SMART HELMET SENSORS TO MONITORHEAD IMPACTS IN SPORTS

Thasni Nassam[1], J.Sanetha Begam[2]

[1]P.G Scholar,Dept. of Biomedical Engineering, Udaya School Of Engineering, Vellamodi, Tamilnadu, India

[2]Assistant Professor,Dept. of Biomedical Engineering, Udaya School Of Engineering, Vellamodi, Tamilnadu, India

***Abstract*—Over the last decade, significant effort has been directed towards the creation of printed electronics using conventional printing technologies. The use of printing technologies to create semiconductors and circuits has overcome some of the drawbacks and high production costs associated with conventional silicon technology. A headgear-based system for tracking and monitoring the occurrence of impacts to a user's head. The present system includes a sensor array disposed on the interior surface of a helmet or other headgear that is adapted to detect when the head contained within the helmet has sustained an impact above a pre- determined threshold value, indicating the potential for the user to have suffered a concussion. The sensor system has multiple applications beyond measurement of head impacts in sports and the military. The sensor and analytical / transmitting circuit can be printed into a wide range of shapes and sizes to conform to any application for aerospace, automotive, construction, sports and the military. Also, the impact sensor can be placed on the outside or inside of a device to detect impacts.**

***Index Terms*—Sensor Array Impact Detection Headgear Helmet Concussion Sports Monitoring Aerospace Safety Automotive Safety Construction Safety Sensor Integration Conducive Inks Semiconductor Printing Real-time Monitoring Head Injury Prevention Adaptive Technology**

I. Introduction

A. General

Sport and physical exercise are increasingly promoted as part of a healthy lifestyle. However, increased participation in physical activity and sport specialization may raise the risk of injury, especially in younger individuals, for whom sport-related accidents are a leading cause of medical attention and emergency department attendance. The burden of sports injuries and their potential impact on quality of life and societal costs call for research and effective interventions in all of the areas associated with sports injury: prevention, assessment, and recovery. Several strategies for the prevention and recovery from injury have been proposed, alongside models of injury causation, classifications of injury factors (e.g., intrinsic vs. extrinsic; modifiable vs. not modifiable), and reviews of the different approaches that could be adopted to study injury mechanisms. From a mechanical perspective, musculoskeletal injuries occur when the load applied to a tissue goes beyond the maximum amount of mechanical energy that bodily elements can accept without compromising their structure and function. Several theories have been developed to explain the occurrence of injuries; all recognize the complexity and multifactorial nature of injury causation, and distinguish between acute and overuse injuries. In acute events, the inciting energy exceeds the maximum tolerated by the tissues involved. In overuse injuries, the repetitive nature of the demands sustained by the body may reduce its tolerance levels to a point where normally acceptable loads can cause micro- or macro-failures. Repetitive submaximal micro traumas can lead to a

cascade of alterations to structural proprieties, function, and behavior, which eventually establish a vicious loop of degeneration, adaptation, and pain. Biomechanical approaches can contribute substantially to the study of sports injuries and their prevention. For example, they can describe injury mechanisms and characterize inciting events, or can assess the effects of interventions on movement behaviors and the ability to withstand mechanical loads. Biomechanical tools also have the potential to help monitor compliance, quality, and progress of movement performance when an injury-prevention or return-to-activity programme is implemented. In vivo, in vitro, and in silico methods have been used to quantify the biomechanical demands generated by sports actions, together with the responses of bodily tissues that are subjected to those loads. However, measuring mechanical quantities in real-world settings—either directly or indirectly—is extremely difficult, and sometimes impossible, because of ethical considerations and lack of adequate technology or sports regulations. In most cases, the assessment is confined to controlled lab conditions. The ongoing development and increased use of wearable technologies, either in isolation or as part of integrated approaches, offers an opportunity to collect quantitative data "in the field", less obtrusively, for extended periods of time, and with fewer spatial limitations than conventional motion-capture technologies. New-generation sensors are small, portable, minimally obtrusive, affordable, and easy to use; they may provide real-time feedback, as well as enable prospective studies on large cohorts.

B. Problem Statement

Several review articles have assessed the use of such devices in different areas of sport science, when applied to the characterization of sport-specific

movements; performance analysis and enhancement; the evaluation of tactical variables; the monitoring of load and inertial forces; the trends and projections in the consumer sports sector; the description of specific disciplines such as running, sprinting, swimming, combat sports, or Paralympic sports; and the assessment of rehabilitative interventions. Injury risk mitigation has been addressed within specific sport and injury domains, such as that of running-related injuries, head impacts, anterior cruciate ligament reconstruction, and dynamic stability in return to sport. However, it appears that no work has systematically investigated the current state of the art on the role of wearable sensors in the different stages of injury assessment, including the characterization of injury mechanisms, and the provision of information to support preventive or rehabilitative interventions. The use of wearable sensors in movement science and sport is widespread; however, their application is still in an "exploratory phase", and is not free from pitfalls, suggesting that both the technology and the associated methods still require further development and careful analysis. Indeed, some of the features that make wearables attractive can also limit their applied impact. For example, the possibility to collect data continuously in an uncontrolled environment can generate the problem of handling large datasets affected by measurement noise, which generates the need for adequate awareness of data quality (e.g., prior validation, care in calibration procedures) and for the use of appropriate processing methods, such as machine learning, for key performance indicator estimates, or advanced data science techniques for data synthesis or prediction. Moreover, there is still little evidence on the causal relationships between specific biomechanical assessments, quantities derived thereof, and injury or injury risks, which can result in many studies being descriptive of the potential of new technologies rather than fully exploiting that potential to unveil the relationships between biomechanics (e.g., movement technique) and injury-related features (e.g., inciting factors, recovery status).

C. *Scope of the Study*

The development of the new device needs to measure the linear acceleration and rotational velocity forces. In addition, to help, monitor, and measure the head impact of the players during contact sport, and send the collected data to be saved in the cloud with an access to it later. The data will help the principal medical professional and the coach to observe and to keep up to date follow up with the player's during the contact sport or the player's training time in case of a serious and dangerous strike occur to the head of the player. That will enable the medical professional and the coach to provide urgent and immediate help to the player to avoid serious head damage and concussions. The Tortuosity analysis is widely used in studies of the associations of retinal micro vascular disease with the cardio vasculature diseases. These Tortuosity values have been suggested to reflect generalized arteriolar narrowing. This Narrowing of arterioles may contribute to the pathogenesis of hypertension by increasing peripheral vascular resistance.

D. *Aim and Objectives*

The goal was to improve the first version of the helmeted prototype device and applying a wireless communication method to enable the prototype to connect to the cloud. Therefore, the new development plan is to offer:

- A development of a new version of the device prototype including both the hardware and the software system that would measure the head impact.
- Wearability: Since the device will be carried on the body, it must be compact and light enough to not block movement or throw the player's center of gravity off.
- Lifetime: The device should have enough battery capacity and storage space to last the length of a three-hour professional sports game, at the very least.
- A use of IoT microcontroller and sensor to obtain the data via wireless communication protocol to send it after to cloud and the collecting device (e.g., smartphone or computer).
- Wireless technology: the IoT components will enable the device prototype to send, store and save the data on the cloud which will provide access to the data for further analyzed and check-up.
- Low cost: providing a low-cost device prototype while having high proficiency and great performance

E. *Overview of the Study*

To design the new device prototype was as such: To use the new IoT sensor and microcontroller and to find the best communication protocol to connect both IoT processors and sensors to receive and transmit data. Hence, when the data can successfully be collected from both the processor and the sensor a programming platform will be needed, and for that Arduino programming platform can be used. After that, using networking protocols such as MQTT or HTTP, with the advantage of Wi-Fi, the gateway effectively aggregates data and transfers it to the cloud. When the data reach the cloud then it will be possible to find a proper method to store and have access to it later. After the development of the device prototype system is ready. It can be implemented inside the helmet of the player. During the game, once the device is suspected to have a high head impact the system is immediately triggered. However, since the data is stored in the cloud, a detailed review such as hit measurements, time of the day, the temperature of the player, all is possible to be sent over to a medical professional on a smartphone or a computer online or over an app.

II. PROPOSED SYSTEM

The hardware system of the device can be divided into five different subsystems as shown in figure 1: inputs/data collection, processing, storage, output, and power unit. The input/data collection comprised of two sensors: an accelerometer and gyroscope. The power unit (bottom of figure 10) consists of either a power bank or AA batteries and a boost converter circuit to regulate voltage powering the two main subsystems. The processing unit include the Arduino microcontroller. The cloud is where all the information is processed as a storage unit, which is the third unit in the block diagram. The final part of the block diagram is the output unit, which is the user interface where the interaction between the human and the device prototype occur.

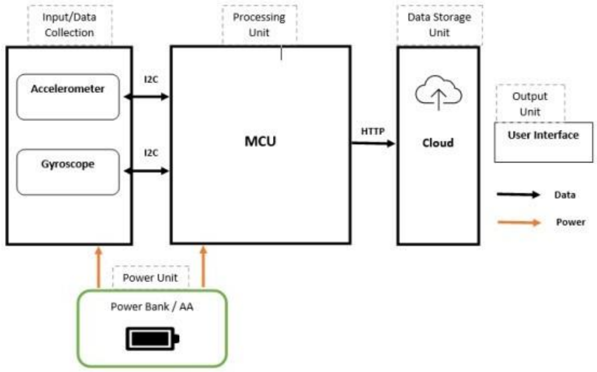

Fig.1. Block Diagram of the proposed helmet system

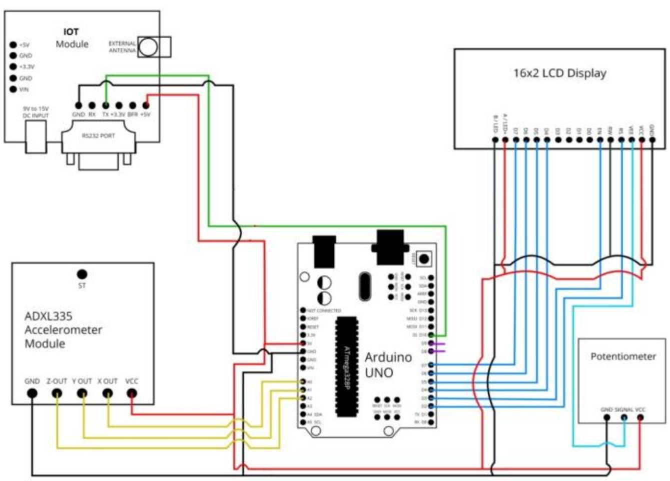

Fig.2. Circuit Diagram of the proposed helmet system

The methodology had been departed into three mainly parts, the Simulation part to expire the circuit that had been depend on in the design and be sure it can provide us by the demanded of monitoring and controlling. The second part is related by the hardware and design the circuit and test it experimentally. And finally the third parts is contents the Application side and connect it with the design and record the sensor values in database. Whenever the sensors are combined with IoT technology, it can be an illustration of a cyber-physical system, smart home, smart grid, smart city, intelligent transportation and virtual power plants. Therefore, the IoT can help in controlling the objects remotely being sensed by the sensors so that the physical systems can be easily integrated by the computing systems. This advantage not only improves the accuracy and efficiency of a machine but also minimizes the human intervention needed for monitoring a machine or a device 24/7. The use of ThinkSpeak platform makes easy to access the data stored into it by means of IoT-Data Analytics. Moreover, the used sensors in the proposed models are of low cost and easily affordable so that the cost of periodic maintenance is also easier. The sensors connected are used for monitoring and controlling the incubator via IoT. The Arduino microcontroller is programmed in such a way to get the output of these sensor and display it on the LCD for monitoring purpose. The values of the sensors are then uploaded in the ThinkSpeak cloud to display it on the wireless device in the receiver side, which is then used for enabling the control of the incubator environment. The overall circuit diagram is shown in figure 2. The overall circuit diagram explanation provides a general overview of the circuit connections for a battery-operated smart helmet injury detection system with accelerometer, LCD, Arduino, and IoT capabilities. Connect the VCC pin of the Arduino board to the positive terminal of the power source (battery or power bank). Connect the GND pin of the Arduino board to the negative terminal of the power source. Connect the VCC pin of the MPU6050 to the positive terminal of the power source. Connect the GND pin of the MPU6050 to the negative terminal of the power source. Connect the SDA pin of the MPU6050 to the Arduino board's SDA (data) pin (A4 on Arduino Uno, or SDA on other Arduino boards). Connect the SCL pin of the MPU6050 to the Arduino board's SCL (clock) pin (A5 on Arduino Uno, or SCL on other Arduino boards). Connect the VCC pin of the LCD display to the positive terminal of the power source. Connect the GND pin of the LCD display to the negative terminal of the power source. Connect the SDA pin of the LCD display to the Arduino board's SDA (data) pin (A4 on Arduino Uno, or SDA on other Arduino boards). Connect the SCL pin of the LCD display to the Arduino board's SCL (clock) pin (A5 on Arduino Uno, or SCL on other Arduino boards). Connect the VCC pin of the Wi-Fi module to the positive terminal of the power source. Connect the GND pin of the Wi-Fi module to the negative terminal of the power source. Connect the TX pin of the Wi-Fi module to the Arduino board's RX pin (pin 0 on Arduino Uno). Connect the RX pin of the Wi-Fi module to the Arduino board's TX pin (pin 1 on Arduino Uno). This is the part of the Arduino code responsible for processing accelerometer data, detecting accidents, and triggering injury alerts. It may not require specific hardware connections, as it is implemented in the Arduino code. The Arduino code will send relevant information to the LCD display to show tilt angle, acceleration values, or status messages. Connect the contrast control pin (VEE) of the LCD to a potentiometer's middle pin, and connect the other two potentiometer pins to VCC and GND. Connect the RW (Read/Write) pin of the LCD to GND to set the LCD in write mode. Connect the RS (Register Select) pin of the LCD to a digital pin on the Arduino (e.g., pin 2). Connect the EN (Enable) pin of the LCD to a digital pin on the Arduino (e.g., pin 3). Connect the data pins of the LCD (D4, D5, D6, D7) to digital pins on the Arduino (e.g., pins 4, 5, 6, 7). The Arduino code, upon detecting an accident, will use the Wi-Fi module to communicate with an IoT platform. Connect the TX pin of the Wi-Fi module to the Arduino board's RX pin (pin 0 on Arduino Uno). Connect the RX pin of the Wi-Fi module to the Arduino board's TX pin (pin 1 on Arduino Uno). Connect the positive terminal of the battery or power bank to all the VCC pins of the components and the negative terminal to all the GND pins. Components used in the proposed Smart Helmet:

- Arduino board (e.g., Arduino Uno or Arduino Nano)
- Accelerometer sensor (e.g., MPU6050 or ADXL345)
- LCD display (e.g., 16x2 or 20x4)

- ESP8266 or ESP32 Wi-Fi module (for IoT connectivity)
- Power source (battery or power bank)

Helmet or helmet-compatible enclosure to house the components securely. Install the Arduino IDE on your computer and ensure that you have the necessary drivers installed for the Arduino board. Wire up the accelerometer, LCD, and Wi-Fi module to the Arduino board following their respective datasheets and pinout guides. The connections may vary depending on the specific components you use. Write the Arduino sketch to read data from the accelerometer, display relevant information on the LCD (such as tilt angle or acceleration), and detect accidents based on sudden changes in motion patterns (e.g., rapid acceleration or deceleration). Upon detecting an accident, the helmet should trigger an alert. Integrate the IoT module (ESP8266 or ESP32) to your Arduino code. Use libraries like ”PubSubClient” to communicate with an MQTT broker on the IoT platform of your choice. Set up an MQTT topic to which the helmet will publish accident alerts. Create an account on an IoT platform (e.g., AWS IoT, Google Cloud IoT, or Adafruit IO) and set up an MQTT broker. Obtain the necessary credentials (e.g., client ID, username, password) to connect your helmet to the platform. On the IoT platform, create a subscriber to the MQTT topic where the helmet publishes accident alerts. Depending on the platform, you can set up actions like sending push notifications, emails, or triggering an emergency response. Implement efficient power management to ensure the helmet's components consume power optimally. Consider using sleep modes for the Arduino and other low-power strategies. Thoroughly test the smart helmet to ensure the accelerometer-based injury detection is working accurately, and the IoT communication is reliable. Remember that safety is paramount when creating a smart helmet for real-world use. Properly secure all components within the helmet to prevent injury, and rigorously test the system to ensure its reliability in detecting accidents.

III. RESULT AND DISCUSSION

The complete working of a smart helmet for injury detection with an accelerometer, LCD, Arduino, and IoT involves several interconnected processes. Let's go through the step-by-step working of the system: The smart helmet's accelerometer continuously measures the acceleration experienced by the helmet in various directions (X, Y, and Z axes). This data is collected by the Arduino board, which acts as the microcontroller. Inside the Arduino, an injury detection algorithm processes the accelerometer data in real-time. This algorithm is designed to analyze the motion patterns of the helmet and identify sudden changes or impact that might indicate an accident. The Arduino communicates with the LCD display and sends relevant information, such as tilt angle, acceleration values, or a status message, to be shown on the LCD screen. During normal operation, the LCD can display useful data like speed, orientation, or battery level. When the accident detection algorithm identifies an unusual motion pattern or an impact above a predefined threshold, it triggers an accident alert. This alert signifies that the helmet has detected a potential accident scenario. The smart helmet is equipped with an ESP8266 or ESP32 Wi-Fi module, which provides the helmet with IoT capabilities. The Wi-Fi module connects to a wireless network, allowing the helmet to communicate with an IoT platform. Upon detecting an accident, the Arduino, through the Wi-Fi module, sends a message containing relevant accident data (such as timestamp, accelerometer readings, and any other relevant information) to the IoT platform. This data is published to a specific topic on the IoT platform's MQTT broker. On the IoT platform, a subscriber listens to the MQTT topic where the smart helmet publishes accident alerts. The platform processes the received data and performs any necessary actions based on the accident alert. This could include sending notifications to emergency contacts, triggering an alarm system, or dispatching emergency services. The smart helmet incorporates power management techniques to optimize battery usage. It might use low-power modes during idle times or employ sleep modes to conserve energy when not actively transmitting accident data. The LCD display also serves as a user interface to configure settings, view system status, or check connectivity information with the IoT platform. Overall, the smart helmet's working revolves around real-time data acquisition, accident detection, IoT communication, and timely assistance to ensure the safety of the helmet wearer in the event of an accident. It's essential to rigorously test the system and follow safety protocols to create a reliable and secure smart helmet. The designed smart helmet is shown in Figure 3.

A. *Advantages*

Enhanced Safety: The primary advantage is improved safety for the helmet wearer. The helmet can detect accidents and promptly notify relevant parties for immediate assistance, potentially saving lives or minimizing the severity of injuries.

Real-time Monitoring: The helmet continuously monitors the wearer's movements and can provide real-time feedback through the LCD display, keeping the user aware of critical information such as tilt angles, acceleration values, and system status.

Rapid Accident Detection: The accelerometer-based accident detection algorithm can quickly identify sudden changes in motion patterns indicative of an accident. This enables prompt alert generation and assistance.

IoT Connectivity: Integration with IoT platforms allows for remote monitoring, data logging, and management of multiple helmets. It enables seamless communication with emergency services, medical professionals, or caregivers.

Customizable Alerts: The system can be tailored to send different types of alerts, including SMS, email notifications, or push notifications to smartphones, ensuring that the appropriate response is activated based on the severity of the accident. Energy-efficient Design: Proper power management ensures that the system operates efficiently and extends battery life, making it suitable for long-duration use.

Expandable Functionality: The modular design of the smart helmet allows for the addition of extra features, such as GPS for location tracking, Bluetooth for wireless communication with smartphones, or cameras for recording evidence in case of an accident.

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 07 Issue: 08 | August - 2023 SJIF Rating: 8.176 ISSN: 2582-3930

B. Applications

Motorcycle Safety: The smart helmet is particularly useful for motorcycle riders, as accidents on motorcycles can be more severe. The system can detect motorcycle accidents and trigger appropriate actions like notifying emergency services or designated contacts.

Bicycle Safety: Cyclists can also benefit from the smart helmet, especially when riding in busy or hazardous areas. The system can help detect accidents and call for assistance if needed.

Construction Industry: Workers in the construction industry often wear helmets for safety. A smart helmet can provide an extra layer of protection by detecting accidents and alerting supervisors or medical teams on construction sites.

Sports Activities: Athletes participating in high-impact sports, such as mountain biking, skiing, or skateboarding, can wear smart helmets to monitor their movements and receive timely assistance in case of accidents or injuries.

Medical Monitoring and Rehabilitation: Smart helmets can find applications in medical settings, where they can be used for monitoring patients during rehabilitation exercises, tracking head movements, and detecting falls.

Military and First Responders: In military or emergency response scenarios, smart helmets can help improve the safety of personnel by monitoring their movements and providing early alerts in case of accidents or impacts.

Industrial Safety: Workers in industrial settings, such as factories or warehouses, can wear smart helmets for accident detection, especially when handling heavy machinery or working in potentially hazardous environments.

Fig.3. Designed Smart Helmet

IV. CONCLUSION AND FUTURE WORK

A. Conclusion

This project proposed a system that monitors sports persons head impacts continuously. The simulated results of this smart helmet project demonstrate its effectiveness in providing safety features for the wearer. The ADXL335 Module 3-axis Accelerometer is used to detect sudden changes in motion that may indicate an accident and it output is connected to the Arduino Nano microcontroller. The microcontroller is responsible for monitoring the sensor's output, determining if an accident has occurred, and triggering a message to be sent to cloud to store the data. An IoT based smart helmet to monitor head impacts using atmega328 microcontroller, which is capable to continuously monitor the sports persons. The battery-operated smart helmet with injury detection using an accelerometer, LCD, Arduino, and IoT is a powerful innovation that significantly enhances safety and can potentially save lives. By combining real-time monitoring, accident detection algorithms, and IoT connectivity, this smart helmet offers a comprehensive solution to address accidents and injuries in various scenarios. The integration of an accelerometer allows the helmet to accurately detect sudden changes in motion patterns, signaling potential accidents. The LCD display provides the wearer with real-time information, helping them stay aware of their surroundings and system status. The IoT connectivity enables seamless communication with remote monitoring systems and emergency response platforms, ensuring timely assistance and support in case of emergencies.

B. Future Work

The battery-operated smart helmet with injury detection has promising future prospects, and there are several avenues for further improvement and expansion: GPS Integration: Adding GPS functionality to the smart helmet would enable precise location tracking during accidents, enabling quicker response times for emergency services. Machine Learning Algorithms: Implementing advanced machine learning algorithms for accident detection can enhance the system's accuracy and robustness, reducing false positives and increasing detection efficiency. Biometric Sensors: Integrating biometric sensors, such as heart rate monitors or blood oxygen sensors, can provide additional health-related data to emergency responders or medical teams. Communication with Vehicles: Smart helmet communication with nearby vehicles equipped with Vehicle-to-Everything (V2X) technology could enhance road safety by sharing critical information with drivers and alerting them to potential accidents involving cyclists or motorcyclists.

Smartphone Integration: Developing companion smartphone apps that work in tandem with the smart helmet can provide additional features like route planning, accident history, and analytics.

Expanded IoT Integration: Integrating with smart city infrastructure and emergency response systems can lead to more comprehensive accident management and improved response times.

Mass Adoption and Standardization: Encouraging mass adoption of smart helmets and establishing industry standards for their design and functionality can ensure widespread usage and interoperability.

Battery and Power Efficiency: Further advancements in battery technology and power management can lead to longer battery life and reduced charging frequency.

Sensor Fusion: Combining data from multiple sensors, such as accelerometers, gyroscopes, and cameras, can provide a more holistic view of accidents and improve the accuracy of detection.

Injury Severity Assessment: Developing algorithms to assess the severity of injuries based on accelerometer data can help prioritize emergency response efforts and medical assistance.

REFERENCES

[1] Barnham, K. J., Masters, C. L. and Bush, A. I. Neurodegenerative diseases and oxidative stress. Nat. Rev. Drug Discov. 3, 205–214 (2004).
[2] Mez, J., Daneshvar, D. H. and Kieman, P. T. Clinicopathological evaluation of chronic traumatic encephalopathy in players of american football. JAMA 318, 360–370. https:// doi. org/ 10. 1001/ jama. 2017. 8334 (2017).
[3] What is a concussion? (2019). https:// www. cdc. gov/ heads up/ basics/ concu ssion whatis. html.
[4] Faul, M., Wald, M. M., Xu, L. and Coronado, V. G. Traumatic brain injury in the united states; emergency department visits, hospitalizations, and deaths, 2002-2006. CDC (2010).
[5] Report to congress on mild traumatic brain injury in the united states: steps to prevent a serious public health problem. Atlanta, GA: Centers for Disease Control and Prevention 45 (2003).
[6] Giza, C. C. and Hovda, D. A. The new neurometabolic cascade of concussion. Neurosurgery 75, S24–S33 (2014).
[7] Vagnozzi, R. et al. Temporal window of metabolic brain vulnerability to concussion: A pilot 1h-magnetic resonance spectroscopic study in concussed athletes–part iii. Neurosurgery 62, 1286–1296 (2008).
[8] Gurdjian, E. S., Lange, W. A., Patrick, L. M. and Thomas, M. E. Impact injury and crash protection (1970).
[9] Gadd, C. W. Use of a weighted-impulse criterion for estimating injury hazard. Tech. Rep., SAE Technical Paper (1966).
[10] Eppinger, R., Kuppa, S., Saul, R. and Sun, E. Supplement: development of improved injury criteria for the assessment of advanced automotive restraint systems: Ii. NHTSA (2000).
[11] Greenwald, R. M., Gwin, J. T., Chu, J. J. and Crisco, J. J. Head impact severity measures for evaluating mild traumatic brain injury risk exposure. Neurosurgery 62, 789–798. https:// doi. org/ 10. 1227/ 01. NEU. 00003 11244. 05104. 96 (2008).
[12] Kleiven, S. Why most traumatic brain injuries are not caused by linear acceleration but skull fractures are. Front. Bioeng. Biotechnol. 1, 15 (2013).
[13] Meaney, D. F., Olvey, S. E. and Gennarelli, T. A. Biomechanical basis of traumatic brain injury. Youmans Neurol. Surg.https:// doi. org/ 10. 1016/ b978-1- 4160- 5316-3. 00328-2 (2011).
[14] Beckwith, J. G., Greenwald, R. M. and Chu, J. J. Measuring head kinematics in football: Correlation between the head impact telemetry system and hybrid iii headform. Ann. Biomed. Eng. 40, 237–248. https:// doi. org/ 10. 1007/ s10439- 011- 0422-2 (2012).
[15] Crisco, J. J., Chu, J. J. and Greenwald, R. M. An algorithm for estimating acceleration magnitude and impact location using multiple nonorthogonal single-axis accelerometers. J. Biomech. Eng. 126, 849–854. https:// doi. org/ 10. 1115/1. 18241 35 (2005).
[16] Duma, S. M. et al. Analysis of real-time head accelerations in collegiate football players (2005).
[17] Moore, N. C. Understanding concussions: Testing head-impact sensors. https:// news. umich. edu/ under stand ing- concu ssions- testi ng- head-impact- senso rs/.
[18] Rains, B. X2 biosystems introduces their next generation x-patch pro head impact monitor (2016).
[19] Camarillo, D. B., Shull, P. B., Mattson, J., Shultz, R. and Garza, D. An instrumented mouthguard for measuring linear and angular head impact kinematics in American football (2013).
[20] Zhong, J. et al. Finger typing driven triboelectric nanogenerator and its use for instantaneously lighting up LEDs. Nano Energy 2, 491–497 (2013).
[21] Zhong, Q. et al. A paper-based nanogenerator as a power source and active sensor. Energy Environ. Sci. 6, 1779–1784 (2013).
[22] Zhong, Q. et al. Paper-based active tactile sensor array. Adv. Mater. 27, 7130–7136 (2015).
[23] Safaei, M., Sodano, H. A. and Anton, S. R. A review of energy harvesting using piezoelectric materials: State-of-the-art a decade later (2008–2018). Smart Mater. Struct. 28, 113001 (2019).
[24] Pastrana, J. et al. Electrode effects on flexible and robust polypropylene ferroelectret devices for fully integrated energy harvesters. ACS Appl. Mater. Interfaces 12, 22815–22824 (2020).
[25] Li, W. et al. Nanogenerator-based dual-functional and self-powered thin patch loudspeaker or microphone for flexible electronics. Nat. Commun. 8, 15310 (2017).
[26] Dsouza, H. et al. Ferroelectret nanogenerators for loudspeaker applications: A comprehensive study. J. Sound Vibr. 468, 115091 (2020).