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Head Impacts during the Direct Frontal (Forehead) and Side (Temple) Collision – Human vs. Hybrid III Dummy

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The paper is focused on the dynamic response of Hybrid III crash-test dummy during low-severity frontal (forehead) and side (temple) head impacts. 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 and construction. The tests were conducted at two various impact intensities (velocities) that did not exceed the speed of 1.6 m/s. The primary outcome variable was a resultant magnitude of acceleration measured on the vertex of dummy's head and the results were compared to 11 human volunteers. The goal of the study was to analyse the biofidelity of Hybrid III Dummy in a pedestrian setting during low-severity frontal and side head impacts by comparing the dynamics and kinematics of the dummy's head to human volunteers.

Keywords: Dummy, Pedestrian, Crash Tests, Biofidelity, Tram, Head impact

1 Introduction

Lately, the world has experienced an economic development, population growth and urbanisation [1,2]. These factors come hand in hand with a growing demand for public transport and the International Transport Forum (ITF) expects the growth of travel aktivity steeply, and according to them it can more than double by 2050 compared to 2015 [3]. In spite of the adverse health issues and effects, the number of motorized vehicles owned by individuals has increased in numbers due to these travel demands [2]. Unfortunately, the cities have also been considered as responsible for three quarters of global energy consumption and greenhouse emissions [1,4]. Therefore, there has been an increasing call and appeal for more frequent use of active transport (such as walking and cycling) and public transport.

Minimizing the effects of climate changes and improving the quality of life in cities (reducing air pollution, emissions, and traffic noise) are other strong reasons for an active promotion of public transport, besides satisfying the needs of growing urban populations [1,2,4]. Specifically, rolling stocks have been shown ecologically and economically beneficial for cities and, therefore, they could be an answer for improving the liveability of cities [5]. Unfortunately, this comes with a several adverse effects too. The growing volume of public transport, rush of people, and the lack of pedestrians' attention, have resulted in an increased number of traffic accidents and the issue of pedestrians' safety has become important [6,7,8].

Although the number of fatalities and severe injuries has been found decreasing in tram-pedestrian collisions, the number of accidents remains high [9]. Lately, this has resulted in a development of methodology, technology, and technial report to improve the design of trams‘ front ends, especially to increase the pedestrian safety, by the European Committee for Standardization (CEN) and rolling stock manufactures [10]. The report predominantly deals with the passive safety measures to minimize the effects of tram-pedestrian accidents. The emphasis is put on the design of trams front ends to minimize the immediate impact on a pedestrian and to reduce the risk of being drawn under the vehicle. Secondly, it is focused on the design of the underframe of a vehicle to decrease the likelihood of severe injuries to a pedestrian lying on the ground, and the recommendations to prevent a pedestrian from being over-run by a vehicle [10]. However, the report only deals with new vehicles, considers a side impact with a pedestrian, and only focuses on the primary (the initial contact of a pedestrian with a front end of tram) and tertiary impact (the risk of being over-run by a vehicle). It provides the description of geometric criteria to decrease the severity of injuries and how to run a numerical simulation of a tram-pedestrian collision. However, the report does not include any recommendations or criteria regarding the crash tests using anthropomorphic test devices (dummies). It only contains a brief description of the desired kinematice, i.e., it should favour either blocking the shoulder and the torso in the quickest possible way while preventing the rotation of the torso, or impacting a pedestrian progressively from the lower legs up to the torso and shoulders [10].

The goal of the study was, therefore, to analyse the biofidelity of Hybrid III Dummy in a pedestrian setting during low-severity frontal and side head impacts by comparing the dynamics and kinematics of the dummy's head to human volunteers [11].

2 Methods

The study was a part of a long-term research project involving the cooperation of The Charles University in Prague, VÚKV a.s. (Research, Development, and Testing of Railway Rolling stock organization), Advanced Engineering s.r.o., and Škoda Transportation a.s. The overall goal of the project was to design and develop new active and passive safety measures that could reduce the frequency and severity of these traffic accidents. One of the important sub-goals of the project was also to verify the biofidelity of anthropomorphic test device for tram-pedestrian collisions during both, the frontal and side impact. The project was funded by Operational Programme Research, Development and Education CZ.02.1.01/0.0/0.0/16_026/0008401.

2.1 Participants

The study included 11 healthy male subjects (age = 26.9 years, *SD* = 10.1; height = 177.4 cm, *SD* = 5.1; weight = 75.7 kg, *SD* = 4.3), each of them exposed to six low-severity impacts for each impact scenario (frontal or side impact) at two different intensities (impact velocities). In the case of frontal impact into a forehead of subjects, mean intensities were 1.37 m/s (*SD* = 0.14) and 1.54 m/s (*SD* = 0.11). In the case of side impact into a temple of subjects, mean intensities were 1.33 m/s (*SD* = 0.26) and 1.55 m/s (*SD* = 0.25). The dynamic response of volunteers' head was measured using a 3-axis accelerometer attached to their occipital bone while the kinematic response was analysed using a passive marker attached at the top of the accelerometer and the motion capture system (Fig. 1).

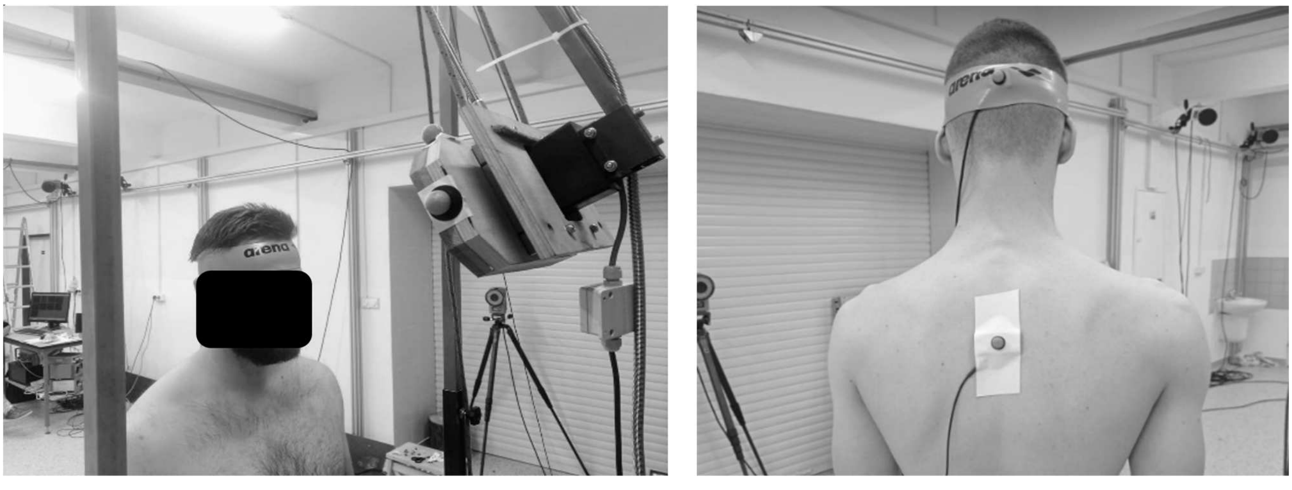

Fig. 1 *An example of the experimental setting of frontal impact with a human volunteer (left) and the sensors attached to the back of their head (right)*

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All methods and measurements conducted in this study were approved by the Faculty of Physical Education and Sport Ethics Committee (Charles University) and participants were explained the experimental protocol in detail, they were given time to ask questions and to give consent before the measurements themselves. In addition, participants were selected to match the anthropomorphic test device (dummy) the best in terms of anthropometric measurements (Tab. 1).

Tab. 10 *Participants' demographics and anthropometry*

Subject no.	Gender	Age (years)	Height (cm)	Weight (kg)
1	Male	20	181.0	77.0
2	Male	38	178.0	79.0
3	Male	20	186.0	86.0
4	Male	47	172.0	74.0
5	Male	20	182.0	75.0
6	Male	21	176.0	73.0
7	Male	21	171.0	75.0
8	Male	22	173.0	75.0
9	Male	44	170.0	70.0
10	Male	19	183.0	70.0
11	Male	24	179.0	79.0
mean		26.9	177.4	75.7
sd		10.1	5.1	4.3

2.2 Anthropomorphic test device (dummy)

Fig. 2 *The Hybrid III Pedestrian Dummy in the experimental setting of a testing device*

The Hybrid III 50th Percentile Male Pedestrian Dummy (JASTI, Tokyo, Japan) was used to simulate the biomechanical response of a pedestrian to the head impact and to compare it to the response of human volunteers (Fig. 2). The height of dummy was 174 cm and its weight was 73 kg. The dummy was exposed to ten low-severity impacts for each impact scenario at two different intensities. In the case of frontal impact into its forehead, mean intensities were 1.37 m/s (SD = 0.01) and 1.56 m/s (SD = 0.01). In the case of side impact into a temple of dummy, mean intensities were 1.34 m/s (SD = 0.07) and 1.54 m/s (SD = 0.24). Similar to human volunteers, the dynamic response of its head was recorded using a 3-axis accelerometer attached to the back of tis head while the kinematic response was measured using a passive marker attached at the top of the accelerometer and the motion capture system of Qualisys (Qualisys AB, Göteborg, Sweden).

2.3 Testing device

The low-severity head impacts were delivered to both, the dummy and human volunteers, using a pendulum impact testing machine with a padded 5kg angular impactor of own unique design (Fig. 3). The impactor was positioned in the way to hit the participants' and dummy's forehead, in the case of frontal impacts, and to hit on their side of the head, just above their left ear, in the case of side impact. The intensity of impact was adjustable using a pendulum system. The impactor was held in its initial position by an electromagnet. A 3-axis accelerometer was attached to the impactor to measure the intensity of impact and to provide a synchronization with sensors attached to the participants' or dummy's head. The kinematics of impactor was analysed using the Qualisys motion capture system with four passive markers attached to the impactor.

Fig. 329 *A unique pendulum impact testing machine (left - the whole construction; right - a detail of impactor with passive markers)*

2.4 Data collection, processing, and analysis

The data collection was provided by technologies mentioned before. The kinematics of the collision was tracked and analysed by the Qualisys motion capture system. The primary outcome variable was the resultant head acceleration in multiples of the acceleration of gravity during each impact scenario:

$$|\vec{a}| = \sqrt{a_x^2 + a_y^2 + a_z^2} \quad (1)$$

Where:

a…The resultant head acceleration (g),

a_x, a_y, a_z…The accelerations of head in each direction (g).

Regarding the statistical analysis, the impact speeds, as well as the resultant head accelerations between the dummy and participants, were compared using Welch's t-test (unequal variances t-test) based on the results of F test (comparing the equality of the two population variances). The results were presented with 95% confidence intervals and those ones with p values <0.05 were considered as significant. The effect size was measured using Cohen's d.

3 Results

3.1 Frontal (forehead) impact

In the case of comparison of frontal (forehead) impact between human participants and dummy (Tab. 2), two low-severity intensities (impact speeds) were used for the analysis (μ_{dummy} = 1.368 m/s, SD = 0.009, 95% CI 1.360-1.375; μ_{human} = 1.374 m/s, SD = 0.141, 95% CI 1.251-1.497) and (μ_{dummy} = 1.563 m/s, SD = 0.010, 95% CI 1.555-1.572; μ_{human} = 1.545 m/s, SD = 0.110, 95% CI 1.449-1.640). The results showed that the impact speeds were not significantly different (p value >0.05), the means of intensities were almost identical (Cohen's d <0.1), a therefore, the reliability and fidelity of a unique testing device was high for the purposes of similar experiments.

Tab. 2 *The results of crash tests*

1st intensity				
	Impact speed – dummy (m/s)	Impact speed – proband (m/s)	Peak head acceleration – dummy (g)	Peak head acceleration – proband (g)
Mean value	1.3676	1.3742	13.1206	7.0109
Standard deviation (SD)	0.0087	0.1405	0.6315	1.8340
95% CI Lower limit	1.3599	1.2511	12.5670	5.4034
95% CI Upper limit	1.3753	1.4974	13.6742	8.6184
Absolute difference of means	0.0066		6.1097	
Relative difference of means (%)	0.4857		46.5659	
P value	0.7938		<0.001	
Cohen's d	0.0048		0.5808	
Effect size	Trivial		Medium	
2nd intensity				
	Impact speed – dummy (m/s)	Impact speed – proband (m/s)	Peak head acceleration – dummy (g)	Peak head acceleration – proband (g)
Mean value	1.5634	1.5445	16.4816	8.2351
Standard deviation (SD)	0.0095	0.1095	0.3384	2.4793
95% CI Lower limit	1.5551	1.4485	16.1850	6.0619
95% CI Upper limit	1.5717	1.6404	16.7782	10.4083
Absolute difference of means	0.0189		8.2465	
Relative difference of means (%)	1.2118		50.0345	
P value	0.3484		<0.001	
Cohen's d	0.0122		0.6330	
Effect size	Trivial		Medium	

For the purposes of statistical comparison between the human participants and dummy, the resultant peak head acceleration represented the primary outcome variable, expressed in the multiples of the free-fall acceleration of standard gravity (g). The results (Fig. 4) showed expected higher values of head acceleration with increasing impact speed in both cases, the dummy and human participants. However, the values for the dummy were found almost twice as high as for the participants, significantly different, and with a higher rate of slope (the rise/run ratio of 17.2 compared to 7.2 in the case of humans).

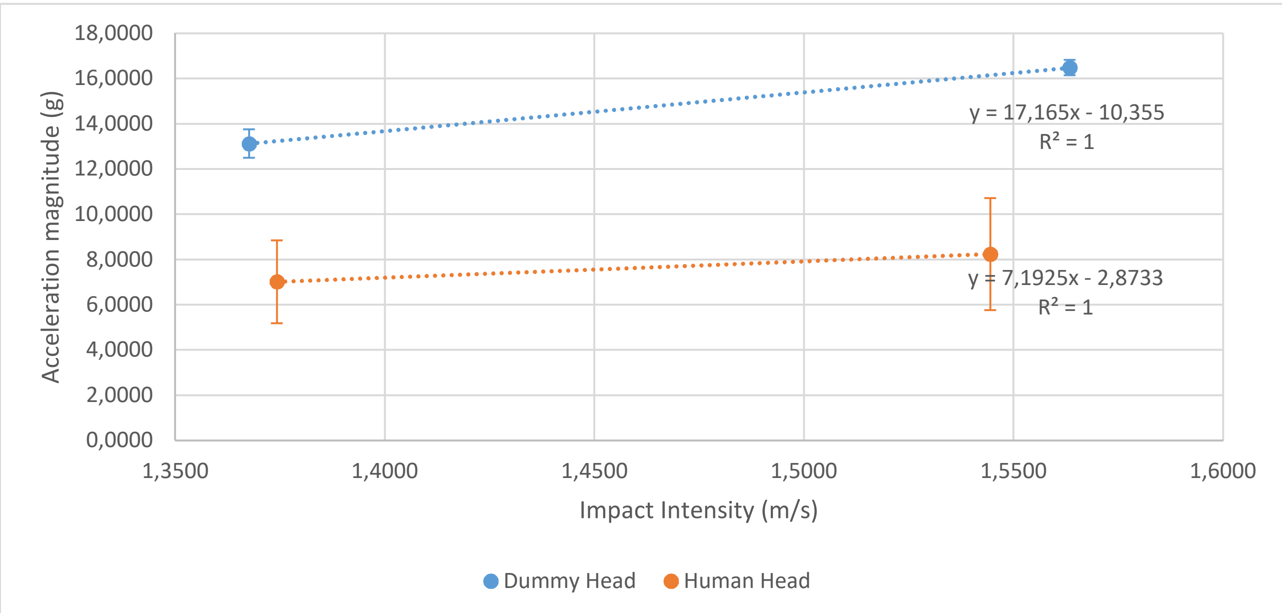

Fig. 4 *The results of peak head acceleration for both, dummy and human participants at two intensities*

3.2 Side (temple) impact

In the case of comparison of side (temple) impact between human participants and dummy (Tab. 3), two low-severity intensities (impact speeds) were used for the analysis (μ_{dummy} = 1.335 m/s, *SD* = 0.065, 95% CI 1.312-1.349; μ_{human} = 1.333 m/s, *SD* = 0.258, 95% CI 1.107-1.560) and (μ_{dummy} = 1.544 m/s, *SD* = 0.236, 95% CI 1.237-1.652; μ_{human} = 1.549 m/s, *SD* = 0.253, 95% CI 1.327-1.771). The results showed that the impact speeds were not significantly different (p value >0.05), the means of intensities were almost identical (Cohen's d <0.1), a therefore, the reliability and fidelity of a unique testing device was high for the purposes of similar experiments.

***Tab. 2** The results of crash tests*

1st intensity				
	Impact speed – dummy (m/s)	**Impact speed – proband (m/s)**	**Peak head acceleration – dummy (g)**	**Peak head acceleration – proband (g)**
Mean value	1.3350	1.3332	13.7424	5.4961
Standard deviation (SD)	0.0652	0.2584	0.8053	1.5322
95% CI Lower limit	1.3120	1.1066	13.0365	4.1531
95% CI Upper limit	1.3492	1.5597	14.4483	6.8390
Absolute difference of means	0.0018		8.2463	
Relative difference of means (%)	0.1381		60.0065	
P value	0.9686		<0.001	
Cohen's d	0.0014		0.7879	
Effect size	Trivial		Medium	
2nd intensity				
	Impact speed – dummy (m/s)	**Impact speed – proband (m/s)**	**Peak head acceleration – dummy (g)**	**Peak head acceleration – proband (g)**
Mean value	1.5444	1.5489	17.7804	6.8151
Standard deviation (SD)	0.2362	0.2531	1.2654	1.4666
95% CI Lower limit	1.2373	1.3270	16.6713	5.5296
95% CI Upper limit	1.6515	1.7707	18.8895	8.1005
Absolute difference of means	0.0045		10.9653	
Relative difference of means (%)	0.2898		61.6709	
P value	0.8491		<0.001	
Cohen's d	0.0029		0.8144	
Effect size	Trivial		Large	

For the purposes of statistical comparison between the human participants and dummy, the resultant peak head acceleration represented the primary outcome variable, expressed in the multiples of the free-fall acceleration of standard gravity (g). The results (Fig. 5) showed expected higher values of head acceleration with increasing impact speed in both cases, the dummy and human participants. However, the values for the dummy were found more than twice as high as for the participants, significantly different, and with a higher rate of slope (the rise/run ratio of 19.3 compared to 6.1 in the case of humans).

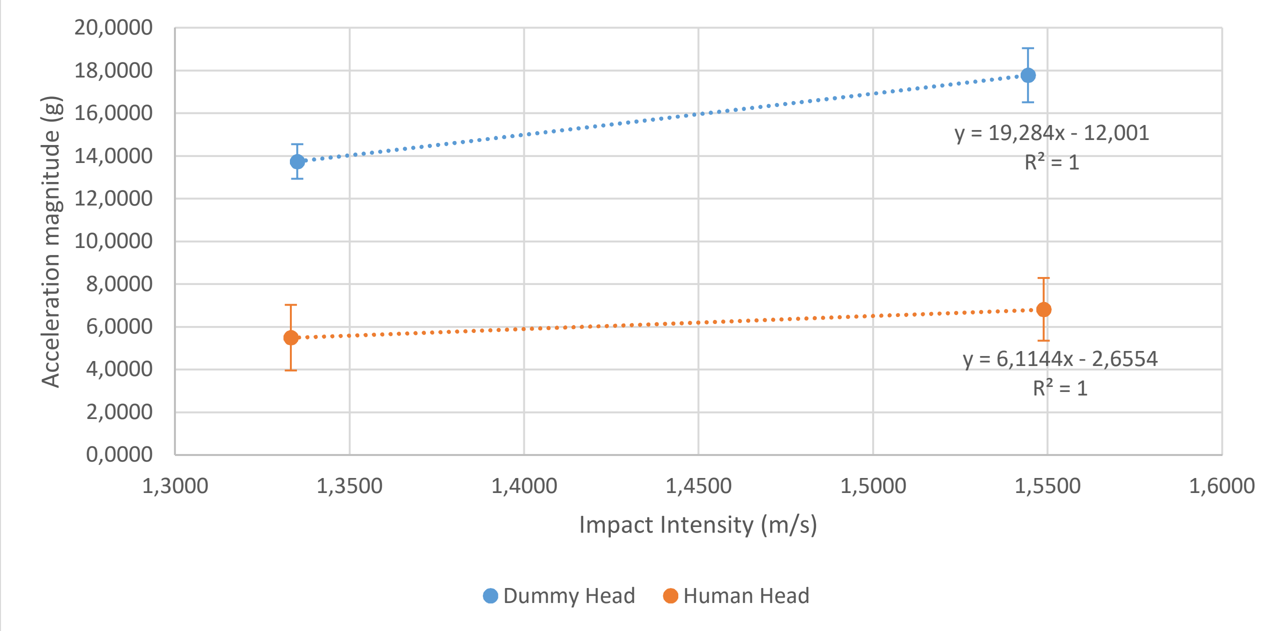

Fig. 5 *The results of peak head acceleration for both, dummy and human participants at two intensities*

4 Discussion

The results of the study showed a high reliability and fidelity of a unique pendulum testing device (impactor), designed and developed for the purposes of crash-test analysis regarding the biomechanical response of human participants and anthropomorphic testing devices (dummies). The device can be used in a variety of collision scenarios that might differ in the site of initial impact and the intensity of impact (impact speed). The proposed methodology could be then used for the validation of biofidelity of crash-test dummies and their biomechanical response to impact.

In the case of frontal (forehead) impact, the results showed that the resultant peak head acceleration of dummy increased with a higher rate compared to human participants with increasing impact speed. Based on the statistical analysis, using Welch's t-test, the values were significantly higher for the dummy (p value <0.05), reaching almost twice the value for human participants and, therefore, the effect size (the influence of dummy) was considerably high as well (Cohen's d >0.5, „medium effect“). The results of this collision scenario suggested that the dummy's biomechanical response to low-severity impact did not correspond to the response of human participants, which decreased the reliability and biofidelity of dummy. However, the responses could be affected by the experiment protocol itself. Based on auditory and visual perceptions, the participants could react and prepare for the coming impact and thereby influencing their biomechanical response adversely.

In the case of side (temple) impact, the results showed similar trends to the previous case. The resultant peak head acceleration of dummy increased with a higher rate compared to human participants with increasing impact speed. Based on the statistical analysis, using Welch's t-test, the values were significantly higher for the dummy (p value <0.05), reaching more than twice the value measured in human participants and, therefore, the effect size (the influence of dummy) was considerably high as well (Cohen's d >0.5, close to 0.8, „large effect“). The results of this collision scenario suggested that the dummy's biomechanical response to low-severity impact did not correspond to the response of human participants, which decreased the reliability and biofidelity of dummy. However, the responses could be affected by the experiment protocol itself. Based on auditory and visual perceptions, the participants could react and prepare for the coming impact and thereby influencing their biomechanical response adversely.

5 Conclusion

The preliminary validation of the Hybrid III Dummy, regarding its head biomechanical response to low-severity impacts, showed significantly low reliability and biofidelity for the similar purposes. Therefore, in these collision scenarios, the results of peak head acceleration of dummy could possibly result in the overestimation of real impact. However, more experiments with a variety of impact speeds, dummies, and site of initial impact need to be conducted for a more thorough comparison of the biomechanical response of dummies to human participants and their validation. Future studies could also focus on minimizing the adverse effects of participants preparing for the impact due to visual and auditory perceptions.

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