Development of an Effective Neck Injury Protection System for High-Speed Car Racing

2024

Development of an Effective Neck Injury Protection System for High-Speed Car Racing

A Thesis by

Md. Asif Zawad (190012108)
Tahia Ilham (190012136)

A Thesis Submitted in Partial Fulfillment of the Requirement for the Degree of Bachelor of Science in Industrial and Production Engineering

Department of Mechanical and Production Engineering (MPE)

Islamic University of Technology (IUT)

July, 2024

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Candidate's Declaration

This is to certify that the work presented in this thesis, titled, "***Development of An Effective Neck Injury Protection System for High-Speed Car Racing***", is the outcome of the investigation and research carried out by us under the supervision of Dr. Mohammad Nasim, Assistant Professor, MPE, IUT, in 2024.

It is also declared that neither this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma.

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Recommendation of the Thesis Supervisor

The thesis titled "**DEVELOPMENT OF AN EFFECTIVE NECK INJURY PROTECTION SYSTEM FOR HIGH-SPEED CAR RACING**" submitted by MD. ASIF ZAWAD Student ID: 190012108 and TAHIA ILHAM Student ID: 190012136, has been accepted as satisfactory in partial fulfillment of the requirements for the degree of B Sc. in Industrial and Production Engineering **on July, 2024.**

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(**Supervisor**)

CO-PO Mapping of IPE 4800 - Thesis and Project

COs	Course Outcomes (CO) Statement	(PO)	Addressed by	
CO1	Discover and Locate research problems and illustrate them via figures/tables or projections/ideas through field visit and literature review and determine/Setting aim and objectives of the project/work/research in specific, measurable, achievable, realistic and timeframe manner.	**PO2**	Thesis Book	✓
			Performance by research	✓
			Presentation and soft skill	
CO2	Design research solutions of the problems towards achieving the objectives and its application. Design systems, components or processes that meets related needs in the field of mechanical engineering	**PO3**	Thesis Book	✓
			Performance by research	✓
			Presentation and soft skill	
CO3	Review, debate, compare and contrast the relevant literature contents. Relevance of this research/study. Methods, tools, and techniques used by past researchers and justification of use of them in this work.	**PO4**	Thesis Book	✓
			Performance by research	
			Presentation and soft skill	
CO4	Analyse data and exhibit results using tables, diagrams, graphs with their interpretation. Investigate the designed solutions to solve the problems through case study/survey study/experimentation/simulation using modern tools and techniques.	**PO5**	Thesis Book	✓
			Performance by research	✓
			Presentation and soft skill	✓
CO5	Apply outcome of the study to assess societal, health, safety, legal and cultural issue and consequent possibilities relevant to mechanical engineering practice.	**PO6**	Thesis Book	✓
			Performance by research	✓
			Presentation and soft skill	
CO6	Relate the solution/s to objectives of the research/work for improving desired performances including economic, social and environmental benefits.	**PO7**	Thesis Book	✓
			Performance by research	✓
			Presentation and soft skill	
CO7	Apply moral values and research/professional ethics throughout the work, and justify to genuine referencing on sources, and demonstration of own contribution.	**PO8**	Thesis Book	✓
			Performance by research	
			Presentation and soft skill	
CO8	Perform own self and manage group activities from the beginning to the end of the research/work as a quality work.	**PO9**	Thesis Book	
			Performance by research	✓
			Presentation and soft skill	
CO9	Compile and arrange the work outputs, write the report/thesis, a sample journal paper, and present the work to wider audience using modern communication tools and techniques.	**PO10**	Thesis Book	✓
			Performance by research	
			Presentation and soft skill	
CO10	Organize and control cost and time of the work/project/research and coordinate them until the end of it.	**PO11**	Thesis Book	
			Performance by research	✓
			Presentation and soft skill	
CO11	Recognize the necessity of life-long learning in career development in dynamic real-world situations from the experience of completing this project.	**PO12**	Thesis Book	
			Performance by research	✓
			Presentation and soft skill	

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Name of the Supervisor: Dr. Mohammad Nasim

K-P-A Mapping of IPE 4800 - Thesis and Project

COs	POs	Related Ks								Related Ps							Related As				
		K1	K2	K3	K4	K5	K6	K7	K8	P1	P2	P3	P4	P5	P6	P7	A1	A2	A3	A4	A5
CO1	PO2		✓	✓						✓											
CO2	PO3					✓				✓							✓		✓		
CO3	PO4								✓	✓							✓				
CO4	PO5						✓			✓			✓	✓			✓		✓		
CO5	PO6							✓													
CO6	PO7							✓				✓				✓	✓		✓		
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CO9	PO10																				
CO10	PO11																✓				
CO11	PO12																				

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Acknowledgement

In the Name of Allah, the Most Beneficent, the Most Merciful

We would like to express our deepest gratitude to Allah (SWT) for granting us the fortitude, patience, and intellectual capacity to compose this dissertation. This work required extensive research, critical thinking, and unwavering dedication, and we are thankful to Allah for the strength and guidance provided to us throughout this process. His mercy and compassion have been our guiding light throughout this journey. We are deeply thankful to Dr. Mohammad Nasim, our project supervisor, for his unwavering and enduring support despite unforeseen challenges. His invaluable guidance and mentorship have been crucial in navigating through the complexities of this project. His benevolence, friendliness, and effective oversight have not only alleviated the stress but also significantly boosted our productivity. We are truly blessed to have had such a dedicated and supportive supervisor.

Moreover, we want to convey our profound gratitude to each of our parents for their unwavering support and commitment to our pursuit of higher education. Their encouragement and sacrifices have been the cornerstone of my academic journey.

Finally, we gratefully acknowledge the Islamic University of Technology for its facilities and unwavering support in completing the thesis. The university's resources and environment played a significant role in shaping this dissertation.

Abstract

High-speed racing car crashes can lead to neck injuries for drivers, particularly in frontal impacts. Current neck protective systems often prioritize protection over comfort, which can restrict driver mobility and lead to discomfort. This thesis suggests a new Neck Injury Protecting System (NIPS) for high-speed racing cars that overcomes the limitations of existing devices. The NIPS aims to reduce neck flexion-extension injuries by controlling the head movement to restrict excessive hyperextension and flexion during impacts. The NIPS also aims to enhance driver comfort by using lightweight and breathable materials, allowing the neck to move within a wider range of movement. In this thesis, we limited our study to flexion injuries that occurred during frontal impacts. We designed the NIPS using SolidWorks. Then, a physical model of the NIPS was 3D printed using advanced additive manufacturing technology. Several real-time experiments were conducted by coupling the NIPS model with a volunteer driver to evaluate its effectiveness. We used the neck injury criterion (N_{ij}) to understand the reduction in the probability of injury while using this NIPS. This thesis suggested that the newly designed NIPS may be a potential solution to address the limitations of existing neck protective devices in high-speed racing. The NIPS can potentially reduce the risk of neck injuries and improve driver safety on racetracks. However, further research and development are needed to optimize and prepare the NIPS design for broader commercial use.

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Nomenclature

NASCAR	National Association for Stock Car Auto Racing
AIS	Abbreviated Injury Scale
AFRL	Air Force Research Laboratory
FDM	Fused Deposition Modelling
ABS	Acrylonitrile Butadiene Styrene
PPE	Personal Protective Equipment
PAIS	Probability of Abbreviated Injury Scale
KMPH	Kilometer Per Hour
HANS	Head And Neck Support
NIPS	Neck Injury Protective System
CAD	Computer Aided Design
ATDs	Anthropometric Test Devices
N_{ij}	Neck Injury Criterion
F_{cc}	Force Interception Value
M_{yc}	Moment Interception Value
F_c	Compressive Force
F_T	Tensile Force
M_y	Moment of Flexion
M_E	Moment of Extension

Chapter One: Introduction

1.1 Importance of the Study

Car racing has a long history, dating back to the late 19th century when it was used to evaluate the durability and performance of automobiles. Over time, the sport has evolved significantly, with the emergence of prestigious events like Formula One and NASCAR, featuring increasingly faster and safer cars. Despite these advancements, there has been a persistent call for additional safety measures to be implemented for the drivers of racing cars throughout the years [1]. The quest to design an efficient system to safeguard occupants or racers from cervical spine injuries, especially in the event of frontal impacts, has become a critical focus in automotive safety and high-speed racing technology. Despite this, there is still a lack of well-defined methods or consistent measures to assess the effectiveness of such systems.

Frontal impacts in racing car collisions can result in the most serious injuries compared to rear-end collisions, side impacts, and rollovers. When a frontal crash occurs, the neck is subjected to significant inertial pressure from the head, similar to what happens in rear-end impacts (Figure 1). At the onset of neck-loading conditions, the head tends to move horizontally in relation to the torso, leading to neck protraction in frontal crashes [2]. These impacts mainly cause injuries through four basic movements of the head-neck system: flexion, extension, lateral bending, and rotation [3].

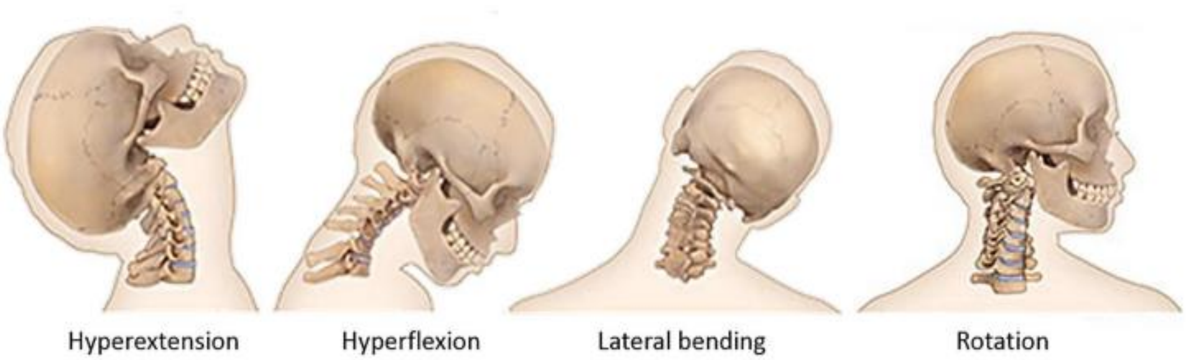


Figure 1: Examples of four different injury mechanisms (bottom) (adapted from [4])

The forces involved in these types of injuries can potentially result in a range of damage to the cervical musculoskeletal system. This can include fractures and dislocations of the vertebrae, tears in the intervertebral discs, ligaments, and joints, as well as cuts to the spinal cord and vertebral arteries [5]. Viano (2001) reported that upper cervical spine injuries are usually more serious and life-threatening compared to those at the lower levels. The AIS (Abbreviated Injury Scale) is widely used to assess the severity of several cervical spine injuries [6]. In Table 1, the AIS code ranges from 1 to 6, with higher numbers indicating greater severity. Examples of injuries listed include abrasions, lacerations, nerve damage, and spinal cord damage with varying degrees of severity.

Table 1: Examples of spinal injuries according to the AIS scale (adapted from [6])

AIS code	Description
1	Abrasion, contusion (hematoma), minor laceration of skin, muscle
2	Minor laceration of vertebral artery Dislocation without fracture of the cervical spine
3	Major laceration of vertebral artery Multiple nerve root lacerations of the cervical spine
4	Spinal cord contusion
5	Spinal cord laceration without cervical spine fracture
6	Decapitation Spinal cord laceration at C3 or higher with fracture

In the field of biomechanics, researchers have established several criteria to evaluate the extent of injuries sustained in frontal collisions. Biomechanical studies utilize metrics like acceleration, force, and torque to understand how individuals in vehicles react to potential accidents. These metrics provide crucial information about the impact of collisions on the human body and aid in assessing the risk of injury [7].

1.2 Background of The Study

Car racing has a long history, dating back to the late 19th century when it was used to evaluate the durability and performance of automobiles. Over time, the sport has evolved significantly, with the emergence of prestigious events like Formula One and NASCAR featuring increasingly faster and safer cars. Despite these advancements, there has been a persistent call for additional safety measures to be implemented for the drivers of racing cars throughout the years. After the event, thirteen injuries were reported, twelve of which occurred in saloon car racing. In single-seater motor racing, the most prevalent type of injury was bruising, accounting for 58% of all injuries. Furthermore, lower limb bruising was more common than upper limb bruising. In saloon car racing, over 53.2% of the injuries were neck sprains. In comparison to other high-risk sports, both groups involved in the competition experienced a significantly higher incidence of concussions [8]. Figure 2 depicts the two types of cars showing varying patterns of injuries. While no serious injuries were reported, unfortunately, there was one fatality. The driver's body experienced significant forces during the collision, resulting in a high prevalence of concussions.

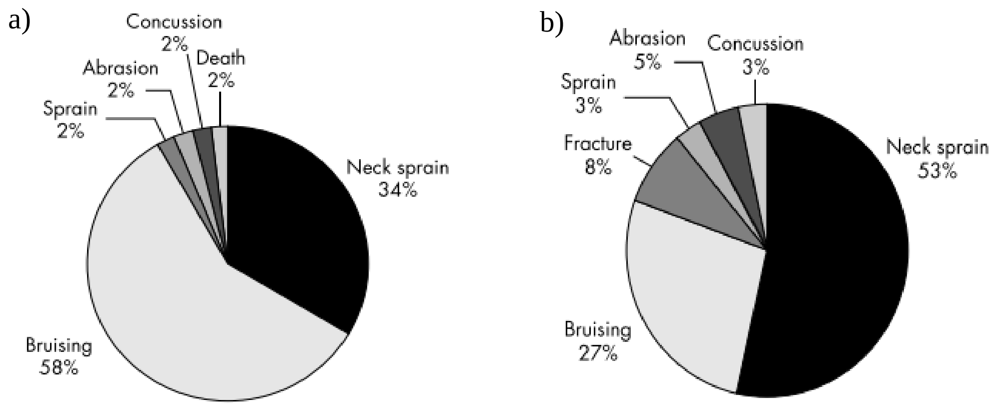


Figure 2: Types of injury acquired during (a) single-seat car and (b) saloon car racing (adapted from [8])

The lack of speed limits or regulations in automotive races, combined with the intricate and twisting race tracks, has significantly increased neck injuries during accidents. This trend has closely followed the advancements in automotive technology. As the occurrence of neck injuries has risen, there is a growing need for specialized gear to either prevent or minimize the severity of these injuries. This has become a key area of focus for engineers and scientists working in the fields of biomechanics and biomedicine.

After considering the aspects mentioned above, it is important to note that some challenges persist despite the advancements in neck injury protective devices. Let's explore some of these limitations below:

1. Limited range of motion can hinder performance in sports and activities.
2. Extended wear can cause discomfort, irritation, and skin sores.

3. Finding a properly fitting device can be difficult, affecting protection and comfort.
4. Many devices are heavy and bulky, making them cumbersome to wear.

The creation of the Head and Neck Support (HANS) device represented a major milestone in the enhancement of safety measures in the world of racing. Dr. Robert Hubbard and Jim Downing are credited with the invention of the HANS device during the 1980s which is presented below in Figure 3. Their innovation was a response to the pressing need for a solution that could effectively minimize the occurrence of basilar skull fractures and other neck injuries resulting from racing accidents [9].

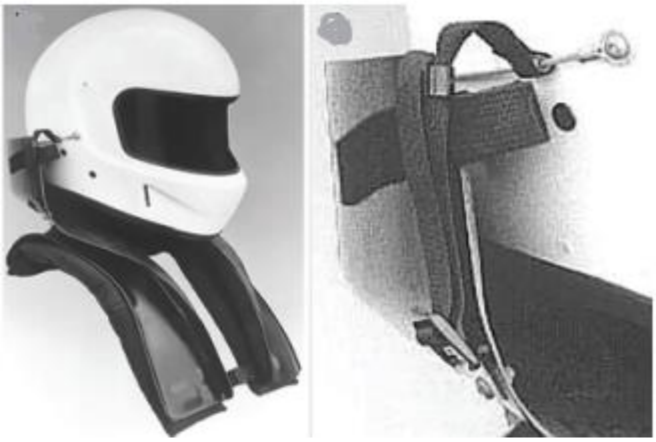


Figure 3: The first-generation HANS device (1980) (from left) and Fixed-length adjustable-length tethers are used to attach the device to the helmet (from right) (adapted from [9])

1.3 Goals and Objectives

Current neck injury protective devices for high-speed vehicle racing often sacrifice comfort for protection, resulting in limited mobility, overheating, and discomfort for riders. Furthermore, the effectiveness of some protective devices is either unproven or limited. Therefore, our thesis aims to address this critical issue by developing and examining an innovative NIPS (Neck Injury Protecting Device) specifically designed for high-speed vehicle racing. The NIPS intends to overcome the constraints of the systems that are currently in use by:

1. **Reducing neck loads**: By distributing impact forces over a larger area of the head and neck, the reduction of neck loads effectively prevents stress from concentrating on vulnerable areas.
2. **Improve head mobility**: Improving head control involves minimizing the head's excessive backward and forward movement during impacts. This can be achieved by promoting more

accurate and controlled head movements.

3. **Enhancing comfort**: When it comes to enhancing the comfort and freedom of movement for drivers, the use of lightweight and breathable materials is key. These materials not only provide a sense of ease and mobility but also contribute to an overall improved driving experience.
4. **Preventing frontal head movement**: During a frontal car impact, it's important to prevent the head from moving forward too quickly or in a way that could restrict its movement and cause less damage to the cervical spine. Preventing injuries is better than having to treat them later.

1.4 Arrangement of The Report

This thesis is divided into several chapters, each focusing on a different aspect of the interface topic. Following this introduction, Chapter 2 explains the history and development of neck protective systems and various injury mechanisms. Chapter 3 covers methodology, protective jacket, the helmet used, sensors and instrumentation, fabrication of the device, experimental setup, neck injury metrics. In Chapter 4, the results and analysis are presented and discussed. Subsequently, in Chapter 5, the conclusion of the thesis and significant findings and benefits are discussed. Additionally, some recommendations for the future are provided in Chapter 6. Finally, the last one contains the references.

Chapter Two: Literature Review

This comprehensive and thorough study provides an in-depth exploration of the evolution of head and neck restraint systems. It specifically highlights the development and effectiveness of the HANS (Head and Neck Support) device in reducing injuries resulting from high-impact collisions. The review meticulously incorporates a wide array of sources, such as academic journals, conference proceedings, and online repositories, in order to offer an exhaustive and detailed insight into the current state of knowledge on this crucial subject.

2.1 Neck Injury Biomechanics

Biomechanics is a fascinating subfield of medicine that involves a wide array of activities. These include in-depth anatomical research, analysis of accidents, conducting experimental measurements, and creating numerical models of living organisms like humans, animals, and plants under different conditions. The primary goal of biomechanics is to gain a deep understanding of the mechanical aspects of biological systems, focusing on how organisms move, support loads, and engage with their surroundings [10].

In the field of biomechanics, there is a specialized area known as injury biomechanics, or trauma biomechanics. This particular branch of study is concerned with understanding the mechanisms and effects of injuries. It delves into the reasons behind how injuries occur, examining everything from major impacts that affect entire parts of the body (at a macroscopic level) to the microscopic damage that impacts tissues and cells (at a tissue level). The field of injury biomechanics aims to analyze and comprehend the specific physical forces and stresses that result in injuries. This knowledge is essential for the development of improved safety equipment, advancements in medical treatments, and the creation of preventive measures to minimize injury risks in a wide range of environments, such as sports, automotive, and occupational settings.

The examination of the arrangement and organization of the human body is a fundamental aspect of medical science known as anatomy. The anatomy of the neck encompasses cervical vertebrae, intervertebral discs, ligaments, facet cartilages, nerves, foramina, and a sophisticated muscular system (Figure 4).

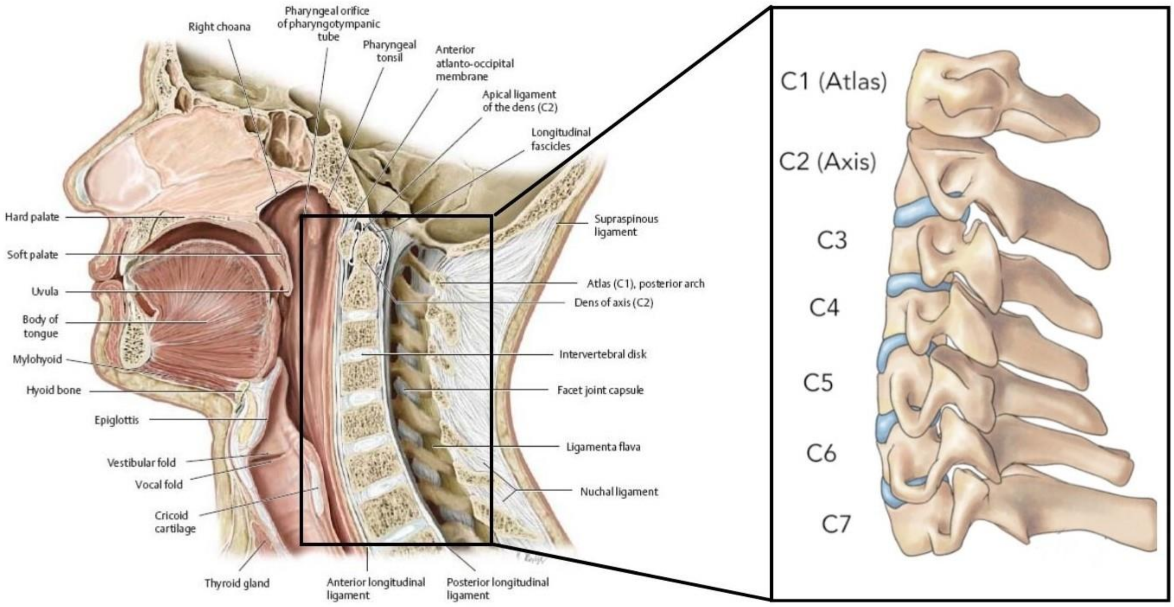


Figure 4: Different parts of neck anatomy and cervical vertebrae (adapted from [11],[12])

The anatomical details of the C1 (atlas), C2 (axis), C3 and C4 vertebrae are also displayed in Figure 4. The neck, medically referred to as the cervical spine, is made up of seven vertebrae categorized into three main groups: the middle cervical spine, which includes vertebrae C3 to C5; the lower cervical spine, consisting of vertebrae C6 and C7, and the upper cervical spine, encompassing vertebrae C1 and C2. Each vertebra has a complex structure, comprising a cancellous (trabecular) bone core, a thin cortical (compact) bone shell, and bony endplates. These components collectively contribute to the overall bony structure of the vertebrae in the cervical spine.

2.2 Injury Mechanisms

During a frontal impact (Figure 5), such as when a racing car collides head-on with another vehicle or a barrier, the sudden deceleration forces the driver's body forward. As a result, the driver's neck and spine are pressed up against the seat and the HANS (Head and Neck Support) device, which is designed to reduce the risk of neck and spine injuries in motorsports. The cervical region of the spine, which is the neck area, is particularly vulnerable to such impacts. The forces involved in the collision can lead to broken vertebrae in the neck region and herniated discs, which are the soft cushions between the vertebrae. These injuries can have serious and long-lasting effects on the driver's health and mobility [2].

Figure 5: Car crashing scenario during frontal impact (adapted from [13])

In a rear-ended collision, the car is struck from behind with significant force, causing the vehicle to abruptly shift forward and then backward. As a result, the driver's body is forcibly propelled in the same manner. This sudden acceleration and deceleration subject the body to intense forces, leading to potential injuries such as hyperextension of the neck, whiplash, and damage to the spinal cord. These injuries can have serious and long-lasting effects on the individual's health and well-being. Figure 6 mimics the motion of our head and neck during the frontal collision.

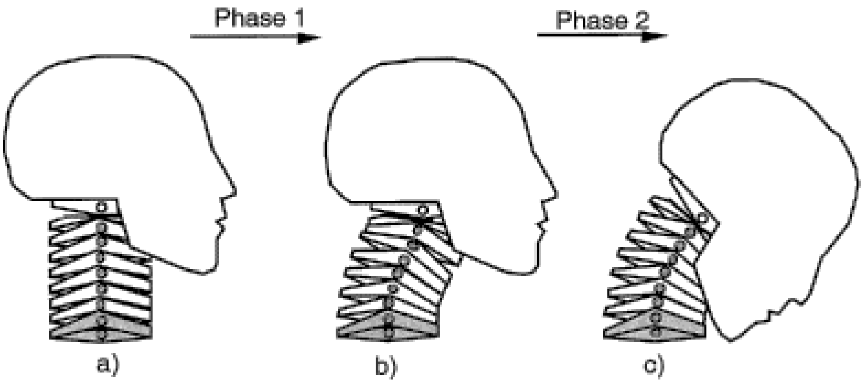


Figure 6: Schematic drawing of the head-neck motion during a frontal collision. Phase 1: Protraction motion. Phase 2: Flexion motion (adapted from [2])

A side-impact collision, also known as a T-bone collision, happens when a car is struck on the side by another vehicle or an obstacle such as a barrier as shown in Figure 1. During a side-impact collision, the force of the impact can cause the driver's body to be compressed from the side, leading to significant stress on the neck and spine. This type of collision often results in injuries such as fractures of the ribs and vertebrae due to the sudden and forceful compression of the body [10].

When a vehicle experiences a rollover or rotation, combined with torque on the head, a head-on collision can lead to whiplash. During the collision, the body is forced forward while the head snaps back, resulting in whiplash. The force responsible for this is the body's deceleration, and the distance is the distance between the center of gravity of the head and the neck joint. Severe consequences of this type of injury can include cervical spine fractures and other whiplash-related injuries.

2.3 The Effectiveness of Neck-Protecting Devices

A neck-protecting device for racers has been specifically designed to limit motion and reduce impact pressure on the cervical spine during collisions. This innovative device provides crucial support to the neck and upper spine, effectively preventing a hard helmet chin from coming into contact with the collarbone. In the event of a rider's head being hit or moving unexpectedly, the helmet makes contact with the neck brace. This interaction serves to disperse the impact and effectively absorb energy, enhancing the overall safety and protection provided to the racer [1].

In a study conducted by Frank Meyer and colleagues in 2018, it was discovered that the use of a neck brace resulted in an average reduction of 39% and 13% in the risk of AIS3+ neck injury at speeds of 5.5 and 6.5 m/s, respectively, when considering the normalized neck injury criterion. The researchers highlighted the significance of neck protective devices in decreasing the occurrence and severity of fatalities, bone fractures, abrasions, and lacerations as shown in Figure 7 [14]. Moreover, a significant reduction of loads is observed while a racer wears a HANS device around his head and collar.

Neck braces have become indispensable for racer safety, significantly reducing the risk of life-threatening neck injuries. Their widespread adoption across motorsports highlights their effectiveness. Continuous advancements in neck brace technology are crucial to meet evolving safety standards and provide optimal protection for athletes.

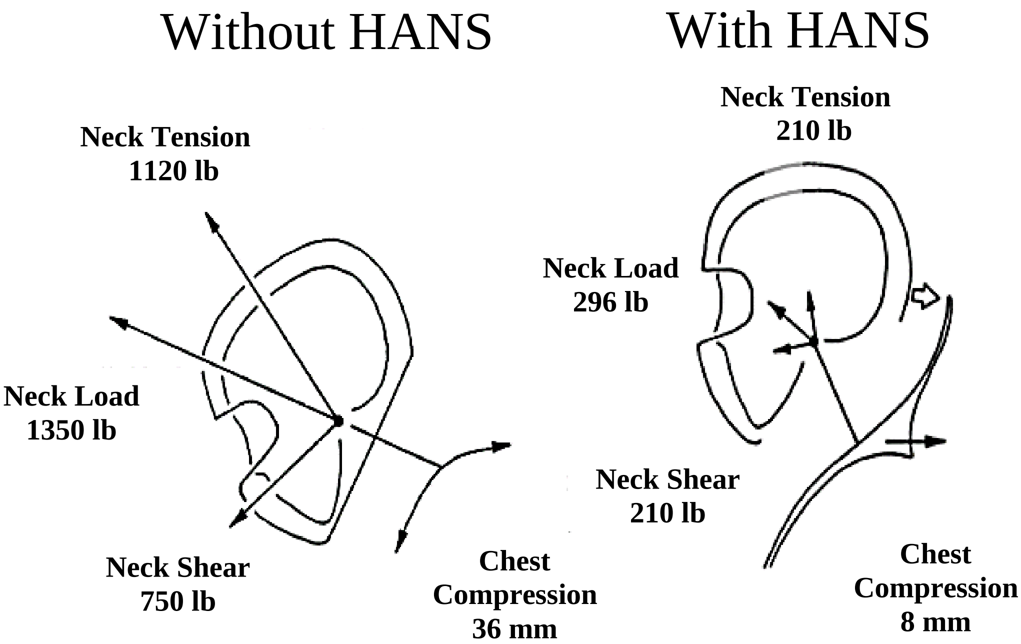


Figure 7: Force diagrams demonstrating typical results from the frontal crash test with and without HANS (adapted from [9])

Chapter Three: Methodology

In this research project, we are focusing on developing a neck injury protective device that effectively transfers the stresses experienced by the head and spine to the torso. The primary goal is to prevent cervical spine trauma while prioritizing rider comfort and mobility. To achieve this, the device will require a biofidelic head and neck model, as well as a torso, for comprehensive development and testing.

3.1 Protective Jacket

Car racing is an exhilarating but high-risk sport that demands the use of Personal Protective Equipment (PPE) to ensure the safety of drivers. This essential gear includes fire-resistant suits, helmets, gloves, and specialized footwear, all meticulously designed to provide protection against the hazards of high-speed racing, such as burns and collisions. Additionally, the use of neck restraints and head-and-neck support systems, commonly referred to as HANS, plays a crucial role in minimizing the risk of severe injuries like whiplash and spinal damage. By adhering to these comprehensive safety measures, drivers can significantly reduce the likelihood of harm, allowing them to approach their races with confidence and an increased sense of security.

For our experiment, we introduced a jacket (Figure 8) that the driver wore and to which our developed device was attached to ensure safety and enhance the comfort of the rider instead of attaching it with a neck collar as done previously that restricts the neck rotation and induces discomfort. Table 2 shows the jacket size that was bought from the market considering the bodily dimensions of our rider.

Figure 8: Jacket used during the experiment as a PPE and rider's injury restriction system

Table 2: Chosen Jacket size chart for the driver

Body Dimensions	Measurement (in inches)
Body Chest	38”
Jacket Chest	40”
Waist	37”
Sleeves	24.5”
Shoulder	20”

These jackets are commonly crafted with a combination of materials such as wool, fleece, and synthetic fibers like polyester, which are carefully selected to provide exceptional insulation against low temperatures. Additionally, some jackets are designed with water-resistant or waterproof exteriors to offer reliable protection against rain and moist environments. The interior linings are typically constructed from soft, breathable materials to ensure maximum comfort and breathability. Furthermore, many jackets are equipped with adjustable cuffs, hoods, and multiple pockets, strategically placed to enhance their functionality and convenience for the wearer.

3.2 Helmet

Car racers rely on helmets to protect them from potential head injuries during high-speed accidents. These helmets are constructed using advanced materials such as carbon fiber and Kevlar, which not only make them lightweight but also highly resistant to impact. To ensure a comfortable and secure fit, these helmets are designed with cushioning and adjustable straps. Modern racing helmets are equipped with anti-glare and anti-fog visors, as well as effective ventilation systems to keep the drivers cool and focused. Additionally, many of these helmets are designed to work seamlessly with Head and Neck Support (HANS) devices, which play a crucial role in preventing neck injuries in the event of a crash.

The effectiveness of helmets in reducing serious injuries and fatalities is 9%, compared to 10% for those not wearing helmets. Additionally, approximately 40% of the AIS 3-6 injuries to helmeted riders were to the head, while about 58% of the AIS 3-6 injuries to non-helmeted riders were to the head. This highlights the importance of wearing helmets in reducing head injuries in motorcycle accidents [15].

During our testing, we took thorough precautions to simulate real-life scenarios. For instance, the driver wore a full-face helmet as shown in Figure 9 to replicate the conditions of a car racer. This allowed us to observe how the helmet would directly impact the protective device instead of the driver's chin in the event of a collision. As a result, we were able to observe that the additional face protector was impacted when the driver applied the brakes. The helmet itself consists of various components including an outer shape, impact absorber liner, padded comfort layer, retention system, vents, and cheek pads.

Figure 9: Full-face helmet used in our experiment

3.3 Sensors and Instrumentation

Racing helmet sensors are designed to meticulously record various parameters including displacement, acceleration, and head rotation to ensure both safety and performance analysis. Through the use of accelerometers and gyroscopes, these sensors are able to accurately track the movement of the helmet in real-time. Specifically, gyroscopes are employed to measure head rotation and angular velocity, while accelerometers are utilized to detect linear acceleration and velocity. This comprehensive understanding of the forces experienced by drivers during races and crashes is integral in the development of superior protective gear and the continual improvement of racing safety standards. It is important to note that racecar drivers are susceptible to concussions during crashes, further emphasizing the critical role of advanced safety measures and equipment in the realm of motorsport. In 1998, the research on head acceleration and injury type and severity began with a lack of existing data in this area. For almost 50 years, the Air Force Research Laboratory (AFRL) Biomechanics Branch has dedicated its efforts to studying human acceleration reactions by using volunteer individuals and instrumented manikins. In 2000, the RHPA (Racing Head Protection Authority) adopted the use of instrumented earplugs to accurately measure head accelerations in racecar drivers. This decision was made after the discovery that helmets were slipping during impact events. The initial earplugs utilized Endevco 7269 triaxial accelerometers, which were specifically manufactured for AFRL [16].

In our quest to accurately capture acceleration data and measure head-neck force, we needed to procure an appropriate accelerometer. We utilized the MPU 6050 Gyro sensor to detect head motion during our testing as shown in Figure 10. Additionally, we opted for the MPU6050 sensor module, which serves as a comprehensive 6-axis Motion Tracking Device. This module integrates a 3-axis Gyroscope, 3-axis Accelerometer, and Digital Motion Processor, all within a compact form factor. Notably, it also incorporates an on-chip temperature sensor. Furthermore, it boasts an I2C bus interface for seamless communication with microcontrollers [17]. The MPU 6050 is equipped with a 3-axis Accelerometer featuring Micro Electro Mechanical (MEMs) technology. This technology allows for the measurement of acceleration along the x, y, and z axes by detecting the displacement of a movable mass. The movement of the mass causes a change in the capacitance of the sensor, which in turn produces a proportional output signal. This output signal is then digitized using a 16-bit Analog-to-Digital Converter (ADC) to provide precise measurements. The device offers a full-scale range of acceleration from +/- 2g, +/- 4g, +/- 8g, to +/- 16g, all measured in g (gravity force) units.

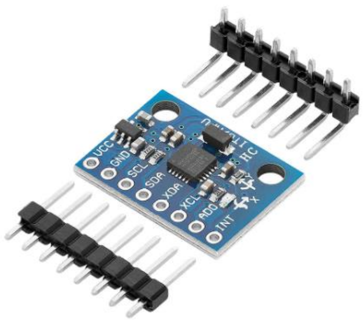


Figure 10: MPU 6050 Module (adapted from [17])

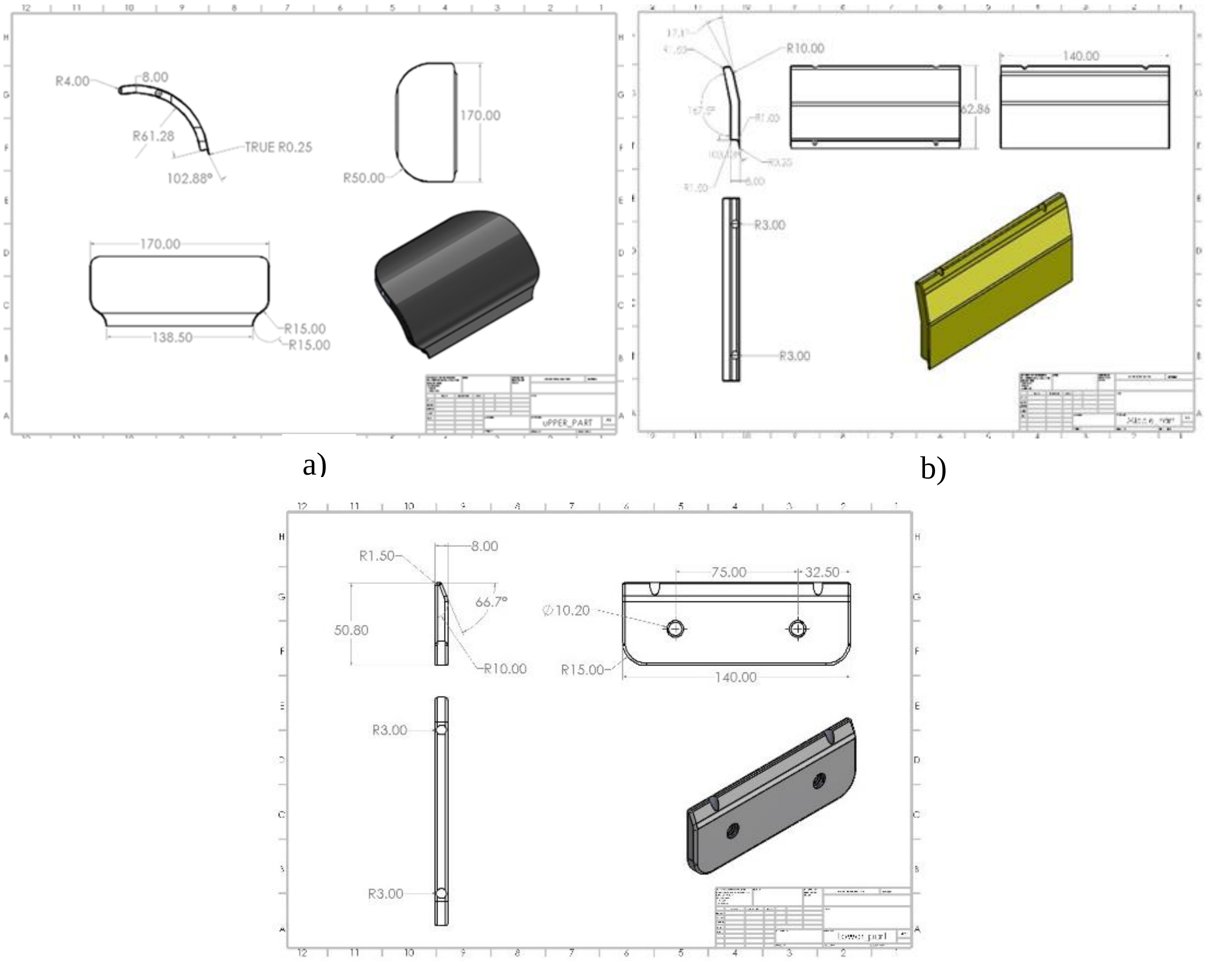
The sensor was securely attached to the lower part of the helmet, or to an additional protective component shown below in Figure 11 (arrow indicates the placement of the sensor). Although the standard recommendation is to place the sensor at the Center of Gravity of the head-neck system to record acceleration data, in our specific case, we performed experiments using a human surrogate. As a result, the sensor was installed on the outer edge of the helmet. Our next step involves conducting a simulation in the upcoming phase to compare the data collected when the sensor is positioned at the center of gravity.

Figure 11: Placement of the sensor on the helmet's periphery while the rider is wearing the modified jacket along with the device

3.4 Fabrication of the Proposed Design

The vision of our research was to build a protective device for the motor car racers so that when frontal impact or collision occurs, our device restrains the head flexion towards the chest as the rider's trunk and lower part of the body remain in place due to wearing seat belts. The available neck braces or head-neck protective devices have proved to be effective. However, there have been issues with those existing devices while rotating the head and thus discomforted the rider – the stiff device made the rider uneasy. At this point, the novelty of our research is carried out. We tried to find how the device would be effective in response to the injury and remove discomfort or uneasiness while racing – not making the head still.

Considering the aforementioned points, we applied the method to not fix our device around the neck and within the shoulder width. We modified and tailored the safety jacket worn by the driver in such a way that it had pockets in various heights to hold our designed and fabricated device along the chest, and we also pivoted three straps or tethering to hold and keep the lower part almost fixed to the chest and the middle portion partially fixed. This combination of jacket and the device was worn by our driver and the straps were attached to its length according to the comfortability of the driver. The device was put into the second pocket (three pockets were provided) so that it initially did not strike the helmet. Rather, a gap was provided. Our protective system has two parts- the jacket and the restraining device made with three distinct parts which were designed using SolidWorks as observed in Figure 12 that shows the three distinct parts of our novel device. The top restraining part was made in an angular shape to ensure a gap between the helmet and the device, initially. Measurements taken matched 50th percentile body dimensions taken from Anthropometric data considering Asian males and also required dimensions to match the profile of our rider.

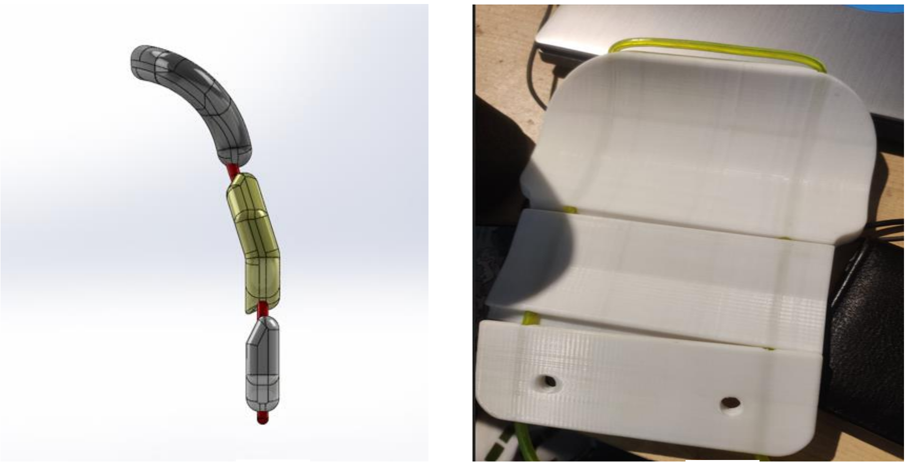


a) b) c)

Figure 12: Design of the safety device using SolidWorks a) top part, b) middle part, c) bottom part

3D printing, which is also referred to as additive manufacturing, is a method of successively layering materials to produce three-dimensional objects from a digital file. The precise and customizable production of intricate shapes and structures is facilitated by this technology, which is impossible or extremely difficult to achieve using conventional manufacturing methods. Polymers, metals, and plastics are the most frequently employed materials in 3D printing. Applications of 3D printing are found in a variety of industries, such as aerospace for lightweight components, healthcare for custom prosthetics, and consumer goods for personalized products. A revolutionary instrument in modern manufacturing and design, 3D printing enables the rapid prototyping and production of on-demand parts [18].

For our device we used Acrylonitrile Butadiene Styrene (ABS) material which took the printing to occur and finish within three days. Fused Deposition Modeling or FDM technique was applied since no other machines were present. However, after the completion of fabrication, we bought elastic bands or tubes to be inserted through the holes that we provided into our device. This kept the parts attached to each other and bent upon head impact but not allow the bottom part to do so, which was attached to the jacket and fixed. Only the other two parts could bend. The middle part constrained the upper part's degree of motion in a way that it bent less than usual. This was the effect of the elastic tube along with the two layers of foam – Eva foam and comfortable foam used. Figure 13 given below, presents the virtual designed device in SolidWorks from a side view and also the realistic fabricated device that we desired for our purpose.



a) b)

Figure 13: (a) The designed device using SolidWorks and (b) the 3D-printed device with elastic tube and foams

3.5 Experimental Setup

We began our test after obtaining authorization and permission from the University Transport Officer and related officials. Our rider was selected based on his driving skills and who matched the bodily dimension profiles as per our requirements. At first, our supervisor made us understand what guidelines we should provide to the rider before riding, and then we made him understand those guidelines. The test was carried out inside the premises of our institution, where people did not often pass by. For caution, we kept one guard who placed barriers for other vehicles, restricting their movement in that particular and for the people who came there.

After taking all precautionary measures possible, we met with our rider to discuss issues like what speed of the car he should provide during the experiment, at what point he should press the brake, and how we want his head to move. That is, the head should not be kept stiff while braking, as he already knew he would brake now. By this, we tried to mimic the real-life situation of a car racer during frontal collisions. Since it was on our premises, we could conduct the testing at only 70 kmph maximum, as permitted by the authority. Thus, getting data that we would rely on for the actual crash collision was impossible [19]. Rider health and safety were also concerns. But at lower speeds, sudden brake head movement was also obvious; that was the idea we relied on.

The driver, after donning a jacket and fastening the seat belt, proceeded to connect a 3-foot adapter wire from the laptop to the sensor. Following instructions, we conducted experiments at two specific speeds: 45 kmph and 65 kmph. These experiments were designed to capture head-neck acceleration data under two conditions: with and without the device. The device, our proposed model, was integrated into the jacket and secured with straps. Each speed was tested six times, with three trials for each condition (with and without the device).

In Figure 14, a clear depiction of the rider's position is presented. It is evident that the seat was tilted at an angle, deviating from the typical driving position. The rider was also observed wearing a jacket and carrying a device. Furthermore, the setup included a variety of components such as sensors, an Arduino UNO, a breadboard, and adapter wires, all interconnected to collect data. Notably, the sensor was linked to the Arduino UNO's serial ports through the use of jumper wires.

a) b)

Figure 14: Rider wearing the modified jacket a) with the protective device and b) without the device inside the car.

The experiment was done considering the rider's comfort. From the above figure, we can notice the white straps attached to the jacket and fastened according to the rider's questions. We kept volunteers around the driving zone during the experiment to avoid any unexpected accidental conditions. Acceleration data was acquired in terms of 'g' and at a mapping scale ranging from 0 to 255. The time frame measured was in terms of milliseconds (ms). After the data was received, it was processed using CoolTerm Software at 9600 bandwidths. Then, it was imported to Microsoft Excel, where an interface of code was done in Python, which was run to organize and import the data we obtained earlier.

Acceleration data was gathered across three sensor axes: the z-axis, which represents vertical movement; the x-axis, for horizontal movement; and the y-axis, for transverse movement. These were the local axes, as demonstrated in Figure 15. In order to determine the moment of the head-neck system, the calculation was performed with the z-axis as the axis of rotation [20].

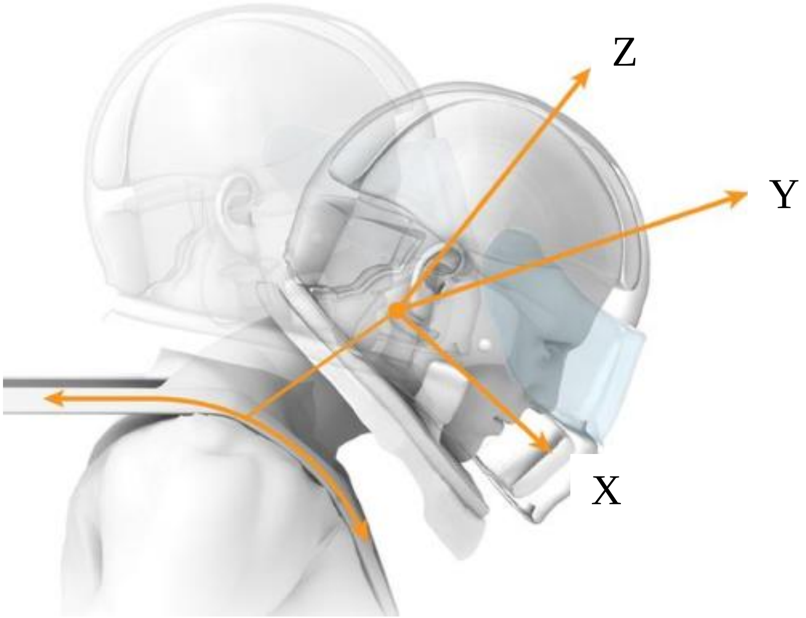


Figure 15: Demonstration of the local axes considered according to the sensor placed on the additional protective part of the full-face helmet

To calculate the Moment of Flexion, we utilized the force acting along the x-axis and the vertical or perpendicular distance from the Occipital Condyle to the sensor, precisely measured at 18 millimeters or 0.018 meters. The compressive force was measured explicitly along the z-axis. It's important to note that our sensor module was the reference level for all measurements and calculations.

Additionally, the rider's height was measured to be 5 feet 1 inch, equivalent to 154.94 centimeters. His mass was also measured and found to be 62 kilograms.

Our methodology also included the utilization of the Butterworth filter in MATLAB to effectively filter the noise generated during data acquisition and reduce data redundancy. In the realm of signal processing, Butterworth filters are widely recognized for their user-friendly characteristics. With their flat response in the passband, they excel at allowing desired frequencies to smoothly pass through. This makes them adept at eliminating unnecessary noise without altering the significant aspects of the signal. The transition from passing to stopping frequencies occurs gradually, and the filter's order can be adjusted to control the sharpness of this transition. These filters are widely favoured for their ability to reduce noise, recover signals, and enhance overall smoothness, making them highly valuable in a variety of engineering applications [23].

In our study, at first, the average or mean of the acceleration values were taken for each condition and speed. Like, for 45 kmph speed and the rider not having our designed device, we took reading for the acceleration data consecutively three times. Likewise, for other speeds and depending on whether the rider wearing the device with the modified jacket or not, we took nine more readings. Each time we obtained acceleration data for the three-axis, but we will particularly focus on the x and z axes values since these two give the compressive force and moment of flexion, respectively. Now, after averaging, the next task was to use the appropriate cutoff frequency and the Butterworth filter order. The 'Low Pass' filtration was applied using a cutoff frequency of 180 Hertz (Hz). Meanwhile, the sampling rate was fixed at 3000 Hz and the filter used was of order 4. These values were chosen for the Crash Analysis Criteria alluding to CFC Filters from the Product Documentation of NI [24].

3.6 Neck Injury Metrics

Various metrics have been proposed by researchers to evaluate neck injuries in automotive crash tests using anthropomorphic test devices (ATDs). These metrics consider factors such as force, moment, acceleration, and displacement to provide comprehensive information on neck injury risk. They are instrumental in understanding the intricacies of injury risk and can contribute to enhancing seat design and injury mechanisms. One of the significant metrics is the Neck Injury Criterion (N_{ij}), which involves the linear combination of normalized axial load and sagittal plane bending moment in frontal impacts. This concept was first introduced by Prasad and Daniel in 1984, utilizing piglets as child surrogates. The N_{ij} formula incorporates intercept values F_{int} and M_{int}, which vary for compression/tension (F_C/F_T) and flexion/extension (M_F/M_E) respectively. This comprehensive approach enables a deeper understanding of the dynamics involved in neck injuries in automotive crash scenarios.

$$N_{ij} = \frac{F_z(t)}{F_{int}} + \frac{M_y(t)}{M_{int}} \quad \text{(Eq. 1)}$$

Lastly, we need to find the chances of the occurrence of injury and the corresponding severity using an equation [22] for the calculation of the probability of AIS2+ injury that is given by:

$$P_{AIS \geq 2+} = \frac{1}{1+e^{5.2545-(4.1\times N_{ij})}} \quad \text{(Eq. 2)}$$

Table 3 shows the severity of the acquired injuries and their corresponding classifications from levels 1 to 6, where level 6 currently has no clinical treatment and is termed the most severe.

Table 3: Individual injury classification using AIS levels (adapted from [8])

AIS Level	Severity
AIS 1	Minor
AIS 2	Moderate
AIS 3	Serious
AIS 4	Severe
AIS 5	Critical
AIS 6	Maximal (currently untreatable)

In order to find the mass of the head-neck of our rider, we used the Mass of Body Segment formulation developed by Zatsiorskji and Selujanov (1979), based on athlete data which is given by [5]:

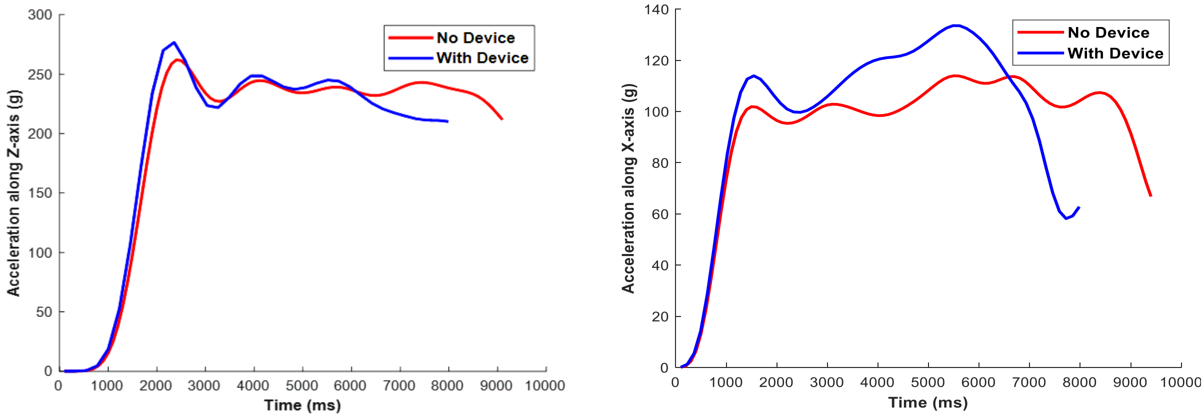
$$\mathbf{m_i = B_0 + B_1 \times m + B_2 \times H} \qquad \text{(Eq. 3)}$$

where,

mi = Mass of the head and neck segment (kg),
m = Mass of the rider (kg),
H = Height of the rider (cm), and
B0, B1, B2 = Coefficient of head and neck segment

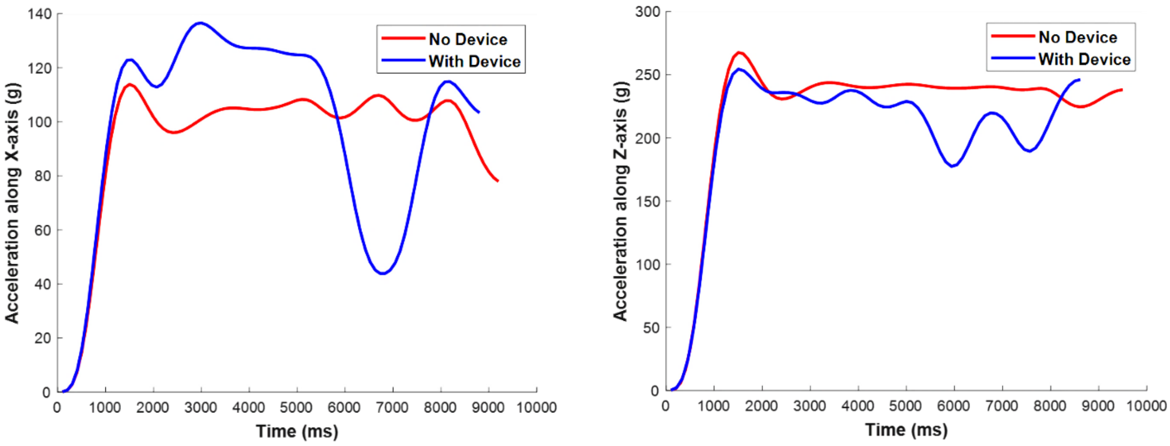
Chapter Four: Results and Discussion

The text describes the presentation of research results through graphical representations in Figures 16 and 17. The data shows the acceleration values plotted against the time frame to evaluate the behavior and response of a protective device created for the research. Figure 16 shows the acceleration at 45 kmph of the head is reduced while the rider is wearing the NIPS, as indicated by the blue curve. If the rider is not wearing the protective device, then the deceleration also occurs, but at the end of his riding session, that is, when he stops the car, not when he brakes.



(a) (b)

Figure 16: Average Acceleration Curves at 45 kmph along (a) X-axis and (b) Z-axis



(a) (b)

Figure 17: Average Acceleration Curves at 65 kmph along (a) X-axis and (b) Z-axis

Figure 17 also shows the same behaviour at the acceleration of 65 kmph, as discussed earlier, for the 45 kmph speed but in a different fashion. The Z-axis deceleration is seen to be greater in the case of the car's 65 mph speed. However, both the figure confirms that the NIPS is effective in reducing the head-neck acceleration during the instantaneous brake of the car and hence reducing the flexion moment and the compressive force on the vertebra.

The primary reason for not examining the y-axis acceleration is that our study focuses explicitly on the impact from the front, rather than from the side. Upon analyzing the filtered curves, it becomes apparent that the head-neck movement is minimized at 6800 milliseconds into the experiment when considering x-axis acceleration. The experiment was conducted for a duration of 10 seconds, which is equivalent to 10000 milliseconds. Similarly, when observing the z-axis acceleration, a reduction in acceleration is also observed, albeit in a manner different from the head-neck response. Therefore, our device design shows promise in reducing acceleration to a significant degree. Through the acceleration data obtained from our experiment earlier, we found the Nij values using Equation 1. The force intercept value used was 6160 N while the moment intercept value was 310 N-m. Acceleration data were used to fine the compressive force and the moment about local Y axis.

From the data and calculation given in Table 4, it is clearly identifiable that during the 45 kmph speed of the car, the device shows its efficacy by reducing the injury probability considering AIS Level-2. While wearing the device, the N_{ij} value is reduced by 8.02%, and the moment of flexion is depleted more.

Table 4: The dynamic experimental variable values of the head-neck system conducted at 45 kmph car speed

Case	**F_c (N)**	**F_c/F_{cc}**	**M_y (N-m)**	**M_y/M_{yc}**	**N_{ij}**
No device	459.49	0.0746	20.16	0.0650	0.1396
With device	582.93	0.0946	10.45	0.0337	0.1284

Again, Table 5 shows that during the 65 kmph speed of the car, the device shows its efficacy by reducing the injury probability. While wearing the device, the N_{ij} value is reduced by 3.56%, and the depletion of the flexion moment is noticed.

Table 5: The dynamic experimental variable values of the head-neck system conducted at 65 kmph car speed

Case	F_c (N)	F_c/F_{cc}	M_y (N-m)	M_y/M_{yc}	N_{ij}
No device	582.93	0.0946	12.43	0.0401	0.1347
With device	560.07	0.0909	12.09	0.0390	0.1299

Now, when the rider wears the device, the probability of injury is reduced, as shown in Table 6, for both the speeds, 45 kmph and 65 kmph, respectively.

Table 6: Probability of injury corresponding to N_{ij} values

Case	Speed	N_{ij}	PAIS2+
No Device	45 kmph	0.1396	0.0092
With device	45 kmph	0.1284	0.0088
No device	65 kmph	0.1347	0.0089
With device	65 kmph	0.1299	0.0088

Based on the probability table shown above, it is evident that all six values of N_{ij} are clustered closely together on the coordinate plane. This indicates that the probability of injury to the rider's cervical spine remains consistent even when driving at lower speeds, as was the case in our study. This suggests that driving at a lower speed does not significantly reduce the probability of injury, which is crucial for analyzing real-life collision scenarios during a car race.

By focusing on the x and z axes, we could understand the rider's compressive forces and moments of flexion under varied scenarios. Our research primarily examines frontal impact; hence, we didn't analyze y-axis acceleration. The above graphs, shown in Figure 18 and Figure 19, exhibit that the x-axis and z-axis acceleration are reduced during the head-neck movement of the rider at the instantaneous stopping of the car. Thus, our creation reduces the acceleration as desired.

While conducting our research, we faced some limitations that might hinder the results. We may need some approximations of the values and consider the results close to accurate. The limitations are given below:

- The material of our jacket used was preferably for winter clothing, but due to the unavailability of racing jackets, we deemed the ready-made jacket for our convenience.

- The acceleration data taken by the sensor showed variations like sudden rise or fall in acceleration where it should not be. This tells us the efficacy of the low-cost sensor used and its sensitivity was an issue.

- For our experiment, we used a private car of the university instead of a racing car, so the accuracy level and the desired result were deviated from the perspective of actual racing conditions.

- The experiment was conducted at the sub-injury level, which is why the probability of the risk of injury came so close while wearing and not wearing our novel device.

- Lastly, since the experiment was conducted through the university's vehicle, we were instructed not to drive the car at speed above 65 kmph, which restricted our research to carried out at a sub-injury level.

Chapter Five: Conclusion

This study delves into the engineering and analysis of a new Neck Injury Protecting System (NIPS) specifically designed for high-speed racing cars. The system effectively addresses the limitations of current devices by reducing neck loads, enhancing head mobility, improving driver comfort, and minimizing frontal head movement that could lead to injuries.

The NIPS was designed using SolidWorks, a three-dimensional CAD software tool that allows for precise design and simulation of the system. This research project aims to create a protective device for preventing neck injuries by transferring head and spine stresses to the torso. The device is intended to minimize the risk of cervical spine trauma while prioritizing rider comfort and mobility. To achieve this, a realistic head and neck model and a torso will be essential for developing the protective device.

The device which has been developed by us in this research project tends to decrease the instantaneous head-neck movement of the rider during the sudden brake of the car. Several real-time experiments have been conducted while maintaining essential boundary conditions. The results of these experiments have been analyzed and compared with results obtained without NIPS. Additionally, metrics such as N_{ij} have been used to compare the NIPS with existing devices, showing that the NIPS design effectively reduces neck loads and improves head control while ensuring driver comfort.

Overall, this research paper provides a comprehensive analysis of the NIPS and its potential to revolutionize safety in high-speed racing cars by minimizing the risk of neck injuries.

Remarkable findings and practical benefits:

- The implementation of NIPS may mitigate the risk of neck injuries in high-speed racing accidents.
- This can improve driver safety and potentially save lives on the racetrack.
- The NIPS design can be further optimized and commercially developed for broader use in racing.

The research findings have noteworthy implications beyond their original application in high-performance racing. While initially developed for this specific context, the insights gained from this research can be instrumental in advancing neck protection systems for a wide range of motorsports and use in passenger vehicles. The data and design principles derived from the development of the NIPS can be adapted and implemented to create improved safety features that benefit everyday drivers. This adaptation has the potential to significantly reduce the prevalence of whiplash and other neck injuries in road accidents, thereby enhancing overall road safety for drivers and passengers alike.

Chapter Six: Recommendations for Future

The successful validation of the NIPS prototype introduces a range of promising opportunities for advancing neck protection technology. In the following discussion, we will delve into potential pathways for further development:

- **Material Innovation:** To enhance NIPS's impact mitigation capabilities, we must explore advanced materials with exceptional energy absorption properties. This will involve incorporating composite materials, shape-memory alloys, or even next-generation auxetic structures known for their superior energy dissipation.
- **Sensor Integration:** Integrating the NIPS with intelligent sensor systems allows for monitoring impact severity and driver biometrics. This data can then be utilized to make real-time adjustments in support and restraint, customizing protection for each individual and specific accident scenario.
- **Universal Applicability:** The NIPS design principles, originally created for high-speed racing, show potential for customization and application across various motorsports categories. Further exploration in research could involve tailoring these principles to meet the distinct requirements of motorcycle helmets, rally car seats, and even aeroplane pilot seats.
- **Everyday Driver Safety:** The insights obtained from developing the Neck Injury Protection System (NIPS) can serve as a foundation for enhancing neck protection systems in passenger vehicles. By incorporating NIPS-inspired design elements into car seats for commercial use, automakers have the potential to effectively mitigate whiplash and other neck injuries in common collision scenarios.
- **Standardization and Regulations:** Engaging with regulatory bodies and safety organizations can facilitate the creation of uniform testing protocols and the possible integration of NIPS-like attributes into compulsory racing car safety standards. This will establish a quantifiable and uniform standard for neck protection across all drivers.

Through the pursuit of these innovations, the Neck Injury Protective Systems (NIPS) aims to transform neck protection, not only in racing but also in all modes of transportation. This has the potential to enhance safety standards and save lives for both drivers and passengers on roadways everywhere.

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