
Angle / joint	±3°	±6°	6°	8°			
Angle total	±36°	±33°	18°	24°	25° / 45°	20°	35°
Cervical							
Vertebra joints	8	4					
Angle / joint	11.5° / 4.5°	20° / 9°					
Angle total	92° / 36°	80° / 36°			75° / 40°	35-40°	45-50°

A joint that stays in the designed original position and does not change characteristics over time, is required for multiple, repetitive testing. The characteristics of the joint must be progressively resilient to the initial position to provide a realistic response during testing. This can be solved with an ordinary rubber element, but from the perspective of repetitive testing, it is not technically possible.

An undesirable property is present in all filled rubbers, created by interstitial bonds. Smaller atoms "get stuck" between the larger molecules. The process takes up to 24 hours and during that time the material changes its mechanical properties. At this stage it would be inappropriate to run a test, as the material becomes softer once it has been stretched. The most sensitive varieties lose up to 50% of their stiffness if stretched to a sufficient extent. The dummy's repetitive properties would not meet the requirements.

The unfilled materials that resemble rubber, such as polyurethane rubber, also do not have the properties allowing them to be used without additional support for long-term loading. After a long period of constant load, the material develops permanent deformation and never returns to its original state. However, in temporary load cases the material works well to create the right properties of the joint.

With half the number of joints compared to a human, there are few mechanical springs that can be incorporated to manage the required angular mobility of the joints. Several different attempts at simple solutions were tried unsuccessfully. The BioRID spine has approximately twice as many joints and the movement of each joint was relatively limited. The torsion bars used were about 70mm long, and would have to be about 140mm long, to achieve the same mobility with half the number of joints. However, it would not be possible to incorporate this into the spine, nor would a coil spring suffice without bottoming out or overloading.

[3] (Kapandji, 1974)

Hence, the solution is a new type of spring that is cut out like a U from a plate. The spring can be easily manufactured with sheet metal cutting equipment and thus quickly varied as needed and is relatively easy to integrate. Further, it can handle large angles within its work area (FIGURE 64).

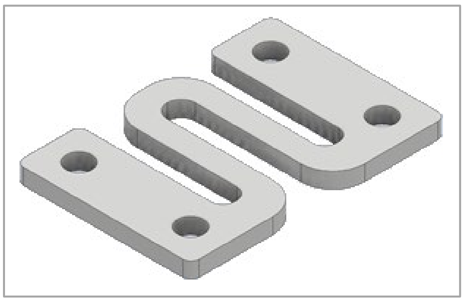

Figure 64. A U-shaped spring can be rotated along a longer distance and can thus handle large angles.

A complete joint with resilient rubber elements unloaded in the neutral position was designed as a test to see if the solution was feasible (FIGURE 65).

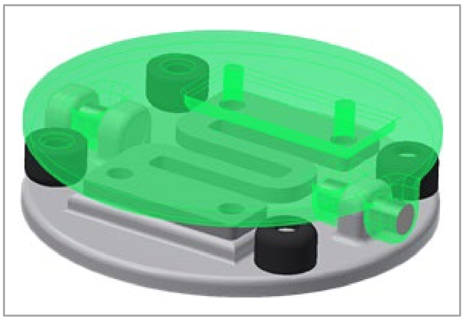

Figure 65. Joint suitable for the range of motion of the thoracic spine.

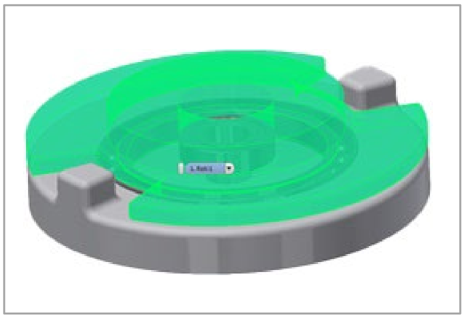

Figure 66. Rotary element for internal rotation of the thoracic spine.

To give the spine a possibility to rotate, a joint able to make the upper body rotate slightly around the spine was also created. In a human, this rotation mainly takes place in the thoracic spine as the lumbar spine would become unstable during a rotation. The chest gives support and the back can be turned (FIGURE 66).

All parts were then packed into the model (FIGURE 67).

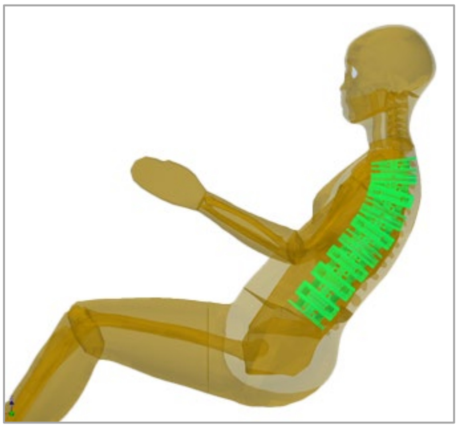

Figure 67. Sample packing of the thoracic and lumbar spine in the ViVA II F50 model.

Figure 68. Neck back with motion control elements placed inside the head of the ViVA II F50.

The design of the cervical spine is similar to that in BioRID but only has half the number of joints. In BioRID II, there is a damper and two springs a bit further down the thoracic spine that control the movement. This means that a load cell cannot be placed between T1 and C7 without losing load in the wires. Dampers and springs were tested for the new model in order to place it inside the head. If it transpires that the number of joints is too small to achieve the right movements at a later evaluation, this design can easily be modified with shorter distances and more joints. The movement between the individual joints is controlled with glued polyurethane elements that have been adapted between the "vertebral bodies". The cervical spine damper and springs have been placed inside the head facilitating placing a load cell between the cervical spine and the thoracic spine (FIGURE 68).

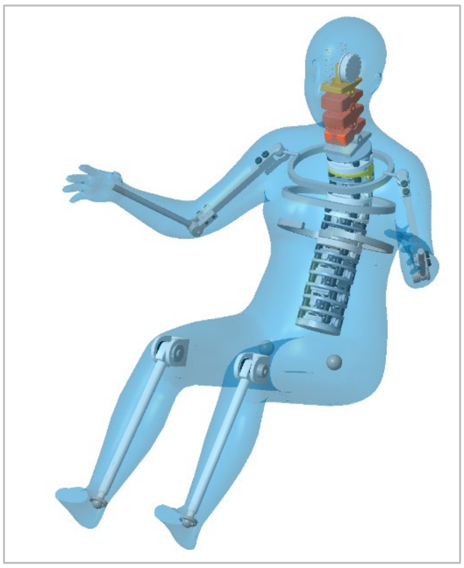

Figure 69. A simplified human-like spine.

The basic principles of the spine and neck from this skeleton (FIGURE 69) have been kept and refined throughout the VIRTUAL project.

Appendix E. SET body concept development

The first skeleton concept, inherited from the ViVA II project, consisted of a spine allowing 3D bend and rotation, a simplified rib cage with three ribs connected to the spine vertebrae and a simplified update of the BioRID neck design, improved with shorter wiring and fewer vertebrae. The basic principles of the spine and neck were kept and refined throughout the project.

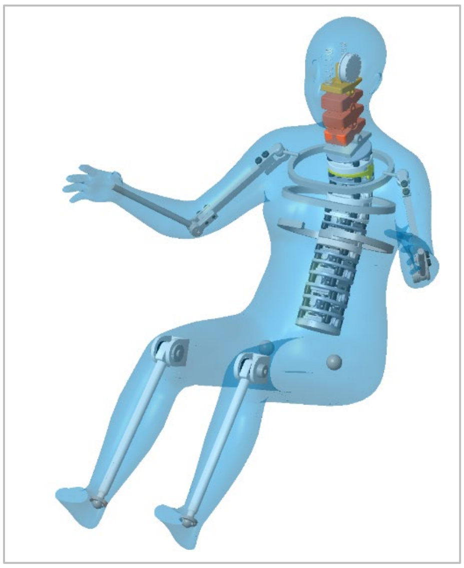

Figure 70. The ViVA II physical model.

Concept I: Segmented torso

During spring 2021, core skeleton parts were further developed, adding a more compact and production-friendly design to the vertebrae. A stiff shoulder bracket was connected to the T1 vertebra, with ball-joint mounting points for the arms. The ribcage was even more simplified with two ribs connected to the spine vertebrae, and a simplified pelvis skeleton was added with ball-joints for the legs. The two ribs of the simplified ribcage and the shoulder bracket acted as support for the torso segments. This way, the geometrical limits of the spine would also limit the movement of the torso segments (inspired by puppets, dolls, etc.). A human-like degree of freedom was applied to the hip joint, ranging from standing to seated positions (FIGURE 71).

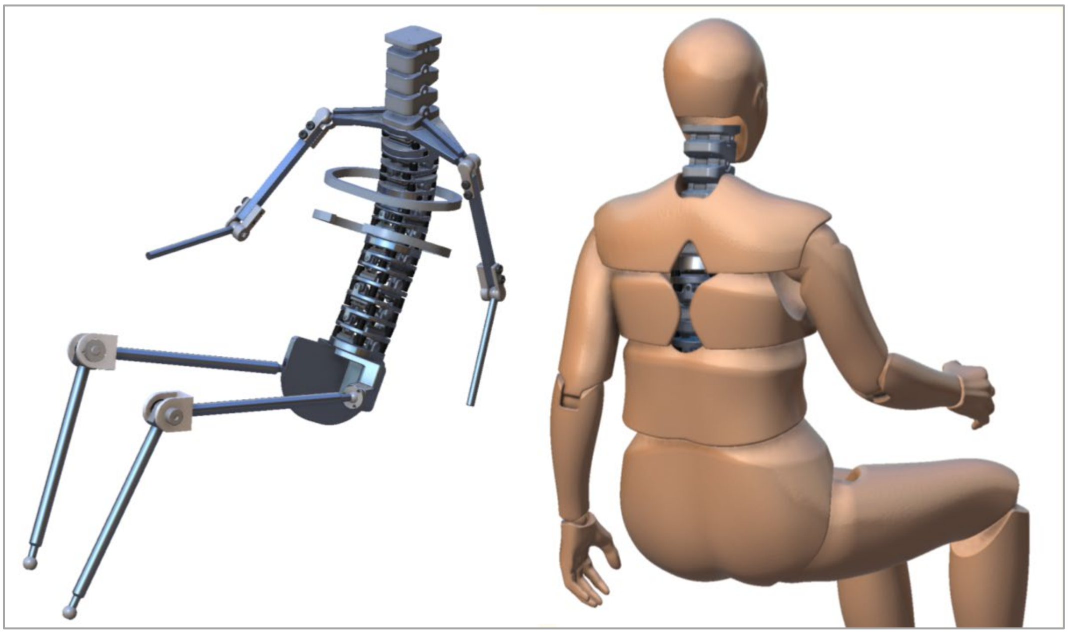

Figure 71. Concept I: The segmented torso; skeleton and body.

Analysis of the body movement highlighted the risk for unnatural movement of the torso. The solution with torso segments connected via ribs to single vertebrae would probably make the torso segments act as levers to their vertebrae, thus applying local bouncing and rotation forces in a non-human-like way (FIGURE 72).

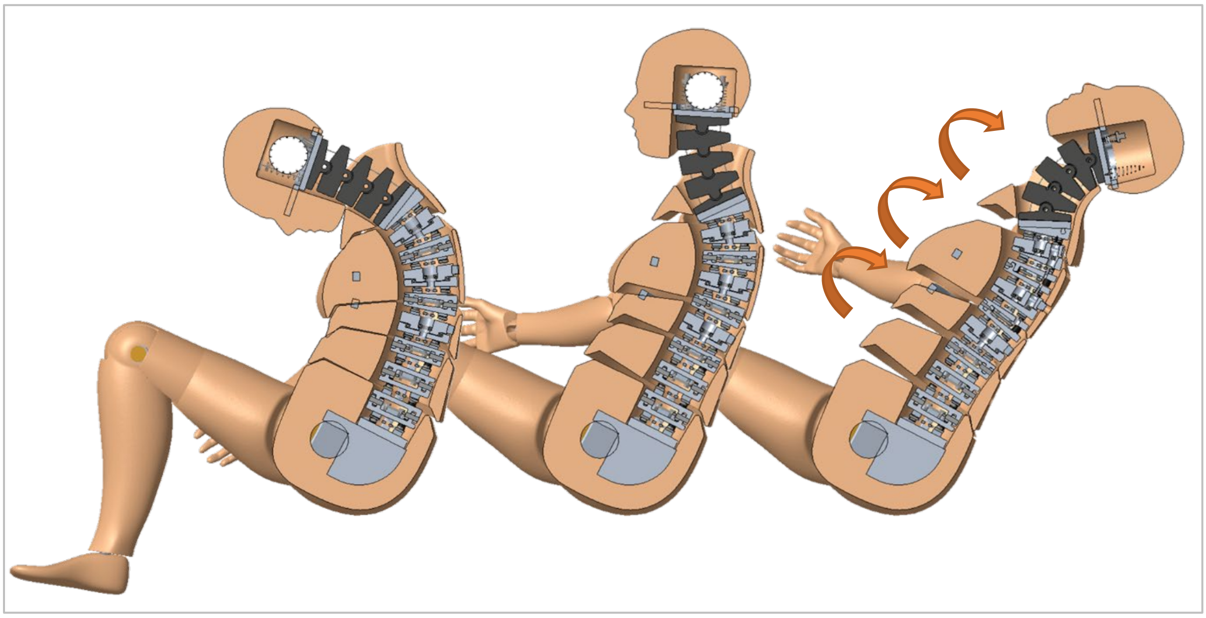

Figure 72. Concept I: Movement of the segmented torso.

Concept II: Multi-segmented torso

New concepts were made with further segmentation of the torso, splitting the torso both in the horizontal and frontal planes to decrease the weight of each segment and thus the moving weight. More complex geometrical connections, like three-point mounting, between body segments were added, to enable more controlled movement and decrease the risk of bouncing body segments.

Although a more segmented and connected torso would reduce the amount of "wobbliness", a complex mesh of joined torso segments would add the risk of sensor disturbance and would require a large amount of calibration time. To date, the body movement is still not human-like (FIGURE 73).

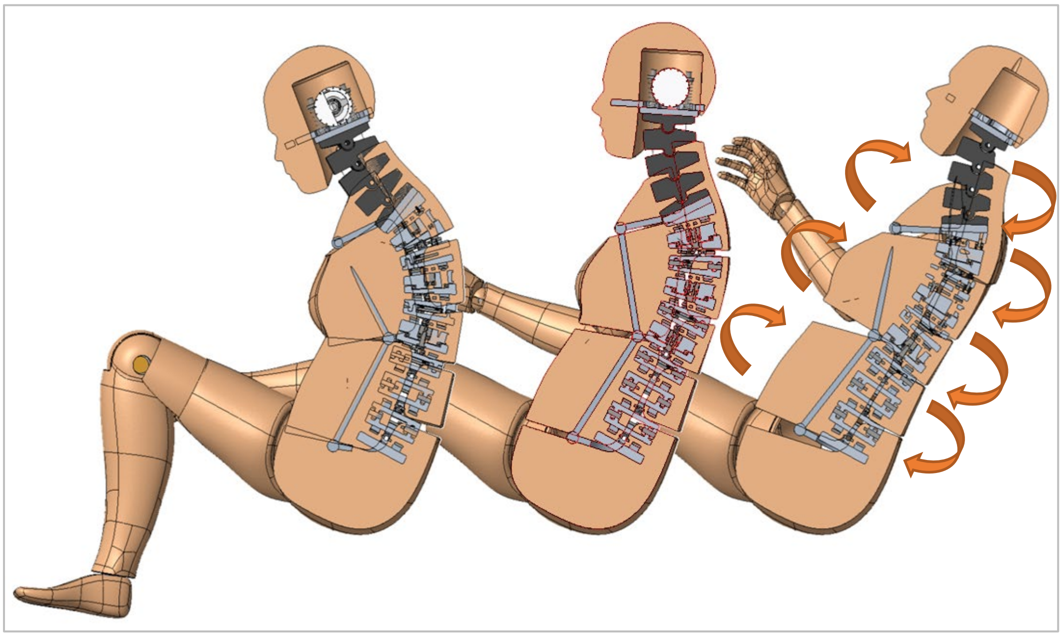

Figure 73. Concept II: Movement of the multi-segmented torso.

Concept III: The soft body

Looking back at the BioRID projects, it was decided to reuse and refine more of the engineering solutions therefrom. The concept of connecting the spine and the soft body with pins mounted to the spine vertebrae was reconsidered and, with a refined material selection for the soft body segments, found to be a suitable solution.

To save time and resources, it was decided to use standard Hybrid III parts for non-modified parts, such as the lower legs, lower arms, pelvis, and the head.

A first soft torso concept was made with a soft chest and back in one piece, connected to the spine vertebrae by pins. Between the chest and pelvis, an abdomen part was provided in even softer material.

Wishlist of features to be included (FIGURE 74):

1. Chest in PUR foam to enable spine movement
2. Abdomen in soft PUR foam to facilitate chest movement
3. Movable shoulders (THOR solution or similar)
4. Hybrid III F5 arms, modified brachii to match F50
5. Hybrid III/BioRID M50 pelvis
6. Hybrid III F5 legs, modified femur to match F50.

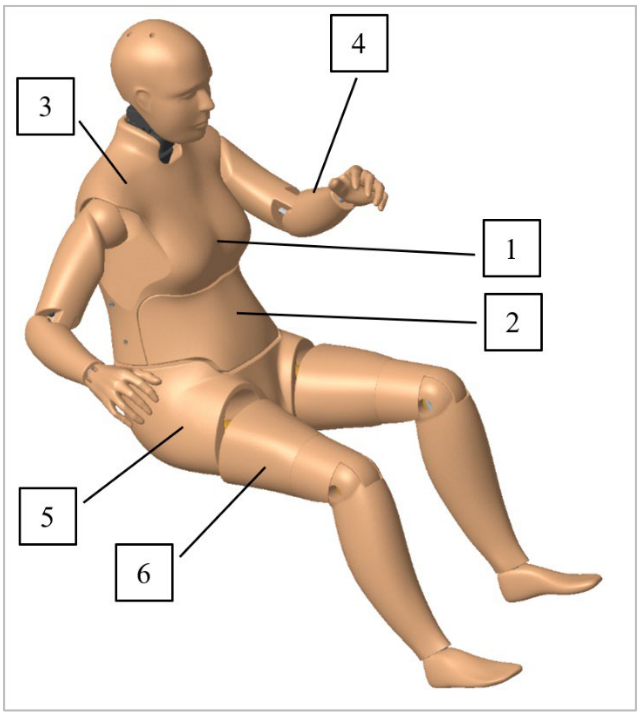

Figure 74. Concept III: The soft body, concept study.

With this design, the torso would most probably follow spine movement in a relatively controlled manner (FIGURE 75, note that the PUR foam flexibility is not represented by the CAD models). The improvement of the hip movement made to the BioRID pelvis was considered sufficient also for this project, since testing solely will represent a seated car occupant at low-speed impact. The soft body concept was considered to have the most significant development potential. A soft torso connected to the spine would facilitate human-like spine movement. It would be beneficial to keep working technical solutions from the BioRID project.

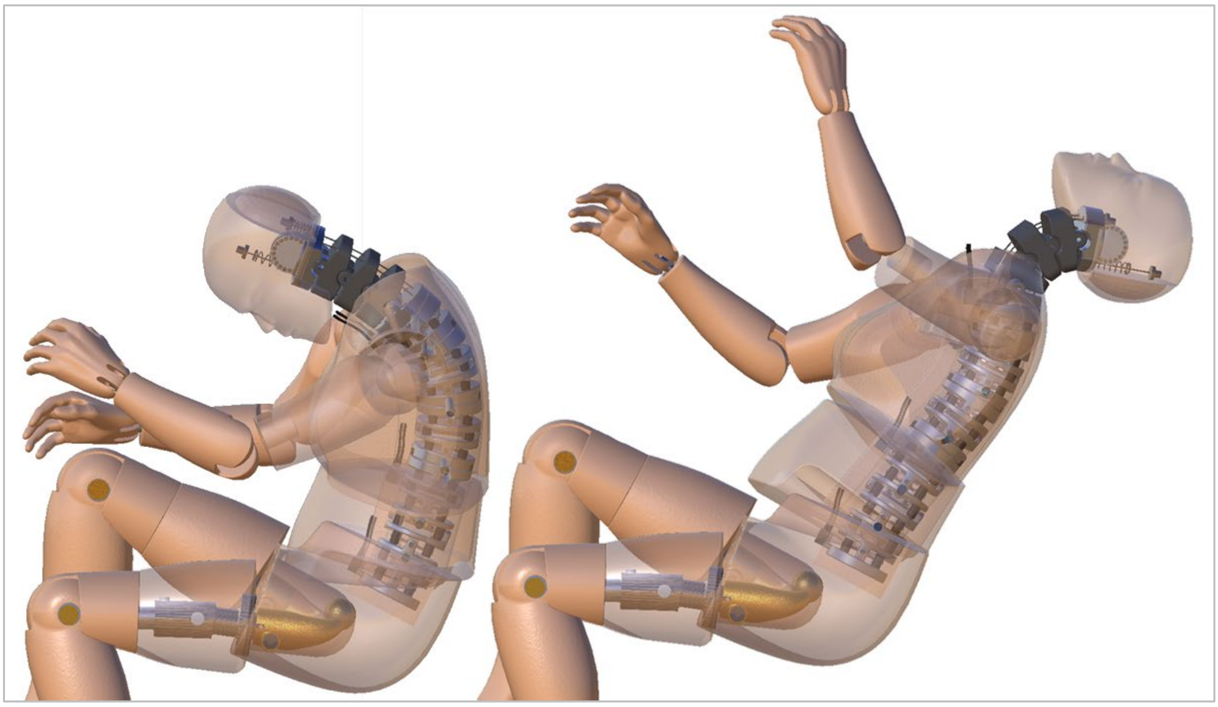

Figure 75. Concept III: Movement of the soft body.

Movable shoulder

The design of the moveable shoulder was inspired by the work of TÖRNVALL (2008) and designed for the intricate interaction with the car seat backrest, which is the target for the SETs. To simplify the shoulder mechanism (from that of TÖRNVALL (2008)), the following considerations were made: Since the scapula is essentially floating freely on the surface of the thorax, the clavicula is the main component in the positioning of the shoulder. A simple and robust mechanism could be created, where the clavicula has been reduced to a moving fixation point for the arm.

In a first shoulder concept, a combined joint enabled horizontal rotation of the shoulder as well as a vertical lifting rotation (FIGURE 76). Discussions (limitation to rear impact at low speed) led to the decision of focusing on the horizontal movement of the shoulder.

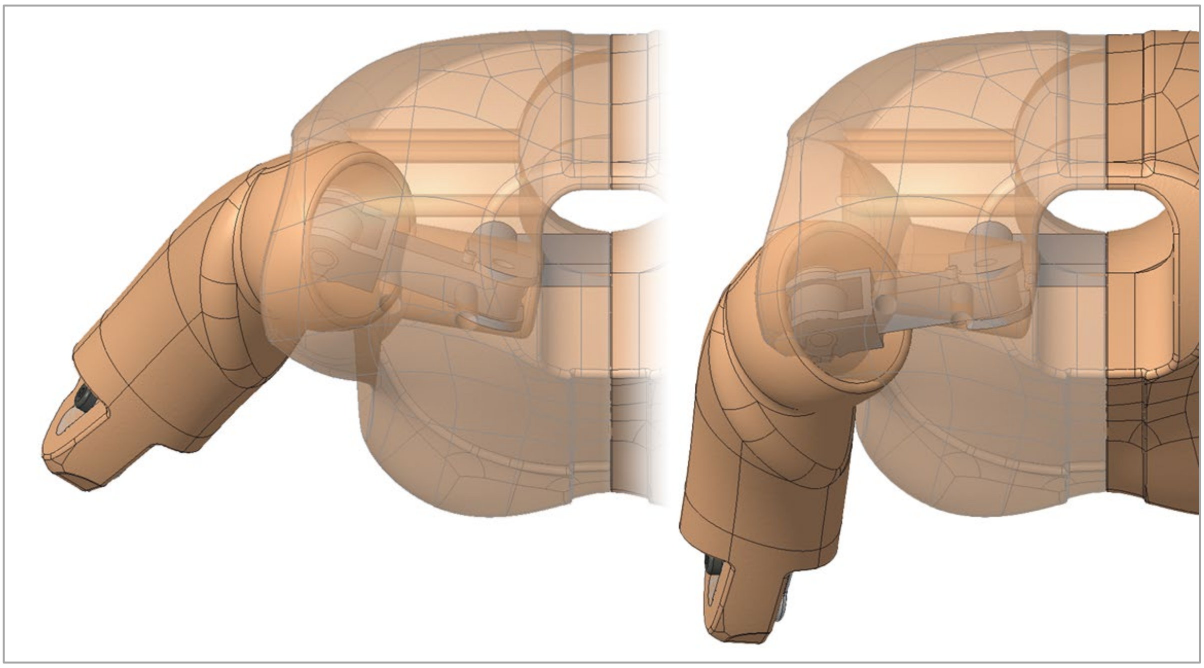

Figure 76. Shoulder concept I: Fully movable shoulder joint.

The following concept shows a shoulder only movable horizontally, connected to chest by a “sternum” plate in the split surface between the chest halves. A connection pin transfers shoulder movement to the soft chest part (FIGURE 77).

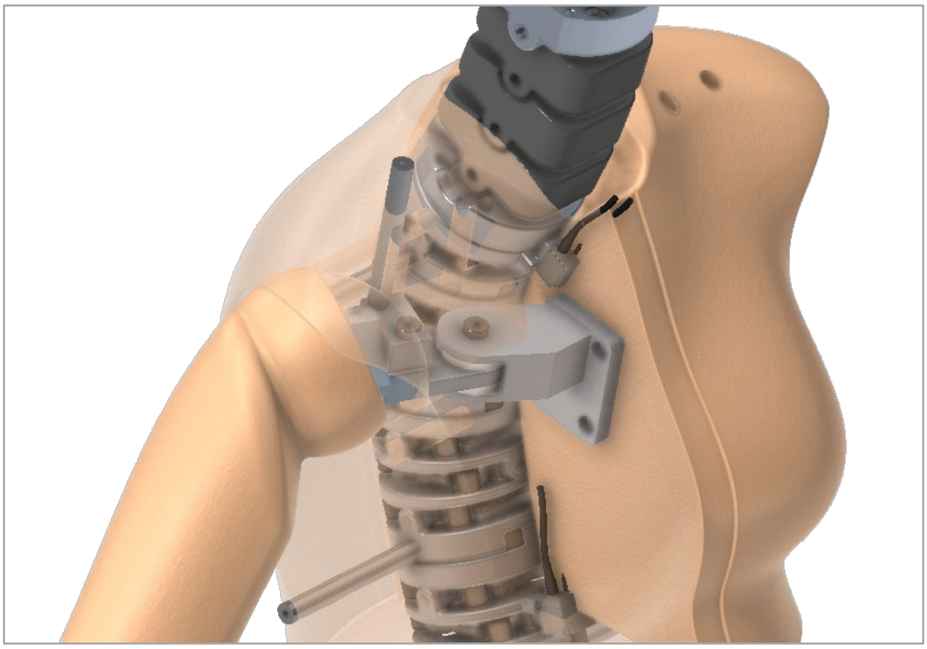

Figure 77. Shoulder concept II: Horizontal movement, fixed sternum.

A refined version of this solution shows a solution where the sternum is reduced to a connector between the left and right shoulder mechanism. The shoulders assembly is kept in place by the geometry of the soft chest and the shoulder movement is transferred via connecting pins. This solution is used in the SETs v0.1 (FIGURE 78).

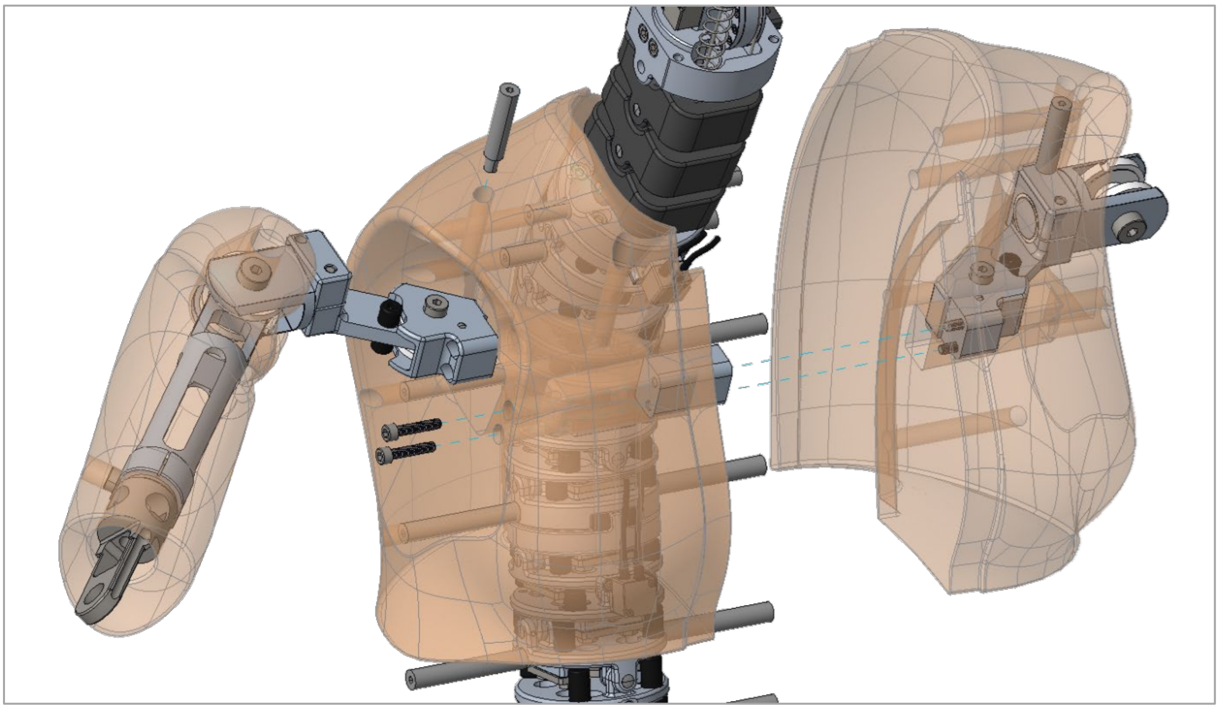

Figure 78. Shoulder concept III: Horizontal movement, free sternum.

Appendix F. Sled test evaluation

The SET 50M and 50F were run on the same seat as used in the volunteer tests described in LINDER ET AL (2013), and the impact pulse was reproduced in a sled with a rearward moving sled into a bending bar braking system. The sled that was used in the SET tests is located at VTI in Linköping, Sweden. The sled accelerates backwards into the braking system, and rails are used to guide the sled. The braking device is a yaw with a large number of vertical pins. Small steel rods are placed between these pins, forming a series of possible transverse openings. The steel rods are deformed in a controlled manner by the oncoming sled and the impacting frontal beam. The position within the braking device of steel rods, and the number of steel rods used, provides a controlled and repetitive deceleration pulse of the test sled.

A new measurement capability was created in the SETs compared to that of the BioRID. Four sensors with gyros together with three accelerometers (TE Connectivity model 633 six-degrees of freedom (6-DOF) sensor), were placed at three levels on the spine (T1, T8 and pelvis) and inside the head. The 633 6-DOF sensor is an analog sensor that includes outputs of three gyroscope/rate sensors and three accelerometers in one package. The gyros and accelerometers are aligned orthogonally to each other which allows the user to measure motions in all six-degrees of freedom. This made it possible to obtain the angular displacement from the measurement and through further development of the data from the sensors, also obtain horizontal and vertical motion.

The acceleration pulse in the volunteer test and test with the SETs are shown in FIGURE 79.

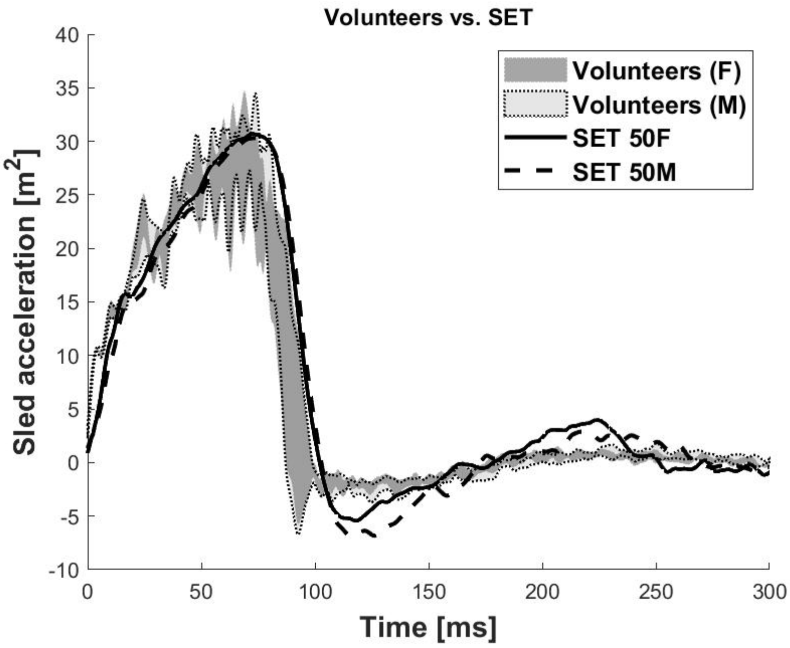

Figure 79. The sled acceleration in the tests with the SET 50F and 50M and the female and male volunteers.

The head, T1, and head relative to T1 responses of the male and female volunteers, and SET 50F and 50M, are presented below in FIGURE 80. In addition to the data in LINDER ET AL. (2013) the response of two females and one male volunteer who had no head restraint (HR) contact during the event, is shown in FIGURE 80 and FIGURE 81. The volunteers who did not reach HR contact are represented by the single curve, while the remaining volunteers who reached HR contact, have been included in the shaded response corridor (defined as mean ± 1 standard deviation).

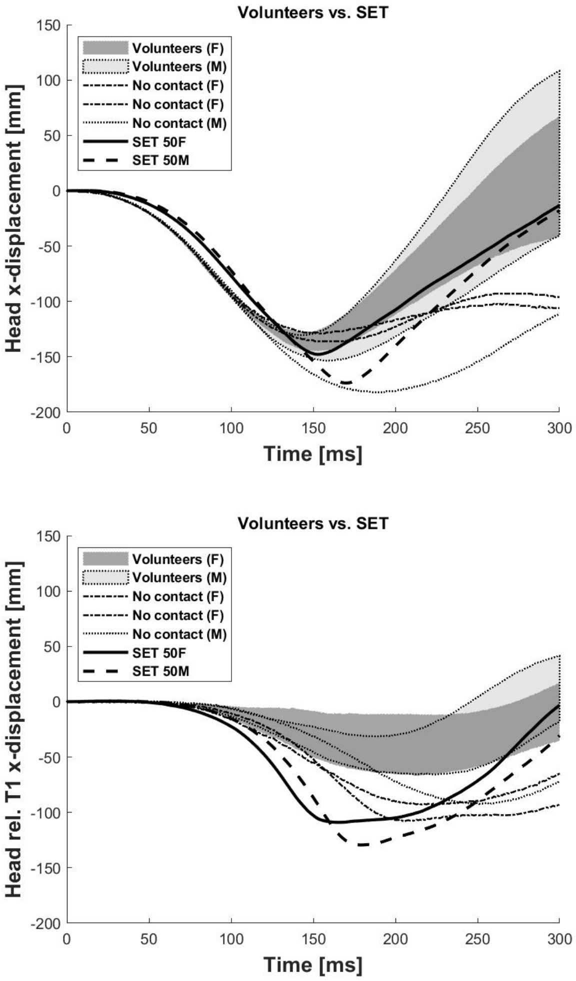

Figure 80. The head, T1, and head relative to the T1 x-displacement of the SET 50F and 50M and the male and female volunteers.

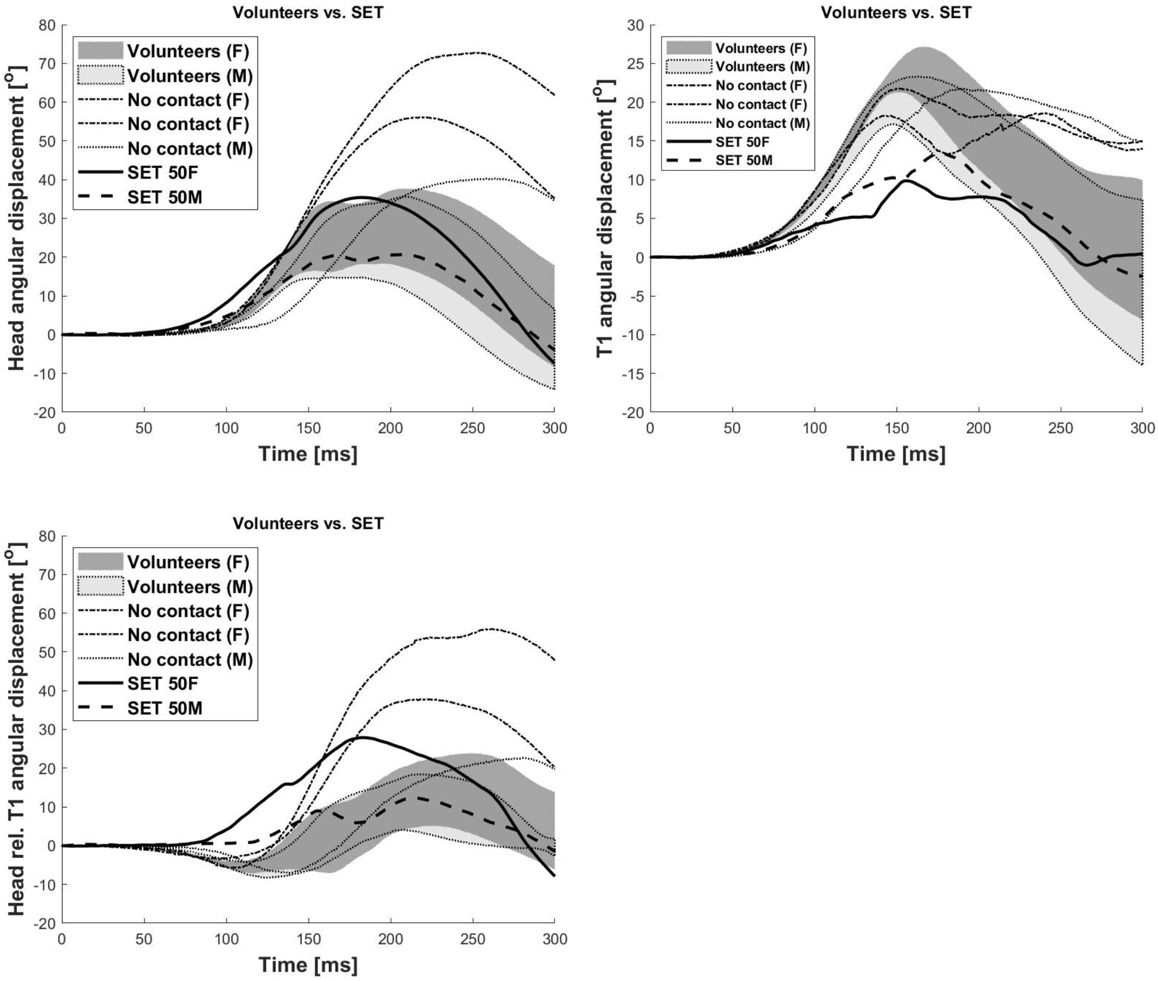

Figure 81. The head, T1 and head relative to the T1 angular displacement of the SET 50F and 50M and the male and female volunteers.

Observations

For the x-displacement, the response of the head of the SETs were similar to the corridors of the volunteers. The motion of the T1 of the SETs, had the same shape as the volunteers although the maximum x-displacement was lower. The same trend was observed for the angular displacement. It may be that the simplified neck with three vertebrae (compared to the seven vertebrae of the BioRID dummy) is too simplified to provide a human-like repose. Furthermore, in the SET v0.1 there were no damping between the vertebrae, which might also be needed. In addition, further analysis of the dynamic response of the abdominal region of the SETs would be required to identify how to achieve the response of the angular motion of the T1, closer to that of the volunteers.

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Our operations cover all modes of transport, and the subjects of pavement technology, infrastructure maintenance, vehicle technology, traffic safety, traffic analysis, users of the transport system, the environment, the planning and decision making processes, transport economics and transport systems. Knowledge that the institute develops provides a basis for decisions made by stakeholders in the transport sector. In many cases our findings lead to direct applications in both national and international transport policies.

VTI conducts commissioned research in an interdisciplinary organisation. Employees also conduct investigations, provide counseling and perform various services in measurement and testing. The institute has a wide range of advanced research equipment and world-class driving simulators. There are also laboratories for road material testing and crash safety testing.

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