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A Novel Low-Cost Machine for Evaluating Helmet Performance in Bike Accident Scenarios †

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Abstract: The increasing mortality rate in bike-related road accidents due to head injuries necessitates stronger helmets. This paper presents a cost-effective machine setup to evaluate helmet behavior during impacts. By employing unique methods to measure impact duration and post-impact energy absorption, this project eliminates the need for high-speed cameras. The results indicate that the developed machine enables scenario-based impact tests directly on helmets, providing valuable insights into collision effects. Validation confirms its effectiveness. The low-cost impact testing machine offers a practical solution for studying helmet performance and addressing the rising concerns surrounding bike accidents.

Keywords: pendulum-based impact testing; cost-effective; impact time; bike helmets; impact test

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1. Introduction

Mechanical impact is the leading cause of brain injury, death, and disability in people aged under 45 in the USA, Europe, and developing countries [1]. Road accidents have contributed largely to this aspect. Although bikers are instructed to wear helmets while riding bikes, the quality of helmets still needs to be assessed before their commercialization [2]. Generally, there are three approaches to helmet testing: physical tests, analytical modeling, and numerical simulations [3]. Among them, physical testing has always been accepted worldwide because of its ability to produce real results, incorporating all the given mechanical conditions [4]. Several studies have investigated helmet performances using different impact environments [5]. However, expensive high-speed cameras for impact time measurements and post impact studies were used in these studies.

In countries such as Pakistan, where motorcycles comprise up to 75% of registered vehicles, local helmet manufacturing companies do not have the facilities to test the helmet material's strength and behavior during collision to make their product robust and reliable before bulk production. Existing global testing equipment is expensive and requires specialized expertise. In this study, a pendulum-based impact testing machine for helmets was designed, fabricated, and experimented directly on helmets. Limit switches were used for impact time measurement. The authors found that the results are approaching the standards and are fair to use. Comparing the cost and effectiveness of the machine, this could be a new commercial testing facility for helmets.

2. Materials and Methods

Table 1 shows the components and their respective materials. The height, length, and width of the machine were assumed to be 244 cm, 180 cm, and 120 cm, respectively.

Table 1. Components used in machine and the respective materials.

Component	Material
Column	Mild Steel (Both ends fixed)
Specimen (bike helmet)	Glass Fiber (E = 72 GPa)
Impactor (variable mass range of 5–20 kg)	Mild Steel (E = 200 GPa)
Instruments used	IR Sensor, Limit Switch, Timer
Guide Rails	Stainless steel (E = 190 GPa)

2.1. Design of Column

The different machine components were designed using the standard procedures of mechanical design. Columns were designed using the Euler formula given in Equation (1).

$$P_E = \frac{\pi^2 EI}{{L_e}^2} \tag{1}$$

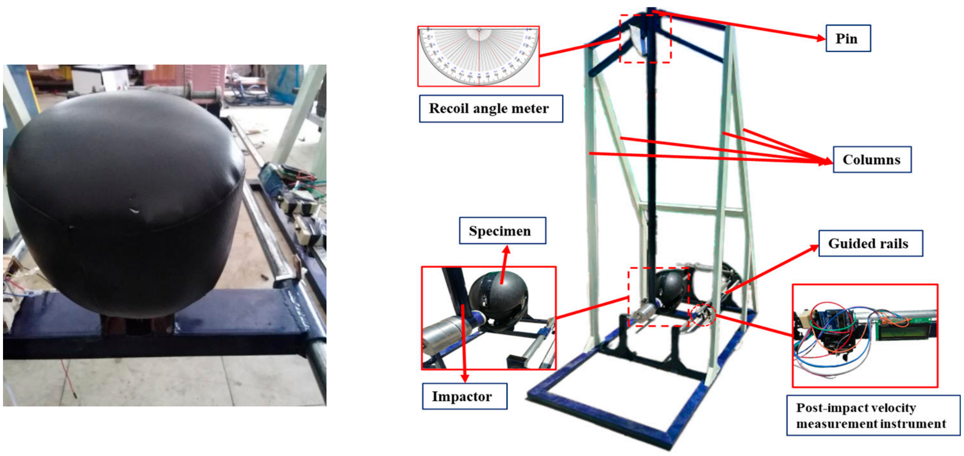
where P_E is the critical load, E is the modulus of elasticity, L_e is the effective length, and I is the moment of inertia. The column was designed with a factor of safety equal to 2. The rectangular column had cross-sections of 30 mm $\times$ 60 mm $\times$ 2 mm. The height of the column was 244 cm.

2.2. Design of Impactor Arm

The machine should be as light as possible. Therefore, the impactor arm was made hollow. The safe diameter was calculated using bending criteria with a factor of safety 2. The pin was designed using both shearing and bending criteria where the bending gave a maximum diameter of 10.7 mm. Equation (2) gives the bending criteria.

$$d^3 = \frac{(B.M)(32)}{\pi(S_y)} \tag{2}$$

The head form was made by filling polyester foam in a head-shaped leather bag over a steel base. The manufactured pendulum-based testing machine is given in Figure 1.



(**a**) (**b**)

Figure 1. (**a**) Head form for helmet rest, (**b**) pendulum-based impact testing machine.

2.3. Impact Duration Measurement

The duration of the impact was measured using the limit switch along with an Arduino controller. When the contact between the impactor and helmet was established, the current started flowing in the circuit, and it broke the circuit when the two were disconnected. The time span was calculated using the Arduino controller.

2.4. Measurement of Energy Absorbed by Helmet

The total energy of the impactor upon impact was converted into three energies, i.e., the energy absorbed by the helmet, the post-impact kinetic energy of the helmet, and the remaining energy in the impactor. Equation (3) is used for the calculation of the total energy absorbed in the helmet,

$$E_T = E_h + K{\cdot}E_h + E_{rec} \tag{3}$$

where E_T is the total energy, E_h is the energy absorbed by the specimen, $K{\cdot}E_h$ is the kinetic energy of the helmet after impact, and E_{rec} is the recoil/remaining energy of the impactor after the collision. The total energy of the impactor was calculated through the maximum kinetic energy achieved by the impactor just before impact. The potential energy of the impactor depended on the height achieved by the impactor measured by measuring the angle of inclination on the protractor attached. The kinetic energy of the helmet was measured through the total distance covered by the helmet on a steel rail, measured using a ruler. The frictional force was responsible for stopping the helmet. The higher the kinetic energy, the higher the distance traveled, as the friction force was assumed to be constant. The following Equations (4) and (5) were utilized to calculate the kinetic energy of the helmet.

$$K{\cdot}E_h = -F_f d \tag{4}$$

$$F_f = \mu_k N \tag{5}$$

3. Results and Discussion

The impact testing was performed on a standard available bike helmet, along with its catalogue in the local market. The experiments were conducted with varying angles of lift of the impactor for a constant mass of the impactor being taken as 10 kg. Table 2 gives the readings taken from the experiment.

Table 2. Experimental results obtained from the pendulum-based impact energy machine.

Sr. No		1	2	3	4
Before Impact attributes of impactor	Angle of lift (degree)	30	45	60	75
	Height attained (m)	0.245	0.536	0.914	1.355
	Velocity just before impact (m/s)	2.19	3.24	4.23	5.15
	Total energy (J)	24.01	52.53	89.57	132.79
Impact Duration (s)		0.13	0.23	0.35	0.4
Post Impact attributes of impactor	Impactor recoil angle (degree)	10	15	20	24
	Height attained (m)	0.028	0.062	0.11	0.16
	Recoil energy (J)	2.744	6.076	10.78	15.68
Post Impact attributes of helmet	Distance travelled by helmet (m)	0.18	0.27	0.3	0.33
	Kinetic energy of helmet (J)	3.70	5.56	6.17	6.79
	Energy absorbed by helmet (J)	17.56	40.89	72.62	110.32

The results highlight the relationship between the angle of lift of the impactor, the distance traveled by the helmet, and the energy absorbed by the helmet. The potential energy was directly proportional to the angle of lift of the impactor, thereby having a direct relation to both the distance traveled by the helmet and the energy absorbed by it. The apparatus in this study measured the total energy transferred to the helmet, along with the energy transferred to the neck. The limitations, however, include no measurement being taken of the peak acceleration values from the helmet to neck.

The maximum energy absorbed by the helmet was reported to be 110.32 J when the impactor was lifted at a 75° angle. The energy absorbed was 80.9 J for a corresponding impact energy of 101.13 J, which was ~80% of the impact energy, including the loss of energy in gaining momentum in the direction of the impact. The energy absorbed was ~88%, as per that given by Bhudolia et al. in 2021, not including the energy transferred to the neck [6].

4. Conclusions

In this research, a simple method for measuring the impact duration and post-impact energy absorption during helmet impact was presented. A pendulum-based impact energy machine was designed and fabricated, and then the experimentation was conducted with a varying angle of lift of the impactor for a constant mass of the impactor taken as 10 kg. The results concluded that a higher potential energy led to an increase in both the distance traveled by the helmet and the energy absorbed by it. The experimental results were then compared to the reference results and based on this comparison, it can be concluded that the novel machine used in the current study was economical and could be utilized for assessing helmet performance and enhancing the scrutiny of helmet designs.

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