DOI: 10.21062/mft.2023.047 http://www.journalmt.com

Experimental Validation of the Biomechanical Response of an Anthropomorphic Testing Device (Dummy) at Low Impact Velocities

Karel Jelen (0000-0002-8151-9810)[1], Petr Kubovy (0000-0001-7634-2910)[1], Frantisek Lopot (0000-0001-9955-0261)[2], Lukas Fara (0009-0004-7491-8292)[3], Roman Jezdik (0000-0002-6691-0600)[4], Filip Hrusa (0000-0003-4522-4350)[1],Hynek Purs (0009-0005-5711-3051)[5], Tommi Tikkanen (0000-0003-4076-4745)[6], Martin Novak (0000-0002-2010-4398)[7], Martin Svoboda (0000-0002-7344-1531)[7], Lubos Tomsovsky* (000-0003-0047-6028)[1].

[1]Faculty of Physical Education and Sport, Charles University in Prague. Jose Martiho 31, 162 52 Prague. Czech Republic. Emails: lubostomsovsky@gmail.com; jelen@ftvs.cuni.cz; kubovy.petr@seznam.cz; filiphrusa@gmail.com.

[2]Department of Designing and Machine Components, Czech Technical University in Prague. Jugoslavskych partyzanu 1580/3, 160 00 Prague 6 – Dejvice. Czech Republic. Email: flopot@seznam.cz.

[3]Research, Development and Technology, Skoda Transportation a. s. Emila Skody 2922/1, 301 00 Pilsen. Czech Republic. Email: Lukas.fara@skodagroup.com.

[4]Research, Development and Testing of Railway Rolling Stock, VÚKV a. s. Bucharova 1314/8, 158 00 Prague 5 – Stodulky. Czech Republic. Email: jezdik@vukv.cz.

[5]Project Engineering, Advanced Engineering, s.r.o. Beranovych 65, 199 21 Prague 9. Czech Republic. Email: hpurs@advanced-eng.cz.

[6]GIM Oy. Turuntie 42, 02650 Espoo. Finland. Email: tommi.tikkanen@gimrobotics.fi.

[7]Faculty of Mechanical Engineering, Jan Evangelista Purkyne University in Usti nad Labem, Pasteurova 3334/7, 400 96 Usti nad Labem. Czech Republic. Email: martin.novak1@ujep.cz; martin.svoboda@ujep.cz

*Lubos Tomsovsky is a corresponding author.

The paper describes the experimental validation of the biomechanical response of the Hybrid III 50th Percentile Male Pedestrian Dummy (JASTI, Tokyo, Japan) at low impact velocity (up to 2.2 m/s) in comparison with that of human probands. The paper is based on previous research that was focused on the tram-pedestrian crash tests using the same dummy. The biofidelity of dummy was analysed in two collision scenarios: the anteroposterior impact (chest impact) and lateral impact (shoulder impact) using a unique pendulum impact testing machine of own design and construction. The primary outcome variable was the peak resultant acceleration of the head and chest during the impact. Based on the lab-based measurements, the unique impact testing machine was found adequate and precise for the purposes of future crash-test analyses in the area of automotive industry. The proposed methodology and measurement protocol were shown proper to compare the data between the dummy and human participants. Following the pilot experiments, the kinematic and dynamic data between the dummy and human participants were analysed to assess the biofidelity of dummy for the frontal and side impact during tram-pedestrian collisions at low impact velocities.

Keywords: Crash test; tram; pedestrian; safety; dummy; biofidelity.

1 Introduction

This section of the paper presents a summary of the important scientific work used to develop the methodology for the experimental investigation of minor impacts performed on human probands and the Hybrid III 50th Percentile Male Pedestrian Dummy.

One of the biggest problems to be solved nowadays is traffic accidents (Vojtíšek, 2008). It is a societal problem that, according to the World Health Organization (WHO), has already caused the deaths of approximately 25 million people worldwide in the past. An average of 1.2 million people worldwide succumb to injuries caused by traffic accidents each year. Pedestrians and cyclists are the least protected group of road users. Injuries can easily occur when they collide with cars, motorcycles, buses, and trams. During a vehicle-pedestrian collision, injuries occur during the collision (the primary impact) and then during the impact with the roadway or terrain obstacle (the secondary impact) [1].

The extreme human load at accidents in transport vehicles is a worldwide issue. Collisions between a person and a vehicle on a traffic road (e.g. a tram) are also an area of concern.

For example, from 2003 to 2020, 245 serious injuries were recorded in the Czech Republic as a result of a pedestrian collision with a tram. Currently, the design of the front bumper of trams is being modified to reduce the likelihood of severe injury or even death in the event of a collision with a pedestrian [2].

The main objective of the work (Bittner, et al., 2019) was to address the impact testing of tram windshields in the analysis of human-machine accident events. Empirical experience shows that the head, which is one of the most sensitive segments of the human body, is particularly affected by these events. Windscreen safety testing (Fig. 1) was based on ECE standards and was also based, among other things, on collision events with a dummy head [3].

Fig. 1 *Tram windscreen after collision with two pedestrians – contact points [3]*

The article (Weber, Muser, & Schmitt, 2015) discussed serious pedestrian injuries in collisions with trams. In most scientific studies, basic crash situations have been investigated, but optimisation of the shape of the front part of the tram (bumper) is rarely addressed. The aim of this study was to optimise the design of the tram bumper to reduce the risk of pedestrian injury. Typical accident scenarios were defined based on an analysis of tram-pedestrian collisions and cases dealt with in previous research. Another objective of the work was to establish general procedures for the design of public transport vehicles. In the MADYMO simulation environment, mathematical models of five different tram bumper shapes were tested on the HIII-50M dummy model. The kinematics of the struck pedestrians, HIC injury criteria, head acceleration and head impact velocity were analysed. The primary impact, secondary impact and the situation when the pedestrian ended up under the tram wheels were solved.

During the simulations, potentially critical areas were identified in different parts of the tram front axle, such as the front cover, windscreen, pillars and headlight height (Fig. 2).

The aim of the study (Untaroiu, et al., 2009) was to develop a reliable methodology that takes into account the vehicle speed and the position in which the pedestrian's body is before impact using Multi-Body simulations (Fig. 3) and optimisation techniques (Fig.4).

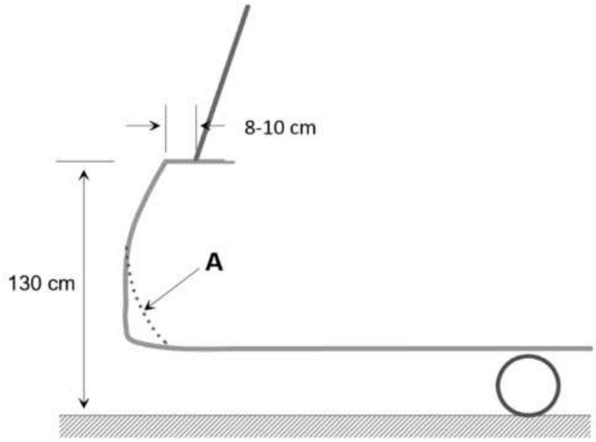

Fig. 2 *Example of tram bumper shape optimisation [4]*

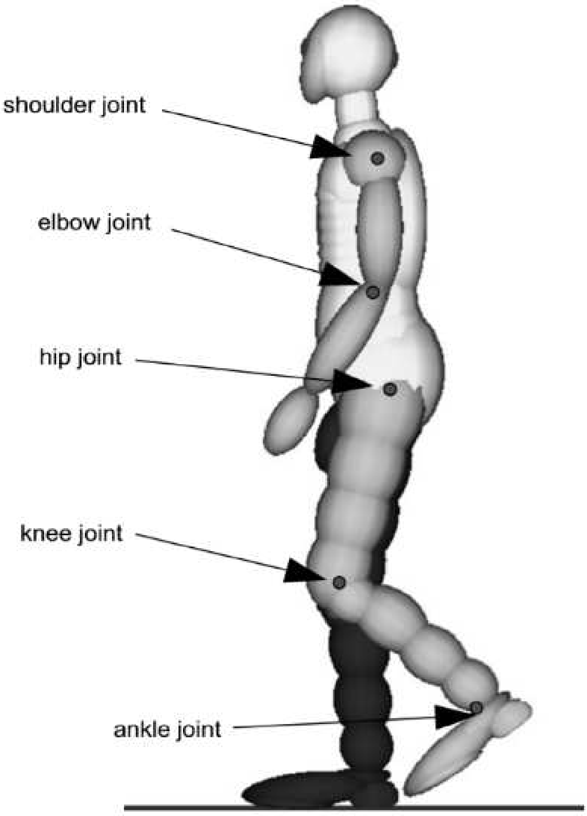

Fig. 3 *MADYMO Multibody Solver – upper and lower limb joints [5]*

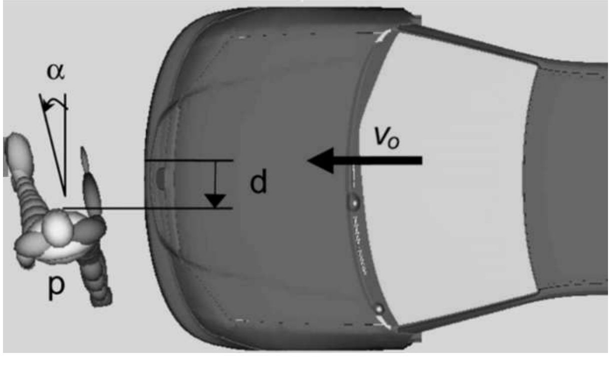

Fig. 4 *Pre-impact parameters of car and pedestrian models used as design variables in crash reconstruction [5]*

It has been shown that numerical simulations of a vehicle striking a pedestrian will be able to be used to understand how pedestrian injuries relate to documented vehicle damage [5].

There are many other scientific papers that address the issue of extreme human load in work, sports or traffic situations, or deal with vehicle dynamics (Černohlávek, 2020; Svoboda 2017, Ježdík 2021, Fanta 2022, and others) [6-12].

Based on the outcomes of previous research, four main hypotheses were developed for the purposes of this study:

- **Hypothesis 1** – A significant difference in biomechanical response in the occipital area of head will be found between the Hybrid III 50th Percentile Male Pedestrian Dummy and human participants during a frontal, low-intensity impact to the chest (anteroposterior direction of impact).
- **Hypothesis 2** – A significant difference in biomechanical response in the area of Th5 vertebra will be found between the Hybrid III 50th Percentile Male Pedestrian Dummy and human participants during a frontal, low-intensity impact to the chest (anteroposterior direction of impact).
- **Hypothesis 3** – A significant difference in biomechanical response in the area of Th5 vertebra will be found between the Hybrid III 50th Percentile Male Pedestrian Dummy and human participants during a side, low-intensity impact to the shoulder (lateral direction of impact).
- **Hypothesis 4** – A significant difference in biomechanical response in the occipital area of head will be found between the Hybrid III 50th Percentile Male Pedestrian Dummy and human participants during a side, low-intensity impact to the shoulder (lateral direction of impact).

2 Materials and methods

Experimental validation of the biomechanical response of the Hybrid III 50th Percentile Male Pedestrian Dummy was carried out in the BEL laboratory (Laboratory of Biomechanics of Extreme Loads) at the Faculty of Physical Education and Sport, Charles University in Prague. The participants were impacted by lowering a 5 kg pendulum. The impacts were directed to the chest (anteroposterior direction – see Fig. 5) and to the left shoulder (lateral direction – see Fig. 6) at various low impact velocities (approx. 1 to 2.2 $m.s^{-1}$). 3-axis accelerometers were attached to the occipital area of head and the area of Th5 vertebra to both, the Hybrid III 50th Percentile Male Pedestrian Dummy, as well as the human participants (see Fig. 7).

The measuring devices used in the pilot experiment consisted of nine motion capture cameras of the Qualisys system (Qualisys AB, Göteborg, Sweden) with passive markers (four on the impact testing machine, one on the occipital bone, one between the shoulder blades), Kistler dynamometer sensors (one on the impact testing machine, one force plate under the participant's feet), a unique pendulum impact testing machine of own design (see Fig. 7), 3-axis accelerometers (one on the impact testing machine, one on the occipital bone, one between the shoulder blades), and an electromagnet that was used to hold and release the pendulum from its initial starting position.

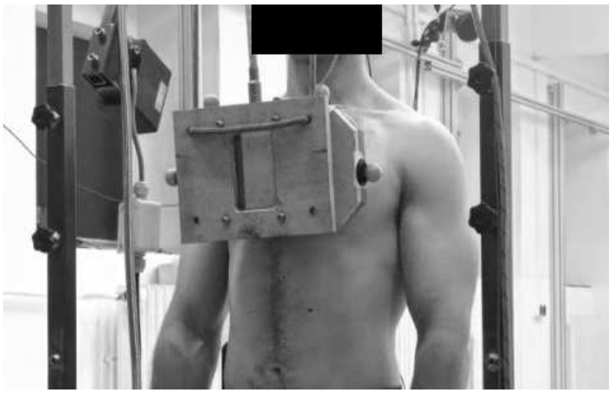
[redacted]

Fig. 5 An example of the impact testing pendulum impacting the participant's chest– pilot experiment


[redacted]

Fig. 6 An example of the impact testing pendulum impacting the participant's shoulder – pilot experiment

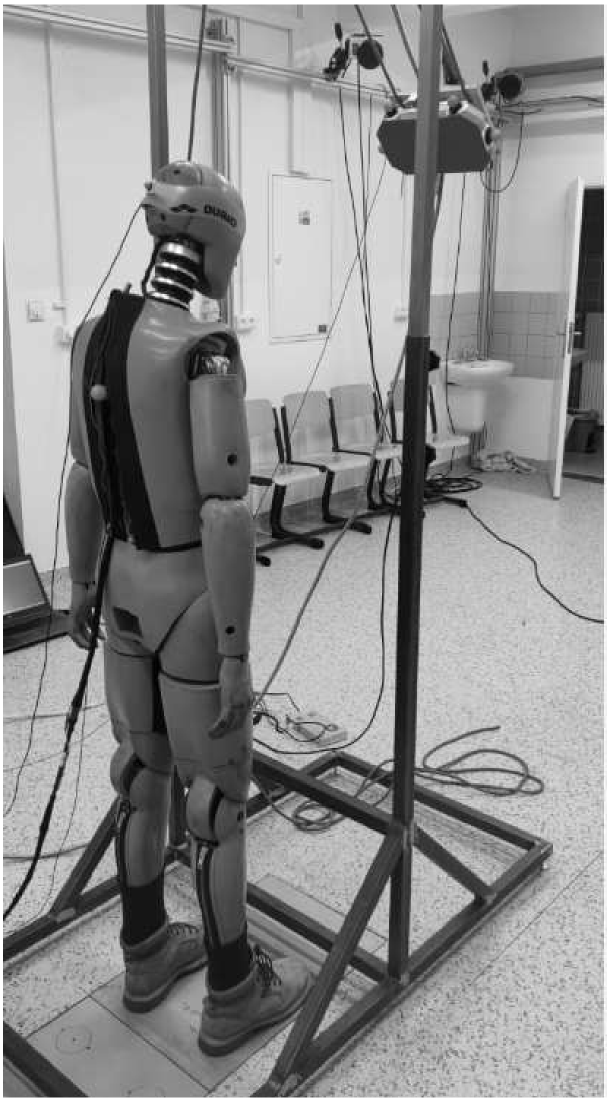

Fig. 7 *Hybrid III Dummy – pilot experiment*

3 Results

3.1 Chest impact (anteroposterior impact)

In the case of frontal chest impact, the data were collected from eleven participants and one dummy. For each impact velocity (intensity), there were three measurements conducted on human participants and five measurements on the dummy (Tab. 1). The intensity, or magnitude of the impact velocity, showed an almost identical increment of 0.5 m/s, from the lowest intensity (μ_{dummy} = 1.081 m.s^{-1}, SD = 0.012, 95% CI 1.071-1.092; $\mu_{proband}$ = 1.074 m.s^{-1}, SD = 0.195, 95% CI 0.904-1.245), over moderate intensity (μ_{dummy} = 1.470 m.s^{-1}, SD = 0.025, 95% CI 1.448-1.492; $\mu_{proband}$ = 1.494 m.s^{-1}, SD = 0.185, 95% CI 1.332-1.657), to the highest intensity (μ_{dummy} = 2.102 m.s^{-1}, SD = 0.061, 95% CI 2.049-2.155; $\mu_{proband}$ = 2.101 m.s^{-1}, SD = 0.157, 95% CI 1.964-2.238).

Mean values of each impact velocity between the dummy and participants were compared using Welch's t-test (unequeal variances t-test) because of the inequality of variances between the two sets that resulted from the F test. The results showed that the impact velocities were not significantly different (p-value >0.05), and the mean values of impact velocities are almost identical (Cohen's d <0.1). Therefore, the results confirmed the reliability and precision of the pendulum impact testing machine for similar following crash-test analyses at low impact velocities.

For the statistical analysis of the head and Th5 areas loading between the dummy and participants during the frontal impact into the chest, the primary outcome variable of interest was the resultant peak acceleration in multiples of the free-fall acceleration of standard gravity (g). In both cases, the dummy and participants, the results followed an almost perfect linear trend of acceleration increase for the head (Fig. 8) and the Th5 thoracic vertebra (Fig. 9) with increasing intensity. Therefore, the results indicated a possible precision and reliability of using a linear regression model to predict the resultant peak acceleration even at higher impact velocity values where the use of human participants is no longer possible due to ethical and safety reasons (coefficient of determination, R^2 >0.98).

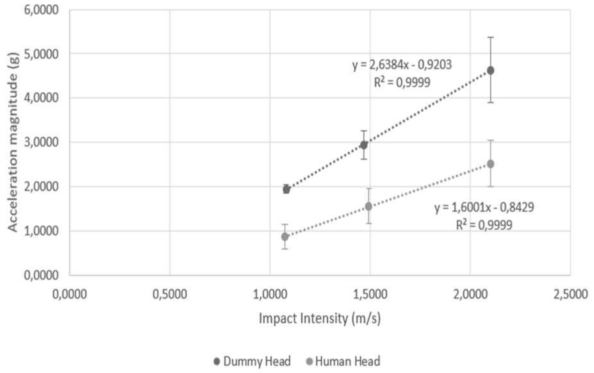

Fig. 8 *The results of resultant peak acceleration for the head of dummy and participants for three impact velocities (intensities)*

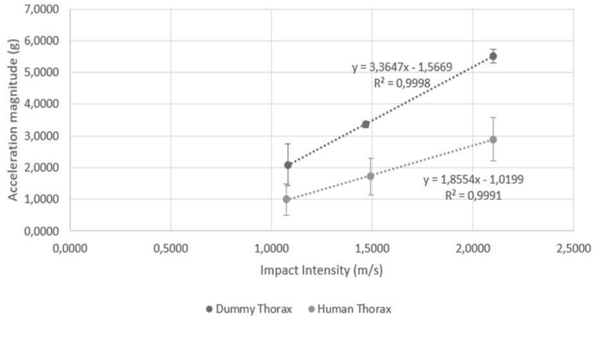

Fig. 9 *The results of resultant peak acceleration for the Th5 vertebra of dummy and participants for three impact velocities (intensities)*

Tab. 1 *Chest impacts human vs. dummy – anteroposterior direction*

First intensity						
	Impact velocity – dummy (m/s)	**Impact velocity – participant (m/s)**	**Peak head acceleration – dummy (g)**	**Peak head acceleration – participant (g)**	**Peak chest acceleration – dummy (g)**	**Peak chest acceleration – participant (g)**
Mean value	1.0810	1.0744	1.9426	0.8711	2.0858	0.9936
Standard deviation	0.0119	0.1948	0.1029	0.2789	0.6637	0.4961
Lower limit 95% CI	1.0705	0.9037	1.8524	0.6266	1.5040	0.5588
Upper limit 95% CI	1.0915	1.2452	2.0328	1.1155	2.6676	1.4285
Absolute difference in mean values	0.0066		1.0715		1.0922	
Relative difference in mean values (%)	0.6061		55.1595		52.3615	
P-value (T-test)	0.8620		<0.001		<0.001	
Cohen's d	0.0061		0.7118		0.6685	
Effect size	Trivial		Medium		Medium	
Second intensity						
	Impact velocity – dummy (m/s)	**Impact velocity – participant (m/s)**	**Peak head acceleration – dummy (g)**	**Peak head acceleration – participant (g)**	**Peak chest acceleration – dummy (g)**	**Peak chest acceleration – participant (g)**
Mean value	1.4698	1.4942	2.9402	1.5570	3.3534	1.7186
Standard deviation	0.0248	0.1852	0.3253	0.3945	0.0873	0.5758
Lower limit 95% CI	1.4481	1.3319	2.6551	1.2112	3.2769	1.2139
Upper limit 95% CI	1.4915	1.6566	3.2253	1.9028	3.4299	2.2233
Absolute difference in mean values	0.0244		1.3832		1.6348	
Relative difference in mean values (%)	1.6629		47.0444		48.7507	
P-value (T-test)	0.5150		<0.001		<0.001	
Cohen's d	0.0165		0.5880		0.6136	
Effect size	Trivial		Medium		Medium	
Third intensity						
	Impact velocity – dummy (m/s)	**Impact velocity – participant (m/s)**	**Peak head acceleration – dummy (g)**	**Peak head acceleration – participant (g)**	**Peak chest acceleration – dummy (g)**	**Peak chest acceleration – participant (g)**
Mean value	2.1016	2.1010	4.6312	2.5153	5.5138	2.8921
Standard deviation	0.0605	0.1565	0.7413	0.5269	0.2270	0.6869
Lower limit 95% CI	2.0486	1.9638	3.9815	2.0534	5.3149	2.2900
Upper limit 95% CI	2.1546	2.2382	5.2809	2.9771	5.7127	3.4941
Absolute difference in mean values	0.0006		2.1160		2.6217	
Relative difference in mean values (%)	0.0300		45.6890		47.5486	
P-value (T-test)	0.9880		0.0024		<0.001	
Cohen's d	0.0003		0.5678		0.5955	
Effect size	Trivial		Medium		Medium	

3.2 Impact to the left shoulder (side impact)

In the case of frontal chest impact, the data were collected from eleven participants and one dummy. For each impact velocity (intensity), there were three measurements conducted on human participants and five measurements on the dummy (Tab. 2). The intensity, or magnitude of the impact velocity, showed an almost identical increment of 0.5 m.s^{-1}, from the lowest intensity (μ_{dummy} = 1.055 m.s^{-1}, SD = 0.047, 95% CI 1.013-1.096; $\mu_{proband}$ = 1.063 m.s^{-1}, SD = 0.121, 95% CI 0.957-1.169), over moderate intensity (μ_{dummy} = 1.478 m.s^{-1}, SD = 0.064, 95% CI 1.422-1.534; $\mu_{proband}$ = 1.472 m.s^{-1}, SD = 0.262, 95% CI 1.242-1.702) to the highest intensity (μ_{dummy} = 2.056 m.s^{-1}, SD = 0.010, 95% CI 2.047-2.065; $\mu_{proband}$ = 2.078 m.s^{-1}, SD = 0.142, 95% CI 1.953-2.202).

Mean values of each impact velocity between the dummy and participants were compared using Welch's t-test (unequeal variances t-test) because of the inequality of variances between the two sets that resulted from the F test. The results showed that the impact velocities were not significantly different (p-value >0.05), and the mean values of impact velocities are almost identical (Cohen's d <0.1). Therefore, the results confirmed the reliability and precision of the pendulum impact testing machine for similar following crash-test analyses at low impact velocities.

***Tab. 2** Impacts to the left shoulder – lateral direction*

First intensity						
	Impact velocity – dummy (m/s)	Impact velocity – participant (m/s)	Peak head acceleration – dummy (g)	Peak head acceleration – participant (g)	Peak chest acceleration – dummy (g)	Peak chest acceleration – participant (g)
Mean value	1.0546	1.0626	0.7380	0.6471	1.4668	1.3070
Standard deviation	0.0474	0.1209	0.0646	0.1823	0.5326	0.1998
Lower limit 95% CI	1.0131	0.9567	0.6813	0.4873	1.0000	1.1318
Upper limit 95% CI	1.0961	1.1686	0.7947	0.8069	1.9336	1.4822
Absolute difference in mean values	0.0080		0.0909		0.1598	
Relative difference in mean values (%)	0.7630		12.3144		10.8945	
P-value (T-test)	0.8365		0.2965		0.5850	
Cohen's d	0.0076		0.1309		0.1150	
Effect size	Trivial		Small		Small	
Second intensity						
	Impact velocity – dummy (m/s)	Impact velocity – participant (m/s)	Peak head acceleration – dummy (g)	Peak head acceleration – participant (g)	Peak chest acceleration – dummy (g)	Peak chest acceleration – participant (g)
Mean value	1.4780	1.4719	1.1996	1.1291	1.9510	2.2962
Standard deviation	0.0640	0.2620	0.0673	0.3316	0.0323	0.6015
Lower limit 95% CI	1.4219	1.2422	1.1406	0.8384	1.9227	1.7689
Upper limit 95% CI	1.5341	1.7015	1.2586	1.4197	1.9793	2.8234
Absolute difference in mean values	0.0061		0.0705		0.3452	
Relative difference in mean values (%)	0.4160		5.8793		17.6924	
P-value (T-test)	0.9199		0.3363		0.0063	
Cohen's d	0.0042		0.0605		0.1620	
Effect size	Trivial		Trivial		Small	
Third intensity						
	Impact velocity – dummy (m/s)	Impact velocity – participant (m/s)	Peak head acceleration – dummy (g)	Peak head acceleration – participant (g)	Peak chest acceleration – dummy (g)	Peak chest acceleration – participant (g)
Mean value	2.0564	2.0776	1.7428	1.8093	2.8024	3.7203
Standard deviation	0.0103	0.1422	0.0871	0.4697	0.1983	0.7438
Lower limit 95% CI	2.0474	1.9529	1.6665	1.3976	2.6286	3.0684
Upper limit 95% CI	2.0654	2.2022	1.8191	2.2210	2.9762	4.3722
Absolute difference in mean values	0.0212		0.0665		0.9179	
Relative difference in mean values (%)	1.0286		3.8163		32.7536	
P-value (T-test)	0.4456		0.5061		0.0806	
Cohen's d	0.0102		0.0374		0.2787	
Effect size	Trivial		Trivial		Small	

In both cases, the dummy and participants, the results followed an almost perfect linear trend of acceleration increase for the head (Fig. 10) and the Th5 thoracic vertebra (Fig. 11) with increasing intensity. Therefore, the results indicated a possible precision and reliability of using a linear regression model to predict the resultant peak acceleration even at higher impact velocity values where the use of human participants is no longer possible due to ethical and safety reasons (coefficient of determination, $R^2 > 0.98$).

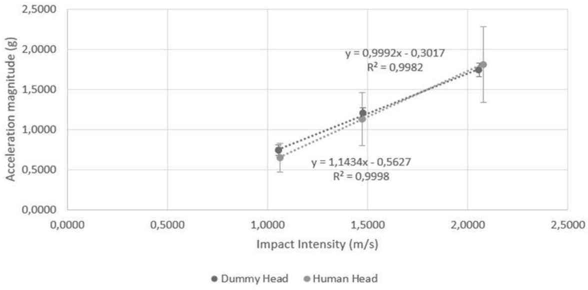

***Fig. 10** The results of resultant peak acceleration for the head of dummy and participants for three impact velocities (intensities)*

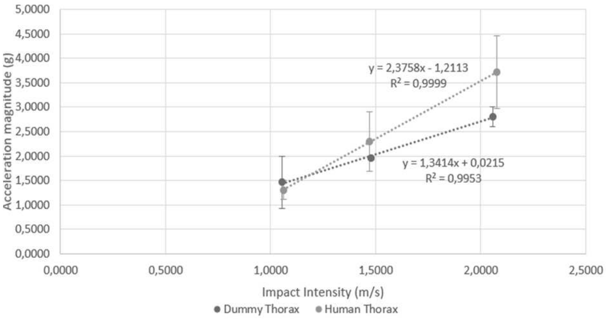

Fig. 11 *The results of resultant peak acceleration for the Th5 vertebra of dummy and participants for three impact velocities (intensities)*

4 Discussion

Based on the outcomes of experiments, the precision and reliability of the unique pendulum impact testing machine has been verified and could be used for following and similar experimental measurements in the automotive industry. The proposed methodology and protocol enabled to obtain the input values of impact velocities at different locations of human and dummy body in the anteroposterior (chest) and lateral (left shoulder) directions. The primary outcome variable was the resultant peak acceleration during the primary impact in the occipital area of head and in the area of Th5 vertebra.

In the case of the frontal chest impact, the resultant peak acceleration values showed a steeper trend of increase for the dummy compared to the participants with increasing intensity (impact velocity) for both, the head (Fig. 8) and the Th5 thoracic vertebra (Fig. 9). In addition, the results of the statistical analysis, based on Welch's t-test, showed significantly higher values of resultant peak acceleration of the head and thoracic vertebra at all three intensity values in the case of the dummy (*p-value* <0.05) compared to human participants (Tab. 1). The values of the acceleration, in the case of dummy, reached almost twice the values of the human participants, hence the effect size (effect of using the dummy) was considerable (*Cohen's d* >0.5, "medium effect"). Thus, the results of the frontal impact to the chest suggest that the dummy does not provide a similar biomechanical response to human participants at low impact velocities, which negatively affects its suitability and reliability for similar crash test purposes. The results thus confirm the first and second hypothesis of this work and significant differences between dummy and human participants were found during frontal impact at low impact velocities. However, the differences could be significantly influenced by the experimental protocol itself, whereby participantss could react to the approaching pendulum based on visual and auditory sensations and unconsciously influence their biomechanical response to the primary impact.

In the case of the lateral impact to the shoulder, the resultant peak acceleration values showed a steeper trend of increase for the participantss than for the dummy with increasing intensity (impact velocity) for both, the head (Fig. 10), and especially for the thoracic vertebra (Fig. 11). From the measured and graphical results, and the results of the statistical analysis, based on *Welch's t-test*, it is clear that the values of the resultant peak head acceleration were very similar between the dummy and the participants, and the small differences were not significant (*p-value* >0.05, *Cohen's d* <0.1). In the case of the thoracic vertebra, a significantly higher value of the resultant peak acceleration was found at the second intensity in human participants compared to the dummy and at the third intensity, but statistical significance was not reached (Tab. 2). Thus, in terms of the hypotheses of the work, the third hypothesis was partially proved, i.e., a statistically significant difference in the response in the thoracic vertebrae between participants and the dummy was found, compared to the fourth hypothesis, which was on the contrary refuted by the results. However, the effect size was small in all cases and thus the mean values did not differ significantly between participants and the dummy (*Cohen's d* <0.3, "small effect"). The results of the low-intensity side impact to the shoulder, therefore, indicate the suitability and reliability of the dummy for similar crash test purposes.

5 Conclusion

In this paper, an experimental validation of the biomechanical response of the Hybrid III 50th Percentile Male Pedestrian Dummy to tram impact tests was performed. Impacts to the human and the dummy were performed at low impact velocity (1 to 2.2 $m.s^{-1}$) using a unique pendulum impact testing machine of own design and construction. The results indicated the suitability of using the dummy for the purpose of similar impact tests at low impact velocities in the case of a side impact. On the other hand, in the case of a frontal impact to the chest, a statistically different biomechanical response between the dummy and human subjects was demonstrated, which significantly affects its suitability and reliability for the purpose of similar impact tests at low impact velocities. In further evaluation, it will be necessary to determine and include the so-called damping coefficient of human muscle activity. The human activates the muscular system in response to the approaching situation and the resulting response may, therefore, be lower than in a dummy hit by the same impact.

Acknowledgement

The project was funded by Operational Programme Research, Development and Education CZ.02.1.01/0.0/0.0/16_026/0008401.

References

[1] VOJTÍŠEK, T. Forenzní hodnocení poranění u smrtelných dopravních nehod chodců při střetu s osobními vozidly (Forensic evaluation of injuries in fatal pedestrian accidents in collisions with passenger vehicles). Brno, 2008. Dissertation. Masaryk University, Institute of Forensic Medicine. Thesis supervisor Prof. MUDr. Miroslav HIRT, CSc.

[2] Statistical evaluation of accidents in the map, Police of the Czech Republic. Website http://maps.jdvm.cz/cdv2/apps/nehodyvmape/Search.aspx; information retrieved on 06/06/2022.

[3] BITTNER, V., JEŽDÍK, R., KUBOVY, P., LOPOT, F., STOČEK, O., HAVLÍČEK, M., SVOBODA, M, JELEN, K.: Possibilities of Using Tram Windscreen Impact Tests in Analysis of Human-Machine Accidents. In: *Manufacturing Technology*, Vol. 19, No. 6 (2019) pp. 912-916, ISSN: 1213-2489

[4] WEBER, T., MUSER, M. H., & SCHMITT, K.-U. (2015). Optimising the design of tramways to mitigate injury risk in pedestrian impacts. *2015 IRCOBI Conference Proceedings* (pages 339-349). Lyon: International Research Council on Biomechanics of Injury.

[5] UNTAROIU, C. D., MEISSNER, M. U., CRANDALL, J. R., TAKAHASHI, Y., OKAMOTO, M., & ITO, O. Crash reconstruction of pedestrian accidents using optimization techniques. *International Journal of Impact Engineering.*

[6] ČERNOHLÁVEK, V., SVOBODA, M., ŠTĚRBA, J., CHALUPA, M., SAPIETA, M.: Analytical and experimental solution of vibrations of a system of bound bodies, In: *Manufacturing Technology*, Vol. 20, No 6 (2020), pp. 699-707, ISSN: 1213-2489, DOI: 10.21062/mft.2020.116

[7] SVOBODA, M., SCHMID, V., SOUKUP, J., SAPIETA, M.: Influence of the spring system in vehicle vibraphone, In *Vibration, Control and Stability of Dynamical systems*, Lodz, 2017, Politechnika Lodz", pp. 505-512, ISBN 978-83-935312-5-7

[8] JEŽDÍK, R., KONOPNÍK, P., RUND, M., SVOBODA, M, DEER, K.: Determination of material properties of laminates of 15T and T3 tram faces. In: *Manufacturing Technology*, Vol. 21, No. 4 (2021) pp. 912-916, ISSN: 1213-2489 DOI: 10.21062/mft.2021.040

[9] CERNOHLAVEK, V.; KLIMENDA, F.; HOUSKA, P.; SUSZYŃSKI, M. Vibration Measurements on a Six-Axis Collaborative Robotic Arm-Part I. *Sensors* 2023, *23*, 1629. ISSN: 1424-8220

[10] SVOBODA, M.; CHALUPA, M.; JELEN, K.; LOPOT, F.; KUBOVÝ, P.; SAPIETA, M.; KROBOT, Z.; SUSZYŃSKI, M. Load Measurement of the Cervical Vertebra C7 and the Head of Passengers of a Car While Driving across Uneven Terrain. *Sensors* 2021, 21, 3849. https://doi.org/10.3390/s21113849

[11] FANTA O, LOPOT F, KUBOVÝ P, JELEN K, HYLMAROVÁ D, SVOBODA M. Kinematic Analysis and Head Injury Criterion in a Pedestrian Collision with a Tram at the Speed of 10 and 20 km.h^{-1}. *Manufacturing Technology.* 2022;22(2):139-145. doi: 10.21062/mft.2022.024.

[12] ČERNOHLÁVEK, V., ŠTĚRBA, J., SVOBODA, M., ZDRÁHAL, T., SUSZYŃSKI, M., CHALUPA, M., KROBOT, Z.: Verification of the safety of storing a pair of pressure vessels. *Manufacturing Technology.* 2021;21(6):762-773. DOI: 10.21062/mft.2021.097.