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Predicting the Kinematic Response of a Helmeted Headform during Oblique Impacts

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ABSTRACT

160 oblique impact tests were performed to study the relationship between the kinematic response of a helmeted headform and impact severity caused by the change of speed (Group 1) and anvil angle (Group 2). For this work, the kinematic response of a helmeted headform is evaluated by measuring linear acceleration, rotational acceleration, and rotational velocity of the headform. In Group 1, a football helmet was tested at 45° anvil angle at four different impact speeds ranging from 4.5m/s and 7.4m/s on five impact locations. Results showed that for all cases, the relationship between impact speed and helmeted headform kinematic response was linear, with an average R^2 value of 0.98. At each impact location, a prediction line was generated using the data points of the lowest and the highest speeds. For the speeds of 5.5m/s and 6.5m/s, the prediction of the helmeted headform kinematic response was validated with an average error of 4.7%. In Group 2, the helmeted headform was tested at 5.5m/s impact speed at six different anvil angles between 15° and 55°, and the response was fitted with a second-degree polynomial (curve) with an average R^2 value of 0.96. The kinematic response of the higher and lower impact speeds was obtained experimentally for one angle, and the fitted curve for 5.5m/s was offset to pass through the obtained kinematic response. The predicted helmeted headform kinematic response was validated experimentally, and the average error was found to be 8.3%. The results showed that it is possible to predict the kinematic response of a helmeted headform by interpolating or extrapolating the data without having to perform extra impact test. Analysis on other research works also showed similar predictable behaviour for headform equipped with other helmet models. Therefore, the number of tests during the process of evaluating a helmet performance can be reduced.

KEYWORDS

Biomechanics, head injury, kinematic response, linear acceleration, rotational acceleration, football helmet

INTRODUCTION

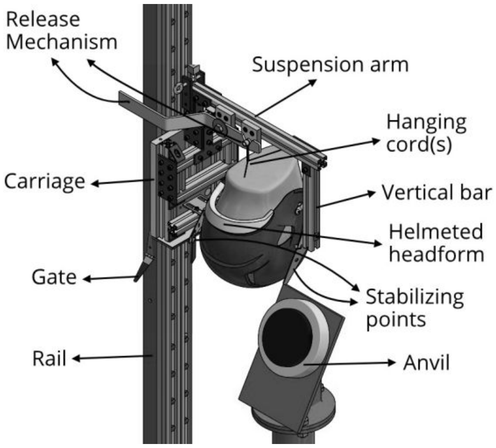
The protective helmet was initially developed to protect the head against severe impacts that may lead to death (Hoshizaki, et al., 2014; Becker, 1998). Many studies have demonstrated that helmets are effective in preventing severe head injuries such as skull fracture (McIntosh, et al., 2011; McIntosh & McCrory, 2005; Haider, et al., 2012; Sone, et al., 2017). However, the most common types of head injuries in sports are mild traumatic brain injuries (mTBI) such as concussions (Noble & Hesdorffer, 2013). In the past, head injury was thought to be caused only by the linear acceleration of the head (Hodgson & Thomas, 1971) However, research studies have shown that rotational acceleration plays a significant role in causing head injury and concussion (King, et al., 2003; Holburn, et al., 1943; Kleiven, 2013) and majority of the impacts to the head result in both linear and rotational motion of the head (Otte, 1991). Rotational acceleration and velocity have a significant correlation to the brain strain response (Kleiven, 2007; Rowson, et al., 2012; Ji, et al., 2014; Patton, et al., 2012), as they render shearing force to the brain tissues. The brain is more susceptible to shearing forces as the bulk modulus of the brain tissues (resistance to the uniform compression) is approximately one million times higher than that of the shear modulus (McElhaney, et al., 1976). Furthermore, the brain deformation is more severe when the linear and rotational motion were applied together (Gennarelli, et al., 1972; Ueno & Melvin, 1995; Pellman, et al., 2003). Yet, helmets for decades have been tested and certified only for linear acceleration (Consumer Product Safety Commission, 1998; NOCSAE, DOC, 2019; NOCSAE, DOC, 2016; UN ECE Regulation 22/05, 2002), and the focus has been on protecting the head against skull fractures (King, et al., 2003). Since an mTBI happens more often than a skull fracture, the general populace is more concerned about the concussion than the skull fracture (Vastag, 2002). As a result, standard bodies and independent researchers have started to measure and analyze the rotational acceleration and rotational velocity of the head, in addition to the linear acceleration, to better gauge the safety level and performance of a helmet (NOCSAE, DOC, 2019; Whyte, et al., 2019). In addition, technologies were developed in recent years to mitigate the injurious effects of rotational motion of the head during impacts (Aare & Halldin, 2003; Halldin, et al., 2003; Abram, et al., 2019; Bliven, et al., 2019). In 2011, Virginia Tech introduced a Summation of Tests for the Analysis of Risk (STAR) rating system where helmets are rated based on factors such as linear acceleration, rotational acceleration, and rotational velocity response during impact (Rowson, et al., 2015; Bland, et al., 2018; Rowson & Duma, 2011). Peter Halldin of MIPS also proposed an oblique impact testing method in 2015 (Halldin, 2015). National Operating Committee on Standards for Athletic Equipment (NOCSAE) Standard for Newly Manufactured Football Helmets introduced rotational acceleration-based testing that will come into effect in November 2019 (NOCSAE, DOC, 2019).

Some of the helmet testing protocols require the helmet to be tested multiple times at different severity levels gauged by the impact speed. This results in many trials, which can be expensive and time-consuming. Finite Element Analysis (FEA) has been widely used to simulate helmet impact (Zhang, et al., 2004; Willinger & Baumgartner, 2003; Aare, et al., 2004; Mills, et al., 2009). FEA is a great tool for a preliminary impact study (Fernandes & Alves de Sousa, 2013). However, in some cases, FEA results may not be sufficiently accurate, and a physical sample of headgear is needed to experimentally validate its performance (Fernandes & Alves de Sousa, 2013).

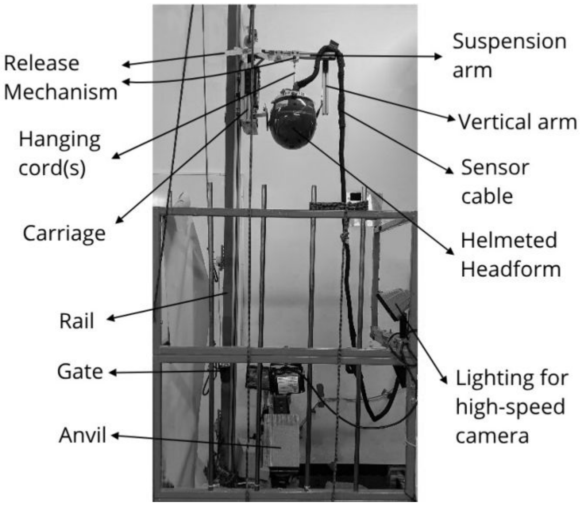
Several studies of helmet response showed that there are linear relationships between linear acceleration and impact severity. DeMarco performed impact tests of various motorcycle and cycling helmets showing a linear relationship between linear acceleration and impact severity as long as the helmet impact-absorbing liner is functional and it is not bottomed-out (DeMarco, et al., 2010; DeMarco, et al., 2016). Cripton, Rowson, and COST 327 performed drop tests on cycling, football, and motorcycle helmets, respectively (Cripton, et al., 2014; Rowson, et al., 2013; Chinn, et al., 2001). However, Cripton, Rowson, and COST 327 did not assess the relationship between impact severity and head kinematic response. Furthermore, no studies have been done on the relationship between impact severity and head rotational acceleration and velocity (Whyte, et al., 2019). In this work, the relationship between the impact severity and the helmeted headform’s kinematic response: linear acceleration, rotational acceleration, and rotational velocity, is studied.

METHODS

An impact test rig was used to perform oblique impact tests at different speeds and different anvil angles. The patent-pending impact test rig (Abram, et al., 2018) was developed and built at the Head Injury Prevention (HIP) Lab at Simon Fraser University (SFU), Surrey, Canada. Figure 1 details the test rig. A Hybrid III 50th percentile male dummy headform without neck was used to perform the tests.



(a)



(b)

Figure 1. (a) CAD model of the Oblique Impact Test Rig at the HIP Lab and (b) Oblique Impact Test Rig at the HIP Lab.

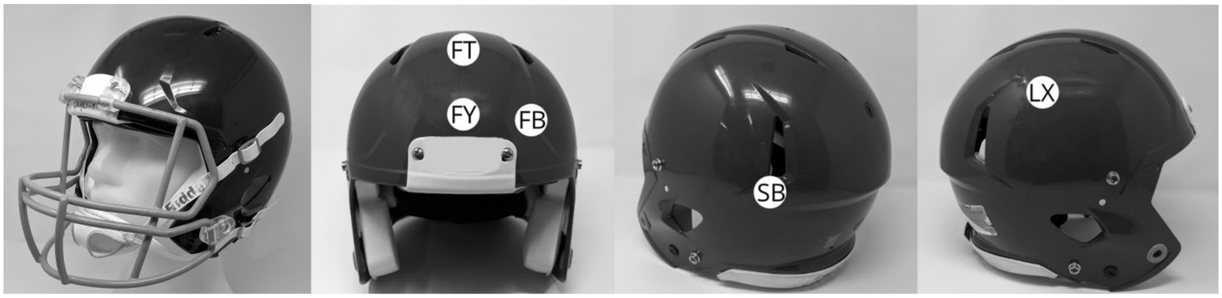
The Hybrid III headform was equipped with nine single-axis linear accelerometers (ENDEVCO 7264C, Meggitt Sensing Systems Irvine, California) arranged on a 3-2-2-2 block array. The rotational accelerations of the head in x, y, and z-axes during an impact were calculated with an algorithm described in Padgaonkar (Padgaonkar, et al., 1975). Data were collected at a sampling rate of 20 kHz.

Accelerometers data were filtered through a 4th order Butterworth low-pass filter with 1000 Hz cut-off frequency according to SAE Recommended Practice J11a (Consumer Product Safety Commission, 1998; NOCSAE, DOC, 2017). The change in the rotational velocity was calculated through the integration of the rotational acceleration graph.

The impact surface was a 42 Shore A Modular Elastomer Programmer (MEP) pad installed on angled support. The MEP pad was selected as it resembles common impact surfaces in football games (Post, et al., 2017; Hoshizaki, et al., 2012). The impact speed was measured using a photoelectric time gate adjacent to the rail guide. A high-speed camera (Edgertronics SC2+) was used to record the impact tests at 4,000 frames/sec in high definition.

A Riddell Speed football helmet (Figure 2a), Size L, was fitted according to the manufacturer's specifications. All tests were performed without using a facemask or other accessories. The helmeted headform was placed onto the test rig, where its orientation, position, and height were secured based on a given impact scenario.

The first part of this study (Group 1) focused on changing the speed of impact while keeping the angle of impact fixed at 45°. Five impact locations were selected for Group 1 based studies on the most prevalent impact locations (Pellman, et al., 2003; Crisco, et al., 2010; Daniel, et al., 2012): Front-Top (FT), Front-Boss (FB), Front-Y (FY), Lateral-X (LX), and Side-Back (SB). The impact locations can be seen in Figure 2b-d. At each impact location, data points was obtained at speeds of 4.5, 5.5, 6.5, and 7.4 m/s. To obtain a data point, five tests with results within 10% of each other are required. In total, 100 tests were conducted for Group 1 testing.



(a) (b) (c) (d)

Figure 2. (a) The Riddell Speed football helmet, (b) front-top FT impact location, front FY impact location, front-boss FB impact location, (c) side-back SB impact location, and (d) lateral LX impact location.

The results of Group 1 testing, including linear acceleration, rotational acceleration, and rotational velocity at different speeds, were examined while keeping the impact angle fixed. A regression analysis was performed on the result of Group 1. The data were fitted with a first-order polynomial (Equation 1).

$$y = a_1 x + a_0 \quad , \quad a_n \neq 0 \tag{1}$$

Then, for each kinematic response at every impact location (one set of data), in Group 1, any combination of two out of four data points was selected, and Equation 1 was fitted through the two selected data points to obtain the prediction line.

The experimental and predicted values of the kinematic response for the other two points were compared. The percent (%) error represents the difference between experimental and predicted values and was calculated with Equation 2.

$$\%\ Error = \left|\frac{Experiment - Prediction}{Experiment}\right| \times 100\% \tag{2}$$

Also, COST 327 reported oblique impact testing of four different models of motorcycle helmets for five different speeds from 6m/s to 12m/s without analyzing the relationship between impact speed and kinematic response (Chinn, et al., 2001). As a part of this study, the results of COST 327 were also analyzed.

In the second part of this study (Group 2), the angle of impact varied while the speed of the impact was fixed, at speed recommended by NOCSAE, 5.5m/s (NOCSAE, DOC, 2019). One impact location, FY, was chosen for all tests. One set of impact test was conducted on six anvil angles between 15°, 22°, 30°, 37°, 45°, and 55°, yielding six data points for each set. In addition, two sets of impact tests, one tested at 4.5m/s and the other 6.5m/s were also conducted on three anvil angles (15°, 30°, and 45°), yielding three data points per set. With five trials for each impact scenario, 60 tests were conducted in total.

Similar to Group 1 test, the results of Group 2 testing, including linear acceleration, rotational acceleration, and rotational velocity at different angles, were examined while keeping the impact speed fixed. To obtain a data point, five tests with results within 10% of each other are required. In total, 60 tests were conducted for Group 2 testing. A regression analysis was performed on the result of Group 2 from fixing the speed at 5.5 m/s. The 5.5 m/s data were fitted with a second-order polynomial (Equation 3).

$$y = a_2x^2 + a_1x + a_0 \quad , \quad a_n \neq 0 \tag{3}$$

The generated curve from 5.5m/s impact speed was used to predict the kinematic response for 4.5m/s and 6.5m/s impact speeds. At each speed level, the curve was offset to pass through one experimental data point. The prediction line was used in three different scenarios. In scenario 1, the prediction line passed through the experimental data points of 15°. In scenario 2, the prediction line passed through the experimental data points of 30°, in scenario 3, the prediction line passed through the experimental data points of 45°. For example in scenario 2, as shown in Figure 5a-c, the curve obtained from 5.5m/s speed was offset to pass through only the 30° data points to predict the kinematic response for impact speeds of 4.5m/s and 6.5m/s for the 15° and 45°. Then, the prediction was validated by comparing the predicted and experimental values. The percent (%) error was calculated with Equation 2.

RESULTS

Group 1 comprises of testing on five locations of the football helmet for four different speeds between 4.5m/s and 7.4m/s. The results of the impact tests at different impact locations were summarized in Table 1. The Coefficient of Variation (CV) was computed from the standard deviations and mean values of each measured kinematic parameter.

Table 1. Average responses of the headform when impacting different areas of the helmet at various speeds.

Impact speed (m/s)	Lin.Acc. (g)	Lin. Acc CV (%)	Rot. Acc. (krad/s^2)	Rot. Acc. CV (%)	Rot. Vel. (rad/s)	Rot. Vel. CV (%)
FY						
4.5	81.52	3.13	3.53	9.37	24.25	1.86
5.5	94.60	2.74	5.02	2.59	29.57	7.05
6.5	124.73	3.76	6.28	8.24	36.06	4.20
7.4	142.00	0.98	7.78	7.17	39.90	3.36
LX						
4.5	68.64	2.57	3.32	8.21	23.71	3.25
5.5	73.84	3.69	4.18	4.91	29.79	6.72
6.5	103.84	3.22	5.30	5.17	36.74	3.34
7.4	125.72	1.41	6.67	9.78	36.18	2.49
FT						
4.5	64.58	2.19	3.01	2.26	24.00	1.43
5.5	81.76	2.38	3.82	3.87	29.22	1.01
6.5	100.60	1.32	4.68	8.41	34.08	2.57
7.4	120.57	3.83	5.97	4.53	40.48	1.52
FB						
4.5	86.85	2.21	3.75	8.64	26.83	5.67
5.5	107.39	2.83	4.46	3.88	31.64	2.79
6.5	125.30	3.05	5.53	1.88	37.10	3.44
7.4	139.18	2.47	6.58	2.80	40.62	2.32
SB						
4.5	53.05	2.22	3.47	4.54	24.56	3.18
5.5	67.87	2.19	3.79	3.12	25.63	3.82
6.5	81.94	3.83	5.70	3.60	39.99	4.09
7.4	98.90	4.69	6.17	1.99	43.94	2.61

Figure 3a-c show the Group 1 data points fitted with Equation 1. The R^2 values for the best-fitted line for all five impact locations were calculated. The average R^2 values for linear acceleration, rotational acceleration, and rotational velocity were 0.9855, 0.9809, and 0.9595, respectively. The equation parameter and the R^2 values were summarized in Table 2. The equation parameter p-value was also calculated. A p-value less than 0.05 is statistically significant.

Table 2. Equation parameters and the coefficients for the best fit lines of the response for Group 1.

	Lin. Acc.				
Loc.	**a_1**	**p-value**	**a_0**	**p-value**	**R^2**
FY	21.6104	0.0033	-18.4855	0.1414	0.9867
LX	20.6462	0.0203	-29.6601	0.2432	0.9545
FT	19.2042	0.0029	-22.8203	0.0796	0.9993
FB	18.5087	0.0056	3.7941	0.3664	0.9973
SB	15.3209	0.0051	-15.6712	0.1415	0.9899

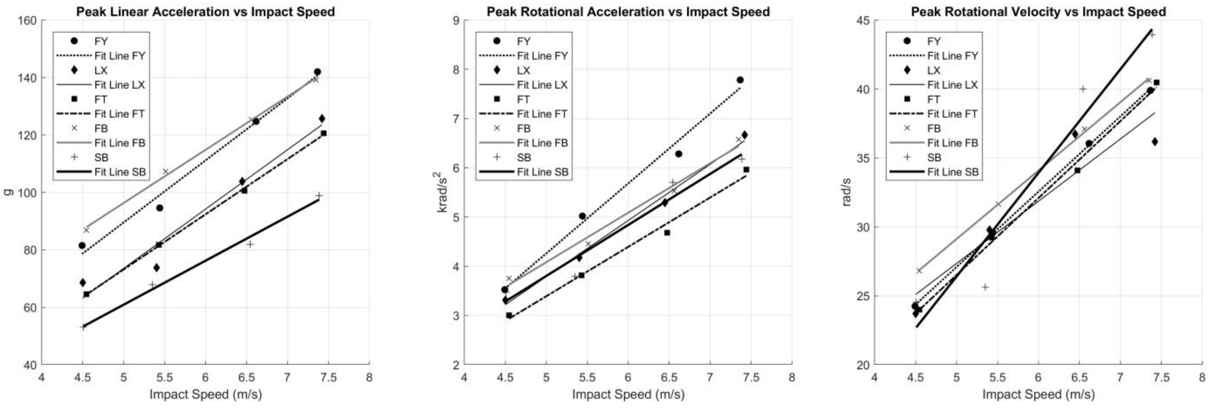
	Rot. Acc.				
Loc.	**a_1**	**p-value**	**a_0**	**p-value**	**R^2**
FY	1.4200	0.0055	-2.8365	0.0492	0.9879
LX	1.1397	0.0077	-1.9073	0.0908	0.9924
FT	1.0020	0.0117	-1.6165	0.1503	0.9883
FB	1.0042	0.0036	-0.9365	0.1928	0.9855
SB	1.0359	0.0250	-1.3744	0.3068	0.9505

	Rot. Vel.				
Loc.	**a_1**	**p-value**	**a_0**	**p-value**	**R^2**
FY	5.4588	0.0019	-0.1927	0.9443	0.9997
LX	4.5123	0.0563	4.7947	0.5735	0.8683
FT	5.5777	0.0068	-1.3656	0.8329	0.9956
FB	4.9605	0.0020	4.3257	0.0472	0.9993
SB	7.5144	0.0332	-11.1584	0.3193	0.9347

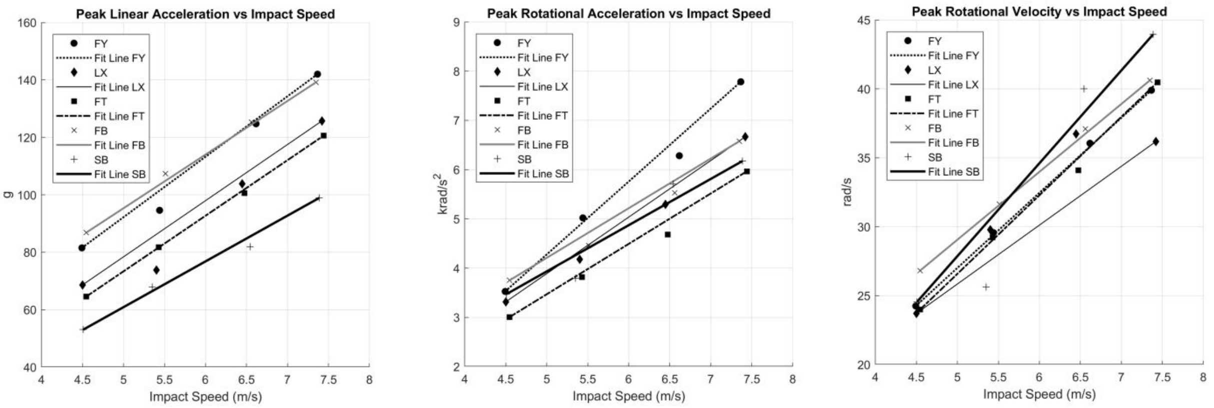
Figure 3d-f showed the prediction line obtained from fitting the data points of the lowest and higest speed with Equation 1. Table 3 compares the experimental and predicted values of the helmeted headform kinematic response for the other two points.

Table 3. Comparison of the experimental versus predicted values of Group 1.

Speed (m/s)	Lin. Acc. (g)			Rot. Acc. (krad/s^2)			Rot. Vel. (rad/s)		
	Experiment	Prediction	% Error	Experiment	Prediction	% Error	Experiment	Prediction	% Error
FY									
5.5	94.60	101.47	7.3	5.02	4.93	1.8	29.57	29.41	0.5
6.5	124.73	126.22	1.2	6.28	6.67	6.2	36.05	35.81	0.7
LX									
5.5	73.84	86.23	16.8	4.18	4.35	4.1	29.79	27.56	7.5
6.5	103.84	106.68	2.7	5.30	5.55	4.7	36.74	32.02	12.8
FT									
5.5	81.76	81.68	0.1	3.82	3.91	2.4	29.22	29.04	0.6
6.5	100.60	101.88	1.3	4.68	4.98	6.4	34.08	34.98	2.6
FB									
5.5	107.39	104.85	2.4	4.46	4.72	5.8	31.64	31.57	0.2
6.5	125.30	124.46	0.7	5.53	5.78	4.5	37.10	36.74	1.0
SB									
5.5	67.87	66.47	2.1	3.79	4.26	12.4	25.63	30.23	17.9
6.5	81.94	85.49	4.3	5.70	5.38	5.6	39.99	38.27	4.3



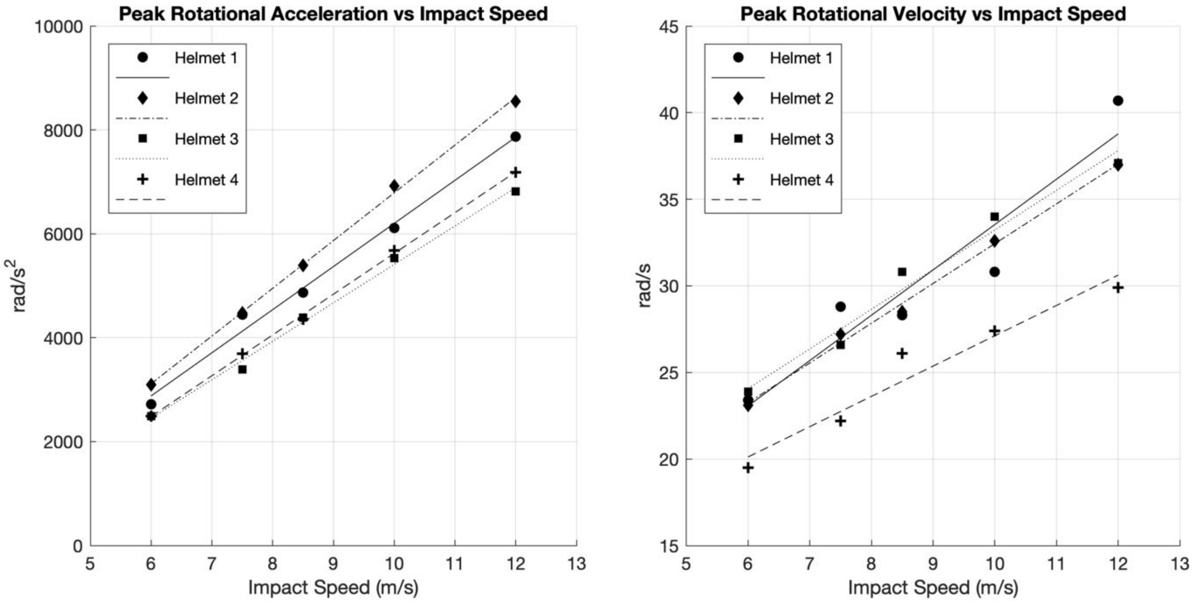
(a) (b) (c)



(d) (e) (f)

Figure 3. Plots of speeds versus (a) linear acceleration, (b) rotational acceleration, and (c) rotational velocity fitted with a polynomial degree 1 through all points and plots of speeds versus (d) linear acceleration, (e) rotational acceleration, and (f) rotational velocity fitted with a polynomial degree 1 through points from speeds of 4.5m/s and 7.4m/s.

The results of COST 327 were plotted, as shown in Figure 4a-b. The R^2 values for the rotational acceleration of the four helmet models were between 0.9903 and 0.9991. For rotational velocity, the R^2 values were between 0.8995 and 0.9952.



(a) (b)

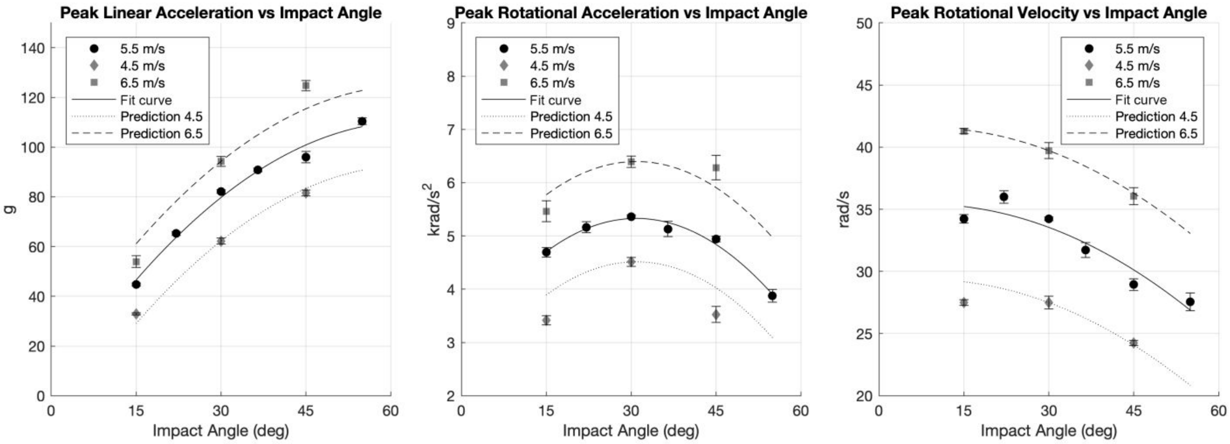
Figure 4. Plots of speeds versus (a) rotational acceleration, (b) rotational velocity of four motorcycle helmets from COST 327 report (Chinn, et al., 2001).

Group 2 comprises of testing on six different anvil angles between 15° and 55° at a fixed impact speed of 5.5m/s and one impact location, FY. The results of the impact tests were summarized in Table 4.

Table 4. Average responses of the helmeted headform struck at the FY region at 5.5m/s, 4.5m/s, and 6.5 m/s with varying angles.

Impact angle (°)	**Linear Acc (g)**	**Lin. Acc. CV**	**Rot. Acc (krad/s^2)**	**Rot. Acc. CV**	**Rotational velocity (rad/s)**	**Rot. Vel. CV**
			5.5m/s			
15	44.74	2.78	4.69	4.39	34.23	2.20
22	65.24	2.69	5.16	4.37	35.99	3.06
30	82.10	1.90	5.36	1.36	34.24	0.92
37	90.85	1.78	5.13	6.14	31.72	4.17
45	95.98	5.41	4.94	2.41	28.94	3.68
55	110.45	2.73	3.88	6.94	27.56	5.73
			4.5m/s			
15	32.97	2.90	3.42	5.47	27.50	1.88
30	62.19	4.33	4.51	4.01	27.49	4.19
45	81.52	3.13	3.53	9.37	24.25	1.86
			6.5m/s			
15	53.93	9.73	5.46	7.97	41.28	1.14
30	94.26	4.88	6.39	3.71	39.72	3.62
45	124.73	3.76	6.28	8.24	36.05	4.20

Group 2 results were plotted in Figure 5a-c, including the fitted polynomial and the prediction line (of scenario 2). The equation parameter and the R^2 values were also summarized in Figure 5a-c. The experimental and the predicted values for all scenarios were compared shown in Table 5.



(a) (b) (c)

Figure 5. Plotting scenario 2 prediction results: (a) linear acceleration, (b) rotational acceleration, and (c) rotational velocity.

Table 5. Comparison of the experimental versus predicted values of Group 2.

	Angle (^{0})	**Lin. Acc. (g)**			**Rot. Acc. (krad/s^2)**			**Rot. Vel. (rad/s)**		
		Experiment	**Prediction**	**% Error**	**Experiment**	**Prediction**	**% Error**	**Experiment**	**Prediction**	**% Error**
Scenario 1	**4.5m/s**									
	30.0	62.19	66.16	6.4	4.51	4.04	10.5	27.49	25.82	6.1
	45.0	81.52	87.31	7.1	3.53	3.55	0.8	24.25	22.40	7.6
	6.5m/s									
	30.0	94.26	87.12	7.6	6.39	6.08	4.8	39.72	39.61	0.3
	45.0	124.73	108.27	13.2	6.28	5.60	10.9	36.05	36.18	0.4
Scenario 2	**4.5m/s**									
	15.0	32.97	29.01	12.0	3.42	3.89	13.8	27.50	29.17	6.1
	45.0	81.52	83.34	2.2	3.53	5.03	14.2	24.25	24.07	0.7
	6.5m/s									
	15.0	53.93	61.07	13.2	5,46	5.77	5.7	41.28	41.39	0.3
	45.0	124.73	115.40	7.5	6.28	5.91	5.9	36.05	36.30	0.7
Scenario 3	**4.5m/s**									
	15.0	32.97	27.19	17.5	3.42	3.39	0.9	27.50	29.35	6.7

	30.0	62.19	60.38	2.9	4.51	4.01	11.1	27.49	27.67	0.7
	6.5m/s									
	15.0	53.93	70.39	30.5	5.46	6.14	12.5	41.28	41.15	0.3
	30.0	94.26	103.58	9.9	6.39	6.77	5.9	39.72	39.48	0.6

DISCUSSION

When the speed of impact is increased, linear acceleration, rotational acceleration, and rotational velocity of the helmeted headform increase proportionally. As shown in the results of Group 1 in Table 1, while keeping the anvil angle fixed at 45^{o}, increasing the speed of impact from 4.5m/s to 7.4m/s increased the linear acceleration from 81.52 g to 142.00 g for the FY location, 68.64 g to 125.72 g for the LX location, 64.58 g to 120.57 g for the FT location, 86.85 g to 139.18 g for the FB location, and 53.05 g to 98.90 g for the SB location. A similar increasing trend can be observed for rotational acceleration and rotational velocity. When the speed of impact was increased from 4.5m/s to 7.4m/s, the rotational acceleration of FY, LX, FT, FB and SB test increased respectively from 3.53 krad/s^2 to 7.78 krad/s^2, 3.32 krad/s^2 to 6.67 krad/s^2, 3.01 krad/s^2 to 5.97 krad/s^2, 3.75 krad/s^2 to 6.58 krad/s^2, 3.47 krad/s^2 to 6.17 krad/s^2. The linearity observed was in concert with the results presented by Cripton, Rowson, and DeMarco.

As shown in Figure 3d-f, the result showed that the overall best result for predicting the other two speeds' kinematic response was achieved when the data points from the lowest (4.5m/s) and the highest speeds (7.4m/s) were chosen. The average error generated from predicting the helmet response at 5.5m/s and 6.5m/s in all impact locations was 4.7%, with a minimum error of 0.1% and a maximum error of 17.9%.

The results of COST 327 also showed that, when the speed of impact varies, the kinematic response of a helmeted headform behaves linearly. The linear behaviour was observed for the peak rotational acceleration and the peak rotational velocity versus the speed of impact.However, COST 327 did not report peak linear acceleration in their study.

In Group 2, as shown in Table 4, fixing the speed at 5.5m/s while increasing the angle from 15^{o} to 55^{o} resulted in an overall increase of linear acceleration from 44.74 g to 110.45 g. On the other hand, a mixed trend in rotational kinematics was observed. Rotational acceleration, unlike linear acceleration and rotational velocity, did not always increase. There was a maximum (most severe) rotational acceleration within the specidied angles of impact (between 15^{o} to 55^{o}), which happened at around 30^{o} . The rotational acceleration increased from 4.69 krad/s^2 (at 15^{o}) to 5.46 krad/s^2 (at 30^{o}), then decreased to 3.88 krad/s^2 (at 55^{o}). The rotational velocity increased from 34.23 rad/s (at 15^{o}) to 35.99 rad/s (at 22^{o}) and then decreased gradually to 27.56 rad/s (at 55^{o}). The results of Group 2 testing showed a relationship between the kinematic response and the anvil angle when the speed of impact was fixed at 5.5m/s. The relationship was best described by a second degree-polynomial (Equation 3).

According to the results shown in Figure 5a-c, a second degree-polynomial was adequate with R^2 values of 0.99, 0.98, and 0.90 for linear acceleration, rotational acceleration, and rotational velocity, respectively. The equation parameters, a_2, a_1, and a_0, for linear acceleration are -0.0268, 3.4169, and 1.2784, respectively. For rotational acceleration, the equation parameters are -0.0025, 0.1523, and 2.9726, respectively. The equation parameters for rotational velocity are -0.0039, 0.0625, 35.1562, respectively. The results in Table 5 showed that in scenario 1, the response was predicted with an average error of 6.3%. In scenario 2, the average error of the prediction response was 6.9%. In scenario 3, the average prediction error was 8.3%.

In total, 160 impact tests were performed with one type of football helmet. It was also observed that the kinematic response of the headform equipped with that specific helmet can be predicted. The prediction model can be used to reduce the number of data points that need to be obtained experimentally. Since the results presented from the other studies on different helmets showed linear behaviour, one can conclude that kinematic response of the helmeted headform can be predicted in most cases as long as the shock-absorbing liner of the helmet is functional and is not bottomed out.

In this study, impact tests were performed using the oblique impact drop test rig with a neckless Hybrid III headform. The NOCSAE standard for newly manufactured football helmet recommend both the linear impactor test and the drop test. However, unlike drop test, linear impactor tests produce little tangential force (Willinger, et al., 2015), a crucial contributor to the rotational acceleration of the head (Finan, et al., 2008). NOCSAE linear impactor test also calls for the use of a Hybrid III neck. Studies on the Hybrid III neck showed that Hybrid III neck is too stiff (Herbst, et al., 1998) compared to the human neck. In addition, the Hybrid III neck is designed only for flexion and extension (Svensson & Lovsund, 1992) and its behaviour for other types of motion such as lateral is not known (Aare & Halldin, 2003; Bartsch, et al., 2012; Myers, et al., 1989; Gwin, et al., 2009). A study on helmeted head impact suggested that for the first 10 ms of an impact, the effect of the neck is minor (Willinger, et al., 2015). Another study showed that it takes 13–14 ms for the muscles of the human neck to respond to an impact to the head (Kuramochi, et al., 2004). A typical acceleration pulse in football helmet impact lasts for approximately 15 ms and may not result in a resisting response from the neck muscles (Pellman, et al., 2003; Zhang, et al., 2004; Deck & Willinger, 2008). Also, there is an atlanto-occipital zone where the neck joint can have motion in the range of 10^o without affecting the kinematic response of the head (Ivancic, 2014; Camacho, et al., 1997). Therefore, using a drop test and a neckless headform seems to be more realistic than using a linear impactor test with a Hybrid III head and neck for performing oblique impact tests.

This study also comes with some limitations, with the main limitation being only one helmet type was used: football helmet. In Group 1, results from other research studies on motorcycle and bicycle helmets were analyzed and similar linearity was observed. However, in Group 2, testing at more angles, locations, and speeds with different helmet models is required. Tests with different apparatus, such as NOCSAE headform which is more anthropomorphically correct than a Hybrid III, may also be done in the future.

CONCLUSION

The relationship between impact speed, impact angle and the kinematic response of a helmeted headform was studied. It was observed that when the speed of impact was varied, and the angle of impact was fixed, the kinematic response behaved linearly. This linear behaviour was then used to predict the response for different speeds with an average error of 4.7%. On the other hand, when the angle of impact was varied, and the impact speed was fixed, the kinematic response of the helmeted headform was best described with a second-degree polynomial (curve). Then, the kinematic response was predicted and validated at different speeds. The result showed that the average error of the prediction was from 6.3% to 8.3%. The prediction model can be used to reduce the number of data points that need to be obtained experimentally. When examining and rating a helmet performance, one can test the helmet at different speeds or angles and use this prediction method to obtain more data points at other speeds and angles. Although, it is known that by increasing the speed, the linear and rotational acceleration increase as well, but the rate of change is not one-to-one. In this study, three different helmet types (football, motorcycle, and bicycle) were examined, and the results can help other researchers to have an educated guess regarding the performance of a helmet in different impact speeds. Particularly, this study shows that the rotational acceleration of a football helmet does not have a linear behaviour when the angle of impact increases. A peak rotational acceleration can be expected when the angle of impact is around 35°. This helps other researchers or tester to know at what range of angles should expect the highest rotational acceleration, and consequently the most severe head injury due to the rotational acceleration. For example, one can test a helmeted headform at 4.5 m/s and 7.4 m/s and interpolate the results to find the helmeted headform's performance at the speeds in between without performing the test. Also, one can test a helmeted headform at different angles, fixing the speed, and extrapolate the data to find the helmeted headform's performance at different speeds without performing the test.

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