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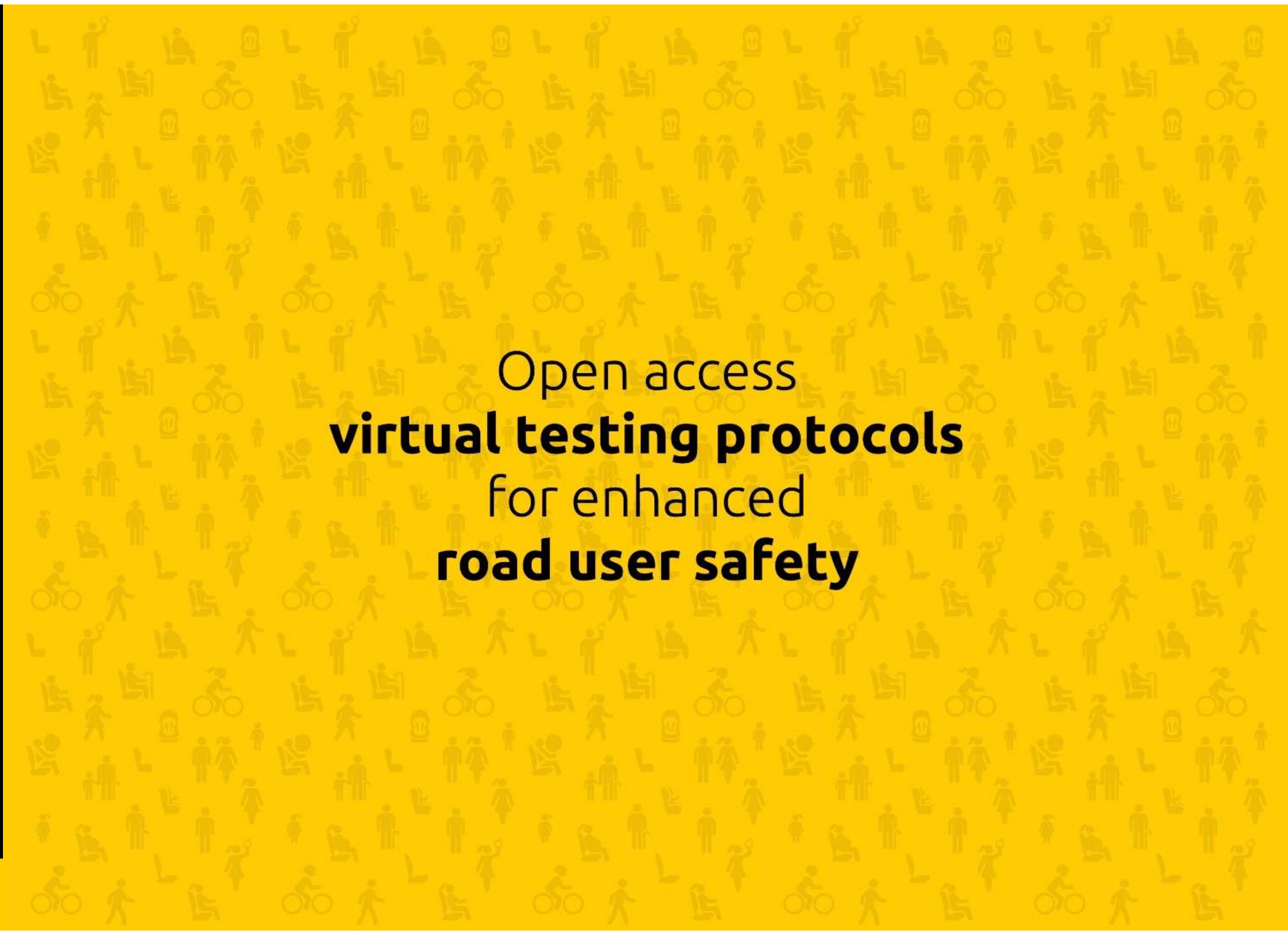

Description of safe operation envelope for erect passengers on public transport

WP number: 5
Deliverable: 5.2

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Executive summary

This deliverable of VIRTUAL summarises the work within the project's work package (WP)5. The lead beneficiary for this WP is VTI, and the specific contributions by VTI, UL, TU Graz, Chalmers, Siemens and UPM are found in each chapter of the report. The objective has been to investigate a safe operation envelope for erect passengers on public transport using open source (OS) Human Body Model (HBM) simulations. In addition, the characteristics of braking and acceleration in public transport which results in injury due to falls of erect passengers has been investigated. The deliverable describes the systematic approach from accidentology to test case simulations with the VIVA+ Standing Passenger HBM (denoted as VIVA+ SP), providing necessary insights into how to increase standing passenger safety on public transport. Suggestions for future work have also been provided.

Chapter 1 provides an overview of the injury statistics and scenarios among standing passengers on public transport. The objective of Chapter 2 was to describe how volunteer data was gathered during braking and acceleration perturbations on public transport. The aim was to both identify different balancing strategies and to provide input data for the development of active HBMs. Volunteer tests to obtain balancing responses were conducted by subjecting 11 females and 13 males to defined perturbations, serving as input data to the VIVA+ models, representing an erect female and male passenger on public transport. Furthermore, balancing strategies were identified and characterised through video analysis of the volunteer tests together with acceleration and jerk magnitude thresholds to limit the risk of falls. The analysis showed no differences between female and male volunteers regarding strategies and ability to maintain balance. The volunteer tests showed that adopting a stance providing the option of lowering the centre of gravity (CoG) and making adjustments by taking smaller steps, represented the most successful stance when aiming to maintain balance on a moving platform.

The volunteer data supported the development of the VIVA+ SP as a standing passenger HBM in Chapter 3. This was done by analysis of the motion of the volunteers using OpenSim, which provided the motion pattern while aiming to maintaining balance for the active response of the VIVA+ SP model (details can be found in Appendix 1). In Chapter 3, the suitability of the VIVA+ models to conduct simulations of standing passengers on public transport for virtual testing (VT) is also demonstrated. In addition, Chapter 3 provides a test protocol for VT of standing passengers on public transport based on the results from the accidentology in Chapter 1 that describes the critical scenarios related to injuries caused by loss of balance. The protocol provides a process to assess the risk of injury for specific loading and occupant positioning. The main accidents of interest include contacts of the head and the chest of a passenger to parts of the vehicle interior while falling forward in their orientation (which is not necessarily the direction of travel of the vehicle). Simulations of a standing passenger without contacting the vehicle interior provide an excursion envelope that is used to position the HBM relative to an interior structure of interest. Standard biomechanical injury assessment metrics can be applied to the output of the model. The VIVA+ SP is freely available on the OpenVT platform created within VIRTUAL at https://openvt.eu/load_cases/standing_passenger, which will be continuously available after the end of the VIRTUAL project (November 2022).

This deliverable suggests steps towards identifying a safe operation envelope for standing passengers on public transport. Each chapter includes a description of the conducted work and how the main results contribute to a description of a safe operation envelope for standing passengers. As a final dissemination activity, four presentations were given at the Public Safety conference in Warzaw, 17-18 May 2022. A concluding discussion on what the WP5 results entail for the safety of standing passengers on public transport is provided at the end of the report, together with identified possible future work. The appendices provide more details on the content described in the chapters.

List of abbreviations

ANOVA	Analysis of Variance
CoG	Centre of Gravity
DSS	Decision Support System
EMG	Electromyography
Euro NCAP	European New Car Assessment Programme
FE Model	Finite Element Model
HGV	Heavy Goods Vehicle
HBM	Human Body Model
HIC	Head Injury Criterion
IK	Inverse Kinematics
MatLab	A programming language and numerical computing environment
OpenSim	A freely available software
OpenVT	Open Virtual Testing platform developed in VIRTUAL
OEM	Original Equipment Manager
OS	Open Source
RRA	Reduced Reaction Algorithm
RSP	Reduced Standing Passenger
SP	Standing Passenger
TRC	A trajectory file
TSI	Technical Specification for Interoperability
VIVA+	OS HBM in the VIRTUAL project
VIVA+ 50F	VIVA+ 50th percentile female model
VIVA+ 50M	VIVA+ 50th percentile male model
VIVA+ SP	VIVA+ Standing Passanger

VRU	Vulnerable Road User
VT	Virtual Testing
WP	Work Package

1. Accidentology of erect passengers on public transport

Arne Keller, Simon Krašna, Ary P. Silvano, Maria Rizzi (former Ohlin), Philipp Heinzl, Corina Klug, Robert Thomson, Astrid Linder

To investigate the critical scenarios causing injuries to public transport passengers, real-world data analysis and state-of-the-art literature studies were conducted. This resulted in two open-access journal publications on accidentology of erect passengers (Silvano and Ohlin, 2019; Elvik, 2019). The derivation of acceleration pulses for preparation of volunteer experiments has been presented in detail in Deliveable 5.1 of the VIRTUAL project (Xu et al. 2021a), and submitted to a special issue of Frontiers in Future Transportation journal. Below, the publications are briefly presented, providing context regarding the progress of work in WP5.

The main contributions from WP5 regarding accidentology of standing passengers include: (1) a synthesis of 11 published studies about the risk of non-collision injuries (Elvik, 2019) and (2) investigattion into the characteristics of events connected to driver manoeuvres, i.e., acceleration or braking, passenger conditions, i.e., boarding, travelling, alighting, and injury severity from accident data (Silvano and Ohlin, 2019). The studies highlight that injuries to occupants on public transport can occur, despite generally being considered a safe mode of transporation, and that there is a risk of loosing balance due to perturbation during regular operation. These published studies not only provide new analysis of accident data in the state-of-the-art literature regarding bus passenger safety, but also the background for the identification of volunteer sled tests (presented in Chapter 2) as well as the development of standing passenger HBMs (presented in Chapter 3). A third publication (currently under review) describing acceleration pulses during public transport operations served as input to the volunteer sled tests.

1.1 Background and scope of testing

The sub-chapters below describe the background and scope of the volunteer studies in Chapter 2 as well as the published studies to provide updated accidentology of standing passengers.

1.1.1 Injuries to standing passengers

The safety of public transport passengers is not as extensively covered in the literature compared to other transport modes. As an example, the SAFETYCUBE (2015-2018) project produced a comprehensive tool describing safety issues and their countermeasures; the Decision Support System (DSS) (2018), which is based on reviews of over 1,200 scientific articles. However, only three references were reported regarding injury mechanisms for passengers of buses and coaches. Furthermore, rail-based transport was outside the scope of the SAFETYCUBE project. Bus and coach safety publications were not as available as those for passenger cars, Heavy Goods Vehicles (HGVs) and Vulnerable Road Users (VRUs). Bus safety, primarily for seated passengers, has been the topic of the studies in ECBOS (2006). These studies focused on bus rollovers, the use of seatbelts, and bus glass structure (safety glass) to reduce ejections and other injury mechanisms. An international review of bus passenger safety by Pedder (200) is an example of non-collision injuries seldom being the focus of bus injury studies.

Another example of bus safety analysis omitting standing, and non-collision events was reported by Prato and Kapland (2014), modelling crash severity and passenger injury. This study relied on police reported data which excludes non-collision events and injury details on different body regions.

Some researchers have identified further scenarios beside collision events as relevant for study, and Kendrick et al. (2015) have provided an overview of studies directed towards non-collision events and older passengers. Their findings highlight the incidence of injuries occurring during braking and acceleration events of a bus.

Buses and trams are comparatively safe transportation modes (compared to passenger cars and motorcycles, for example) and reported to represent less than 1% of European fatalities, based on injury statistics reviews by Alberstsson & Falkner (2005) for public transport passengers, see Figure 1-1 for bus and HGV related fatalities in Europe ERSO (2018). They noted that earlier research identifying a division of injuries related to collision events and non-collision events. The latter is an issue as vehicle operation may cause passengers to lose balance and fall, resulting in injuries that would generally not be classified in road safety statistics. Video camera recordings on-board buses in London, England, have been studied, identifying injuries caused by sudden, non-collision manoeuvres for both standing and seated passengers and that passengers holding onto handrails could still strike interior objects causing injuries (Edwards et al. 2019).

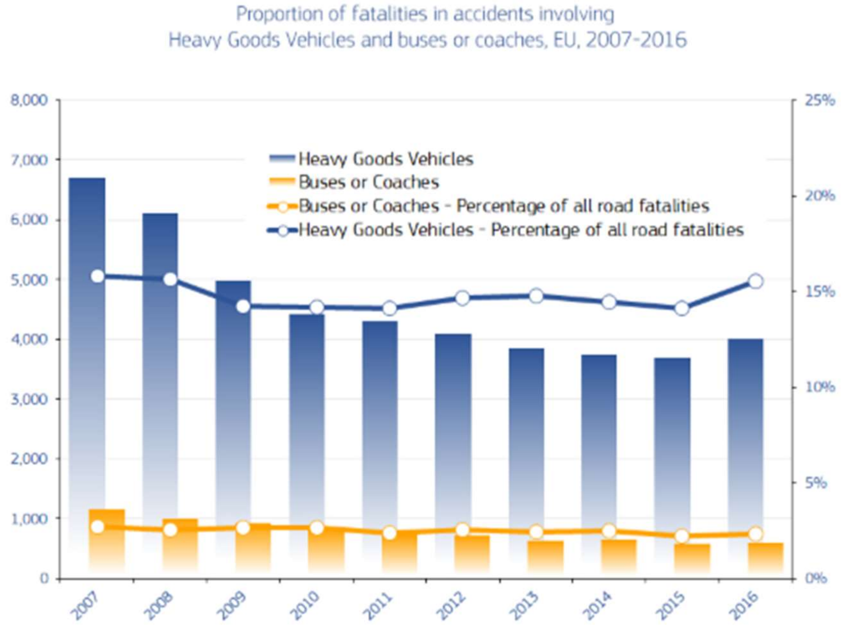

Figure 1-1: Bus and HGV fatalities in Europe (ERSO, 2018). Approximately 30% of these fatalities are pedestrians.

A literature review was conducted within the VIRTUAL project to investigate the balance of standing passengers in public transport and their response to sudden disturbances, such as the bus braking. Two studies were found, Robets (2006) and Martin & Litwhiler 2008), that analysed quantitative information on passenger response and comfort during transport operations. An overview of balancing strategies was provided by Robert (2006), highlighting how different muscle groups are engaged when a standing passenger tries to maintain balance on a moving platform. The strategies have two key phases, first the ankle, knee, and hip joints try to coordinate a favourable position of the body's CoG without moving the feet, and subsequently a stepping phase that adjusts the CoG through new placement of the feet.

1.1.2 Standards directing public transport vehicles

The construction of public transport vehicles such as buses and trams are directed by different mandatory and voluntary regulations and standards. VIRTUAL is focused on personal injury prevention, thus prioritising the standards addressing safety.

Table 1-1 is an overview of the standards defining the interiors of vehicles that standing passengers may impact or affect the vehicle's general safety performance.

Table 1-1: Standards for public transport vehicles design and construction

EN 45545	Fire protection on railway vehicles
EN 12663	Railway applications; structural requirements of railway vehicle bodies
EN 15085	Welding in railway vehicle construction
UIC 566	Loadings of coach bodies and their components
DIN 6701	Adhesive bonding of railway vehicles and parts
Commission Regulation No 1300/2014	Technical Specification for Interoperability (TSI); accessibility for persons with disabilities and persons with reduced mobility
EN 60721	Classification of environmental conditions
ISO 2768	General tolerances
DIN 25201	Design guide for railway vehicles and their components – bolted joints
UNECE 107	General construction requirements for buses

The standards in Table 1-1 indicate that interior structures for road or rail vehicles have general requirements for designing the interior for seated or standing comfort, yet no explicit requirements for safety can be identified for standing or seated passengers. Any interior design requirements to reduce injuries would be customer requirements in a purchase order and are not likely to be included, as the increased production costs over the legal requirements may not be feasible for most customers.

1.1.3 Test scenarios related to injuries

There are many different causes of injuries when impacting the interior of public transport vehicles. A process to assess testing scenarios for the testing application was developed and carried out by the partners of VIRTUAL. The review of injury types and causations led to a table of possible scenarios subsequently evaluated in a pairwise analysis, allowing the scenarios to be weighted according to occurrence rate. In addition, the feasibility of using virtual tools to simulate and evaluate the consequences in situations described by the various scenarios was identified. A list of all possible scenarios, and their justification, was created, see Table 1-2.

The basic idea of pairwise comparison (Institut für angewandte Arbeitswissenschaft, 2019) is to compare aspects or variants of an issue in pairs. This makes it easier to compare two aspects at the time to ultimately make a priority list for all aspects. The reduced complexity of the process also facilitates the focus on a single question. By interviewing several participants, the individual errors of the estimators can also be compensated for.

A team within the VIRTUAL consortium developed a list of potential scenarios that could lead to injury when a standing passenger falls during a non-collision event. Table 1-2 lists the 11 possible accident scenarios, where certain similar scenarios have been grouped as variants of a scenario, i.e., scenario 1a) and 1b). The scenarios were arranged in a square matrix with identical labels for the rows and columns (Table 1-3). This allows one scenario in a row to be compared separately with all other possible scenarios. Only the cells above the diagonal are filled in with the assessment of the VIRTUAL team. The diagonal contains no information (as it compares the scenario to itself) and has been blacked out in Table 1-3. The team were asked to use three values, where "2" means that the scenario in the row is more frequent than the scenario in the column. A "1" means that they occur at an equal rate and "0" indicates that the row scenario is less frequent than the column scenario. To correctly assess the scenario weightings, the diagonal opposite cell has been updated so that the sum of the two cells is “2”. These values are calculated for each row and displayed as normalised weighting (proportion of the total). This is intended to filter out the scenarios that occur most frequently.

Table 1-2: Scenarios defined by the team

1a	Slip/tilt backwards - Hit vertical surface (vehicle component)
1b	Slip/tilt backwards - Hit horizontal surface (vehicle component)
2a	Stumble/fall forwards- Hit vertical surface (vehicle component)
2b	Stumble/fall forwards - Hit horizontal surface (vehicle component)
3a	Fall to the side in a curve - Hit vertical surface (vehicle component)
3b	Fall to the side in a curve - Hit horizontal surface (vehicle component)
4	Struck by adjacent passenger falling
5	Struck by falling object
6	Slip/tilt backwards - Hit cargo/other object
7	Stumble/fall forwards- Hit cargo/other object
8	Fall to the side in a curve - Hit cargo/other object

A group of 10 participants from the VIRTUAL project, eight from industry and two researchers, completed the form based on their experiences. The average results are shown in Table 1-3.

Table 1-3: Evaluated standing passenger injury scenarios using pairwise comparison of occurrence.

Nr.		Slip/tilt backwards - Hit vertical surface (vehicle component)	Slip/tilt backwards - Hit horizontal surface (vehicle component)	Stumble/fall forwards- Hit vertical surface (vehicle component)	Stumble/fall forwards - Hit horizontal surface (vehicle component)	Fall to the side in a curve - Hit vertical surface (vehicle component)	Fall to the side in a curve - Hit horizontal surface (vehicle component)	Struck by adjacent passenger falling	Struck by falling object	Slip/tilt backwards - Hit cargo/other object	Stumble/fall forwards- Hit cargo/other object	Fall to the side in a curve - Hit cargo/other object	**Sum**	**Normal. weighting [%]**
1a	Slip/tilt backwards - Hit vertical surface (vehicle component)		1,3	0,9	1,4	0,8	1	1,2	1,8	1,3	1,5	1,3	**12,5**	**11,4**
1b	Slip/tilt backwards - Hit horizontal surface (vehicle component)	0,7		0,7	1,2	0,5	1,1	0,8	1,4	1,1	1,1	0,8	**9,4**	**8,5**
2a	Stumble/fall forwards - Hit vertical surface (vehicle component)	1,1	1,3		1,2	1	1,3	1,3	1,8	1,7	1,3	1,4	**13,4**	**12,2**
2b	Stumble/fall forwards - Hit horizontal surface (vehicle component)	0,6	0,8	0,8		0,7	0,8	0,9	1,4	1,3	0,9	1	**9,2**	**8,4**
3a	Fall to the side in a curve - Hit vertical surface (vehicle component)	1,2	1,5	1	1,3		1,7	1,3	1,7	1,7	1,2	1,2	**13,8**	**12,5**
3b	Fall to the side in a curve - Hit horizontal surface (vehicle component)	1	0,9	0,7	1,2	0,3		0,8	1,3	1,4	0,8	0,9	**9,3**	**8,5**
4	Struck by adjacent passenger falling	0,8	1,2	0,7	1,1	0,7	1,2		1,6	1,4	1,1	1,2	**11,0**	**10,0**
5	Struck by falling object	0,2	0,6	0,2	0,6	0,3	0,7	0,4		0,4	0,4	0,6	**4,4**	**4,0**
6	Slip/tilt backwards - Hit cargo/other object	0,7	0,9	0,3	0,7	0,3	0,6	0,6	1,6		0,9	0,9	**7,5**	**6,8**
7	Stumble/fall forwards - Hit cargo/other object	0,5	0,9	0,7	1,1	0,8	1,2	0,9	1,6	1,1		1	**9,8**	**8,9**
8	Fall to the side in a curve - Hit cargo/other object	0,7	1,2	0,6	1	0,8	1,1	0,8	1,4	1,1	1		**9,7**	**8,8**
												SUM	**110**	**100,0**

1.1.4 Prioritisation of Scenarios for Virtual Testing Protocol Development

The results from the pairwise comparison identified three prominent scenarios. In order of ranked priority, Scenarios 1a, 2a, and 3a involve passengers losing balance and contacting a vertical surface. These vertical surfaces may be a wall, window, handrail, etc. Even the fourth scenario, contact with another passenger, is a common scenario that can be connected to the top three scenarios as contact with a neighbouring passenger closer resembles Scenarios 1a, 2a, and 3a, than 1b, 2b, 3b, falling to the floor and striking a horizontal surface.

The orientation of the passenger in the vehicle was not included in the scenario descriptions. While it is common for people to stand facing the direction of travel, it is not unusual for standing passengers to face rearward or sideways. Scenarios 1a and 2a imply a passenger facing in the the direction of travel and thus the applied loading would cause fore-aft (sagittal plane) motions. Cornering causes predominantly lateral accelerations to the vehicle, and passengers oriented along the vehicle centreline would experience lateral motions. However, a sideways facing passenger would experience predominantly fore-aft accelerations during cornering, resulting in potential impacts with a window, handrail, or seat frame.

Some of the scenarios listed in Table 1-3 involved contacts with cargo or other passengers. When defining and running a simulation representing an interaction between a passenger and an interior object, it must be determined if it is the HBM's motion causing the interaction (especially if more than inertial motions such as movement of a limb are involved) or if the object falls on or strikes the HBM. Potentially harmful objects such as shopping bags, suitcases, etc., vary in size, mass, stiffness and most likely position in the vehicle. Therefore, to capture all relevant scenarios, many different potential objects and locations would have to be replicated, making the simulation testing requirements too comprehensive.

Complementary to the scenario definition, computer simulation experts assessed the feasibility of simulating the proposed scenarios within the scope of the VIRTUAL project and current state-of-the-art HBMs. A score of 1 to 5 was assigned to each scenario, 1 meaning "possible to achieve results within the time and resources of VIRTUAL" and 5 meaning "impossible." This score was multiplied with the ordinal ranking of the scenario, Table 1-3, to combine the occurrence rate of the perceived safety issue and the feasibility for demonstration in the VIRTUAL project.

A priority for developing testing protocols for standing passengers in the VIRTUAL project is shown inTable 1-4. Essentially, the first two cases represent the same situation depending on how much the lower extremities moves. The third case, falling in a curve, may have elements of the first two scenarios, but also involves a more complex lateral loading of the body. The focus of the research in VIRTUAL was on developing a test protocol for assessing safety related to the fore-aft balancing model of a passenger.

Table 1-4: Weighted priority for simulation of standing passengers

Scenario Number	Description	Simulation Feasibility	Ranking	Weighted Result
2a	Stumble/fall forwards - Hit vertical surface (vehicle component)	1	2	2
1a	Slip/tilt backwards - Hit vertical surface (vehicle component)	1	3	3
3a	Fall to the side in a curve - Hit vertical surface (vehicle component)	4	1	4
5	Struck by falling object	1	10	10
7	Stumble/fall forwards - Hit cargo/other object	2	7	14
6	Slip/tilt backwards - Hit cargo/other object	2	9	18
8	Fall to the side in a curve - Hit cargo/other object	3	6	18
4	Struck by adjacent passenger falling	5	4	20
1b	Slip/tilt backwards - Hit horizontal surface (vehicle component)	4	7	28
2b	Stumble/fall forwards - Hit horizontal surface (vehicle component)	4	8	32
3b	Fall to the side in a curve - Hit horizontal surface (vehicle component)	5	8	40

The subsequent sub-chapters (1.2. – 1.4.) describe three publications related to injuries of public transport passengers and a methodology to derive generic representative acceleration pulses for passenger safety testing. These publications served as motivation for the volunteer studies and balancing strategy analyses in Chapter 2 and, as mentioned above, the potential with virtual testing for standing passengers using HBMs which is presented in Chapter 3. Note that the development of the standing passenger models occurred in WP2 and is documented in Deliverable 2.5 (Thomson and Kranjec, 2021).

1.2 Risk of non-collision injuries to public transport passengers, Synthesis of evidence from eleven studies

The risk of non-collision injuries to public transport passengers was synthesised by Elvik (2019). This paper provides an overview of the current knowledge about injury frequency and risk among standing passengers and identified inconsistencies among studies in the state-of-the-art literature, describing distribution of non-collision injuries by severity. In this study, the mean risk of falling during travel was estimated to be 0.3-0.5 per million passenger kilometres, with a mean risk of injury during boarding or alighting at about 0.8-1.7 per million passengers. The estimates of risk were uncertain and varied substantially due to the limited number of studies. Little data was found to estimate variations in the number of non-collision events. Thus, Elvik concluded that there was too little data to identify the risk of non-collision passenger injury between different types of public transport.

1.3 Non-collision incidents on buses due to acceleration and braking manoeuvres leading to falling events among standing passengers

To understand injury scenarios in detail, this study by Silvano and Ohlin (2019) characterised falling events due to driver manoeuvres (acceleration or braking), passenger conditions, and injury severity.

A review of Swedish statistics of non-collision events (primarily derived from hospital data) led to the conclusion that most injury producing events were associated with boarding, stemming from the bus accelerating when leaving the bus stop. The second most common case involved falls associated with hard braking events during the journey or when alighting (or preparing to alight) from the bus. Similar to other injury statistics for public transit, elderly women were more often reported to be injuried (Kendrick et al. (2015). Details on how each event led to injury were limited to free-text comments in the database from individuals and witnesses. These data elements have not been reviewed or verified by professional investigators and lack important details, in particular the injury source for each injury. Although the location of the injury within the bus or tram was usually provided, similar details for the object struck were excluded (floor, handrail, seat, etc.). Furthermore, referring to the term as a “fall” may not be specific enough (Kendrick et al. (2015). One paper by Edwards et al. (2019) reported specific information on the object within the bus that caused injuries. The study analysed video data inside the bus to observe passenger responses during different conditions. The study identified that 76% of injured bus passengers had sustained their injuries in non-collision events. Impacts with the interior included the floor (20%), vertical handrails (19%) and partition panels (19%). Some of the injured standing passengers had been transitioning in or out of their seat and were more susceptible to fall during a sudden bus manoeuvre.

Overall, the acceleration/deceleration thresholds seem to differ by gender and falling mechanisms are dependent on driver manoeuvres and passenger conditions. The results are in line with previous studies that found that elderly female passengers were the most commonly injured. For example, older passengers (aged 65+) were often involved in a fall immediately after boarding, caused by acceleration manoeuvres. Similar, but for braking manoeuvres, falls were induced during travel but involved younger passengers (between 25-64 years old). The common factor between these age groups is represented by female passengers being injured more often than males. These findings suggest that acceleration and braking perturbations should be studied separately. It also highlights the need for further research regarding the dynamic responses of passangers during acceleration and braking related to exposure, gender and age.

Both Elvik (2019) and Silvano and Ohlin (2019) identified that critical events occur in free-standing passenger postures, where injury scenarios were induced by perturbations caused by driver manoeuvres during non-collision incidents and in non-emergency events.

A literature study was conducted to establish appropriate pulse magnitudes and generate acceleration pulses for passenger safety testing. The next sub-chapter describes a new method for generating representative pulses to understand human tolerance of perturbations similar to those encountered during normal operation of public transport.

1.4 Acceleration of public transport vehicles: a method to derive representative generic pulses for standing passenger safety testing

An analysis of available acceleration data showed that a set of pulses ranging from 0.1 to 0.3g were viable load cases for further investigating standing passenger safety in non-collision events. The literature review also presented a need to investigate the time history of the acceleration pulse and to include the jerk (m/s^3) to understand its effect on passenger balance. This sub-chapter describes the process of deriving generic acceleration pulses. These pulses can provide perturbation thresholds for balance recovery among standing passengers. Such knowledge is needed for safe normal operation of public transport. The methodology for the data analysis was based on the work by Kirchner et al. (2014), who suggested a Legendre expansion of isolated acceleration and deceleration events (so-called acceleration pulses). AGU and UL developed an automated splitting algorithm allowing the application of the Legendre method to larger data sets. Furthermore, a method for deriving representative average pulse shapes from a set of measured acceleration pulses without over-representing high magnitude events was proposed. To demonstrate this new methodology and to derive sample acceleration pulses, AGU measured acceleration signals on buses of the Zurich public transport network during normal operation. The resulting translational acceleration and braking pulses were used as input for the design of the test pulses applied during the volunteer tests described in the upcoming chapter. This work has been submitted as a manuscript by Keller and Krašna (2022), to a scientific journal.

A set of volunteer tests was designed to cover the lower range of pulses causing injuries identified in real crashes (Edwards et al., 2019) - 0.14 to 0.89g – and to cover the range of comfort for passengers identified by Hoberock (1976) - 0.11 to 0.15g. Therefore, sled experiments with volunteers subjected to different magnitudes of acceleration and braking, with varied jerk, were conducted at UL in collaboration with UL, TU Graz, AGU and VTI.

2. Volunteer tests to investigate the muscle response for HBMs and validation of HBMs of erect passengers onboard public transport

Simon Krašna, Jia-Cheng Xu, Arne Keller, Ary P. Silvano, Jiota Nusia, Corina Klug, Robert Thomson, Astrid Linder

As described in the previous chapter, accidentology into standing passengers on public transport was defined with respect to injury risk, driver manoeuvres, and passenger conditions. This provided necessary insight when acquiring more knowledge on biomechanical characteristics of postural balance during perturbations that occur during normal operation of public transport. The objective of the work described in this chapter was to evaluate how free-standing postural balance, i.e., without holding on to support aids such as handrails, is affected by acceleration perturbations of the support similar to that fitted on public transport. A free-standing position, such as during boarding and alighting, was found in the literature as the position where injuries most often occur. The next step was to obtain reference data on the active muscle responses in these events, however published data describing the kinematics of a standing passenger reacting to an acceleration perturbation is limited. Laboratory tests with volunteer participants standing on a platform (standing sled test) subjected to a translational motion were conducted, where the participants were facing or facing the opposite direction of travel. The participants were attached to a safety harness which prevented them from falling off the platform in case they lost their balance. Representative acceleration and braking pulses as described in the previous chapter were used. Details of the volunteer tests and recorded biomechanical responses are available as open-access publications in the journal Frontiers of Bioengineering and Biotechnology, Krašna et al. (2021) and Xu et al. (2021b). These papers were collaborative efforts including the partners VTI, AGU, TU Graz, UL, and Chalmers.

Volunteer tests were conducted with 24 volunteers (11 females and 13 males close to their respective 50th percentile anthropometry). The volunteers had a mean age of 33.8 years, representing a younger and healthy group. The tests were designed to identify acceleration and jerk thresholds for standing postural balance and were conducted at UL with assistance from AGU, TU Graz and VTI. The study was designed to include gender aspects with respect to different parameters of the applied perturbation pulses.

The volunteers were exposed to five different perturbations in forward and rearward directions on a linear translational platform. To ensure volunteer safety, a full-body safety harness and a cushion placed at a location on the platform where a fall could potentially happen was used (Figure 2-1). The volunteers were perturbed from a stationary position (both feet on the moving platform, hip wide apart) without any knowledge about the pulse characteristics. They were instructed to maintain a relaxed free-standing posture as they would as passengers on a bus.

Figure 2-1: Forward and rearward orientation of the volunteers on the sled with the safety harness attached.

The corresponding perturbation profiles were severe enough to exceed published passenger comfort levels and also of magnitudes that are typical during regular travel at non-collision incidents, to ensure that the volunteers were challenged to actively attempt to recover their balance. Furthermore, the pulses should be long enough to estimate whether the resulting body motions would put a real bus passenger at risk of colliding with the vehicle interior. Table 2-1 and Figure 2-2 illustrate the perturbation profiles and the sequence of their application, where *Br1* and *Br2* denote the braking pulses and combinations of *Acc*[1,2]-*J*[1,2] denote the different acceleration pulses, which differ in shape and can therefore evoke different muscle and kinematic responses of the passenger, possibly influencing the risk of injury.

Table 2-1: Perturbation profile characteristics

Profile name	Sequence	Magnitude	Rise time	Duration	Jerk	Displacement	Max. velocity
		m/s	S	S	m/s3	m	m/s
Br1	1	1.0	4.4	4.7	0.3	2.94	2.4
Acc1-J1	2	1.5	0.4	2.3	5.6	2.65	2.0
Acc1-J2	3	1.5	0.2	2.2	11.3	2.58	2.0
Acc2-J1	4	3.0	0.8	1.8	5.6	2.69	3.1
Br2	5	2.5	2.2	2.5	1.7	1.82	3.2

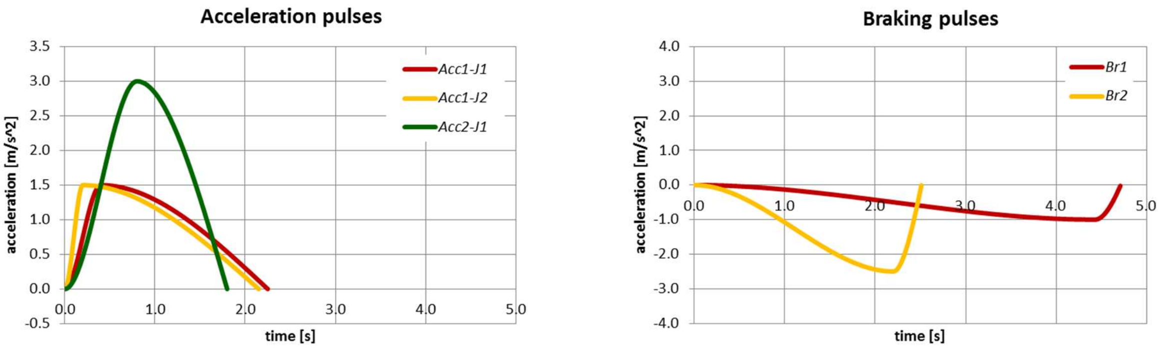

Figure 2-2: Perturbation profiles used in the volunteer tests.

The study of the volunteer responses was limited to the initial rise time of the braking pulses and to the duration of the acceleration pulses, before the start of the sled deceleration to bring the platform to a stop. As the bus braking and acceleration pulses were simulated in the same sled direction, a forward-facing volunteer experienced the accelerations similar to a passenger facing the direction of travel, whereas the braking pulses were experienced as if the passenger was facing rearward in the vehicle, opposite the direction of travel. The opposite was true for the rearward facing passenger.

The perturbations were chosen to assure the magnitudes of acceleration and jerk mimicked vehicle manoeuvres accelerating and braking during a non-emergency event. The data served as input data for the VIVA+ SP. Krašna et al. (2021) presented step sequences with identified contact-off, swing, and contact-on times, which were identified through high-speed video recordings. Furthermore, muscle responses through electromyography (EMG) measurements were presented. Two-way analysis of variance (ANOVA) was performed to examine the volunteer responses dependending on pulse type and direction. In general, the first recovery step was longer for braking than accelerating pulses. A connection between jerk and faster compensatory steps was seen, as the jerk was a more important factor than acceleration magnitude in the excitation of active muscle response, coherent with previous studies. In the acceleration range tested, higher magnitudes did not provoke faster recovery stepping. In terms of body orientation, rearward perturbations, i.e., the test subject facing the opposite direction of travel, induced more recovery steps.

As for acceleration thresholds, although the experimental setup was different from previous studies, the increasing harness deployment rate, i.e., unrecoverable loss of balance, with increased acceleration magnitude confirms that acceleration magnitude is a relevant factor for human postural balance. The identified acceleration threshold is in line with previous studies. The review of the safety standards and the expert panel evaluation of possible scenarios related to the occupant injuries (described in Chapter 1.1.2-1.1.4.), showed that free-standing occupants with forward and rearward orientation relative to the vehicle represent the worst-case scenarios, as well as the most likely case of accidents. Furthermore, the analysis of the results of the volunteer tests identified that pulse shape, magnitude and duration, are the most important characteristics of balance perturbations. The perturbation pulses used in the volunteer testing were defined by acceleration profiles consisting of cubic curves for the rise and the drop segments derived from the methodology by Keller and Krašna (2022). The cubic curves enable smooth transition between the segments and allow easy and repeatable modification of the profile characteristics, representing a suitable basis for defining generic pulses to be used in VT procedures and parametric HBM simulations, as well as in experimental studies.

The motivation for the volunteer tests stems from lack of available detailed data in the literature regarding human postural balance subjected to translational motion, comparable to perturbations occurring during normal operation on public transport. To complement the publication of the volunteer tests serie (Krašna et al. 2021), a qualitative study (Xu et al. 2021b) of the high-speed video recordings to characterise balancing strategies was conducted to understand the influence of acceleration and jerk on standing passenger safety. In short, a specific stance occurring during compensatory stepping was characterised in more detail to describe compensatory stepping as a coping mechanism for more severe perturbations. The recommended acceleration threshold to limit body displacement, and thus the need for compensatory stepping that might increase the risk of falling and impacting surrounding surfaces, was identified as 1.5 m/s^2. This is consistent with the quantitative findings from Krašna et al. (2021) and previous studies referenced in both publications.

Overall, this work provided new data and analyses with the application of postural balance to the field of public transport, where applied research for standing passenger safety. Also, in addition to the WP5 description of work covered by the activities above, a minor study utilising the volunteer data further was conducted by VTI through a quantitative analysis of the identified balancing strategies in Xu et al. (2021c), using an open-source platform for musculoskeletal modelling called OpenSim (https://opensim.stanford.edu/). This biomechanical simulation and analysis software could utilise motion capture data obtained from the volunteer tests (Krašna et al. (2021). This study was presented as a short communication at the IRCOBI conference 2021 (Xu et al., 2021c). More details about the process from raw experimental data to OpenSim kinematic output can be found in Appendix B. The outputs and insights from the work described in this chapter served as input for the development of the standing passenger VIVA+ HBMs, developing a controller to calibrate the standing VIVA+ models developed in VIRTUAL with the volunteer data.

3. Test specification for VT and simulation of erect passengers on public transport

Robert Thomson, Matej Kranjec, Christian Lackner, Philipp Heinzl, Luis Martinez, Raquel Peláez

3.1 Background and scope

The VIVA+ models are finite element (FE) models representing 50th percentile females and males, which are being developed to predict injuries to road users that may be sustained inside or outside a vehicle. This document describes the application of an erect standing passenger VIVA+ HBM – denoted VIVA+ SP - to virtual testing of a standing passenger in public transport during a sudden braking or acceleration event. The final version of the model will be provided on the OpenVT platform[1] developed by the VIRTUAL project members.

The model is based on the standing pedestrian model developed within the project. The standing model was developed in WP2 and adapted for applications in WP4 for pedestrians. This pedestrian model also provides the foundation for post-processing simulation output for injury risk assessment. The model was being enhanced in WP2 to include muscle activity to maintain an upright posture under the gravitational loading as well as the reflexive reaction due to a perturbation. The anthropometries of the VIVA+ models are shown in Table 3.1.

Table 3-1: Anthropometry of the VIVA+ models

Gender/Size	Height (m)	Weight (kg)	Age (year)
Average Male (50M)	1.75	76	50
Average Female (50F)	1.62	62	50

The VRU model developed for VIRTUAL is designed for high severity impacts from vehicle fronts (up to 50 km/h). Biomechanical signals used to assess injury risk are exported from the model through "sensors" defined in the model to export loads, accelerations, or displacements relevant for injury valuation. The requirements for VIRTUAL standing passenger HBM simulation assessments are similar to those published by the European New Car Assessment Programme (Euro NCAP, 2017).

The specific functions needed to simulate a standing passenger in a public transit vehicle are outlined in Chapter 3.2. Muscle activity as a reaction to an applied motion of the support under the feet (a bus or tram floor) is included in the model to represent the reactions of a passenger attempting to maintain balance. This is a substantial deviation from standard pedestrian or similar applications of HBMs. The gravity load and muscle activity applied before and during the perturbation (sudden braking or acceleration of the vehicle) to the HBM are of the same order of magnitude and cannot be ignored, as opposed to the initial impact of a pedestrian, which is dominated by the horizontal impact loads. Gravity loading can be introduced simultaneously to impact loads in a pedestrian impact as there is no requirement to have the joints reach equilibrium due to gravity prior to, or during, the impact. For the standing passenger model, the loading environment must start with a gravity settling period so the

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[1] https://virtual.openvt.eu/

model can reach equilibrium (due to gravitational loading) before the imposed perturbation is presented. Data from volunteer studies conducted in WP5 were used to calibrate and validate the model.

The load cases of interest for this model have been mentioned previously in Section 1.1.3. Volunteer studies were conducted to investigate the load cases and are shown in Figure 3-1. The model should address both forward and rearward motions of the platform causing the passenger to possibly fall forward or rearward.

Figure 3-1: Forward and rearward orientation of the volunteers representing potential falls.

This chapter describes the virtual testing procedures for assessing standing passenger safety. The reader is referred to Deliverable 2.5 for the detailed description of the development and calibration of the model. A detailed virtual testing protocol for standing passengers is also available in D1.2. It describes the basic model setup, the input file structure and the key files that are needed to control the simulation and positioning of the VIVA+ SP HBM. Post-processing to obtain the injury data is documented in the Dynasaur tutorial on the OpenVT platform.

3.2 VIVA+ Standing Passenger model information

3.2.1 Summary of enhancements to VIVA+

The VRU pedestrian model in WP4 provides a basis for the standing passenger model. To best represent the test data, both the VIVA+ 50F and 50M models were positioned to correspond to the volunteers' initial postures as recorded in the study (Figure 3-). The VIVA+ SP posture was modified using the Open Source PIPER[2] positioning tool, also used for preparing the pedestrian and cycling HBM models. The standard VIVA+ model (John et al. 2022) was enhanced for the application as a standing model to include posture control. The main change from the standard model was the addition of revolute joints in the knees and hips to simplify the model application with muscle activity. The use of revolute joints also simplifies the initial settling of the model under gravity loading by eliminating the calculation of internal contact forces in the lower joints. Figure 3-2 shows the position of the torque actuators being identically implementated on both legs. LS-Dyna requires revolute joints to be connected to rigid bodies and elements of the surrounding anatomy were modified to address this.

The muscle activity was originally envisioned to employ a closed loop controller to dynamically react to the applied loads. The simple Proportional-Derivative controller available in LS-Dyna was unable to adequately reproduce the muscle torques that represent a standing passenger maintaining balance. An

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[2] PIPER Positioning tool framework [piper-project.org]

open loop controller was implemented thus limiting the model to a-priori muscle activity defined by the applied pulse.

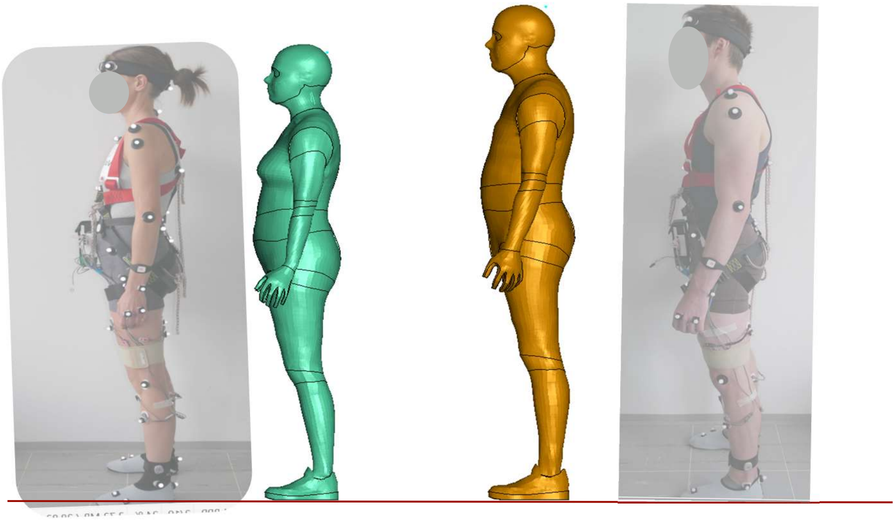

Figure 3-2: Standing Passenger Postures.

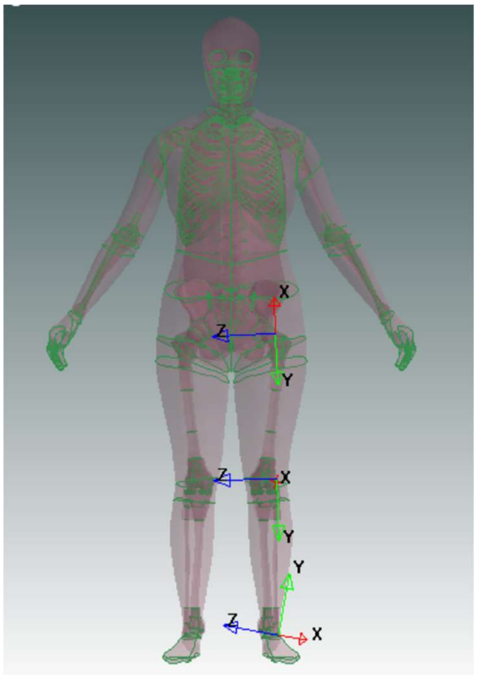

Figure 3-3: Position of torque actuators exhibited (only left leg visualised).

The definition of muscle torques was generated in a smaller, more time efficient model shown in Figure 3-3. The reduced model (VIVA+ Reduced Standing Passenger (RSP), Figure 3-4) is based on the standing passenger VIVA+ SP model but has a rigid lower extremity skeleton and no soft tissues. Additional lumped masses were added to replace the mass of the soft tissues and body segments that were removed. This reduced model represents half of the full model and assumes symmetrical loading across the sagittal plane. The same joint definition and torque application system have been used in both the full and reduced models allowing the response information in the reduced model to be uploaded directly to the full model. This approach was done to reduce the model tuning process time for the volunteer data. Once the joint response data to an acceleration pulse has been generated in the reduced model, the controller output can be reused in the full model any time that acceleration pulse is simulated.

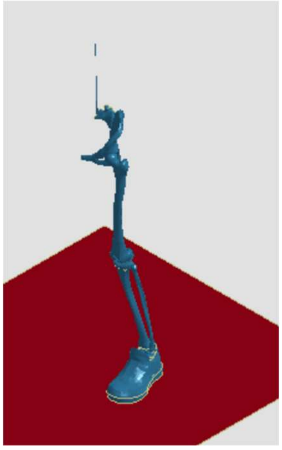

Figure 3-4: Reduced Standing Passenger VIVA+ model (VIVA+ RSP) for calculation of muscle activity.

The muscle activity influencing the joint force history is unique to the acceleration pulse and direction of interest. If these boundary conditions are changed, for example to study a new pulse or a new initial posture, the open loop muscle controller must be recalibrated in VIVA+ RSP to the new conditions before application in the full model.

The injuries for investigation were head and chest injuries in Chapter 1. Injuries can be caused in contacts with vertical structures like walls, handrails and seatbacks. The VIVA+ SP can be used to evaluate impacts to the body above the waist. The main injuries of interest are head injuries calculated with the Head Injury Criterion (HIC) and rib fractures predicted from strain. These injury criteria are calculated from post-processing scripts available for the VIVA+ SP. Due to the modifications made to the lower body to incorporate muscle activity, the VIVA+ SP is not appropriate for lower leg injuries. There are currently no injury prediction procedures for the upper extremities (bone fractures) or other soft tissue injuries due to a lack of reliable injury criteria. The VIVA+ SP will be able to provide data for these injuries when appropriate algorithms and material models have been developed.

The data reviewed indicate that falls related to passengers having just boarded or preparing to exit the bus were the most relevant, which led to an investigation of the loading conditions due to acceleration away from a bus/tram stop or braking event when approaching a stop. The set of acceleration pulses identified in this investigation led to a set of five reference acceleration pulses investigated in the volunteer test series described in Chapter 2. It was anticipated the model would be used for the three most severe pulses from the test series as a platform for virtual testing. Further review of the model capabilities and risk for interior contacts led the team to focus on the most severe braking pulse applied in the direction rearward to the passenger’s orientation. This load case represents the longest time both feet are on the floor before a compensatory step is taken. Once a step has been taken, the model is unable to duplicate the complex stepping motion. With this configuration of open loop controller and applied load, the model can reasonably replicate the trajectory of a person for 1.1-1.3 seconds. After this time, volunteers were initiating a step, lifting one foot from the floor which is beyond the current capability of the model. Furthermore, for longer simulation times, also the behaviour of the upper extremities (both as balancing strategy and as a protection reflex) and the trajectory during a fall would have to be replicated, which is currently beyond the scope of the VIVA+ SP.

A final performance requirement for the VIVA+ SP is the use of the LS-Dyna Rigid-to-Deformable keyword. The extended run times of the model will result in settling of soft tissues in the upper body, most notably the inner structures representing the internal organs. Other applications (typically less than 300 m/s) do not have any significant soft tissue motion due to gravity and any motion would be insignificant compared to other external loads applied to the HBM. The VIVA+ SP takes advantage of an LS-Dyna feature that allows some components to switch from a rigid state to a deformable state. Elements defining the skin in the upper torso are made rigid to maintain the internal organ structure positions and shape as well as the spinal alignment, while the lower extremities are flexible and free to rotate. The upper body is switched to the flexible state just prior to impact.

3.2.2 Interior model requirements

The level of injury to a standing passenger during a fall will be determined by the obstacle the passenger strikes. The interior objects most often documented in the injury reports for public transport included handrails, interior bulkheads, and seats. Examples of these structures are shown in Figure 3-5.

Good modelling procedures require documentation of the model's quality. The VIRTUAL project provides validation documentation for the VIVA+ family of HBMs. The public transport vehicle structures are the responsibility of the model user, more details about this is found in Appendix B. Even if manufacturers of public transport vehicles will have their own internal design requirements, the VIRTUAL generic models of a bus and tram available on the OpenVT platform are useful for study purposes and as generic examples of bus and tram structures.

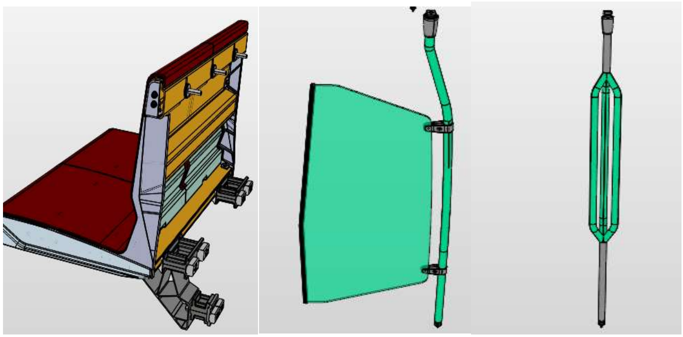

Figure 3-5: Interior structures.

3.3 Description of operation

There are some differences between the VRU applications of HBMs and public transport applications. The main new features specific to the VIRTUAL standing passenger model include: initial positioning, balance dynamics, gravity settling, and injury evaluation.

3.3.1. Initial positioning of the VIVA+ SP as standing occupant

The positioning of the VIVA+ SP and tram models is specified in the main input file containing all the included files for the simulation. As described in Chapter 3.2, the FE model of the vehicle interior should be located in a sub-directory under the "Common" directory.

The outline of the test protocol of a standing passenger are documented in Appendix B. These documents were prepared with the expectation that a specific offset from an obstacle could be defined in a test protocol, and an offset range would be provided identifying the useful range of the model. Exploration of the model identified key issues regarding the interaction of the model with the interior structures that must be addressed when testing the system.

Figure 3-6 depicts the trajectory of three regions of the body if the HBM were to move unrestricted within the bus interior. This figure is needed to position the HBM relative to the obstacle of interest. Different times are noted on the curves, so the position of each body region can be identified at the time of contact with another body part. This process is required to define the time to switch the rigid elements in the upper torso to be deformable.

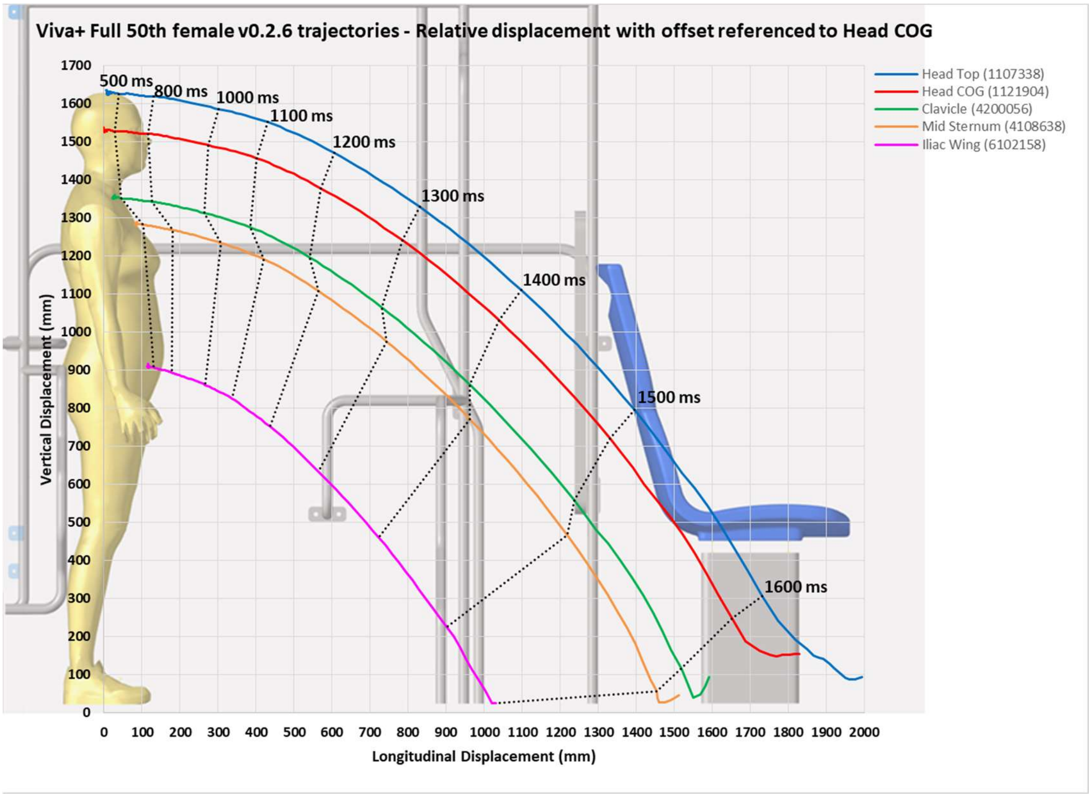

Figure 3-6: Trajectory of key body regions of 50% Female.

The protocol recommends two impact conditions: direct contact with the head and an offset of 100 mm laterally to create an impact with the chest or clavicle. These two positions are presented in Figure 3-7. The trajectories in Figure 3-6 are needed to identify the maximum impact speed for the segment of interest, head or chest.

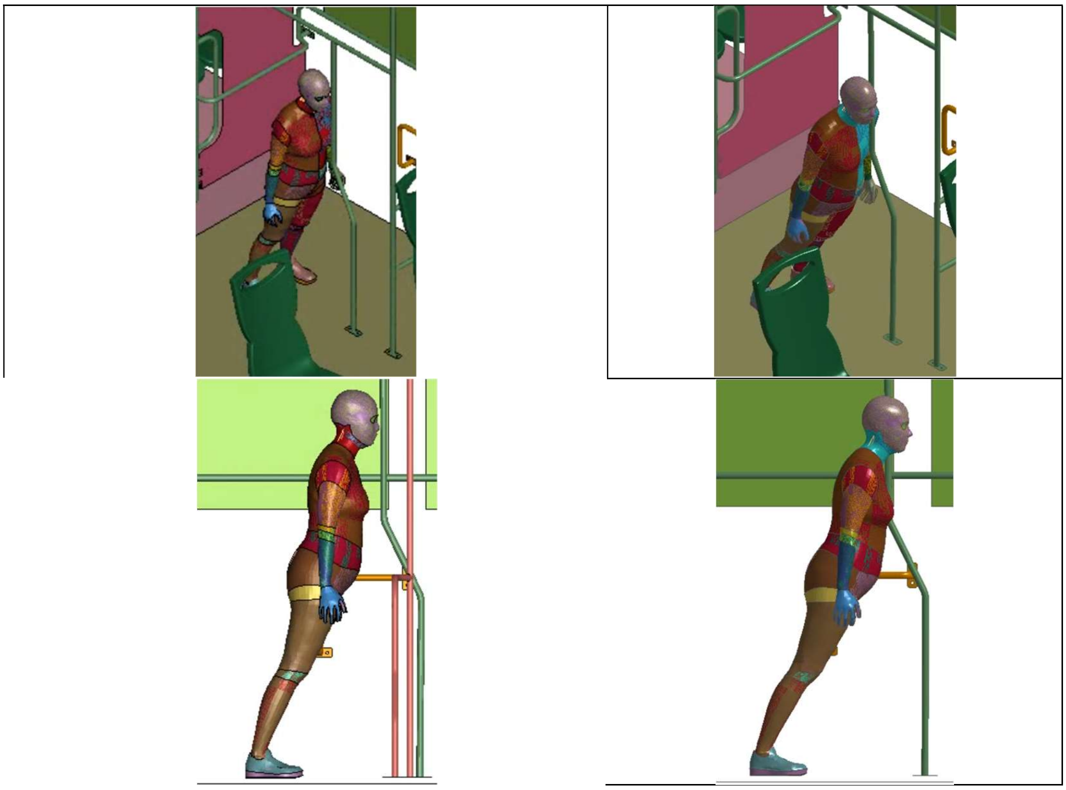

Figure 3-7: Impact Configuration-Left: Centred on head, Right: Offset 100 mm laterally.

The importance of using the trajectories in Figure 3-6 is illustrated in Figure 3-8. This shows how the geometry of the structure, in this case a vertical handrail, influences the HBM interaction impact. In this case, the head impact occurs, but the chest is not in contact with the lower part of the bar until much later due to the geometry. If the bar had been oriented the opposite way with the lower section closer, the head and chest would impact first and reduce the impact velocity of the head.

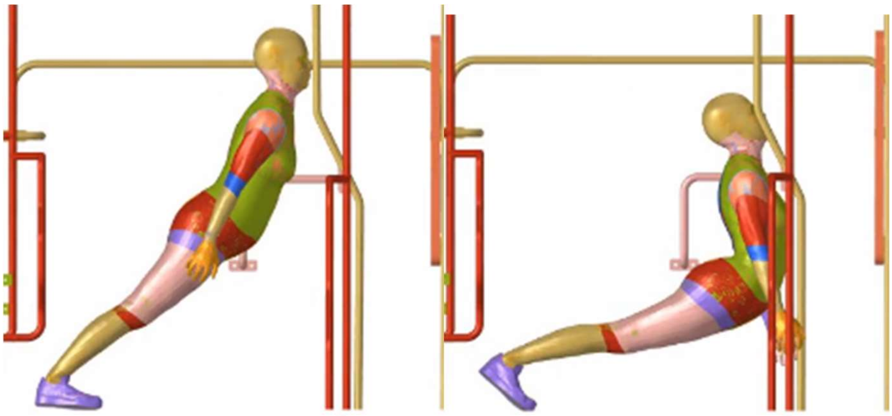

Figure 3-8: Interaction of Head and Torso.

The minimum recommended test matrix for the VIVA+ 50F SP is shown in Table 3-2: Test Matrix for Standing PassengerTable 3-2. The reference position for reporting the longitudinal reference position for the VIVA+ SP is the location of the hip joint, node **7124289**.

Table 3-2: Test Matrix for Standing Passenger

HBM	Minimum Distance [mm]	Maximum Distance [mm]
50F: Head impact	300	800
50F: Chest impact	300	550
50M: Head impact	300	900
50M: Chest impact	300	600

The vertical position of the passenger should include a 2 mm offset from the top floor surface to the shell elements on the soles of the shoes to account for the contact offset defined in the shoes.

3.3.2. Gravity Settling

The VIVA+ SP model has revolute joints in the knees and hips, in addition to the existing ankle revolute joints in VIVA+. These joints reduce the amount of settling, as joint contacts cannot be established on the interior joint surfaces. The soft tissues in the body must also be exposed to a gravity field to achieve equilibrium. The model loading history includes a short, 5 ms, ramp-up period of the gravity field to 9.81 m/s^2, which was maintained for the remainder of the simulation. Parts of the upper body are predefined for a Rigid-to-Deformable switch that should activate just prior to contact. The information in Figure 3-6 is used to determine the switch time. To reduce the vibration of the remaining soft tissues in the HBM, a global damping setting was used to dampen the deformation process over a 100 ms period. During this time, the revolute joints were also restricted from motion. Application of the gravity settling procedure is already configured in the model "simulation_control.k" file, which also includes the information for the programmed acceleration pulses for the load case.

3.3.3. Muscle activation

Active control of the stature is a key feature being developed for the VIRTUAL standing passenger model, representing the balance recovery strategy of a passenger. This is a new feature and a unique contribution of the VIRTUAL project. This feature is critical if the head excursion within the vehicle interior will be captured as a "living" passenger and not a "passive" structure that only responds as a simple mechanical system. Details of balance dynamics and demonstration of their implementation are described in the VIRTUAL D2.5 report.

The control signals and stiffness properties for the lower limbs are defined in input files in the "Controller" sub-directory files: ankle.k, knee.k and hip.k. The muscle activity is defined by the initial pulse applied to the floor and does affect the injury output during the actual input. Open loop joint torque histories are specified in the controller files.

Simulation of new pulses requires the generation of new open loop control signals from the offline simplified model. This involves the VIVA+ RSP mentioned earlier and is documented in the VIRTUAL D2.5 report.

3.3.4. Demonstration example

An example of the hard braking pulse proposed for virtual testing is shown below. This virtual test represents the VIVA+ 50F SP positioned 440mm (pelvis reference point to the nearest surface to the head). Images in Figure 3-9 show the motion of the HBM relative to the vehicle. The initial impact with the vertical handrail occurs at around 1110 ms.

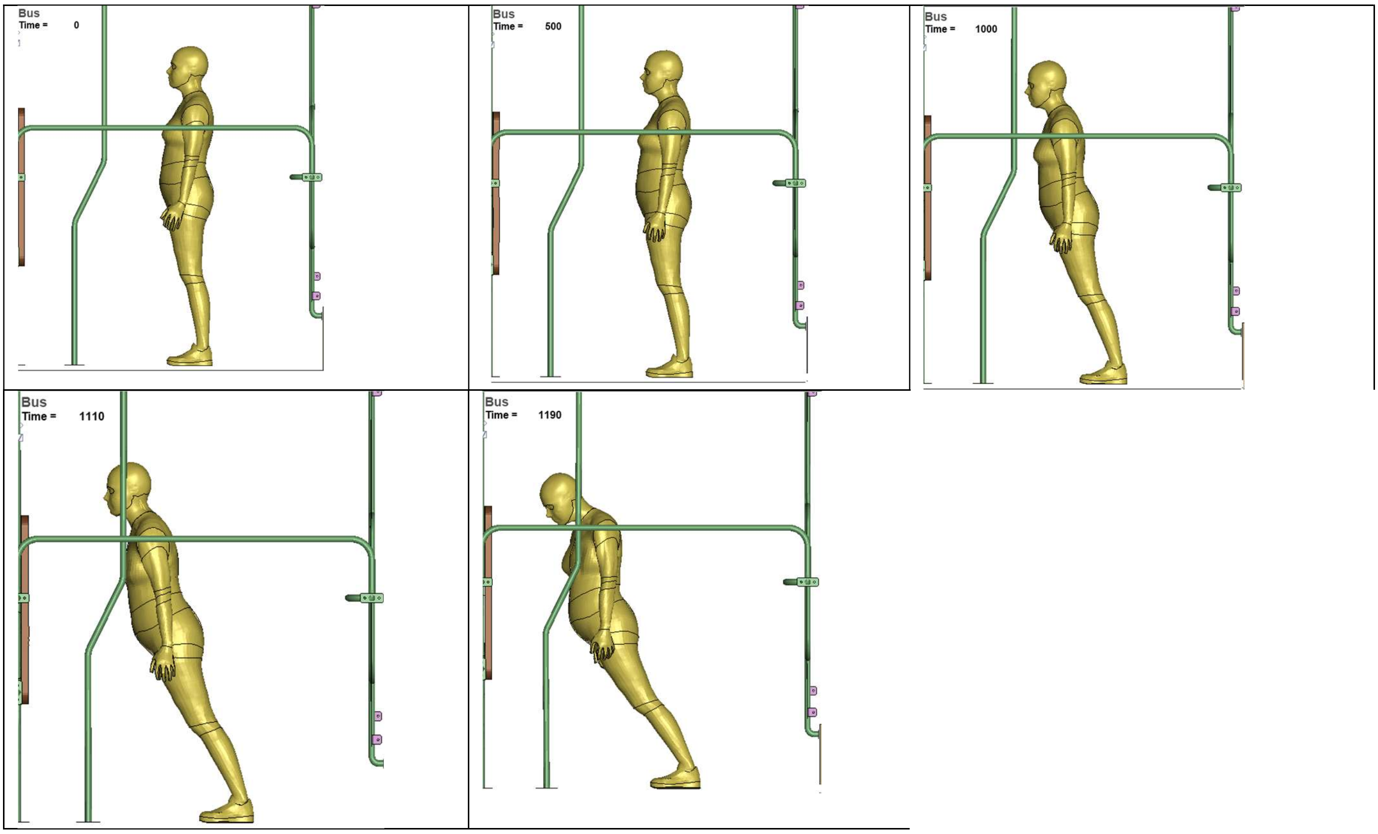

Figure 3-9: Motion of VIVA+ SP during chest impact: Top Row – Prior to impact; Bottom Row Initial Contact and Maximum Chest Compression.

The power of virtual testing is shown in Figure 3-10 and Figure 3-11. The local (tissue level) deformation of the body is calculated in the VIVA+ models and the resulting stress and strain information can be used to predict injury. The yellow and red fringes in the left ribs in Figure 3-10 show the local stresses created by the impact with the handrail. This information is used to predict the risk of rib fractures in the post-processing scripts available on the OpenVT.

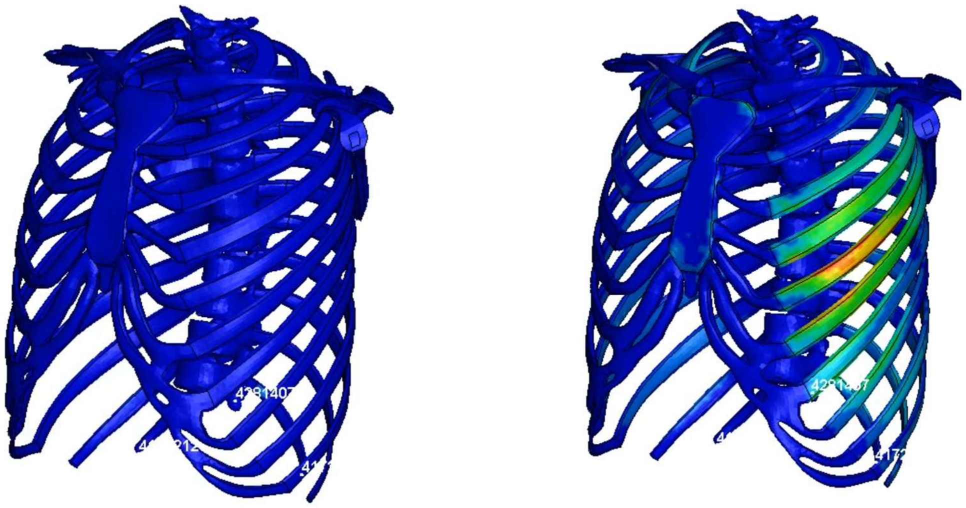

Figure 3-10: Strain distribution in Rib cage before contact (left) and after contact (right).

The difference in head acceleration between a test condition with or without initial contact of the head to the vertical handrail is shown in Figure 3-11. The green curve shows how the initial acceleration due to the contact (nose in this case) is much higher than the case, when the head does not directly load the handrail, but is indirectly loaded by the deceleration of the chest (red curve). The option to look at several body parts in the same test is important to ensure all potential injury sources are assessed.

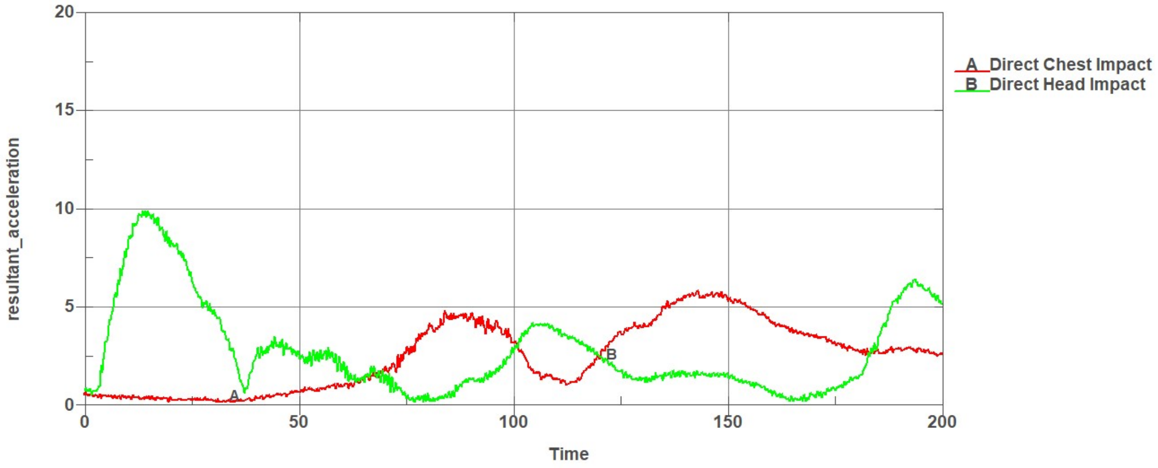

Figure 3-11: Head Accelerations for two load cases.

3.3.5. Presentation of results

The output of interest from the simulations are primarily injury prediction. VIRTUAL's OpenVT platform contains resources to automatically generate relevant output diagrams and indicators using Dynasaur. A tutorial for its function is available from Postprocessing with Dynasaur — VIVA+ Tutorials (vivaplus.gitlab.io). The process is illustrated in Figure 3-12.

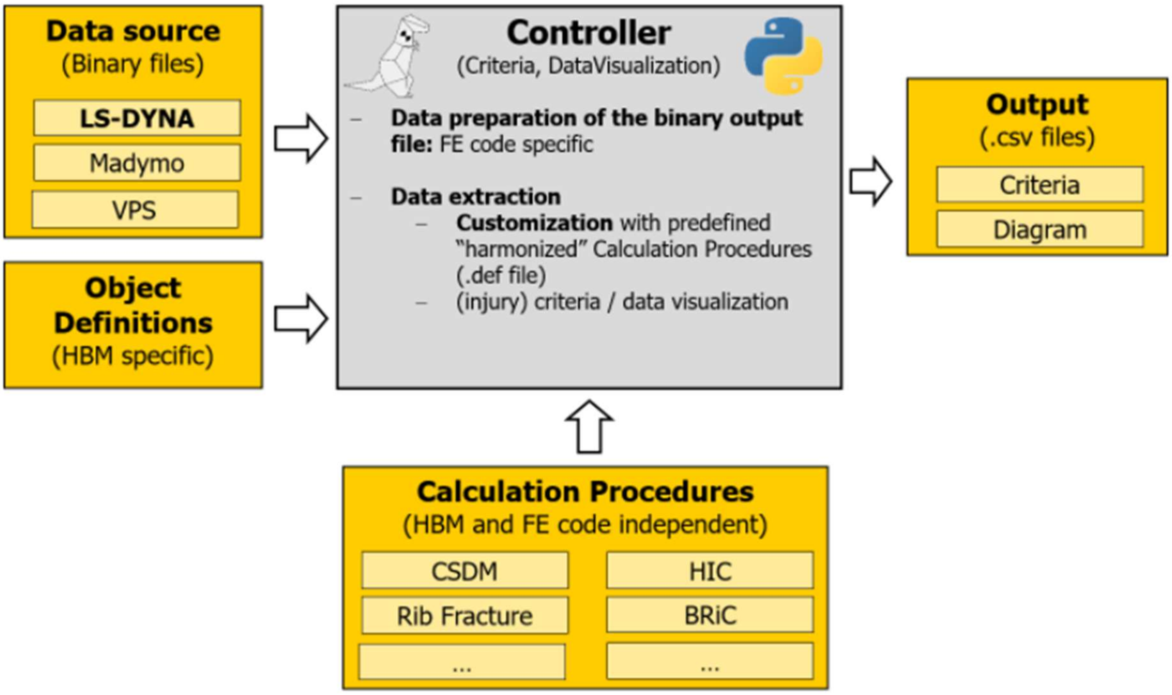

Figure 3-12: Post Processing data with Dynasaur.

Output from a VIVA+ model is ready to be submitted to Dynasaur and scripts to produce standard output reports are available. The VIVA+ SP model already contains the reference nodes and similar landmarks to generate relevant injury criteria such as HIC, Rib Fracture, etc. Most relevant for the standing passenger cases of interest are head injuries where HIC and BRiC can provide information on the probability and severity of head injury.

3.4 Summary

The procedure to simulate a standing passenger and to predict potential injuries due to falls inside a public transport vehicle was presented in this chapter. The VIVA+ SP model has been developed as a "plug and play" tool that can be simulated in the environment desired by the user. Open loop joint control activities are programmed for the proposed load case. The user of the model must have access to their own vehicle interior model with accurate representation of interior objects. The procedures and functions described in this document are identical for the VIVA+ 50F and 50M.

The specific description of the standing passenger test protocols is provided in VIRTUAL D1.2. The VIVA+ SP is available from https://openvt.eu/load_cases/standing_passenger. An example file of a main input file for VIVA+ SP can be found in Appendix C.

4. Dissemination

The work in the VIRTUAL project on the topic of occupants in public transport has resulted in multiple scientific publications (Elvik, 2019, Sylvano and Ohlin, 2019, Krašna et al. 2021, Xu et al. 2021b, Xu et al. 2021c, Keller and Krašna 2022).

The work described in each of the chapters in this deliverable, constituting the main topics of WP5, was presented at the "Safety of Vehicle – Safety of Passengers" 2022 conference in Warsaw, Poland on 17-18 May 2022, with the common goal for the presentations being "Zero Fatalities in EU Public Transport by 2030". At this conference, four presentations from WP5 were delivered:

- Non-collision incidents on buses due to acceleration and braking manoeuvres leading to falling events among standing passengers (Ary P. Silvano, based on the corresponding publication in Chapter 1.3)
- Volunteer tests on balance of erect occupants on public transport (Simon Krašna, based on the experimental sled tests and publication in Chapter 2)
- Balancing strategies for standing passengers during perturbations on public transport (Jia-Cheng Xu, based on the publications about the analysis of balancing strategies from the experiments in Chapter 2)
- Banging heads on board buses: A description of the model developed to assess injury risk of standing passengers with demonstration of the model performance for a 50th percentile female. (Robert Thomson, based on Deliverables 2.5 and 5.2.).

The balance strategies and tolerance levels for perturbations on public transport will also be presented at Transportforum 2022, Linköping, Sweden on 17 June. This conference has been coordinated by VTI for over 30 years and is the largest transport conference in Scandinavia, gathering a community for the opportunity of sharing knowledge and networking about transport-related topics.

5. Discussion and future studies

Standards related to safety of public transport vehicles were reviewed in Chapter 1, showing that most regulations are focused on production quality and requirements for entering and leaving vehicles. Literature reviews, including both injury statistics and biomechanical responses of standing passengers, resulted in multiple scientific publications (Elvik, 2019, Sylvano and Ohlin, 2019, Krašna et al. 2021, Xu et al. 2021b, Xu et al. 2021c, Keller and Krašna 2022). They all demonstrate that injuries to standing occupants on public transport are of high importance both in current and future autonomous public transport. A long-term focus to promote usage of public transport exists in many parts of the world. All aspects of safety and comfort should address both seated and standing passengers in public transport. However, no passenger safety requirements and testing procedures are being addressed through current standards and regulations.

The different tasks of WP5 cover multiple aspects related to passive safety of public transport passengers, with specific focus on injury prevention for free-standing passengers. The term free-standing in this context is relevant for all passengers, since even seated passengers temporarily are free-standing during boarding, alighting and walking inside the bus. The injury occurrence, as presented in Chapter 1, is most common in free-standing scenarios, motivating the need to gain more knowledge on how perturbations during normal operation affect balance (as investigated through the work described in Chapter 2). The volunteers in the sled tests comprised of younger and healthy females and males. However, injury statistics show that knowledge about balance control during perturbations encountered during normal transport operation is also needed for the elderly (aged 65+) and future studies should address the influence of age on ability of maintaining balance as a standing occupant in public transport.

The identified balancing strategies were studied for a body orientation in the direction of travel. A lateral posture would most likely lead to a wider symmetrical stance and sideways compensatory stepping during perturbation (Borelli et al. 2019; Carty et al. 2012; Rogers et al. 2003), as opposed to the forward or rearward stepping and postural stance. However, to the authors' knowledge, lateral perturbations are extensively studied but not during external perturbations similar to those on public transport. Hence, this is an important topic for future studies, to derive perturbation tolerances with respect to postural balance among standing passengers, especially since sideways falls can cause serious injuries such as hip fractures. This is a major issue among the elderly in both the acute and post-surgery phase (Feldman and Robinovitch, 2007).

An advanced injury prediction tool for the complex situation of a standing passenger was developed in this project. The VIVA+ SP represents a state-of-the-art human body model that can simulate how passengers interact with the vehicle interior. This tool is an important first step to distinguish between well and poorly performing designs.

The current standing model developed in this project includes functions that represent the muscle response of real passengers. It is important to replicate the actual motions of a human inside the vehicle. Without these "reflex" actions, the model will underpredict the excursion and movement within the vehicle during maneouvring events. Simplified, usually rigid, human surrogates could not effectively identify the role of interior geometry identified in this report.

Increased knowledge on the tolerance for different perturbations for standing occupants on public transports can provide a safe operation envelope for public transport coaches. Controlling the vehicle dynamics to avoid collision injuries is important, as are also non-collision injuries.

An ongoing internal development project at VTI is investigating a driving simulator (known as SimIV) and its potential in reproducing acceleration pulses, such as those derived for the sled experiments with the methodology by Keller and Krašna (2022). The experience and knowledge from this work package can provide recommendations to OEMs for safe operation of future autonomous buses. Autonomous shuttle buses, part of the EU funded project SHOW, are found in Linköping, Sweden, and are part of a demo coordinated by VTI. Knowledge sharing has been initiated, investigating issues with hard braking that have been a concurrent problem. The thresholds identified in Krašna et al. (2021) and Xu et al. (2021b) provide a basis for future studies and collaborations with OEMs and other stakeholders. A first step to analyse acceleration time series from these shuttles is under development. The purpose is to derive deceleration thresholds to avoid hard braking and allow standing passengers to travel with reduced risk of losing balance inside these shuttles. Identifying jerk levels during hard braking events in the time series and where these occur on the route are crucial inputs to autonomous bus and shuttle designs. The work carried out in VIRTUAL and described in this report serves as a starting point for deriving these thresholds.

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Appendix A OpenSim methodology using volunteer test data

Jia-Cheng Xu, Ary P. Silvano

OpenSim is an open-source simulation tool used to study musculoskeletal movement and neuromuscular control of human and animal dynamics (Seth et al., 2018). It can predict kinematic adaptations of human gait and changes in musculoskeletal dynamics. OpenSim automates and solves the equations of motion of neuromusculoskeletal systems, first by describing the topology and secondly by the dynamics of a biomechanical system. It can also track the movements observed experimentally, which enables computing the muscle forces required as well as being able to compute movement trajectories over time (Seth et al., 2018). As such, OpenSim allows for the computation of joint kinematics and reaction forces. It works in four steps: (1) scaling a generic musculoskeletal model to match the anthropometry of the subject using marker data; (2) performing inverse kinematics (IK) to estimate the joint angles and translations documented by the marker data; (3) applying a residual reduction algorithm (RRA) to the joint angles and translations to make them consistent with ground reaction forces and moments, and (4) computing muscle excitations to reproduce the movement of the subject through simulation. Therefore, the analysis of the volunteer test data using OpenSim complements the analysis of the volunteer tests by Krašna et al. (2021).

The kinematics of the volunteers were tracked by a motion capture system (Krašna et al. 2021, Xu et al. 2021). The tracked motions were extracted, processed and fed into OpenSim. The data processing included data migration and exporting from the motion capture system to an ASCII-file, a trajectory file format (file extension .TRC). TRC files contain the data of the markers in the laboratory coordinate system, i.e., body movement responses of the volunteers, tracked by the markers. The laboratory coordinates of the raw files were rotated to match the standard engineering coordinate system of OpenSim (X: depth; Y: length; Z: width), Figure A-1. The rotation was performed differently for forward-facing and rearward-facing pulse orientations. For forward-facing, the coordinates were rotated in the X-axis by -90 degrees and in the Y-axis by +180 degrees. For rearward-facing, the rotation was performed by -90 degrees in the X-axis, see Figure A-1. To automate the rotation process, a Python script was written which is available on the OpenVT platform. Once the coordinate system was rotated, the TRC data were ready to be uploaded into OpenSim.

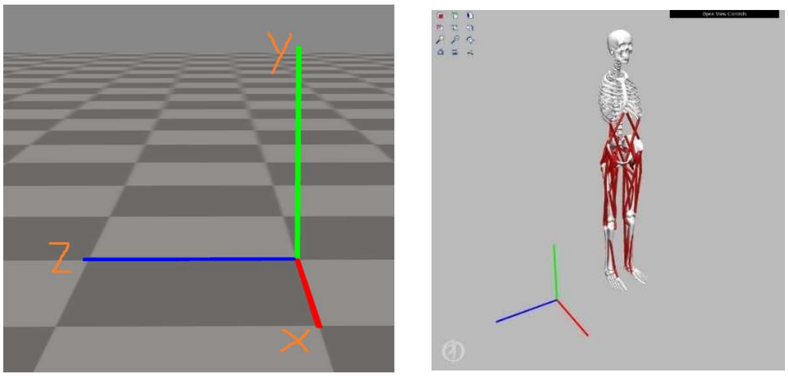

Figure A-1: OpenSim coordinate (X: depth; Y: length; Z: width).

The converted marker coordinate data were used in OpenSim to calculate the joint angles of the volunteers during the pulse sequence in which the volunteers were supposed to maintain balance. A full-body multi-segment model developed by Rajagopal et al. (2016) was used to perform the simulations. The model represents an average male of 170 cm and 75 kg. The Rajagopal model was scaled to match the anthropometry of each of the six volunteers. This process, called scaling, was based on the volunteers' corresponding marker data.

Scaling is the process of modifying the anthropometry of the model to match an individual based on corresponding marker data, such as a volunteer in an experimental test. It is perfomed by assigning marker pairs to body segments, where the distance of each marker pair in the model and the corresponding marker pairs from the experimental data are compared. This comparison is used to calculate a so-called scale factor, which denotes a factor to increase or decrease the anthropometry of the body segment defined by the marker pairs. For example, if the distance of a model marker pair is shorter compared to the experimental marker pair distance, OpenSim applies a scale factor larger than 1.0 to increase the distance of the model marker pair to match the experimental marker pair distance. The marker placements of the model markers are attached at the same location as before the scale factor is applied. Thus, the increased model marker distance changes the anthropometry of the model by enlarging each body segment. This process was performed for all marker pairs selected to scale the model.

The scaling process requires a frame interval with marker coordinate data. Due to the dynamics of the captured movements, i.e., different balancing strategies, a few markers might not be visible to the Motion Capture (MoCap) system on different frames. Therefore, it is important to identify non-empty cell frames to perform the scaling. In other words, the scaling is only possible for frames where all markers chosen to define the body segments have been captured by the MoCap system. It is preferable for the volunteers to be in an upright position, which requires choosing a frame as close as possible to the 'zero' frame, or the beginning of the pulse, when the volunteers are standing upright waiting to react to the pulse. This is due to the marker pairs used to scale the body segments in the X-, Y-, or Z-direction. A script was written in Python to identify the earliest non-empty frame to use in the scaling tool. To enable the execution of the scaling tool, it proved advantageous to use the data of the lowest possible intensity pulse as these tend to have the highest number of non-empty cells at the beginning of the pulse.

The Rajagopal full-body model uses a standard to place and name the markers on the model body landmarks. These markers were modified and adapted to match the placement and name of each marker used in the volunteer tests. In total, 61 markers were used on body segments and six markers on the moving sled. The scaling was performed in the three directions of the coordinate system (see Figure B-1). For each coordinate direction, at least one marker pair must be chosen. If more than one marker-pair is chosen, a mean value for the scale factor will be calculated by OpenSim. The scale factor for each direction of the body segments is based on the distances between the model and experimental marker pairs chosen, as explained above. Scale factors larger than 1.0 scale up body segments in the model and scale factors less than 1.0 scale down the body segments.

The anthropometry was scaled following the placement of the markers on each specific volunteer with the help of pictures from the experimental tests. To match the anthropometry of each volunteer, an individual specific Rajagopal model was created, where the model markers were proportionally placed according to the pictures from the experimental tests. This step is the key to scaling the anthropometry of each volunteer. Any reported errors of interest should be below the recommended threshold after scaling, i.e., root mean square error (rms < 1 cm) and maximum error (max < 2 cm).

Frames chosen for scaling the anthropometry will vary due to an empty cell problem in the TRC-files, with data missing from different frames during the motion capture. The position of the volunteer will therefore be different and hence the scaling along the x, y and z axes will be different. Ideally, the frame should be static and as similar as possible for all the volunteers. For example, a static t-position (arms parallel to the ground) would enable the volunteers to have their arms in the same position keeping the torso and lower body upright, which gives consistent scaling along the coordinate axes.

It is worth noting that the Rajagopal model is based on the male anatomy. For example, it is known that the male and female pelvis areanatomically different (Lewis et al., 2017; Leong 2006, Wang et al., 2004). A typical characteristic is that the male pelvis is narrower and longer while the female pelvis is wider and shorter. However, since the purpose of using OpenSim in VIRTUAL is inverse kinematics, only the marker placements on the model must be accurate for correct implementation of the experimental marker data into the software. This procedure will ensure reasonable scaling of the pelvis geometry.

Once the model anthropometry of each volunteer has been scaled, the next step is to reduce the marker errors as much as possible. This step is conducted by manually moving the virtual markers (pink coloured) and placing them on top of the experimental markers (blue coloured) in the scaled model Once the virtual markers are moved and placed accordingly, the model is scaled one more time to evaluate the new marker errors. Thus, the scaling process is iterative, where the anthropometry is scaled in the first step and the errors are minimised in the second step. It is worth noting that if the scaled anthropometry is close to the real anthropometry, where markers placed on anatomical landmarks are anatomically correct, the markers will be in the same place. This is easily visualised in OpenSim by "associating the motion data" when the scaled model appears after running the scaling tool, and can be explained by the model markers being placed on the same landmarks on the OpenSim model, corresponding to the markers placed experimentally on the volunteers. Hence, the scaling must be appropriately executed before manually moving the markers to reduce any residual errors from the antropometric scaling. Figure A-2 shows the unscaled generic model with coloured muscles in red and the scaled model with virtual and experimental markers in blue.

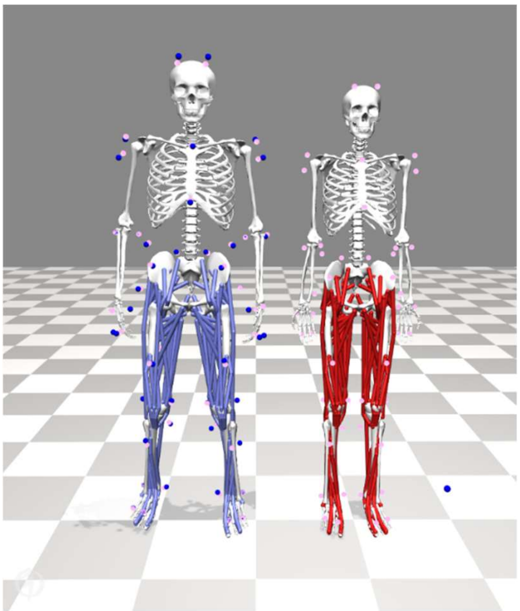

Figure A-2: The scaled model (blue) versus the Rajagopal full-body model (red).

After the model was scaled, IK was performed to obtain the joint angles. IK tracks the marker movements during the volunteer responses to calculate the joint angles of the different body segments at each time frame. The data provided by OpenSim comprise the joint motions in their defined coordinate system. Using joint rotation in these applications is convenient as they are less dependent on each segment length, essentially representing normalised data facilitating comparison of different volunteers.

IK performs the tracking of the markers during each volunteer's response to a pulse. It calculates the joint angles of the different body segments at each frame. The more accurate the tracking of each marker is, the lower the reported errors are. The errors reported by the IK must be below the recommended threshold at each frame, and the recommendend IK error thresholds are < 2 cm rms error and <4 cm maximum error. However, the recommended thresholds can vary depending on the motion under examination. Performing IK below the recommended thresholds requires a properly scaled anthropometry with the reasonably small marker placement errors. Therefore, it is advisable to perform the previous steps carefully to meet the prescribed thresholds. Weights can be used to emphasise the tracking of important markers. For instance, the weight of the markers on the ankles, knees, and hips can be higher, e.g., 3 to 1, to enable OpenSim to track these markers more accurately, reducing any errors.

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Appendix B Developing a Standing Passenger Virtual Test Protocol

Corina Klug, Simon Krašna, Arne Keller, Robert Thomson

The proposed test protocol is found in the Deliverable D1.2 (which will be finalised June 2022).

The review of scenarios led to the selection of test scenarios representing the loss of balance and striking a vertical surface within the vehicle interior. From the volunteer tests, the likelihood of falling rearward or forward was essentially rated equal and indicates that both these scenarios should be used in the VIRTUAL standing passenger VT development.

The pulses collected and documented by Keller and Krašna (2022) represent a range of possible test severities that can be experienced in non-collision events. Lower severity pulses were used in volunteer tests to identify strategies used to maintain balance and input to the development of tools predicting the response of standing passengers. Several different responses were demonstrated by the volunteers. Initially, most volunteers resisted the applied pulse through their feet by tensing the muscles of the lower leg (ankle strategy), upon which they applied a compensatory step to regain a favourable CoG position (stepping strategy). This step response varied among the volunteers, including single large steps, several smaller steps and rotation of their hips and feet. However, the extent of their balancing strategies were too comprehensive to address within the scope of the VIRTUAL project. Hence, a reduced set of balancing strategies was developed to address the common responses observed including any significant variations between the sexes (Xu et al. 2021c). As described in Chapter 3, balancing dynamics was implemented in a standing VIVA+ HBM to capture the excursion envelope for an active passenger, as opposed to a static load device represented in the VIVA+ VRU models.

Interior model requirements

The interior objects most often documented in the injury reports included handrails and interior bulkheads. Examples of these structures are shown in Figure B-1. These structures must be modelled such that the structural properties of the installed feature are properly represented. Component tests demonstrating the local (point of occupant contact) and global (installation in vehicle) properties will be provided together with the simulation results of the injury risk assessment, in order to validate that the evaluated structures conform to the properties of the final production version.

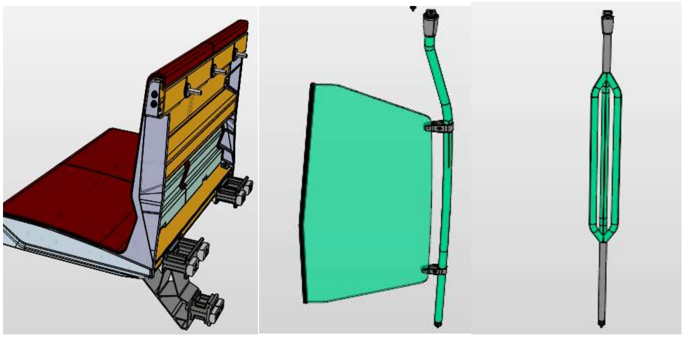

Figure B-1: Example of Interior Structures.

Geometric Requirements

The requirements in UNECE 107 specify that handrails must be available in accordance with Figure B-2. This requirement results in a horizontal spacing of at least 1.25 m between handrails. In addition to the placement of the handrails, the allowance for wheelchair areas in UNECE 107 (UNECE, 2019) requires a 1.3 m object free area. Thus, a 1.3 m wide area for unrestrained occupant motion is a recommended minimum excursions space to evaluate.

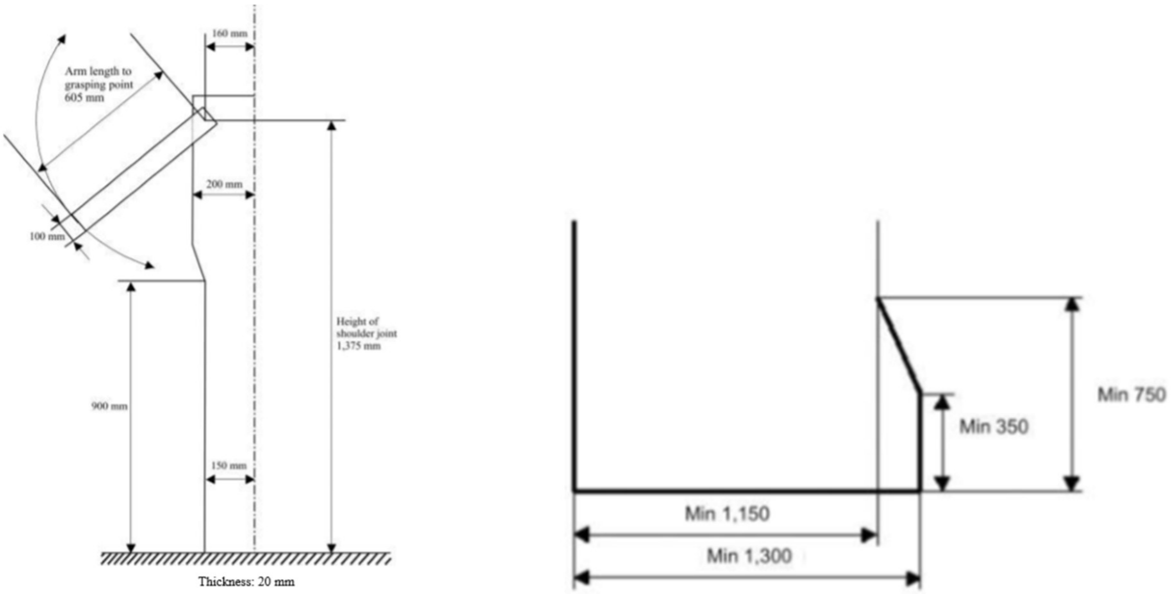

Figure B-2: Positioning requirement of handrails and wheelchair space.

The area to be assessed for occupant safety must include the handrails structures within 1.3 m horizontal distance from any passenger at risk of head impacts, extending upwards from the floor to the height at risk of head impact. The proposed height is the point of intersection of an arc of radius *R* intersecting a vertical plane 1.3 m forward or rearward from a passenger as demonstrated in Figure B-3, which is based on the UNECE R107 manikin exemplifying passenger dimensions. The values of R will correspond to different occupant statures. These positions will be evaluated with the excursion envelope identified in the volunteer experiments and updated during the development of the HBM.

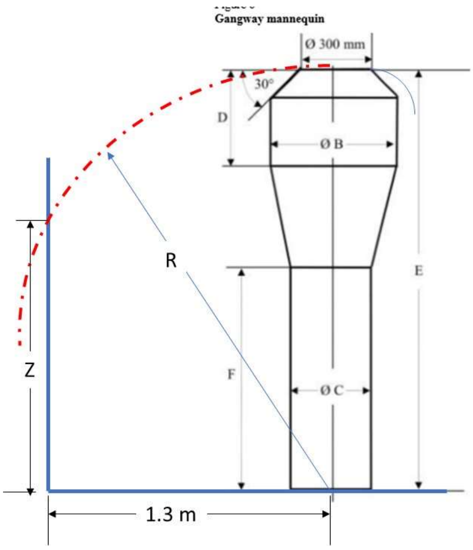

Figure B-3: Vertical area of interest.

Load Case Definitions:
Each interior object will be tested with pulses in the forward and rearward direction. At least one test will be with the HBM placed 1.3 m away from the object that may be struck by a falling passenger.

Loading Conditions

The background data and collected information on non-collision events provided in Chapters 1 and2 produced the load conditions illustrated in Figure B-4.

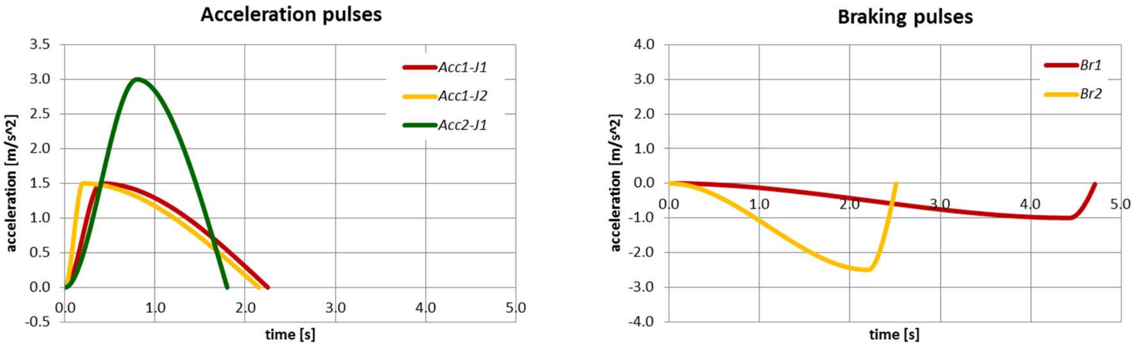

Figure B-4: Generic perturbation profiles used in the volunteer tests of balancing strategies of erect passengers on public transport vehicles.

These pulses represent lower severity conditions deemed acceptable for volunteer testing. The acceleration characteristics modelling with Legendre polynomials provides a scaling opportunity to extend the pulses to different magnitudes, shapes, and durations that are representative of public transport vehicles (Keller and Krašna, 2022).

The initial development of the standing HBM with balancing dynamics should apply the three pulses identified in Chapter 2 that proved particularly challenging for the volunteers. The pulses are denoted in Figure B-4 and tabulated as test numbers in the matrix for the proposed virtual test protocol. articularly, *Br2* and *Acc2-J1* are important to study as they were the most difficult for the volunteers. The more severe *Acc1-J2* provoked muscular engagement earlier and may be an important feature to incorporate in a model of a standing passenger. These pulses should be applied to the model in both the forward and rearward direction.

Different manufacturers of public transport vehicles will have their own internal design requirements. Therefore, it is important to propose a minimum test matrix that would identify system performance to a reasonable "worst-case" scenario, thereby guaranteeing state-of-the-art protection. The test protocol developed in VIRTUAL is based on the pulses used in volunteer testing. The proposed test protocol is found in the Deliverable D1.2 (which will be finalised June 2022) and is based on the hard braking, rearward oriented bus motion that displays the longest period for the HBM to maintain an upright postures before falling. Positioning of the HBM should result in direct contact with the head or chest to evaluate the main injuries reported in the literature.

The model can be updated to address other pulses. However, updating requires information on a standing passenger's response to specific pulses. The use of Legendre polynomials to create generic pulses is a foundation for specifying future load cases. Bus and trams have different performance envelopes that are limited by engine power and available friction. Only physically feasible pulses should be proposed.

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Appendix C VIVA+ Standing Passenger: Example main input file

Matej Kranjec, Robert Thomson

Unique files for VIVA+ SP identified with call outs

```
$# LS-DYNA Keyword file created by LS-PrePost(R) V4.6.15 - 16Aug2019
$# Created on Oct-24-2021 (12:50:07)
*KEYWORD
*PARAMETER
$#   prmr1     val1    prmr2     val2    prmr3     val3    prmr4     val4
RMCL_l_off0.
RLCL_l_off0.
RACL_l_off0.
RPCL_l_off0.
R PL_l_off0.
R SEX     0.
R AGE     50.
*PARAMETER_EXPRESSION
R HE_MASS 0.4182+SEX*0.0703
R TX_DENS 1.0e-6+SEX*0.1e-6
R LX_DENS 1.12e-6+SEX*0.135e-6
R LX_MCL  1+SEX*0.06
R LX_LCL  1+SEX*0.24
R LX_ACL  1+SEX*0.14
R LX_PCL  1+SEX*0.39
R LX_PL   1+SEX*0.19
RLX_QuadL0364.2+SEX*49.
*TITLE
$#                                                      title
VIVA+ 50F v0.2.2
*DEFINE_TRANSFORMATION_TITLE
NoRotation
$#  tranid
       1
$#  option       a1        a2        a3        a4        a5        a6        a7
TRANSL     -1343.7 -1676.968      -15.2       0.0       0.0       0.0       0.0
*INCLUDE_PATH
../common/
*INCLUDE_PATH
../common/Passenger/
*INCLUDE_PATH
../common/Controller/
*INCLUDE_PATH
```

Positioning command

```
../common/Tram/
*INCLUDE
$#                                      filename
vivaplus_50F-standing_nodes.k
*INCLUDE
$#                                      filename
vivaplus-controls.k
*INCLUDE
$#                                      filename
vivaplus-global-contact.k
*INCLUDE
$#                                      filename
VIVA_plus_APF_CONTROLLER.k
*INCLUDE
$#                                      filename
vivaplus-joints.k
*INCLUDE
$#                                      filename
vivaplus-elements.k
*INCLUDE
$#                                      filename
vivaplus-misc.k
*INCLUDE
$#                                      filename
vivaplus-10-Head.k
*INCLUDE
$#                                      filename
vivaplus-22-Neck-Muscles.k
*INCLUDE
$#                                      filename
vivaplus-20-Neck.k
*INCLUDE
$#                                      filename
vivaplus-30-Upper-Extremity.k
*INCLUDE
$#                                      filename
vivaplus-40-Thorax.k
*INCLUDE
$#                                      filename
vivaplus-50-Abdomen.k
*INCLUDE
$#                                      filename
vivaplus-60-Pelvis.k
*INCLUDE
$#                                      filename
vivaplus-70-Lower-Extremity.k
*INCLUDE
$#                                      filename
vivaplus-constraineds-landmarks.k
*INCLUDE
$#                                      filename
```

Controller file (references joint input files)

```
vivaplus-50F-standing_reference_points.k
*INCLUDE_TRANSFORM
$#                                         filename
vivaplus-80-Shoes.k
$#  idnoff    ideoff    idpoff    idmoff    idsoff    idfoff    iddoff
   2000000   2000000   2000000   2000000   2000000   2000000   2000000
$#  idroff
   2000000
$#  fctmas    fcttim    fctlen    fcttem   incout1    unused
       1.0       1.0       1.01.0              1
$#  tranid
         0
*INCLUDE
$#                                         filename
vivaplus-81-Shoes_Contact.k
*INCLUDE
$#                                         filename
vivaplus-90-outputs.k
*INCLUDE
$#                                         filename
vivaplus-91-outputs-elements.k
*INCLUDE_TRANSFORM
$#                                         filename
inside_generic_tram_data_R9.1.key
$#  idnoff    ideoff    idpoff    idmoff    idsoff    idfoff    iddoff
  10000000  10000000  10000000  10000000  10000000  10000000  10000000
$#  idroff
  10000000
$#  fctmas    fcttim    fctlen    fcttem   incout1    unused
       1.0       1.0       1.01.0              1
$#  tranid
         1
*INCLUDE
$#                                         filename
Contacts-tram-interior.k
*INCLUDE
$#                                         filename
vivaplus-passenger-materials.k
*INCLUDE
$#                                         filename
vivaplus-passenger-constraineds-contacts.k
*INCLUDE
$#                                         filename
Standing-passenger-LX-contacts.k
*INCLUDE
$#                                         filename
simulation_control.k
*INCLUDE
$#                                         filename
standing_lower_extremity_v5.k
*INCLUDE
```

Additional components used to model lower extremity

Deformable to rigid commands

```
$#                                          filename
vivaplus-controls-old.k
*INCLUDE
$#                                          filename
def-to-rigid.key
*COMMENT
This is the VIVA+ 50th Percentile Female Standing Passenger Model, which
is a repositioned model from VIVA+50th Percentile Female Standing
Pedestrian Model, which is a morphed derivative of the baseline 50th
Percentile Female Model

This is version 0.2.4 released on 2021-07-09

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This is a beta version of the model for "friendly users"
The model is still under development and currently not sufficiently validated

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```