MOTORCYCLE HELMET DROP TESTS USING A HYBRID III DUMMY

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ABSTRACT

Falling headform tests, which are used to simulate impacts of a helmeted head in a motorcycle accident, take no account of the rider's body. In order to investigate the influence of the body mass on the dynamics of the head, drop tests using a complete helmeted Hybrid III dummy were carried out under various impact conditions. The comparison to equivalent falling headform tests showed that the linear and rotational accelerations of the head depend on the dynamic effects of the body and on the mechanical properties of the neck. For oblique impacts onto an abrasive anvil the body of the dummy led to increased linear and rotational accelerations of the head. In case of impacts onto a flat anvil the results systematically depended on the body impact angle. Due to an increased effective mass of the head lower linear accelerations were found for dummy drop tests. This work was part of the European research action COST 327 Motorcycle Safety Helmets (www.cordis.lu/cost-transport/home.html).

Key words: COST 327, rotational acceleration, linear acceleration, dummy drop test, falling headform test, flat anvil, oblique anvil.

THE MECHANICAL BEHAVIOUR OF MOTORCYCLE HELMETS in impact situations is directly related to head injury risks such as linear and rotational acceleration of the brain. In real accidents rotational and linear acceleration usually occur together and both cause injury (COST 327 Literature Review, 1997). Whereas current helmet standards provide shock absorption tests measuring linear acceleration using a falling headform, so far no reliable test methods are available concerning the risk of rotational acceleration. Furthermore, the use of a detached headform may not adequately simulate the dynamics of the head for all motorcycle accidents. Particularly, the effect of the body mass on the linear and rotational acceleration experienced by the head is not fully understood. Full scale crash tests in which a complete helmeted dummy riding a motorcycle was impacted into the side of a car showed much greater peak values of rotational acceleration and lower linear accelerations than observed in falling headform tests which were carried out in order to replicate helmet damages in the laboratory (Dixon et al., 1997; COST 327 Reconstruction, 2000). The different results were interpreted as a consequence of the interaction between the dummy's body and the head by the neck during the impact. The conclusion was that the dynamic behaviour of a human head in an impact would be between that of a free headform and that of a headform attached to a body via a stiff dummy neck.

Full scale crash tests impacting a complete dummy riding a motorcycle are the most realistic reproduction of an accident. A disadvantage of these tests is that they are very time consuming and expensive. Thus, as a link between standard falling headform tests and full scale crash tests, a complete dummy was used for drop tests in the laboratory. Its helmeted head impacted on a flat or on an oblique anvil, respectively. The results were compared to those obtained with an identical test configuration but using a detached headform. It is expected that the complex dynamics of the human head and neck in an accident can be simulated more realistically with a dummy. The aim of this study was to determine the influence of the neck and the body on the linear and rotational acceleration experienced by the dummy headform in comparison with the detached headform. It was further investigated how far falling headform tests as used in current helmet standards can replace dummy drop tests if appropriate test parameters are defined. This work was performed at EMPA (Swiss Federal Laboratories for Material Testing and Research) as part of the European research action COST 327.

Only a few experiments similar to those described here have been reported in the literature. Aldman et al. (1978) dropped a helmeted Ogle-Opat dummy onto an impact surface made of asphalt concrete, using a test car to release the dummy and, at the same time, to define a vertical and a horizontal velocity component. Peak values of angular acceleration between 4.8 and 12.4 krad/s^2 were measured in the head. The results were similar to those obtained by dropping the same helmeted headform, which was attached to a rail-guided carriage, onto a simulated road surface mounted on a rotating disc (Aldman et al., 1976). To our knowledge, no previous experiments of a dummy being dropped onto an oblique abrasive anvil have been published.

EQUIPMENT

A standard 50th-percentile adult male Hybrid III pedestrian dummy was used for the drop tests. The Hybrid III dummy head was equipped with nine accelerometers (Endevco 7264B-2000) positioned on a mounting block in a 3-2-2-2 array following the recommendations of Padgaonkar et al. (1975). The accelerometer signals were amplified by three voltage amplifiers (Endevco Model 136) and recorded at a sampling rate of 100 kHz using two Nicolet BE490XE transient recorder boards.

For both the flat and the oblique anvil, a tri-axial Kistler type 9366AB force transducer was used, allowing the measurement of normal and tangential force components. Impacts with the flat anvil were performed directly onto the smooth mounting plate (230x300 mm) of the force transducer, whereas for oblique impact tests the force transducer was inclined at 15° to the vertical and the impact area was covered with a sheet of abrasive paper (grade 80 closed-coat aluminium oxide) according to the British Standard (BS 6658, 1985). The abrasive paper was replaced after each impact.

A computer program was used for data acquisition and to process the accelerometer data. Force signals were measured directly, whereas linear and rotational accelerations, as well as additional parameters had to be computed (rotational acceleration was calculated according to Padgaonkar et al., 1975). The accelerometer and force transducer signals were filtered according to CFC600. Data were recorded at intervals of 25 ms in order to measure the first and primary head impact. Secondary head impacts are considerably less violent (Aldman et al., 1978).

All dummy tests were performed at ambient room temperature in the EMPA helmet test laboratory. The experimental set-up is shown in Figure 3 (left). It consists of a suspended, helmeted dummy, an anvil equipped with the force transducer, and shock absorbing material placed around the anvil to protect the dummy from damages. The dummy was suspended using a four-chain device with an automatic quick-release mechanism. Its orientation could be adjusted by changing the length of the chains. The vertical drop height and thus the impact velocity was selected using a crane. After being released the dummy fell in a free fall without horizontal displacement. The dynamic behaviour of the dummy head during the impact was filmed with a high-speed video camera at 2250 frames per second. An additional video camera recorded the impact of the whole dummy.

The test configurations were selected such that the helmet contacted the anvil at a defined impact point. After the first contact between the helmet and the anvil the body of the dummy moved on for several milliseconds before being stopped by shock absorbing materials. This allowed the head impact to be observed without any effects due to contacts of other parts of the body.

All joints of the dummy were preloaded with a force equivalent to the gravity and the neck was fixed in the 0° position. Prior to the experiments the dummy was calibrated at the DTC (Dynamic Test Center, Biel, Switzerland).

For comparison falling headform tests were performed using a detached Hybrid III headform in combination with the flat anvil and a Hybrid II headform in combination with the oblique abrasive anvil, respectively (both 50^{th}-percentile adult male). It is expected that the Hybrid II and the Hybrid III headform will perform in the same way under impact conditions (COST 327 Headforms, 1999). Apart from the flat anvil, which was equipped with a Kistler type 9361B force transducer, the same instrumentation was used as for dummy tests. The standard EMPA helmet test facility (satisfying ECE Regulation 22-04, 1995) was used for impacts onto the flat anvil (Figure 1). For impacts onto the oblique abrasive anvil the drop test rig was adapted to satisfy the requirements of BS 6658 for oblique impact tests (Figure 2).

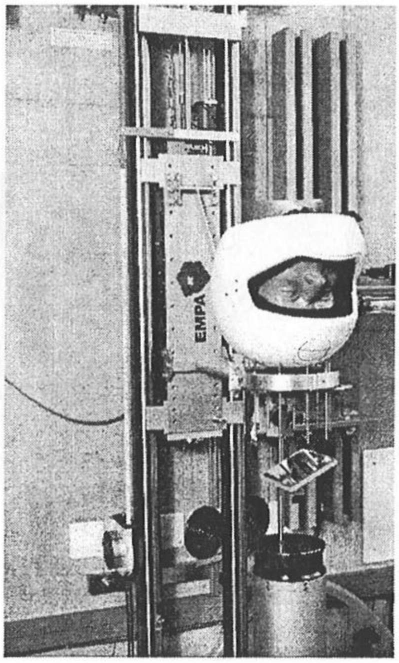

Figure 1: Standard helmet test facility (flat anvil).

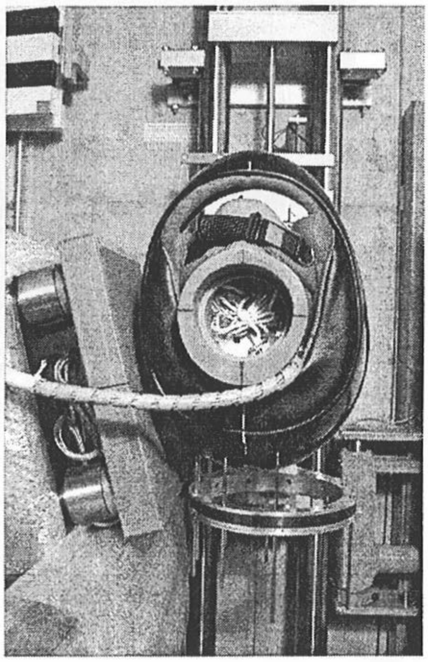

Figure 2: Oblique abrasive anvil and helmet positioning.

TEST PROGRAMME AND PROCEDURE

The following experiments were carried out:

- Hybrid III dummy drop tests onto the flat anvil and onto the oblique abrasive anvil
- Headform drop tests onto the flat anvil (Hybrid III) and onto the oblique abrasive anvil (Hybrid II)

The dummy test programme consisted of 31 drop tests onto the flat anvil and 18 impacts onto the oblique abrasive anvil. 18 new helmet samples were available for the test series. Three different body angles and four locations on the helmet were investigated (Table 1). The body impact angle is defined as the angle between the longitudinal axis of the dummy and the horizontal, in accordance with the COST 327 Accident Data Working Group (e.g. Chinn et al., 1999). The results of this Working Group showed that about 50% of the motorcyclists impacted with a body angle between 0° and 10° during an accident. About 20% collided at angles around 30° and another 13% impacted at an angle around 90° (D. Otte, personal communication, 1999). These findings were combined with the statistical distribution of the head impact angles in accidents in order to define the geometrical configurations of the laboratory drop tests (Table 1). Some restrictions were imposed by the dummy's geometry as well as the suspension system. In addition, the impacts had to be as reproducible as possible to obtain a high repeatability of the measurements. Vertical velocities of 4.4 m/s, 5.2 m/s and 6.0 m/s were defined to simulate realistic impact conditions and to limit the risk of severe damages to the dummy. The test programme of the falling headform experiments is shown in Table 2.

The same impact points on the helmet as specified in ECE R22-04, i.e. B (frontal), P (parietal) and R (occipital), were defined for dummy impacts onto the flat anvil. For each impact point the dummy was positioned with a defined body angle and released from the selected drop height when it was completely motionless. The corresponding test configurations are shown in the Figures 3 and 4 (left). In case of impacts with the oblique anvil the dummy was dropped with a body angle of 0° (Figure 4 right). The left and right lateral impact points as well as the positioning of the helmets were in accordance with BS 6658 for oblique impact tests using a headform (Figure 2).

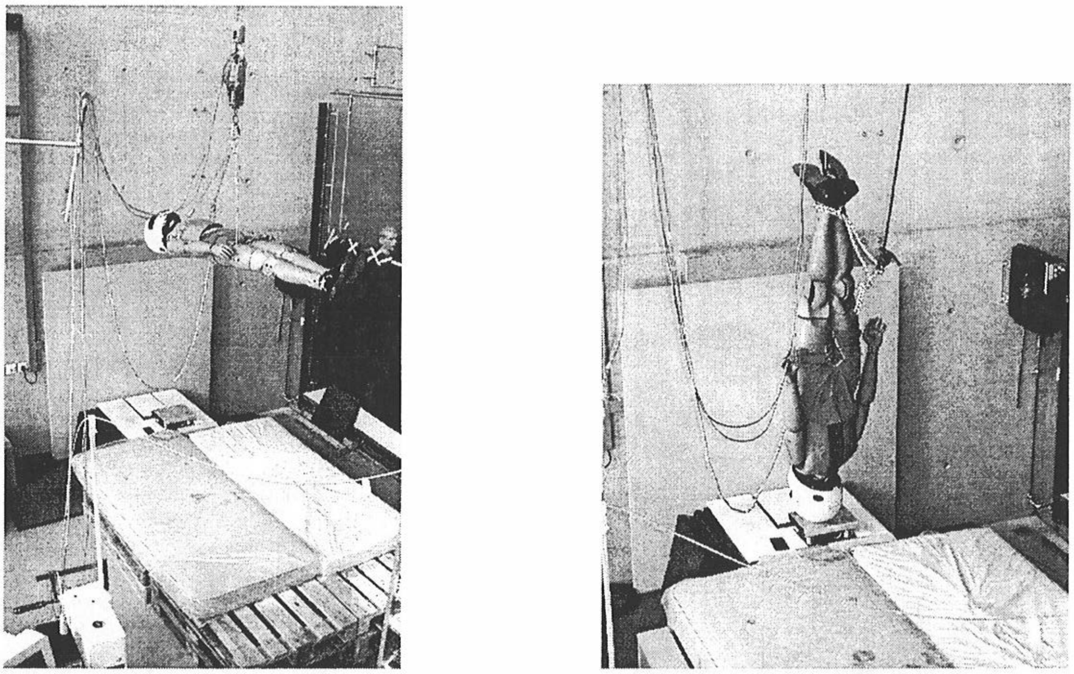

Figure 3: Experimental set-up for dummy drop tests: configuration for R/0°-impacts (left) and for P/90°-impacts (right).

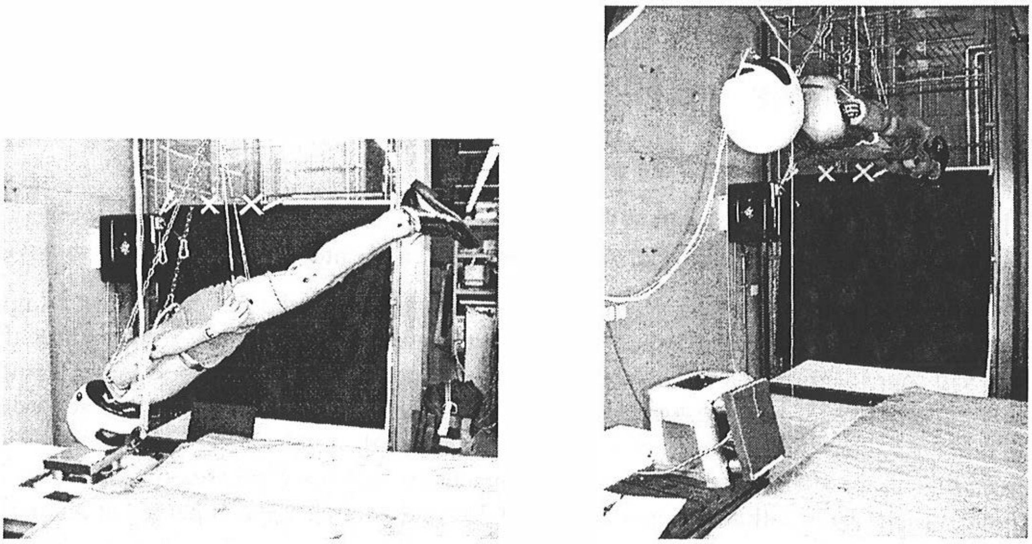

Figure 4: Drop test configuration for B/30°-impacts (left) and lateral/0°-impacts onto the oblique abrasive anvil (right).

Helmet samples of the same size (58) and of the same type, an AGV R3/R4 fibreglass helmet certified according to ECE R22-04, were used in all experiments to provide a good comparability between the results. Each helmet was impacted at the points B, P and R onto the flat anvil and on the left and right lateral side onto the oblique anvil. The visors as well as the visor mounts were removed from all helmets. Before each drop test a helmet was positioned on the headform with a fixed distance between the eyeline and the helmet rim, and the retention system was fastened tightly. Body, legs and arms of the dummy were arranged in the correct position.

Table 1: Summary of the dummy test programme

No. of Tests	Impact velocity [m/s]	Anvil	Body impact angle	Head impact point
9	4.4, 5.2, 6.0	flat	30°	frontal (B, ECE R22-04)
11	4.4, 5.2, 6.0	flat	90°	parietal (P, ECE R22-04)
11	4.4, 5.2, 6.0	flat	0°	occipital (R, ECE R22-04)
18	4.4, 5.2, 6.0	oblique abrasive (15°)	0°	lateral left and right (BS 6658)

Table 2: Summary of the headform test programme

No. of Tests	Impact velocity [m/s]	Anvil / Headform	Head impact point
9	4.4, 5.2, 6.0	flat / Hybrid III	frontal (B, ECE R22-04)
4	4.4, 6.0	flat / Hybrid III	parietal (P, ECE R22-04)
6	4.4, 5.2	flat / Hybrid III	occipital (R, ECE R22-04)
8	6.0, 7.5	oblique abrasive (15°) / Hybrid II	lateral left and right (BS 6658)

OBLIQUE IMPACT TESTS USING A DUMMY: RESULTS AND DISCUSSION

Table A.1 (Appendix) contains the results of the dummy drop tests onto the oblique abrasive anvil. The measured peak values of linear acceleration are relatively low and range from 25 g to 44 g depending on the impact velocity. The peak values of rotational acceleration vary between 1579 rad/s^2 and 3680 rad/s^2 and those of the tangential forces between 639 N and 1154 N.

Figure 5 shows mean time histories of the resultant linear and rotational accelerations of the headform and of the tangential forces measured on the anvil for oblique impacts of the dummy (left) and the headform (right) at an impact velocity of 6.0 m/s. Very similar curves are found for all three impact velocities, but the peak values increase with velocity (not shown in Figure 5).

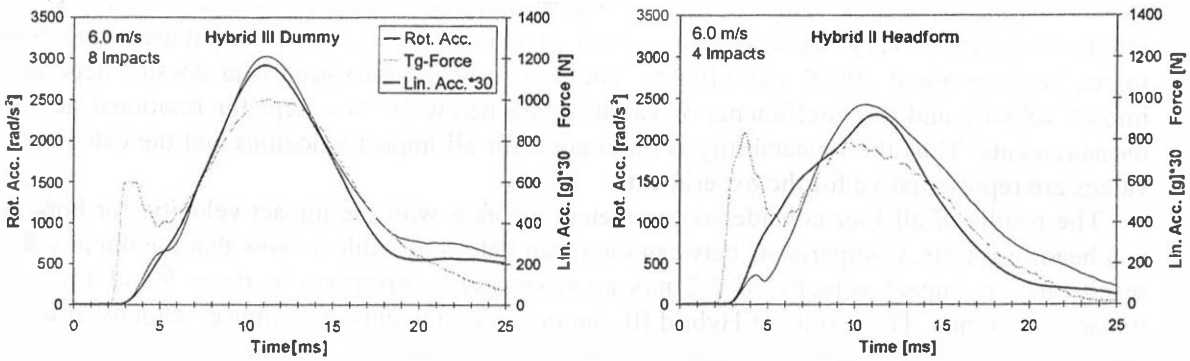

Figure 5: Mean time histories for drop tests onto the oblique abrasive anvil. For a better representation linear acceleration values on the right axis are multiplied by a factor of 30. The mean values were calculated using all available measurements (the number is indicated in the plots).

The plots in Figure 5 show that the force signal rises about 1 ms earlier than the accelerometer signals, indicating the first contact between the helmet shell and the abrasive anvil. Acceleration and rotation of the dummy headform follow with a short time delay. The curves for linear and rotational acceleration are qualitatively similar and reach their maximum at the same time (the correspondence is better for dummy tests). The broad peaks of the tangential forces also coincide with the peaks of linear and rotational acceleration. The signal forms of all three plotted parameters are comparable for dummy and headform tests, although the peak values are somewhat greater using the dummy. The time histories of the tangential forces show narrow peaks during the first phase of the contact. As high-speed videos confirm these peaks are associated with the onset of considerable helmet shell deformations.

The analysis of high-speed videos reveals that the trajectory and the orientation of the dummy's body (Figure 4 right) are practically not influenced by the contact between the head and the oblique abrasive anvil. The great body mass and the stiffness of the neck are probably the main reason for this. In contrast, the contact between the helmet shell and the anvil induces a strong rotation of the head and the neck about the vertical dummy axis. The dynamics resembles that observed for a detached headform colliding with the oblique anvil.

STATISTICAL ANALYSIS

In Table 3 mean values, standard deviations (sd) and coefficients of variation (v), i.e. standard deviations expressed as percentages of the means: v = 100·sd/mean, are listed for the peak values of rotational and linear acceleration, tangential force and rotational velocity resulting in dummy drop tests and falling headform tests. The peak tangential force was determined from the broad maximum of the force signal which is closely related to the headform rotation (see Figure 5).

Table 3: Mean peak values resulting in oblique impact tests onto an abrasive anvil using a Hybrid III dummy and a Hybrid II headform (#).

Imp. Vel. [m/s]	No. of Tests	Rot. Acc. [rad/s^2]	sd [rad/s^2]	v [%]	Tg-F. [N]	sd [N]	v [%]	Rot. Vel. [rad/s]	sd [rad/s]	v [%]	Lin. Acc. [g]	sd [Ns]	v [%]
4.4	6	1939	226	11.7	712	53	7.4	18.8	1.6	8.5	26.7	1.3	5.0
5.2	4	2468	418	17.0	895	47	5.2	21.4	0.8	3.7	33.3	2.0	6.1
6.0	8	3087	451	14.6	1080	57	5.2	25.3	1.6	6.4	41.2	2.2	5.4
6.0 (#)	4	2488	158	6.3	801	86	10.7	23.9	2.7	11.3	30.9	2.7	8.8
7.5 (#)	4	3393	289	8.5	1238	79	6.4	26.6	4.3	16.1	49.1	2.7	5.6

In dummy tests the mean peak values of linear acceleration are relatively low and range from 27 g to 41 g and the mean peak values of rotational acceleration from about 1900 rad/s^2 to 3100 rad/s^2. The rotational velocities vary between 19 rad/s and 25 rad/s and the mean peak values of the tangential forces between about 700 N and 1100 N. The scatter of the measured data doesn't depend on the impact velocity and the coefficients of variation are below 10 % except for rotational acceleration measurements. Thus the repeatability is quite good for all impact velocities and the calculated mean values are representative for the experiments.

The results of all four considered parameters increase with the impact velocity, for both dummy and headform tests. Comparisons between the mean values in Table 3 show that the dummy drop test results for an impact velocity of 5.2 m/s approximately correspond to those found for headform impacts at 6.0 m/s. The results of Hybrid III dummy measurements at an impact velocity of 6.0 m/s lie between those of the Hybrid II headform measurements at 6.0 m/s and at 7.5 m/s, respectively. Consequently, for the same impact velocity the values of the measured parameters are greater for dummy drop tests than for falling headform tests. The differences may be due to the inertial effects of the body mass acting on the head through the neck. Since the motion of the dummy's body is practically unaffected by the impact, the vertical velocity of the body slightly exceeds that of the head after the contact with the anvil. This causes a momentum forcing the head to rotate about an axis in the neck area parallel to that passing through the ears. The corresponding contribution to the resultant rotational acceleration can clearly be identified in the data measured in dummy drop tests, whereas it is not found in headform tests. Although this component is considerably smaller than the rotation about the longitudinal axis of the headform, it accounts for the most part of the differences between dummy and headform experiments.

DUMMY HEADFORM ROTATION

In Figure 6 rotational accelerations are plotted against tangential forces measured in 18 dummy drop tests onto the oblique abrasive anvil. The results of impacts on the right and on the left helmet side at impact velocities of 4.4 m/s, 5.2 m/s and 6.0 m/s are shown. The calculated linear regression and the correlation coefficient (r = 0.90) indicate a significant linear relationship between the peak values of rotational acceleration and tangential force. In previous experiments at EMPA, in which a helmeted Hybrid II headform was impacted with an oblique anvil at five velocities between 6 m/s and 12 m/s (84 impacts), a very similar relationship was found between these two parameters (COST 327 Test Procedures, 2000).

Figure 7 shows a direct comparison of the dummy drop test results (Figure 6) with the results of falling headform tests. For both test series rotational accelerations and tangential forces increase with the impact velocity. The results of the dummy tests are in line with those of the headform experiments, indicating a common relationship between rotational acceleration and tangential force. However, for the same impact velocity the data points for dummy drop tests are shifted towards higher values (see also Table 3 and the related text above). It can be concluded that in order to assess rotational acceleration in dummy drop tests at a certain impact velocity, falling headform tests have to be carried out at a slightly higher velocity.

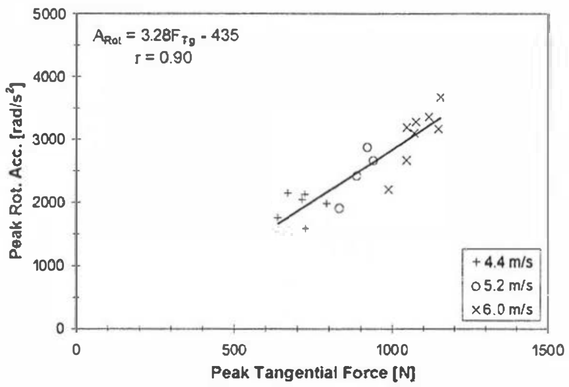

Figure 6: Peak rotational acceleration versus peak tangential force for dummy impacts onto the oblique abrasive anvil.

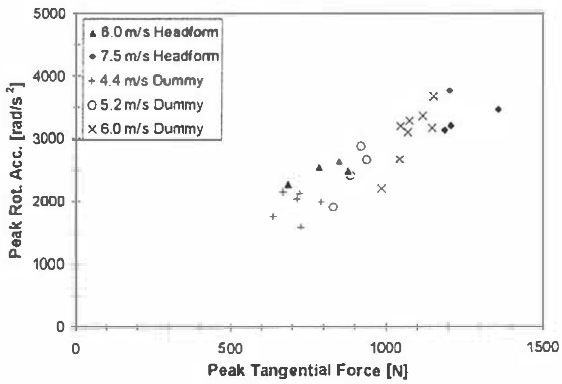

Figure 7: Peak rotational acceleration versus peak tangential force for dummy and headform impacts onto the oblique abrasive anvil.

DUMMY DROP TESTS ONTO A FLAT ANVIL: RESULTS AND DISCUSSION

The results of the dummy drop tests onto the flat anvil are summarised in Table A.2 (Appendix). Peak values of linear acceleration between 83 g and 171 g were measured depending on impact velocity and test configuration. The peak values of rotational acceleration range from about 2900 rad/s^2 to 5900 rad/s^2 and those of the normal forces on the anvil from about 6500 N to 17600 N.

Figure 8 (left side) shows examples of mean time histories of the resultant linear and rotational accelerations and normal forces for the different dummy drop test configurations. The results of corresponding headform tests are plotted on the right side. The signal forms of all three parameters are more complicated in dummy tests than in headform tests. Especially the rotational acceleration curves show important differences, indicating that both linear and rotational motion of a headform connected to a dummy are more complex than for a detached headform. On the other hand, qualitatively similar linear accelerations assuming their peak values at comparable times, are found in dummy and headform experiments. At a given impact point the average signals of rotational and linear acceleration and normal force are qualitatively similar for all investigated impact velocities (not shown in Figure 8). The dummy headform is accelerated with a time delay of about 1 ms after the first contact between helmet shell and anvil, regardless of being attached to the dummy or not.

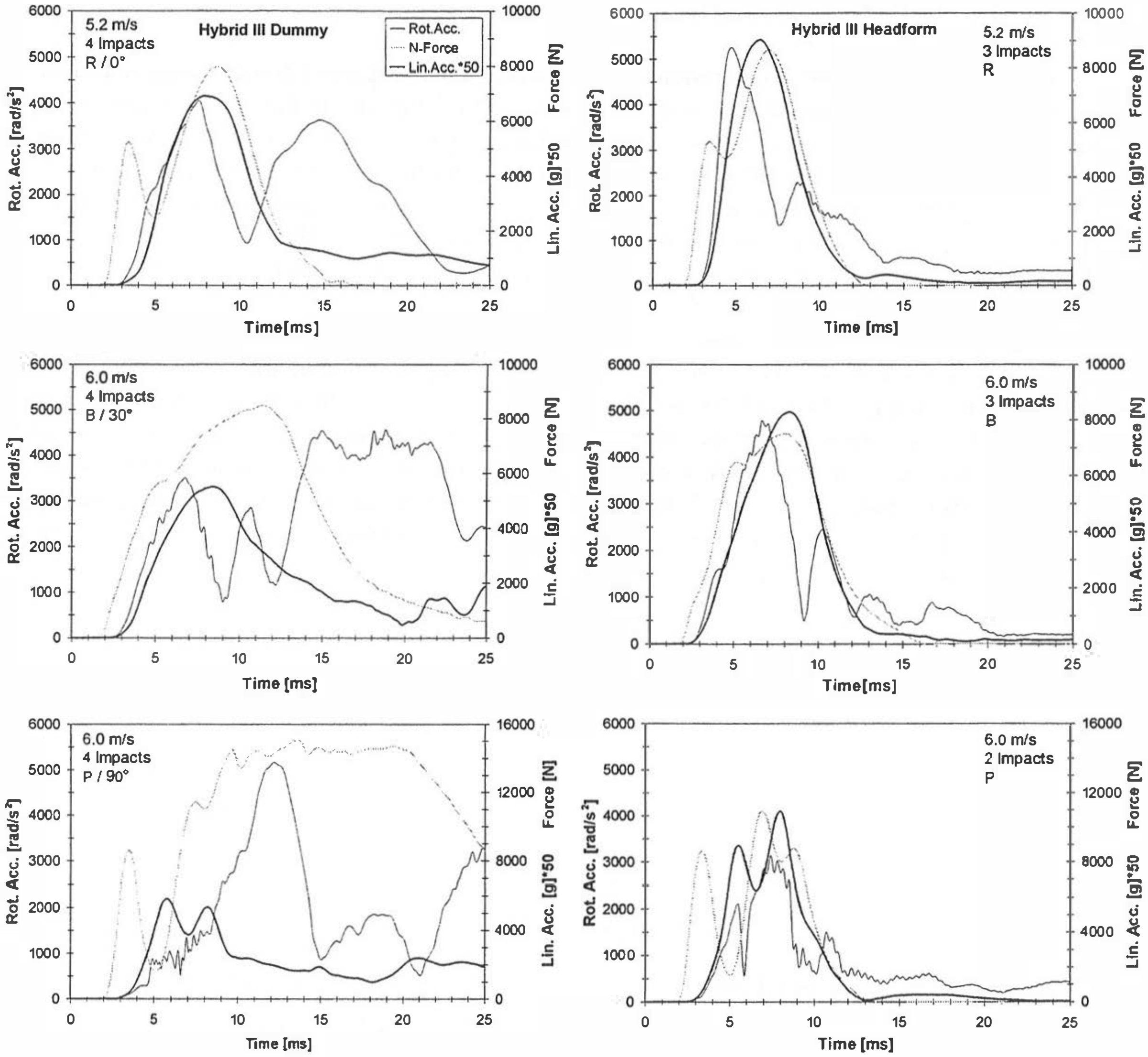

Figure 8: Mean time histories for dummy (left) and headform (right) impacts onto the flat anvil for different impact configurations. B/30°- and P/90°-impacts are shown for the velocity of 6.0 m/s. R/0°-impacts are shown for the velocity of 5.2 m/s because headform impacts at 6.0 m/s are not available. Linear acceleration values on the right axes are multiplied by a factor of 50 for a better representation. The mean values were calculated using all available measurements (the number is indicated in the plots).

The high-speed videos of R/0°-impacts (Figure 3 left) show that the dummy headform continues to move downwards during the first phase of the contact between helmet shell and anvil. After a contact time of about 8 ms the headform seems to rotate inside the helmet, while the helmet itself remains in the same position. This moment in time coincides with a local minimum of the rotational acceleration (Figure 8 left). About 12 ms after the first contact, the helmet also begins to rotate in the direction of the chin, about an axis passing through a point in the neck area rather than through the centre of gravity, as would do a detached headform. The first peak of the rotational acceleration signal coincides with a great external force and is therefore directly related to the impact. On the other hand, the second peak corresponds to a period with very low external force and is probably a consequence of the elastic properties of the neck. Presumably, the neck releases the energy accumulated in the first phase of the impact by rotation or compression or flexion. This behaviour of the neck does not exactly simulate a human neck, which is more flaccid than the Hybrid III neck. The detached headform shows a qualitatively similar signal for the normal force and the linear acceleration (Figure 8 right), but the missing of a second peak in rotational acceleration confirms that this peak is a consequence of the combined effects of the body dynamics and neck properties in dummy tests. Thus for the data analysis the first peak of rotational acceleration is interpreted as the relevant maximum. The behaviour of a human head in a motorcycle accident would probably be between that of a dummy headform attached to a body by a stiff neck and a detached headform. It is found that the peak values of linear and rotational acceleration are greater in headform tests, whereas peak normal forces are comparable.

The analysis of impacts at point B with a body angle of 30° (Figure 4 left) shows that the motion of the dummy headform is not affected by the impact in the first phase of the contact between helmet and anvil. Film analysis as well as the shape of the normal force signal indicate that the helmet contacts the anvil without rebound during this period (Figure 8 left). About 7 ms after the first contact, the helmet begins to slide forward and then to rotate backwards until the chin guard touches the anvil. The rotational acceleration signal shows two small peaks followed by a broad and high maximum. This large maximum corresponds to a period with low external force and seems to be a consequence of the elastic behaviour of the neck (an analogous observation was made for impacts at point R). The maximum of rotational acceleration is thus determined from the first two peaks. The results of the falling headform tests in Figure 8 (right) differ from the dummy measurements, although rotational acceleration is qualitatively similar for the first two peaks. In headform tests, greater peak values are found for linear and rotational acceleration, but lower peak values for the normal force. In dummy tests, the normal force reaches its peak value later than in falling headform tests, indicating the effect of the dummy's body.

The most complex signal forms are found in case of impacts at point P with a body angle of 90° (Figure 3 right). The high-speed videos show that the helmet practically remains in the same position after the first contact with the anvil, while body and neck of the dummy continue to move downwards. A rebound of the helmet can be observed during which the helmet seems to loose contact with the anvil for a short time. The rebound motion is reversed about 3 ms after the first contact when the normal force assumes a local minimum (Figure 8 left). At a contact time of 8 ms the helmet begins to rotate backwards and then to slide forwards onto the anvil while the legs and the body of the dummy follow in the opposite direction. Throughout this period very high and approximately constant normal forces are exerted on the anvil. The rotational acceleration peak takes place during this phase, when the linear acceleration has fallen to relatively low values following a double peak. In most of the accidents the sustained injuries are a consequence of the combined effect of linear and rotational acceleration (COST 327 Literature Review, 1997). The two types of accelerations can also occur one after the other. Thus for the data analysis, the rotational acceleration peak at the centre of the measuring time is considered to be the relevant maximum. Even if the results of falling headform tests deviate from those of dummy drop tests, the rebound of the helmet can be observed in the first part of the normal force signal (Figure 8 right). The linear acceleration signals are qualitatively similar, although the peak values are much greater in falling headform tests. The rotational acceleration peaks are higher and occur later for dummy tests. The measured signals demonstrate that in case of the impact configuration P/90° the dynamic behaviour of the dummy head is essentially influenced by the forces which are transmitted to the head through the neck.

STATISTICAL ANALYSIS

Table 4 contains mean values, standard deviations (sd) and coefficients of variation (v) for the peak values of rotational acceleration, normal force, linear acceleration and HIC, which were calculated for the dummy and the headform drop tests. The listed values represent the results of two, three or four drop tests with the same configuration.

The mean peak values of rotational acceleration vary between about 2900 rad/s^2 and 5300 rad/s^2 in dummy tests. The peak values of linear acceleration range from 85 g to 165 g and those of the normal force from about 6500 N to 15600 N. At a given impact point the results of all four parameters considered in Table 4 clearly increase with impact velocity. The results of headform drop tests show an analogous behaviour, except for rotational acceleration. As expected, impacts at 6.0 m/s represent the worst case of linear and rotational acceleration of the dummy head. For dummy tests most of the coefficients of variation in Table 4 are below 12 % at a given impact point and velocity and only a few vary between 13 % and 24 %. It seems that the scatter of the data does not depend on the impact velocity or on the impact point and that it lies in the same order of magnitude for dummy and headform tests. Despite the complexity of the Hybrid III dummy drop tests in comparison with headform tests, it can be concluded that the repeatability of these results is quite good and that the calculated mean values are representative.

Table 4: Mean peak values for Hybrid III dummy tests and Hybrid III headform (#) drop tests onto the flat anvil.

Imp. Point / Velocity		No. of Tests	Rot. Acc. [rad/s^2]	sd [rad/s^2]	v [%]	N-F. [N]	sd [N]	v [%]	Lin. Acc. [g]	sd [g]	v [%]	HIC	sd	v [%]
B/30°	**4.4**	2	2897	31	1.1	6507	56	0.9	85	1.9	2.2	251	8.1	3.2
	5.2	3	3551	355	10.0	7736	319	4.1	99	3.2	3.3	368	27.6	7.5
	6.0	4	3735	654	17.5	8758	561	6.4	111	4.6	4.1	510	53.2	10.4
R/0°	**4.4**	4	3677	370	10.1	7013	307	4.4	122	4.2	3.5	568	43.6	7.7
	5.2	4	4338	409	9.4	8071	196	2.4	142	5.8	4.1	820	41.8	5.1
	6.0	3	4789	427	8.9	8940	425	4.8	165	6.3	3.8	1106	75.1	6.8
P/90°	**4.4**	3	4172	548	13.1	11243	511	4.5	102	24.5	24.1	218	50.1	23.0
	5.2	4	4616	307	6.7	12936	864	6.7	113	13.6	12.1	320	37.8	11.8
	6.0	4	5304	559	10.5	15560	1430	9.2	134	10.3	7.7	387	34.4	8.9
B (#)	**4.4**	3	3905	642	16.5	5601	322	5.8	120	6.7	5.6	505	28.5	5.6
	5.2	3	4941	271	5.5	6119	459	7.5	126	11.3	9.0	635	84.2	13.3
	6.0	3	4814	66	1.4	7505	462	6.2	166	3.7	2.2	1074	59.0	5.5
R (#)	**4.4**	3	5504	519	9.4	7109	436	6.1	138	5.1	3.7	689	39.0	5.7
	5.2	3	5557	117	2.1	8715	265	3.0	182	8.7	4.8	1198	66.2	5.5
	6.0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
P (#)	**4.4**	2	1574	47	3.0	6908	673	9.7	136	10.5	7.7	535	82.8	15.5
	5.2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	6.0	2	3390	244	7.2	10951	41	0.4	219	8.0	3.7	1515	88.5	5.8

n.a.: not available

For a given impact velocity the mean values systematically depend on the impact point and the test configuration. The greatest normal forces result in impacts at point P with a body angle of 90°. This is not surprising because the dummy is dropped perpendicularly to the impact surface. The measured forces are much greater than for the other test configurations. Also the greatest rotational accelerations are measured in P/90°-impacts, although the differences are less significant. Considering linear acceleration and HIC, the greatest values are found for impacts at point R.

Table 4 shows that for the same impact velocity the normal forces for B/30° and P/90°-impacts are greater when using a dummy instead of a headform. For impacts at point R the normal forces are similar in both cases. These findings are not surprising because the mean time histories of the normal forces in Figure 8 are most similar for R-impacts, indicating only a weak influence of the additional body mass. In contrast, there is an evident effect for B/30°-impacts and, even more, for P/90°-impacts. Rotational acceleration is much greater using a complete dummy in P/90°-impacts than a detached headform, probably due to the body dynamics transmitting large forces to the head trough the neck. On the other hand, B/30° and R/0°-impacts show lower peaks of rotational acceleration using a dummy. Presumably the freedom of movement of the impacting headform is reduced if it is connected to the body.

For the same impact point and velocity the linear accelerations and HIC values are lower for dummy drop tests than for falling headform tests (Table 4). The greatest differences are found for impacts at point P, followed by impacts at B, whereas the differences are small for impacts at R. During an impact the force acting on the head of the dummy is transmitted by the neck to the body. For the same impact force the resulting linear acceleration of the head will therefore be reduced compared to the unattached headform, due to an increased effective mass of the dummy headform (COST 327 Reconstruction, 2000). Dixon et al. (1997) found lower linear acceleration in a full scale crash test than in falling headform tests in which equivalent helmet damages were replicated. It was assumed that the same external force will produce the same helmet damage, since the force of the full scale impact had to be estimated.

In our study the information on forces and linear accelerations is available for both dummy and headform tests, so that impacts at the same point with a similar level of normal force can be compared by means of the equation:

$$m_e \cdot a_e = m_h \cdot a_h$$

where:

m_e: effective mass of the helmeted dummy head
a_e: linear acceleration of the helmeted dummy head
m_h: mass of the detached helmeted headform
a_h: linear acceleration of the detached helmeted headform

The assumption that the same kinetic energy is required to produce equivalent helmet damage in falling headform tests and dummy drop tests provides a second equation:

$$\tfrac{1}{2} m_e \cdot v_e^2 = \tfrac{1}{2} m_h \cdot v_h^2$$

where:

v_e: impact velocity of the dummy head
v_h: impact velocity of the detached headform

The mass of the Hybrid III headform is 4.6 kg and the mean helmet mass about 1.4 kg, thus 6 kg is used as the mass of the detached helmeted headform. Table 4 shows that comparable normal forces are measured on the anvil in B/30°-impacts at 5.2 m/s (dummy) and 6.0 m/s (headform), in R/0°-impacts at 4.4 m/s (both) and in P/90°-impacts at 4.4 m/s (dummy) and 6.0 m/s (headform). With the known velocities and the measured linear accelerations the following effective masses of the helmeted dummy headform can be calculated from the energy/force equations:

B/30°: 8 kg / 10 kg; R/0°: 6 kg / 7 kg; P/90°: 11 kg / 13 kg

These results confirm that an increased effective mass of the dummy headform reduces the linear acceleration of the head. The greatest effective mass and thus the greatest difference between dummy and headform tests occurs in P/90°-impacts, whereas R/0°-impacts increase the effective mass only slightly. The effect of the dummy's body and the neck are thus more important for greater body impact angles, where the direction of the normal impact forces coincides with the longitudinal neck axis.

Only a few experiments similar to this study have been reported in the literature. In the following, our results are compared with the measurements carried out by Aldman et al. (1976, 1978) using an Ogle-Opat dummy wearing a polycarbonate jet helmet. The main difference from our measurements was the use of a test car to release the dummy, imposing an additional horizontal velocity component (typically 8-9 m/s) which caused an oblique impact with a flat surface made of asphalt concrete. Vertical impact velocities of 4.4 m/s and 5.2 m/s were used in the drop tests. Considering the test configurations which were similar to our experiments (impacts onto the flat anvil at the helmet impact points and body impact angles of R/25°, R/0° and B/30°), there is a good correspondence between Aldman's and our results with regard to linear acceleration. This could be explained by the fact that linear acceleration mainly depends on the vertical impact velocity which is given by the drop height. On the other hand, Aldman measured rotational accelerations up to two or three times higher than our results. Despite differences in the impact surfaces and in neck and headform characteristics, the differing horizontal impact velocities can explain the large discrepancies in rotational acceleration. This is confirmed by extrapolation of our results of dummy drop tests onto the oblique abrasive anvil (see Table 3) to higher impact velocities where the vertical and horizontal velocity components allow a direct comparison with one experimental configuration of Aldman. The extrapolated rotational accelerations lie in the same order of magnitude as Aldman's results.

LINEAR AND ROTATIONAL ACCELERATION

In Figure 9 peak values of rotational acceleration are plotted against peak values of linear acceleration for dummy drop tests onto the flat anvil. The regression lines for the different impact configurations can clearly be distinguished. Impacts at point R show the strongest linear relationship between linear and rotational acceleration (r = 0.85), whereas the correlation is weaker for B/30°-impacts (r = 0.64) and not significant for impacts at point P (r = 0.33). A higher coefficient of correlation is found, if linear and rotational acceleration reach their peaks simultaneously. As can be observed in Figure 8 (left) this is approximately the case for impacts at point R (considering the first rotational acceleration peak). For impacts at point P the situation is completely different because the peak of rotational acceleration arises much later than the peak of linear acceleration. The correlation between linear and rotational acceleration is decreased by the influence of the neck and the body on the dynamics of the dummy head.

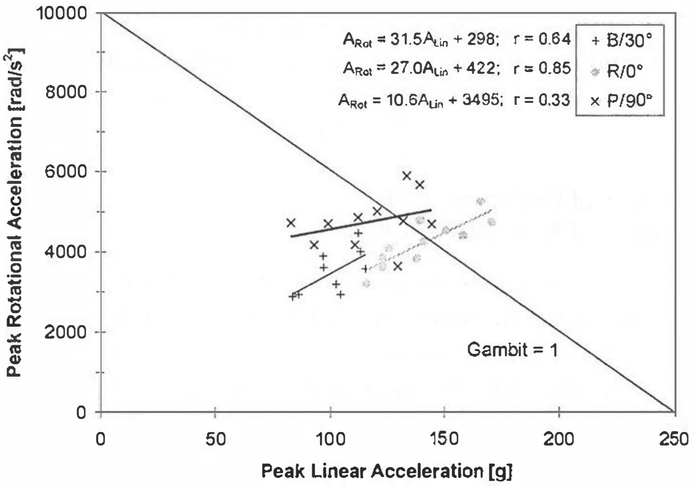

Figure 9: Peak rotational acceleration versus peak linear acceleration for dummy impacts onto the flat anvil at 4.4 m/s, 5.2 m/s and 6.0 m/s; the linear GAMBIT function line is plotted.

The linear GAMBIT function (G = 1), based on 250 g for pure linear and 10'000 rad/s^2 for pure rotational acceleration, is a brain injury threshold that takes into account the combined effect of both types of acceleration in an accident (Newman, 1986). Most of the data points in Figure 9 are located below the GAMBIT line (G < 1), but a few points are located above the line (G > 1), of which some result from impacts at a velocity of only 5.2 m/s. In spite of the relatively low impact velocities which were chosen for the dummy drop tests, according to Newman, some of the measured values can thus be considered as critical with respect to head injury, i.e. the onset of brain injury is possible.

CONCLUSIONS

A helmeted Hybrid III dummy was dropped onto a flat anvil at three different geometrical configurations and three impact velocities (31 tests). The helmeted dummy was also impacted with an oblique abrasive anvil using the same impact velocities (18 tests). Linear and rotational accelerations of the dummy head as well as normal and tangential forces on the anvil were measured and compared to the results obtained in falling headform tests with identical impact configurations. The repeatability of the test results was good and comparable for dummy and headform experiments.

Both dummy and headform drop tests onto the oblique abrasive anvil showed a clear increase in rotational acceleration, tangential force and linear acceleration with the impact velocity. The linear relationship between peak rotational acceleration and peak tangential force in the dummy tests was significant (r = 0.90) and very similar to that found in falling headform tests (r = 0.97). There was a good qualitative correspondence between the measured values of both test configurations, but it turned out that impacts using a detached headform have to be carried out at slightly greater vertical velocities to produce the same results as dummy tests. Dummy impacts onto the oblique abrasive anvil at 5.2 m/s were comparable to headform impacts at 6.0 m/s. The results of dummy drop tests at 6.0 m/s lay between those of headform measurements at 6.0 m/s and 7.5 m/s. The differences between dummy and headform tests could be attributed to the inertial effects of the body mass acting on the head through the neck. These effects cause an additional rotation of the dummy headform about an axis in the neck area parallel to that passing through the ears. Its contribution to the resultant rotational acceleration accounts for the most part of the difference in rotational acceleration.

In dummy drop tests onto the flat anvil the motion of the head is more complex than for a detached headform. The measured linear and rotational accelerations, normal forces and HIC values increase with the impact velocity. For a given impact velocity the results systematically depend on the impact point and on the test configuration. For impacts at point P the peak rotational acceleration is much greater using a complete dummy instead of a detached headform. It was concluded that this is probably due to the body dynamics transmitting large forces to the dummy head trough the neck. On the other hand impacts at the points B and R showed lower rotational acceleration peaks when using a dummy. The reduced freedom of movement of the head, coupled to the body by the neck, could be the reason for this.

For drop tests onto a flat anvil the peak values of linear acceleration were significantly lower for dummy tests than for the equivalent headform tests. This was attributed to an increased effective mass of the headform when attached to the dummy. The greatest effective mass was found in P/90°-impacts where the normal impact forces act in the direction of the neck axis, whereas R/0°-impacts showed only a small increase.

The performed dummy drop tests demonstrate the combined effects of the body mass and the neck on the dynamics of an impacting dummy headform. The effects are less significant for oblique impacts than for impacts onto the flat anvil. Falling headform tests onto the oblique abrasive anvil are a good replacement for dummy tests if they are carried out at a slightly greater impact velocity. In case of impacts onto the flat anvil the influence of the dummy strongly depends on the impact configuration. Headform drop tests onto the flat anvil represent the worse case than dummy tests with regard to linear acceleration of the head, but this is not generally valid for rotational acceleration. Further investigations should include additional drop test configurations, as well as greater vertical and horizontal impact velocity components.

In future helmet standards falling headform tests will still be important to assess the linear acceleration of an impacting head. However, if rotational acceleration turns out to be an important head injury mechanism for certain impact configurations, dummy drop tests could be considered as a possible test method. In any case, dummy drop tests are an interesting alternative helmet test method to simulate full scale impacts of a dummy riding a motorcycle against an obstacle.

Since the dynamics of the impacted headform depends on the dummy neck, the mechanical properties of the neck as well as the forces and moments occurring during the impact should be studied in more detail. It is known that the Hybrid III standard neck is stiffer than a human neck, so that it is not clear how accurately the Hybrid III dummy drop tests replicate a rider in a motorcycle accident. Future experiments should be carried out with an improved neck model, in order to simulate the impact of a head more realistically.

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APPENDIX

Table A.1: Hybrid III dummy drop tests onto the oblique abrasive anvil: peak values of tangential and normal anvil force, headform rotational acceleration, rotational velocity, linear acceleration, and tangential impulse

Test No.	Vel. [m/s]	Head impact point/ body angle	Helmet Mass [g] (without visor)	Peak Tg-Force [N]	Peak N-Force [N]	Peak Rot. Acc. [rad/s2]	Peak Rot. Vel. [rad/s]	Peak Lin. Acc. [g]	Tg-Imp. [Ns]
1	4.4	LEFT/0°	1363	639	1131	1755	17.2	25	8.3
2	4.4	LEFT/0°	1320	729	1223	1579	19.8	25	10.1
3	4.4	LEFT/0°	1320	793	1315	1984	21.3	28	10.4
4	4.4	RIGHT/0°	1311	671	1169	2149	18.4	27	8.3
5	4.4	RIGHT/0°	1363	716	1321	2043	18.6	28	8.4
6	4.4	RIGHT/0°	1320	724	1239	2125	17.2	27	8.0
7	5.2	LEFT/0°	1370	833	1459	1906	21.2	31	11.0
8	5.2	LEFT/0°	1322	939	1668	2667	20.5	34	9.7
9	5.2	LEFT/0°	1340	887	1566	2421	22.4	32	10.7
10	5.2	RIGHT/0°	1370	921	1635	2877	21.4	36	9.9
11	6.0	LEFT/0°	1330	1069	1890	3103	24.3	41	11.8
12	6.0	LEFT/0°	1325	987	1744	2210	23.1	37	12.2
13	6.0	LEFT/0°	1337	1044	1791	2678	23.6	40	12.1
14	6.0	LEFT/0°	1332	1147	1954	3173	25.0	42	12.6
15	6.0	RIGHT/0°	1317	1046	1865	3201	25.3	40	11.5
16	6.0	RIGHT/0°	1330	1116	1941	3362	26.9	44	12.2
17	6.0	RIGHT/0°	1325	1154	1955	3680	27.6	44	12.7
18	6.0	RIGHT/0°	1356	1075	1859	3289	26.5	42	12.1

Table A.2: Hybrid III dummy drop tests onto the flat anvil: peak values of normal anvil force, headform rotational and linear acceleration, and HIC

Test No.	Velocity [m/s]	Head Impact point/ body angle	Helmet Mass [g] (without visor)	Peak N-Force [N]	Peak Rot. Acc. [rad/s2]	Peak Lin. Acc. [g]	HIC
1	4.4	B/30°	1311	6547	2875	84	245
2	4.4	B/30°	1363	6468	2919	86	257
3	5.2	B/30°	1340	7626	3883	97	344
4	5.2	B/30°	1370	7487	3177	102	398
5	5.2	B/30°	1340	8096	3594	97	362
6	6.0	B/30°	1317	9473	3995	113	527
7	6.0	B/30°	1330	8125	4457	112	541
8	6.0	B/30°	1325	8595	3567	115	540
9	6.0	B/30°	1356	8841	2920	104	430
10	4.4	R/0°	1311	7113	3603	123	584
11	4.4	R/0°	1363	7244	4065	126	602
12	4.4	R/0°	1320	6562	3199	116	504
13	4.4	R/0°	1320	7134	3840	123	584
14	5.2	R/0°	1340	8238	4776	139	835
15	5.2	R/0°	1370	7943	3821	138	790
16	5.2	R/0°	1322	7863	4238	141	783
17	5.2	R/0°	1340	8239	4518	151	872
18	6.0	R/0°	1317	9347	5242	166	1170
19	6.0	R/0°	1325	8499	4393	158	1023
20	6.0	R/0°	1356	8974	4730	171	1124
21	4.4	P/90°	1363	11735	3626	129	275
22	4.4	P/90°	1320	10714	4723	83	198
23	4.4	P/90°	1320	11278	4165	93	180
24	5.2	P/90°	1340	12476	4757	132	363
25	5.2	P/90°	1370	14225	4697	99	272
26	5.2	P/90°	1322	12620	4846	112	330
27	5.2	P/90°	1340	12422	4165	111	313
28	6.0	P/90°	1317	14482	5656	139	411
29	6.0	P/90°	1330	14656	5881	133	352
30	6.0	P/90°	1325	15507	5000	120	363
31	6.0	P/90°	1356	17597	4681	144	421