Research Article

Impact Device for Biomechanics of Human Head-Neck Injuries

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1. Introduction

Head injuries are related to traffic collisions, runovers, contact sports, and daily life actions. The frequency of these events is high, and in some cases, the consequence could be fatal. In terms of traffic collisions, the Association for Safe International Road Travel (ASIRT) reports approximately 1.35 million deaths per year and 20 to 50 million nonfatal injuries [1]. In sports where physical contact is required, the most common injury suffered is a concussion. The Program for Injury Prevention, Education & Research reports a frequency ranging from 7.5 to 10.5 concussions per 10,000 athletes in football, soccer, and ice hockey; these disciplines have the highest rate in the US [2]. In literature, it is possible to find test methods that analyze these events to establish standards, improve safety equipment, and reduce injuries reported [3–6]. However, these tests are focused on evaluating and improving the elements outside of the human body, like airbags and seatbelts in vehicles or protective equipment in sports, avoiding going further in a complete analysis on the head after receiving an impact. Different indexes help to estimate injuries suffered by humans as consequences of impacts. HIC (Head Injury Criteria) and NIC (Neck Injury Criteria) are the most commons for the events presented in this work. These indexes evaluate the acceleration and velocity on the head and neck, respectively, during impact and estimate the injury’s severity [7–9].

This paper presents a low-cost impact device developed in LARM2 in Rome to evaluate and characterize the biomechanics in human head impacts. Considerations from results are used to formulate a new criterion for head-neck injury by impacts.

2. Methods and Design Requirements

Several methods that involve head impact testing are available in the literature. Most commons evaluate vehicle accidents and improve sports safety, as shown in Figure 1, the vehicle impact test method. This method uses a full-body human anthropometric mannequin in a passive position (sit) to test the car’s safety during crashing events and the whiplash effect in terms of the neck zone [14]. This effect occurs when an acceleration force produces a neck injury due to the head’s sudden movement. These tests are performed by different companies, such as Euro NCAP...
(European New Car Assessment Programme), which develops several tests to publish safety reports on new cars. It is important to mention that these tests are expensive due to the elements required to perform them. Figure 1(b) and Figure 1(c) illustrate the test performed to evaluate the safety index of protective equipment used in sports and motorcycle helmets. These tests are focused on the head, specifically on athletes’ brain damage due to a received impact and the protective equipment materials to reduce the injuries. A linear pneumatic actuator or a linear free-falling impactor is common on this type of test. NOCSAE (National Operating Committee on Standards for Athletic Equipment) develops standards to evaluate the athletic equipment’s safety as an example of these tests. For example, the standard NOCSAE 081-18am19a [15] gives detailed information about the requirements to perform the safety evaluation on football helmets using a linear pneumatic ram.

On the other hand, the standard ASTM F1446-15b [16] establishes the test methods and procedure to evaluate head protective equipment’s performance characteristics by developing a free-falling impact on a head model. Each method previously reported evaluating in a different way and on a different scale the head impacts. For example, the first one evaluates the injuries by considering the acceleration on the neck, while the other ones characterize the impact of the head’s acceleration.

This paper presents a new test impact device to analyze impacts on the head by directly hitting the head model. The head is not protected by any safety equipment or affected by external forces, as in car crash events. The device presented to take into consideration the acceleration force actuating on both head and neck zones. Table 1 lists the requirements for proper testing, in the first row the ones reported by the standards and in the second row the ones required by authors, considering the standards, to develop the impact device.

### 2.1. Design of Experimental Test

The experiment proposed in this work consists of a low-cost test for head impact analysis using a pendulum mechanism. The main objective is to characterize biomechanics of head impact in acceleration, force, and angular displacement. In Figure 2(a), a scheme of the test layout is presented, showing the elements used for the test. The experimental test consists of one commercial rubber head mannequin, two IMU sensors, and three force sensors. The head mannequin consists of a real-size head model with the following dimensions: chin to the top of head: 25 cm, head length (back to forehead): 21 cm, and head breadth (ear to ear): 16.5 cm. The material of the head model is rubber. This material is used to simulate the force absorption of the human skin. The neck of the head model is 15 cm from its bottom to the chin. The head model has a spherical joint at the bottom part of the neck, allowing it to move after an impact. This spherical joint will simulate the joint/connection between the neck and the torso. The IMU sensors are positioned on the forehead (1) and on the neck (2) to analyze acceleration and angular displacement.

Three force sensors are used to capture the force used to hit the head model to simulate the impact. They are located on the lateral (1), rear (2), and top (3) areas of the head; these are the most common areas to simulate head impact events. Figure 2(b) shows the test impact device build-in LARM2 in Rome. The mannequin is fixed on a table using a gripper. The elements used in the pendulum are one 0.034 m diameter steel sphere attached to a 0.375 m stainless-steel pipe. The weight of the elements used in the pendulum gives a total of 0.25 kg. A revolute joint is used to connect the stainless-steel pipe to a 70 cm height rigid frame. The revolute joint helps keep the pendulum’s trajectory to ensure the impact on the force sensor. IMU sensors used in these experiments are BMI 160, consisting of an accelerometer and gyroscope that can measure the acceleration and the angular displacement.

These sensors are fixed inside 3D printed boxes to fix the mannequin’s rubber head better. The 3D printed boxes consist of two different elements, the IMU case, and its cover. The IMU case is a square-shaped box with a hole in one of its faces. The hole has the IMU dimensions, and the IMU sensor is placed in the hole of the 3D printed box to keep it in place. The cover element is thicker than the IMU case. This box element will help to protect the IMU from dust or anything that could damage the sensor. The cover has a small circle that goes through the square face so that the communication cable of the IMU goes through this hole.

Both elements are kept together with screws. The IMU box is shown in Figure 2(b) together with the rest of the setup. The force sensors consist of a resistor that modifies its values when a force, pressure, or stress is applied, like those
used for TEMARI Machine [17]. The ones used in this experiment have a maximum range of 100 N, and the diameter of the resistive area is 5 mm. Figure 2(c) shows a block diagram that represents the steps to perform the test. First, it is necessary to establish the pendulum’s initial position and the head, depending on the test. Then, a digital interface was programmed to read the data from sensors in real-time. The head’s positioning is done accurately to ensure that initial conditions are the same during all the tests. The impact is made by dropping the pendulum. The pendulum angle is set at 60° for lateral impacts, 90° for top impacts, and 180° for large lateral impacts. It is to note that the same configuration used in lateral impacts can be used in rear impacts and front impacts. This can be easily achieved by changing the Y-axis orientation of the head model. Data acquisition is carried out by connecting the sensors to an Arduino MEGA 2560. The data transmission speed is increased up to 115200 bits/s to prevent loss of information.

The sensors calibration was carried out in terms of force sensors and IMU sensors. Force sensors were calibrated before placed on the mannequin. As mentioned before, the force sensors consist of a circular sensing area. First, each sensor was calibrated on a rigid surface using weight calibration, which applies a known force on the sensor. Then they were calibrated again considering the surface of the mannequin to acquire a correct measurement considering the absorption of the mannequin material. Finally, the force sensors were placed on the head of the strategic zones to measure the impact. IMU sensors were calibrated similarly. First, the IMU was fixed in a rigid place to measure the sensors’ distortion at the data acquisition moment. Then, a low-pass filter was applied to reduce the distortion to its minimum rate. The filter helps to reduce the noise in the sensors caused by possible impact vibration. This method is worked out for each degree of freedom of the IMU sensor. The sensors were placed on the head mannequin, and the measurements were verified as expected, considering each sensor’s location. Finally, the angular displacement was calculated using the values from the accelerometer and gyroscope of the IMU. A second filter was used to reduce the noise due to the vibration at the moment of the impact.

The following table shows the standards and user requirements:

| Standards requirements                  | User requirements                  |
|----------------------------------------|------------------------------------|
| Standardized mannequin model           | Suitable dimensions                |
| High-quality video and photo device    | Low-cost elements                  |
| Extensive laboratories to perform the test | Repeatability                      |
| Impact velocity range: 3.0–9.0 m/s     | Different impact locations         |
| Impactor weight: >15.5 kg ± 3%         | The mannequin is able to mimic neck motion |
| Different impact locations             | Force sensor range: 100 N          |
|                                       | IMU acceleration range: ±16 g      |
|                                       | IMU acceleration sensitivity: 2048 LSB/g |

**Figure 2**: Experimental layout at LARM2 in Rome: (a) a scheme; (b) lab layout photo; (c) block diagram.
2.2. Testing and Results. Test performed by the impact device developed in LARM2 in Rome consists of evaluating the head impact on the most common events: lateral impacts and top impacts. A series of 75 tests’ impacts, 25 lateral impacts, 25 top impacts, and 25 rear impacts, were performed during 5 different days at the laboratory. These tests can be considered statistically significant for valid experimentation according to ISO 17025 standard. The standard deviation was calculated for each set of tests. For lateral impacts, top impacts, and rear impacts, the standard deviation was 0.31, 0.36, and 0.41, respectively. The low value of the deviation indicates that the results are correctly obtained, indicating the test’s accuracy and the results are reliable. Figure 3 shows the scheme of each impact test performed. The lateral impact test scheme shown in Figure 3(a) illustrates that the head and the pendulum fixed point must be aligned. The pendulum is raised to 60° and dropped in a free falling to impact the head model’s right side, where the force sensor is located. In order to keep the same amplitude in the pendulum in all of the lateral tests performed, an additional piece of trapezoidal shape is made in 3D printing to have the pendulum link set up in home position at an angle of 60° degrees. It can be seen in Figure 2(b). The pendulum is dropped and impacts the head with an energy of 0.45 J. Figure 3(b) shows a variation of the lateral impact evaluating a larger lateral impact. This test’s initial conditions are similar to the lateral test but changing the pendulum’s amplitude up to 180°. The kinetic energy for this test is 1.83 J. The last test developed analyzes the top impact shown in the scheme in Figure 3(c). This test’s initial conditions include locating the pendulum’s fixed point horizontally to the head’s top. The pendulum amplitude is set at 90°. The pendulum is dropped, and after it hits the head model, the pendulum needs to be stopped by the user to avoid a second impact on the head model. The kinetic energy for this test is 0.91 J.

Table 3 shows a summary of results from the tests that were performed in the LARM2 laboratory. Five tests of each impact layout were performed to discuss and validate the impact device’s repeatability.

As an illustrative example, Figure 4 shows the graphics of the results from lateral test number 1 reported in Table 3. Figure 4(a) shows the force applied by the pendulum and acquired by the force sensor (1). As seen, the impact occurs in less than 0.1 seconds, and the sensor can acquire the data. Figure 4(b) shows the values of the head acceleration obtained by IMU 1 (blue line) and the neck acceleration obtained by IMU 2 (orange line). It is to notice that head acceleration values are almost twice larger than neck acceleration values. For example, head acceleration values are presented from 4.33 g to 5.88 g. Meanwhile, the values from the neck acceleration are between 2.98 g and 3.6 g.

Figure 4(c) shows the angular displacement suffered by the head model after the impact. The larger displacement is shown in the roll angle, representing the lateral motion on the head, while the pitch angle represents small displacement towards backward. Figure 5 shows the graphics of the results from a larger lateral impact. As expected, most of the values increased in relation to the lateral test impact results. Figure 5(a) shows the force sensor (1) values reported in test no. 1 of the larger lateral impact test. The force values are between 6.96 and 7.53 N. Figure 5(b) shows the head and neck accelerations’ values. It is to notice that, meanwhile neck acceleration values increased almost twice concerning the values obtained in the small lateral impact; the values from head acceleration suffered just a small increment with values that goes from 4.81 g to 7.51 g. This information explains that neck acceleration seems more affected than head acceleration when an increment in the force is applied. The graphic shows the highest acceleration peak at the beginning of the plot with smaller peaks after it represents a bouncing on the head model as a consequence that spherical joint in neck reaches its maximum displacement. Figure 5(c) shows the angular displacement plot in terms of roll and pitch angles. As expected, the roll angle values show an increment that is more noticeable than pitch angle values applying force towards a roll movement.

Results from the top impact are shown in Figure 6. These tests’ force values were the highest, with values ranging from 10.18 N to 12.8 N (Figure 6(a)). This could be caused by the head model’s geometry and material properties. This means a larger stiffness on the top of the head than the lateral area. In terms of acceleration, the values acquired by IMUs were lower than those in both lateral impact tests. This was expected as the force applied in these tests does not generate a large displacement of the head model, as is shown in Figure 6(c), which shows the angular displacement. Tests nos. 2, 3, and 4 show larger head acceleration values, while tests nos. 1 and 5 show a larger neck acceleration and the highest acceleration values of all 5 top impact tests. This means that when suffering a maximum impact, the neck zone’s values could be more extensive.

2.3. A New Head-Neck Injury Criterion. The evaluation of head impacts using different indexes allows for estimating and predicting injuries considering the acceleration suffered in different events. NIC (Neck Injury Criteria), proposed by Boström et al. [18], is the most common index used to predict injuries in low-speed car accidents. This criterion evaluates the acceleration and velocity parameters from the neck, taking into consideration the distance from cervical vertebra C7 to C1 using the formula

| Table 2: Parameters for testing. |
|----------------------------------|
| **Elements** | **Parameter** | **Unit** |
| Pendulum | Impact energy | kg·m²/s² |
| Head mannequin | Mass | kg |
| Force sensor | Impact force | N |
| IMU 1 | Head acceleration | g/(m/s²) |
| IMU 2 | Neck acceleration | g/(m/s²) |
| Angular displacement | Degrees |
Table 3: Tests of data and results.

| Test           | Force (N) | Head acceleration (g) | Neck acceleration (g) | Pitch (°) | Roll (°) |
|----------------|-----------|-----------------------|-----------------------|-----------|----------|
| Small lateral impact |           |                       |                       |           |          |
| 1              | 5.82      | 5.75                  | 2.98                  | −2.58     | 7.34     |
| 2              | 5.36      | 5.57                  | 3.45                  | −2.51     | 7.22     |
| 3              | 6.1       | 4.33                  | 3.6                   | −2.22     | 7.2      |
| 4              | 5.97      | 5.88                  | 3.56                  | −2.86     | 7.57     |
| 5              | 5.36      | 4.95                  | 3.38                  | −2.56     | 7.79     |
| Large lateral impact |           |                       |                       |           |          |
| 1              | 7.6       | 6.44                  | 4.77                  | −4.54     | 19.13    |
| 2              | 7.29      | 6.76                  | 4.81                  | −6.46     | 19.86    |
| 3              | 7.15      | 7.89                  | 5.89                  | −7.3      | 21.64    |
| 4              | 6.96      | 5.83                  | 5.3                   | −8.29     | 22.47    |
| 5              | 7.53      | 7.51                  | 4.63                  | −10.44    | 24.11    |
| Top impact |           |                       |                       |           |          |
| 1              | 11.75     | 2.09                  | 3.81                  | 2.26      | 1.8      |
| 2              | 12.8      | 1.75                  | 1.65                  | 2.49      | 1.98     |
| 3              | 10.18     | 2.38                  | 1.35                  | 1.47      | 1.18     |
| 4              | 11.34     | 2.81                  | 2.53                  | 2.07      | 1.76     |
| 5              | 10.89     | 1.82                  | 3.79                  | 1.82      | 1.36     |

Figure 3: Scheme test performed: (a) lateral impact test; (b) large lateral impact test; (c) top impact test.

Figure 4: Test results for lateral impact test no. 1 in terms of (a) force impact; (b) accelerations; (c) angular displacement.
where $a_{rel}$ is the relative linear acceleration between vertebrae C7 and vertebrae C1, $l$ is the distance between these two cervical vertebrae, and $v_{rel}$ is the relative velocity of C1 with respect to C7. The mathematical model equation (1) evaluates the relative horizontal acceleration considering the cervical as a constant distance. Many authors proposed that the neck’s length variation should be considered better to estimate neck injuries [19–21].

HIC (Head Injury Criteria) is used to estimate cranioencephalic injuries caused by impacts in sports events [22–24]. This index evaluates just the acceleration suffered by the head on a small period using the formula

$$\text{HIC} = \max \left\{ \frac{1}{(t_2 - t_1)^{3/2}} \left[ \int_{t_1}^{t_2} a(t)\,dt \right]^{5/2} \right\}. \quad (2)$$

This index is used for sports event impacts because protective equipment is developed to reduce the impact acceleration on the head. However, sports activities are not exempt from suffering head and neck injuries due to force applied, angular displacement, or velocity on the impact. The impact device presented allows the user to evaluate new parameters as the angular displacement, which could be calculated in terms of roll and pitch angles during the impact. These parameters allow us to know the position vector $X_i$ of the head after the impact by using a rotation matrix (R) considering the roll and pitch angles in $X_i = (R)X$, where $X$ is the initial position vector of the head. By using the test results in Table 3 and Figures 4–6, an impact evaluation index can be expressed considering the impact force, the impact energy, the acceleration of the head and the neck, and the new position vector of the head. Likewise, in previous work, as reported in [10], it seems convenient to formulate a specific criterion for a specific evaluation of the biomechanics in head impacts considering new contributions from neck response. A new criterion is formulated considering the parameters evaluated on this work, in a period of $\Delta t \leq 0.1$ s, as

$$\text{NIC}_N = \frac{F}{M_h v^2} \frac{a_h}{a_n} |X_i - X|, \quad (3)$$

where $F$ is the applied force by the pendulum, $M_h$ is the weight of the head which in this case is 0.782 kg, $v^2$ is the velocity from the pendulum at the moment of the impact, $a_h$ is the maximum head acceleration measured by IMU 1, $a_n$ is...
the maximum neck acceleration obtained from IMU 2, and $X_i$ is the position of the head at after the impact. Thus, it is possible to determine the NHIC (Head-Neck Injury Criterion) as a function of the impact impulse, head structure, and response of both head and neck. A test developed in the LARM2 and reported in Table 3 is evaluated considering the consequent angular motion with perturbation to cause some damage to the neck yet. It is also to note that relation is observable between the impulsive acceleration sensed by IMU 1 keeps its value as double as in the IMU 2 on the neck. This means that, during a head impact, the hit’s energy reaches the neck zone with enough acceleration to cause some damage to the neck yet. It is also to note that relation is observable between the impulsive impact force and the consequent acceleration on the head during a very similar period. The reported lab experiences have suggested a new formulation of the NIC criterion to consider the consequent angular motion with perturbation to evaluate a head impact’s risk severity.

**Data Availability**

The data used to support the findings of this study are available from the corresponding author upon request.

**Conflicts of Interest**

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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