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Verification of Usability of the Hybrid III Dummy for Crash Tests – Pilot Experiment

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The study is focused on the dynamic response of head and thoracic area of an anthropomorphic test device (ATD) during low-impact collisions with a tram. Two collision scenarios were analysed: the frontal impact (a chest as a primary contact area) and side impact (a thigh as a primary contact area). The measurements used a pedestrian dummy (Hybrid III 50th percentile male dummy, Jasti Co., ltd., Tokyo, Japan) and a unique pendulum impact testing machine (impactor) of own design. The crash tests were conducted at various impact intensities (velocities) into the chest and left thigh of dummy. The primary outcome variable was a resultant magnitude of acceleration measured in the area of thoracic vertebra Th5 and on the vertex of head. The differences between both areas of interest were analysed as well. The results provide the analysis of dynamic behaviour of head and chest of the dummy at low impacts, the validation of impactor for crash-test analyses and a possible way to verify the use of dummy in similar experimental settings.

Keywords: Tram, Pedestrian, Crash Tests, Anthropomorphic Test Device, Validation

1 Introduction

Vehicle-pedestrian collisions (such as with a tram) has been a global issue mainly due to an increasing number of vehicles, a general rush, and pedestrians paying less attention to the surrounding traffic. For instance, from 2003 to 2020, there were 245 serious injuries related to trams registered in the Czech Republic. Therefore, the research has been lately focused on the design of tram front ends to reduce the probability of serious or fatal injuries, and thus to increase the pedestrians' safety [1].

The main objective of study by Bittner et al. (2019) was to demonstrate the possibilities of using the crash tests of tram windscreens in analysing the human-machine accidents. The empirical evidence indicated that it was mainly the head, which is one of the most vulnerable parts of a human body, that sustains injuries in such accidents. The windscreen safety testing was done according to the ECE standards, and it was based on, but not limited to, the collisions with a head of dummy. However, in terms of numerical simulations, it is crucial to determine the material characteristics of windscreens as well. In terms of validity, reliability and economic costs, it appears to be advantageous to use collisions with a solid body because the entire kinetic energy of the collision is absorbed only by the windscreen. The results of these tests were the course of the contact force magnitude based on deformation in the direction of its action. Along with the time response of the buffer acceleration and the size of its kinetic energy, such information can be used as boundary conditions for verification of mathematic models [2].

The purpose of study by Lopot et al. (2022) was to introduce the first results of the long-term project, at the end of which a validated pedestrian model for simulating the crash tests of front ends of trams and perhaps of other light rail vehicles would be available. The results of the pilot experiment with the dummy, supplementing the results of simulations, are available in the current phase of research. The results indicate how important it is to pay extraordinary attention to the individual phases of the collision (Fig. 1) and how significant the localisation and shaping of the individual panels of the tram front end are for the character of the phases being monitored. In the first phase, the inertia of the individual body segments plays an important role, whereas the primary contact occurs between the tram buffer and the dummy's thigh. This is followed by the dummy copying the shape of tram front end and impacts into the shoulders and the head. At this moment, the tram is already applying the brakes and the dummy starts detaching from the front-end surface. The friction force between the dummy's shoe sole and the rail track surface apparently plays an important role for the character of this phase. The dummy then falls onto the ground. This is an accelerated fall, and we can conclude that under the given conditions, this is a phase with the most devastating impact on the dummy. The simulation then shows the way how to modify this dangerous phase so that it has a lower impact on a pedestrian [3].

Fig. 1 *Example of the collision process [3]*

The paper by Kang and Cui (2019) dealt with the estimated speed of the obstacle movement outside the tram. In this paper, the authors intended to come up with a way that should provide a reduction in the number of collisions between the tram and pedestrian or vehicle. In order to avoid such traffic accidents, a system using the infrared emission sensor and the Kalman filter (Fig. 2) was designed. This remote sensor continuously transmitted infrared rays at the frequency of 40 kHz in the direction of the tram travel. If a signal reflected from a obstacle was detected, it was processed by the computer. The result was an equation that calculated the warning threshold of distance from the relative speed. The theoretical test proved that this method could significantly improve the precision of detection of the tram distance from an obstacle in the real time [4].

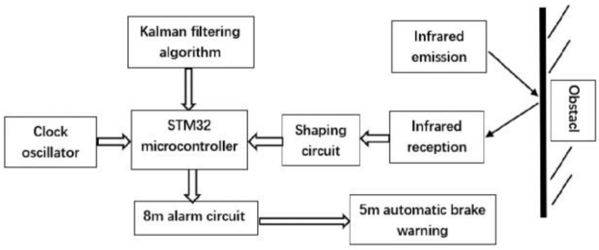


Fig. 2 *Flow chart of detection of the tram distance from obstacle in real time [4]*

The paper by Weber et al. (2015) examined the injury severity of pedestrians as a result of collision with a tram. Most scientific studies have explored the basic emergency situations, but optimisation of the shape of the tram front end (buffer) is rarely analysed. The purpose of this study was, therefore, to optimise the tram buffer design first in order to reduce the risk of injuries of pedestrians, and then to develop practical procedures for designing the services of public transport and manufacturers. Typical accident scenarios were defined based on the analysis of the collisions of trams and pedestrians in a large Swiss city and based on cases known from the literature. Mathematical models of five different tram shapes were tested in the Madymo simulation environment on a dummy model that corresponded to a 50-percentile man. The analysis focused on the kinematics of pedestrians after the collision with a tram and the head injury criterion (HIC), head acceleration and head impact speed were compared. The analysis was focused on the primary impact as well as the secondary impact and situations when the pedestrian ended up underneath the tram. Several critical areas of the front-end geometry of tram were identified, such as the front lid, windscreen, columns and lamp height. Based on these findings, procedures were developed for designing shapes for the front parts of tram in a cooperation with the Swiss public transport services [5].

There are a lot of other scientific papers dealing with the issue of severe impacts on human body at work, playing sports or traffic related situations (Černohlávek, 2020; Chevalier, 2019; Ballo 2016; Svoboda 2019 and 2015, Smolík 2010, Meller 2010, etc.) [6-12].

This paper's goal was mainly to verify the validity of the Hybrid III Dummy for crash tests of tram-pedestrian collisions in the case of frontal and side impact.

2 Experimental measurement

The validity of the Hybrid III Dummy for the tram-pedestrian collision analyses was evaluated at the BEZ laboratory at the Faculty of Physical Education and Sport, Charles University in Prague. A pendulum impact testing machine (impactor), with the weight of

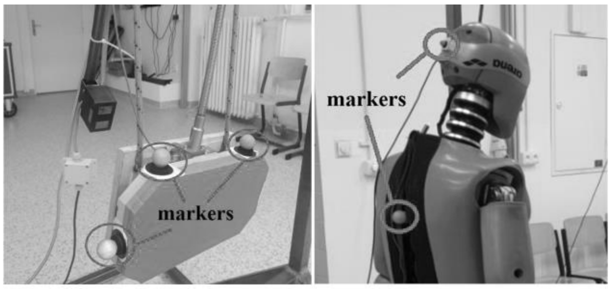
5 kg, was used. The impacts were led towards the chest (the frontal impact) and the left thigh (the side impact) of dummy (Fig. 3) at three different impact intensities (velocities):

- intensity I – average crash (impact) speed v_I = 1 m.s^{-1}
- intensity II – average crash (impact) speed v_{II} = 1.35 m.s^{-1}
- intensity III – average crash (impact) speed v_{III} = 2 m.s^{-1}

Fig. 3 *Pendulum crashing into the Hybrid III Dummy – left thigh*

Measuring equipment used:

- Laboratory model of the self-designed pendulum impact testing machine
- Qualisys MoCap System (nine cameras)
- Passive markers (four on impactor, one on occipital bone, one between shoulder blades) – Fig. 4a and Fig. 4b
- Kistler dynamometric sensors (one on impactor, one dynamometrical plate underneath the dummy feet)
- 3-axis accelerometers (one on impactor, one on occipital bone, one between shoulder blades)
- Holding electromagnet – Fig. 4a



a) Markers on the pendulum *b) Markers on the Hybrid III Dummy*

Fig. 4 *Markers located on the pendulum and on the dummy*

The pendulum was held in the initial position using an electromagnet. The pendulum was set in motion after the measuring equipment was switched on, and it hit the measured part of dummy's body. A Kistler dynamometric sensor was installed in the pendulum body and used to synchronise the times with the measuring equipment of the acceleration sensors on the dummy's body. The pendulum impact surface was fitted with a tatami foam plate so as not to endanger the proband. 3-axis accelerometers were used to measure the response magnitude on the dummy. The first sensor was placed in the area of thoracic vertebra Th5. The second one was placed in the cantle area (Occiput).

The Qualisys system was used to synchronise the acceleration sensors. The markers were placed on the acceleration sensors on the dummy body and four markers were placed on the pendulum. After the measurement completion, the pendulum impact speed was read for the individual impact intensities using the Qualisys system and markers placed on the pendulum. The measurement was conducted using the Hybrid III Dummy which was fitted with 3-axis accelerometers in the vertex area and in the Th5 area.

3 Measurement results

The experiments were conducted using a unique pendulum impact testing machine. There were two impact scenarios typical for tram-pedestrian collisions, the frontal impact into the dummy's chest (Tab. 1, Fig. 5) and the side impact into the dummy's thigh (Tab. 2, Fig. 6). Five measurements were taken for each scenario and for each of three impact intensities (speeds). The primary variables were the resultant acceleration magnitude (g) in the area of Th5 and head. The Shapiro-Wilk test was used for a test of normality. The differences of mean values between Th5 and head were compared using two-tailed, two-sample T-Test and significance level of 0.05. The effect size was evaluated by Cohen's D.

Tab. 1 *The results and statistical analysis for the impact into the dummy's chest*

IMPACT INTO THE DUMMY'S CHEST			
1ST INTENSITY			
	impact intensity (speed, m/s)	**Acceleration magnitude_Th5 (g)**	**Acceleration magnitude_head (g)**
MEAN VALUE	1.081	2.086	1.943
STD	0.012	0.664	0.103
LOWER BOUND 95% CI	1.071	1.504	1.852
UPPER BOUND 95% CI	1.091	2.668	2.033
NORMALITY (SHAPIRO-WILK TEST)	Normal distribution	Normal distribution	Normal distribution
ABSOLUTE DIFFERENCE OF MEANS	0.143		
RELATIVE DIFFERENCE OF MEANS (%)	6.865		
P-VALUE (T-TEST)	0.681		
COHEN'S D	0.302		
EFFECT SIZE DESCRIPTION	Medium		
2ND INTENSITY			
	impact intensity (speed, m/s)	**Acceleration magnitude_Th5 (g)**	**Acceleration magnitude_head (g)**
MEAN VALUE	1.470	3.353	2.940
STD	0.025	0.087	0.325
LOWER BOUND 95% CI	1.448	3.277	2.655
UPPER BOUND 95% CI	1.492	3.430	3.225
NORMALITY (SHAPIRO-WILK TEST)	Normal distribution	Normal distribution	Normal distribution
ABSOLUTE DIFFERENCE OF MEANS	0.413		
RELATIVE DIFFERENCE OF MEANS (%)	12.322		
P-VALUE (T-TEST)	**0.040**		
COHEN'S D	1.735		
EFFECT SIZE DESCRIPTION	Very large		
3RD INTENSITY			
	impact intensity (speed, m/s)	**Acceleration magnitude_Th5 (g)**	**Acceleration magnitude_head (g)**
MEAN VALUE	2.102	5.514	4.631
STD	0.060	0.227	0.741
LOWER BOUND 95% CI	2.049	5.315	3.981
UPPER BOUND 95% CI	2.155	5.713	5.281
NORMALITY (SHAPIRO-WILK TEST)	Normal distribution	Normal distribution	Normal distribution
ABSOLUTE DIFFERENCE OF MEANS	0.883		
RELATIVE DIFFERENCE OF MEANS (%)	16.007		
P-VALUE (T-TEST)	**0.052**		
COHEN'S D	1.610		
EFFECT SIZE DESCRIPTION	Very large		

Regarding the impact into the dummy's chest, the results showed an increasing value of resultant acceleration with increasing impact intensity (speed) for both areas of interest, the Th5 and head area (Tab. 1), following a linear trendline almost perfectly (Fig. 5). Comparing both areas, the data resulted in significantly higher values of acceleration in the Th5 area than in the head, especially in the case of the second and third impact intensities (speed). The corresponding values of Cohen's D exceeded the value of 1, i.e. a very large effect size, which suggests a trend towards a significant attenuation of impact by the chest. However, there were only three low impact intensities (speeds) used during these tests, which is a limitation of the study.

Tab. 2 *The results and statistical analysis for the impact into the dummy's thigh*

IMPACT TO THE DUMMY'S CHEST			
1ST INTENSITY			
	impact intensity (speed, m/s)	**Acceleration magnitude_Th5 (g)**	**Acceleration magnitude_head (g)**
MEAN VALUE	0.965	0.467	0.474
STD	0.025	0.025	0.098
LOWER BOUND 95% CI	0.943	0.445	0.388
UPPER BOUND 95% CI	0.987	0.489	0.560
NORMALITY (SHAPIRO-WILK TEST)	Normal distribution	Normal distribution	Normal distribution
ABSOLUTE DIFFERENCE OF MEANS		0.007	
RELATIVE DIFFERENCE OF MEANS (%)		1.498	
P-VALUE (T-TEST)		0.894	
COHEN'S D		0.098	
EFFECT SIZE DESCRIPTION		Small	
2ND INTENSITY			
	impact intensity (speed, m/s)	**Acceleration magnitude_Th5 (g)**	**Acceleration magnitude_head (g)**
MEAN VALUE	1.393	0.660	0.653
STD	0.052	0.035	0.051
LOWER BOUND 95% CI	1.347	0.629	0.608
UPPER BOUND 95% CI	1.439	0.691	0.698
NORMALITY (SHAPIRO-WILK TEST)	Normal distribution	Normal distribution	Normal distribution
ABSOLUTE DIFFERENCE OF MEANS		0.007	
RELATIVE DIFFERENCE OF MEANS (%)		1.061	
P-VALUE (T-TEST)		0.827	
COHEN'S D		0.160	
EFFECT SIZE DESCRIPTION		Small	
3RD INTENSITY			
	impact intensity (speed, m/s)	**Acceleration magnitude_Th5 (g)**	**Acceleration magnitude_head (g)**
MEAN VALUE	1.984	1.068	1.120
STD	0.028	0.121	0.097
LOWER BOUND 95% CI	1.959	0.962	1.035
UPPER BOUND 95% CI	2.008	1.174	1.206
NORMALITY (SHAPIRO-WILK TEST)	Normal distribution	Normal distribution	Normal distribution
ABSOLUTE DIFFERENCE OF MEANS		0.052	
RELATIVE DIFFERENCE OF MEANS (%)		4.868	
P-VALUE (T-TEST)		0.522	
COHEN'S D		0.473	
EFFECT SIZE DESCRIPTION		Medium	

Regarding the impact into the dummy's thigh, the results showed an increasing value of resultant acceleration with increasing impact intensity (speed) for both areas of interest, the Th5 and head area (Tab. 2), following a linear trendline almost perfectly (Fig. 6). Comparing both areas, the data showed no significant differences between the Th5 area and head. The corresponding Cohen's D values were small, and the third intensity (speed) was the only one to reach a medium effect size. However, there were only three low impact intensities (speeds) used during these tests, which is an additional limitation of the study.

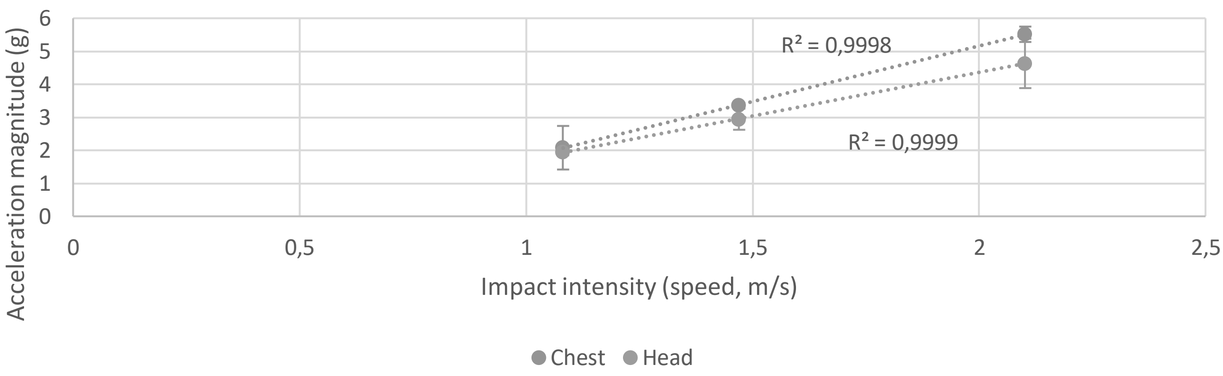


Fig. 5 *The effect of the impact intensity (speed) on the resultant acceleration magnitude in the area of Th5 and head in the case of impact into the dummy's chest*

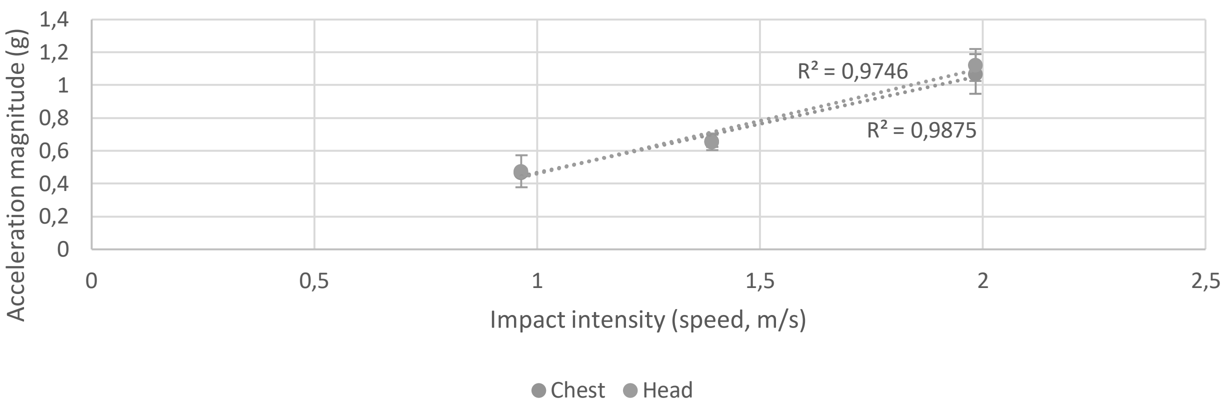


Fig. 6 *The effect of impact intensity (speed) on the resultant acceleration magnitude in the area of Th5 and head in the case of impact into the dummy's thigh*

4 Conclusion

The paper has presented the experimental evaluation of the usability of the crash tests by the self-designed pendulum hitting the Hybrid III Dummy for purposes of further use of the dummy for tram crash tests.

The subject impacts into the dummy were conducted at low impact speed (1 to 2 $m.s^{-1}$) using a self-designed pendulum (impactor). The low impact speed was chosen due to the future need to verify the data measured on the dummy with a human in order to verify the validity of the Hybrid III Dummy for impact tests in the frontal and lateral directions.

The impacts were directed at the chest and left thigh. The tree-axis acceleration sensors measured the body response in the area of the thoracic vertebra Th5 and on the vertex. The Kistler dynamometric plate was installed in the pendulum which provided the impact intensity magnitudes.

The results of the paper verified the possibility of using the self-designed pendulum for the crash dummy tests and expanded the possibilities of using the Hybrid III Dummy for further experimental measurements which can be used, for instance, in the crash tests simulating collisions of a man with a tram.

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