Seat Belt Safety in Rollover Accidents: Investigating Buckle Release Force and its Impact on Occupant Protection

by

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Abstract

Seat belts have been a crucial safety feature in vehicles for over a century. They undoubtedly remain the most effective safety device in a vehicle for reducing both fatal and nonfatal injuries resulting from motor vehicle crashes when used correctly. However, the persistence of high numbers of road transportation crashes and fatalities worldwide necessitates continued efforts to improve vehicle safety. Despite numerous safety and technological advancements, in the United States, motor vehicle accidents continue to be a leading cause of death for people aged 1–54, and the leading cause of work-related fatalities. Over the past two decades there has been an increase in belted fatalities with more than half of all fatalities being belted. Additionally, rollover accidents, which account for 30% of all fatalities and are the most fatal motor vehicle accident in the U.S., are on the rise.

Current seat belt buckle standards require that a force of no more than 133 N be applied for the buckle to release. This standard threshold has not been modified since its inception in 1965 and is more than double the requirement of European and Australian standards. Given the rising sales of SUVs, prevalence of obesity, use of pretensioners, and rise in belted fatalities in the U.S., it is imperative to examine the adequacy of existing seat belt standards, reconsider certain standards, and explore opportunities for improvement. In addition to the use of seat belts in cars, the issue of seat belt usage on school buses has been a topic of debate in recent years, with growing advocacy for their installation. The lack of seat belts raises concerns over the ability of children to unlatch them in emergency situations. This is particularly concerning in the case of school buses, where the driver may be the only adult present, leaving children responsible for their own safety.

Concerns exist regarding situations in which individuals may be inverted and are unable to release their seat belts, including both passenger vehicles and school buses. The research conducted in this dissertation aimed to address important gaps in the existing literature by exploring two critical elements. Firstly, it investigated whether adults can safely unlatch a motor vehicle seat belt in a rolled-over position. Secondly, it explored the design of seat belts for children on school buses, and their ability to operate and unlatch them in the event of a rollover accident. The research involved two primary studies and was split into four experiments. The first experiment measured the force that adults (18 years and older) could exert on a seat belt buckle in different orientations (0°, 90°, 180°, 270°). The second experiment evaluated their ability to unlatch a seat belt in different rolled over orientations (90°, 180°, 270°). The third experiment recorded the strength capabilities of children (5 – 16 years) to exert force on a seat belt buckle in both upright and rolled over orientations (90°). The fourth experiment evaluated their physical capabilities to unlatch a seat belt buckle in both orientations.

The findings of this dissertation suggest that while the majority of adults were able to unlatch seat belts in different orientations, they were not able to exert the force of 133 N required by existing seat belt standards. Additionally, around 13% of children were unable to unlatch their seat belt in a rolled over orientation and none of the children were able to exert a force of 133 N. These findings suggest the need to reconsider and reduce the maximum force required to unlatch seat belt buckles in order to improve safety standards. The study provides valuable insights into potential areas for improvement in seat belt design and safety standards. It highlights the need for future research in developing new seat belt standards and evaluating the capabilities of children to unlatch seat belts on school buses in emergency situations.

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List of Abbreviations

AGA	Auburn Gymnastics Academy
AIS	Abbreviated Injury Scale
AL	Alabama
ANCOVA	Analysis of Covariance
ANOVA	Analysis of Variance
ATDs	Anthropometric Test Devices
BLS	Bureau of Labor Statistics
BMI	Body Mass Index
CDC	Centers for Disease Control and Prevention
CDS	Crashworthiness Data System
CG	Center of Gravity
CI	Confidence Interval
CIREN	Crash Injury Research and Engineering Network
cm	Centimeter
COVID-19	Coronavirus Disease 2019
CumN	Cumulative N

DOC	Department of Commerce
DOT	Department of Transportation
DTI	Department of Trade and Industry
EC	European Commission (formerly Commission of European Communities)
ECU	Electronic Control Unit
EEC	European Economic Community
EMS	Emergency Medical Service
EU	European Union
Euro NCAP	European New Car Assessment Programme
FaAA	Failure Analysis Associates, Inc.
FARS	Fatality Analysis Reporting System
FIA	Fédération Internationale de l'Automobile
FMVSS	Federal Motor Vehicle Safety Standards
GDP	Gross Domestic Product
GES	General Estimates System
GVWR	Gross Vehicle Weight Rating
HR	Hazard Ratio
HSD	Honest Significant Difference

IL	Illinois
IQR	Inter Quartile Range
IRB	Internal Review Board
kg	Kilogram
kg/m^2	Kilogram per meter square
lb.	Pound
LF	Left Finger
LT	Left Thumb
LTVs	Light Truck Vehicles
mm	Millimeter
MVC	Motor Vehicle Collisions or Crash
MxVC	Maximum Voluntary Contraction
MY	Model Year
N	Newton
NASCAR	National Association for Stock Car Auto Racing, LLC
NASS	National Automotive Sampling System
NASS-CDS	National Automotive Sampling System-Crashworthiness Data System
NCAP	New Car Assessment Program

NCSA	National Center for Statistics and Analysis
NEMSIS	National Emergency Medical Services Information System
NHTSA	National Highway Traffic Safety Administration
NIOSH	National Institute for Occupational Safety and Health
NOPUS	National Occupant Protection Use Survey
NTDB	National Trauma Data Bank
NTSB	National Transportation Safety Board
$PaCO_2$	Partial Pressure of Carbon Dioxide
PaO_2	Partial Pressure of Oxygen
PV	Passenger Vehicles
RA	Research Assistants
RF	Right Finger
RJ	Ryan Joiner
ROCS	Rollover Component test System
ROC	Rollover Crashes
RT	Right Thumb
SAE AS	Society of Automotive Engineers Aerospace Standards
SAE	Society of Automotive Engineers

SgRP	Seating Reference Point
SSF	Static Stability Factor
StDev	Standard Deviation
SUV	Sports Utility Vehicles
UK	United Kingdom
UN	United Nations
UNECE	United Nations Economic Commission for Europe
U.S.	United States
VMT	Vehicle Miles Travelled
WHO	World Health Organization
3D	Three-Dimensional

Chapter 1

Introduction

1.1 Overview

The number of motor vehicle crashes and traffic deaths on the world's roads remains unacceptably high. According to data obtained from World Health Organization (WHO), every 24 seconds, someone dies on the road around the world [1]. In 2016, the number of road traffic deaths was a shocking 1.35 million [1]. Road traffic crashes cost most countries three (3) % of their Gross Domestic Product (GDP) [2]. In the United States (U.S.), traffic crashes are a leading cause of death for people aged 1–54, and they are the leading cause of nonnatural death for U.S. citizens residing or traveling abroad [3], [4].

Seat belts have been in use for nearly 140 years. The earliest known use of seat belts in a transportation system dates back to 1885, when they were used on horse-drawn vehicles to keep passengers from being thrown out of the vehicle on bumpy roads [5]. Restraint systems have come a long way from horse-drawn carriages to inflatable seat belts in modern vehicles. According to the Centers for Disease Control and Prevention (CDC) and the National Highway Traffic Safety Administration (NHTSA), the use of seat belts is the single most effective means of reducing fatal and nonfatal injuries in motor vehicle crashes [6], [7]. Since 1975, seat belts are estimated to have saved over 374,276 lives in the U.S. alone [8].

To establish safety standards and combat the alarming rate of highway related motor vehicle accidents, President Lyndon Johnson signed the National Traffic and Motor Vehicle Safety Act of 1966 and the Highway Safety Act of 1966 [9]. Since 1966, a number of Federal

Motor Vehicle Safety Standards (FMVSS) have been issued for vehicles manufactured on and after January 1, 1968 [9], [10]. The FMVSS 209, which establishes requirements for seat belt assemblies, was the first standard to become effective, on March 1, 1967 [11]. According to FMVSS 208, all cars manufactured since 1972 in the U.S. were required to be equipped with a passive restraint system in the driver's seat [12]. Today in the U.S., all motor vehicles are equipped with a restraint system for the driver's position, and all cars sold come with a 3-point restraint system for all the seating positions [12]. Except for New Hampshire and American Samoa, all states, territories, and the District of Columbia require adult front-seat occupants to use seat belts [13]. In 2020, the national estimate of seat belt use by adult front-seat passengers was 90.3% [14].

Despite significant technological advancements in vehicular structures, sensors, safety features, and despite the historically highest seat belt usage rates, motor vehicle crashes result in more than 30,000 fatalities on average every year in the U.S. [15]. A particularly fatal type of motor vehicle accident is a rollover crash. Rollover Crashes (ROCs) contribute to only 3% of all motor vehicle crashes but they account for almost 30% of all fatalities and more than 30% of the injury costs every year in the U.S. [16], [17]. Rollover crashes are influenced by a wide range of factors, including the types of vehicles, drivers, and roadway characteristics involved. These factors can impact several post-crash variables, such as the occupant's physical orientation, position, medical and psychological condition, and even the functionality of the seat belt buckle.

When used properly, the three-point lap/shoulder seat belt is considered, almost universally, to be the most effective safety device for protecting vehicle occupants in collisions. Numerous studies over the past eight (8) decades have proved the effectiveness of seat belts in reducing fatalities and non-fatal injuries in motor vehicle collisions [13], [18]–[26]. Studies have reported that for both front and rear seated occupants, seat belts reduce fatalities and severe injuries from motor vehicle collisions [19]–[23].

However, belted fatalities still occur, and since 2003, on average every year *more than 40% of fatalities were restrained* [16]. Even for rollover accidents, since 2009, on average almost 30% of rollover fatalities were belted [15]. The government and the auto industry have repeatedly identified seat belt use as a critical safety element for occupants in rollover crashes, but neither have seriously considered the potential issue with high buckle release forces.

1.2 Research Objective

The seat belt buckle according to the FMVSS 209 S4.3 (d) of a Type 1 or Type 2 seat belt assembly shall release when a force of not more than 133 N is applied [27]. Not only is this force requirement more than double that of the European and Australian standards, but the standard also does not mention a maximum webbing tension associated with the buckle release standard. Manufacturers are required to balance the forces required for normal operation with the potential for inadvertent release. High belt tension following a rollover crash may result in a higher-than-expected buckle release force.

The primary objective of this research is to study the force required to release a seat belt in a rolled over orientation and analyze its implications on the egress ability of an occupant. To provide a greater understanding of the underlying issues, this research is divided into two components:

1) Assessing seat belt buckle release forces in passenger vehicles after rollover accidents
2) An analysis of seat belt buckle release forces in school buses after rollover accidents: Considerations for child passengers

This research aims to fill crucial gaps in the literature and answer the following questions:

1) What are the strength capabilities of children and adults to unlatch a seat belt buckle?
2) Can the majority of adults unlatch a motor vehicle seat belt in a rolled over orientation?
3) Are seat belt buckles adequately designed for children riding school buses?

Assessing the strength capabilities of occupants of passenger vehicles (children and adults) can provide a better understanding of potential issues with buckle release forces and identify potential design improvements to increase the overall safety of occupants in motor vehicle transportation.

1.3 Research and Dissertation Organization

The chapters of this dissertation are organized according to the Auburn University dissertation guide. The dissertation is comprised of six chapters and is organized as follows:

- Chapter One provides a traditional introduction.
- Chapter Two is a comprehensive and systematic literature review to identify research gaps. Topics reviewed include current standards and regulations for seat belt assemblies on passenger vehicles and school buses in the United States, existing literature on buckle release forces, strength and anthropometry of adults and children, motor vehicle fatalities, and factors affecting buckle release force. Each of the remaining chapters is a stand-alone manuscript describing the purpose, methods, results, discussion, and conclusion of the corresponding experiments conducted.
- Chapter Three describes the experiment conducted to evaluate the strength capabilities of adults 18 and older to exert the required buckle release force to unlatch a seat belt. Thirty

(30) male and thirty (30) female subjects were recruited for this study. The maximum force exerted on a push-button buckle prototype and the ability to unlatch an end-release push-button seat belt in both upright and rolled over orientations were analyzed.

- The experiment described in Chapter Four evaluates the physical capabilities of children (18 male and 35 female children between 5-16 years old) to unlatch a standard end-release seat belt buckle in upright and rolled over orientations. The experiment also measured the maximum force exerted by the subjects on an end-release seat belt buckle prototype in both orientations.
- The limitations of the experiments, study recommendations, and overall conclusions are presented in Chapter Five.
- The appendices contain details of internal review board study approvals, study flyers, approved informed consent forms, study protocols, minor assent process, data collection sheets, statistical summaries of the collected data, and other information to support the results presented in the chapter manuscripts.

1.4 Closing Statement

Despite the COVID-19 pandemic, an estimated 42,060 motor vehicle deaths occurred in 2020, which is an 8% rise from 39,107 in 2019. This increase occurred despite a 13% drop in miles driven from 3,260 billion miles in 2019 to 2,830 billion miles in 2020 [28], [29]. The estimated cost of these motor-vehicle deaths, injuries, and property damage was around $474 billion [28]. There is no doubt that the use of seat belts is one of the most effective and widely used means of reducing fatalities and non-fatal injuries in motor vehicle crashes. However, it is crucial to study other aspects of seat belts because many occupants of motor vehicle crashes are found dead every year despite wearing seat belts.

A dearth of research on buckle release forces indicates an opportunity for this study to fill this gap in the literature. The potential impact from this research could be highly beneficial to the society as **every day** in the U.S., more than 132 million people (84% of U.S. workers) commute to work in a car, truck, or van [30] and more than 25 million children travel in school buses [31]. Analyzing the strength capabilities of the population riding the vehicles, especially women and children, would be a significant step in determining whether seat belt buckles are designed to accommodate everyone adequately. The primary purpose of this research is to determine if an occupant is able to exert enough force to unlatch a restraint system.

Chapter 2

Literature Review

2.1 Seat Belts

A seat belt assembly refers to any strap, webbing, or similar device designed to secure a person in a motor vehicle in order to mitigate the results of any accident, including all necessary buckles and other fasteners, and all hardware designed for installing such seat belt assembly in a motor vehicle [27]. In the United States, passenger cars must have a Type 1 or a Type 2 seat belt assembly with a detachable upper torso portion at each designated seating position [12].

Seat belts have come a long way since their first documented use almost 140 years ago. One of the first noted uses of seat belts in a transportation system was in 1885. Belts were used on horse-drawn vehicles to prevent passengers from being ejected from the vehicle on rough roads [5]. In 1908, during a New York to Paris race around the world, the mechanic of the winning 1907 Thomas Flyer utilized a leather strap restraint to restrict himself from bouncing out of his seat [32]. In 1926, seat belts were first required in the cockpit of commercial airplanes [5].

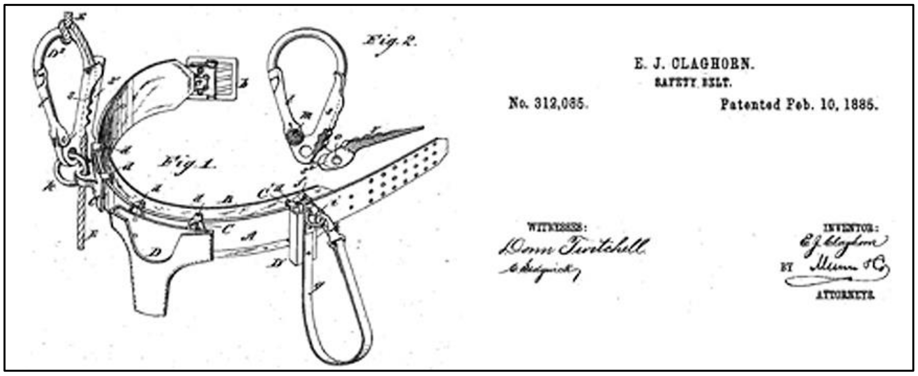


Figure 2.1: First Patented Seat Belt by Edward J Claghorn in 1885 [33]

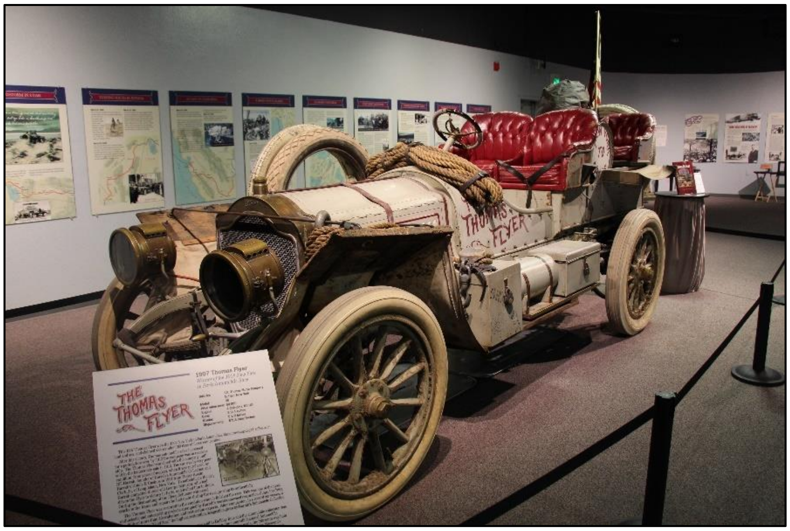


Figure 2.2: Seat Belt Used in the 1907 Thomas Flyer [34]

Figure 2.3: Nils Bohlin: Inventor of the Original Seat Belts in 1959 [35]

2.1.1 History of Federal Motor Vehicle Safety Standards

In September of 1966, with the enactment of the National Traffic and Motor Vehicle Safety Act of 1966 and the Highway Safety Act of 1966, the Federal Government's regulatory role in motor vehicle and highway safety began [9]. To establish safety standards and combat the alarming rate of highway related motor vehicle accidents, President Lyndon Johnson signed these acts into law [10]. The National Traffic and Motor Vehicle Safety Act of 1966 provides for the establishment and enforcement of safety standards for vehicles and related equipment and the conduct of supporting research [8]. In October 1966, these activities, originally under the jurisdiction of the Department of Commerce (DOC), were transferred to the Department of Transportation (DOT) to be carried out by the National Traffic Safety Bureau within the Federal Highway Administration [10]. Following this the Federal Motor Vehicle Safety Standards (FMVSS) were issued in 1967. In March 1970, the National Highway Traffic Safety Administration (NHTSA) was established as a separate organizational entity in the DOT.

NHTSA has a legislative mandate under Title 49 of the United States Code, Chapter 301, Motor Vehicle Safety, to issue FMVSSs and regulations to which manufacturers of motor vehicles and items of motor vehicle equipment must conform and certify compliance [11]. NHTSA is responsible for motor vehicle safety, highway safety behavioral programs, motor vehicle information, and automobile fuel economy programs [8].

2.1.2 Seat Belt Standards

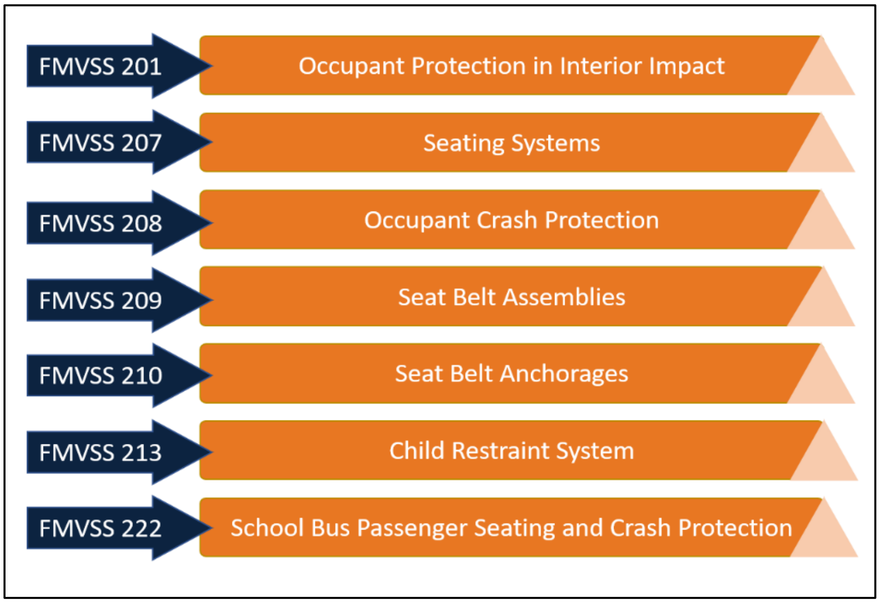


Figure 2.4: FMVSS Related to Seat Belt Assemblies

Since 1966, several FMVSSs have been issued for vehicles manufactured on and after January 1, 1968. FMVSSs are regulations for minimum safety performance requirements for motor vehicles or motor vehicle equipment [11]. These requirements are specified to ensure the public is protected against unreasonable risk of accidents occurring as a result of the design, construction, or performance of motor vehicles and is also protected against unreasonable risk of death or injury from crashes [11].

FMVSS 209 was the first standard to become effective, on March 1, 1967. This standard establishes requirements for seat belt assemblies. The FMVSS 208 specifies performance requirements for occupant crash protection [12]. According to this standard, all cars manufactured since 1972 in the U.S. were required to be equipped with a passive restraint system in the driver's seat [12]. Over the years, through research and awareness, several restraint laws have been introduced throughout the country and the world. All cars manufactured in the U.S. after 1996 are required to have a Type 2 seat belt assembly in all forward-facing designated seating positions [36]. A Type 2 seat belt assembly is a combination of pelvic and upper torso restraints [27], commonly referred to as the 3-point restraint system. [36]

2.1.3 Seat Belt Laws in the U.S.

Except for New Hampshire, all states and the District of Columbia require adult front-seat occupants to use seat belts [13]. As of July 27, 2020, primary laws were in effect in 34 states and the District of Columbia, 15 states had secondary laws, and New Hampshire and American Samoa are the only state and territory without a seat belt law for adults. Primary enforcement laws allow a police officer to stop and cite a motorist solely for not using a seat belt. In states with secondary enforcement, police can only enforce the law if the motorist has been pulled over for another violation first [13]. Figure 2.5 illustrates the various seat belt laws across all the states and territories in the U.S. in 2019.

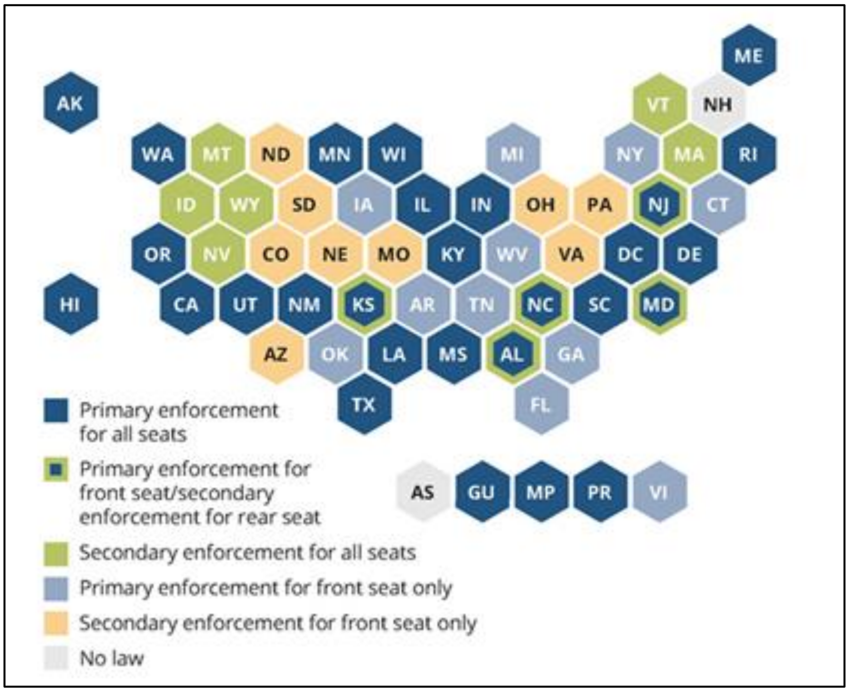


Figure 2.5: Adult Seat Belt Laws in the U.S. [37]

2.1.4 Seat Belt Laws in Europe

According to the Commission of the European Communities (EC), “Seat belts are the easiest and cheapest way to avoid injury in a crash. They do not require any special technology and are fitted in all cars” [38]. Since 2006, wearing seat belts has been compulsory in all vehicles throughout the European Union (EU). Under EU law, drivers and passengers must wear a seat belt in any seat fitted with one [38].

Since 1991, all occupants of passenger cars and light vans are required to use seat belts on both front and rear seats [39]. In 2003, a new Directive extended this obligatory use of seat belts to occupants of all motor vehicles, including trucks and coaches [40]. In some EU member states, drivers are also responsible for passengers not wearing their seat belts. These laws in particular countries are summarized in Table 2.1 by the driver liability status.

Table 2.1: Driver's Liability for Seat Belt Usage for Other Occupants in EU [39]

Driver Liability	**Countries**
Not Liable	BG, CZ, ES, NL, RO, SK
Liable for passengers under 18 years old	AT, BE, CY, DE, DK, FI, FR, HU, IT, LU, PT, SE, SI, UK
Liable for all passengers	EE, GR, IE, LT, LV, PL

2.1.5 Seat Belt Use in the United States

Mandatory seat belt laws were adopted in Europe and Australia as early as the 1970s, but it was not until December 1984 that such laws were adopted in the United States, New York being the first state to do so [41]. Observational studies showed that in 1983, only 14% of motor vehicle occupants wore seat belts [42]. The national estimate of seat belt use by adult front-seat passengers in 2020 was 90.3% [14]. The seat belt use rate estimate represents the percentage of occupants who are belted during an average daylight moment [14]. Figure 2.6 showcases the trend in seat belt use since 1994. These results are from the National Occupant Protection Use Survey (NOPUS); it is conducted annually by the National Center for Statistics and Analysis (NCSA) branch of the NHTSA.

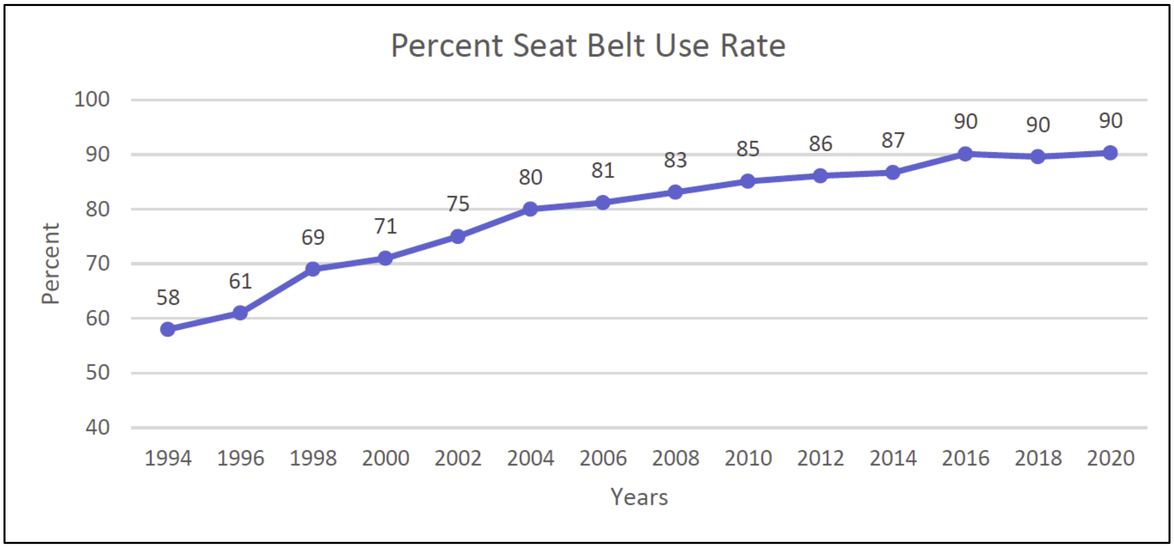


Figure 2.6: National Seat Belt Use Rate (Data Source: [14])

Statistically, primary enforcement laws are more effective at achieving higher belt use rates. In 2019, the belt use rate observed for front-seat occupants was 6% higher (92% vs 86.2%) in states with primary seat belt enforcement laws in comparison to the states where they are not [43]. Studies have shown strong evidence that seat belt laws significantly increase seat belt use and that primary enforcement laws are more effective than secondary enforcement laws [41], [42], [44], [45].

2.1.6 Importance of Seat Belts

The number of road traffic deaths worldwide in 2016 was 1.35 million [1]. Road traffic injury is the 8th leading cause of death for all age groups and the leading cause of death for children and young adults aged 5-19 years [1]. The World Health Organization (WHO) predicts that by 2030, road crashes could become the fifth (5th) leading cause of death [46]. Motor vehicle crashes were the 13th leading cause of death overall among all causes in the year 2015 in the U.S. [47].

According to the CDC and NHTSA, the use of seat belts is the single most effective means of reducing fatal and nonfatal injuries in motor vehicle crashes that exists today [6], [7]. Since 1975, seat belts are estimated to have saved over 374,276 lives in the U.S. [7], [8]. Seat belt use in passenger vehicles saved an estimated 14,955 lives in 2017 alone [7], [8]. An additional 2,549 lives could have been saved in 2017 if all passenger vehicle occupants older than age 4 had used seat belts [7].

Numerous studies over the past eight (8) decades have proved the effectiveness of seat belts in reducing fatalities and non-fatal injuries in motor vehicle collisions [13], [18]–[26]. Seat belts are designed to spread crash forces across the stronger body regions like the pelvis, rib cage, and shoulder, and also prevent occupants from being ejected [13]. When a vehicle slows down or comes to a stop after colliding with another vehicle or object, unbelted occupants keep moving at the same travel speed until they crash into whatever is in front of them. Seat belts help to prevent this second collision or reduce injuries from it by securing occupants to their seats, allowing the vehicle’s crush zone to absorb most of the kinetic energy associated with the vehicle and the occupant's pre-crash motion [13].

Studies have reported that for both front and rear seated occupants, seat belts reduce fatalities and severe injuries from Motor Vehicle Collisions (MVCs) [19]–[23]. Research has shown a 45% reduction in the risk of a fatal injury, and a 50% reduction in the risk of a moderate to critical injury to front-seat car occupants when lap and shoulder belts are used [23]. For occupants of light trucks (Sports Utility Vehicles (SUV), vans, and pickups), the use of lap and shoulder belts reduces the risk of a fatal injury by 60% and a moderate to critical injury by 65% [23]. In the center rear seat, lap and shoulder belts reduce the risk of fatal injury by 58% in cars and 75% in Light Truck Vehicles (LTV) [24].

Seat belts are also highly effective in preventing occupant ejection, especially in rollover crashes. According to a NHTSA report [25], avoiding complete ejection decreases the risk of death and injury by an estimate of:

1) 64% for fatalities
2) 70% for serious injuries
3) 65% for moderately severe injuries
4) 39% for incapacitating injuries

Compared to occupants who are not ejected from automobiles, occupants are nearly twice as likely to die if ejected in non-rollover crashes, and those who are ejected in rollover crashes are 4 times more likely to die [25].

Unbelted occupants are a serious danger to other occupants inside the vehicle. Exposure to unbelted occupants increases the risk of injury or death to other occupants in the vehicle by 40% [19]. In a frontal crash, an unbelted rear seat passenger sitting behind a belted driver increases the risk of fatality for the driver by 137% compared to a belted rear seat passenger [26].

2.2 Motor Vehicle Accidents

Motor vehicle crashes are a leading cause of death among those aged 1-54 in the United States [48]. According to the data from Fatality Analysis Reporting System (FARS), in the U.S., statistically, almost 5 people die every hour, and more than 100 die every day due to road related accidents [15], [49]. More than 2.2 million drivers and passengers were treated in emergency departments as a result of being injured in motor vehicle crashes in 2018 [50].

Motor vehicle crashes are the leading cause of work-related deaths in the U.S. [51]. According to the Bureau of Labor Statistics (BLS), there were 5,333 fatal work injuries recorded in the U.S. in 2019 (Figure 2.7) [52]. Fatalities resulting from transportation incidents accounted for 2,122 cases, marking the highest number since 2011. Furthermore, these events continued to be responsible for the largest share of fatalities. Nearly one out of every five workers who suffered a fatal injury was employed as a driver, salesperson, or truck driver [52].

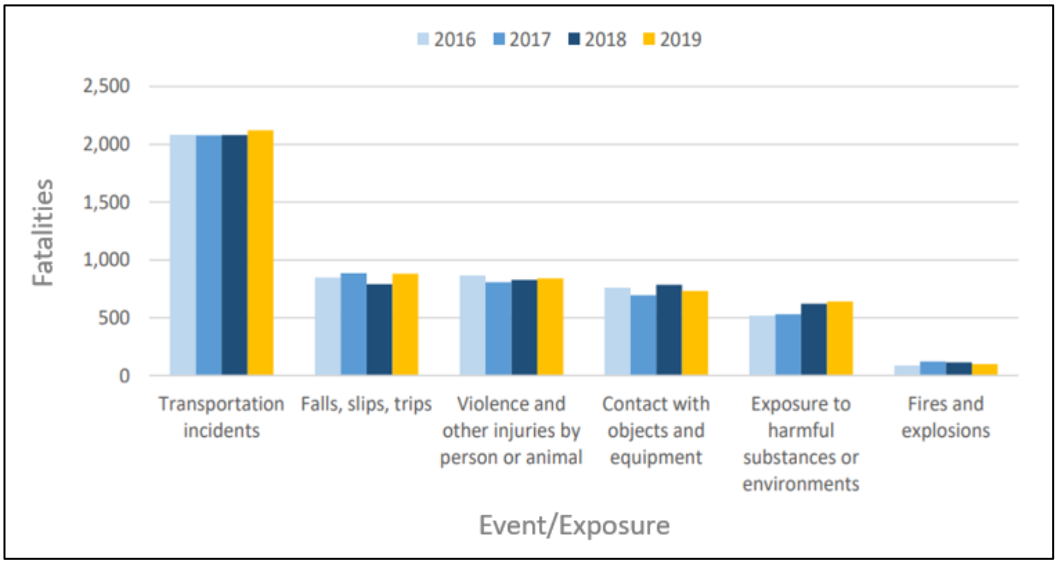


Figure 2.7: Fatal Work Injuries in U.S.by Major Event or Exposure, 2016-19 [52]

In 2010, NHTSA conducted a comprehensive study to examine the expenses resulting from motor vehicle crashes [53]. That year, there were 32,999 people killed, 3.9 million injured, and 24 million vehicles were damaged in motor vehicle crashes. They found that the economic costs of these crashes totaled $242 billion. Included in these losses are lost productivity, medical costs, legal and court costs, Emergency Medical Service (EMS) costs, insurance administration costs, congestion costs, property damage, and workplace losses. This amounted to 1.6% of the United States' GDP, which was valued at $14.96 trillion in 2010 [53].

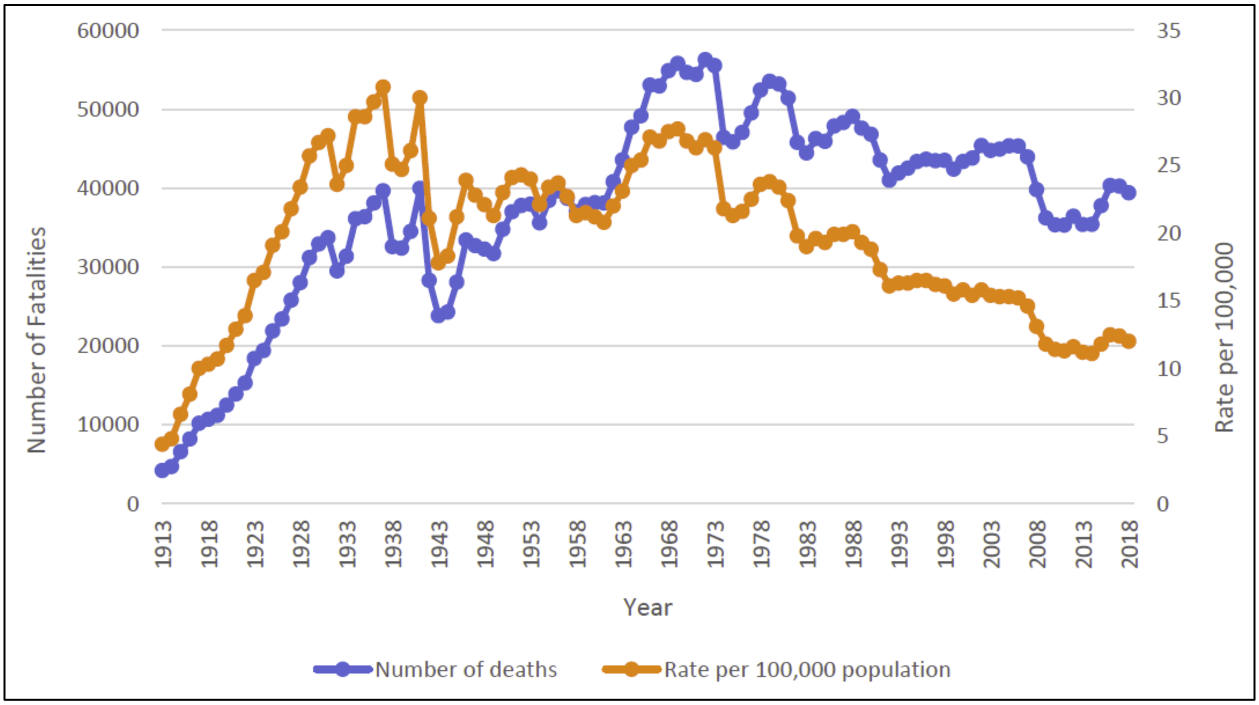


Figure 2.8: Motor Vehicle Crash Deaths vs Population MVC Death Rates from 1915 – 2020 in the U.S. (Data Source: [8])

As illustrated in Figure 2.8, the rate for motor vehicle deaths per 100,000 population has improved drastically since 1937. In fact, in 1920 it was 11.7 compared to 12.9 in the year 2020. However, the number of deaths has increased more than 300% from 1920 to 2020 [8]. An estimated 42,060 motor vehicle deaths occurred in 2020, which is an 8% rise from 39,107 in 2019 despite the COVID-19 pandemic [28]. Additionally, the estimated cost of motor-vehicle deaths, injuries, and property damage in 2020 was $474.4 billion [28].

2.2.1 Types of Motor Vehicle Crashes

In the U.S., more than 6.7 million police-reported motor vehicle crashes occurred in 2018. 1.8 million of those crashes resulted in an injury, and 33,654 resulted in a death [54]. According to an annual report conducted by NHTSA in 2018 [16], some important crash statistics to be noted are:

1) Comparing single vehicle crashes to multiple vehicle crashes, 57% of total fatal crashes involved only one vehicle, as compared to 29% of all injury crashes and 28% of all property-damage-only crashes.
2) Collision with another motor vehicle in transport was the most common first harmful event for fatal, injury, and property-damage-only crashes.
3) Twenty eight percent (28%) of all fatal crashes involved alcohol-impaired driving, where the highest blood alcohol concentration among drivers involved in the crash was .08 g/dL or higher.
4) Ninety four percent (94%) of the 12 million vehicles involved in motor vehicle crashes in 2018 were passenger cars or LTVs.
5) Rural areas account for 71% of the nation's public road miles, and 30% of vehicle miles traveled, but account for nearly half of the crash fatalities [55].
6) Collisions with fixed objects (pole, post, guard-rail, tree, etc.) and non-collisions (rollovers and unknown) accounted for only 17% of all crashes, but they accounted for 38% of fatal crashes.
7) **Twenty nine percent (29%) of passenger car and light truck occupant fatalities were a result of Rollovers.**

2.2.2 Rollover Accidents

One of the most dangerous types of motor vehicles accidents are rollover crashes (ROCs). They have long been recognized as a significant hazard compared to other modes of crashes. ROCs only contribute to about 3% of all motor vehicle crashes but they account for almost 30% of all fatalities, and more than 30% of the injury costs every year in the U.S. [16], [17]. The estimated fatalities involving ROCs in Europe is around one in every ten fatalities [56].

In Australia, ROC is responsible for about one in every five fatalities [57]. Data from the National Automotive Sampling System (NASS) General Estimates System (GES) indicate that an occupant in a rollover is 14 times more likely to be killed than an occupant in a frontal crash [58].

The term “rollover” describes the condition of at least a 90° rotation about the longitudinal axis of a vehicle, regardless of whether the vehicle ends up laying on its side, roof, or even returning upright on all four wheels [59]. NHTSA classifies rollovers into two categories: Tripped and Untripped [59]. A tripped rollover event occurs when a vehicle runs off the road and is tripped by a ditch, soft soil, a curb, or other object causing a vehicle to roll over. An untripped rollover event happens when the tire/road interface friction is the only external force acting on a vehicle, thereby inducing it to roll over. NHTSA analysis indicated that only around 5% of rollover crashes are untripped, whereas approximately 95% of rollovers in single-vehicle crashes are tripped [59], [60].

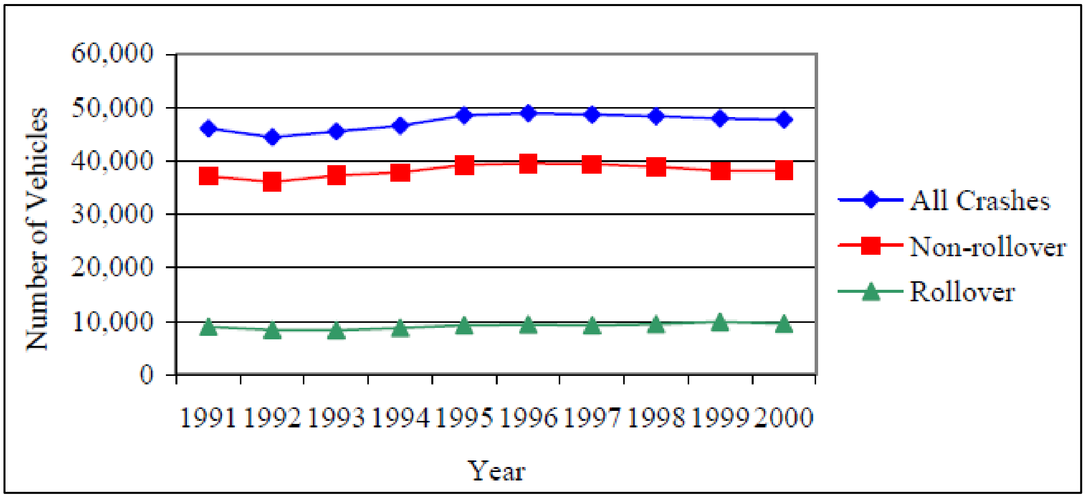


Figure 2.9: Passenger Vehicles Involved in Fatal Crashes [61]

During the last two decades, several agencies including NHTSA have carried out numerous research initiatives and standard improvements on vehicular safety innovations to ensure fatality and injury reduction in motor vehicle crashes, like advanced frontal and side air bags, electronic stability control, roof crush standards, seat belt load limiters and pretensioners, front end crumple zones, crash severity sensing system, roof crush strength, occupant compartment strength, child safety seats, booster seats, antilock braking systems, lane departure warning systems, and forward collision warning systems, among others [62].

Despite all these advancements, rollover crashes continue to be a prominent concern. Each rollover involves a distinct set of vehicle, driver, and roadway factors which influences crucial post-crash variables such as the occupant's physical orientation, position, medical and psychological condition, and also the functionality of the buckle [17], [63]. In a NHTSA report to examine rollover crash mechanisms and their related injury patterns to the occupants, Ana Maria Eigen reviewed the NASS - Crashworthiness Data System (CDS) data over the years 1995 through 2001 [64]. In that duration, there were an estimated 17.1 million crashes involving passenger vehicles that occurred on roadways in the U.S. Among these, 4.5 million were single vehicle events and approximately 28% of these crashes resulted in rollovers. 81% of the 1.6 million rollover crashes were single vehicle encounters. Approximately 55% of rollover crashes ended in one or two quarter turns (90° or 180°) contacting either the roof of the vehicle or the near side of the roll.

2.2.2.1 SUVs, Pickup Trucks, and Rollovers

Despite their popularity, SUVs pose unreasonably high rollover risks for occupants. Sixty-one percent (61%) of SUVs and 45% of pick-up truck occupant fatalities occur due to rollover crashes [65]. According to NHTSA, SUVs roll over in fatal crashes three times as often as passenger cars [61]. In 2018, 3,900 occupants were killed in rollovers involving light trucks (pickup, utility, and van) which accounted for almost 60% of the total rollover fatalities [16].

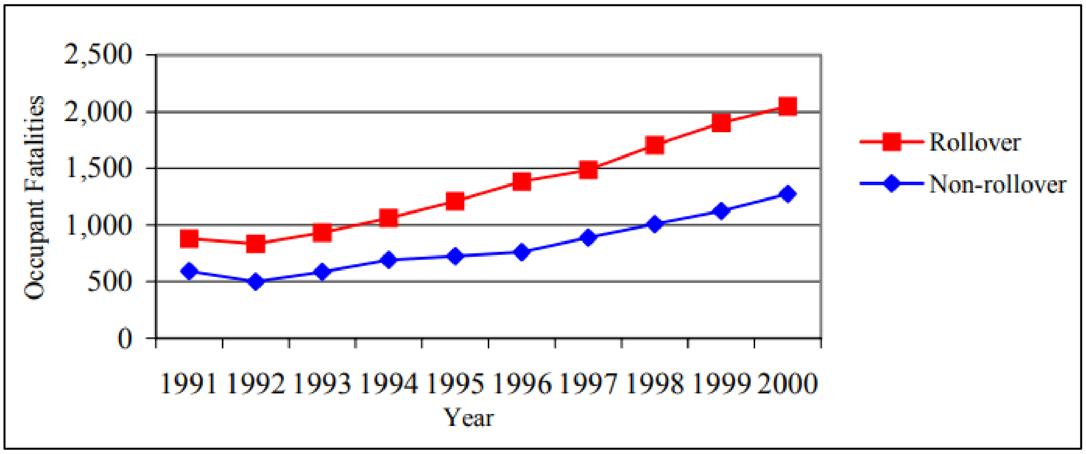


Figure 2.10: SUV Occupant Fatalities by Crash Type [61]

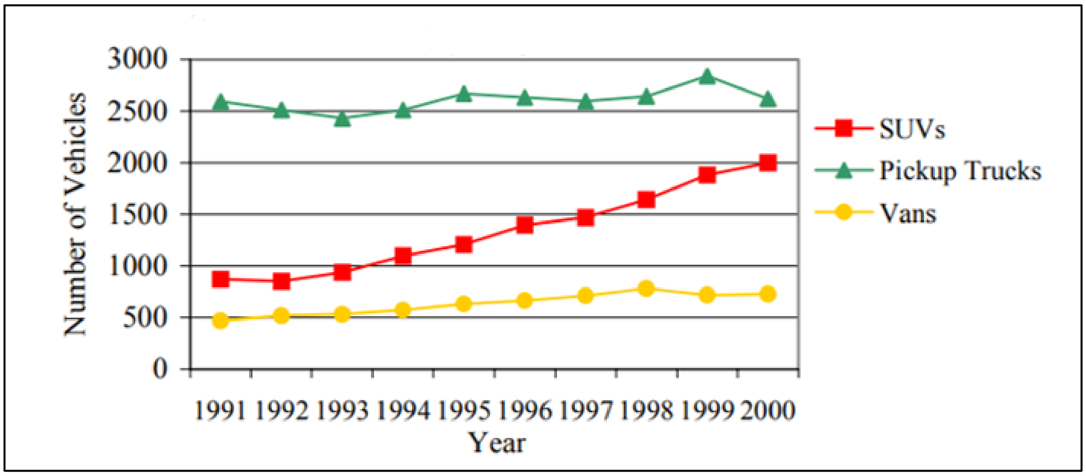


Figure 2.11: Light Trucks Involved in Fatal Rollover Crashes [61]

Two main reasons for this high rollover fatality rate in the light truck category could be:

1) Rise in the sales of light trucks

2) Higher center of gravity for light truck vehicles.

2.2.2.1.1 Rise in the Sales of Light Trucks

Light Truck Vehicles (LTVs) include SUVs, pickup trucks, and vans which are constructed on a truck frame [66]. In 2019, SUVs surpassed 40% of all car sales worldwide with more than 200 million vehicles, which is eight times the number a decade ago [67]. In the U.S., light trucks accounted for almost 76% of auto sales in 2020 [68].

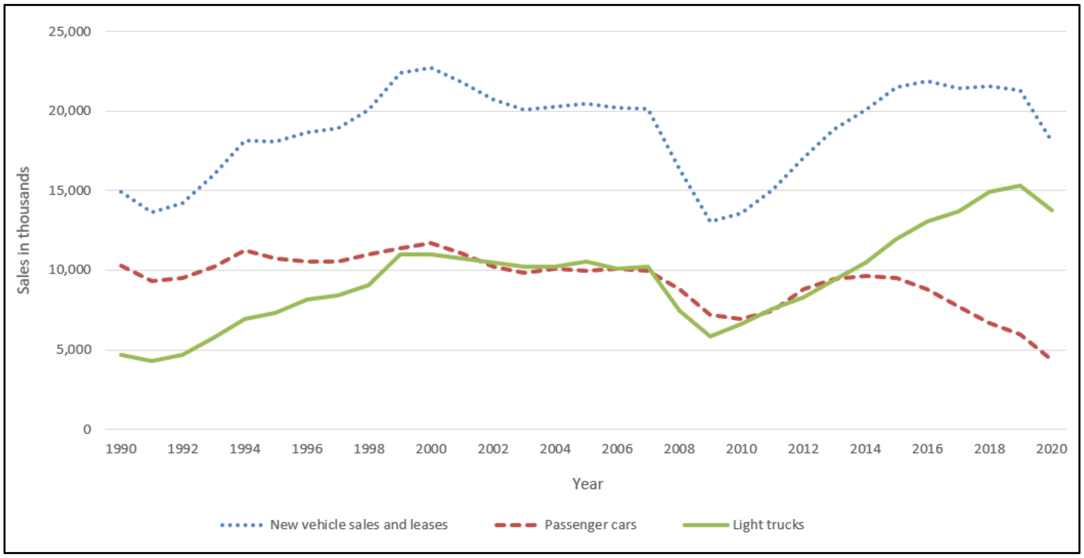


Figure 2.12: Vehicle Sales (in Thousands) in the U.S. (Data Source: [69])

2.2.2.1.2 Higher Center of Gravity for Light Truck Vehicles

NHTSA's New Car Assessment Program (NCAP) created the 5-Star safety ratings program to provide consumers with information about the crash protection and rollover safety of new vehicles beyond what is required by federal law [70]. SUVs are generally rated between one and three stars for rollover resistance, pickup trucks between one and four stars, vans between two or three stars, and passenger cars between four or five stars [59]. This is mainly because of the low Static Stability Factor (SSF) of LTVs.

The SSF of a vehicle is defined as its track width, divided by twice its center of gravity height.

$$\text{SSF} = \frac{\text{Track Width}}{2 \cdot (\text{Center of Gravity Height})}$$

The Static Stability Factor (SSF) was introduced to NHTSA in 1973 by vehicle manufacturers as a scientifically potential substitute for dynamic rollover tests, and NCAP began reporting SSF in early 2001 [71]. NHTSA considers the SSF as a crucial factor of rollover resistance, as it represents the vehicle’s geometric properties associated with rollover events. LTVs typically have a Center of Gravity (CG) that is several inches higher than that of passenger cars, and loading the vehicle further increases it. Consequently, the SSF is reduced because loading the vehicle usually places the loads above the CG of an unloaded vehicle [59].

NHTSA STAR RATING (Higher the Better)		Roll Over Risk	Static Stability Factor (SSF)
FIVE	★★★★★	<10%	1.45 or more
FOUR	★★★★	10% to 20%	1.25 to 1.44
THREE	★★★	20% to 30%	1.13 to 1.24
FOUR	★★	10% to 20%	1.25 to 1.44
ONE	★	40% or greater	1.03 or less

Figure 2.13: NHTSA Star Rating vs Roll Over Risk vs SSF (Data Source: [72])

Association between NHTSA’s star ratings, corresponding SSF, and risk of rollover is displayed in Figure 2.13. The average Static Stability Factors by vehicle type for each model year weighted by vehicle sales from the data available from NHTSA Technical Reports DOT HS

809868 and 182444 are illustrated in Figure 2.14 [71], [73]. Passenger cars have always had the highest average SSF and have remained highest. Trends have indicated that SSF values of SUVs have considerably improved over the years. Minivans have also shown significant improvements. Full-sized passenger vans have the lowest weighted average of SSF in all model years since 2001. The significance of this lies in the fact that, apart from rollovers caused by passenger cars in multi-vehicle accidents on wet roads, an increase in SSF has been demonstrated to have a statistically significant impact on reducing rollovers [71].

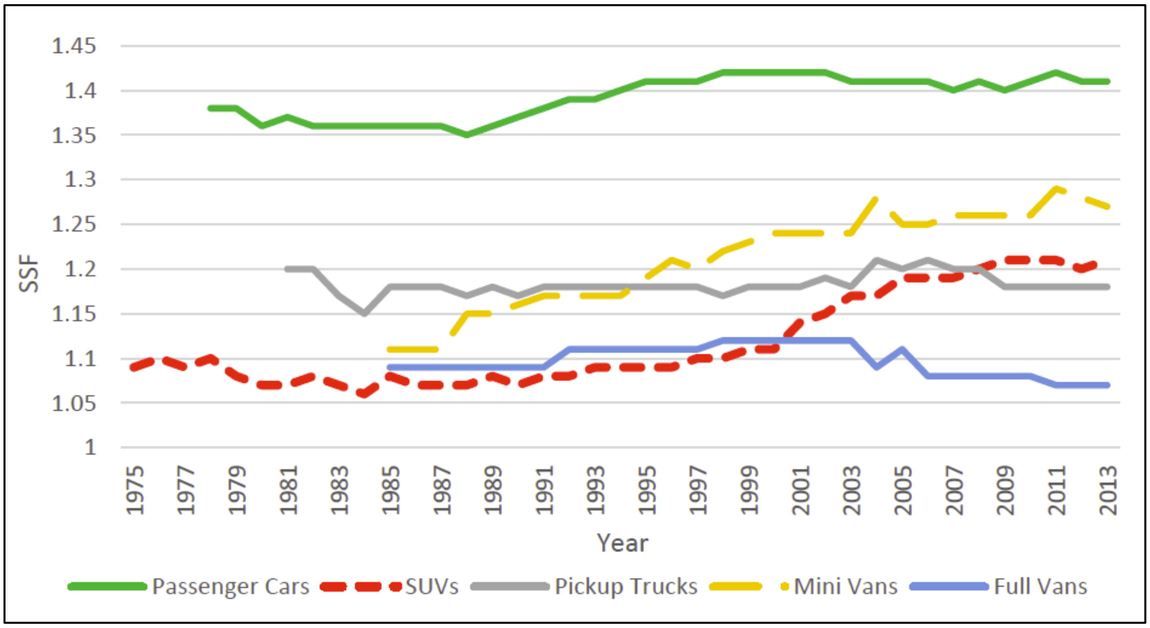


Figure 2.14: Weighted Average of SSF for MY 1975-2013 (Data Source: [71], [73])

Acierno et al. reviewed 200 cases in the Seattle's Crash Injury Research and Engineering Network (CIREN) database to establish patterns and source of injury [66]. Despite a steady decrease in the number of fatalities resulting from Passenger Vehicles (PV) versus PV collisions from 1980 to 1998, there was an increase in fatalities resulting from the collision of PV and LTV. They believe that the increase in fatalities among passenger vehicle occupants when their vehicles collide with LTVs is due to vehicle mismatch and the increasing number of LTVs on roads in the U.S. Vehicle mismatch or crash incompatibility is defined as the design differences including weight, frame height, and stiffness between vehicle types that result in disproportionate damage patterns to the vehicles involved in a collision [66].

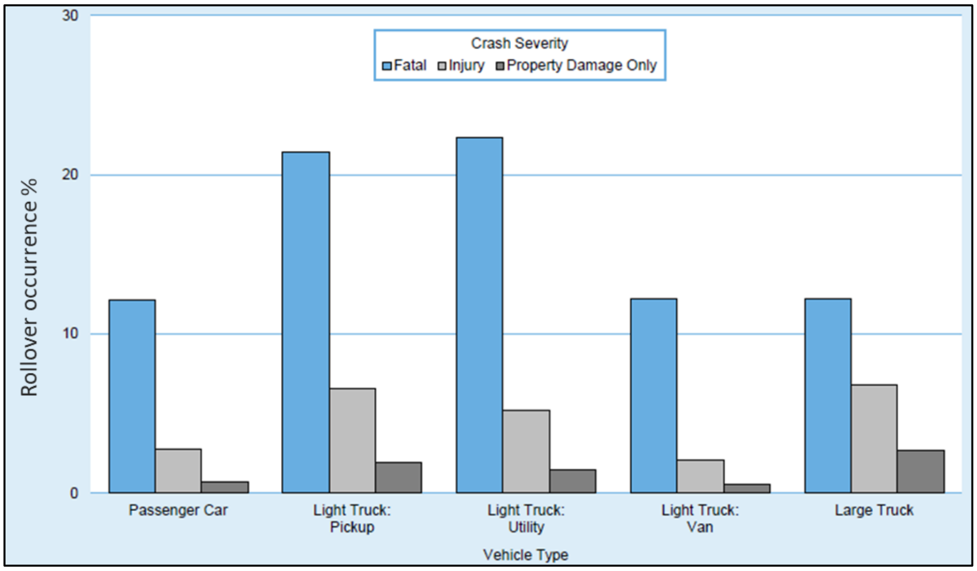


Figure 2.15: Percentage Rollover Occurrence by Vehicle Type and Crash Severity [16]

2.2.2.2 Injuries from Rollovers

Motor Vehicle Collisions (MVCs) continue to be a major concern around the world and especially in the United States, not only because of fatalities, but also due to the huge number of injuries they cause. Since 1988, on average, around 2.5 million occupants of Motor Vehicles involved in crashes are injured every year [16]. In 2018, almost 2.45 million people were injured in the U.S. in MVCs, out of which almost 86% were restrained [16].

In order to understand the scope of rollover crashes comprehensively, Eigen studied the NASS-CDS data from 1995 through 2001 for passenger vehicle crashes [64]. They found that approximately 81% of all rollovers were single vehicle rollovers and approximately 55% of rollover crashes ended in one or two quarters contacting either the near side of the roll or the roof of the vehicle. They reported that 33% of all injuries occurring in non-planar crashes affected the head. Also, restrained occupants sustained nearly half of the injuries to extremities, and the thorax sustained serious injuries most frequently.

To examine the issues related to the ejection status of passenger vehicle occupants in fatal crashes, Burgess et al. analyzed the FARS crash data for the 5-year period from 2003 through 2007 [74]. There was a total of 398,274 occupants out of which 155,359 were fatally injured occupants, 157,440 non-fatally injured, 83,651 received no injury, and 1,824 occupants whose injury severity was unknown. As illustrated in Figure 2.16, among the total occupants, 54,505 passenger vehicle occupants were ejected, and more than 77% (42,137) were fatally injured, while 15.1% had incapacitating injuries, and only 150 occupants (0.3%) had no injuries. Eighty-six percent of the 54,505 ejected occupants were unrestrained, while only 8.5% were restrained, and the restraint use of the remaining 5.5% was unknown.

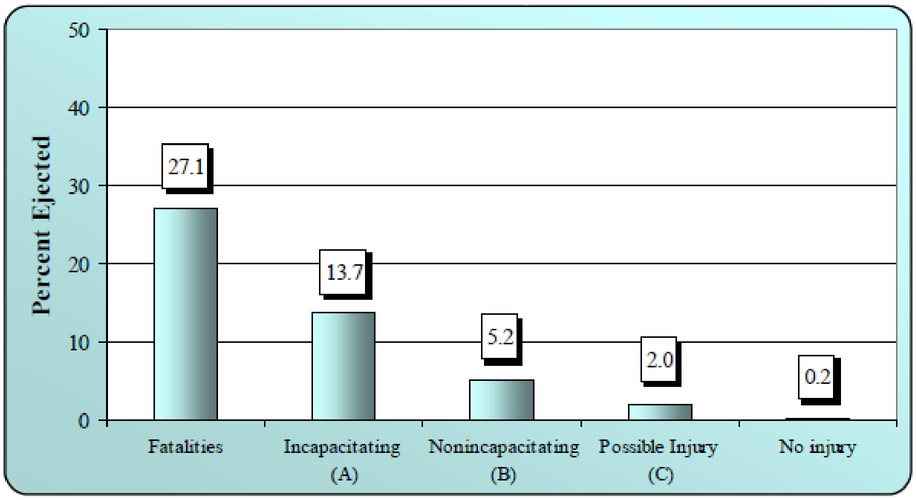


Figure 2.16: Passenger Vehicle Occupants in Fatal Crashes by Injury Severity and Ejection Status [74]

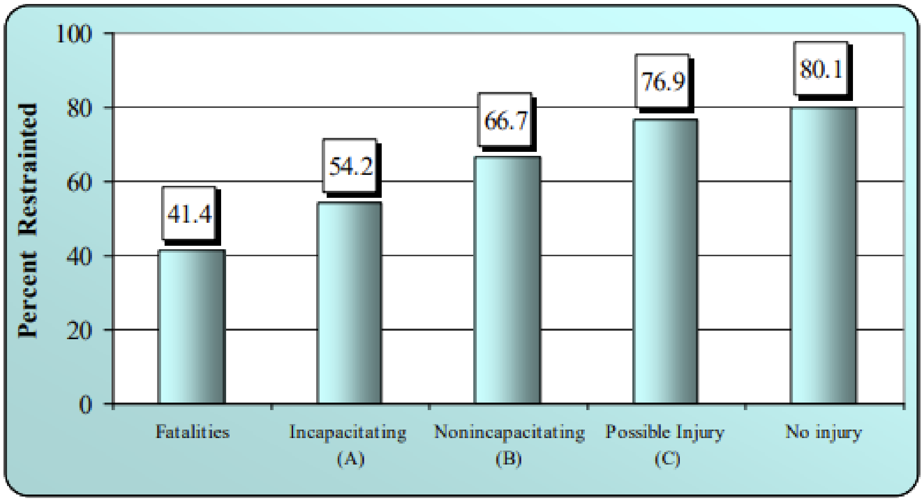


Figure 2.17: Passenger Vehicle Occupants in Fatal Crashes by Injury Status and Restraint Use [74]

Approximately 60% of all occupants were restrained. Of the occupants who suffered fatal injuries, 41% were restrained, whereas 54% of occupants with incapacitating injuries, 66.7% of occupants with non-incapacitating injuries, and 76.9% of occupants with possible injuries were restrained [74]. Figure 2.17 illustrates these descriptive statistics.

J.R. Funk et al., investigated various risk factors associated with cervical spine injuries in field rollover crashes and compared them with risk factors associated with head, serious, and fatal injuries [75]. They studied the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) cases from 1995-2008 in which occupants aged 16 and older were involved in a rollover crash. Their inclusion criteria yielded a sample size of 6,015 cases from 2.5 million cases in which pure rollover (single event) was the most harmful event.

Injuries were identified on the Abbreviated Injury Scale (AIS), which ranks injuries on a 0–6 scale based on their threat to life, with 0 indicating no injury and 6 indicating a fatal injury [76]. They found 390 occupants had AIS 2+ cervical spine injuries, 584 had AIS 3+ head injuries, 1320 occupants had overall injuries of AIS 3+ and 492 occupants died. Figure 2.18

describes injury risk as a function of seat belt use for both ejected and non-ejected occupants in a rollover. Figure 2.19 describes the injury risk to belted occupants in a rollover. The injury distribution of passenger vehicle occupants in side impact collisions and frontal impact collision with vehicle mismatch can be seen Figure 2.20.

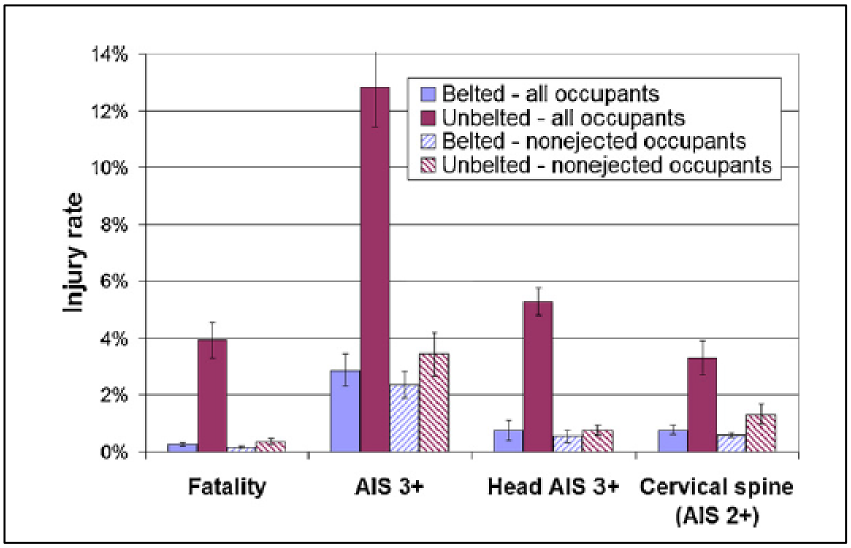


Figure 2.18: Injury Risk as a Function of Seat Belt Use for All Occupants [75]

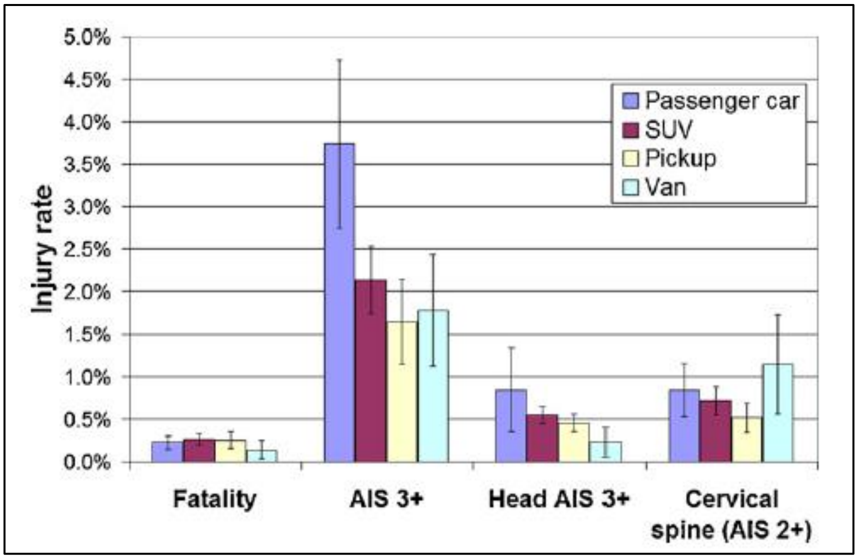


Figure 2.19: Injury Risk to Belted Occupants in a Rollover [75]

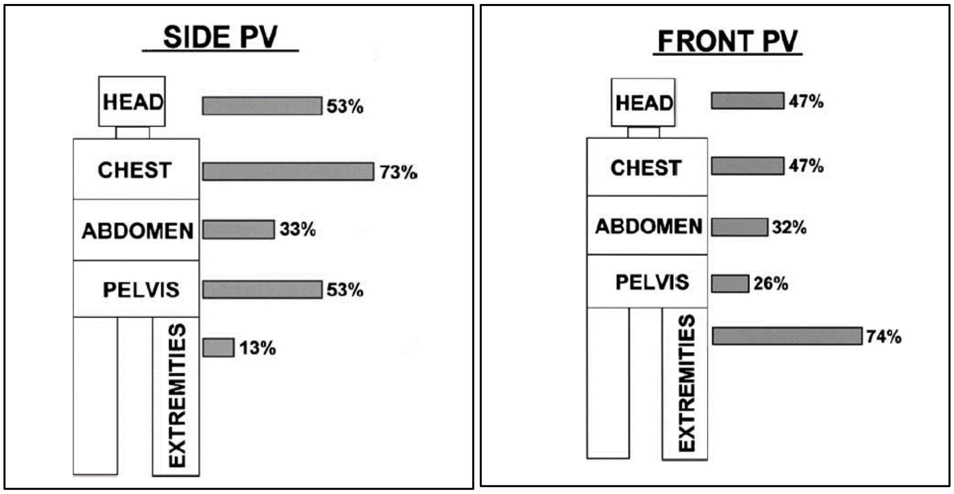


Figure 2.20: Injury Distribution (AIS≥2) for PV Occupants in Side and Front Impact Collision [66]

As these studies indicate, seat belts do help in reducing fatalities but there are still belted fatalities and severe injuries. It is believed that these incapacitating injuries could impede the egress of the occupant and could eventually lead to a fatality. Injuries to the head and the extremities could result in severe difficulty in unlatching a seat belt in a rolled-over orientation and could eventually lead to a fatality. The information presented regarding the distribution of injuries in side impact and frontal collisions is critically important, and its significance will be discussed in the subsequent sections of this dissertation. These incapacitating injuries may hinder the occupant's ability to exit the vehicle, especially their ability to unlatch a seat belt as they might not be able to exert enough force, making it a critical factor to consider.

2.2.3 Belted Fatalities

Undeniably, seat belts offer significantly greater safety compared to not using them, as they effectively reduce the probability of fatality and severe injury in most accident scenarios. However, belted fatalities still occur and since 2003, on average every year *more than 40% of fatalities were restrained* [16]. As seat belt use is at a historic record high, it is essential to study the effectiveness of seat belts in rollover crashes. Turner et al., feels the push to increase seat belt use has occurred in the absence of any substantial upgrades in the effectiveness of this technology in rollover crashes [77]. It is critical that belts perform effectively in rollover crashes, yet evidence suggests that seat belts are tragically ineffective in many rollover crashes [77]. Figure 2.21 depicts the percentage distribution of occupant fatalities categorized by their restraint use for passenger cars and light trucks from 1990 to 2018. According to an annual report from NHTSA, since 2013 the percentage of restrained fatalities for passenger car and light truck occupants is more than unrestrained [16]. In 2018, 48.4% of occupant fatalities in this category were restrained compared to 43.1% that were unrestrained, as reported by the police [16].

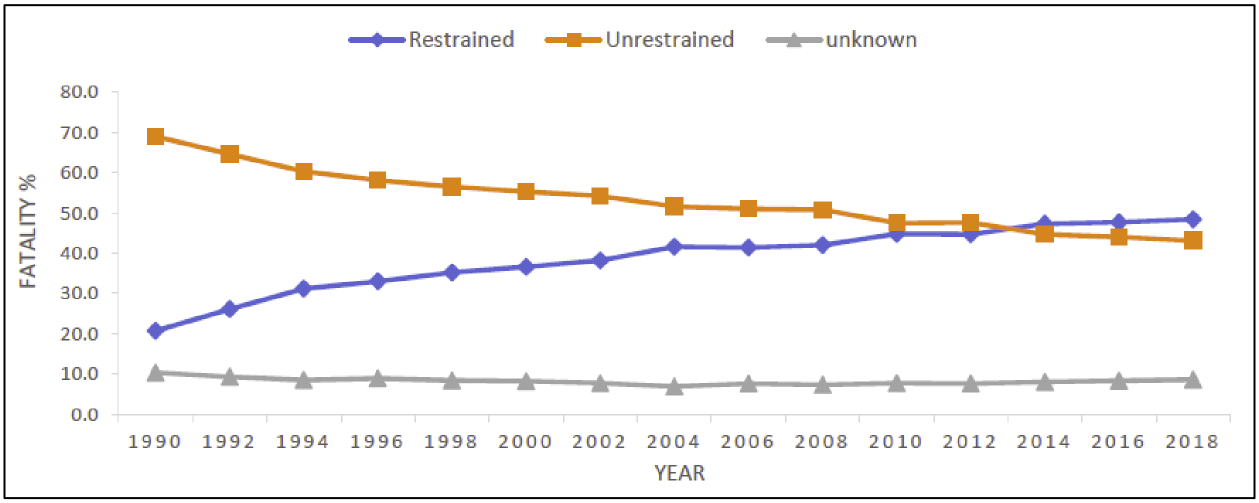


Figure 2.21: Occupant Fatality Percent by Restraint Use for Passenger Cars and Light Trucks:1990-2018 (Data Source: [16])

According to NHTSA, most vehicles come to rest at two quarter turns in a single and multi-vehicle rollover crash [64]. Sixty-four percent of multi-vehicle rollovers and 55% of single vehicle rollover crashes last up to 2 quarter turns. This could be a promising sign once the rollover has occurred for the following reasons:

1) Firstly, if the roof meets the required standard, it should withstand the mass of the vehicle.
2) Secondly, the roof has not been debilitated with repeated strikes since the vehicle undergoes two quarter turns and comes to rest.
3) Lastly, since undue force has not been exerted during the first roof strike, the windshield will generally be intact. The windshield is an important structural element for roof integrity and strength [78].

Digges and Eigen, suggest that multiple event vehicle crashes that cause vehicle rollovers, injure the occupant differently when compared to single event because the occupant may be injured during the non-rollover portion of the crash due to high severity planar impact prior to the rollover or other similar incidents [79]. Based on years of data from NHTSA’s Fatality Analysis Reporting System (FARS), it is evident that the unbelted occupant is the most vulnerable to ejection and fatality. However, even the belted occupant is at risk because some current seat belts, and most retractors, are primarily designed to withstand the demands imposed by a planar crash [64]. Furthermore, the complexities of rollover crashes suggest that vehicle integrity, in particular roof strength, in conjunction with restraint use must provide adequate protection to minimize occupant injury [64].

Fatality data shows that since 2010, on average, 30% of rollover fatalities (more than 2,000 fatalities) were restrained [15]. Turner et al., did a detailed analysis of rollover crashes from 1992-2002 to document the inadequacies in current belt design [77]. They found that 21% of the people killed in rollover crashes were documented in police reports as restrained by seat belts at the time of the crash. Between 1992 and 2002 in the U.S., approximately 22,000 people died in rollover crashes while still wearing a seat belt. From 2009 to 2019, this number rose to

24,560 people. The authors reason that belted occupants, not unbelted occupants, suffer the majority of non-ejection-related injuries and fatalities [77].

According to these studies and scenarios, there appears to be an underlying issue with the seat belt design that requires further investigation. With seat belt usage rates currently being at an all-time high, and increasing every year [14], with increasing sales of SUVs and vehicles in general, and increasing average miles driven, an increase in exposure to rollover deaths involving belted occupants seems an inevitable consequence, making an understanding of belted fatalities in rollovers significant. If the structural integrity of the vehicle is intact and if the occupant is restrained, then further research is needed to understand these fatalities. The government and the automotive industry have repeatedly identified belt use as a critical safety element for occupants in rollover crashes, but neither have considered this potential issue with seat belts, that being seat belt buckle release force.

2.3 Potential Issue with a Seat Belt Standard

The seat belt buckle according to the FMVSS 209 S4.3 (d) of a Type 1 or Type 2 seat belt assembly shall release when a force of not more than 133 N is applied [27]. The Standard specifies only a maximum buckle release force (i.e., 133 N) to unlatch a seat belt in any orientation and does not mention a maximum belt tension [27]. S4.1(e) states that a buckle must be “readily accessible to the occupant to permit his easy and rapid removal from the assembly,” and states that the “release mechanism shall be designed to minimize the possibility of accidental release”. Since these FMVSSs only regulate the maximum force to release a seat belt buckle, manufacturers must balance the possibility of accidental release by inadvertent contact with the requirement of easy and rapid removal to maximize safety and promote seat belt usage [80]. This can result in relatively high buckle release forces during crashes, especially because of high belt tension.

Figure 2.22: End-Release Push-Button Buckles

Vehicle safety in European Union countries is regulated mainly by international standards and regulations devised by the European Union (EU) and the United Nations Economic Commission for Europe (UNECE) [81]. UNECE or UN regulations are also followed by several countries across the world [82]. The European Economic Community's (EEC) Directive 77/541/EEC regulates seat belts and restraint systems in motor vehicles in Europe [83]. Similarly, UN Regulation 16 governs seat belts, restraint systems, and child restraint systems for occupants of power-driven vehicles [84]. EEC Standard 2.4.2.2 and UNECE standard 6.2.2.2 mention that the seat belt buckle release force, even under no load, shall not be less than 1 daN (10 N), and EEC Standard 2.4.2.5 and UNECE standard 6.2.2.5 mention that the force required to open the seat belt buckle shall not exceed 6 daN (60 N) [83],[84].

The Society of Automotive Engineers (SAE) develops and publishes technical standards for aerospace, automotive, and commercial vehicle industries [85]. Several SAE Standards are incorporated by reference in various FMVSSs [86]. The SAE J4C standard provides specific performance requirements for Type 1, 2 and 3 seat belt assemblies for use in motor vehicles in order to minimize the risk of bodily harm in an accident [87]. SAE J4C 5.4 states the buckle of a

Type 1 or Type 2 seat belt assembly shall release when a force of not more than 30 lb. (133 N) is applied [87]. SAE J386 standard establishes the minimum requirements for restraint belts suitable for use on construction equipment. SAE J386 6.1 specifies that the buckle hardware shall meet all the applicable requirements of SAE J4C [88].

SAE AS (Aerospace Standard) 8043B (superseding 8043A) specifies laboratory test procedures and minimum requirements for the manufacturer of restraint systems for use in civil aircraft. This standard specifies the requirements for Type 1, Type 2, and Type 3 restraint systems [89]. SAE AS 8043B 5.4.1.3 and 9.4 state the buckle shall release when a force of not more than 130 N is applied to the release mechanism under a balanced loop load of at least 760 N on the pelvic restraint [89].

SAE J4C 8.4 mentions for testing the buckles for the maximum buckle release force, the loop load for testing a Type 1 seat belt assembly should be maintained at 150 ± 10 lb. (667 ± 45 N) and for type 2 seat belt assembly it should be reduced and maintained at 75 ± 5 lb. (333 ± 22 N) [87].

FMVSS 209, S5.2 (d) (1) mentions that the seat belt assemblies shall be tested to determine compliance with the maximum buckle release force requirements [27]. It mentions that the buckle release forces shall be measured when the loop load forces are reduced and maintained at 667 N on the assembly loop of a Type 1 seat belt assembly and 334 N on the components of a Type 2 seat belt assembly [27].

According to the National Center for Health Statistics, the average weight of adult female in the U.S. is 170.8 lb. (77.5 kg) and the average weight of an adult male is 199.8 lb. (90.6 kg) [90]. The webbing tension of an average inverted occupant could be as high as 775 N for females and 906 N for males. The 95th percentile male weight is 287.2 lb. (130.3 kg), which indicates that the webbing tension could be as high as 1,300 N. This suggests that the webbing tension of 667 N for Type 1 and 334 N for Type 2 mentioned in the standard is too low and in order to accommodate 95th percentile, the webbing tension for testing the maximum buckle release force could be higher.

Figure 2.23: Illustration of Seat Belt Release Force [80]

The SAE J4C was published in 1955 (last revised in July 1965) and FMVSS 209 in 1967 [27]. The buckle release force and several testing criteria in these standards have remained unchanged for the last six (6) decades. Two major issues with these standards which will be discussed in detail in the following sections are:

1) The buckle release force may be high for a majority of the vehicle occupant population.
2) Webbing tensions are high in a rollover accident, potentially causing the release force to increase.

We believe that high buckle release forces may be responsible for some of the belted rollover fatalities as it could impede an occupant's timely egress from the vehicle in an accident.

2.3.1 High Buckle Release Force

Most of the research involving issues with automotive seat belt buckles over the past few decades has focused on inertial release [91], partial engagement [92], inadvertent contact [80], or structural overload [93]. Despite conducting an extensive search of the literature, any basis for how the maximum buckle release force of 133 N was determined, could not be found. Only a few published papers [63], [80], [94] discussed the issue of high buckle release forces.

One of the only detailed studies on buckle release forces that was found was by Noy [63]. To study the adequacy of safety regulations regarding buckle release resistance under full load, Noy conducted a study with Transport Canada recruiting 543 volunteers (72% males). The average age of the participants was 40, average weight 167 lb., and the average height was 68 inches.

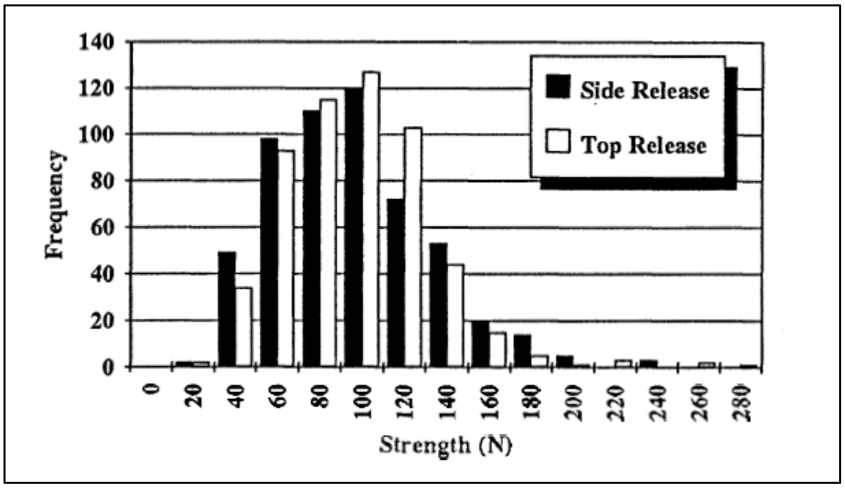


Figure 2.24: Distribution of Maximum Exerted Force Using Side and Top-Release Buckles [63]

Peak buckle release forces exerted by the participants in an upright seated posture on side release and top release belt buckles were recorded. He found out that around 80% of the subjects were unable to exert the 133 N force on the top or side release buckles. The data indicated that about 99% of females and 75% of males were unable to exert 133 N force on either buckle.

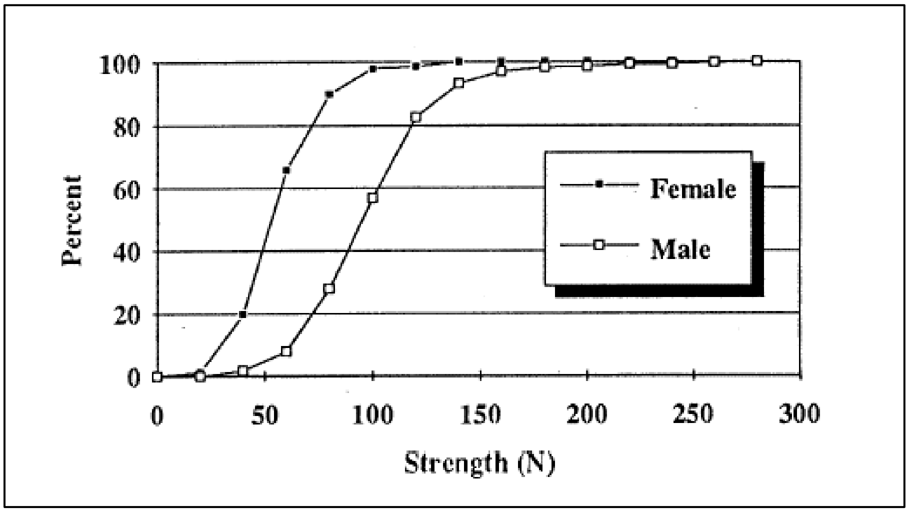


Figure 2.25: Cumulative Force Distribution for Males and Females Using Top-Release Buckles [63]

A few limitations of this study were:

a) 72% of the participants were males.
b) Only driver's side seat belt assembly having the belt buckle on the right side was tested.
c) Noy did not turn the test device to simulate a rollover. He believed this would introduce significant risk and fear to the subjects, and he also believed this would not have yielded different strength data.

Kumaresan et al., conducted a study to test the buckle release forces at different webbing tensions [94]. Side release RCF 67 buckles, top release TRW type II, and top release Autoliv Lockarm were statically tested with a force of up to 1,157 N applied to the latch plate to determine the maximum buckle release force with a Mecmesin force gauge applied to the buckle. They found that the buckle unlatching force increases with an increase in belt tension and exceeds the standard requirement of 133 N. Results from this study for average buckle release force at different webbing tensions are mentioned in Figure 2.26.

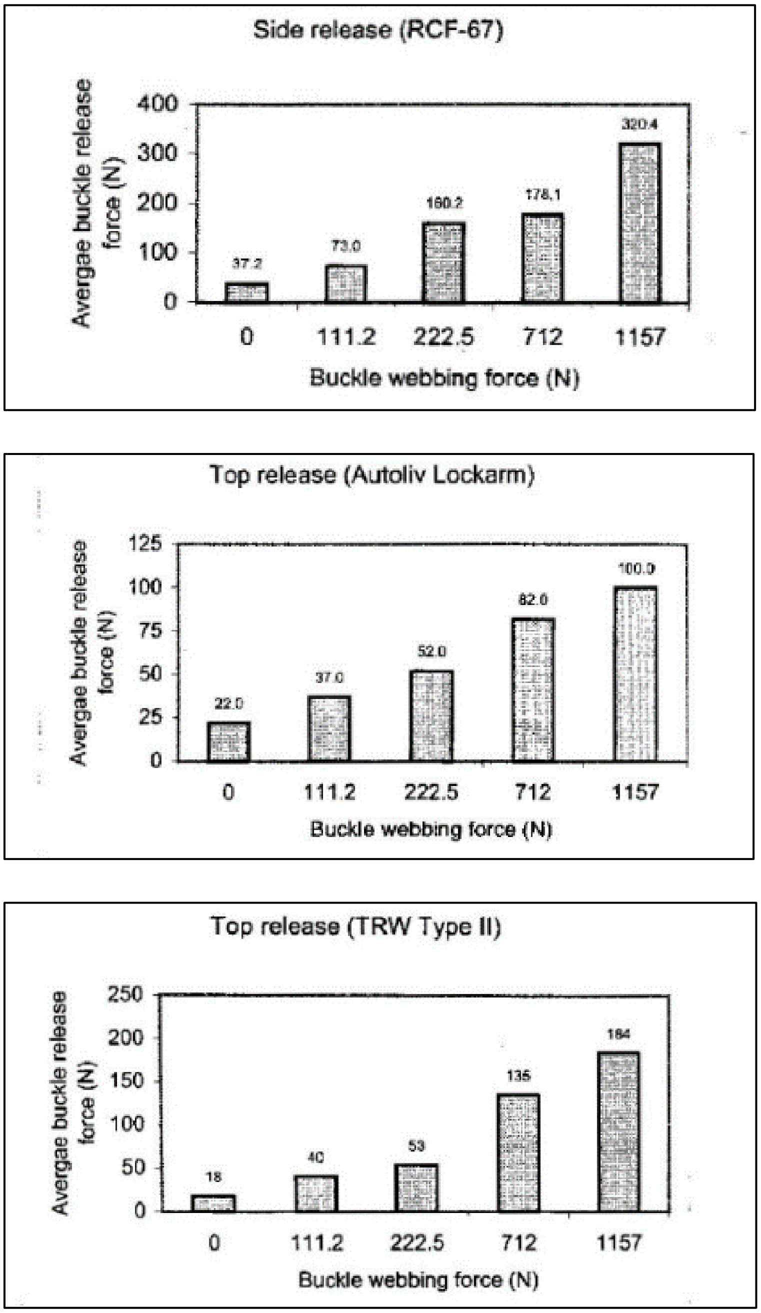


Figure 2.26: Average Buckle Release Forces for Different Seat Belt Buckles [94]

Davee et al., conducted a set of tests to study the conditions required to cause an automotive seat belt buckle release by inadvertent contact [80]. They studied the buckle release force, direction of force application, and the push button travel. Three different end-release seat belt buckles that are used in both the U.S. and countries that follow the EU/UNECE standards were tested to illustrate the typical push button force levels and the button travel distance. Tests were conducted by applying webbing tension at different levels up to 1,112 N (250 lb.) and measured the push-button force required to release the buckle. The study reported that push-button force required to release the buckle *depended on web tension and the force increased with webbing tension.*

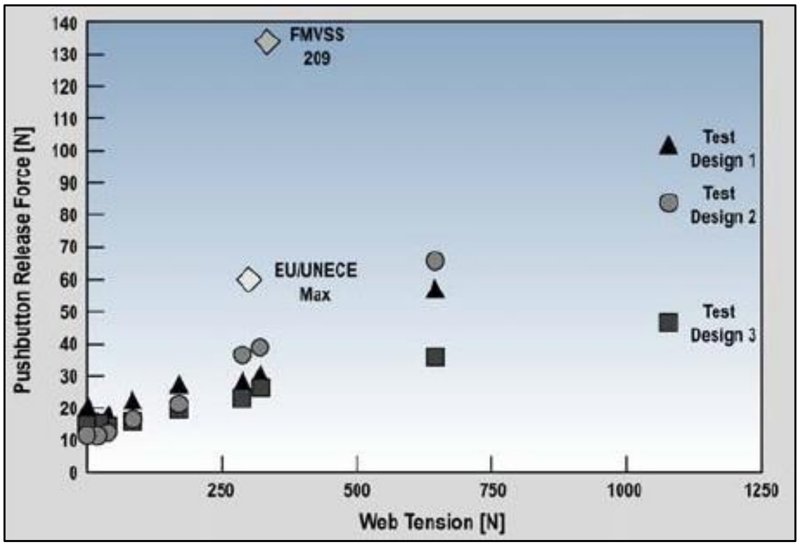


Figure 2.27: Push-Button Force Release Data and FMVSS and EU Requirements [80]

These studies suggest that there is a possibility that the high buckle release force requirement could result in an inability to release the buckle in a rollover accident and may contribute to entrapment in the vehicle.

2.3.2 Webbing Tension Increase Post Rollovers

Studies have shown that webbing tension increases during an accident and goes into several thousands of newtons during a rollover accident [91], [93], [95]. This could be a potentially fatal issue because it can result in a high buckle release force. Hare et al., conducted a series of tests to study rollover test protocols and occupant protections provided by seat belt systems in rollover crashes [93]. Using a 2001 Nissan Pathfinder, they conducted eight rollover tests with a modified FMVSS 208 dolly rollover test method to analyze the driver and front passenger dummy restraint performance.

Figure 2.28: Rollover Test Rig Setup for the Hare et al., Study [93]

Three tests were conducted where the pretensioner was activated at 383 ms, and three without the pretensioners, and these were done utilizing AM50 dummies in the driver and the front passenger seat. Table 2.2 shows the shoulder belt loads during pretensioning in the rollover tests. Non-pretensioning tests found a maximum shoulder belt load of 527 N. Driver and passenger shoulder belt loads at different roll angles are shown in Figure 2.29 and Figure 2.30. Higher belt loads seen during the pretensioning tests were due to the pyrotechnic forces of the pretensioner and resistance of the occupant against the belt. Weight was a significant factor, which could be seen by the maximum shoulder belt load of almost 650 N for an AM95 passenger dummy.

Table 2.2: Shoulder Belt Loads and Belt Retractions During Pretensioning in Rollover Tests [93]

Pretensioner tests	Peak Shoulder Belt Load attained (N)	
	Driver	Passenger
Test #6	955	1271
Test #7	1163	1470
Test #8	854	1136

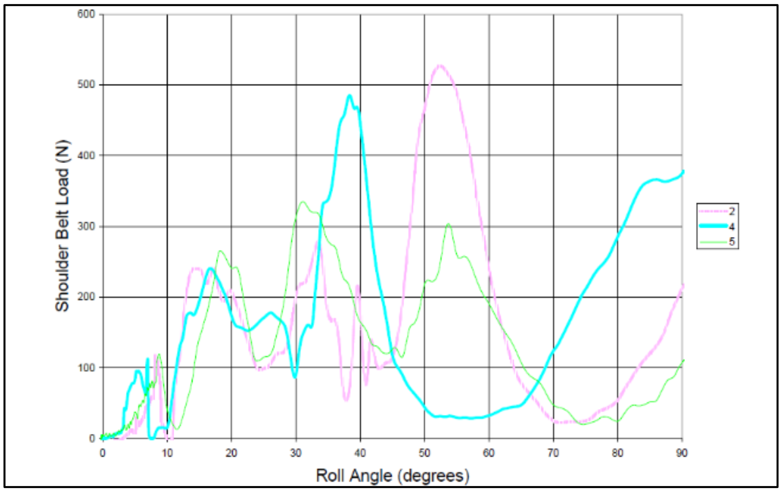


Figure 2.29: Shoulder Belt Loads for Driver vs Roll Angle for Non-Pretensioner Tests [93]

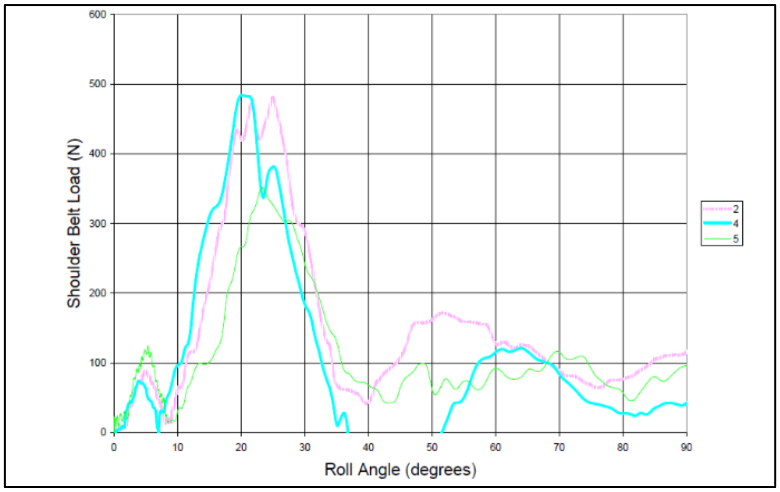


Figure 2.30: Shoulder Belt Loads for Right Front Passenger vs Roll Angle for Non-Pretensioner Tests [93]

To evaluate the conditions necessary for the inertial unlatching of the TRW Type 1 buckle, Moffat et al., conducted a series of rollover and sled tests using anthropometric dummies [91]. Using a 1984 Chevrolet S-10 Blazer (Figure 2.31), a series of six full scale FMVSS 208 dolly-type rollover tests and fifteen sled tests were conducted using a FaAA (Failure Analysis Associates, Inc.) deceleration-type sled. Each test included 4 anthropomorphic dummies; 50th percentile hybrid III male dummies were seated in the left side front and rear seating positions, a 95th percentile male hybrid III dummy was seated in the right front seat, and a six-year-old child dummy with a seated/standing pelvis was in the right rear. For the sled tests, these configurations were 5th percentile female dummy for right front, six-year-old child dummy for right rear, 95th percentile male hybrid III male dummy for the left front and a 50th percentile male hybrid II dummy was in the left rear.

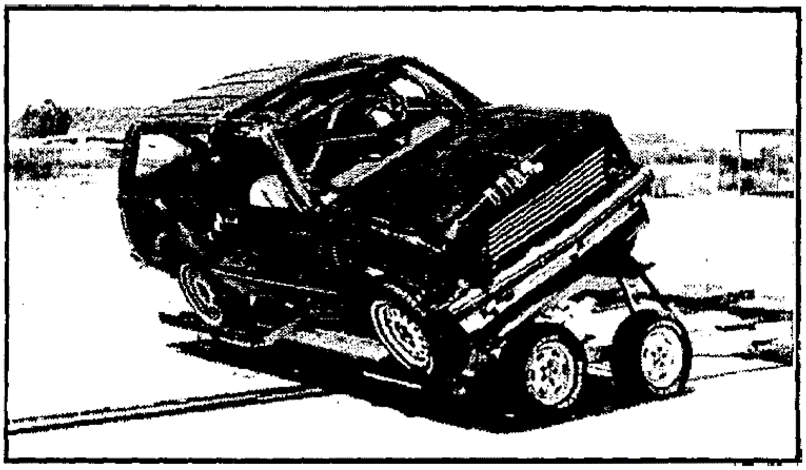


Figure 2.31: 1984 Chevrolet S-10 Blazer on the Rollover Dolly [91]

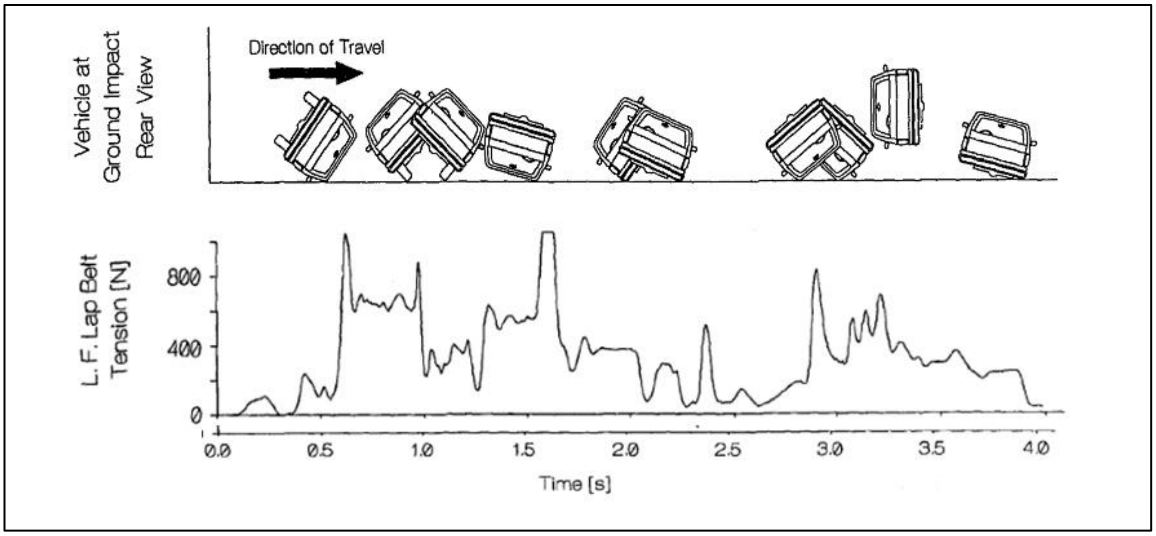


Figure 2.32: Left Front Lap Belt Tension vs Position of Vehicle Rear View [91]

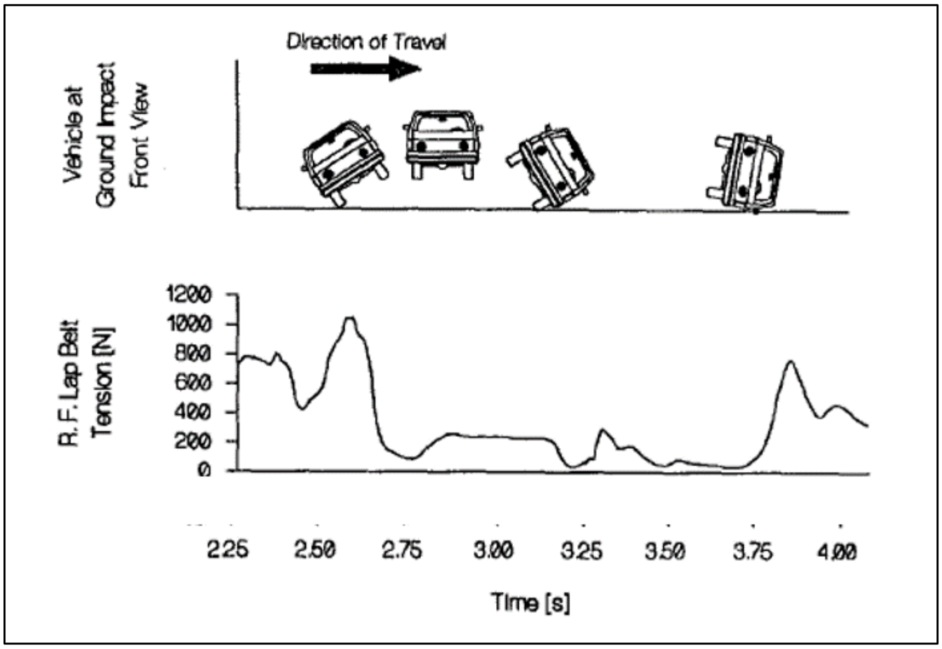


Figure 2.33: Right Front Lap Belt Tension vs Position of Vehicle Front View [91]

They recorded peak acceleration, pulse duration and webbing tensions during the rollover tests. Figure 2.32 and Figure 2.33 show the webbing tension relative to the vehicle's position. The study found that none of the crash tests inertially unlatched the belt buckles, however as seen from the data, they found that during a rollover accident, webbing tension increases and often reaches more than 1,000 N. In one of the rollover tests, they found the minimum belt load for the six-year-old dummy (right rear lap belt load) was greater than 445 N.

To study the effects on driver and front right passenger head and pelvis excursions by a pyro-mechanical pre-tensioner and an electrical retractor activation, McCoy and Chou conducted an experimental study utilizing a dynamic Rollover Component Test System (ROCS) [95]. With Hybrid III Anthropometric Test Devices (ATDs), a total of fifteen rollover tests were conducted. 5th, 50th, and 95th percentile ATDs were placed in the driver and 1st row passenger seating positions of the mid-size SUV and were restrained by a standard 3-point seat belt system.

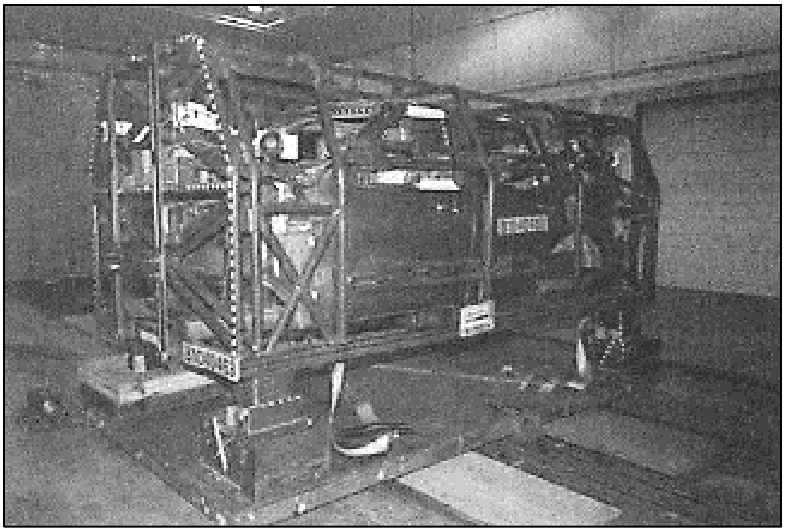


Figure 2.34: Dynamic Rollover Component Test System used by McCoy and Chou [95]

The ROCS system was designed to be a reusable device, hence it does not appropriately simulate vehicle deformation and it changes the vehicle kinematics that occur in a typical vehicle to ground contact. The peak seat belt loads recorded during the rollover tests for the lap, shoulder, and retractor portion are displayed in Table 2.3.

Table 2.3: Peak Seat Belt Loads During Rollover Tests [95]

Test Number	Driver Lap (N)	Driver Shoulder (N)	Passenger Lap (N)	Passenger Shoulder (N)
1	3065	504	4380	No Data
2	3783	No Data	5961	1444
3	4503	2204	5641	2101
4	1372	643	2699	844
5	2616	979	3641	1610
6	2450	No Data	3779	1308
7	3358	742	3531	1298
8	4572	1516	4672	1298
9	4261	1595	4860	1254
10	4308	2149	4424	1361
11	3773	1496	3466	No Data
12	4412	2134	5110	1362
13	4606	No Data	5309	2078
14	4833	1515	6388	1065
15	3798	1308	1270	3584

It is evident from the discussions in sections 2.3.1 and 2.3.2 that during a rollover accident, the seat belt webbing tension increases, and that with the increase in webbing tension, the buckle release force also increases. The webbing loads discussed in the section considered both dynamic and static forces. Research involving just static loads in a rollover and their impact on different parts of seat belt (i.e., lap, shoulder) was not found. However, it could be speculated that static webbing loads for subjects in a rollover may be high due to body weight and gravity. We hypothesize that in the event of a rollover accident, the buckle release force required to unlatch a seat belt could be high and we believe this could be a potential reason for some of the belted rollover fatalities and injuries. This issue may be worsened by factors such as obesity and the use of pretensioners. The following sections will explore how these factors may contribute to increased buckle release forces and will further examine their impact on occupant safety during rollover events.

2.3.1.2 Obesity

Two major public health issues that have emerged in the past few decades for the U.S. and rest of the world are the increasing prevalence of obesity and increasing motor vehicle fatalities [96]. Obesity has been linked with an increased risk of motor vehicle fatalities and severe injuries [96]–[102]. Higher number of pelvic and chest injuries and difficult airway control in morbidly obese trauma patients may be causing increased mortality after trauma [103]. Zarzaur et al. reported both belted and non-belted drivers with obesity are at an increased risk of abdominal injuries and mortality in an MVC when compared to belted drivers that are non-obese [104].

According to the Center for Disease Control and Prevention (CDC), obesity is a national epidemic and a major contributor to certain leading causes of fatality in the U.S. [105]. The prevalence of obesity among U.S. adults was 42.4% in 2017-2018 [106]. From 1980 to 2000, the age-adjusted prevalence of obesity in Americans increased from 14.4% to 30.5% [107], and from 1999–2000 through 2017–2018, it rose from 30.5% to 42.4%. The prevalence of severe obesity increased from 4.7% to 9.2% [106]. According to Finkelstein et al., the estimated annual medical costs of obesity in the U.S. in 2008 were $147 billion, almost double the amount in 1998 of $78.5 billion [108]. As of 2018, it is estimated that among adults, obesity accounted for $172.74 billion of annual expenditure [109]. Ward et al., found that among adults, obesity was associated with $1,861 excess medical cost per individual and $3,097 for severe obesity annually [109].

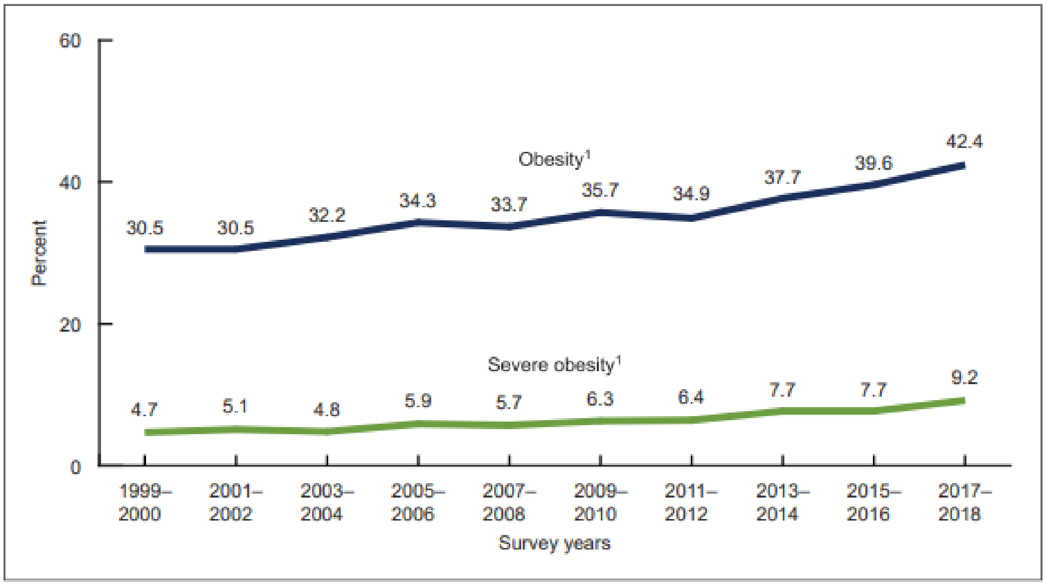


Figure 2.35: Prevalence of Age Adjusted Obesity and Severe Obesity Among Adults Aged 20 and Over in the U.S. [106]

One of the most commonly used screening tools to measure and characterize obesity is the Body Mass Index (BMI), which is calculated as weight in kilograms (kg) divided by height in meters (m) squared [110]. Table 2.4 mentions BMI ranges for adults associated with the standard weight status categories [111].

Table 2.4: BMI Ranges for Standard Weight Status

BMI (kg/m^2)	Weight Status
Below 18.5	Underweight
18.5-24.9	Normal or Healthy Weight
25.0-29.9	Overweight
30.0 and above	Obese

Obesity is often subdivided further into 3 categories [112]:

1) Class 1: $30 < BMI < 35$ - Low-risk obesity
2) Class 2: $35 \leq BMI < 40$ - Moderate-risk obesity
3) Class 3: $40 \leq BMI$ - High-risk obesity

Note: Class 3 obesity is commonly referred to as “severe” obese.

Joseph et al., conducted a retrospective analysis of MVC occupants with blunt trauma using the National Trauma Data Bank (NTDB) from 2007 to 2010 [100]. Of the 1,968,051 blunt trauma patients, 214,306 MVC occupants were included, out of which 10,260 (4.8%) were morbidly obese. They found that among occupants with morbid obesity, the odds of death were 52% higher compared to those with no morbid obesity. The odds of death for drivers with seat belt were 48% higher in occupants with morbid obesity. The odds of death were 49% higher in motorists with morbid obesity among occupants with both airbag deployment and seat belt use. When comparing based on injuries, the odds of death were 1.40 times higher among severely injured occupants with morbid obesity compared to their non-obese counterparts. For non-severe injuries, the odds of death were 2.03 times higher in occupants with morbid obesity compared to non-obese occupants.

A retrospective cohort study using the data from CIREN and NASS CDS was conducted by Donnelly et al., to describe variations in the risk of MVC fatality and injury by occupant body mass index (BMI) class and vehicle type [99]. They found that obese individuals had the greatest injury and fatality rate for all vehicle types, compared to under-weight, normal weight, and overweight individuals. They also concluded that in larger vehicles, including light trucks and vehicles with above-average curb weights, obese individuals were at increased risk of death.

To understand the association between obesity and non-fatal MVC injuries and the related sex differences in these associations, Ma et al., analyzed the data from NASS CDS from 2003 to 2007 [96]. They found that obese male drivers showed much higher risks of non-fatal injuries of various severity than did non-obese male drivers, and these risks increased with injury severity. They also found that male drivers had greater percentages of vehicle rollover and lower percentages of seat belt use than did female drivers.

Arbabi et al., speculated that the difficulty of post-injury care of obese victims or medical comorbidities associated with obesity could be attributable to increased risk of fatal motor vehicle crashes [102].

To investigate the association between risk of motor vehicle driver injury and BMI, Whitlock et al., conducted a cohort study of 10,525 men and women from New Zealand [98]. Baseline BMI was assessed in 1992-1993, and for the period 1988-1998, data on deaths and hospitalizations for motor vehicle driver injury were obtained by linking records to the national health databases. They observed a U-shaped association between driver injury risk and BMI, which included age, sex, driving exposure, and alcohol intake. “Participants in the highest (28.7 kg/m2; hazard ratio (HR) = 2.00, 95% CI: 1.18–3.39) and lowest (23.5 kg/m2; HR = 2.17, 95% CI: 1.27–3.73) quartiles of BMI were *twice as likely to have experienced a driver injury* during the follow-up period as participants in the reference quartile (25.9–28.6 kg/m2; HR = 1.00)” [98].

Zhu et al., investigated the association between obesity and regional injuries during MVCs using real-world data and simulated crash data using computational models of obese occupants [97]. Using the NASS CDS, they extracted injury and BMI data for 10,941 adults aged 18 years or older involved in a frontal MVC between 2001 and 2005. Analysis of the real-world data showed that obese men had substantially greater risk of injury to the upper body than men with normal weight. Additionally, they found that obese men were more prone to be critically injured than obese women for all body regions except the extremities and the abdominal region. They also found a U-shaped relation between BMI and serious injury in the abdominal region for both male and female drivers.

2.3.1.3 Pretensioners

In a crash, it is important for a seat belt to firmly engage the occupant’s pelvis, clavicle, and rib cage to restrict the occupant’s motion and minimize injuries from contact with the interior components [113]. Loose webbing due to various factors like poor seat belt adjustment, bulky clothing, etc., can result in increased displacement of the head, chest, hips, and knees in a crash [114], [115], [116]. A quicker coupling of occupant to the car seat increases the likelihood of the seat belt engaging with the shoulder and consequently increasing the level of restraint provided to an occupant in far-side impacts, providing the most controlled ride-down [113], [117]. Pretensioners are a major advancement in seat belt technology that are able to achieve this in a relatively short duration. Seat belt pretensioners retract the seat belt to remove the slack in the lap and/or torso portion of the belt almost immediately when a crash occurs [113].

In 1981, the W126 series Mercedes-Benz S Class became the world’s first car to come with an airbag and a seat belt pretensioner [118]. While pretensioners were offered on some cars as early as 1981, around 1998 is when industry-wide application began. By 2003, pretensioners were available in over 75% of new vehicle models sold in the U.S. [119]. By model year 2008, all new cars and LTVs sold in the U.S. were equipped with pretensioners at the driver’s and right-front passenger’s seats [113].

Seat belt pretensioners employ different mediums to tighten the seat belt in the initial phase of an impact with the goal of removing loose webbing before the occupant has significantly moved [116]. The three most common methods are:

1) Mechanical Pretensioner: This design consists of an inertial wheel combined with a pendulum which moves to lock the belt into place [120]. It uses the energy stored in a spring which is compressed and latched in place to apply tension to the belt webbing in case of immediate acceleration or deceleration [116], [121].
2) Electrical Pretensioner: This is a motorized pretensioner, in which the sensor is connected to the Electronic Control Unit (ECU), which is sometimes the same sensor used to deploy airbags. When the sensor detects a sudden deceleration, a signal triggers the motor to retract the belt webbing. Advantage of electrical over mechanical pretensioners is that the electrical sensors can be interconnected with other systems in the vehicle [122].
3) Pyrotechnic Pretensioners: These are electronically triggered pyrotechnic devices. Upon receiving an electrical pulse, an explosive charge generates pressurized gas which acts on a mechanical linkage to apply tension to the webbing, in turn pulling the seat belt closer to the occupant [116], [121], [123]. These pretensioners are also connected to the ECU that work in tandem with airbag sensors, forward collision warning sensor, and other systems available in the vehicle.

Currently, pyrotechnic pretensioners are the most common version found in modern cars [121]. These are the most reliable among the available pretension activation technologies, but their biggest drawback is that they are a one-time use device. They can only be triggered after a crash irreversibly; once activated, the entire system will have to be replaced [121], [122]. There are two common locations for pretensioners available for manufacturers, both of which are equally effective in removing the slack from the belt [124]:

a) Buckle Pretensioners: they pull the belt buckle downwards towards the vehicle floor.
b) Retractor Pretensioners: these are located in the B-pillar and pull the belt tight from the top attachment.

Both buckle and retractor pretensioners increase webbing tension. Another significant concern is that buckle pretensioners move the buckle away from the occupant [80]. As mentioned above, pretensions could cause higher webbing tensions (in turn causing higher buckle release forces) and certain types of pretensioners move the buckle away from the occupant. We believe these factors could make unbuckling in a MVC difficult, especially after a rollover accident.

2.4 Positional Asphyxia

A major issue associated with high buckle-release force post rollover accident is occupant entrapment, and a serious threat in this condition is positional asphyxia. Asphyxia is a condition characterized by the lack of oxygen in the body that is caused by interruption of breathing or inadequate supply of oxygen that could result in unconsciousness or even death [125]. Positional or postural asphyxia is a form of mechanical asphyxia that occurs when an individual is trapped or immobilized in a position that does not allow for sufficient pulmonary ventilation (breathing) and thus results in respiratory failure [126]–[129]. In some cases, normal circulation and venous return (blood flow) to the heart may be directly hindered because of body position and in turn can contribute to the obstruction of normal gas exchange [130].

Asphyxia could be elicited in different ways:

a) Hyperflexion or hyperextension of the neck can cause partial or complete airway obstruction [131].
b) Inversion of the upper part or the whole body can interfere with blood circulation and regular respiration [132].
c) Compression or flexion of the torso could reduce the total lung volume, pulmonary expansion, and functional residual capacity (volume of gas remaining in the normal lungs at the end of an expiration [133]), thus making breathing ineffective [134], [135].

To investigate the effects of head-down position on respiration and circulation, Uchigasaki et al., suspended 14 rabbits in reverse (upside down) position [136]. They found that the arterial oxygen tension or partial pressure of oxygen (PaO_2) increased by 20%-40% suddenly, the arterial carbon dioxide tension or partial pressure of carbon dioxide ($PaCO_2$) decreased a little in the beginning, and then the PaO_2 started gradually decreasing. PaO_2 is the pressure of oxygen dissolved in the blood, which is the measure of how well oxygen is able to move from the airspace of the lungs into the blood, and similarly $PaCO_2$ is respectively the same measure for carbon dioxide [137]. Towards the end, the number of respiratory movements reduced suddenly, the PaO_2 began to decrease rapidly, and the $PaCO_2$ increased. All the rabbits in a head-down position died in 17-44 hours. The cause of death was suggested to be postural asphyxia resulting from fatigue of the respiratory muscle by hindered respiratory movements.

Martin et al., suggest that in many scenarios in the automotive world, positional asphyxia is caused by the seat belt holding an occupant in an upside-down position when their vehicle is inverted [126]. They further added that one of the most common positions that result in death by positional asphyxiation is the inverted position.

Two possible causes of death when an individual is trapped in a head-down position:

a) Increased work of breathing [136], [138]
b) Hemodynamic malfunction [139]

Increased work of breathing or difficulty in respiration in either phase for an individual can be caused by:

1) The stretching effect of suspension that tenses the abdominal muscles, fixing the chest in expiration while the weight of the arms and upper body hanging freely have a complementary effect, inducing difficulty in inspiration [138].
2) The weight of the abdominal parts pressing on the diaphragm causing fatigue of the respiratory muscle [136].

Hemodynamic malfunction refers to an abnormality or failure in the circulation of blood in the body, which can result in insufficient delivery of oxygen and nutrients to organs and tissues [140]. Belviso et al., [139] suggests that hemodynamic malfunction is caused by:

1) Increase of pressure in the veins that carry blood from the brain.
2) Uneven distribution of blood pressure in the neck.
3) Increase of hydrostatic pressure in the upper regions of the body (head, neck, and thorax) and stagnation of blood in areas of the body where the mechanisms of return blood flow to the heart are less efficient.

2.4.1 Case Reports on Positional Asphyxia

The following case was discussed by Martin et al., in their study [126]. “A 16-year-old driver with a body mass index (BMI) of 60.8 died after a motor vehicle collision when the vehicle went off the road and flipped over in a water-filled ditch. He was suspended in an inverted position with his face submerged in water by both lap and harness seat belts. A passenger, who was able to exit the vehicle, noted that the driver had been conscious, conversant, and able to pull his head and face out of the water. A first-responder was able to help him hold his head out of the water, but prior to extrication by emergency medicine personnel he became less and less conscious and eventually became unresponsive. He was suspended in an inverted position for approximately 15 minutes total. He was pronounced dead at the scene" [126]. The cause of death was deemed to be positional asphyxia due to the prolonged suspension of the decedent in an inverted position, with a contributing factor of morbid obesity.

Conroy et al., discuss five cases of fatal asphyxia in occupants suspended upside-down from their seat belt after rollover crashes in San Diego County, California during 1995 to 2004 [141]. These deaths as described in Table 2.5 all occurred because the drivers were suspended upside down from their seat belt after a rollover crash in which the vehicle came to rest on its roof. These occupants may have been unable to modify their position due to various incapacitating factors. Martin et al., suggests if evidence is available, while other severe/lethal injuries are present, positional asphyxia may be considered responsible to the overall injury complex or cause of death [126].

Table 2.5: Case Studies of Fatal Asphyxia from Rollover Crashes in San Diego

Age	Sex	BMI (Weight, height)	Type of Vehicle and Accident	Injuries	Notes
58	Male	38.6 (225 lb., 5’4”)	Pickup Truck ran off the roadway, down a ravine, rolled several times and came to rest upside-down.	Bilateral rib fractures, subdural hematoma (small)	EMS arrived 13 minutes after the incident to find him suspended upside down by his seat belt. After cutting the seat belt and removing him from the vehicle, he was pronounced dead.
38	Male	31.4 (183 lb., 5’4”)	Mid-sized automobile struck a pole guide wire, went airborne over an embankment, struck a tree and building and overturned	External contusions/abrasions	He was found suspended by his seat belt with his head resting on the roof and his chin against his neck.
71	Male	22.2 (164 lb., 6’)	Full-sized automobile ran off the roadway and rolled, landing on its roof.	Rib fractures	Unwitnessed incident hence unknown how long he was inverted before death
34	Male	35.6 (234 lb., 5’8”)	Full sized pickup truck ran off the road, struck an embankment and rolled over	External contusions/abrasions, external lacerations, subgaleal hemorrhage	The cab was crushed, and his head was hyperflexed forward against his chest. He was suspended from the seat belt with his shoulders, neck, and head extending out the driver door.
66	Female	38.4 (210 lb., 5’2”)	Full sized automobile ran off the road, went down an embankment, and rolled over.	Rib fractures, wrist fracture, subgalea hemorrhage, facial contusions	The incident was not discovered for almost 24 hours. When found she was suspended upside down from the seat belt. The report also specified that she might have had an altered level of consciousness (due to her head injury) that may have made it difficult for her to remove herself from the inverted position.

2.5 Emergency Medical Service Response Time

Emergency Medical Service (EMS) response time is defined as the time elapsed between EMS notification and EMS arrival on scene [142]. Arrival of EMS on time at the crash scene could be the difference between life or death [143]. Prompt arrival of first responders allows for stabilization of the occupants, timely triage, and transport to the hospital, whereas a delay could lead to an increased risk of death [142]–[144].

To measure the association between EMS response time and MVC related deaths at the county level in U.S., Byrne et al., conducted a population-based analysis of MVC related death within U.S. counties from 2013-2015 using data from the National Emergency Medical Services Information System (NEMSIS) [142]. There were close to 78 million EMS activations from 2,497 U.S. counties, around 2.21 million responses from 2,268 counties met the inclusion criteria; these counties accounted for 75% of the total U.S. population. The study found that the median response time for the counties was 9 minutes. The median county response time among rural/wilderness counties was 10 minutes, and for urban/suburban counties it was 7 minutes. The proportion of crash fatalities in rural/wilderness counties for EMS response time of 10 minutes or longer was 9.9%, the same for urban/suburban counties for EMS response time of 7 minutes or longer was 14.1%.

The authors found that counties with longer response time were more often rural, had less access to level I or II trauma centers, lower helicopter EMS availability, and longer on-scene and transport time. The study concluded that in both rural/wilderness and urban/suburban settings a significant proportion of MVC-related deaths were associated with prolonged response times.

According to NHTSA, rural areas account for 71% of the nation's public road miles, 30% of vehicle miles traveled, but account for nearly half of the crash fatalities [55]. Figure 2.36 depicts the comparison of highway statistics between rural and urban areas in 2018. Figure 2.37 represents the fatality rate per 100 million Vehicle Miles Traveled (VMT) by land use from 2009-2018. In 2018, the fatality rate per 100 million vehicle miles traveled was almost 2 times higher in rural areas than in urban areas (1.68 vs .86) [145].

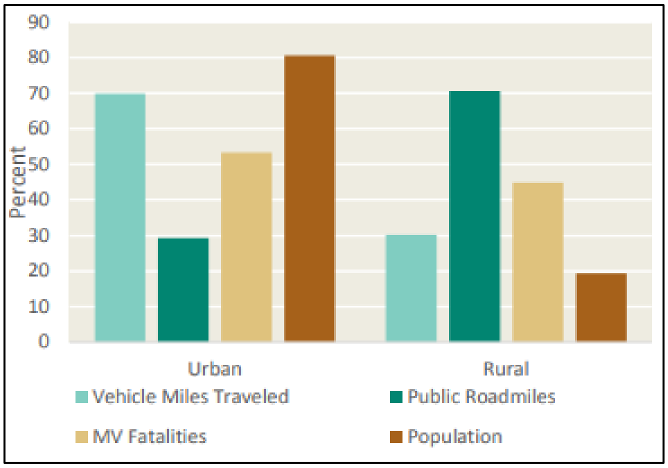


Figure 2.36: MVC Fatality Distribution Considering Miles Traveled and Population: Urban vs Rural 2018 [55]

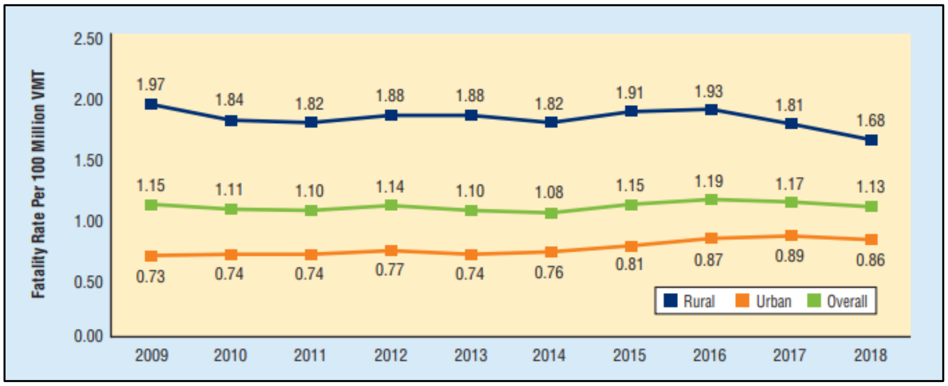


Figure 2.37: Yearly MVC Fatality Distribution: Urban vs Rural - 2009 – 2018 [145]

Rollover accidents with a fire can be particularly dangerous, as they can trap vehicle occupants inside the burning vehicle. Figure 2.38 illustrates instances of fatalities after a rollover accident in which the vehicle was caught on fire. On average there are more than 400 fatalities associated with such scenarios. Digges et al. found that the percent of fatal crashes with fires that were rollovers was 24.9% [146]. In these situations, if an occupant is unable to unlatch their seat belt due to the extreme forces of the accident or a damaged or jammed latch, they can become trapped and face a potentially fatal situation. The heat and flames from the fire can quickly engulf the vehicle, making it difficult or impossible to escape. In addition, the smoke and toxic fumes produced by the fire can be deadly, even if the flames themselves do not directly harm the occupant.

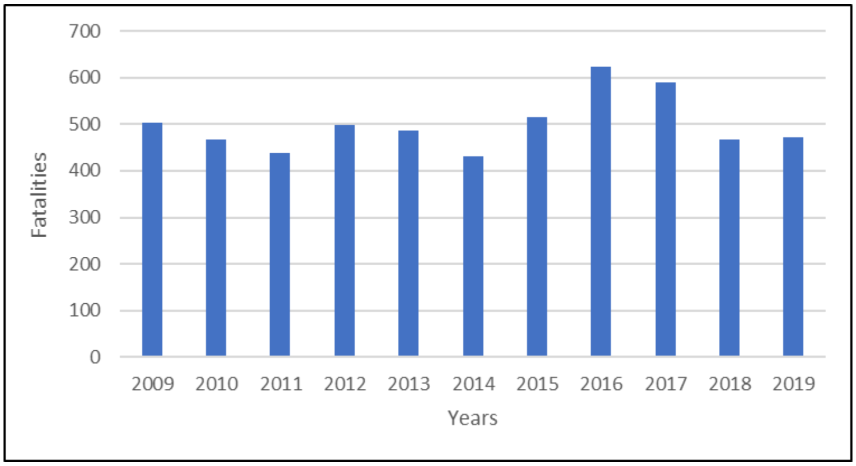


Figure 2.38: Occupants Involved in Fatal Rollovers with Fire Occurrences (Data Source: [49])

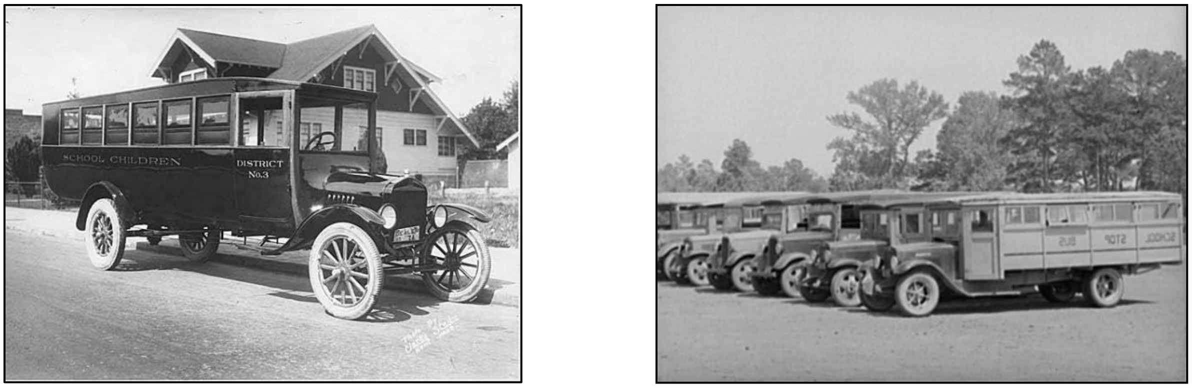
Studies have shown that longer EMS times are associated with higher risk of fatalities. We believe that high buckle release force could cause an occupant to be stuck in the vehicle and with longer EMS time, the injury could worsen and could result in a fatality, especially if there is submersion or fire associated with the accident. With EMS response time being longer and fatality rates being almost double in rural areas when compared to urban areas, it is essential to research potential issues with higher buckle release forces resulting from rollover crashes.

Until this point the chapter was focused on passenger vehicles. Another critical form of transportation widely used in the U.S. is the school bus. The focus from here on will be on evacuation considerations for children riding school buses equipped with seat belts and the discussion of potential issues.

2.6 School Buses in the United States

School buses are an integral part of the U.S. education and transportation sector. Today, in the U.S., 471,461 school buses transport around 25.2 million children every day and travel approximately 3.4 billion miles every year [31]. As of 2019, 47% of total public students were transported on school buses [31]. Since 2010, the annual sale of new school buses in the U.S. has averaged over 33,000 [31].

Pupil transportation started in the late 1800s, with horse-drawn carts borrowed from local farmers being the first vehicles to transport students [147]. In 1886, Wayne Works of Richmond, produced horse drawn "school cars," also known as "school carriages" or "school hacks" [148]. In 1912, Wayne works developed a motorized kid hack, a predecessor to the modern school bus, and in 1915, Navistar (then International Trucks) manufactured the first school bus, the Model F, for Ravinia school district in South Dakota [148]. The Commonwealth of Massachusetts passed the first legislation to allow the use of public funds for transporting school children in 1869 [149]. By 1919, 48 states enacted similar laws to encourage compulsory school attendance and to consolidate public schools. Motorized school buses have been used to transport children for over a century now. Despite being more than a century old, school buses have not changed drastically compared to other means of transportation. Figure 2.39 illustrates the evolution of school buses over the last century.



1926 [150]

1939 [151]

1950 [152]

1978 [153]

2003 [154]

2020 [155]

Figure 2.39: Evolution of School Buses

2.6.1 School Bus Standards

In April 1939, Frank W. Cyr organized a conference at Teachers College that attracted transportation officials from each of the then 48 states, as well as specialists from school bus manufacturing and paint companies, to establish national school bus standards and recommendations, including the standard color of yellow for the school bus [156]. Cyr believed that one uniform color would make bus travel safer and standardization would cost districts less as construction specifications would make mass production possible for manufacturers [157]. Around 44 standards were voted on during that conference, including standards for body lengths, ceiling heights, the aisle width, and the door widths.

Today, school buses are the most regulated vehicles on the road [158]. In comparison to other vehicle transportation methods, NHTSA claims that students are about 70 times more likely to get to school safely when riding a school bus [158]. 37 out of the 60 federal motor vehicle safety standards apply to school buses and some are specifically written only for school buses like FMVSS 131, FMVSS 220, FMVSS 221, and FMVSS 222 [159].

2.6.2 Seat Belt Assembly Standards for School Buses

Federal Motor Vehicle Safety Standard 208 and 209 specifies the requirements for seat belt assemblies and FMVSS 222 establishes occupant protection requirements for school bus passenger seating and restraining barriers [12], [27], [160]. FMVSS 209 mandates all passenger cars after 1996 to have a Type 2 (lap/shoulder) seat belt assembly [27]. FMVSS 222 only requires new school buses of 4,536 kilograms (10,000 pounds) or less gross vehicle weight rating (GVWR) (small school buses) that are manufactured on or after September 1, 2011, to have lap/shoulder belts [160].

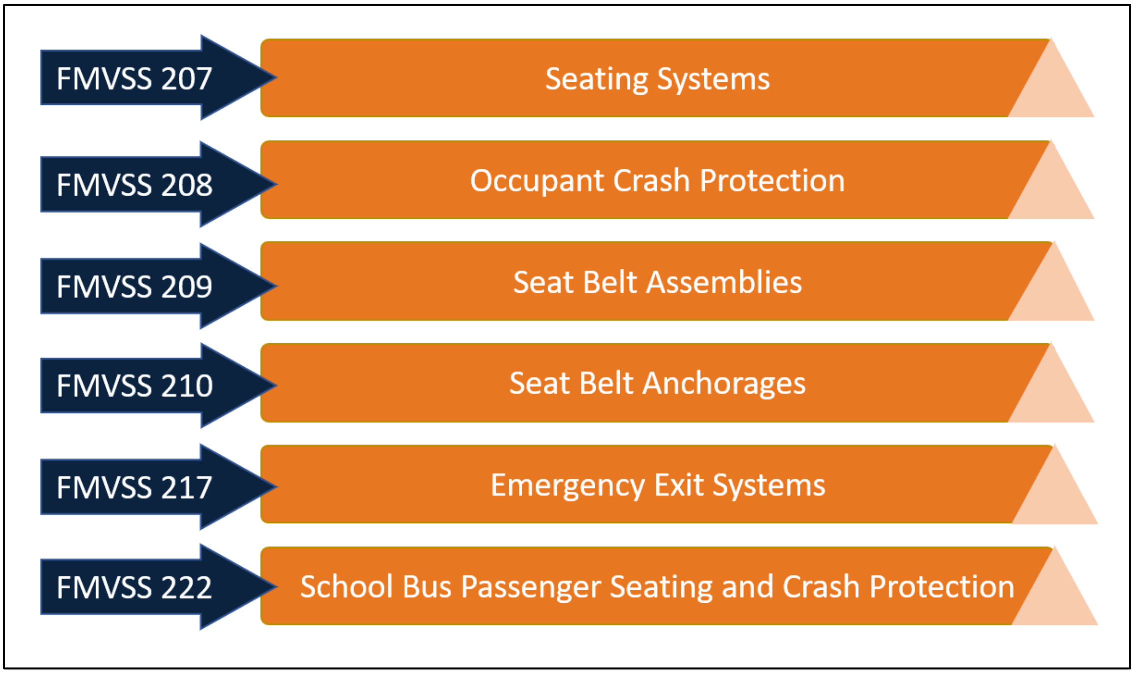


Figure 2.40: Federal Restraint Standards Associated with School Buses

NHTSA determined that the best method to provide crash protection to children on large school buses was to implement a concept called "compartmentalization." This method provides a protective envelope consisting of strong, closely-spaced seats, which have energy absorbing seat backs [161]. Compartmentalization is applicable to all school buses with a GVWR greater than 4,536 kg (10,000 lb.). Small school buses with a GVWR of less than 4,536 kg (10,000 lb.) are required to have a lap belt or a lap shoulder belt assembly at each seating position in addition to the compartmentalization.

School buses, an integral part of the education and transportation sector in the U.S., are currently only required to have seat belts in eight states; Arkansas, Louisiana, and Texas' laws, however, are subject to appropriations, approval, or denial by local jurisdictions [162].

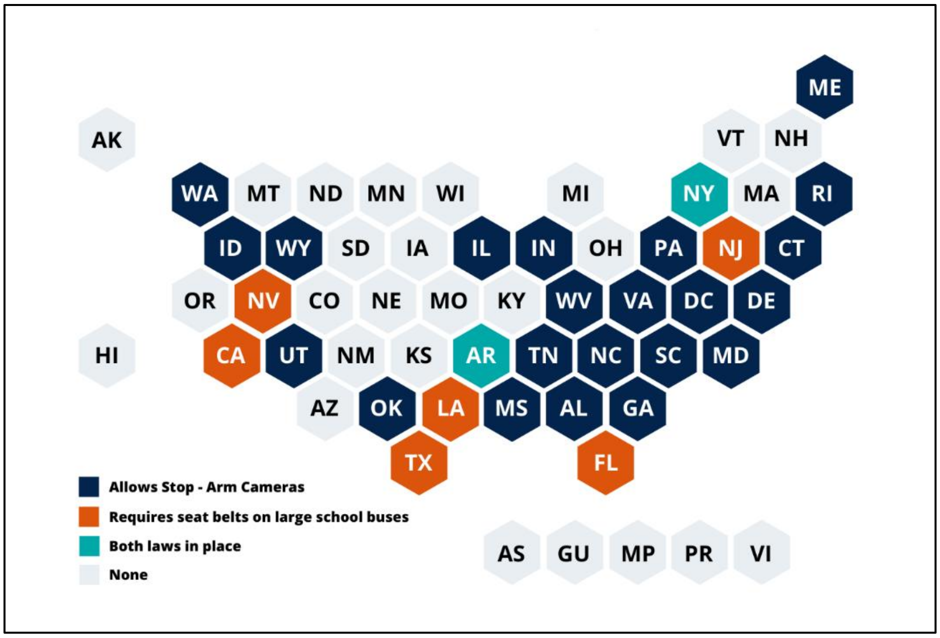


Figure 2.41: State Wise School Bus Safety Laws in 2021 [162]

2.6.4 Issue with Seat Belt Standard in School Buses

Statistically, school buses are extremely safe and highly researched but most of the school bus seat belt research is focused on the economical aspect [163]–[167]. No article has been found that discusses any issue related to seat belt buckle design. The biggest problem with seat belts on school buses could be that they are not adequately designed for the riding population, i.e., children.

Seat belts for school buses follow the same laws as for passenger cars, light trucks, etc. Basically, the belts that are used for adults are what are used for school children as well. The seat belt buckle according to the FMVSS 209 S4.3 (d) of a Type 1 or Type 2 seat belt assembly shall release when a force of not more than 133 N is applied [27]. FMVSS 217 establishes requirements for the retention of windows other than windshields in buses and establishes operating forces, opening dimensions, and markings for bus emergency exits [168]. The purpose of this standard is to minimize the likelihood of occupant ejection from a school bus and to provide a means of readily accessible emergency egress. However, the effects of seat belts and the buckle release force in an emergency evacuation scenario is not discussed nor mentioned in any of these standards.

2.6.5 Strength Data on School Children

Research on strength of whole hand or single digits (fingers) in the occupational safety field usually focuses on industrial design of hand intensive tasks to minimize discomfort and the risk of upper extremity injuries and their associated costs. Consideration of hand and finger strength is critical for designing products for everyday use. An extensive literature review could not uncover any tests done on the buckle release force capabilities of children. The closest comprehensive study on the strength capabilities of children to push a button using their digits to the best of our knowledge was a major research program by the University of Nottingham in association with the Consumer Affairs Directorate of the United Kingdom's (UK) Department of Trade and Industry (DTI) [169], [170]. This research produced a series of publications that compiled all available design-related data into a compilation of easy-to-use design resources. They later undertook a two-stage research program, with the second phase aimed at addressing gaps in the data and providing designers with ergonomic data for direct use in product design to aid in the design of safer products [170].

To measure the maximum static pushing strength using the digits (fingers and thumbs), two studies were conducted:

a) Maximum static forwards and downwards pushing force of the index finger and thumb, exerted for five seconds [169].

In this, the subject was asked to stand in front of the measuring device, adopt a free posture, and exert a static pushing force with the pad of the index finger or the thumb of the dominant hand on a circular plate 20 mm in diameter.

Figure 2.42: Experimental Setup for (a) Circular Force Plate (20mm) by the DTI Study [169]

b) Maximum static pushing strength using the thumb or two or more fingers [170].

In this, the subject was asked to exert a static pushing force on a button (a 50 mm plastic cube) using either the thumb or two or more fingers of their dominant hand. The subject was either standing with the button positioned at elbow height or seated with the button positioned at the side of the hip, at seat pan height. Small children were allowed to rest their feet on a box.

Figure 2.43: Experimental Setup for (b) Plastic Cube (50mm) by the DTI Study [170]

For the present research, the primary focus is on the static pushing force exerted downwards with the thumb and fingers. The force exertion data from the DTI study is summarized in Table 2.6.

Table 2.6: Summary of Mean Push Force from the DTI Studies [169], [170]

Mean Push Force (N)							
		(20 mm Circular Plate)			(50 mm Cube)		
Sex	Age	2-5	6-10	11-15	2-5	6-10	11-15
Male	Fingers	21.8	43.30	66.70	31.95	56.18	117.60
Female		24.50	42.00	63.00	22.26	66.81	103.20
Male	Thumb	26.9	85.10	115.10	26.8	66.62	124.43
Female		34.4	71.10	94.30	24.16	82.75	97.24

This data is graphically illustrated in Figure 2.44. Average force measurements of none of the categories were able to meet the FMVSS 209 buckle-release force requirement of 133 N. This is extremely concerning because the subjects in these studies are exerting force on a button that is bigger (in case of the 50 mm cube) and not shrouded like a regular seat belt button, and they are observing a neutral posture with their feet relaxed on a box for support. In a typical school bus seat due to the height of the seat from the bus floor, not every child is able to rest their feet on the floor.

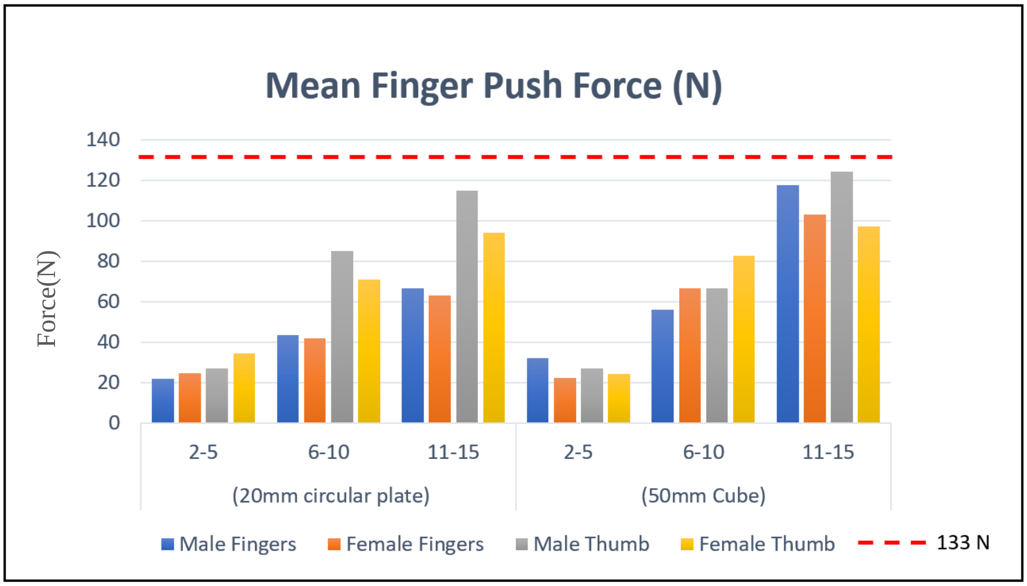


Figure 2.44: Mean Finger Push Force for Children Aged 2-15 Years (Data Source: [169], [170])

FMVSS 209 S4.3(d) states that a buckle designed for push-button application of buckle release force shall have a minimum area of 452 mm^2 with a minimum linear dimension of 10 mm for applying the release force [27]. FMVSS 209 S4.1 (e) states that the buckle release mechanism shall be designed to minimize the possibility of accidental release/inadvertent release [27]. Too large a buckle button could cause an inadvertent or accidental release [80]. It is currently unknown what strategies young children employ when pushing the release push-button; fingers, thumb, or a combination of both. As push-buttons are often enclosed or shrouded and the available surface area to exert force is limited, it is possible that the force exerted may not be as significant as in the experiments conducted by the DTI mentioned earlier.

Abulhassan et al., conducted a study to determine if children in (K-2) are capable of opening and evacuating from a school bus roof hatch in an emergency rollover scenario [171]. They identified that 42% of kindergarten students were unable to exert the maximum permissible design force of 89 N necessary to operate the roof hatch. Gunter et al., performed a study to explore an alternative rear emergency door hold-open device that allows the door to be held partially open and provide unobstructed passage [172]. The primary reason for this is because the rear emergency door weighs approximately a 100 lb. (45 kg) and the force required to open the door and egress in a rolled over orientation would be extremely difficult for most adults and improbable for a young child.

Research by Abulhassan et al., and Gunter et al., have shown that several aspects of school buses are not designed adequately for children and that they are designed with adults in mind [171]–[175]. The disconnect between the design of emergency exits of school buses and the physical capabilities of children necessitates further research to ensure the design of school seat belts is compatible with the capabilities of young children.

School bus rollover accidents are rare, but they are complex and usually fatal. There is no debate that seat belts are highly effective in reducing deaths and injuries in motor vehicle collisions, especially in rollover crashes. However, the majority of those situations were involving adults, and an extensive review of the existing literature was unable to uncover any studies done on the strength capabilities of children to unlatch a seat belt in a rolled over orientation of a school bus. Furthermore, no reason was found for using end-release push-button buckle on school buses and any design changes to the buckle to accommodate for children’s anthropometry and strength.

Chapter 3

Assessing Seat Belt Buckle Release Forces in Passenger Vehicles After Rollover Accident

3.1 Introduction

The number of motor vehicle crashes and road traffic deaths on the world's roads remains unacceptably high. According to the World Health Organization, every day, almost 3,700 people die globally in road traffic crashes [1]. In 2016, the number of road traffic fatalities was at a shocking 1.35 million [1]. Road traffic crashes cost most countries 3% of their GDP [2].

Motor vehicle crashes are a leading cause of death among those aged 1-54 in the U.S.[48]. More than 2.2 million drivers and passengers were treated in emergency departments because of injuries sustained from motor vehicle crashes in 2018 [50]. According to the Bureau of Labor Statistics, from 2003 – 2018, around 29,000 workers died from work-related motor vehicle crashes making them the leading cause of work-related deaths in the U.S. [51], [176]. Figure 3.1 shows the number of fatalities in traffic related crashes in the last 20 years (2000-2020). It is evident that the total number of fatalities has reduced but only by a small percentage.

Despite advances in road and vehicle technology, the number of fatalities on U.S. roads has remained high, with an average of about 35,000 deaths annually since 2015. According to NHTSA's early estimates of motor vehicle fatalities, 2020 showed an increase of 7.2% in the total MVC fatalities compared to 2019, despite the pandemic [177]. One of the most dangerous types of motor vehicle accidents are rollover crashes (ROCs). They have long been recognized as a significant hazard compared to other modes of crashes.

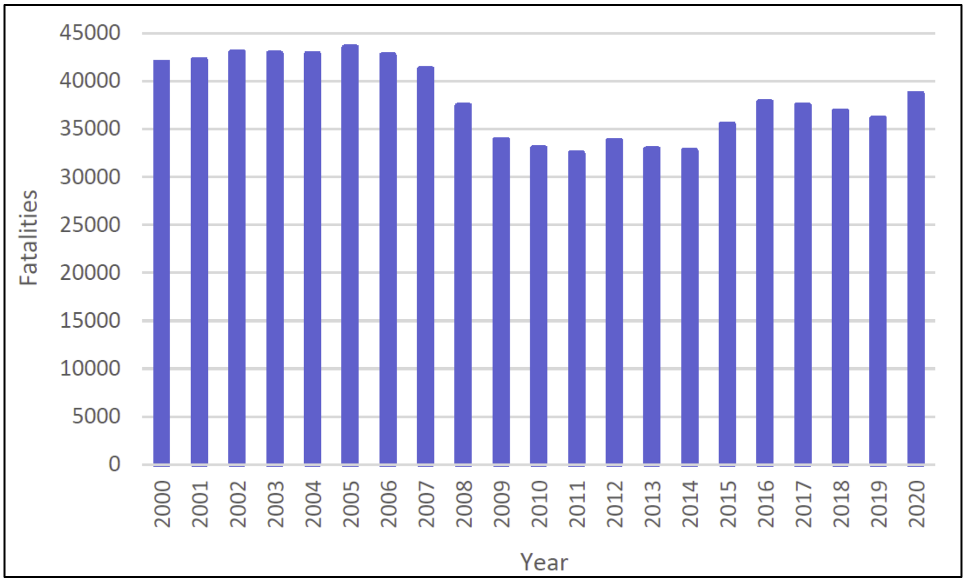


Figure 3.1: Number and Rate of Road Traffic Deaths from 2000 to 2020 (Data Source: [15], [177])

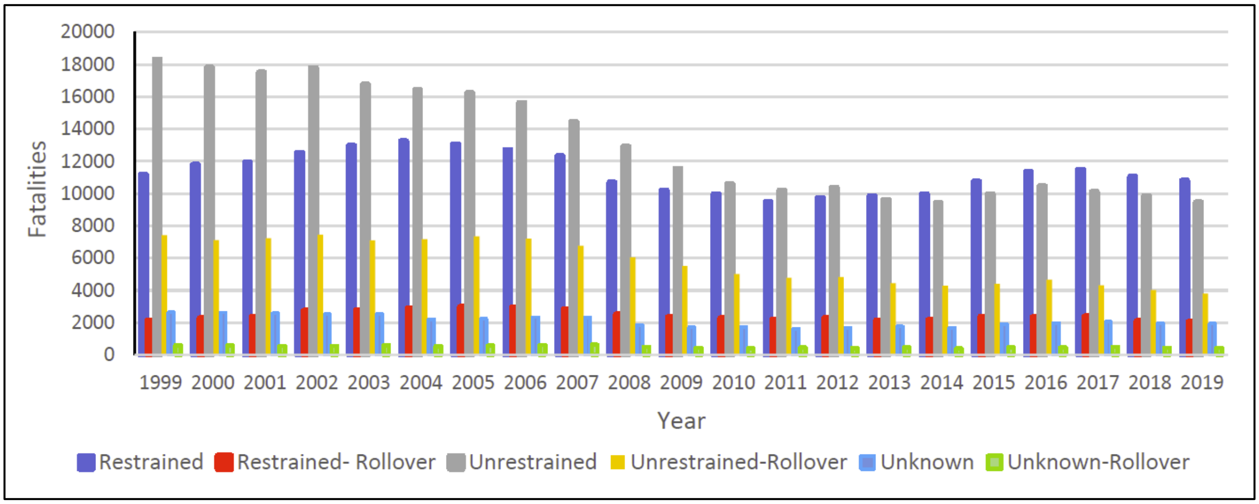


Figure 3.2: Passenger Vehicle Occupant Fatalities from FARS Data 1999-2019 (Data Source: [15])

Figure 3.2 illustrates passenger vehicle fatality data arranged by restraint condition and rollover occurrence using data from the FARS Database between 1999 and 2019. This database illustrates the following key points:

1) ROCs contribute to about 3% of all motor vehicle crashes but they account for almost 30% of all fatalities.

2) On average, around 20% of rollover fatalities were restrained.
3) Since 2000, on average, every year, more than 40% of all motor vehicle fatalities were found to be belted.
4) Since 2013, the number of restrained fatalities is found to be more than unrestrained.

There is no doubt that using a seat belt is far safer than not using one as it reduces the likelihood of a fatality or severe injury for most accident scenarios, but belted fatalities still occur. We believe that a potential reason for some of the belted fatalities and injuries could be high seat belt buckle release force. An occupant may find himself/herself restrained upside down in a seat, struggling to unlatch the seat belt in order to eject and avoid further harm after a motor vehicle crash [63]. Post-accident conditions such as fire, submersion, positional asphyxia, etc., can turn fatal due to entrapment. Even if the occurrence of such events is rare, it is necessary to research this topic and ensure that the release force standard is compatible with the capabilities of vehicle occupants.

3.2 Objective and Hypothesis

The primary goal of this experiment is to study the strength capabilities of adults to unlatch a push-button seat belt buckle in a rolled over orientation. The specific aims of this study were:

a) Measure the maximum buckle release force (push) exerted by the occupant in different orientations.
b) Determine if the occupant orientation affects their force exertion.
c) Determine if the occupant is able to unlatch the seat belt buckle in different orientations.

The hypotheses of the experiment were:

Hypothesis 1: The maximum push force exertion on push-button seat belt buckle for subjects is greater than the maximum buckle release force of 133 N mentioned in the standard.

$$H_0 : F_{\text{exerted by subjects}} \geq 133 \text{ N}$$

$$H_1 : F_{\text{exerted by subjects}} < 133 \text{ N}$$

Hypothesis 2: Force exerted by an occupant in an upright orientation is same as the force exerted in a rolled over orientation.

$$H_0 : F_{\text{exerted in rolled over orientation}} = F_{\text{exerted in upright orientation}}$$

$$H_1 : F_{\text{exerted in rolled over orientation}} \neq F_{\text{exerted in upright orientation}}$$

Hypothesis 3: Capability of subject to unlatch a seat belt in a rolled over orientation is same as the capability of subject to unlatch a seat belt in an upright orientation.

$$H_0 : N_{\text{unable to unlatch in rolled over orientation}} = 0$$

$$H_1 : N_{\text{unable to unlatch in rolled over orientation}} \neq 0$$

3.3 Research Equipment

The following equipment were used for data collection:

1. Custom Built Rollover Simulator
    a) Summit Racing Engine Stand - SUM-908300GA
    b) Kirkey 55 Series Aluminum Pro Street Drag Seats 55200

    c) Ford F-150 3-Point Driver and Passenger Harness
    d) Racequip FIA Camlock Harnesses - 854014

2. Force Gauge
    a) Chatillon Model DFS2-R-ND Digital Force Indicator
    b) Chatillon SLC-0500 Remote Force Load Cell
3. Seca 700 Physician Scale with Height Measuring Rod
4. Rubbermaid Pelouze P250SS Weight Scale

Figure 3.3: Seca 700 Physician Scale

Figure 3.4: Rubbermaid Pelouze P250SS Weight Scale

3.4 Experimental Design

The experiment was divided into 2 phases:

a) Phase 1: Force exertion

b) Phase 2: Unlatching ability

Sixty (60) subjects (30 males and 30 females) aged 18 and older were recruited from Auburn University, AL. A breakdown of the subjects is displayed in Table 3.1. Following comprehensive discussions, the Internal Review Board (IRB) gave its approval for the study. Subjects were recruited using flyers across campus and in-class announcements. A pre-screening of subjects was conducted before they came for data collection to ensure they met the eligibility criteria and understood the requirements of the experiment.

To participate in this study, subjects had to meet all the following eligibility requirements:

- 18 years of age or older.
- No history of physician-diagnosed musculoskeletal disorders, injury, or surgery in the back region.
- No chronic pain in back, shoulders, neck, or low back during the last 6 months.
- No history of physician-diagnosed musculoskeletal disorders, injury, or surgery in the hand and/or digits (fingers and thumbs).
- No chronic pain in the digits (fingers and thumbs) of both hands in the last 6 months.
- No physician-diagnosed neurodegenerative disease (e.g., Parkinson’s Disease, Multiple Sclerosis, etc.).
- No history of vertigo or motion sickness.
- Not pregnant.

Subjects were also requested to refrain from eating at least 2 hours prior to the study and not to eat too much prior to the study as they would be inverted during the experiment. IRB approved consent documentation was required prior to the data collection. The flyers, in-class announcement script, and informed consent form can be found in the Appendix (A, B, C).

Table 3.1: Sex Wise Subject Demographic and Anthropometric Data

Variable	Sex	Total	Mean	StDev	Minimum	Maximum	Range
Age	F	30	26.17	6.97	18.00	47.00	29.00
	M	30	28.47	6.84	19.00	55.00	36.00
BMI	F	30	23.679	3.773	16.830	35.700	18.870
	M	30	25.984	5.278	17.370	39.530	22.160

3.4.1 Rollover Simulator

In order to study the hypothesis, a test apparatus was designed and built in-house to replicate a passenger vehicle front seat rollover. Solidworks - Dassault Systems (2022) (computer aided design software), was used to design and develop the 3-Dimensional (3D) model prototype. Figure 3.5 depicts a 3D model of the rollover device during the design phase. The objective was to design a fixture that could house a passenger vehicle seat along with seat belts for both sides, to account for the driver and passenger side seat belt configuration. The goal was to rotate the subject to three (3) different angles (90°,180°, and 270°) to mimic the three (3) most common scenarios for a passenger vehicle after a rollover accident and test their buckle release strength capabilities. The most critical aspect of the design was to introduce a fall protection mechanism in order to prevent the occupant from falling and hurting themselves when they were rolled over for the experiment.

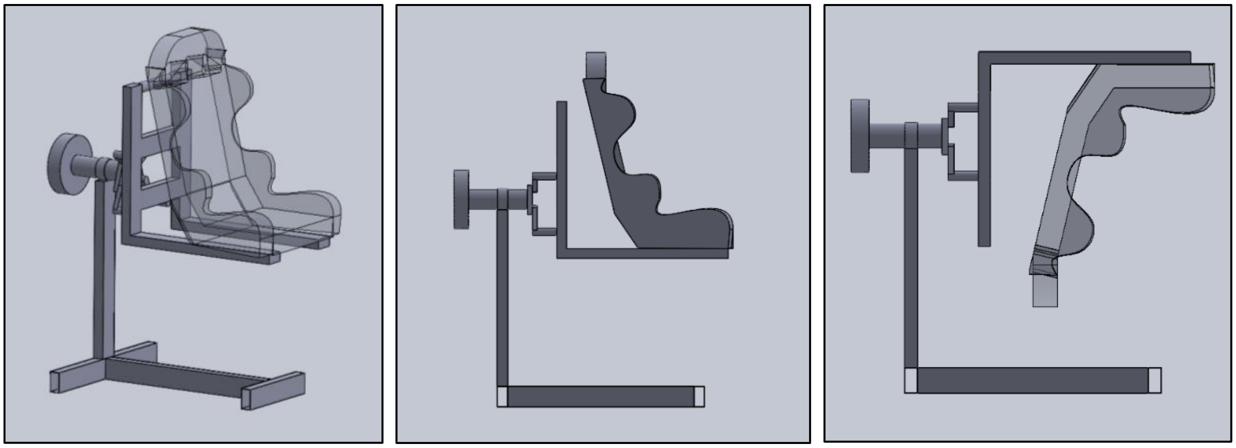


Figure 3.5: 3D Model of the Rollover Device Built in Solidworks

A 1,000 lb. weight capacity engine stand was purchased from Summit Racing Equipment (Figure 3.6) and was used as the base for this apparatus. This engine stand has a 63:1 geared head permitting it to rotate 360° with the capability of holding a mounted engine (in our case the seat) at any desired angle, due to a worm gear assembly as seen in Figure 3.7. This worm gear setup ensures the seating assembly maintains its position regardless of force or movement on the seating side. This was especially beneficial in keeping the subjects safe during the unlatching phase.

Figure 3.6: Summit Racing 1,000 lb. Engine Stand [178]

Figure 3.7: Worm Gear Assembly Used in Engine Stand [179]

A custom metal frame was designed and fabricated in order to mount a seat to the engine stand and house all the necessary anchor points for the seat belts. A typical racing style bucket seat style was chosen as it was capable of housing a 6-point harness, Figure 3.8, which would act as the fall protection harness for this experiment.

The widest commercially available bucket seat with a width of 20 inches as shown in Figure 3.9, was used in order accommodate a broader range of subjects. To test the unbuckling capability of a subject, the fixture was equipped with a 3-point restraint system with an end-release push-button buckle. The restraint system was from a 2012 Ford F-150 pickup truck, for the passenger and driver side.

Figure 3.8: Racequip 6-Point Racing Harness [180]

Figure 3.9: Kirkey Racing 55200 Aluminum Bucket Seat [181]

The primary reasons for using a Ford F150 restraint system were:

a) Pick-up truck fatalities are one of the highest in rollover crashes.

b) For more than four decades, the Ford F150 has been the best-selling vehicle and the best-selling pickup truck in America [182], [183].

Post unbuckling, to prevent the subject from falling out from the seat, a Racequip 6-point FIA Camlock Harnesses, model 854014 (Figure 3.8) was used. A challenging aspect of the design was to establish accurate anchor points for the belts (both 3-point aned 6-point) to represent the seat belt effects of a real passenger car.

3.4.1.1 Seat Belt Anchorage Locations

Federal Motor Vehicle Standard 571.210 establishes requirements for seat belt assembly anchorages to ensure their proper location for effective occupant restraint and to reduce the likelihood of their failure [184]. For accurate mounting of the Type 2, 3-point lap-shoulder seat belt, guidelines from FMVSS 210, SAE J826, SAEJ1100, seat belt anchorage and seating position points described in EU Regulation 14, and the European New Car Assessment Programme (Euro NCAP) protocols were followed [184]–[188].

For seat design and seat belt anchor points, the Seating Reference Point (SgRP) holds critical significance in automobiles as it is used to locate the occupant's seating position within a vehicle to ensure their comfort and safety. The SgRP or the H point, according to FMVSS 571.3 and as defined in the SAE J1100, is a point that "Establishes the rearmost normal design driving or riding position of each designated seating position, which includes consideration of all modes of adjustment, horizontal, vertical, and tilt, in a vehicle" [186], [189]. Figure 3.10 illustrates the SgRP along with other dimensional relationships within a vehicle.

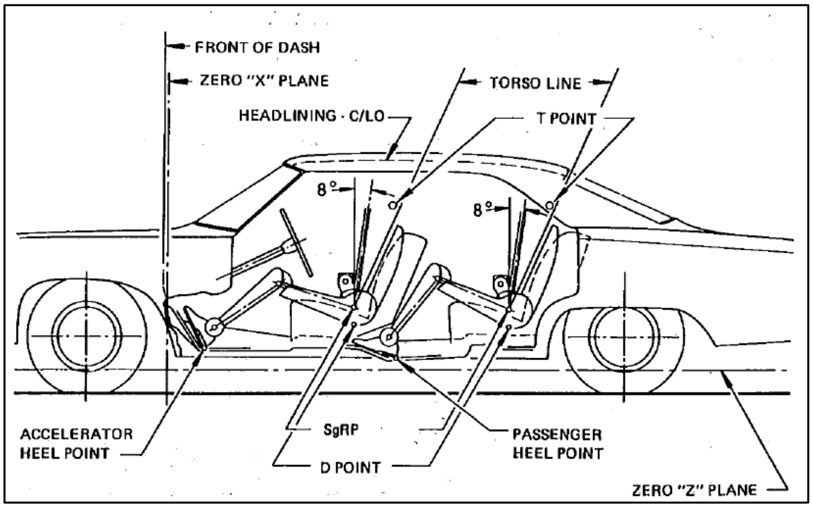


Figure 3.10: Seating Reference Point in a Vehicle (SAEJ1100) [186]

For the lap belt portion, according to the FMVSS 210 S4.3.1.1, an installation where the seat belt does not bear upon the seat frame and if the seat is nonadjustable, then a line from the SgRP to the nearest contact point of the belt with the anchorage shall extend forward from the anchorage at an angle with the horizontal of not less than 30° and not more than 75° [184].

For the shoulder, FMVSS 571.210 S4.3.2 mentions that the upper end of the upper torso restraint shall be located within the acceptable range shown in Figure 3.11, with reference to templates and H-points described in SAE Standard J826 and SAE J1100 [184].

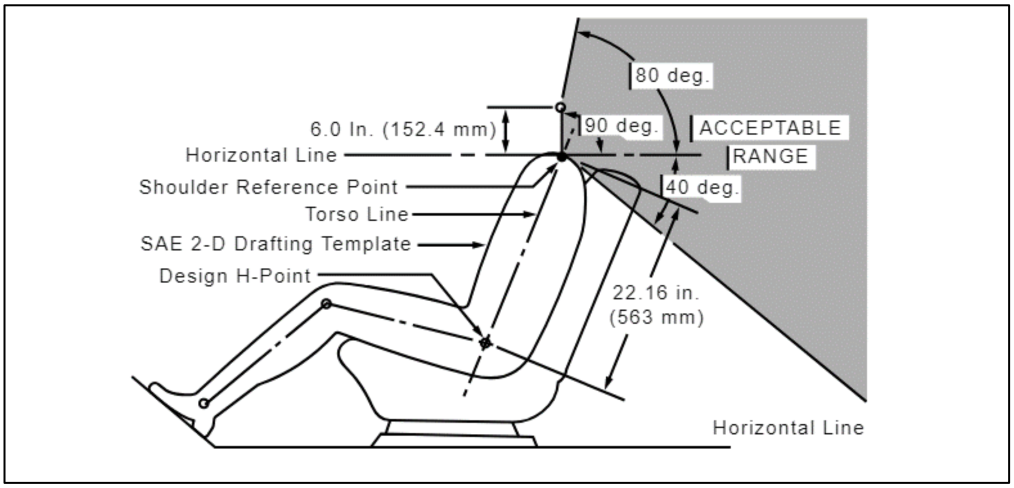


Figure 3.11: Location of Shoulder Strap Anchorage (FMVSS 571.210) [184]

Due to the vague nature of the federal standards for anchor points, EU regulations were also reviewed. Regulation 14 of the UNECE provides uniform provisions concerning the approval of vehicles with regard to seat belt anchorages, in which detailed requirements for seat belt anchors have been outlined [187]. Figure 3.12 illustrates the areas of location of effective belt anchorages according to the EU Regulation 14. The standard (Regulation 14 - 5.4.2.1) mentions that the angle α1 (other than buckle side) shall be within the range of 30° to 80° and the angle α2 (buckle side) shall be within the range of 45° to 80° [187]. Here, at least one of the angles α1 and α2 is constant in all normal positions of use, and its value shall be 60° ± 10° [187].

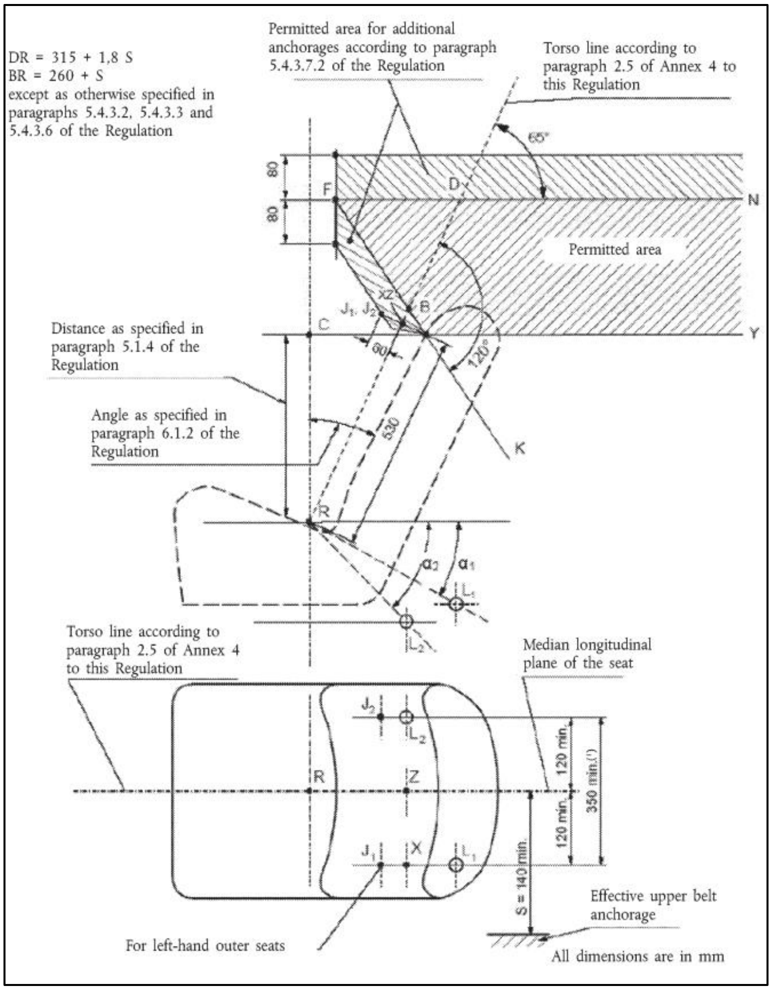


Figure 3.12: Location of Effective Seat Belt Anchorages as per EU 14 [187]

Due to the fact that both the FMVSSs and the EU standards are for passenger vehicles and talk about seat belt anchor points pertaining to production models of passenger vehicles, the guidelines from EuroNCAP were also reviewed. EuroNCAP is a European voluntary vehicle safety performance rating system which provides consumers with information regarding the safety of passenger vehicles [190]. To dynamically test and evaluate all forward-facing front motor vehicle seats and head restraint assembly, EuroNCAP performs experiments using a test sled to simulate a variety of crash scenarios. For these tests, the generic three-point lap-shoulder seat belts anchorages should be positioned as shown in Figure 3.13 [188]. The illustrated marks correspond to the arrangement of the anchorages where the ends of the belts are to be connected to the sled.

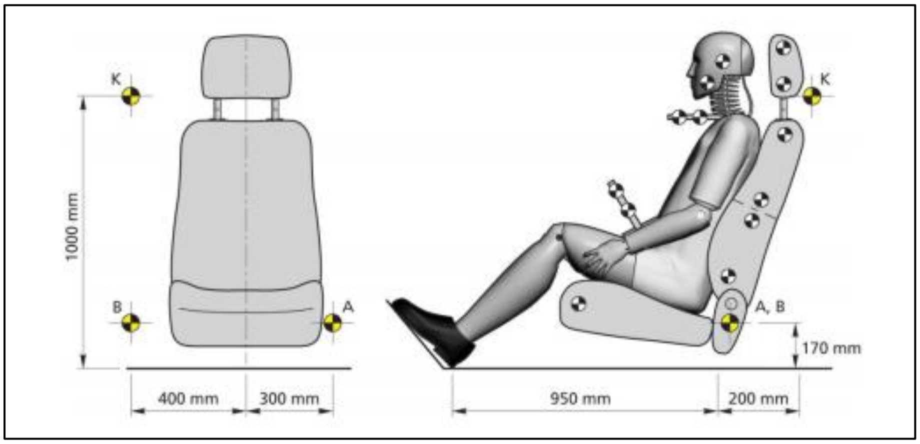


Figure 3.13: Belt Anchorage Positions for a Three-Point Lap-Shoulder Seat Belt [188]

Federal standards only mention anchorage requirements for Type 1 and Type 2 seat belts. The 6-point racing harness that is used as a fall protection harness in this experiment is not covered under those federal standards. Hence, racing harness installation guides from the SFI Foundation, FIA, and NASCAR approved racing harness manufacturer’s installation guides were followed.

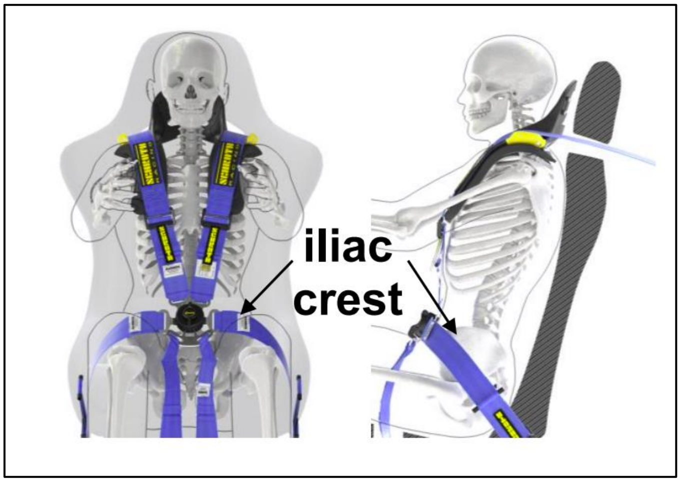


Figure 3.14: Mounting Point Positions [191]

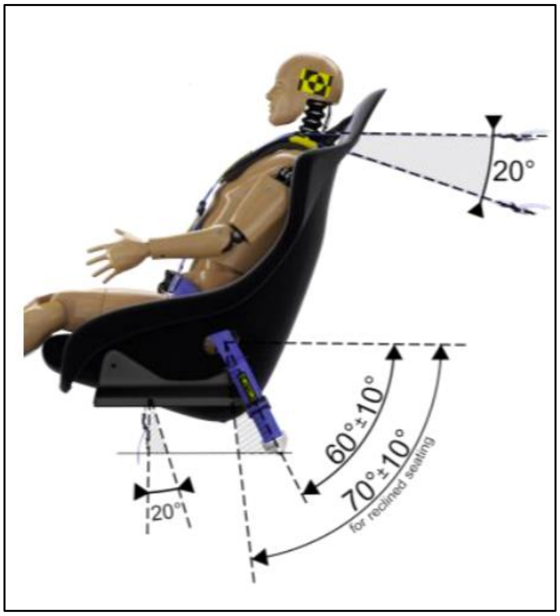


Figure 3.15: Restraint Angles Guideline [191]

SFI foundation is a non-profit organization that sets safety standards for the racing industry along with developing and certifying safety equipment and gear for use in motorsports, including racing suits, gloves, harnesses, helmets, and other safety gear [192]. According to the SFI foundation's seat belt installation guide [193], some of the main recommendations were:

1) To keep the shoulder belt angle between 0° to 20°.
2) For the lap belt, the recommended angle was between 45° and 80° from the horizontal and that belt should ride within the curvature of the pelvic bone preferably just below the iliac crest.
3) Crotch belt angle should be between 0° to 20° for a 6-point harness.
4) Most importantly, all the belts should be as short as possible from the mounting point.

Based on these guidelines, a frame was constructed as shown in Figure 3.16 to accommodate both the 3-point and 6-point harnesses. In addition, extra slots were incorporated to allow for testing with different types of seats if required.

Figure 3.16: Mounting Frame with Anchor Points

Figure 3.17: Device with Seat and Restraints Mounted

Figure 3.17 shows the bucket seat and both the restraints mounted to the frame. During initial testing, it was realized that the wheels for the engine stand were not ideal because the brakes were not strong enough to prevent the entire device from sliding due to lack of friction. The device was modified by removing the wheels and adding extender arms for stabilization. Figure 3.18 shows this modified setup. To prevent injuries, a wooden platform was built to go over the base of the frame. A 6-inch gel memory foam mattress was placed on top of the wooden platform to provide cushioning and absorb the impact in the unlikely event of a subject falling from the device.

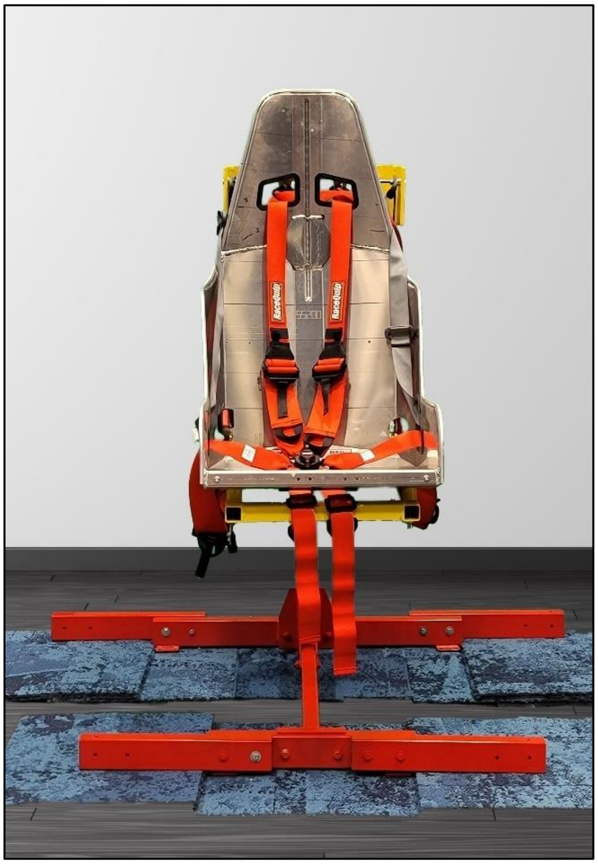


Figure 3.18: Modified Base

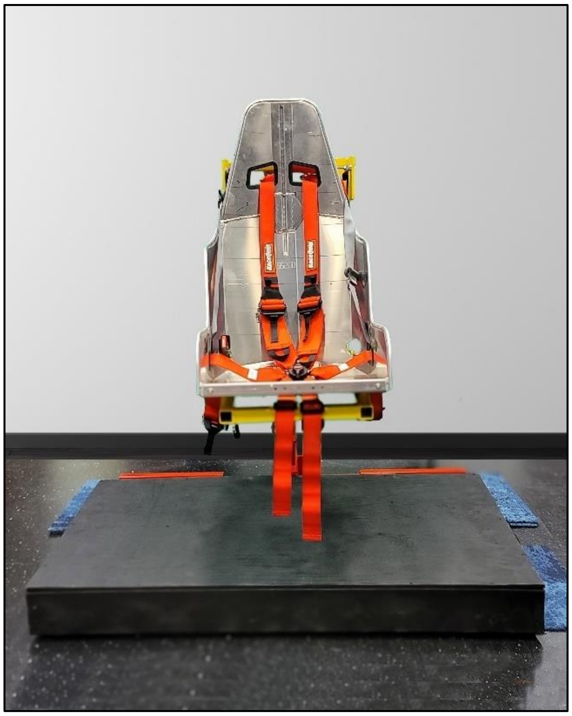


Figure 3.19: Wooden Platform on Base

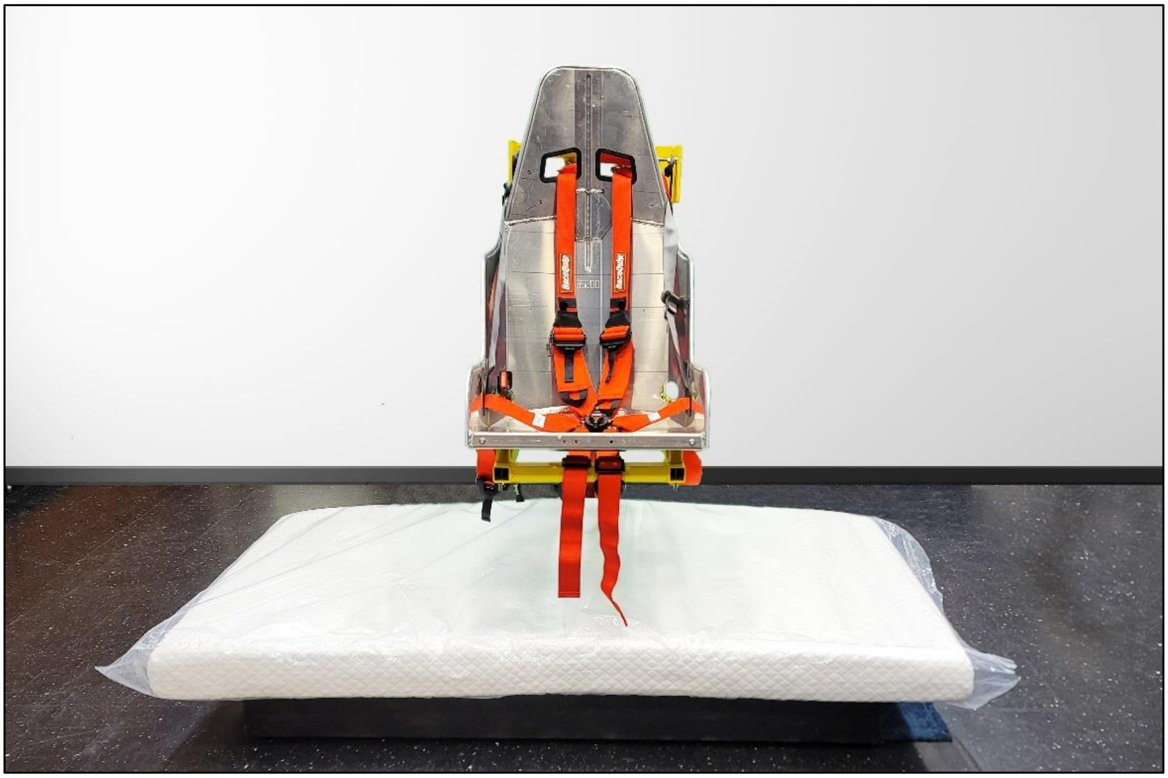


Figure 3.20: Final Test Device Setup

Figure 3.21 shows a subject sitting in the device with both the 3-point and the 6-point harness, to illustrate the typical angles observed with a subject on the rollover simulator.

Figure 3.21: Subject Wearing Both Restraints Illustrating Belt Angles

3.4.2 Force Measurement Setup

A Chatillon DFS2-R-ND Digital Force Dynamometer with the Chatillon SLC-0500 Remote Force Load Cell, Figure 3.22, was used to measure the maximum force exerted by the subjects in different orientations. Arrangements were made to mount the external load cell to both sides of the seat to measure the force exerted using both hands one at a time in all orientations, as seen in Figure 3.29.

Figure 3.22: Chatillon DFS2-R-ND Digital Force Dynamometer with the Chatillon SLC-0500 Remote Force Load Cell

According to the FMVSS 209 (d)(2), a buckle designed for push-button application of buckle release force shall have a minimum area of 452 mm^2 with a minimum linear dimension of 10 mm for applying the release force [27]. UNECE Regulation 16 Standard 2.4.2.2 mentions that a buckle which is released by pressing a button shall have an area of not less than 4.5 cm^2 and a width of not less than 15 mm [84].

Keeping these standards in mind, a custom push button prototype was designed to represent a potential seat belt push button with the minimum dimensions possible. The dimensions for the button were 15 mm by 31 mm with a surface area of 465 mm^2. This custom button was 3D printed on a Markforged Mark 2 3D printer using a mixture of a special composite base material Onyx^{TM} (a micro carbon fiber filled nylon) along with carbon fiber layers near stress points [194].

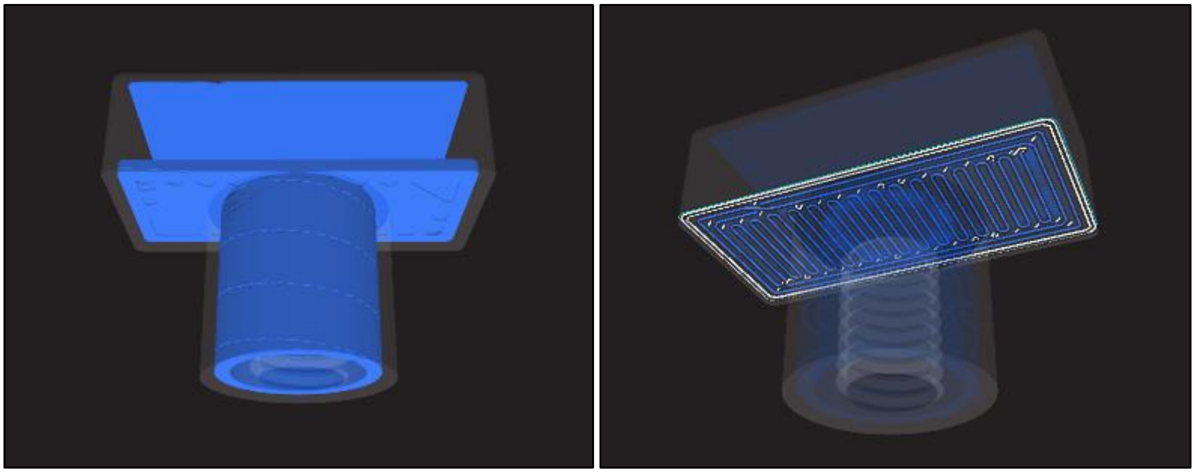


Figure 3.23: Custom 3D Printed Push Button Prototype illustrating Filament Layout

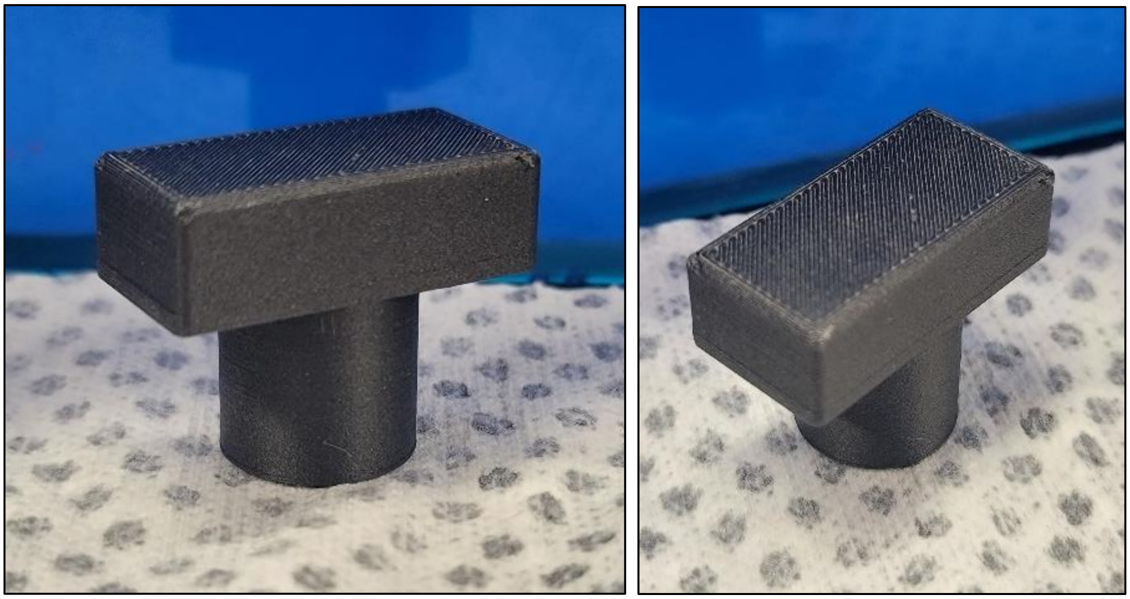


Figure 3.24: 3D Printed Push Button Prototype

Figure 3.25: Push Button Load Cell Setup

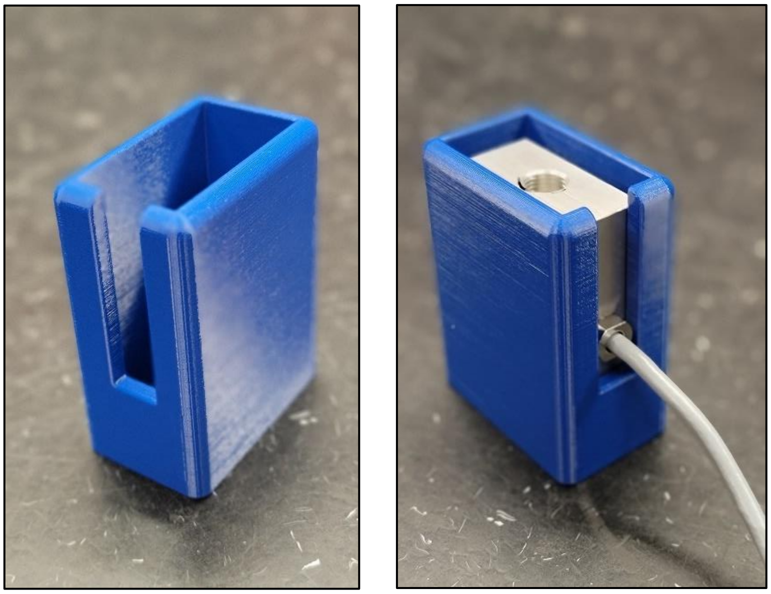


Figure 3.26: Custom 3D Printed Load Cell Cover

The load cells as seen in Figure 3.25, have very sharp edges and due to the nature of the study and their location, a custom protective casing was designed and 3D printed to fit the load cell and cover the sharp edges (Figure 3.26). To simulate the load cell's position and function to pressing an actual seat belt button, it was important to mount the load cell to have the button at the same height and angle to its belt buckle counterpart. Figure 3.27 shows the mounting bracket that was designed to mount the load cell. With this, both the height of the load cell and the angles could be adjusted. Figure 3.28 shows the side-by-side comparison of load cell assembly to the seat belt buckle assembly.

Figure 3.27: Load Cell Assembly Mount

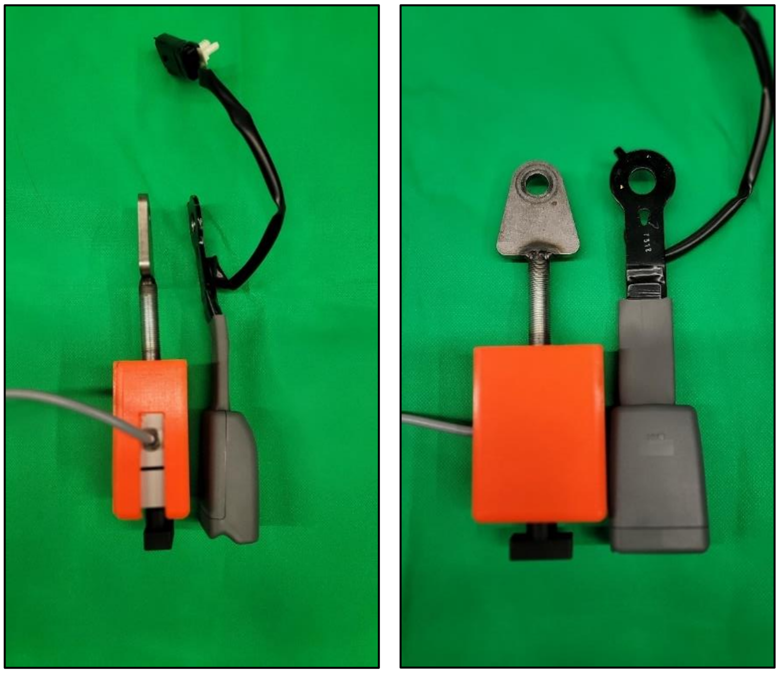


Figure 3.28: Push-Button Load Cell Setup Position Comparison

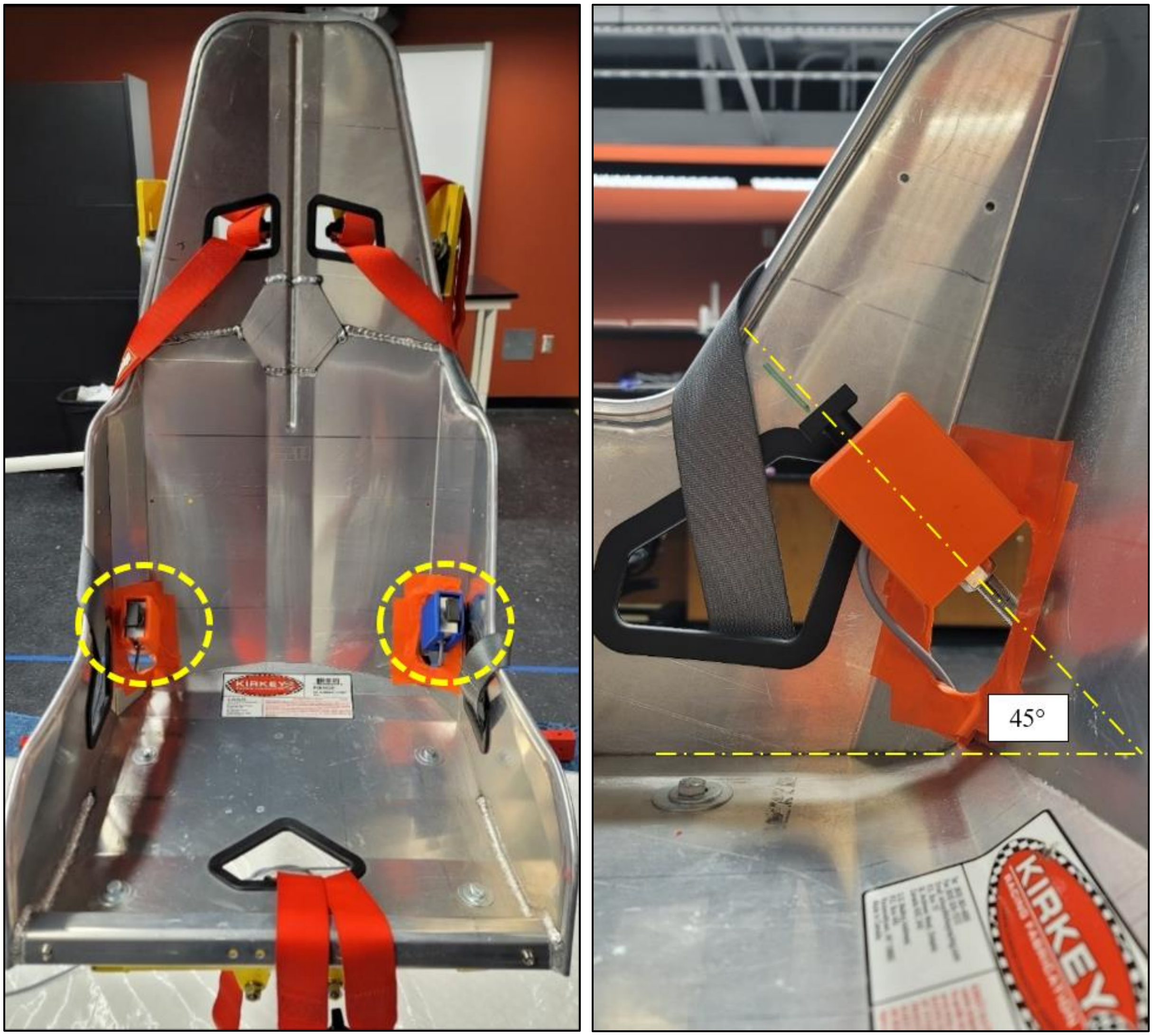


Figure 3.29: Final Load Cell Assembly - Front and Side View

Figure 3.30 illustrates the final load cell assembly with a subject. The covers had different colors to make it easier for the subjects and the Research Assistants (RA) to identify the side. Figure 3.31 illustrates pressing the load cell from a side view.

Figure 3.30: Force Measuring Push Button Setup with Subject

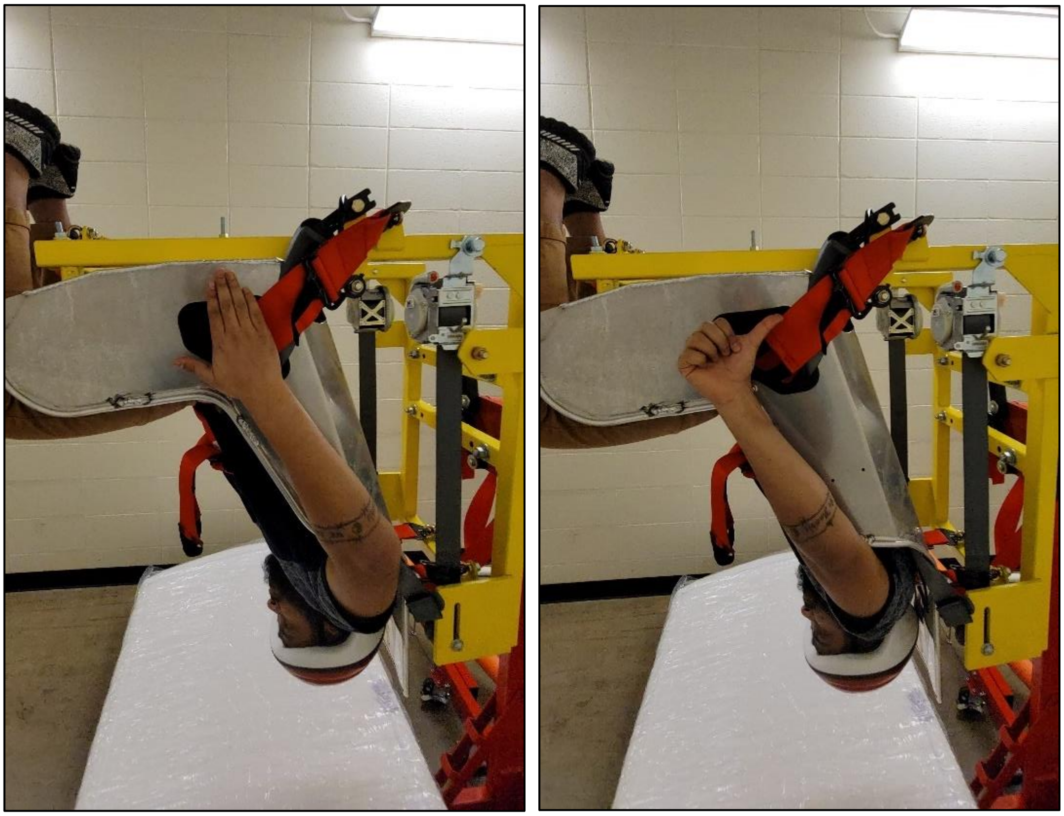


Figure 3.31: Force Exertion Illustration of 180° Orientation Side View

3.5 Trial Methodology

The experiment was conducted in 2 phases. The primary reason for splitting the experiment into 2 phases was to change the key components (switching between load cell and 3-point seat belt buckle) within the equipment according to the requirements of the study. The order of the phases was randomized. Phase 1 measured the force exertions at different orientations and Phase 2 measured the unlatching ability of the subjects. After the pre-screening process, subjects were scheduled for data collection. For data collection, 2 stations were allocated. At station 1, the subjects' consent was obtained, then their personal demographics were noted, and their height and weight were recorded. The subject recruitment sheet is attached in the Appendix (D). Station 2 is where the test equipment was kept. The starting phase was determined based on a randomized order (Appendix V).

3.5.1 Phase 1: Force Exertion

The goal of this phase was to measure the maximum push force exerted by an occupant in different orientations on a push-button buckle prototype. 3 angles were selected to represent the 3 most common scenarios a car can end up in after rollover, with 0° being the normal orientation. In a passenger car, an occupant could wear a seat belt either with the buckle on the left side or the right side and they could unlatch it by pressing the push-button with either their fingers or thumb. For the purpose of this study, the number of fingers was not treated as different groups because depending on the anthropometry of an individual, he or she can fit anywhere between 1 or 4 fingers on the button to exert force. Only 2 groups were made based on the digits, pressing with just the thumb as group 1 and pressing with fingers (independent of number of fingers) as group 2. Originating from these, a total of 16 different variations of force exertions are possible as displayed in Figure 3.32. For determining the order of force exertion for each subject, a split-plot randomization technique was used for this phase. The experimental trial order is attached in the Appendix (W).

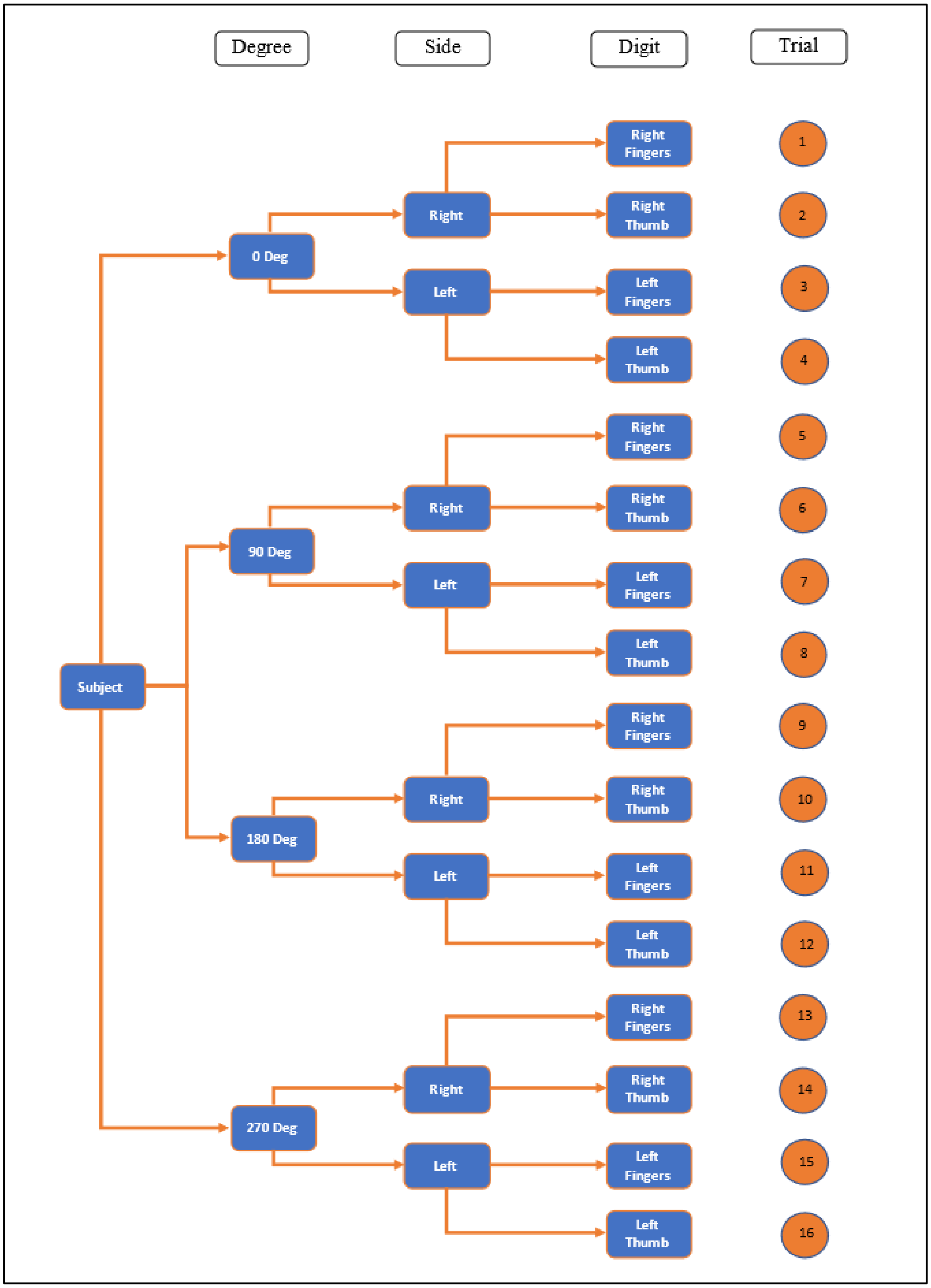


Figure 3.32: Force Measurement Experiment Trial Layout

Once the subject was ready to begin trial, they were asked to wear a bicycle helmet and sit on the bucket seat and don the 6-point harness. The harness was tightened with minimum slack to prevent movement within the seat while being rotated. They were then rotated to the required orientation based on the randomized order and upon receiving the signal from the research associate, they were asked to exert force on push button prototype connected to the load cell situated at the corresponding side.

3.5.1.1 Maximum Voluntary Contraction

For measuring the maximum force exerted by the subject, the methods prescribed by previous studies to measure Maximum Voluntary Contraction (MxVC) [170], [171], [195]–[199] were followed. Upon signal from the research associate, the subject was asked to slowly start exerting the force on the push button prototype and reach their maximum effort after 3 seconds. They were asked to hold the maximum effort for 3 seconds and were then asked to slowly relax over a duration of 3 seconds. Between MVC sets, several studies prescribe a resting period of 2 minutes [170], [195]–[199]. Based on that, a rest period of 2 minutes was observed between each MxVC set that involved the same digit.

The subjects were brought to 0° (upright orientation) during this rest period. For trials involving a different hand (side), the greater value between a 30 second rest period or the time to get to that particular orientation, was observed. Note: the standard seat belt buckle was removed to avoid hinderance in exerting force and to avoid confusion as to which button is required to be pressed. Figure 3.34 illustrates the setup for this phase.

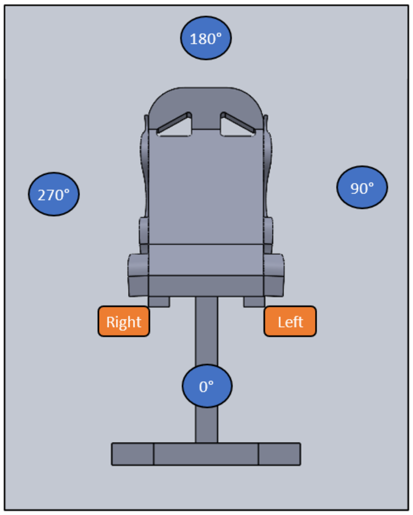


Figure 3.33: Rollover Simulator Position Illustration

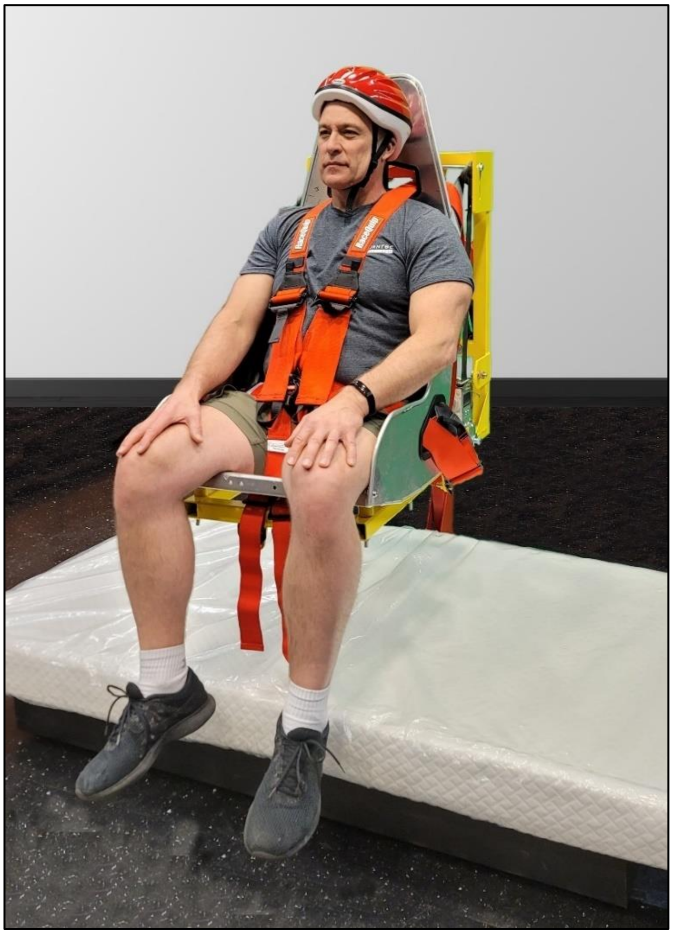


Figure 3.34: Subject in 0° Orientation During Force Exertion Phase

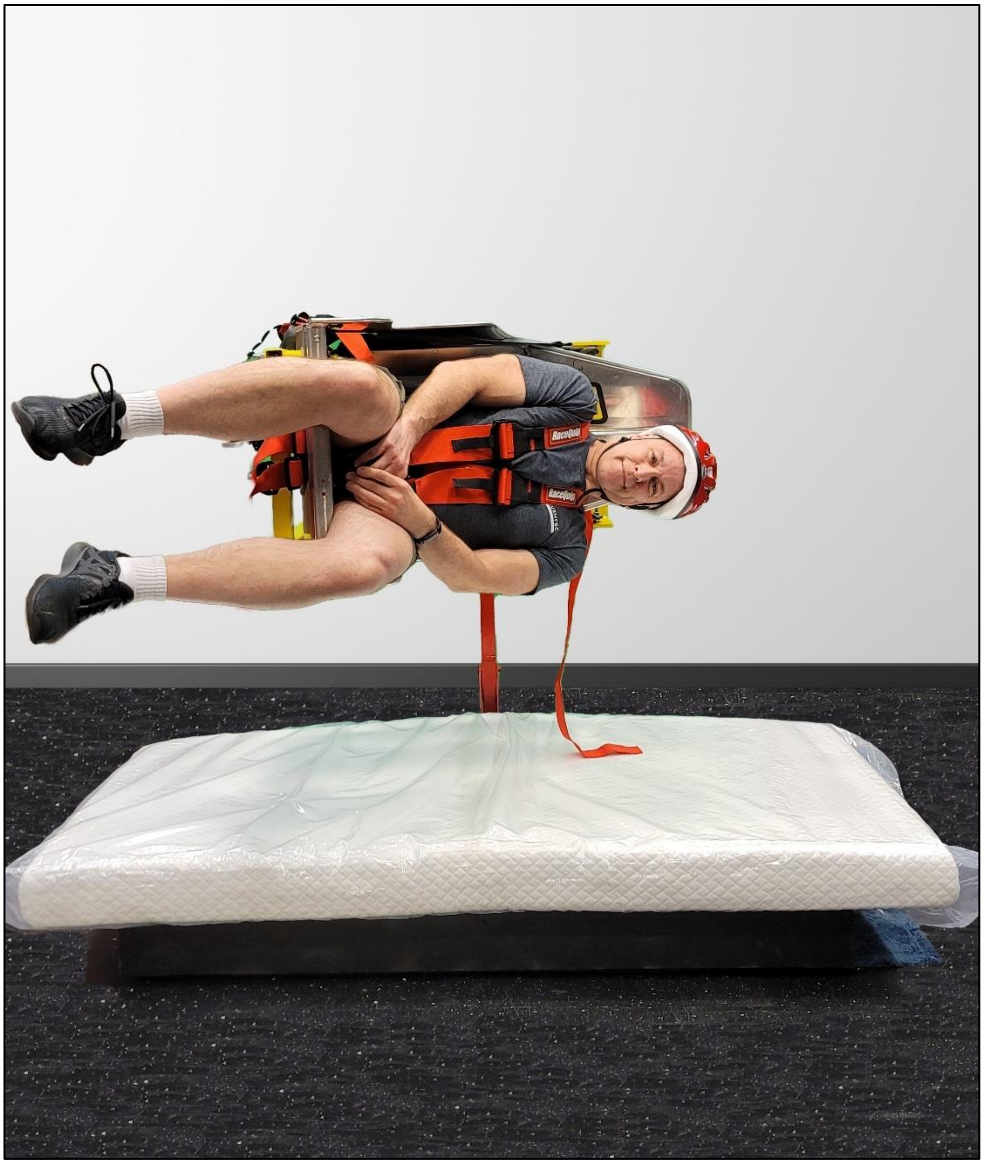


Figure 3.35: Subject in 90° Orientation During Force Exertion Phase

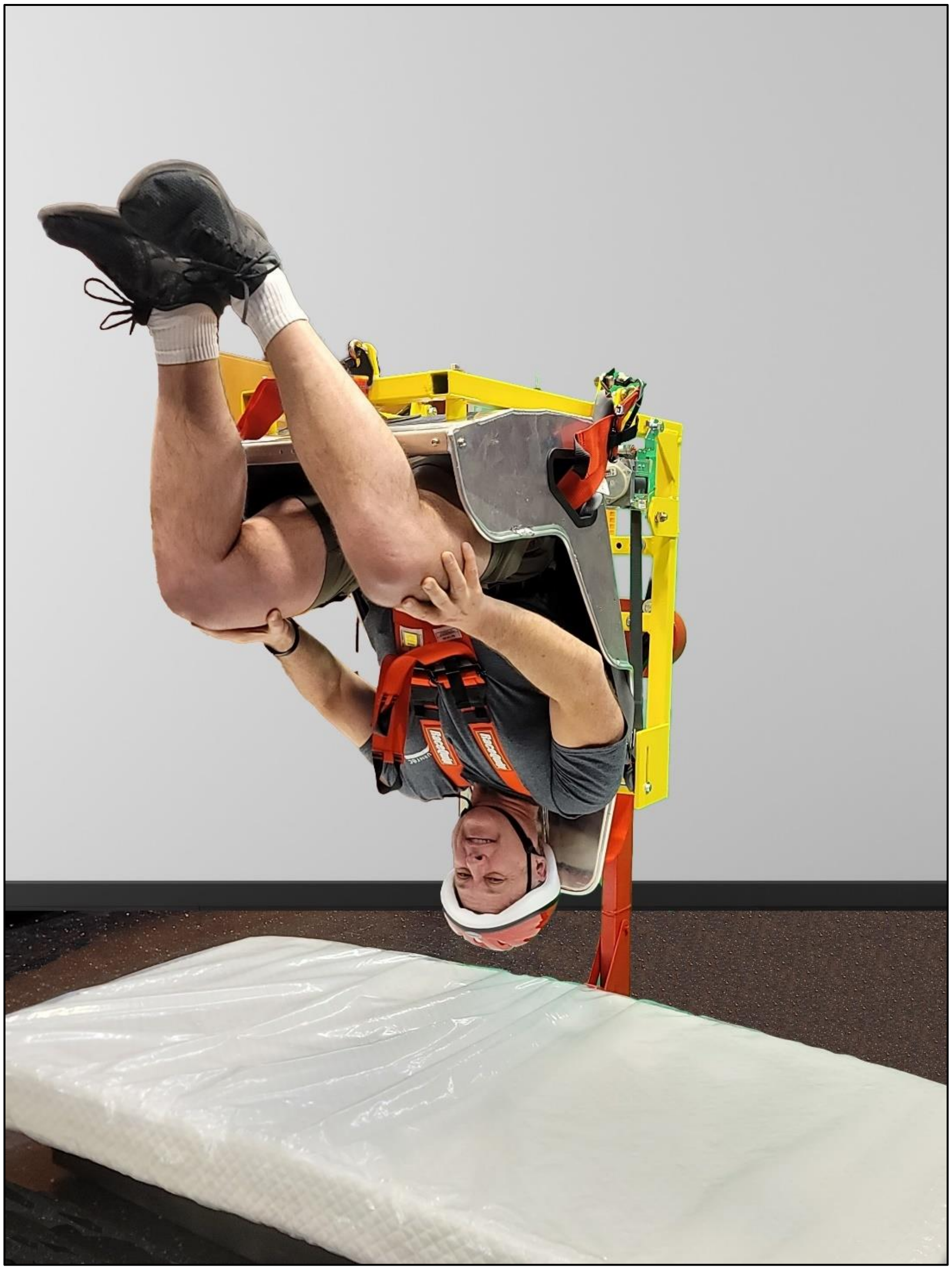


Figure 3.36: Subject in 180° Orientation During Force Exertion Phase

After all the force exertion trials were conducted, the subjects were brought back to 0° (upright orientation), the 6-point harness was unlatched, and they were helped to step out of the device. The subjects were asked to rest as the researchers switched the load cell setup with the 3-point harness seat belt buckle for the next phase.

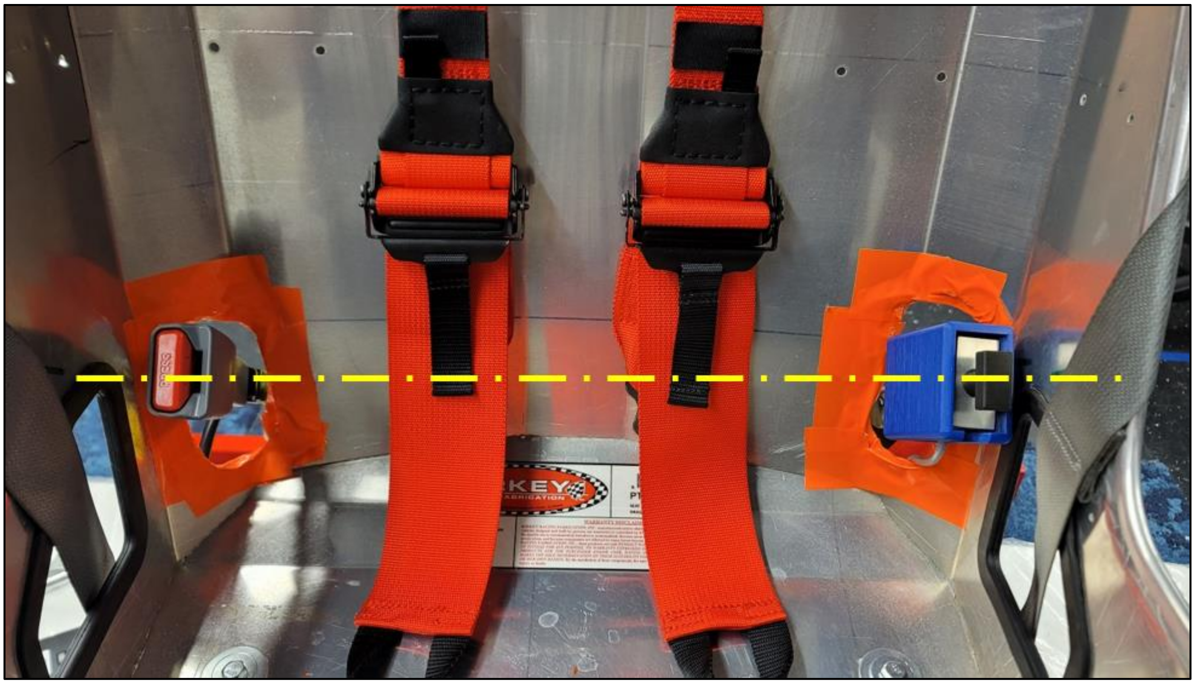


Figure 3.37: Example of Relative Positions of Buckle and Load Cell

Figure 3.38: Illustration of Push Button Buckle and Load Cell Superimposed

3.5.2 Phase 2: Seat Belt Unlatching

The goal of this stage was to determine if an occupant is able to unlatch a seat belt in a rolled over orientation. Three (3) angles were selected to represent the 3 most common scenarios after a rollover. In a passenger car, an occupant could wear a seat belt either with the buckle being on the left side or the right side, and they could unlatch it by pressing the push-button with either their fingers or thumb.

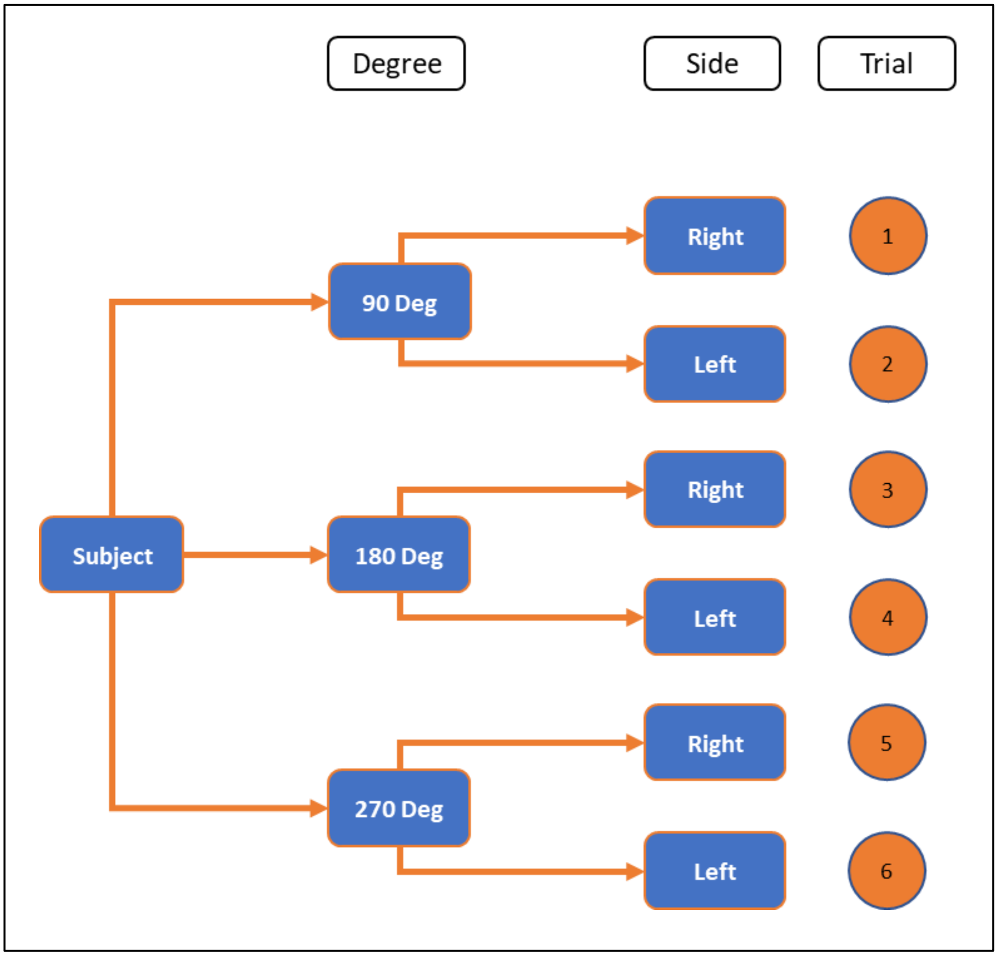


Figure 3.39: Unlatching Ability Experiment Trial Layout

In a real-world scenario, during an accident/emergency an occupant could unlatch their seat belt using any method – fingers, thumb, or a combination of both and egress the vehicle. Hence, for the purpose of this study, the digits used to unlatch were not treated as different groups. A total of 8 different variations are possible for unlatching the seat belt in different orientations as shown in Figure 3.39. The order in which these unlatching trials were performed was randomized. When the subject was ready for the trial, they were asked to sit in the seat and don the 3-point harness for the side based on the randomized trial order. The 6-point racing harness was then fastened onto the subject with slack in order to maintain webbing load on the 3-point seat belt similar to a conventional vehicle. The slack limit was restricted to not more than about 4-inches (fist size) between the subject's body and the harness (Figure 3.41). This limit was required by the IRB while approving the study and is a limitation of this study that will be discussed later in this chapter.

After making sure both the 3-point and 6-point harness was secure, the subject was rotated to the desired angle (based on trial order). Once they reached that position, upon receiving instruction from the RA, the subject was asked to press the 3-point seat belt push button in order to unlatch themselves. For consistency in data collection, the subject was requested to unlatch only using the side of the hand coinciding with the side of buckle. After each trial the subject was brought to the upright position and the process was repeated. Subjects were given 3 attempts to unlatch the seat belt buckle. Each attempt was defined by a subject taking their hand out and reaching the button to unlatch and if unsuccessful, taking their hand away from the button for the RA to see and then trying again. They had the option to stop the experiment at any time if they felt uncomfortable or were unable to unlatch.

Figure 3.40: Phase 2 Subject Orientation at 0°

Figure 3.41: Fall Protection Harness Slack Illustration

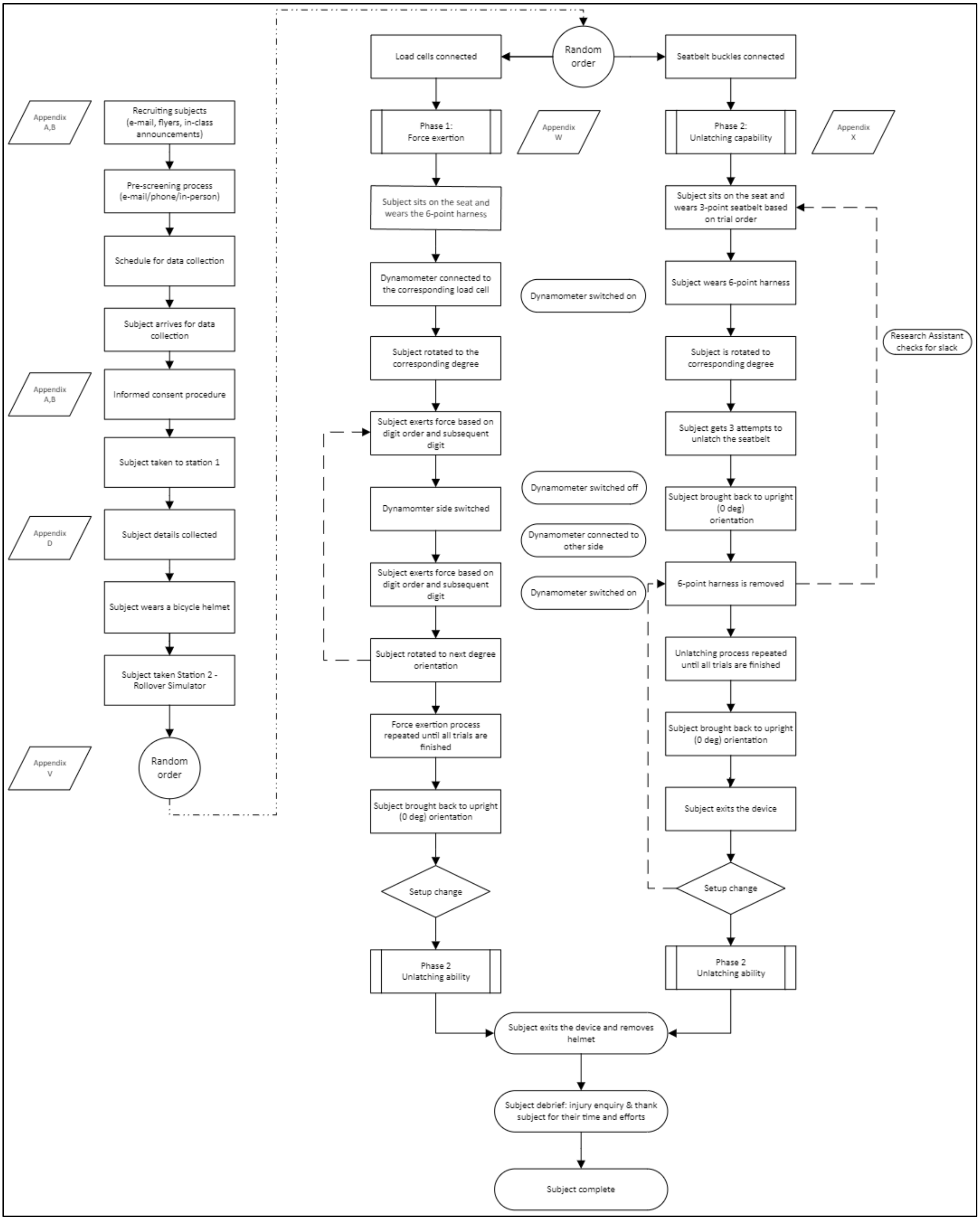


Figure 3.42: Experiment Data Collection Process Flow Chart

3.6 Statistical Analysis Methods

The data collected from the experiment underwent both visual inspection and statistical testing to determine its suitability for various analytical techniques such as Analysis of Variance (ANOVA), Analysis of Covariance (ANCOVA), linear regression models, and binary logistic regression. Visual inspection included examining box plots, individual value plots, normality plots, histograms, residual plots, and checking for outliers. The statistical testing took into account the assumptions of normality of residuals and equality of variance. These analyses were conducted using Minitab 21 (2023) Statistical Software, State College, PA, USA: Minitab Inc., SPSS statistics software (2023 IBM SPSS Statistics 29, Chicago, IL, USA) and StatistiX 9.0 statistical software (Analytical Software; Tallahassee, FL, Maryland, USA).

The independent variables for the experiment were: Categorical - sex (male, female), degree (0°, 90°, 180°, 270°), side (right, left), digit (finger, thumb), and Continuous - BMI, age.

The dependent variables of this experiment were force (N) exerted in different orientations, and binary output for ability to unlatch (1-yes, 0-no).

The statistical significance of the main and interaction effects of the independent variables on the dependent variables were tested using ANOVA following a split-split-plot factorial design for each sex. The degrees were assigned as the main plot, side (hand) as sub plot and digit as sub-sub plot. Tukey Honest Significant Difference (HSD) post-hoc tests were conducted to compare each possible pair of the factors for each sex.

For studying the effects of BMI and age on the force exertion, a linear regression model was developed for the data set and an analysis of covariance (ANCOVA) was performed. Regression Analysis for force versus age, BMI, sex, degree, side, and digit was performed. For this analysis, a backward elimination process was used using Minitab with an alpha value ($\alpha = 0.05$) to remove. "This method starts with all potential terms in the model and removes the least significant term for each step. Minitab stops when all variables in the model have p-values that are less than or equal to the specified Alpha to remove value" [200].

The objective of the unlatching study was to investigate the capability of a participant to release a seat belt while in a rolled-over position. The study focused on three prevalent orientations that a vehicle could assume following a rollover incident, namely 90°, 180°, and 270°. Unlatching at 0° was not tested. If a subject was able to unlatch in any of the six (6) rollover orientations, then it was assumed that they could unlatch in an upright (0°) as well. There were no instances where a subject was unable to unlatch the buckle in all of the non-upright orientations. Therefore, it was assumed that all subjects could unlatch the buckle in the upright orientations. The outcome of each orientation was recorded as binary as only two (2) outcomes were possible. All 60 subjects performed all the possible six (6) unlatching orientations. There were 6 instances where a subject could not unlatch. Three (3) male subjects and one (1) female could not unlatch in 1 orientation and 1 female subject could not unlatch in 2 orientations.

A binary logistic regression was performed on the unlatching ability of subjects at different orientation against independent variable – BMI, age, sex, degree, and side. All terms and interaction effects were added to the model, and a backward elimination process was used to determine the best fitting model with an alpha value ($\alpha = 0.05$) to remove.

3.7 Results

3.7.1 Descriptive Statistics

A summary of subject demographic and anthropometric data is presented in Table 3.2. Table 3.3 represents this data sex wise. Each of the 60 subjects performed all the trials for both phases – force exertion and unlatching ability.

Table 3.2: Subject Demographic and Anthropometric Data

Variable	Total Count	Mean	StDev	Minimum	Maximum	Range
Age	60	27.317	6.947	18.000	55.000	37.000
BMI	60	24.831	4.695	16.830	39.530	22.700

Table 3.3: Sex Wise Subject Demographic and Anthropometric Data

Variable	Sex	Total Count	Mean	StDev	Minimum	Maximum	Range
Age	F	30	26.17	6.97	18.00	47.00	29.00
	M	30	28.47	6.84	19.00	55.00	36.00
BMI	F	30	23.679	3.773	16.830	35.700	18.870
	M	30	25.984	5.278	17.370	39.530	22.160

Table 3.4: Subjects in each BMI category

	Male	Female	Total
Underweight (below 18.5)	2	1	3
Normal (18.5-24.9)	13	19	32
Overweight (25-29.9)	9	8	17
Obese (above 30)	6	2	8
Total	30	30	60

3.7.1.1 Force Exertion Descriptive Statistics

Table 3.5 summarizes the results of the force exertion trial and Table 3.6 represents the same separated by sex. Table 3.7 and Table 3.8 illustrate the force exerted by female and male subjects at different degrees. Figure 3.43 and Figure 3.44 illustrate the distribution of age and BMI for both sexes. Figure 3.45 displays the individual values of force exertion for both male and female subjects. From Figure 3.46 to Figure 3.50, multiple force exertion descriptive statistics are graphically illustrated for sex, degree, side and digit.

Table 3.5: Results of the Force (N) Exertion Trial

Variable	**Total Count**	**N**	**Mean**	**StDev**	**Minimum**	**Maximum**	**Range**
Force	960	904	65.059	27.380	13.600	267.800	254.200

Table 3.6: Results of the Force (N) Exertion Trial by Sex

Variable	**Sex**	**Total Count**	**N**	**N***	**Mean**	**StDev**	**Minimum**	**Maximum**	**Range**
Force	F	480	460	20	54.040	20.232	13.600	177.400	163.800
	M	480	444	36	76.47	29.11	20.20	267.80	247.60

Table 3.7: Force (N) Exerted by Female Subjects in Each Orientation

Variable	**Degree**	**Total Count**	**N**	**N***	**Mean**	**StDev**	**Minimum**	**Maximum**	**Range**
Force	0	120	120	0	59.44	19.75	24.80	120.00	95.20
	90	120	113	7	50.21	18.76	15.20	107.80	92.60
	180	120	116	4	55.79	23.03	13.60	177.40	163.80
	270	120	111	9	50.27	17.58	18.80	97.40	78.60

Table 3.8: Force (N) Exerted by Male Subjects in Each Orientation

Variable	**Degree**	**Total Count**	**N**	**N***	**Mean**	**StDev**	**Minimum**	**Maximum**	**Range**
Force	0	120	120	0	90.68	32.79	43.00	267.80	224.80
	90	120	99	21	67.67	24.55	22.20	135.60	113.40
	180	120	120	0	78.47	27.83	23.60	170.80	147.20
	270	120	105	15	66.25	22.54	20.20	147.60	127.40

The N* in Table 3.6, Table 3.7, and Table 3.8 represents the number of trials for which no data was registered.

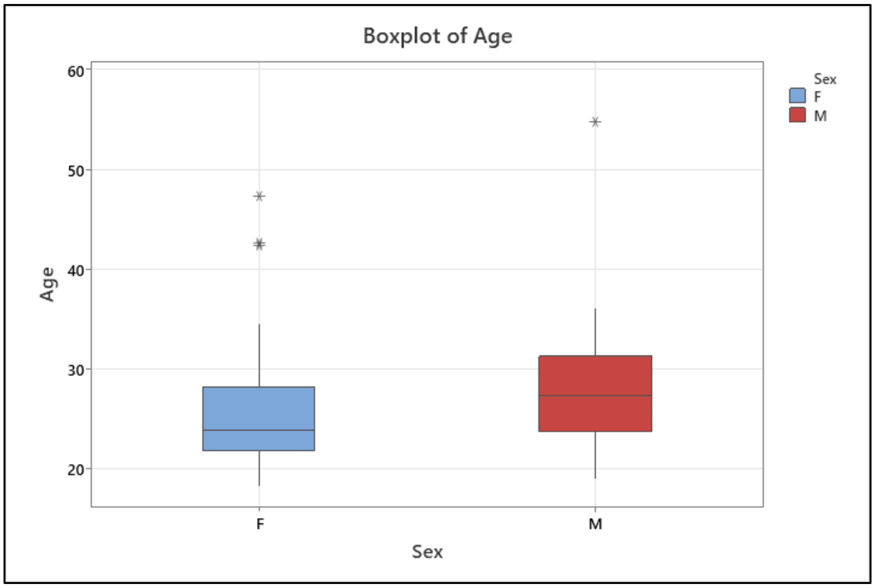


Figure 3.43: Age vs Sex

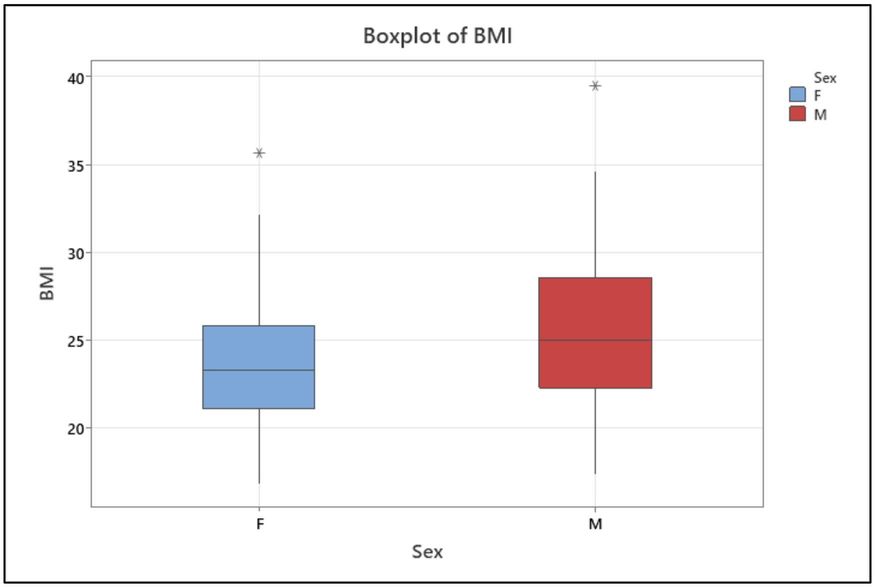


Figure 3.44: BMI vs Sex

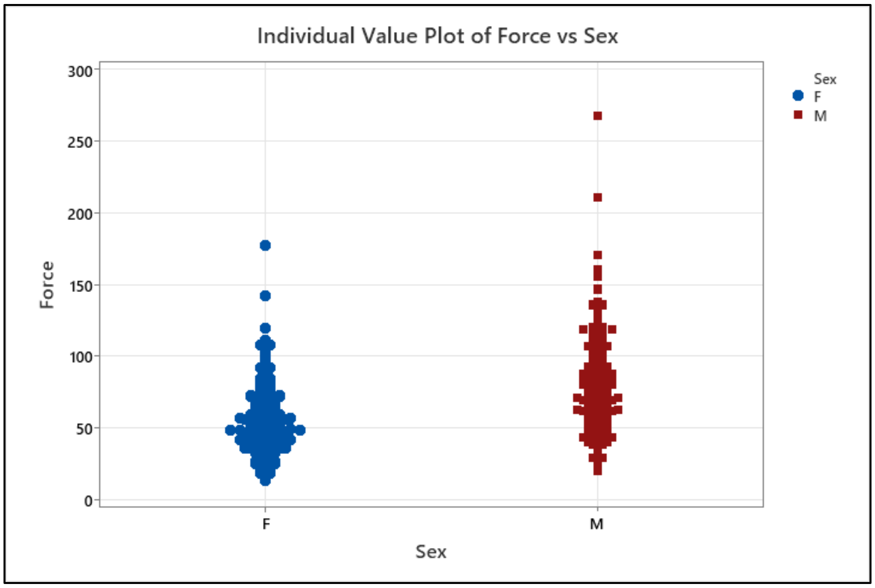


Figure 3.45: Force (N) Exertions Individual Value Plot vs Sex

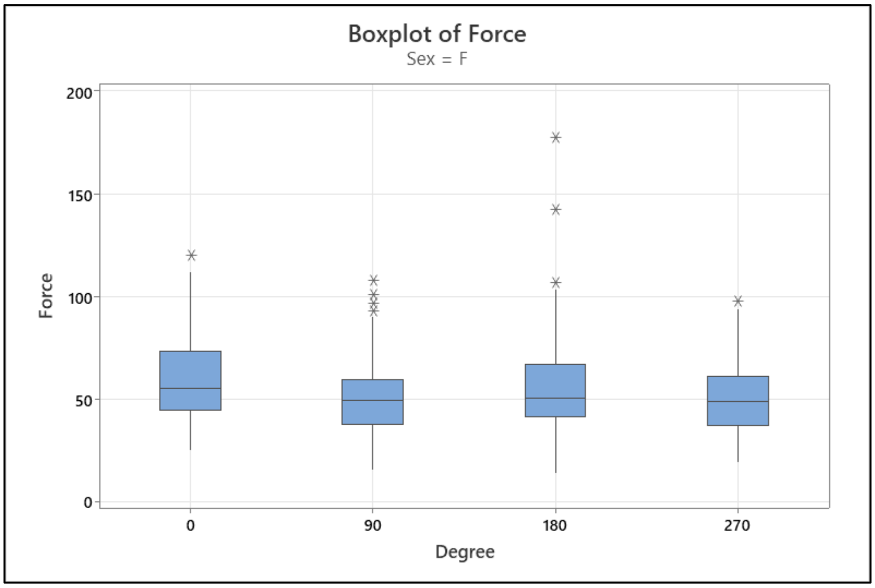


Figure 3.46: Force (N) Exerted by Female Subjects in Each Degree

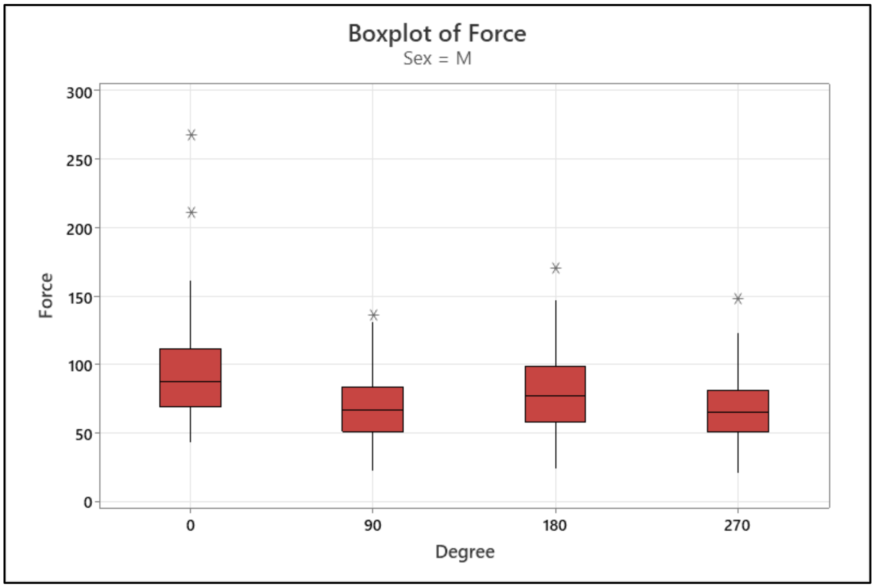


Figure 3.47: Force (N) Exerted by Male Subjects in Each Degree

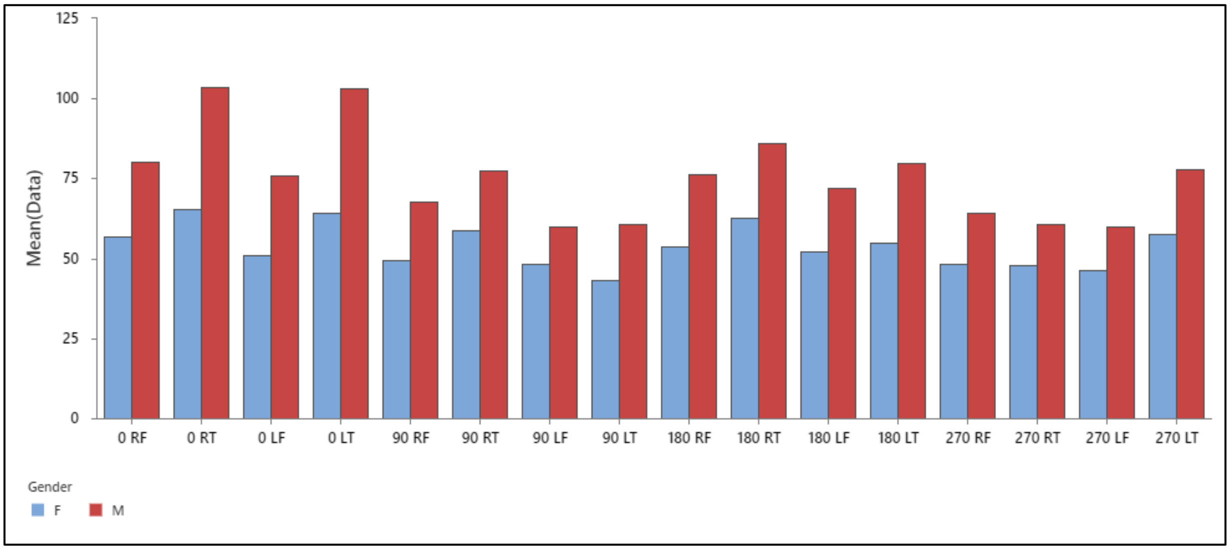


Figure 3.48: Gender Wise Graphical Representation of Mean Force (N) vs Orientation

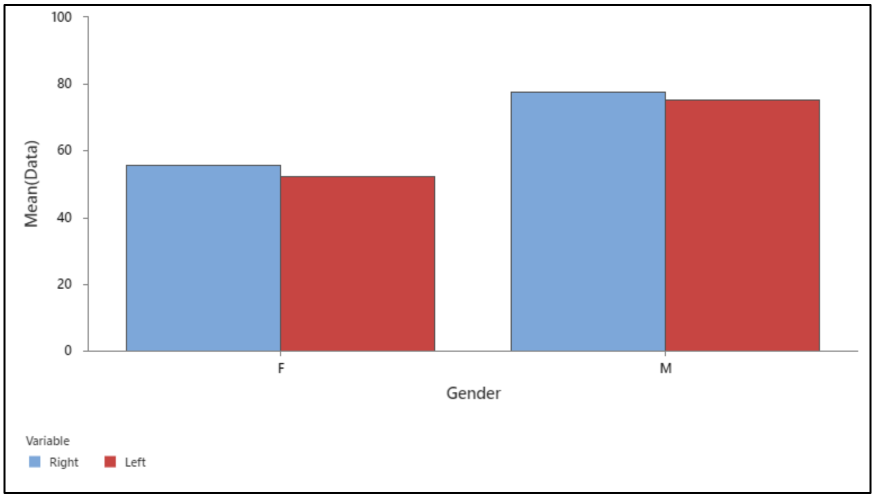


Figure 3.49: Force (N) Exerted Side Wise – Right Side vs Left Side

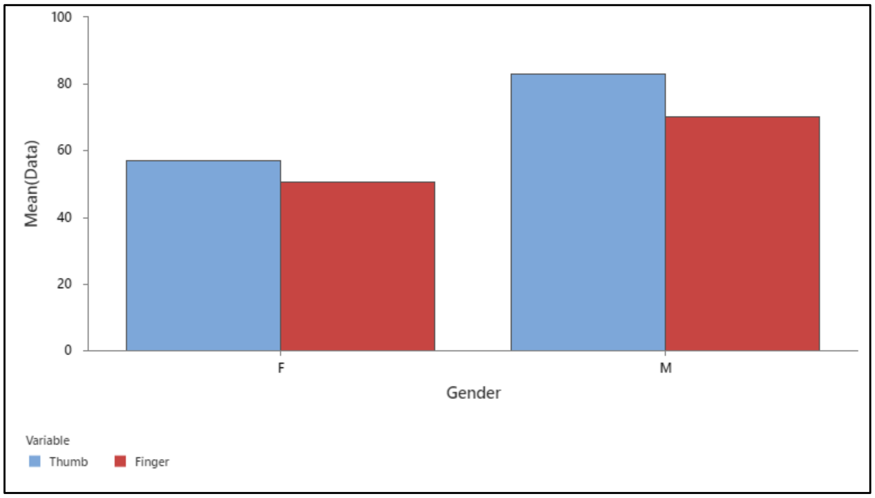


Figure 3.50: Force (N) Exerted Digit Wise – Thumb vs Finger

3.7.1.2 Seat Belt Unlatching Descriptive Statistics

All 60 subjects (30 male and 30 female) performed the six (6) unlatching orientations mentioned earlier. A total of 360 unlatching trials were conducted. **There were 6 occasions on which an individual could not unlatch their seat belt**. Table 3.9 represents the distribution of subjects able to unlatch their seat belt in different trial orientations. Table 3.10 represents scenarios in which the subjects could not unlatch. Three (3) male and two (2) female subjects could not unlatch the seat belt in at least 1 condition.

Table 3.9: Distribution of Successful Unlatching of Seat Belts in Different Trial Orientations

Degree	90°		180°		270°	
Side	Right	Left	Right	Left	Right	Left
Total Possible	30	30	30	30	30	30
Male	30	27	30	30	30	30
Female	30	29	29	30	29	30

Table 3.10: Scenarios where Subjects Could Not Unlatch

Sex	BMI	Age	90°R	90°L	180°R	180°L	270°R	270°L
M	28	23		NO				
M	39.53	55		NO				
F	20.01	31			NO			
F	35.7	22		NO			NO	
M	28.13	26		NO				

3.7.2 Inferential Statistics

3.7.2.1 Force Exertion Inferential Statistics

To determine if the force exerted by subjects was greater than or equal to the maximum buckle release force specified in FMVSS 209 of 133 N, a one-Sample t-test was performed. As shown in Table 3.11, the null hypothesis: The maximum push force exertion on a push-button seat belt buckle for subjects is greater than the maximum buckle release force of 133 N mentioned in the standard is **rejected at all orientations**.

When conducting multiple comparison tests, the probability of type 1 error increases with the increase in number of comparisons. Using the equation for calculating inflated significance level, (Inflated $\alpha = 1 - (1 - \alpha)^N$, N = number of hypotheses tested), the inflated α for 16 tests was found to be 0.5598 [201]. In order to control for the possibility of Type I error inflation due to multiple hypothesis testing, the Bonferroni correction method of familywise error rate (FWER) correction was performed on the one-sample t-test results presented in Table 3.11. The significance level (alpha) was divided by the number of tests performed, which in our case was 16. Therefore, a new significance level of 0.003125 was used instead of the conventional 0.05 level for each individual t-test. All the t-tests yielded a p-value smaller than 0.003125, indicating that the null hypothesis could be rejected at the new alpha level as well. Strong evidence was found to reject the null hypothesis that the mean of each group is greater than or equal to 133 N. This indicates that the mean of each group is significantly less than 133 N.

Table 3.11: One-Sample t-test Results H_0: $\mu \geq 133$ N

Orientation	N	Mean	StDev	95% Upper Bound	T-Value	P-Value
0° RF	60	68.53	25.04	73.93	-19.94	0.000
0° RT	60	84.53	37.22	92.56	-10.09	0.000
0° LF	60	63.42	20.69	67.88	-26.05	0.000
0° LT	60	83.78	34.03	91.12	-11.2	0.000
90° RF	60	58.64	21.27	63.23	-27.08	0.000
90° RT	59	68.05	23.97	73.27	-20.81	0.000
90° LF	46	53.46	20.7	58.59	-26.06	0.000
90° LT	47	50.63	23.68	56.43	-23.85	0.000
180° RF	59	65.10	26.43	70.85	-19.73	0.000
180° RT	59	74.49	32.33	81.53	-13.9	0.000
180° LF	59	62.18	24.83	67.58	-21.91	0.000
180° LT	59	67.54	26.81	73.37	-18.76	0.000
270° RF	50	55.99	20.37	60.82	-26.73	0.000
270° RT	46	53.86	21.96	59.29	-24.45	0.000
270° LF	60	53.2	16.61	56.79	-37.21	0.000
270° LT	60	67.80	24.06	72.99	-20.99	0.000

As seen in Table 3.11, there were instances of no force exertion. With 60 subjects, exerting force 16 times, there were 960 possibilities. There were 56 occasions where no force was recorded. It was observed that one (1) of these observations occurred in 90° right side, 27 occurred in the 90° left hand side, four (4) occurred in 180°, and 24 occurred in 270° right hand side. Those subjects that had a missing data point (i.e., unable to exert force at any trial orientation) were grouped together and analyzed to see if there was a factor that elicited this response. Table 3.12 shows the descriptive statistics for this group.

Table 3.12: Descriptive Statistics of Subjects with Missing Data

Variable	**Sex**	**N**	**Mean**	**StDev**	**Minimum**	**Maximum**
BMI	F	8	26.25	5.37	20.01	35.70
	M	13	26.64	5.93	17.37	39.53
Age	F	8	27.47	8.77	21.61	47.35
	M	13	30.09	8.60	20.94	54.78

A two-sample t-test was performed for BMI and age between subjects with all data points vs subject with missing data points for each sex (Table 3.13 and Table 3.14). Two-sample t-tests were also performed for forces for all data points and individually at each degree (Table 3.15 and Table 3.16). No statistically significant differences were found in any of the t-tests. After a thorough examination of the trial videos and images, it was determined that the primary reason for this was that some subjects were unable to reach the button with their respective digits, which could be due to different body structures and flexibility of each individual.

Table 3.13: Two Sample t-test for BMI and Age, Female and Male – Subjects with Missing Data vs Subjects without Missing Data

Variable	T-Value	P-Value
BMI_F	1.77	0.114
Age_F	0.55	0.597
BMI_M	0.57	0.572
Age_M	1.05	0.306

Table 3.14: Two Sample t-test for Force, Female and Male – Subjects with Missing Data vs Subjects without Missing Data

Force	T-Value	P-Value
Male	-0.66	0.507
Female	0.74	0.458

Table 3.15: Two Sample t-test for Force at Each Degree, Female – Subjects with Missing Data vs Subjects without Missing Data

Degree	T-Value	P-Value
0°	1.99	0.052
90°	0.69	0.495
180°	-1.05	0.299
270°	1.41	0.167

Table 3.16: Two Sample t-test for Force at Each Degree, Male – Subjects with Missing Data vs Subjects without Missing Data

Degree	T-Value	P-Value
0°	-0.15	0.88
90°	-0.82	0.415
180°	0.9	0.369
270°	-0.23	0.822

Subjects that were unable to exert force in any of the trials were removed from the data set. After excluding these from the data set, a final data set was formed. This final data set was then used to perform inferential statistical analyses in order to better understand the effects of the main and interaction factors. Figure 3.51 illustrates the process of elimination and acquiring the final data set. The final data set descriptive stats are represented in Table 3.17, Table 3.18, and Table 3.19.

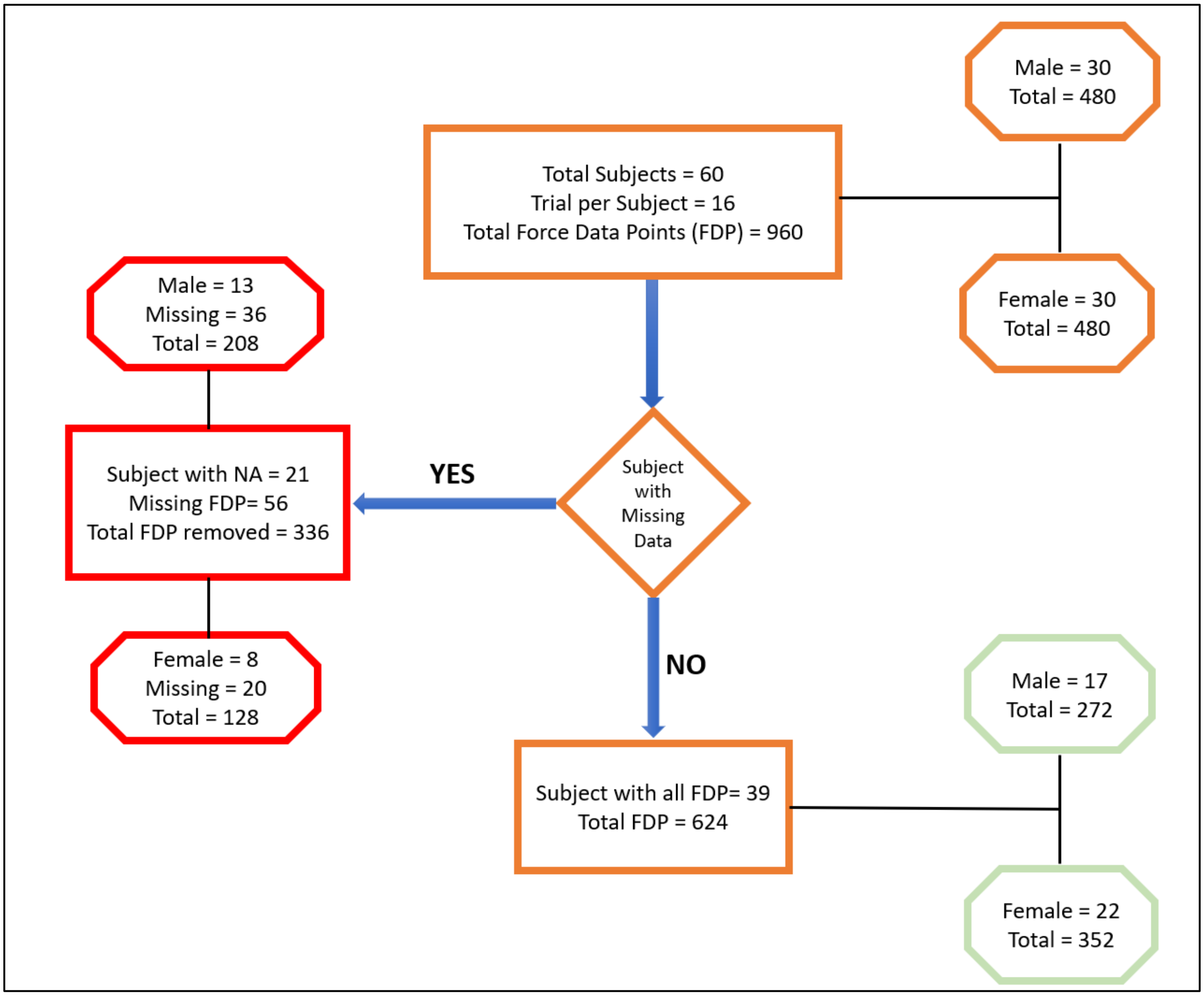


Figure 3.51: Final Data Set Acquiring Flow Chart

Table 3.17: Descriptive Statistics for BMI and Age for Final Data Set

Variable	Sex	Total Count	Mean	StDev	Minimum	Maximum
BMI	F	22	22.75	2.57	16.83	26.91
	M	17	25.48	4.84	17.51	34.65
Age	F	22	25.61	6.40	18.36	42.70
	M	17	27.28	4.91	19.02	35.78

Table 3.18: Descriptive Statistics for Force (N) for Females for Final Data Set

Variable	Degree	Total Count	CumN	Mean	StDev	Minimum	Maximum
Force	0°	88	88	61.51	19.86	24.80	120.00
	90°	88	176	50.85	18.85	15.20	107.80
	180°	88	264	54.08	18.15	13.60	106.60
	270°	88	352	51.47	17.52	18.80	93.80

Table 3.19: Descriptive Statistics for Force (N) for Males for Final Data Set

Variable	Degree	Total Count	CumN	Mean	StDev	Minimum	Maximum
Force	0°	68	68	90.29	35.38	43.00	267.80
	90°	68	136	66.28	24.31	22.20	135.60
	180°	68	204	80.52	26.07	33.40	170.80
	270°	68	272	65.90	23.41	20.20	147.60

Table 3.20: Results of Split Plot ANOVA for Force - Female Subjects

Source	**DF**	**SS**	**MS**	**F**	**P**	**Partial Eta^2 - η2**
Subject (A)	21	69142.4	3292.49			
Degree (B)	3	6325.3	2108.44	12.76	**0.0000**	0.378
Error A*B	63	10410.3	165.24			
Side (C)	1	634.0	633.98	4.12	**0.0455**	0.057
B*C	3	2524.7	841.56	5.47	**0.0017**	0.163
Error A*B*C	84	12919.7	153.81			
Digit (D)	1	4373.8	4373.82	43.33	**0.0000**	0.295
B*D	3	1436.8	478.92	4.74	**0.0033**	0.121
C*D	1	5.3	5.30	0.05	0.8190	
B*C*D	3	2217.2	739.06	7.32	**0.0001**	0.115
Error A*B*C*D	168	16956.8	100.93			
Total	351					

Table 3.20 displays the result of the split-split plot ANOVA for force for female subjects. The results of the ANOVA indicate that for female subjects, the main effects of degree, side, and digit had a statistically significant ($p<0.05$) effect on the force exertion. Additionally, there were significant interactions between degree and side, degree and digit, and the combined interaction of degree, side, and digit. This means that the relationship between degree and force exertion may be different depending on the side or digit being used or potentially both factors together. The effect size for this interaction was found to be medium with a partial eta-squared (η^2) value of 0.115. The effect size categories are small .01, medium .06, and large .14 [202].

Table 3.21 represents the Tukey HSD all-pairwise comparisons test of degree for females. Table 3.22 represents the Tukey HSD all-pairwise comparison test of force for the interaction of degree, side, and digit. There were 6 groups in which the means were not statistically significantly different from one another. This also suggests that the relationship between degree and force exertion is dependent on the levels of side and digit.

Table 3.21: Tukey HSD All-Pairwise Comparisons Test of Force for Degree – Female

Degree	**Mean**	**Homogeneous Groups**	
0	56.683	A	
180	50.244		B
270	49.894		B
90	47.669		B

Table 3.22: Tukey HSD All-Pairwise Comparison Test of Force for Degree*Side*Digit - Female

Degree	**Side**	**Digit**	**Mean**	**Homogeneous Groups**
0	Left	Thumb	68.127	A
0	Right	Thumb	67.473	AB
270	Left	Thumb	60.664	ABC
90	Right	Thumb	60.045	ABCD
180	Right	Thumb	59.655	ABCD
0	Right	Finger	58.309	ABCDE
180	Left	Thumb	55.527	BCDE
90	Right	Finger	52.155	CDEF
0	Left	Finger	52.145	CDEF
180	Right	Finger	50.609	CDEF
180	Left	Finger	50.536	CDEF
270	Right	Thumb	49.718	CDEF
270	Right	Finger	48.600	DEF
90	Left	Finger	48.382	DEF
270	Left	Finger	46.891	EF

Table 3.23: Results of Split Plot ANOVA for Force - Male Subjects

Source	**DF**	**SS**	**MS**	**F**	**P**	**Partial Eta^2 - η2**
Subject (A)	16	112031	7001.9			
Degree (B)	3	28628	9542.8	37.37	**0.0000**	0.700
Error A*B	48	12257	255.4			
Side (C)	1	1031	1031.2	3.32	0.0731	
B*C	3	1323	440.9	1.42	0.2451	
Error A*B*C	64	19869	310.5			
Digit (D)	1	14225	14224.6	48.22	**0.0000**	0.537
B*D	3	5965	1988.2	6.74	**0.0003**	0.327
C*D	1	214	213.5	0.72	0.3965	
B*C*D	3	1063	354.3	1.20	0.3122	
Error A*B*C*D	128	37757	295.0			
Total	271					

Table 3.23 displays the result of the split-split plot ANOVA for force for male subjects. The results of the ANOVA indicate that for female subjects, the main effects of degree and digit had a statistically significant ($p<0.05$) effect on the force exertion. The ANOVA also found a significant interaction between degree and digit. The effect size for this interaction was found to be large with a partial eta-squared (η^2) value of 0.327. Table 3.24 represents the Tukey HSD all-pairwise comparisons test of force for degree for males. Table 3.25 represents the Tukey HSD all-pairwise comparison test of force for degree and digit interaction. There were 4 groups in which the means were not statistically significantly different from one another. This suggests that the relationship between degree and force exertion is dependent on the digit being used. Detailed reports of all the Tukey HSD pairwise comparison tests are attached in the Appendix (O, P).

Table 3.24: Tukey HSD All-Pairwise Comparisons Test of Force for Degree – Male

Degree	Mean	Homogeneous Groups		
0	83.937	A		
180	75.993		B	
270	62.023			C
90	61.677			C

Table 3.25: Tukey HSD All-Pairwise Comparison Test of Force for Degree*Digit - Male

Degree	Digit	Mean	Homogeneous Groups		
0	Thumb	105.29	A		
180	Thumb	87.28		B	
0	Finger	75.30		BC	
180	Finger	73.76			CD
270	Thumb	70.10			CD
90	Thumb	69.26			CD
90	Finger	63.31			CD
270	Finger	61.69			D

The results from the linear regression analysis are summarized in Table 3.27. The regression equations from the analysis performed are shown in Appendix (S). The BMI, age, sex, degree, and digit were seen to have a statistically significant effect on the force exertion along with the mentioned interaction effects. The adjusted R^2 of the model was 45.80%. Figure 3.53 illustrates that the residuals exhibit a normal distribution.

Table 3.26: Regression Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
19.3586	47.54%	45.80%	43.63%

Table 3.27: Results of ANCOVA for Force vs Age, BMI, Sex, Degree, Side, and Digit

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Partial Eta^2 - η2
Regression	20	204748	10237.4	27.32	0.000	
BMI	1	9053	9053.1	24.16	0.000	.038
Age	1	5124	5123.6	13.67	0.000	.022
Sex	1	30161	30161.1	80.48	0.000	.118
Degree	3	909	302.9	0.81	0.490	
Side	1	184	184.4	0.49	0.483	
Digit	1	9369	9368.7	25.00	0.000	.040
BMI*Age	1	4283	4283.4	11.43	0.001	.019
Age*Sex	1	19032	19031.6	50.78	0.000	.077
Sex*Degree	3	6291	2097.0	5.60	0.001	.027
Sex*Digit	1	2108	2108.1	5.63	0.018	.009
Degree*Side	3	3613	1204.4	3.21	0.023	.016
Degree*Digit	3	5970	1989.9	5.31	0.001	.026
Error	603	225978	374.8			
Total	623	430725				

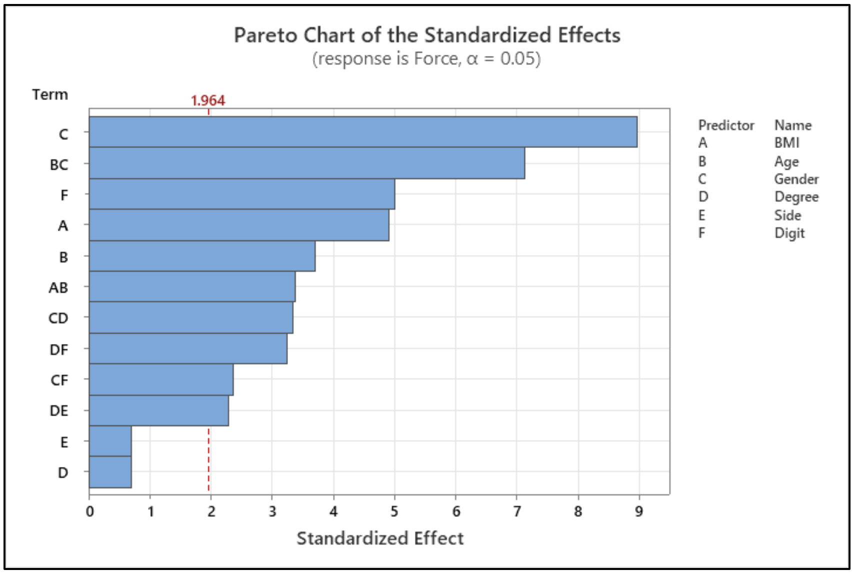


Figure 3.52: Pareto Chart of the Standardized Effects

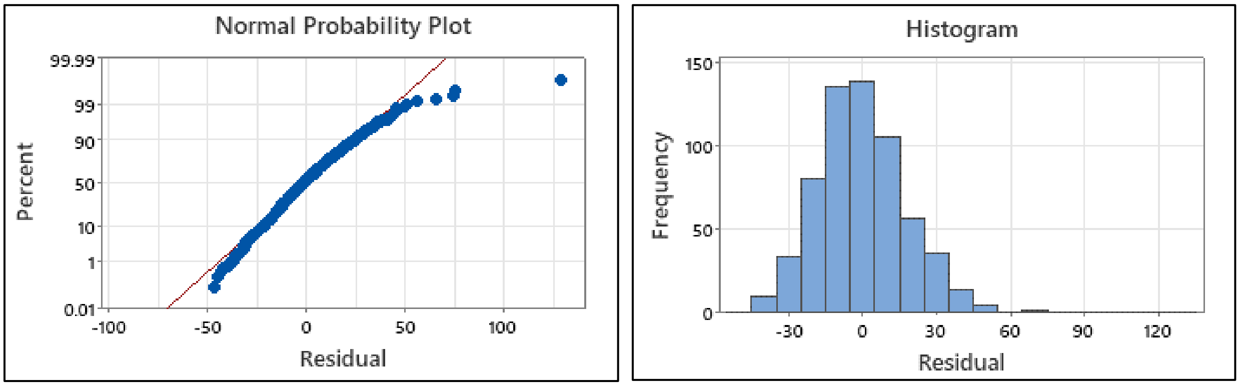


Figure 3.53: Residual Plots for Force

Looking at the partial eta-squared values in Table 3.27, we can see that sex has the largest effect size ($\eta^2 = 0.07$), followed by age*sex ($\eta^2 = 0.03$), BMI ($\eta^2 = 0.02$), and BMI*age ($\eta^2 = 0.01$). The remaining variables have smaller effect sizes, with partial eta-squared (η^2) values less than 0.01. To better understand the observed interactions, interaction plots were plotted for significant interaction effects. Interaction plots were used to graphically illustrate the effect of one independent variable on the dependent variable, while holding the other independent variable(s) constant. Figure 3.54 illustrates the main effects and Figure 3.55 illustrates the interaction effects for these factors.

Figure 3.54: Main Effects Plot for Independent Variables vs Force (N)

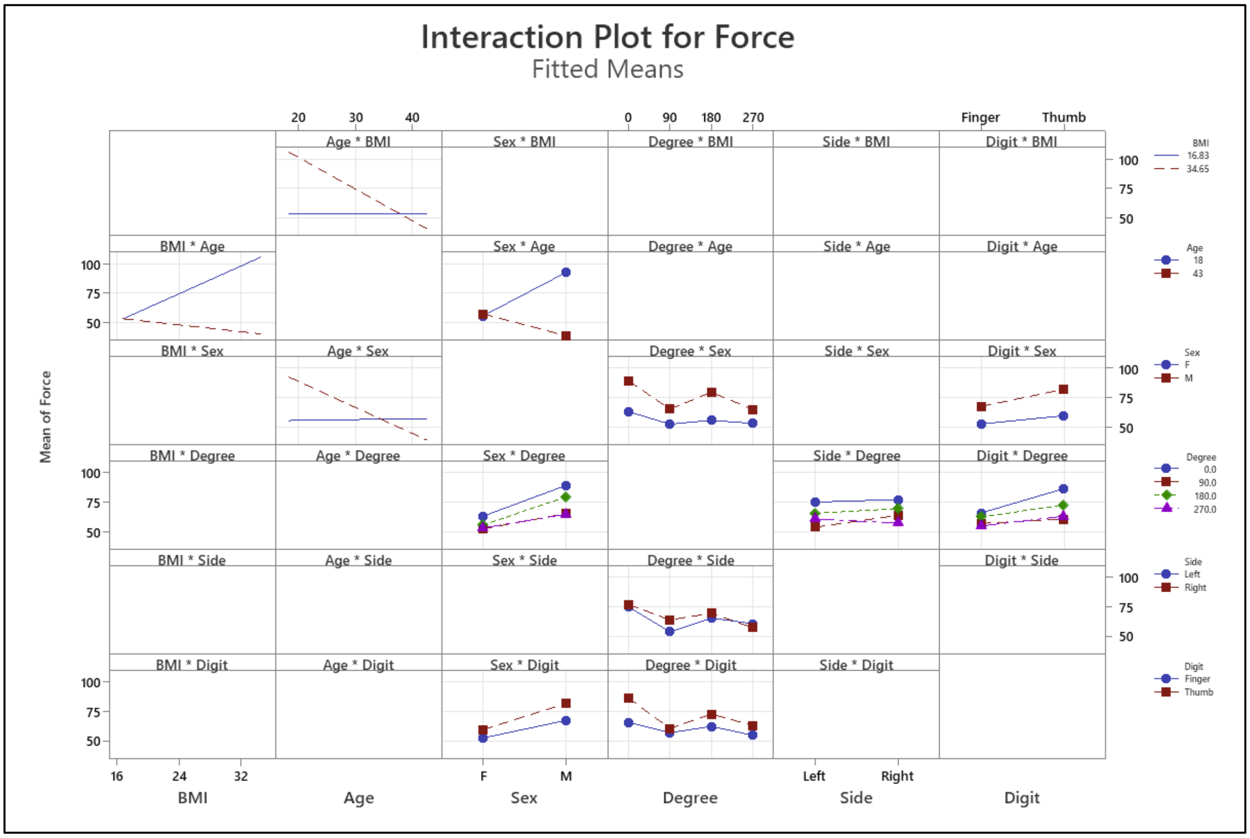


Figure 3.55: Interaction Plot of Interaction Effects of Independent Variable vs Force (N)

3.7.2.2 Seat Belt Unlatching Inferential Statistics

Results of the binary logistic regression are presented in Table 3.30. The subject BMI was determined to have a statistically significant effect on the response (unlatching).

Table 3.28: Response Information

Variable	Value	Count	
Response	1	354	(Event)
	0	6	
	Total	360	

Table 3.29: BMI and Age

Variable	Sex	Total Count	Mean	StDev	Minimum	Maximum	Range
BMI	F	2	27.86	11.09	20.01	35.70	15.69
	M	3	31.89	6.62	28.00	39.53	11.53
Age	F	2	26.27	6.24	21.86	30.69	8.83
	M	3	34.8	17.4	23.1	54.8	31.7

Table 3.30: Analysis of Variance for Unlatching – Wald Test

Source	DF	Chi-Square	P-Value
Regression	13	10.26	0.673
BMI	1	8.98	**0.003**
Age	1	0.24	0.622
Sex	1	0.04	0.844
Degree	2	0.01	0.994
Side	1	0.01	0.940
Sex*Degree	2	0.00	1.000
Sex*Side	1	0.00	0.993
Degree*Side	2	0.02	0.992
Sex*Degree*Side	2	0.00	0.999

Between Figure 3.56 and Figure 3.57, the differences between the BMI and age of subjects that were unable to unlatch and the rest split by sex are illustrated. As shown in these figures, the BMI of the group that was unable to unlatch for both males and females appear to be higher than the group that was able to unlatch. The difference between the force exerted by the group of subjects who were able to successfully unlatch versus the group that were not able to are illustrated in Figure 3.58. It is visible that the female subjects who were unable to unlatch had a significantly less mean force than the rest of the group.

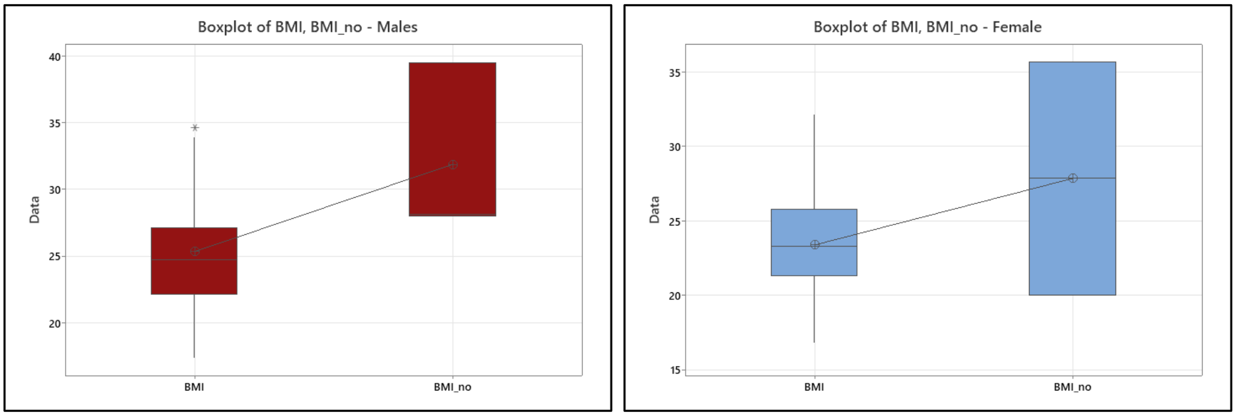


Figure 3.56: Box Plot for BMI Comparison for Subject Unable to Unlatch vs Rest.

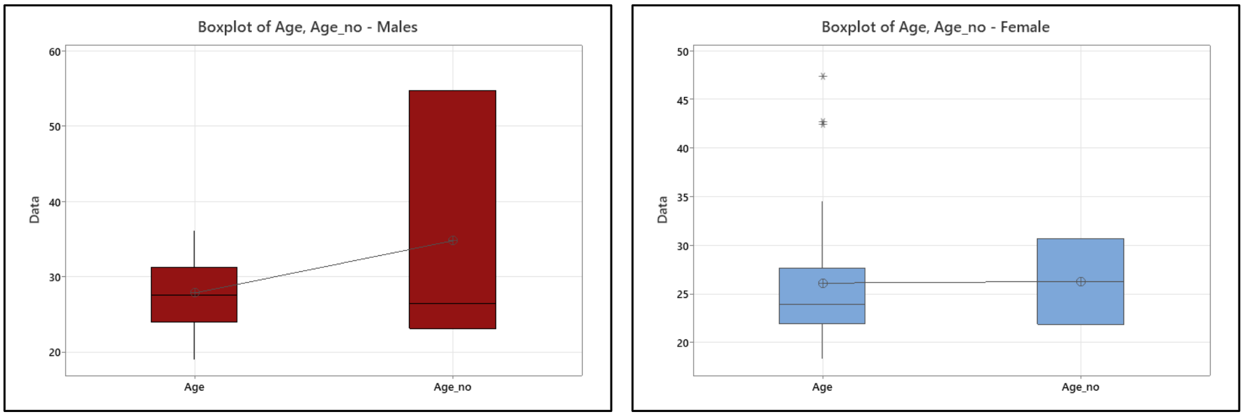


Figure 3.57: Box Plot for Age Comparison for Subject Unable to Unlatch vs Rest.

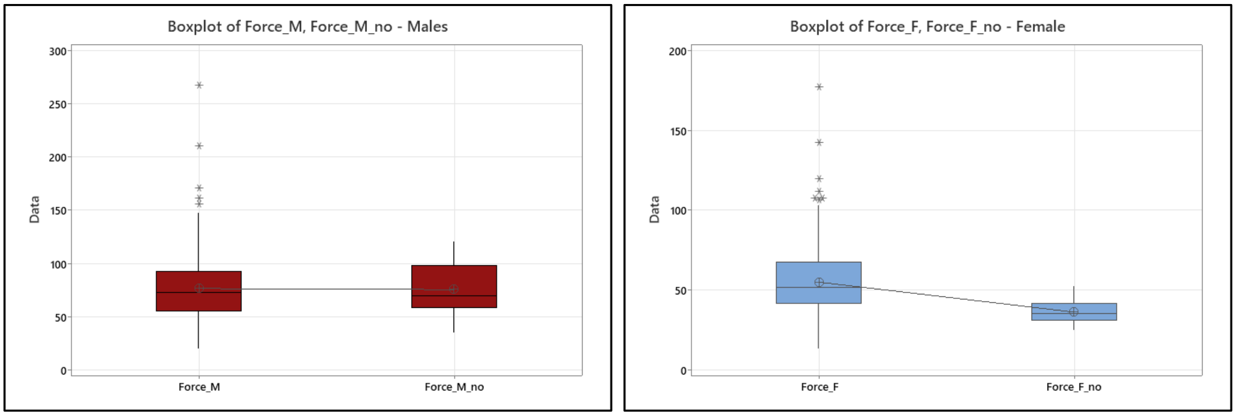


Figure 3.58: Force (N) Comparison.

3.8 Discussion

The primary purpose of this experiment was to determine if an occupant could unlatch themself from their seat belt following a rollover accident. It was critical to understand force exertion of subjects in different scenarios and compare it to FMVSS seat belt buckle release force standards. The majority of subjects were able to unlatch their seat belt in a rolled over orientation. However, analysis of the force exertion data suggests that the subjects did not have the strength capabilities to exert the FMVSS 209 standard specified maximum buckle release force of 133 N to unlatch a seat belt buckle. For both male and female subjects, there was a statistically significant difference in force exertion between the upright and rolled-over orientations. Figure 3.59 illustrates the mean force exertion for male and female subjects at different orientations and their relative distance to mean male force, mean female force, and the FMVSS 209 buckle release force limit of 133 N.

The force exertion data published in the study by Noy [63], mentions that the mean force for female subject was 74.72 N and for male subjects was 117.60 N. Our study found the overall mean push force for female subjects was 54.04 N and 76.47 N for male subjects. The mean push force at upright orientation was 59.64 N for female subjects and 90.68 N for male subjects. The Noy study only measured force exerted by the right hand in an upright orientation and only reported the maximum forces. Subjects were not given specific instructions as to how to apply the force and proper explanation for force data applied by the digits is also not provided. The mean of the maximum force applied at 0° for the current study was analyzed, and it was observed that the mean of maximum forces at 0° for male subjects was 115.52 N and for female subjects it was 78.11 N.

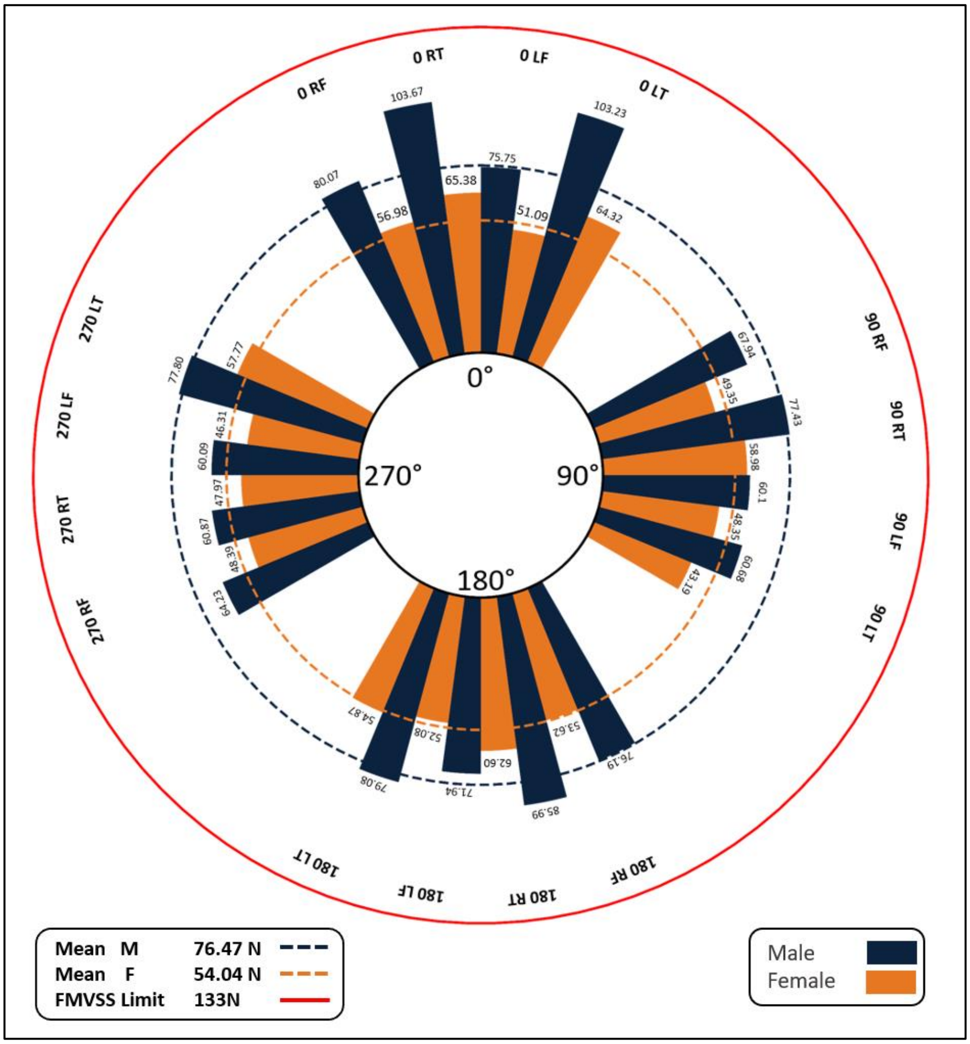


Figure 3.59: Mean Force (N) Exertion Comparison for Different Orientations

Study videos and images were analyzed to understand force exertion methods practiced by different subjects. One of the key observations was that different subjects used different methods to exert force, especially in the rolled over orientation. Flexibility of a subject played an important role in their ability to access the button. Figure 3.60, Figure 3.61, and Figure 3.62 display the position of hand and digits of different subjects while exerting force for the same orientation between different subjects.

Several subjects were unable to exert force in the 90° Left and 270° Right orientations. Statistically, no statistically significant differences were found between the anthropometry or the force exertion data for these subjects. Trial videos and images revealed that different body structures and flexibility of the subjects might have contributed to this. Figure 3.63 illustrates how a subject is able to access the push-button at 90° with the right hand but unable to access it with the left hand. In the same scenario, another subject is able to access the push button with their left hand as illustrated in Figure 3.64. The individual’s varying body structures resulted in a unique manner in which the 6-point harness held them in place and facilitated their movement within the seat. Therefore, some subjects found it challenging to reach the push-button to apply force. Additionally, due to this, for some individuals, their body positioning caused the button to be obscured, thereby impeding their access to it.

Figure 3.60: Force Exertion at 0° Right Hand - Male vs Female

Figure 3.61: Force Exertion 0° Left Hand - Male vs Female

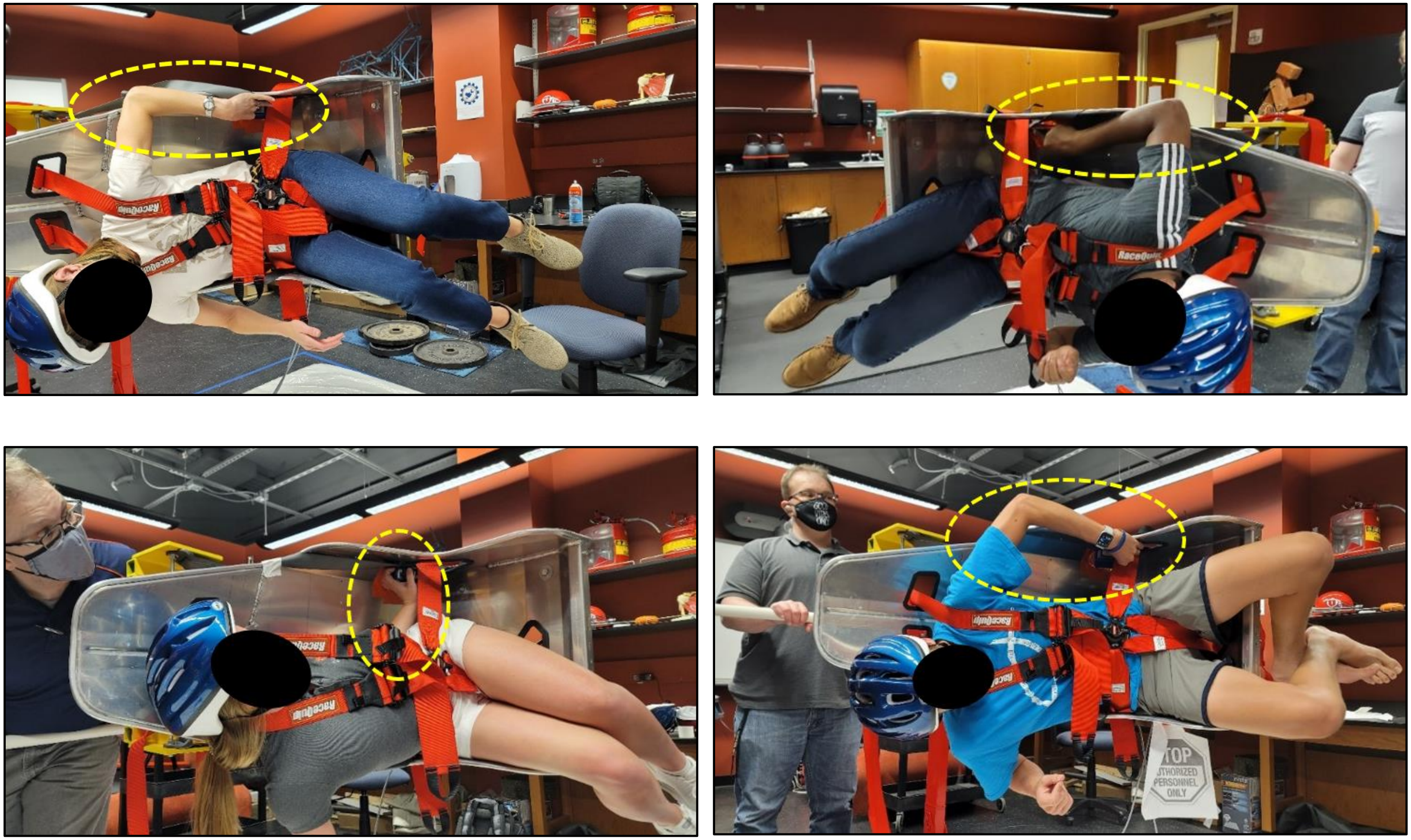


Figure 3.62: Force Exertion at 90° and 270°

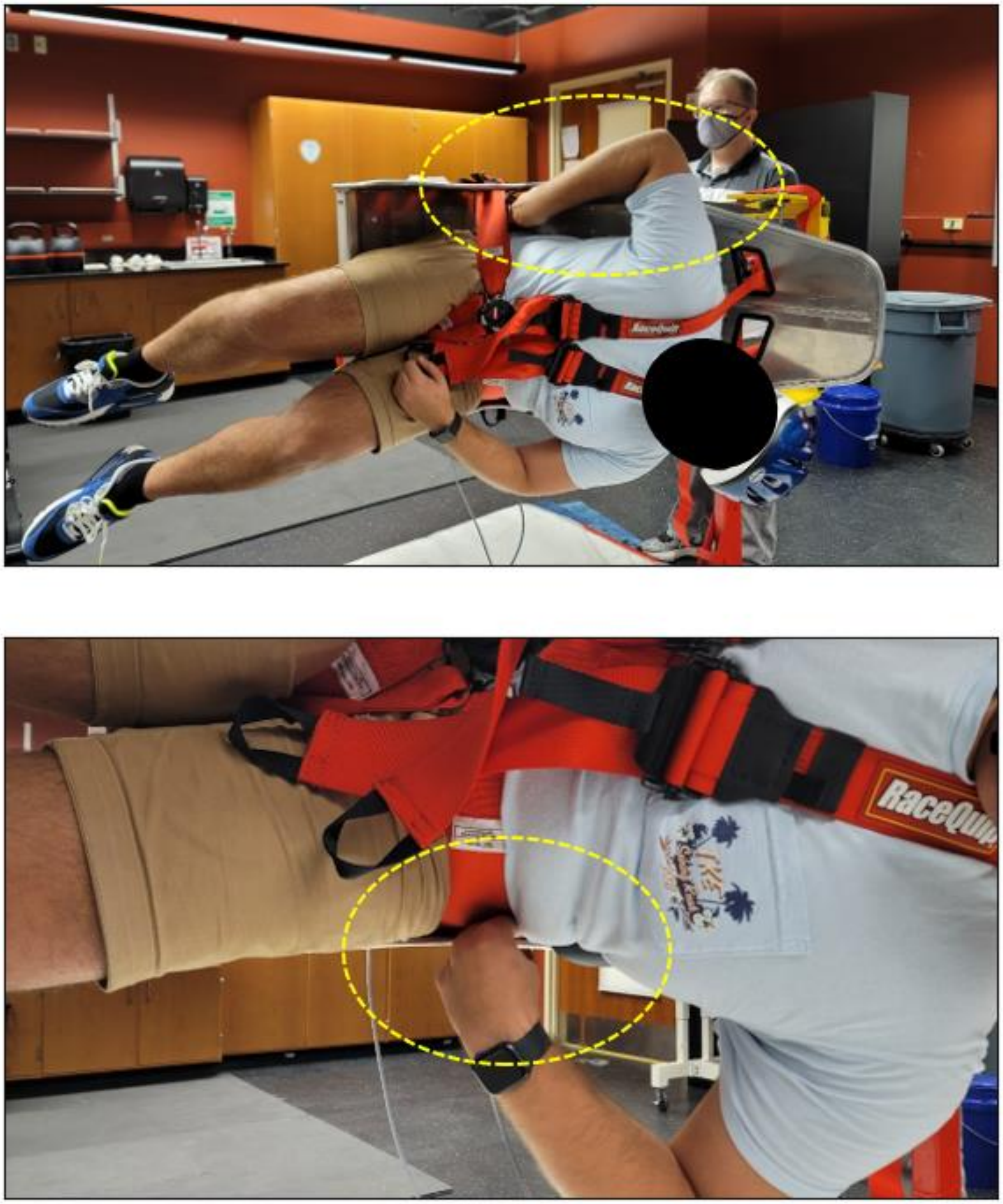


Figure 3.63: Example of Subject Unable to Access Push- Button to Exert Force at 90°

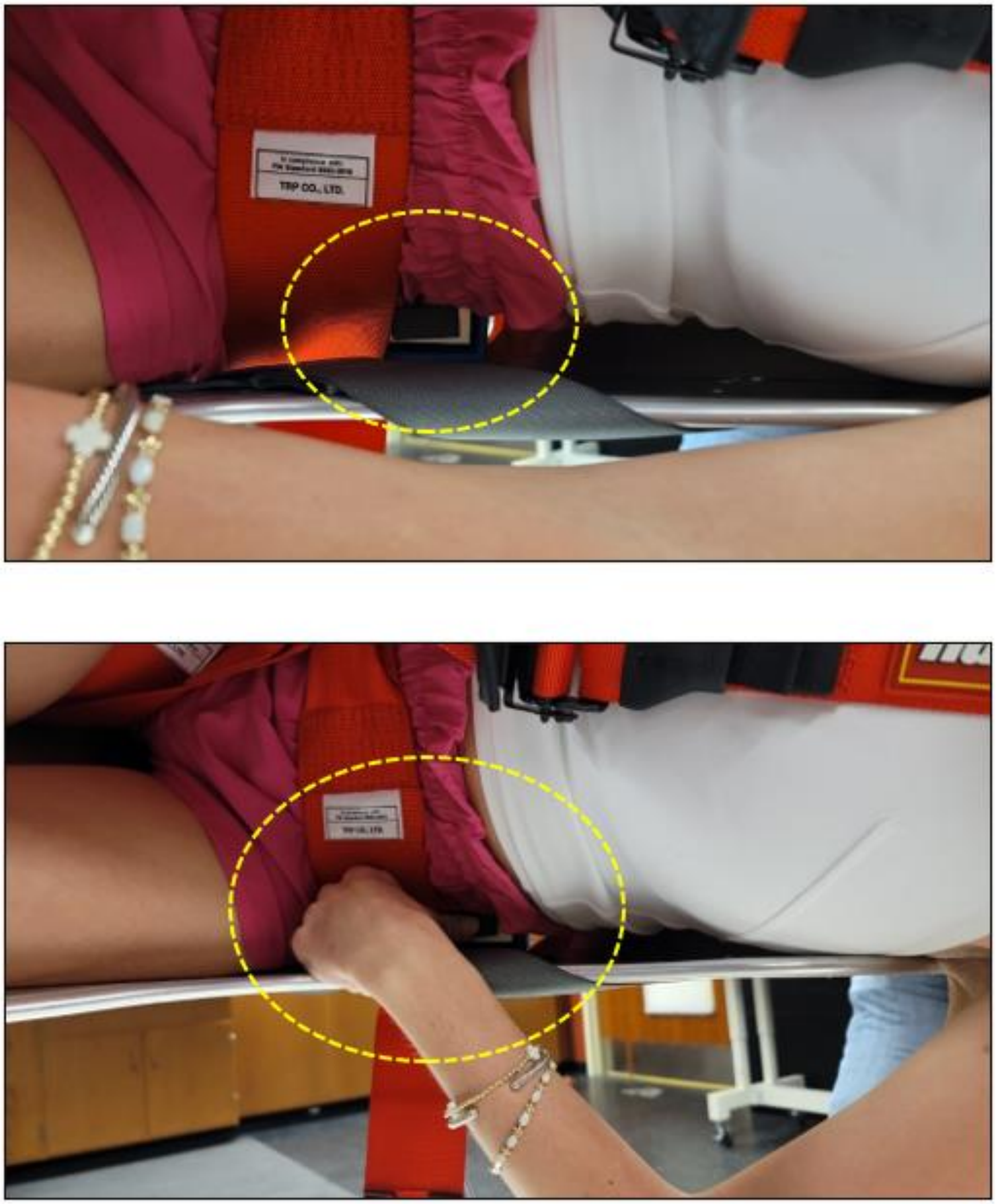


Figure 3.64: Load Cell Visibility and Force Exertion Close Up at 90°

Despite having low force exertions compared to the standard specified limit, the majority of the subjects were able to unlatch themselves in all the orientations. There were 6 instances where a subject could not unlatch. Three (3) male subjects and one (1) female could not unlatch in one (1) orientation and one (1) female subject could not unlatch in two (2) orientations. It was identified that four (4) out of the five (5) subjects that could not unlatch were among the subjects who could not exert force in some of the orientations. It was observed that the male subjects who could not unlatch the seat belt had a significantly higher BMI than their counterparts (Figure 3.56) and the female subjects who could not unlatch had a significantly lower mean force than their counterparts (Figure 3.58).

It is possible that the unlatching number was higher than expected because of the fall protection harness slack limitation requested by the IRB during study approval. It was observed that in most instances, the fall protection harness was bearing some of the occupant’s body weight when they were in rolled over orientation, particularly during 180° orientation, causing the 3-point harness belt load to reduce compared to a scenario without the fall protection harness or full slack.

As seen from studies mentioned earlier in the dissertation, an increase in belt tension resulted in an increase in the force required to unlatch and hence it is believed that if the slack was greater, the belt tension would have been higher, and the corresponding force required to unlatch could have been higher as well.

During the unlatching experiments, a few subjects found it difficult to locate the buckle and struggled to unlatch. It is possible that due to modern pretensioners, after an accident, if the buckle moves further away from an occupant, it might make it difficult for one to find the buckle and unlatch.

Figure 3.65: Fall Protection Harness with Slack in Regular Orientation – Female and Male

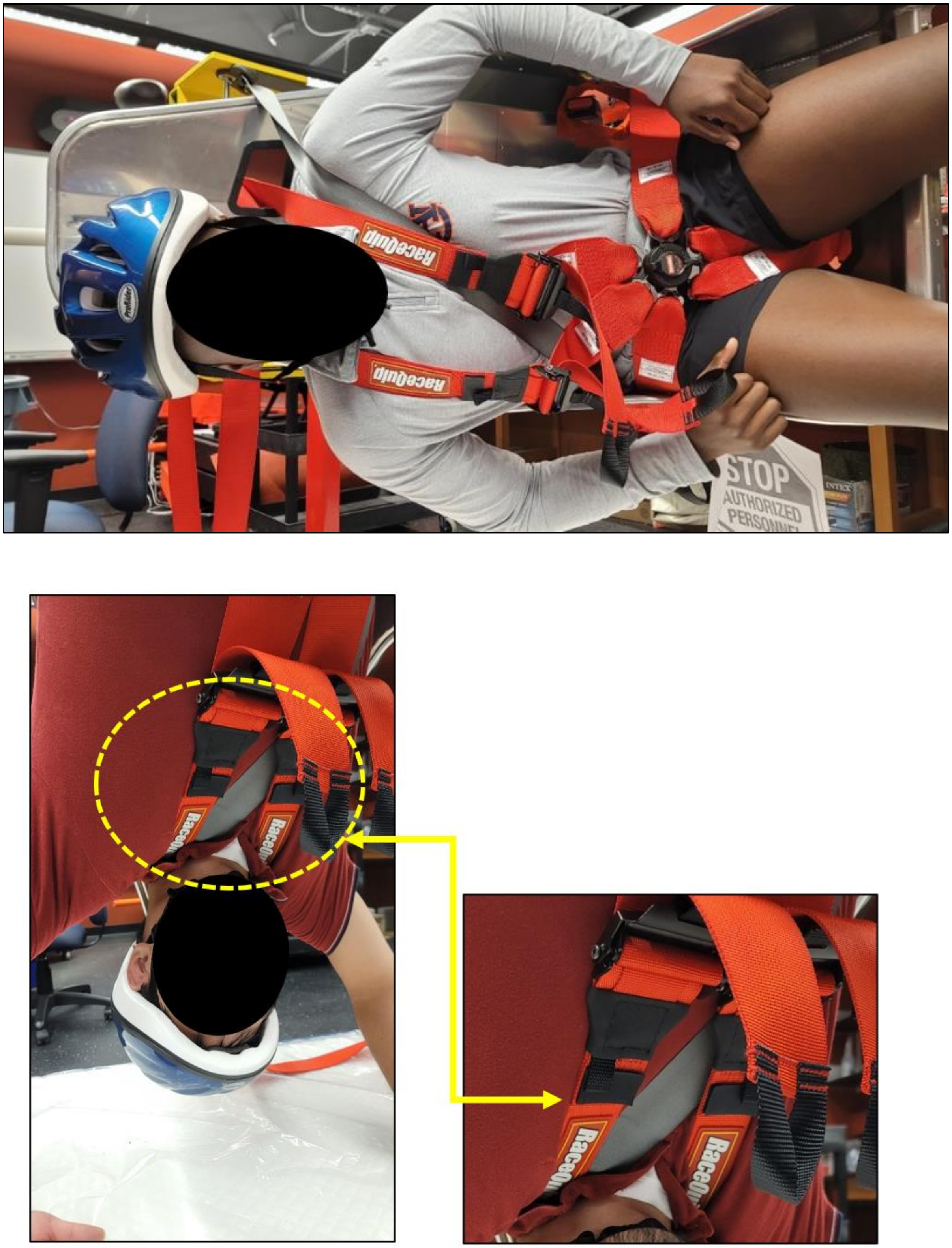


Figure 3.66: Fall Protection Harness Bearing Subject’s Load

3.9 Limitations

There are several limitations associated with this study.

1) The sample size was relatively small and might not be the best representation of the driving population. The majority of subjects were students at Auburn University, with the remaining being employees at Auburn. These may limit the generalizations of findings especially with the age range not being broad.
2) Broader sample size especially with equal representation of each of the BMI groups could provide a better understanding of how BMI affects the force exertion of subjects, especially in rolled over orientation and their ability to unlatch.
3) The study was conducted in a laboratory setup with research assistants readily available to guide the subjects. Post-accident scenarios like smoke, fire, darkness, injuries, fear, or other environmental stressors could generate very different results. While recruiting subjects, it was observed that several people (especially females) did not want to participate in such a study that involved being upside down, due to fear of heights and motion sickness.
4) During force exertion data collection, only 1 repetition per trial was conducted. Due to the nature of the study and time and scheduling limitations, it was not possible to collect repeated measures of each trial.
5) The bucket seat may have provided a slight hindrance for some subjects while applying force, thereby preventing them from exerting force in certain orientations. For future work, designing a setup that could test different production model car seats could provide better understanding of force exertions.

6) One limitation pertaining to the unlatching phase was the slack offered by the fall protection harness. As mentioned in the discussion, due to slack restrictions, the fall protection harness ended up taking a portion of the body weight, in turn reducing the load on the 3-point harness which theoretically reduced the force required to unlatch the seat belt buckle. Future research could design a study with the full weight of the subject on the 3-point harness.

Several gaps in the literature were attempted to answer with this pilot study. While this study has several limitations, it is important to note that to the best of our knowledge it is the first of its kind to examine the physical capabilities of a subject to exert force and unlatch a seat belt buckle in rolled over orientation. Despite these limitations, we believe that the results of our study provide valuable insights. A significant amount of effort and resources was invested to conduct this study, and we hope that it will serve as a foundation for future research in this area.

3.10 Conclusion

Except for 5 subjects, the majority of the subjects in this study were able to unlatch their seat belt in rolled over orientations. However, 96% of the female subjects and 83% of the male subjects were **unable** to exert enough force to exceed the standard specified 133 N at any given orientation. The mean of maximum force exerted by subjects at upright orientation was 68% for males and 45% for females of standard specified maximum limit of 133 N. The mean of maximum force exerted by subjects in rolled over orientation was 53% of standard limit for males and 39% of standard limit for females.

For male subjects, a reduction of almost 27% in the mean push force from upright to rolled over orientation was observed. For female subjects, a reduction of almost 16% in the mean push force from upright to rolled over orientation was observed. Mean push force for female subjects was found to be 70% of that for male subjects. The seat belt standard, and as a result seat belts, can be improved by reducing the force required to unlatch a belt buckle. A maximum buckle release force of 50 N is recommended in order to ensure 95% of subjects can exert enough force and unlatch the seat belt buckle in any orientation. Additionally further research may be done to find a better position for the belt buckle to prevent difficulty in accessing it in the event of a rollover, and a different unlatching method could be considered, which is independent of the belt tension.

3.11 Acknowledgments

Gratitude is expressed to the following:

1) Deep South Center for Occupational Safety and Health (NIOSH) Pilot Project Research Training Program for partially funding this study.
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3) Savannah Maples and Nathan Pool for their immeasurable help during data collection.

Chapter 4

An Analysis of Seat Belt Buckle Release Forces in School Buses After Rollover Accidents: Considerations for Child Passengers

4.1 Introduction

In the United States, school buses play a crucial role in both education and transportation. Currently, over 25 million children are transported daily on approximately 470,000 school buses, covering a distance of around 3.4 billion miles annually [31]. As of 2019, school buses transported 47% of all public students [31]. It is worth noting that an average of over 33,000 new school buses are being sold in the U.S. annually since 2010 [31].

According to NHTSA, school buses are subject to the most stringent regulations of any vehicle on the road. NHTSA reports that school buses are significantly safer than other modes of transportation for students and that students are approximately 70 times more likely to reach their destination safely when traveling on a school bus [158]. Despite being an incredibly safe mode of transportation, in the past 11 years, there have been approximately 26,000 school bus accidents in the U.S. annually [203]. On average, annually, 128 fatalities were associated with school buses between 2008-2017 and 13 of these fatalities involved occupants of school buses [204]. Almost 50% of these 13 fatalities were involved in a rollover [49].

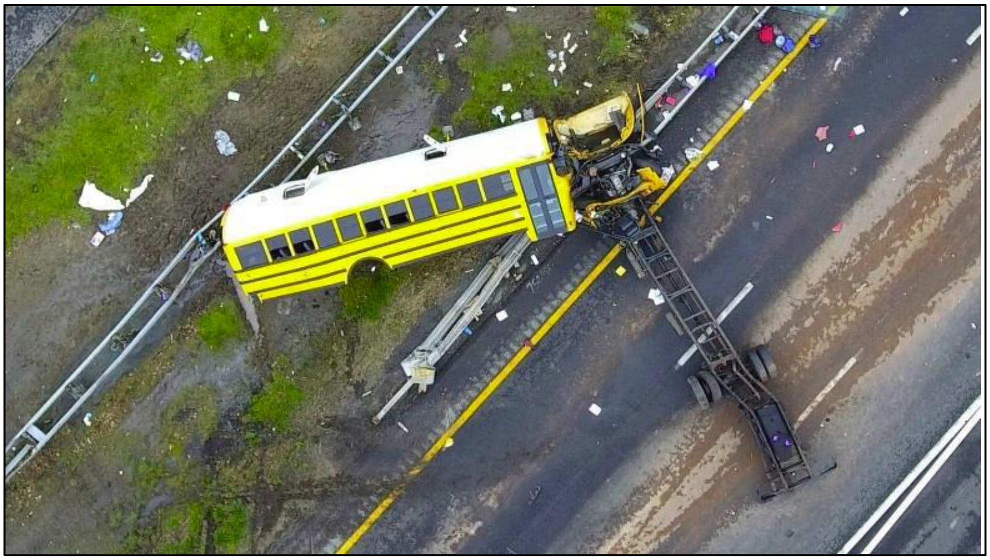


Figure 4.1: School Bus Accident in New Jersey Highway [205]

Several federal motor vehicle safety standards have evolved over the years with some minor changes and several new ones have also been added. Occasionally there are some considerable changes to the standards, and most of these are due to a major accident. Recently, there have been 2 major school bus rollover accidents that are encouraging law makers to consider seat belts on all school buses. The New Jersey Turnpike accident involved a school bus making an illegal U-turn on interstate 80 in northwestern New Jersey, which collided with a dump truck on the highway and overturned in the median. It was carrying 44 passengers, 38 students and 7 adults, A 10-year-old student and a 51-year-old teacher were killed, and 43 injured had to be taken to the hospital [206].

In the November 21, 2016, crash in Chattanooga, Tennessee, a driver was speeding while using a cell phone and ran off the road. The Woodmore Elementary School bus transporting 37 students, flipped over and crashed into a tree killing six children between the ages of six (6) and 10; six (6) were seriously injured and 20 received minor injuries [207].

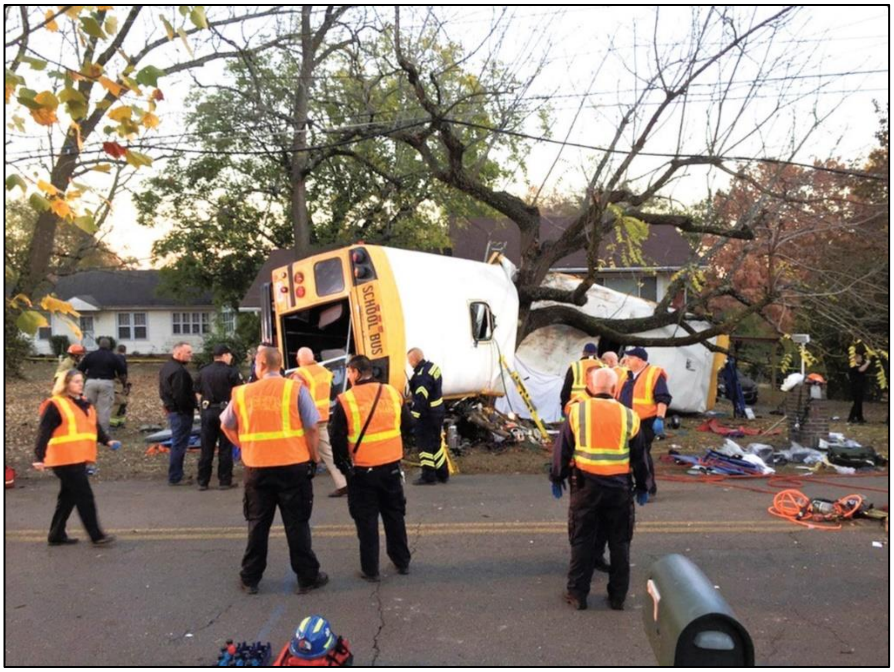


Figure 4.2: School Bus Accident in Chattanooga, Tennessee [208]

Following multi-fatality crashes involving school buses, the National Transportation Safety Board (NTSB) conducted a special investigation [207]. The NTSB routinely conducts such investigations to determine the probable causes of the accidents, issue safety recommendations, study transportation safety issues, and evaluate the safety effectiveness of government agencies involved in transportation [207]. In 2018, after the special investigation, the NTSB recommended states to "Enact legislation to require that all new large school buses be equipped with passenger lap/shoulder belts for all passenger seating positions in accordance with Federal Motor Vehicle Safety Standard 222" [207]. Further, they requested states to "Amend your statutes to upgrade the seat belt requirement from lap belts to lap/shoulder belts for all passenger seating positions in new large school buses in accordance with Federal Motor Vehicle Safety Standard 222" [207].

Currently only eight states require seat belts, but with this recommendation from NTSB, more states are considering seat belts for school buses, and there is heightened attention every time there is a major accident. We are just one major accident away from a spectrum shift on seat belts, hence it is critical to research different aspects of seat belts. It is important to investigate if seat belts on school buses are safe for children in all scenarios, especially in a rollover accident.

Although school buses are statistically very safe and have been extensively researched, surprisingly, there appears to be no research literature discussing any issues with the design of seat belt buckles on school buses. This lack of attention to seat belt design is particularly problematic because the riding population on school buses is predominantly made up of children who may not be adequately accommodated by current seat belt designs. Seat belts used in school buses are subject to the same laws and regulations as those used in passenger cars, light trucks, and other motor vehicles. The seat belt buckle according to the FMVSS 209 S4.3 (d) of a Type 1 or Type 2 seat belt assembly shall release when a force of not more than 133 N is applied [27]. FMVSS 217 regulates bus window retention and sets standards for emergency exit operating forces, markings, and opening dimensions [168]. However, the effects of seat belts and the buckle release force in an emergency evacuation scenario is not discussed nor mentioned in any of these standards.

An extensive review of the existing literature was unable to uncover any studies done on the strength capabilities of children to unlatch a seat belt in a rolled over orientation of a school bus. Multiple studies have demonstrated a discrepancy between the design of school bus emergency exits and the physical abilities of children [171]–[175], highlighting the need for further research to ensure that school bus seat belt design is appropriate for the capabilities of young children.

4.2 Objective and Hypothesis

The primary goal of this experiment is to assess the physical capabilities of children to exert the force required to unlatch a seat belt. The purpose was to study the strength capabilities of school bus riding children to unlatch a push-button seat belt buckle in a rolled over orientation. The specific aims of this study were:

a) Measure the maximum buckle release force (push) exerted by the occupant in different orientations.
b) Determine if the force exerted in different orientations by an occupant is distinct.
c) Determine if the occupant is able to unlatch the seat belt buckle in different orientations.

The hypotheses of the experiment were:

Hypothesis 1: The maximum push force exertion on push-button seat belt buckle for subjects (5-16 years old) is greater than the maximum buckle release force of 133 N mentioned in the standard.

$$H_0 : F_{\text{exerted by subjects}} \geq 133\text{ N}$$

$$H_1 : F_{\text{exerted by subjects}} < 133\text{ N}$$

Hypothesis 2: Force exerted by an occupant in upright orientation is same as the force exerted in rolled over orientation.

$$H_0 : F_{\text{ exerted in rolled over orientation}} = F_{\text{ exerted in upright orientation}}$$

$$H_1 : F_{\text{ exerted in rolled over orientation}} \neq F_{\text{ exerted in upright orientation}}$$

Hypothesis 3: Capability of subject to unlatch a seat belt in rolled over orientation is same as the capability of subject to unlatch a seat belt in upright orientation.

H_0 : N unlatching in rolled over orientation = N unlatching in upright orientation

H_1 : N unlatching in rolled over orientation ≠ N unlatching in upright orientation

4.3 Equipment

The following equipment were used for data collection:

1) Custom built rollover simulator
2) IMMI Safeguard School Bus Bench Seat
3) Force Gauge
    a) Chatillon Model DFS2-R-ND Digital Force Indicator
    b) Chatillon SLC-0500 Remote Force Load Cell
4) Seca 700 Physician Scale with Height Measuring Rod
5) Rubbermaid Pelouze P250SS Weight Scale

4.4 Experimental Design

A total of fifty-three (53) subjects (35 females and 18 males) between the ages of 5 and 16 were recruited from gymnastics camp run at the Auburn Gymnastics Academy. The experiments were conducted at the Auburn Gymnastics Academy (AGA) facility in Auburn, AL. After receiving IRB approval, flyers were distributed to the parents and a website for scheduling was set up. Informed consent documents detailing the experiment procedure and expectations were distributed to the parents that were interested. A copy of the IRB approved document, flyer, and informed consent (parental permission) can be found in the Appendix (I, K, L, M).

Data collection was performed over a course of 4 days during the evening AGA camp. According to the schedule, both parents and their child (the subject) arrived at the study location. A separate space along with an individual foam pit was provided for the research at the corner of AGA building in order to not disrupt classes. Figure 4.3 illustrates the AGA setup. When the subjects arrived, RAs explained the experiment to the subjects and their parents. After obtaining the parental permission, the RAs went over the assent process with the subjects, and once they agreed, they were accompanied to Station 1.

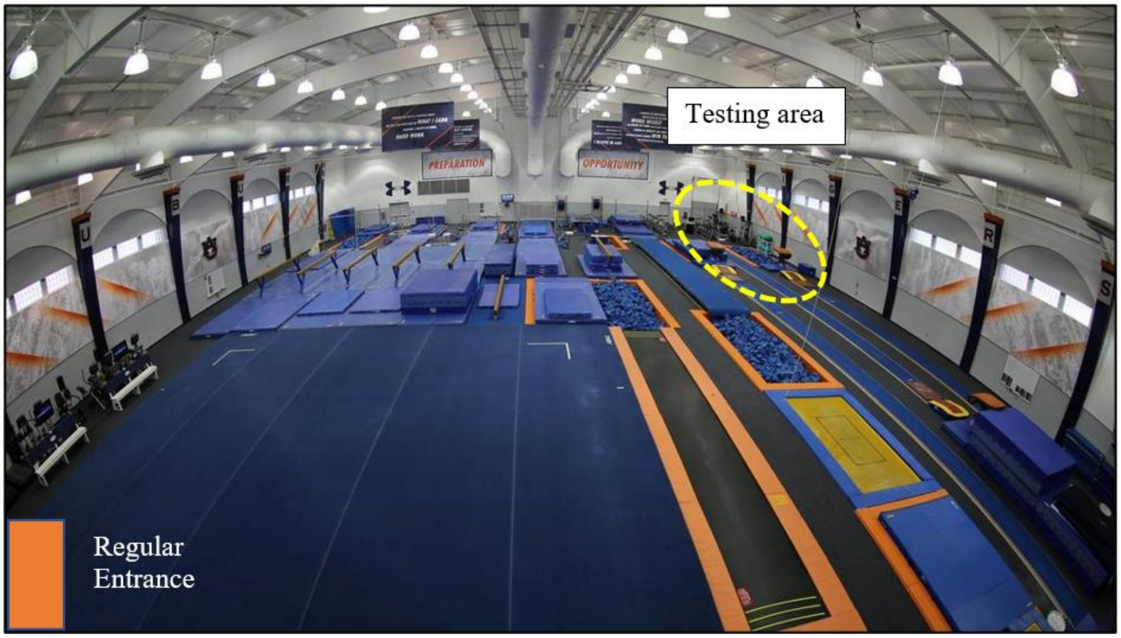


Figure 4.3: Auburn Gymnastics Academy Test Setup [209]

In order to test the hypothesis, a custom test apparatus consisting of a school bus seat rollover simulator was designed and built to simulate an occupant belted in a rolled over school bus orientation as shown in Figure 4.5. The goal of the test device was to tilt a subject sitting in a school bus seat wearing their seat belts, 90° from the horizontal surface (ground). A key component of the design was to ensure a method for subjects to fall safely when they unlatched their seat belts in the rolled over orientation. After analyzing the subjects at AGA, observing them fall from great heights into a foam pit multiple times without sustaining any injuries, and coming out of the pit safely countless times, the conclusion was reached that upon unlatching their seat belt, it would be safe for a subject to fall into a foam pit. Keeping in mind the dimensions of the foam pit and its outer padding borders, the test apparatus frame was designed so that the top of the surface is flush with the foam pit wall and enough clearance is available for the subject to fall into the foam pit. Figure 4.4 illustrates a 3D model of the experiment setup.

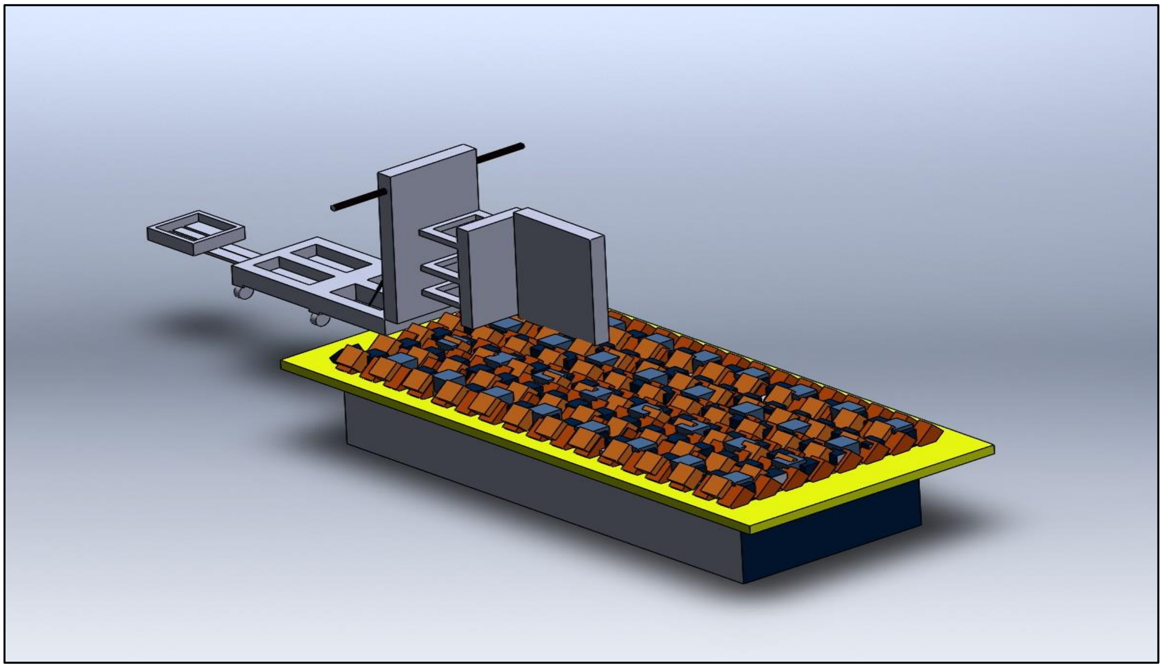


Figure 4.4: 3D Illustration of Experimental Setup in Solidworks

A standard IMMI school bus bench seat with adjustable seat belts on both sides was mounted on the apparatus. The framework was constructed to be sturdy and capable of sustaining an individual weighing as much as 300 lb. Considering the nature of the research, it was determined that RAs would carry out the tilting to enable the subject to be closely and continuously monitored, as well as to enable controlled tilting as required. This also ensures that in case of an emergency or if the subject wishes to discontinue, the assistants can promptly return the device to its normal position. For assisting the manual tilting process, hydraulic pistons were used at both ends of the structure. The structure was designed such that the upper frame will not go beyond 90°. To prevent the structure from toppling, counter-balance weights and extended counterbalance weights were provided.

Figure 4.5: School Bus Rollover Test Device

Figure 4.6: School Bus Rollover Test Device in Rolled Over Orientation

Unlike cars, which were discussed in the previous chapter while designing the anchor points for the rollover device, the seat belts and buckles for this testing device did not require additional mounting points to be designed, as they were already secured to the frame of the seat itself. School bus bench seats usually come pre-assembled with seat belts. The standard IMMI school bus bench seat that was used for the experiment was an actual production model seat designed to be anchored to the floor of a school bus. A Chatillon DFS2-R-ND Digital Force Dynamometer with the Chatillon SLC-0500 Remote Force Load Cell was used to measure the maximum force exerted by the subjects in different orientations. One of the challenges was figuring out a mounting mechanism for the load cell to closely represent the buckle push button position. As mentioned in Chapter 3, a custom push-button prototype was designed and fabricated. Because the same federal standards exist for school buses as well, the same button was used. To mount the load cell, an external rod/mounting bracket was designed and mounted.

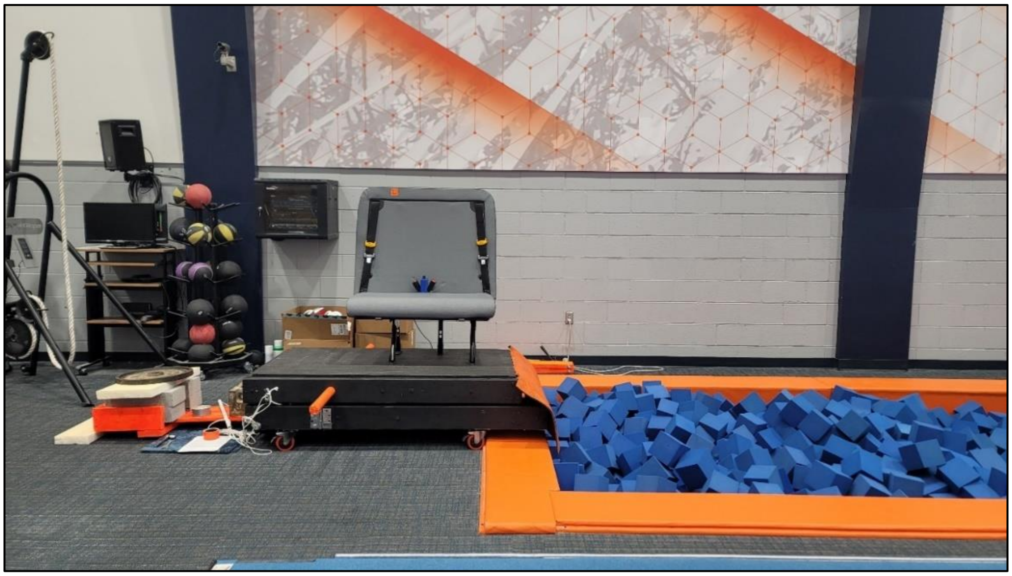


Figure 4.7: Test Device Front View

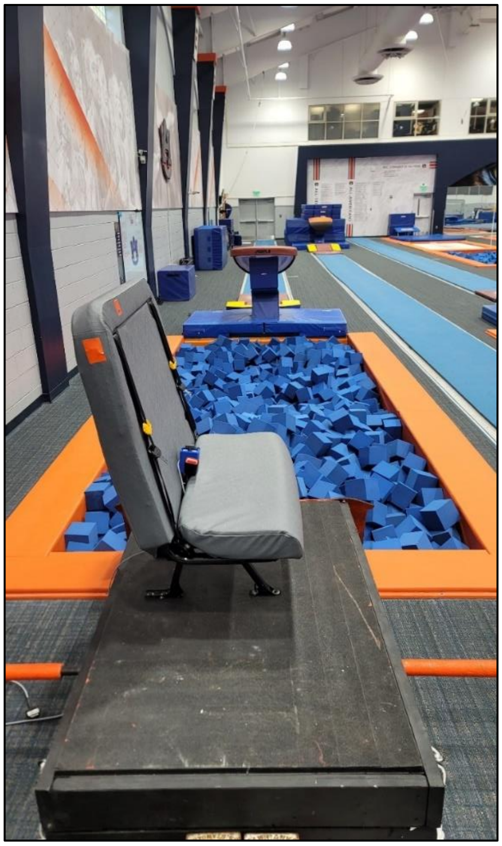


Figure 4.8: Test Device Top View

4.5 Trial Methodology

When the subject arrived, a RA explained the experiment to the subject and their parents. After obtaining parental permission, the RA went over the assent process with the subject, and if they agreed, they were accompanied to Station 1. The research area was split into two (2) separate stations.

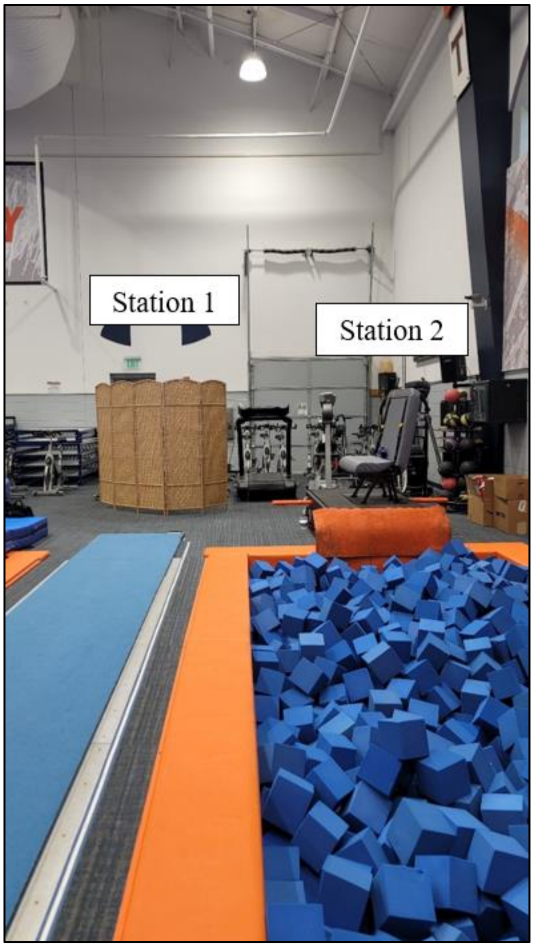


Figure 4.9: Station Positions for Data Collection

Station 1: Subject demographic details like age, sex, and grade were collected here, and their height and weight were recorded behind a screen. A copy of this data collection sheet is attached in the Appendix (J).

After this, they donned a bicycle helmet and were accompanied to the 2nd station.

Station 2: The test apparatus was present at this station and was placed such that upon tilting it 90° from the horizontal, the base of the upper frame on which the seat was mounted was in line with the walls of the foam pit and the school bus bench seat was directly above the pit (as illustrated in Figure 4.12).

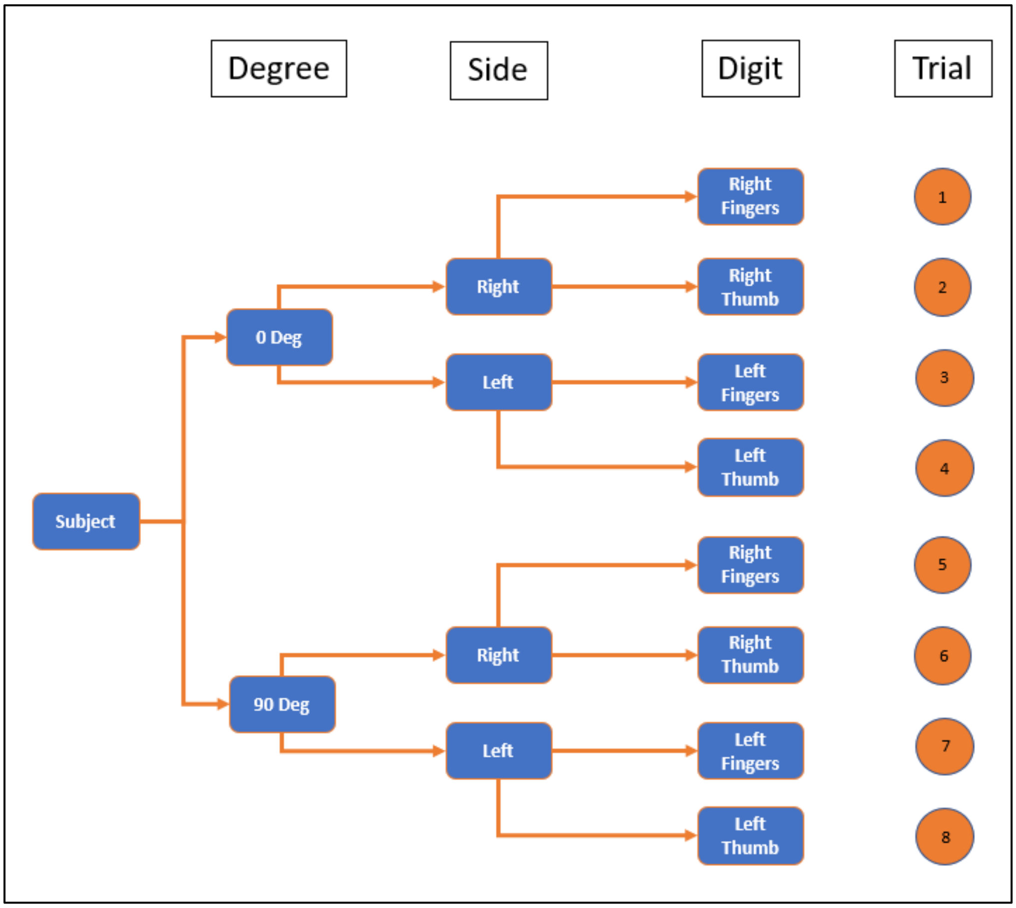


Figure 4.10: Force Exertion Trial Orientation

The experiment was conducted in 2 phases. The primary reason for splitting the experiment in 2 phases was to change the key components (switching between load cell) within the equipment according to the requirements of the study. The order of the phases was randomized. Phase 1 measured the force exertions at different orientations (0° and 90°) and Phase 2 measured the unlatching ability of the subjects. The order in which the phases were assigned is mentioned in Appendix Y.

4.5.1 Phase 1: Force Exertion

The goal of this phase was to measure the maximum push force exerted by an occupant in different orientations on a push-button buckle prototype. School bus rollover accidents are rare, and a fatal accident in which the school bus is completely flipped upside down (180°) is extremely rare. Hence, 2 angles (0° and 90°) were selected for studying force exertion and unlatching capabilities. Since an extensive literature review failed to find any data on force exertion capabilities of children on a seat belt buckle in a regular orientation, 0°or upright orientation force measurements were also measured. In a school bus, an occupant could wear a seat belt either with the buckle being on the left side or the right side and they could unlatch it by pressing the push-button with either their fingers or thumb. For the purpose of this study, the number of fingers was not treated as different groups because depending on the anthropometry of an individual, they can fit anywhere between 1 or 4 fingers on the button to exert force. Only 2 groups were made based on the digits, pressing with just the thumb as group 1 and pressing with fingers (independent of number of fingers) as group 2. Originating from these, a total of 8 different variations of force exertions were possible as displayed in Figure 4.10. For determining the order of force exertion for each subject, a split-plot randomization technique was used for this phase.

When the subject was ready for the trial, they were asked to sit on the side (left or right) of the seat according to the randomized trial order. The subject was then asked to don the 3-point seat belt. These seat belts came with a height adjuster for the shoulder strap (as illustrated in

Figure 4.11). Research associates adjusted the shoulder strap height adjuster to ensure a proper fit and made sure it did not hurt the occupant when they were rolled over.

Figure 4.11: School Bus Rollover Study Seat Side and Belt Height Adjuster Illustration

The RAs also assisted the subjects in buckling if needed and ensured that they were properly secured. A tape was then put over the push button buckle to prevent accidental unlatching of the seat belt. After getting a signal from the research associate (who would confirm with the subject if they were ready), if the trial involved 90° orientation, they were tilted 90°. Upon receiving the go from the research associate, the subject was asked to push on the load cell push button according to the maximum voluntary contraction protocol followed in Chapter 3 (section 3.5.1.1). After they finished pressing both thumb and finger for that side, they were brought back to the upright orientation, asked to change sides, and the process was repeated. When force exertion for the upright orientation was required, upon receiving a go from the research associate, the subject was asked to push the button, and once they were done for a particular side, they were asked to switch positions accordingly.

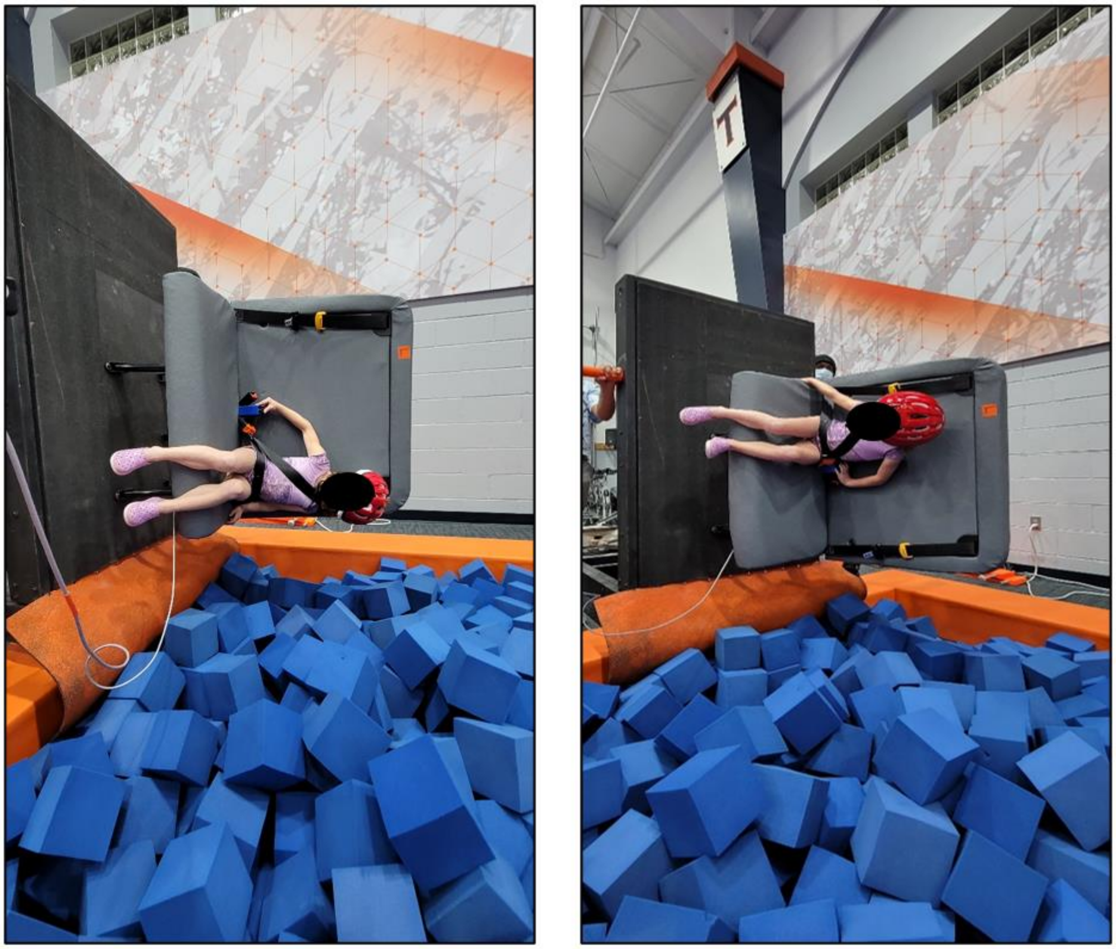


Figure 4.12: Force Exertion at 90° Orientation

After all the force exertion trials were conducted, the subject was brought back to 0° (upright orientation) and the 3-point harness was unlatched, and they were helped to step off the device. The subjects were asked to rest as the researchers removed the load cell setup for the next phase. The experiment trial order is mentioned in Appendix (Z).

Figure 4.13: Data Collection Study Whole Setup

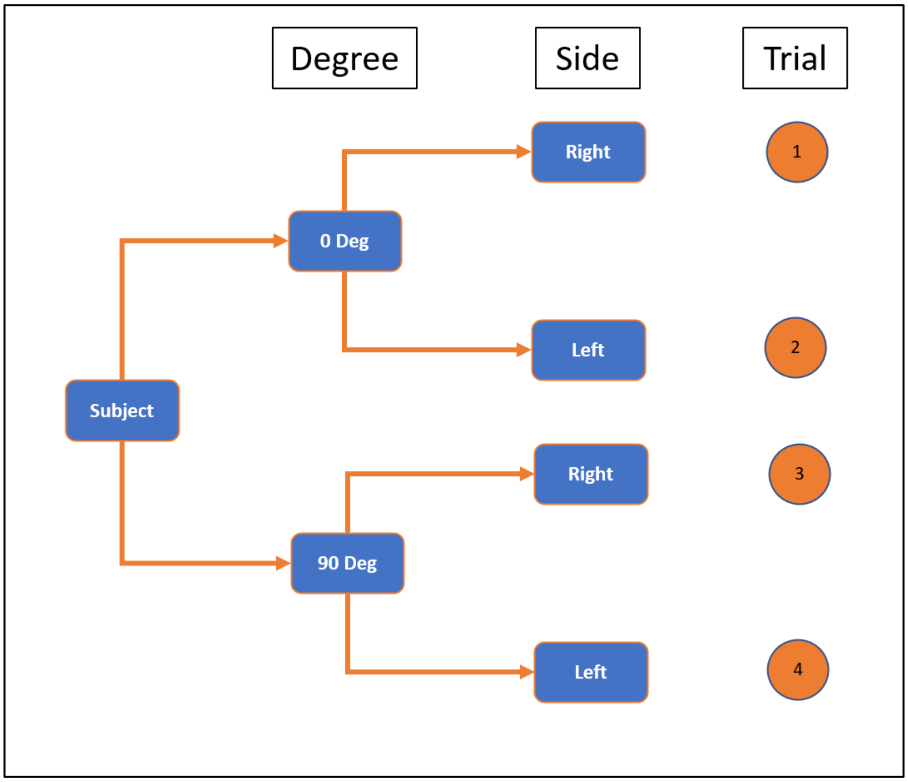


Figure 4.14: Seat Belt Unlatching Trial Orientations

4.5.2 Phase 2: Seat Belt Unlatching

The goal of this phase was to see if an occupant was able to unlatch a seat belt in different orientations. An extensive literature review failed to find any data on the unlatching capabilities of children on a seat belt buckle in any orientation, hence both 0° or upright orientation and 90° or rolled over orientations were considered for this experiment. In a school bus, an occupant could wear a seat belt either with the buckle being on the left side or the right side and they could unlatch it by pressing the push-button with either their fingers or thumb. However, in a real-world scenario in an accident/emergency, an occupant could unlatch their seat belt using any method – fingers, thumb, or a combination of both and egress the vehicle. Hence, for the purpose of this study, the digits used to unlatch were not treated as different groups. A total of 4 different variations are possible for unlatching seat belt in the 2 different orientations as shown in Figure 4.14. The order in which these unlatching trials were performed was randomized. When the subject was ready for the trial, they were asked to sit on the side of the seat according to the randomized trial order. The subject was then asked to don the 3-point seat belt. These seat belts came with a height adjuster for the shoulder strap. Research associates adjusted the shoulder strap height adjuster to ensure a proper fit and made sure it did not hurt the occupant when they were rolled over. Subjects were assisted in buckling if needed, and RAs ensured that the occupant was properly secured.

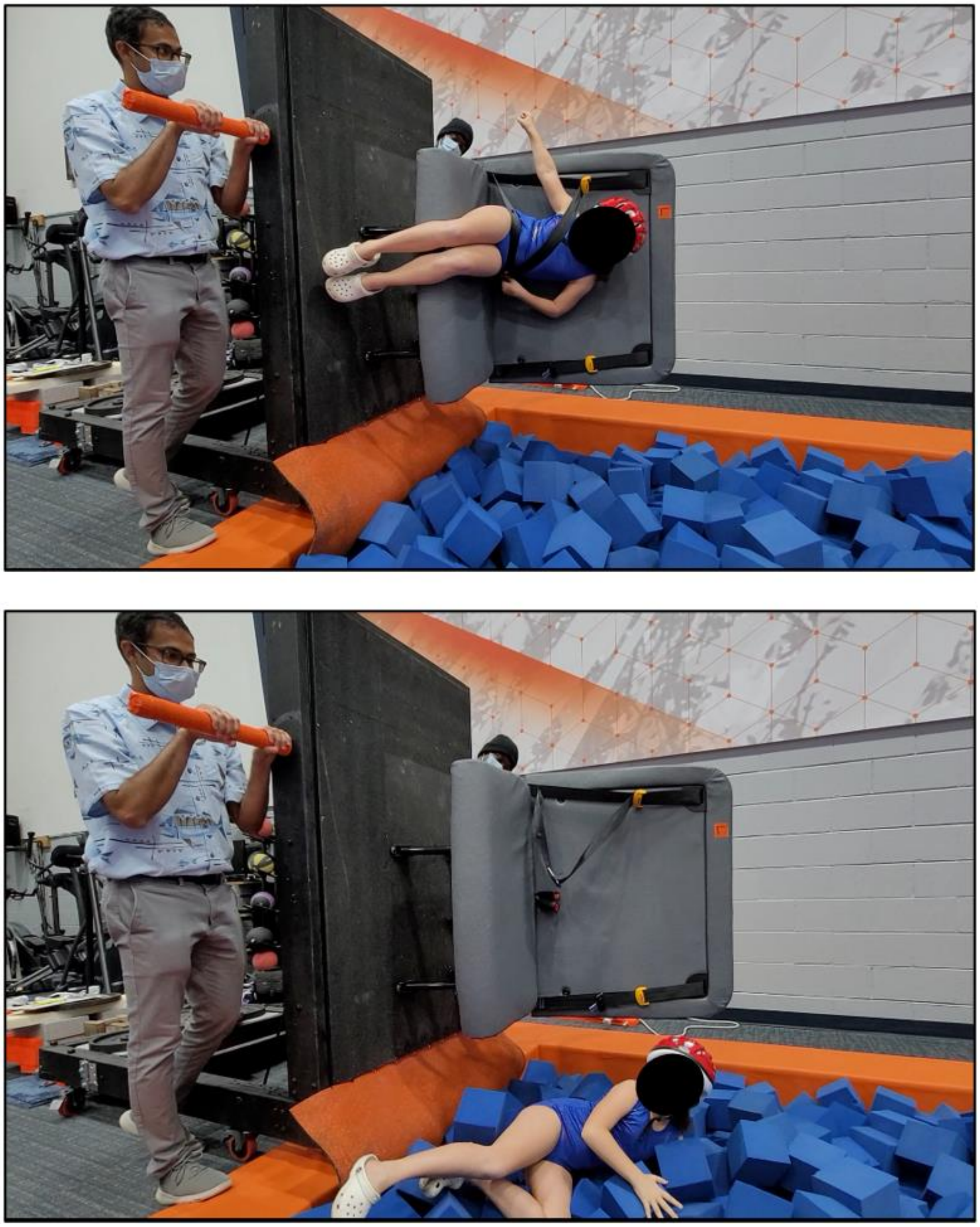


Figure 4.15: Subject in Unlatching Phase

If the trial order involved tilting, then subjects were required to give a signal that they were ready, and the RA would signal them that they would be tilted. Once they reached 90°, upon receiving instruction from the RA, the subject was asked to press the seat belt push button in order to unlatch themselves. For consistency in data collection, the subject was requested to unlatch only using the hand on the side of their body coinciding with the side of buckle. If the subjects were successful in unlatching, they gently fell into the foam pit below. Once the subject came out of the foam pit, and was at a safe distance, the device was lowered, and the process was repeated. If the subject trial was at 0°, upon receiving a signal from the RA, they were asked to unlatch the buckle. Once it was observed that the buckle was unlatched, they were asked to stand up and move to the next position to be tested.

The subjects were given 3 attempts to unlatch the seat belt buckle. Each attempt was defined by subjects taking their hands out and reaching the button to unlatch and if unsuccessful, taking their hand away from the button for the RA to see and then trying again. They could also ask to stop the experiment anytime if they felt uncomfortable or were unable to unlatch.

A detailed protocol of the experiment can be found in the appendix. The experimental data collection sheet is attached in the Appendix (J). The experiment trial order is mentioned in Appendix (AA). The experiment data collection process flow chart is illustrated in Figure 4.16.

4.6 Statistical Analysis Methods

The experimental data underwent both visual inspection and statistical testing to determine its suitability for various analytical techniques such as Analysis of Variance (ANOVA), Analysis of Covariance (ANCOVA), linear regression models, and binary logistic regression. Visual inspection included examining box plots, individual value plots, normality plots, histograms, residual plots, and checking for outliers. The statistical testing took into account the assumptions of normality of residuals and equality of variance. These analyses were conducted using Minitab 21 (2023) Statistical Software, State College, PA, USA: Minitab Inc., SPSS statistics software (2023 IBM SPSS Statistics 29, Chicago, IL, USA) and StatistiX 9.0 statistical software (Analytical Software; Tallahassee, FL, Maryland, USA).

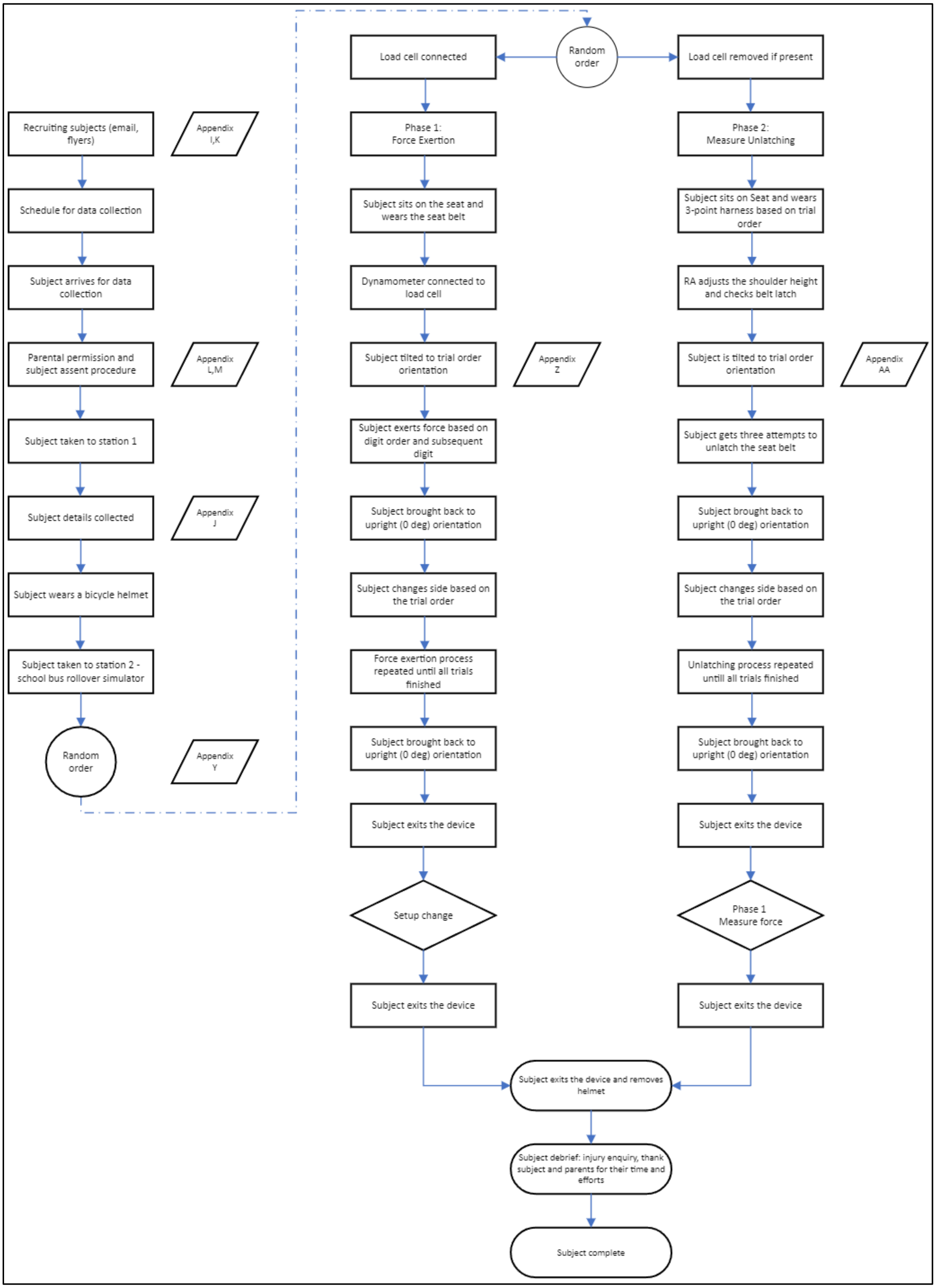


Figure 4.16: Experiment Process Flow Chart

The independent variables for the experiment were: Categorical - sex (male, female), degree (0°90°), side (right, left), digit (finger, thumb), and Continuous – BMI, age, and grade. The dependent variables of this experiment were force (N) exerted in different orientations, and binary output for ability to unlatch (1-yes, 0-no).

There were five (5) subjects (3 males and 2 females) excluded from data analysis as they did not participate in the experiment after the initial descriptive data collection, or after sitting in the equipment, or quit very shortly after the device began to tilt. Forty-eight (48) subjects (33 females and 15 males) completed the study, and their data was included for analysis.

ANOVA tests following a split-split-plot factorial design for each sex were conducted to study the statistical significance of the main and interaction effects of the independent variables on the dependent variables. The degrees were assigned as the main plot, side (hand) as sub plot and digit as sub-sub plot. Tukey HSD post-hoc tests were conducted to compare each possible pair of the factors for each sex. For studying the effects of sex, BMI, grade, and age on force exertion, a linear regression model was developed for the data set and an analysis of covariance (ANCOVA) was performed. Regression Analysis for force versus age, grade (coded), BMI, sex, degree, side, digit was performed. For this analysis a backward elimination process ($\alpha = 0.05$ to remove) was used in Minitab to find the factors that best represent the model. For analysis, Pre-Kindergarten was coded as 1, Kindergarten as 2, and subsequently other grades were coded.

All 48 subjects (15 male and 33 female) performed the 4 unlatching orientations mentioned earlier. A total of 192 unlatching trials were conducted. **There were 8 occasions on which an individual could not unlatch their seat belt**. 3 Male and 3 Female subjects could not unlatch the seat belt in at least 1 condition. A binary logistic regression was performed on the unlatching ability of subjects at different orientation against independent variable – BMI, age, grade, sex, degree and side. All terms and interaction effects were added to the model and using Minitab, a stepwise elimination process was used to determine the best fitting model. The following were the criteria: α to enter = 0.05, α to remove = 0.05. "Minitab stops when all variables not in the model have p-values that are greater than the specified Alpha to enter value and when all variables in the model have p-values that are less than or equal to the specified Alpha to remove value" [200].

4.7 Results

4.7.1 Descriptive Statistics

A total of fifty-three (53) subjects (35 females and 18 males) between the ages of 5 and 16 years old were recruited from a gymnastics camp run at the Auburn Gymnastics Academy to participate in this study. Table 4.1 represents a summary of the subject demographics. Figure 4.17 to Figure 4.19 represent this information graphically.

Table 4.1: Summary of Subject Demographic

Variable	Sex	N	Mean	StDev	Minimum	Median	Maximum
Age	F	35	7.457	1.615	5.000	8.000	10.000
	M	18	8.333	2.275	5.000	8.500	12.000
Grade	F	35	3.914	1.738	1.000	4.000	7.000
	M	18	4.722	2.321	2.000	5.000	9.000
Weight (lb.)	F	35	54.60	12.03	38.00	55.00	78.00
	M	18	64.17	18.34	42.00	59.50	95.00
Height (in)	F	35	50.218	3.288	44.882	50.394	57.087
	M	18	52.975	3.694	46.457	52.953	60.630
BMI	F	35	15.044	1.916	12.092	14.536	19.262
	M	18	15.810	3.115	11.447	14.665	23.295

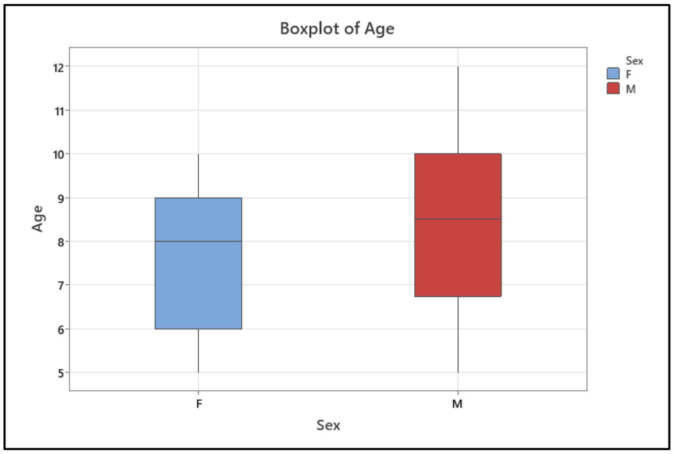


Figure 4.17: Boxplot for Age by Sex

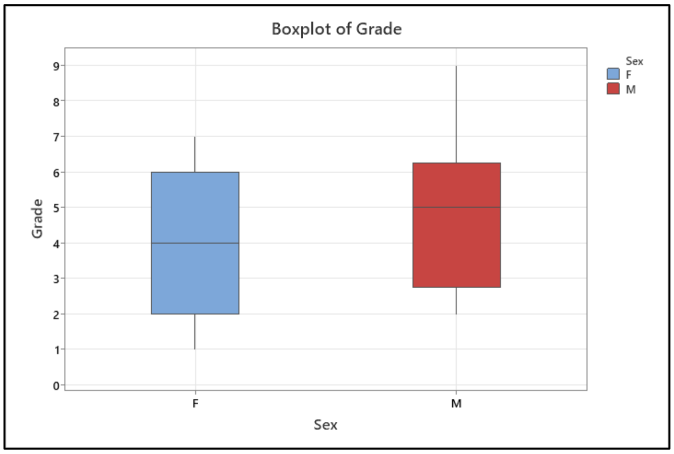


Figure 4.18: Boxplot for Grade by Sex

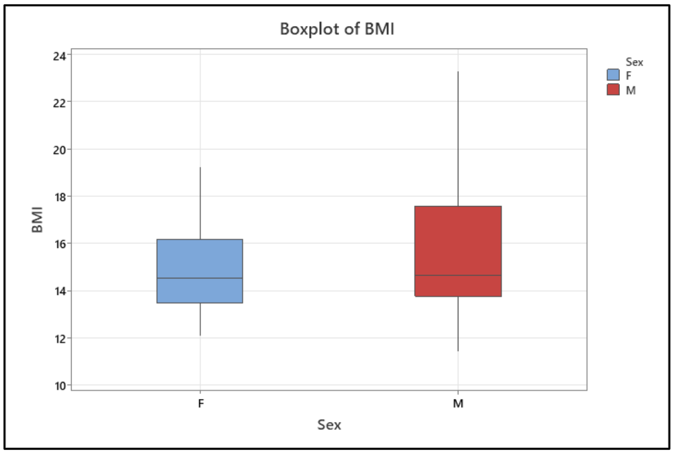


Figure 4.19: Boxplot for BMI by Sex

The BMI categories for children and adolescents are different than those for adults. Their BMI is age and sex specific and is often referred to as BMI-for-age [210]. The CDC provides BMI-for-age growth charts for children and adolescents, which take into account age and sex, in addition to height and weight [211]. These growth charts categorize children and adolescents into percentiles, ranging from underweight to obese, based on their BMI values. An example of a BMI-for-age growth chart is illustrated in Appendix (AB). Using the CDC's Child and Teen BMI Percentile Calculator [212], the Table 4.3 was compiled for categorizing subjects in the different BMI percentile categories.

Table 4.2: BMI-for-age weight status categories and the corresponding percentiles

Weight Status Category	**Percentile Range**
Underweight	Less than the 5th percentile
Healthy Weight	5th percentile to less than the 85th percentile
Overweight	85th to less than the 95th percentile
Obesity	Equal to or greater than the 95th percentile

Table 4.3: Subjects in Each BMI Category for Current Study

	Male	**Female**	**Total**
Number of children assessed:	18	35	53
Underweight (< 5th percentile)	28%	23%	25%
Normal BMI (5th - 85th percentile)	61%	71%	68%
Overweight or obese (≥ 85th percentile)	11%	6%	8%
Obese (≥ 95th percentile)	11%	3%	6%

4.7.1.1 Force Exertion Descriptive Statistics

Table 4.4 provides the descriptive statistics for the force exerted by subjects. Table 4.5 and Table 4.6 present the mean of the force exerted by male and female subjects at both the orientation. Figure 4.20 graphically illustrates the force exerted at each orientation by each sex.

Table 4.4: Descriptive Statistics for the Force (N) Exerted by Subjects

Variable	Sex	N	Mean	StDev	Minimum	Maximum
0°LT	F	33	45.51	17.99	10.20	82.20
	M	15	54.69	19.26	25.00	83.00
0°LF	F	33	40.67	15.32	11.20	66.00
	M	15	44.39	15.25	18.60	78.20
0°RT	F	33	47.97	17.53	13.80	88.40
	M	15	59.97	22.98	11.80	88.80
0°RF	F	33	41.27	14.59	12.60	70.60
	M	15	47.15	18.58	13.60	78.80
90°LT	F	33	40.30	17.84	12.40	82.40
	M	15	47.01	23.20	11.60	91.60
90°LF	F	33	36.92	17.00	10.40	73.20
	M	15	38.29	21.72	10.20	79.00
90°RT	F	33	39.85	15.80	11.60	77.40
	M	15	54.39	20.32	27.20	94.00
90°RF	F	33	34.33	13.42	10.20	58.20
	M	15	46.85	17.83	17.40	78.20

Table 4.5: Mean Force (N) Exerted by Male Subjects at Each Degree

Variable	Degree	Total Count	Mean	StDev	Minimum	Maximum	Range
Force	0	60	51.55	19.72	11.80	88.80	77.00
	90	60	46.64	21.12	10.20	94.00	83.80

Table 4.6: Mean Force (N) Exerted by Female Subjects at Each Degree

Variable	Degree	Total Count	Mean	StDev	Minimum	Maximum	Range
Force	0	132	43.85	16.51	10.20	88.40	78.20
	90	132	37.85	16.10	10.20	82.40	72.20

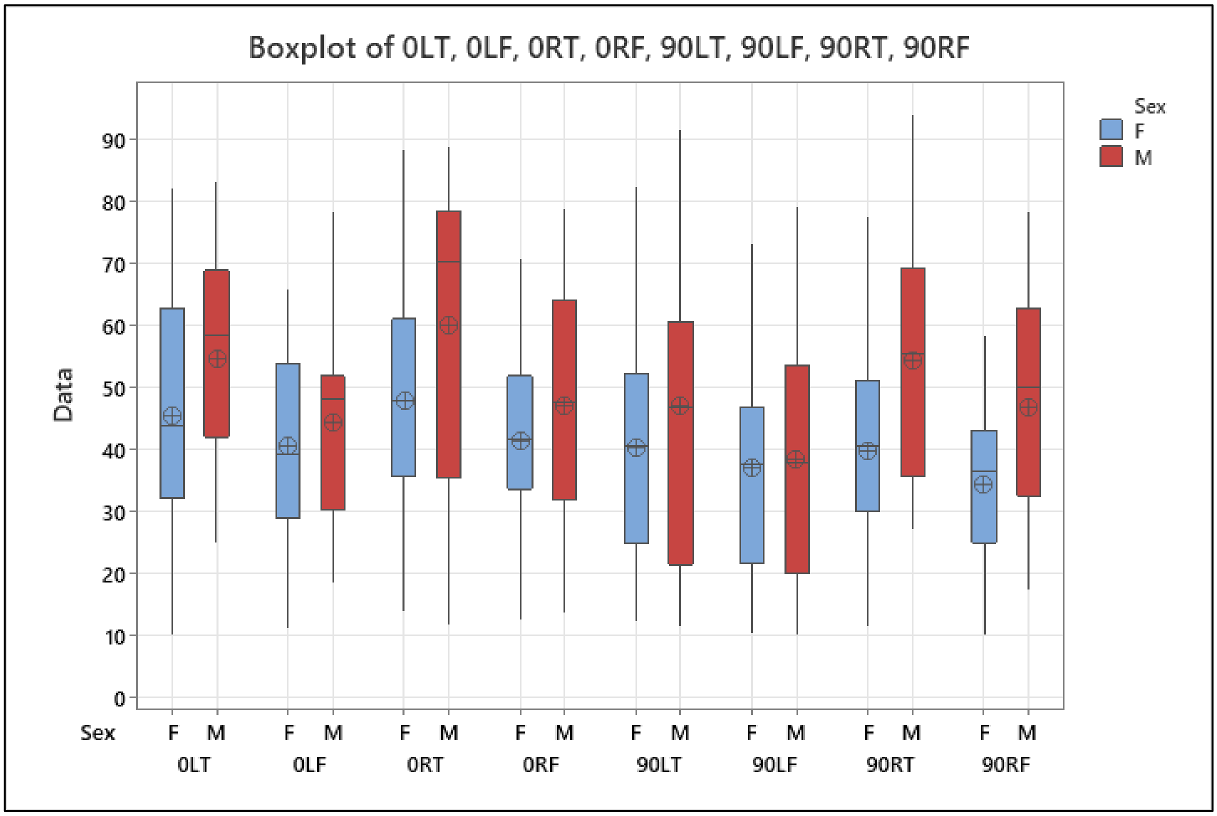


Figure 4.20: Force (N) Exerted at Each Orientation Split Sex Wise

4.7.1.2 Unlatching Descriptive Statistics

Table 4.7 and Table 4.8 represent the distribution of subjects able to unlatch their seat belt in different trial orientations. Table 4.9 represents scenarios in which the subjects could not unlatch. 3 male and 3 female subjects could not unlatch the seat belt in at least 1 condition.

Table 4.7: Unlatching Distribution for Males

Degree	0°		90°	
Side	Right	Left	Right	Left
Total Possible	15	15	15	15
Result	15	15	13	13

Table 4.8: Unlatching Distribution for Females

Degree	0°		90°	
Side	Right	Left	Right	Left
Total Possible	33	33	33	33
Result	33	33	31	31

Table 4.9: Unsuccessful Unlatching Scenarios

Sex	Age	Grade	BMI	90R	90L
M	7	1	14.76		NO
F	5	K	12.60	NO	NO
M	6	K	13.79	NO	
F	5	pre-K	13.03	NO	
F	5	pre-K	18.59		NO
M	7	1	23.29	NO	NO

4.7.2 Inferential Statistics

4.7.2.1 Force exertion Inferential Statistics

The results of Ryan-Joiner normality tests illustrated in Table 4.10 and Table 4.11 suggest that the maximum push force data for each orientation exhibited a normal distribution ($\alpha = 0.05$) A one sample t-test was performed at each orientation to determine if the maximum push force exerted by subjects was greater than the standard specified maximum buckle release force of 133 N. Due to multiple tests, a new significance level of 0.00625 was determined instead of the conventional 0.05 level for each individual t-test using the Bonferroni Correction method. All the t-tests yielded a p-value smaller than 0.00625.

Table 4.10: Ryan-Joiner Normality Test Results for Force (N) Exertions - Male

Orientation	N	Mean	StDev	RJ Value	P-Value
0° Left Thumb	15	54.69	19.26	0.982	> 0.10
0° Left Finger	15	44.39	15.25	0.95	= 0.098
0° Right Thumb	15	59.97	22.98	0.962	> 0.10
0° Right Finger	15	47.15	18.58	0.978	> 0.10
90° Left Thumb	15	47.01	23.2	0.983	> 0.10
90° Left Finger	15	38.29	21.72	0.979	> 0.10
90° Right Thumb	15	54.39	20.32	0.981	> 0.10
90° Right Finger	15	46.85	17.83	0.99	> 0.10

Table 4.11: Ryan-Joiner Normality Test Results for Force (N) Exertions - Female

Orientation	N	Mean	StDev	RJ Value	P-Value
0° Left Thumb	33	45.51	17.99	0.992	> 0.10
0° Left Finger	33	40.67	15.32	0.993	> 0.10
0° Right Thumb	33	47.97	17.53	0.996	> 0.10
0° Right Finger	33	41.27	14.59	0.987	> 0.10
90° Left Thumb	33	40.3	17.84	0.987	> 0.10
90° Left Finger	33	36.92	17	0.987	> 0.10
90° Right Thumb	33	39.85	15.8	0.992	> 0.10
90° Right Finger	33	34.33	13.42	0.988	> 0.10

Table 4.12: Results of One Sample t-Tests for Force Exertion for All Orientations

Null hypothesis $H_0: \mu \geq 133$

Sample	**T-Value**	**P-Value**
0°LT	-31.37	0.000
0°LF	-41.47	0.000
0°RT	-28.22	0.000
0°RF	-38.97	0.000
90°LT	-31.92	0.000
90°LF	-36.06	0.000
90°RT	-33.33	0.000
90°RF	-41.38	0.000

Results of the one sample t-tests summarized in Table 4.12 indicate that the null hypothesis that subjects can exert force greater than the standard specified 133 N maximum buckle release force was **rejected.** Table 4.13 and Table 4.14 display the results of the ANOVA for force for male subjects and female subjects.

Table 4.13: Results of Split Plot ANOVA for Force - Male Subjects

Source	**DF**	**SS**	**MS**	**F**	**P**	**Partial Eta^2 - η2**
Subject (A)	14	35178.9	2551.35			
Degree (B)	1	724.2	724.23	6.03	**0.0277**	**0.301**
Error A*B	14	1681.5	120.11			
Side (C)	1	1078.8	1078.80	10.96	**0.0026**	**0.281**
B*C	1	116.4	116.43	1.18	0.2860	
Error A*B*C	28	2755.5	98.41			
Digit (D)	1	2906.7	2906.74	33.32	**0.0000**	**0.214**
B*D	1	88.4	88.41	1.01	0.3184	
C*D	1	3.3	3.33	0.04	0.8457	
B*C*D	1	25.8	25.76	0.30	0.5890	
Error A*B*C*D	56	4885.8	87.25			
Total	119					

Table 4.14: Results of Split Plot ANOVA for Force - Female Subjects

Source	**DF**	**SS**	**MS**	**F**	**P**	**Partial Eta^2 - η2**
Subject (A)	32	50509.9	1578.43			
Degree (B)	1	2376.60	2376.60	17.41	**0.0002**	**0.352**
Error A*B	32	4367.15	136.473			
Side (C)	1	0.00186	0.00186	0.00	0.9957	
B*C	1	153.796	153.796	2.40	0.1260	
Error A*B*C	64	4095.03	63.9849			
Digit (D)	1	1723.30	1723.30	25.31	**0.0000**	**0.165**
B*D	1	28.8685	28.8685	0.42	0.5161	
C*D	1	65.9000	65.9000	0.97	0.3271	
B*C*D	1	0.30004	0.30004	0.00	0.9472	
Error A*B*C*D	128	8716.32	68.0962			
Total	263					

The effects of degree and digit were found to have a statistically significant effect ($p<0.05$) for both male and female subjects. For male subjects, side was also found to have a statically significant effect on the force exertion. The partial eta-squared values for all these main effects were found to be higher than 0.14 indicating that the magnitude of these effects was statistically large. Table 4.15 represents the Tukey HSD all-pairwise comparisons test of force for degree for males, and Table 4.16 represents the same for females. Detailed reports of all the tests are attached in the Appendix (Q, R).

Table 4.15: Tukey HSD All-Pairwise Comparisons Test of Force for Degree – Male

Degree	**Mean**	**Homogeneous Groups**	
0	51.550	A	
90	46.637		B

Table 4.16: Tukey HSD All-Pairwise Comparisons Test of Force for Degree – Female

Degree	**Mean**	**Homogeneous Groups**	
0	43.852	A	
90	37.852		B

The regression equations from the analysis performed are shown in Appendix (T). The results from the analysis are summarized in Table 4.18. The BMI, age, grade, sex, degree, side, and digit were seen to have a statistically significant effect on the force exertion along with the mentioned interaction effects. The adjusted R^2 of the model was 60.27%. Figure 4.21 illustrates that the residuals exhibit a normal distribution.

Table 4.17: Model Summary

S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**
11.5059	62.24%	60.27%	58.13%

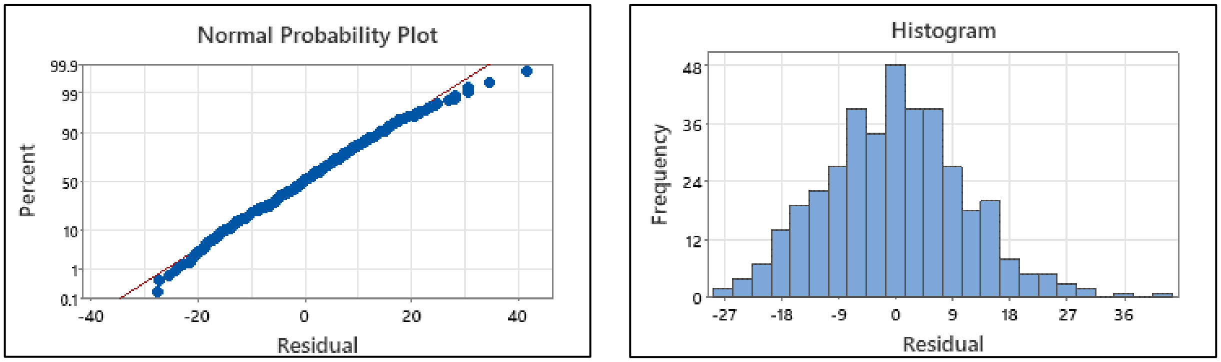


Figure 4.21: Residual Plots for the Regression Model

Table 4.18: Results of ANCOVA for Force vs Age, Grade, BMI, Sex, Degree, Side, and Digit

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**Partial Eta^2 - η2**
Regression	19	79438	4180.9	31.58	0.000	
Age	1	655	655.3	4.95	0.027	0.013
Grade	1	883	883.3	6.67	0.010	0.018
BMI	1	683	682.5	5.16	0.024	0.016
Sex	1	886	885.7	6.69	0.010	0.018
Degree	1	3076	3076.4	23.24	0.000	0.149
Side	1	1079	1078.8	8.15	0.005	0.022
Digit	1	4168	4167.9	31.48	0.000	0.198
Age*Grade	1	1069	1069.2	8.08	0.005	0.022
Age*BMI	1	613	612.9	4.63	0.032	0.012
Grade*BMI	1	934	934.1	7.06	0.008	0.018
Age*Sex	1	767	767.0	5.79	0.017	0.015
Grade*Sex	1	582	581.6	4.39	0.037	0.011
BMI*Sex	1	882	881.5	6.66	0.010	0.018
Sex*Side	1	740	740.4	5.59	0.019	0.015
Age*Grade*BMI	1	1023	1022.7	7.73	0.006	0.018
Age*Grade*Sex	1	790	789.6	5.96	0.015	0.015
Age*BMI*Sex	1	776	776.3	5.86	0.016	0.014
Grade*BMI*Sex	1	516	515.6	3.89	0.049	0.010
Age*Grade*BMI*Sex	1	750	749.6	5.66	0.018	0.014
Error	364	48188	132.4			
Total	383	127626				

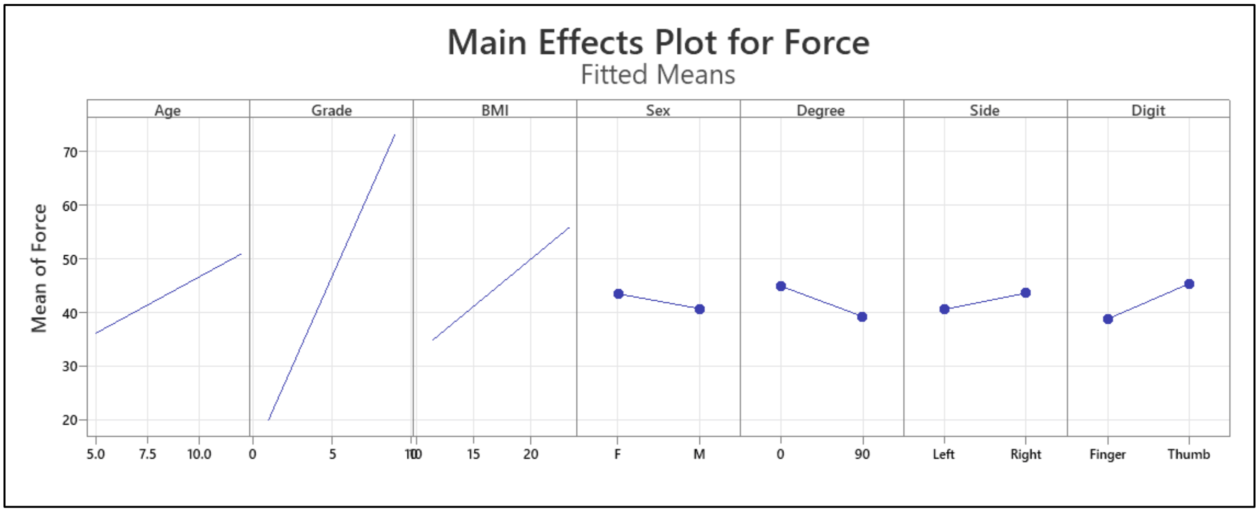


Figure 4.22: Main Effects Plot for Force vs Independent Variables

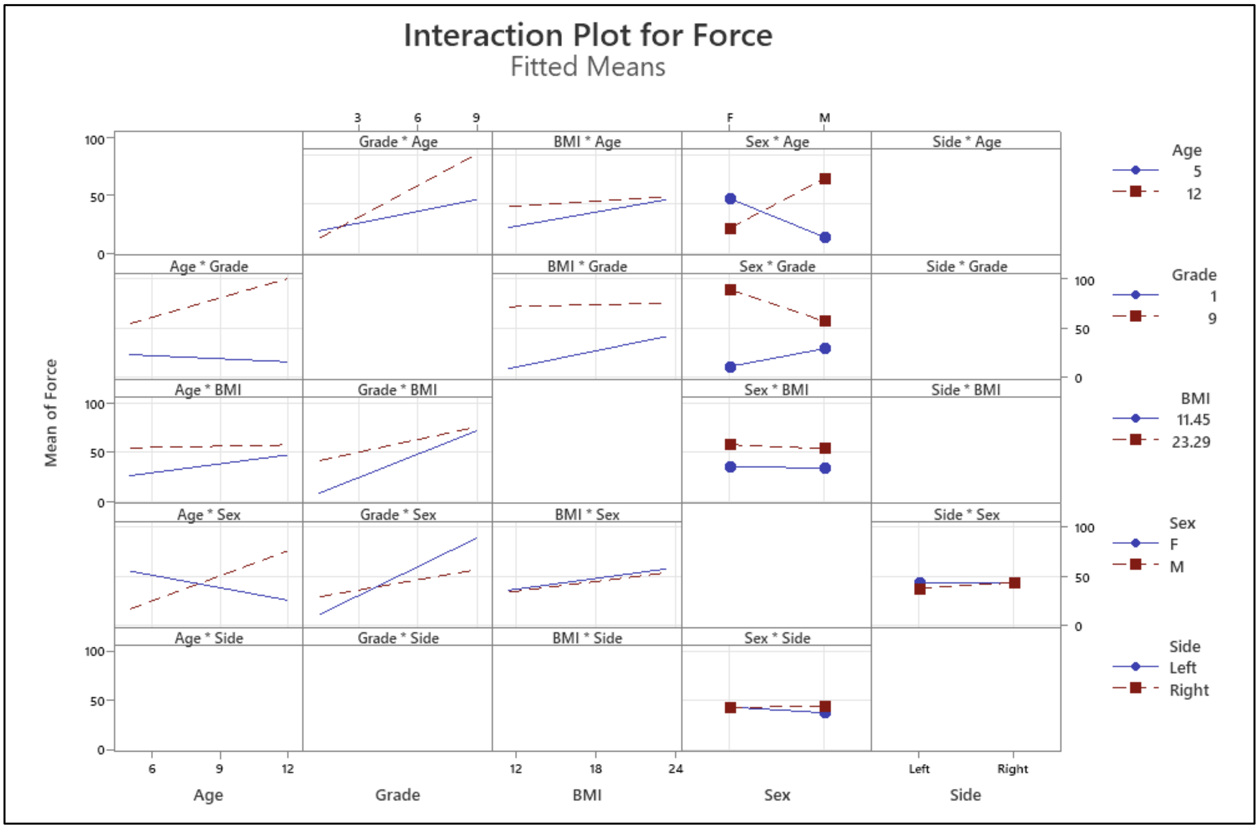


Figure 4.23: Interaction Plot for Force

According to the partial eta-squared values in Table 4.18, the largest effect size ($\eta^2 = 0.20$) is associated with digit, followed by degree ($\eta^2 = 0.10$), and age*BMI had the smallest effect size with $\eta^2 = 0.01$. The majority of the variables in the ANOVA table have small effect sizes, with partial eta-squared (η^2) values around 0.01. To better understand the observed interactions, interaction plots were plotted for significant interaction effects. Interaction plots were used to graphically illustrate the effect of one independent variable on the dependent variable, while holding the other independent variable(s) constant. Figure 4.22 illustrates the main effects and Figure 4.23 illustrates the interaction effects for these factors.

4.7.2.2 Unlatching Inferential Statistics

The subject's grade was determined to have a statistically significant effect on the response.

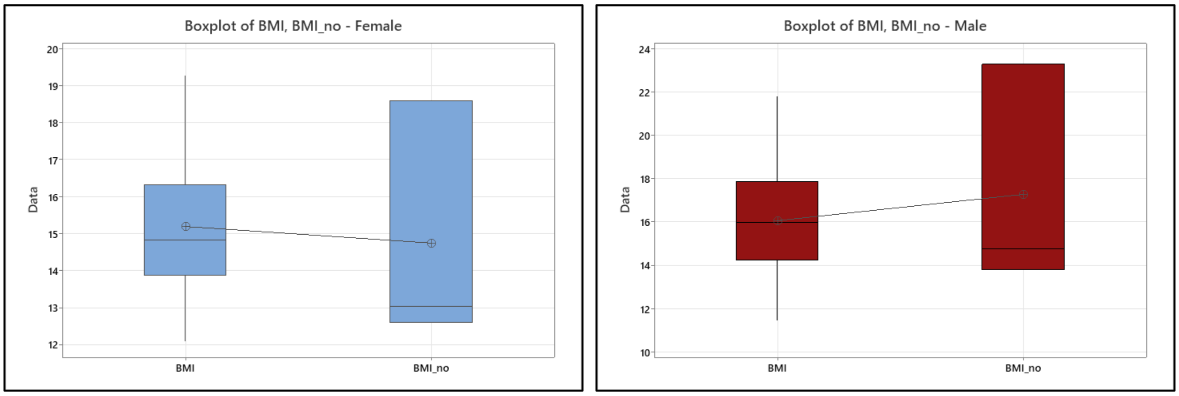
Table 4.19: Response Information

Variable	Value	Count	
Unlatching	1	184	(Event)
	0	8	
	Total	192	

Table 4.20: Analysis of Variance – Wald Test

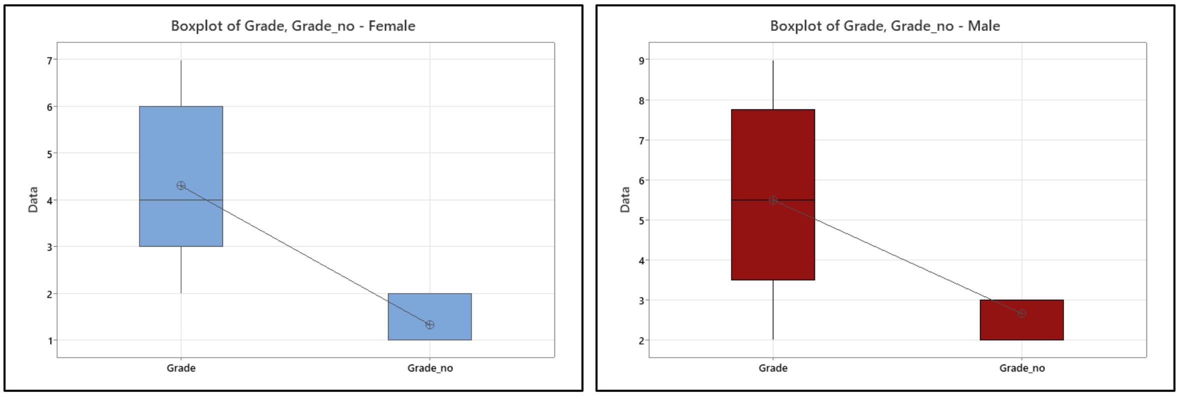
Source	DF	Chi-Square	P-Value
Regression	1	7.52	0.006
Grade	1	7.52	**0.006**

The unlatching data was further analyzed to identify if there could be any other underlying reason for these outcomes. Figure 4.24 to Figure 4.27 show descriptive differences between the subjects who could not unlatch versus those who could. Their forces were also analyzed. It was observed that the mean of the grade was significantly lower for subjects that could not unlatch compared to those who could. Similarly, the mean of force exerted for both male and female subjects who could not unlatch was significantly lower than those who could.


Boxplot of BMI, BMI_no - Female

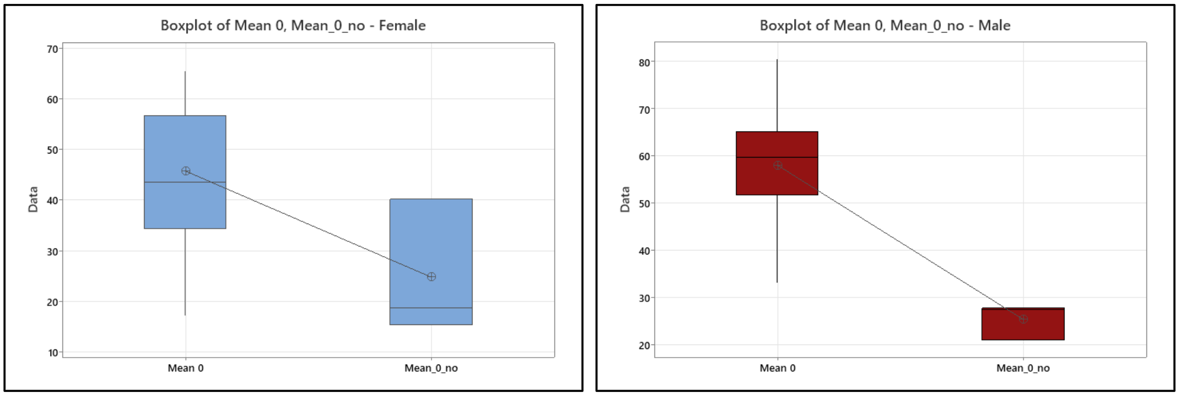
Boxplot of BMI, BMI_no - Male

Figure 4.24: BMI Comparison for Subjects Unable to Unlatch – Female & Male


Boxplot of Grade, Grade_no - Female

Boxplot of Grade, Grade_no - Male

Figure 4.25: Grade Comparison for Subjects Unable to Unlatch – Female & Male


Boxplot of Mean 0, Mean_0_no - Female

Boxplot of Mean 0, Mean_0_no - Male

Figure 4.26: Mean Force (N) Comparison for Subjects Unable to Unlatch (0°) Female & Male

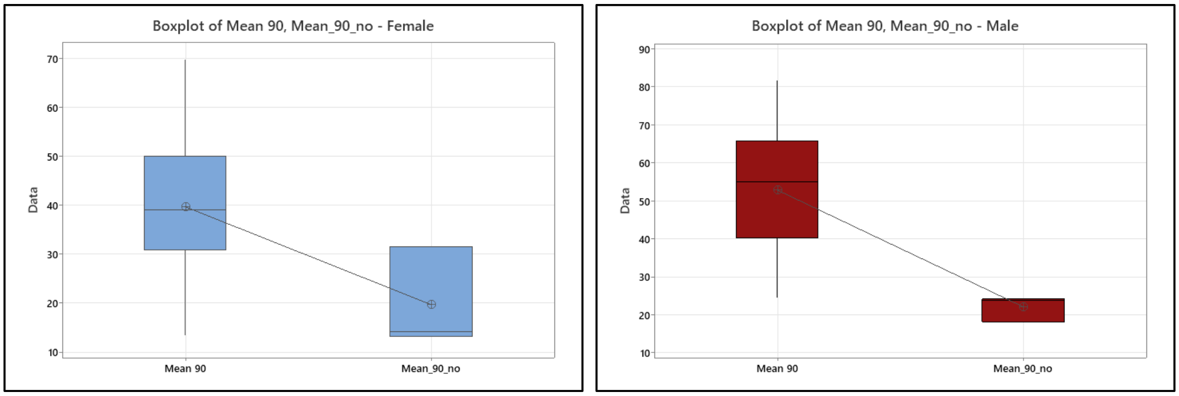


Figure 4.27: Mean Force (N) Comparison for Subjects Unable to Unlatch (90°) Female & Male

4.8 Discussion

Millions of children ride school buses every day in the United States. Currently, only eight states require seat belts on school buses. However, there is a push by several local communities all over the country, and several lawmakers are considering implementing seat belts on all school buses. It is essential to study the ability of children to unlatch a seat belt especially if they were in an accident because in the majority of the routes, the bus driver is the only adult on the bus. The primary purpose of this experiment was to evaluate the physical capabilities of children to unlatch a seat belt buckle in a rollover orientation and to see if it would have an impact on their evacuation. It was essential to collect force data in different scenarios and compare it to the FMVSS seat belt buckle release force standard.

The majority of the subjects (>95%) were able to unlatch the seat belt in a rolled over orientation. However, analysis of the force exertion data suggests that the subjects did not have the strength capabilities to exert the FMVSS 209 Standard specified maximum buckle release force of 133 N to unlatch a seat belt buckle. It was also observed that force exertion at an upright orientation was statistically significant than rolled over orientation for both male and female subjects.

Table 4.21 and Table 4.22 illustrate force exertion values for a similar comparison from the Department of Trade study [169], [170], and the current study. Differences in the force measurements can be observed for the 6-10 age group for 20 mm circular plate thumb and for 50 mm cube both for thumb and finger. The DTI study followed a standing posture and did not account for pushing force generated by the whole body in that position for the 20 mm circular plate experiment. The small area and rectangular dimension of the custom push-button prototype used in this study and the sitting posture observed while exerting force might have resulted in lower force output.

Table 4.21: Summary of Mean Push Force from the DTI Studies [169], [170]

Mean Push Force (N)							
		(20 mm circular plate)			(50 mm Cube)		
Sex	Age	2-5	6-10	11-15	2-5	6-10	11-15
Male	Fingers	21.8	43.3	66.7	31.95	56.18	117.6
Female		24.5	42	63	22.26	66.81	103.2
Male	Thumb	26.9	85.1	115.1	26.8	66.62	124.43
Female		34.4	71.1	94.3	24.16	82.75	97.24

Table 4.22: Summary of Force (N) for Current Study

Sex	Age	5	6-10
Male	Fingers	31.85	43.8
Female		25.48	43.73
Male	Thumb	37.6	55.45
Female		34.14	48.98

4.8.1 Effect of Seat Belt Laws in the U.S.

Observational studies showed that in 1983, only 14% of motor vehicle occupants wore seat belts [42]. The national estimate of seat belt use by adult front-seat passengers in 2020 was 90.3% [14]. Statistically, primary enforcement laws are more effective at achieving higher belt use rates. In 2019, the belt use rate observed for front-seat occupants was 6% higher (92% vs 86.2%) in states with primary seat belt enforcement laws in comparison to the states where they are not [43]. Studies have shown strong evidence that seat belt laws significantly increase seat belt use and that primary enforcement laws are more effective than secondary enforcement laws [41], [42], [44], [45].

After analysis of the panel data on 50 states and the District of Columbia for the years 1983 to 1997, Cohen and Einav, found that Primary enforcement increases belt usage by about 22 percentage points, whereas secondary enforcement increases it by only half as much [41]. Ruth et al. reviewed six evaluations of primary enforcement seat belt laws and recorded the pre and post law measurements of observed belt use [45]. They found states that directly enacted primary laws showed a median increase of 33 percentage points in observed seat belt use. Effectiveness of primary enforcement seat belt laws is illustrated in Figure 4.28 by comparing the observed seat belt use before and after the enactment. Median increase of 33 percentage points in belt use were observed in states that replaced secondary with primary laws [45]. The seat belt laws are also highly effective for rear-seat occupants' belt usage rate. In 2018, 81% of occupants in back seats used belts in states with seat belt laws for all seating positions, while 68.7% of occupants in rear seats used belts in states with front-seat-only belt laws [213].

Research has shown that seat belt laws are effective in increasing seat belt usage. With more communities and lawmakers considering mandatory seat belt policies for school buses, it is reasonable to hypothesize that seat belt usage among children who ride the bus will also increase. Therefore, it is crucial to carefully consider the potential impact of seat belts on child safety and to ensure that any new regulations are designed to provide maximum protection.

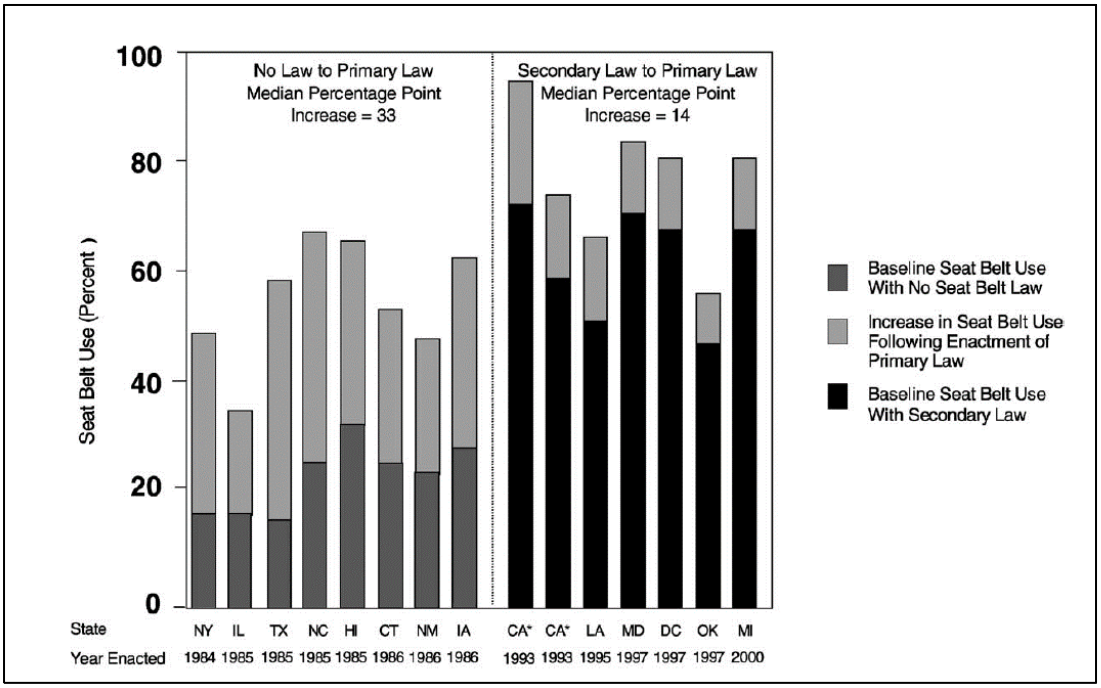


Figure 4.28: Observed Seat Belt Use Before and After Enactment of Primary Enforcement Laws [45], [214]

The current study has highlighted that the force exertion of children on seat belts is nearly 55% less than the standard limit of 133 N. However, the majority of children in the study were able to unlatch their seat belts, with a success rate of 95%. These findings, combined with the growing push for seat belts in school buses, highlight the need for continued efforts to improve the effectiveness of seat belts and, in turn, the safety of children riding school buses.

4.9 Limitations

There are several limitations associated with this study:

1) The sample size was relatively small and might not be the best representation of the entire student population. The subjects were recruited from one specific area (Auburn, AL). Broader sample size especially with equal representation of different BMI groups, age, and grade could provide a better understanding of how these factors

affect the force exertion of subjects and their ability to unlatch, especially in a rolled over orientation. These may limit the generalizations of findings.

2) Equal number of male and female subjects were not recruited.
3) One of the limitations of this study was the sample selection. The subjects were recruited from a gymnastics camp, and many of the subjects had previous experience as gymnasts in prior seasons. This raises the possibility of a selection bias, as these individuals may have developed enhanced physical abilities compared to subjects who have not been exposed to such physical training. The force exerted by this group may be higher than the general population.
4) The study was conducted in a laboratory setup with research assistants readily available to guide the subjects. Post-accident scenarios like smoke, fire, darkness, injuries, fear, or other environmental stressors could generate very different results.
5) During force exertion data collection, only 1 repetition per trial was conducted. Due to the nature of the study and time and scheduling limitations, it was not possible to collect repeated measures of each trial.
6) For both the unlatching and force exertion phase, the tests were conducted in only one rollover orientation. Future work could involve the seat being flipped the other way and having load cell on both sides to test a different rollover configuration. In the current scenario, when a subject sitting on the right side is tilted, the body is away from the buckle; if the seat was flipped, a scenario where the buckle was on the right and the subject’s body was falling on the buckle, could also be tested.
7) An important limitation of this study is that it was conducted in a space where other individuals were present, which may have affected the behavior or responses of study

subjects. While efforts were made to minimize any potential distractions, complete privacy to subjects was not provided, which may have impacted the outcome of results.

This study aimed to address several gaps in existing literature. It provides valuable insight into the force exertion capabilities of children and their ability to unlatch a seat belt. To the best of our knowledge, it is the first study to measure the force exertion of children in a rolled over orientation and their ability to unlatch a seat belt in the same. Despite the limitations, there were noteworthy results, and it will serve as a useful guide for future work.

4.10 Conclusion

Except for six (6) subjects, the majority of the subjects in this study were able to unlatch their seat belt in a rolled over orientation. However, none of the subjects (female or male) were able to exert a force that exceeded the standard specified 133 N at any given orientation. The mean of maximum force exerted by subjects at upright orientation was 45% of the standard limit for males and 36% of the standard limit for females. For male subjects, a reduction of almost 10% in the mean push force from an upright to a rolled over orientation was observed. For female subjects, a reduction of almost 14% in the mean push force from an upright to a rolled over orientation was observed. Mean push force for female subjects was found to be 83% of that for male subjects. The seat belt standard, and as a result, the seat belts can be improved by reducing the force required to unlatch a belt buckle. Additionally further research may be done to experiment with a different unlatching method and/or develop a seat belt release mechanism independent of the belt tension.

4.11 Acknowledgments

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Chapter 5

Conclusions

5.1 Introduction

The persistence of high numbers of road transportation crashes and fatalities worldwide necessitates continued efforts to improve vehicle safety. Despite numerous safety and technological advancements, in the United States, motor vehicle accidents continue to be a leading cause of death for people aged 1–54, and the leading cause of work-related fatalities. Here, motor vehicle crash fatalities total over 30,000 every year on average. Seat belts undoubtedly remain the most effective safety device in a vehicle for reducing fatal and nonfatal injuries resulting from motor vehicle crashes when used correctly.

Over the past two decades, rollover fatalities have remained steady and are slowly on the rise but there has been an increase in belted fatalities with more than half of the fatalities being belted. Current seat belt buckle standards require that a force of no more than 133 N be applied for the buckle to release. This standard has not been modified since its inception in 1965, and it is more than double the requirement of European and Australian standards. Extensive literature review failed to uncover any evidence to support this specific threshold. Given the rising sales of SUVs, prevalence of obesity, and rise in belted fatalities in the U.S., it is imperative to examine the adequacy of existing seat belt standards, reconsider certain standards, and explore opportunities for improvement.

In addition to the use of seat belts in cars, the application of seat belts in school buses has also garnered significant attention in recent years. The probable issues with seat belts on passenger cars go beyond just cars and prompt a need to examine the ability of children to properly use and unlatch them. The lack of seat belts on school buses has long been a controversial issue, with arguments for and against their use. However, in light of recent high-profile accidents involving school buses, there has been a growing push for the installation of seat belts on school buses across the U.S.

Concerns exist regarding situations in which individuals may be inverted and are unable to release their seat belts, including both passenger vehicles and school buses. One major concern with school buses is that in many cases, the driver is the only adult present on the bus. In the event a driver becomes incapacitated, it becomes the responsibility of the children on board to evacuate the bus safely. In such a situation, seat belts that cannot be easily released could pose a serious risk to the safety of the children. Therefore, it is crucial to investigate the ease with which children can unlatch seat belts on school buses in order to ensure their safety in emergency situations.

5.2 Summary of Findings

The research conducted in this dissertation aimed to address important gaps in the existing literature by exploring two key questions. First, the study aimed to investigate whether the majority of adults are able to safely unlatch a motor vehicle seat belt in a rolled over orientation. Second, the study examined the current design of seat belts for children riding school buses and whether they are able to operate them and unlatch them following a rollover accident. Two primary studies were conducted to address these questions and were split into 4 experiments. The first experiment measured how much force adults (18 years and older) could exert on a seat belt buckle in different orientations (0°, 90°, 180°, 270°). The second experiment evaluated the ability of adults (18 years and older) to unlatch a seat belt in different rolled over orientations (90°, 180°, 270°). The third experiment recorded the strength capabilities of children (5 – 16 years) to exert force on a seat belt buckle. The fourth experiment evaluated the physical capabilities of children (5-16 years) to unlatch a seat belt buckle in both regular and rolled over orientations (90°). By addressing these questions, this study aimed to contribute to the existing understanding on seat belt safety and provide insights into potential areas for improvement in seat belt design and safety standards.

The summarized findings of the first study were:

1) Around 91% of the subjects were able to unlatch their seat belt in all orientations. Five (5) subjects were unable to unlatch their seat belt in at least 1 orientation.
2) The BMI was a statistically significant factor in the ability to not unlatch their seat belt.
3) Almost 96% of female subjects and 83% of the male subjects were unable to exert a force that exceeded the FMVSS 209 specified limit of 133 N in any given orientation.
4) The Mean of maximum force exerted by subjects at upright orientation was 68% for males and 45% for females of the standard specified maximum limit. The mean maximum force exerted by subjects during rolled over orientation was 53% of the standard limit for males and 39% of the standard limit for females.

The summarized findings of the second study were:

1) Around 87% of the subjects were able to unlatch their seat belt in all orientations. Six (6) subjects were unable to unlatch their seat belt in at least 1 orientation.
2) None of the subjects (female or male) were able to exert force that exceeded the standard specified 133 N at any given orientation.

3) The mean maximum force exerted by subjects at upright orientation was 45% of the standard limit for males and 36% of the standard limit for females. In a rolled over orientation, it was 40% for males and 30% for females.
4) Grade had a statistically significant effect on the unlatching capabilities of subjects.

5.3 Limitations

General limitations of this research include:

1) The sample size was relatively small and might not be the best representation of the population of interest. Equal representation of different subject factors like BMI, Age, Grade was not present.
2) For force exertion, only 1 repetition for each trial was performed.
3) Only one type of seat belt assembly was tested.
4) The study was conducted in a laboratory setup, and the effect of post-accident scenarios were not tested.

Limitations specific to study 1 were:

1) A racing style bucket seat was used instead of a production model seat. For force exertion, the bucket seat provided slight hindrance for some subjects, and they could not exert force in some orientations.
2) The fall protection harness took a portion of the body weight, reducing the load on the 3-point harness, theoretically reducing the force required to unlatch the seat belt buckle.

Limitations specific to study 2 were:

1) The subjects were recruited from a gymnastics camp, and it is possible that these individuals had comparatively enhanced physical abilities.

2) An equal number of male and female subjects could not be recruited.
3) For both the unlatching and force exertion phase, the tests were conducted in only one rollover configuration.

To the best of our knowledge, it is the first of its kind to examine the physical capabilities of a subject to exert force on a seat belt buckle in a rolled over orientation and also to examine the physical capabilities of a subject to unlatch a seat belt buckle in a rolled over orientation. A significant amount of effort and resources was invested to conduct this study, and we hope that it will serve as a foundation for future research in this area. Despite the limitations, the results still provide valuable insights.

5.4 Recommendations for Future Research

Future research is warranted to address the limitations of this study, fill remaining gaps in the literature, and work towards developing safer seat belts and improved safety standards to potentially save lives.

1) A larger and broader sample size to study the effects of age and BMI of the force exertion capabilities in different orientations to represent the population of interest.
2) Different seat belt buckles should be tested to see if the manufacturer has an effect on the unlatching outcome. Seat belt buckles of different sizes and different shrouding options should also be tested.
3) For accurate force exertion measurements, designing a seat that does not provide hinderance during 90° and 270° orientation but at the same time still keep the subjects stationary at a given position.

4) Conducting multiple repetitions of force exertion to get a better understanding of the force data.
5) For study 1 (Chapter 3) unlatching phase, the biggest limitation was the fall protection slack. Designing a mechanism to mimic full belt load in a rollover orientation and the possibility to still test the unlatching capability. For those who cannot unlatch, repeating the experiment with a different scenario to study the cause of failure.
6) For study 2 (Chapter 4), recruiting children who are not part of a gymnastics program could help in understanding the physical capabilities of the general minor population.
7) A detailed study to evaluate unlatching forces at different seat belt loads could be conducted to properly understand how to design an improved seat belt buckle release mechanism.

In conclusion, the findings of this study have shed light on critical safety concerns related to seat belts. The study emphasized the need for a greater focus on developing safer seat belts and associated safety standards, particularly for children on school buses. The research has also exposed significant gaps in the literature, which can be better addressed through additional studies. More data is required to evaluate the force exertion capabilities of adults in different orientations. Similarly, more data is needed on the ability of children to operate and unlatch seat belts in different scenarios. These efforts could provide a comprehensive understanding of the system and help in developing safer seat belts and potentially save lives.

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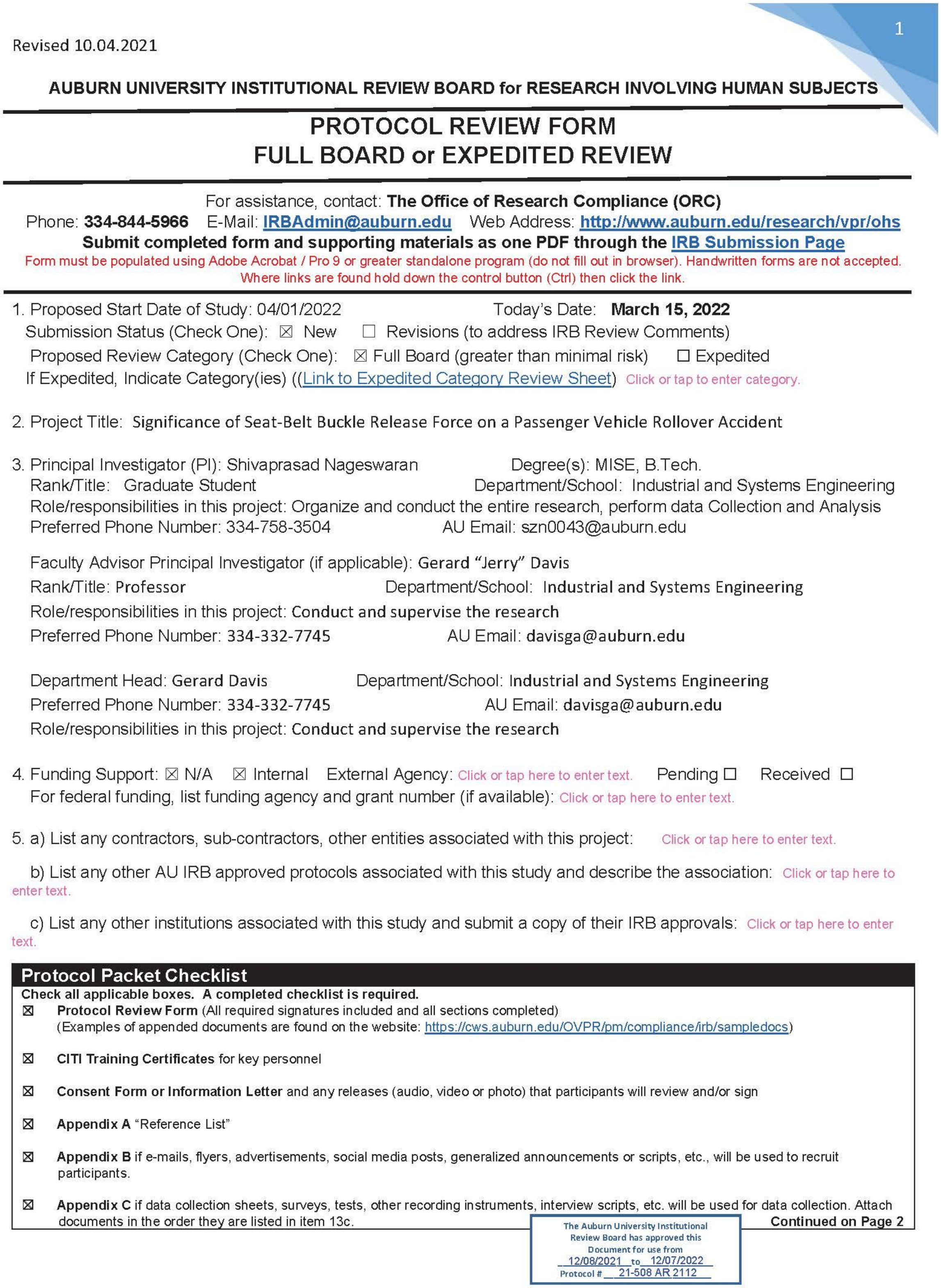
Appendices

For the following section:

Chapter 3 refers to “Assessing Seat Belt Buckle Release Forces in Passenger Vehicles After Rollover Accident”.

Chapter 4 refers to “An Analysis of Seat Belt Buckle Release Forces in School Buses After Rollover Accidents: Considerations for Child Passengers”.

Appendix A: Chapter 3 Study IRB Approval



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Submit completed form and supporting materials as one PDF through the IRB Submission Page
Form must be populated using Adobe Acrobat / Pro 9 or greater standalone program (do not fill out in browser). Handwritten forms are not accepted.
Where links are found hold down the control button (Ctrl) then click the link.

1. Proposed Start Date of Study: 04/01/2022 Today's Date: **March 15, 2022**
Submission Status (Check One): ☒ New ☐ Revisions (to address IRB Review Comments)
Proposed Review Category (Check One): ☒ Full Board (greater than minimal risk) ☐ Expedited
If Expedited, Indicate Category(ies) ((Link to Expedited Category Review Sheet) Click or tap to enter category.

2. Project Title: Significance of Seat-Belt Buckle Release Force on a Passenger Vehicle Rollover Accident

3. Principal Investigator (PI): Shivaprasad Nageswaran Degree(s): MISE, B.Tech.
Rank/Title: Graduate Student Department/School: Industrial and Systems Engineering
Role/responsibilities in this project: Organize and conduct the entire research, perform data Collection and Analysis
Preferred Phone Number: 334-758-3504 AU Email: szn0043@auburn.edu

Faculty Advisor Principal Investigator (if applicable): Gerard "Jerry" Davis
Rank/Title: Professor Department/School: Industrial and Systems Engineering
Role/responsibilities in this project: Conduct and supervise the research
Preferred Phone Number: 334-332-7745 AU Email: davisga@auburn.edu

Department Head: Gerard Davis Department/School: Industrial and Systems Engineering
Preferred Phone Number: 334-332-7745 AU Email: davisga@auburn.edu
Role/responsibilities in this project: Conduct and supervise the research

4. Funding Support: ☒ N/A ☒ Internal External Agency: Click or tap here to enter text. Pending ☐ Received ☐
For federal funding, list funding agency and grant number (if available): Click or tap here to enter text.

5. a) List any contractors, sub-contractors, other entities associated with this project: Click or tap here to enter text.

b) List any other AU IRB approved protocols associated with this study and describe the association: Click or tap here to enter text.

c) List any other institutions associated with this study and submit a copy of their IRB approvals: Click or tap here to enter text.

Protocol Packet Checklist

Check all applicable boxes. A completed checklist is required.

☒ **Protocol Review Form** (All required signatures included and all sections completed)
(Examples of appended documents are found on the website: https://cws.auburn.edu/OVPR/pm/compliance/irb/sampledocs)

☒ **CITI Training Certificates** for key personnel

☒ **Consent Form or Information Letter** and any releases (audio, video or photo) that participants will review and/or sign

☒ **Appendix A** "Reference List"

☒ **Appendix B** if e-mails, flyers, advertisements, social media posts, generalized announcements or scripts, etc., will be used to recruit participants.

☒ **Appendix C** if data collection sheets, surveys, tests, other recording instruments, interview scripts, etc. will be used for data collection. Attach documents in the order they are listed in item 13c.

Continued on Page 2

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Appendix B: Chapter 3 Study Flyer

Significance of Seat Belt Buckles during a Passenger Vehicle Rollover

Are you 18 years of age or older?

Have you ever been in a passenger car?

Have you ever worn a seat belt?

Are you interested in making road travel safer?

Are you willing to participate in Seat Belt Safety Research?

If you answered YES to these questions, you may be eligible to participate in the following study:

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Significance of Seat-Belt Buckle Release Force on a Passenger Vehicle Rollover

More than 100 million Americans drive a motor vehicle every day. All cars in the United States are required to have a Lap-Shoulder Safety belt for all seating positions. Decades of research has shown that use of safety belts or seat belts is the single most effective means of reducing fatal and nonfatal injuries in motor vehicle crashes that exists today.

Despite all the technological advancements, every year more than 30,000 people die from motor vehicle crashes (MVC) in the United States. 30% of these crashes are caused by rollover accidents and 30 % of these occupants were wearing their seat belts. We believe that it is essential to analyze the cause of belted fatalities.

The purpose of this study is to determine if participants are able to unlatch themselves from a seat when they are rolled over to different orientations. The physical capabilities of adults to unlatch a seat-belt buckle in a rolled-over orientation will be analyzed.

There is no monetary compensation, and no direct benefit for participating in this study. However, this is a unique opportunity for an individual to experience being belted in a custom vehicle rollover simulator and encounter unbuckling in different orientations. To the best of our knowledge, this is the first time such a research study is being conducted.

This Study is being conducted by the Occupational Safety and Ergonomics team of the Industrial and Systems Engineering Department at Auburn University. If you are interested in participating or have any questions, please feel free to contact: **Shiva Nageswaran (shiva@auburn.edu, or 334-758-3504).**

Appendix C: Chapter 3 Informed Consent

AUBURN
UNIVERSITY
SAMUEL GINN
COLLEGE OF ENGINEERING

(NOTE: DO NOT AGREE TO PARTICIPATE UNLESS AN APPROVAL STAMP WITH CURRENT DATES HAS BEEN APPLIED TO THIS DOCUMENT.)

INFORMED CONSENT
for Research Study entitled

"Significance of Seat-Belt Buckle Release Force on a Passenger Vehicle Rollover"

Concise Summary: You are being asked to take part in a research study as you meet the eligibility criteria. This research study is Voluntary, meaning you do not have to take part in it. The procedures, risks, and benefits are fully described further in the consent form. The purpose of this study is to measure the maximum force one can apply on a seat belt buckle to successfully unlatch it. Decades of research studies have proved the effectiveness of seat belts in reducing fatal and non-fatal injuries in motor vehicle crashes. Despite the technological advancements in motor vehicle safety, every year there are around 30,000 motor vehicle crash fatalities and more than 30% of these were a result of rollover accidents. To our knowledge, this would be the first study to examine the physical capability of an occupant to unbuckle a seat belt in a rolled over orientation. There will be an initial screening and then you will be scheduled at your convenience for the experiments. The experiments will take place in two (2) phases. The 1st phase will involve measuring the maximum force you can exert on a push-button in different orientations and the 2nd phase will evaluate your ability to unlatch a seat belt in different orientations. The entire process will last approximately 30 minutes. There are several risks associated with this study including physical injury. Your safety is our utmost priority. There are no direct benefits to you for participating in this study. The benefit to the researchers is a greater understanding of this under-researched field that could potentially benefit the community. The alternative is to not participate in this study.

You are invited to participate in a research study *as you met the eligibility requirements during the screening process.* This research aims to evaluate the physical capabilities of adults to unbuckle themselves in a motor vehicle rollover. The research is being conducted by Shiva Nageswaran (Auburn University Ph.D student) under the supervision of Dr. Jerry Davis, Ph.D., CSP, CPE (Daniel F. and Josephine Breeden Professor, Associate Chair) in the Department of Industrial and Systems Engineering at Auburn University. You were selected as a possible participant because you represent the average population that travels in a passenger vehicle.

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To participate in this study, you need to meet all the following eligibility requirements:

- 18 years of age or older
- No history of physician-diagnosed musculoskeletal disorders, injury, or surgery in the back region
- No chronic pain in back, shoulders, neck, or low back during the last 6 months
- No history of physician-diagnosed musculoskeletal disorders, injury, or surgery in the hand and/or digits (fingers and thumbs)
- No chronic pain in the digits (fingers and thumbs) of both hands in the last 6 months
- No physician-diagnosed neurodegenerative disease (e.g.,Parkinson's Disease, Multiple Sclerosis, etc.)
- No history of Vertigo or Motion Sickness.
- Not pregnant

We request participants to refrain from eating at least 2 hours prior to the study and not to eat too much prior to the study as you will be inverted during this experiment. *Please do not participate in this study if you have consumed food in the last 2 hours.*

What will be involved if you participate?
The study is being performed to better understand the strength capabilities of an individual in different orientation. If you decide to participate in this research study, the following information will be recorded:

1) Height, weight (in private), age and sex.
2) Maximum force exerted on a push-button in different orientations
3) Ability to unbuckle seat belt in different orientation

Figure 1: Test Device

You will be part of an experiment that will be conducted in two phases to simulate 3 different rollover-orientations of passenger vehicle (during an accident). Before beginning the trials, we will request you to perform some basic light stretching and low aerobic exercise for 3-4 minutes for warm-up.

Phase 1: ***Force Measurement:*** You will be asked to wear a bicycle helmet and proceed to the testing device (figure 1). A research associate will demonstrate how to correctly restraint oneself on the bucket seat using the appropriate restraint. You will then be asked to sit on the bucket seat and voluntarily buckle up using the red colored 6-point harness. The research associate will assist you if you need. After you have properly restrained yourself and are ready, you will be rotated to one of the trial orientations. The order of trial will be random for everyone and there are 4 trial orientations possible for this study (figure 2) and 16 possible trials. For each orientation angle, force will be measured from the thumb and the fingers of each hand.
Once you have been rotated to a particular orientation, you will be asked to press the push button located to the corresponding trial. You will be required to increase the force exerted to the maximum over a period of 3 seconds. You will be asked to exert the maximum force for 5 seconds and after that you will be asked to relax. Once this is done, you will be rotated to the next orientation. At any given time, if you need a break, you can inform the research associate and we will pause the trial till you are ready to do so. 2 minutes of rest is prescribed if force exertion by the same digit is required. For the rest period, you will be rotated back to the normal orientation (0Deg) (figure 3).

A break of up to 5 minutes can be taken before the beginning of next phase.

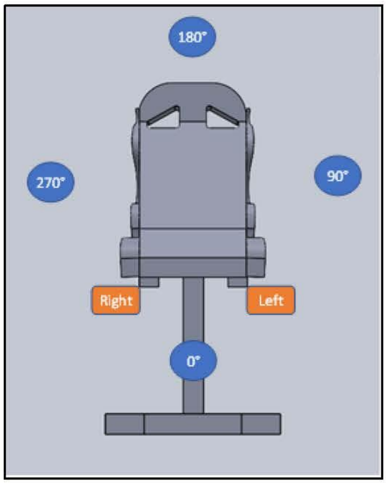

Figure 2: Seat orientations

Participant's initials ______________

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Figure 3: Example of 0 Degree Orientation

Figure 4: Examples of 90 Degree and 180 Degree Orientations

Participant's initials ______________

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Phase 2: ***Unbucking ability:*** You will be asked to wear a bicycle helmet and proceed to the testing device. For this study both restraints are needed. A research associate will demonstrate how to correctly restraint yourself on the bucket seat for this study. You will then be asked to sit on the bucket seat and voluntarily buckle up. Based on the random trial sequence, you will first don one of the available 3-point seat belt (used in regular cars) ensuring snug fit. You will next restraint yourself using the red colored 6-point harness. This time the restraint will be loosely fitted. The research associate will assist you to ensure loose fitting of the 6-point harness.
After you have properly restrained yourself and are ready, you will be rotated to the orientation mentioned earlier based on the order. Once you are at that orientation, you will be asked to exert force on the push-button buckle and unbuckle the regular 3-point seat belt. When you unbuckle you will gently progress an inch or two into the 6-point harness which will behave like a fall-protection harness. You will be given 3-attempts to do unbuckle yourself in each orientation. If you successfully unbuckle or if you are unable to unbuckle after 3 attempts, you will be rotated back to normal orientation (0Deg)(figure 3). You will once again don the regular seat belt based on the trial order and the process will be repeated. If you no longer wish to continue the experiment, we can stop it at any time.

You will be videotaped during testing to observe the unbuckling method, and your postures while wearing and releasing the seat belt. All videotape records are confidential and will be destroyed when the study is complete. We estimate your total commitment time will be approximately 30 minutes.

Male and Female Research Assistants will be available. Participants can inform the team if they would like a research team member of a particular gender to assist them.

Are there any risks or discomforts?
The risks associated with participating in this study are minimal and are limited to falls, muscle strain or minor impact with equipment.

- It is highly unlikely but there is a risk of falling. You will be wearing a 6-point racing harness at all times during the experiment. We are also using a 5-inch gel memory foam mattress to protect you again any possible falls. The maximum distance of fall is approximately 36 inches.
- Participants will be required to wear bicycle helmet to eliminate any additional risks involved. Helmets of multiple sizes are available, and they will be sanitized by the research team before reuse.
- All edges that may lead to injury upon contact are covered by a high-density impact absorbing foam padding.
- We will not allow any horse play around the equipment.
- Temporary fatigue, muscle soreness, sprains, strains, or delayed onset of muscle soreness may result from the rotation of subjects to different orientations. Subjects may get a minor irritation due to potential rubbing from the seat belt during the rotation and unlatching phases.
- Subjects may perceive some level of discomfort as the bucket seat they are belted to is being tipped to different degrees.
- Confidentiality of the study data is of utmost importance. All research personnel are trained in research ethics and are aware of procedures to

protect the confidentiality of subjects and associated data. Paper files will be kept in a locked cabinet in a lab which only the PI and Faculty Advisor will have access to. Electronic data will be maintained on a password-protected computer and will be accessible only to the research team. Data will not be directly linked to any participant.

Additionally, our research team will be present throughout the test.
In the unlikely event that you sustain an injury from participating in this study, the researchers have no current plans to provide funds for any incurred medical or other costs. Auburn University has not provided for any payment if you are harmed as a result of participating in this study.

Risks & Precautions for COVID-19?
Due to face-to-face interactions with the research team, there is a risk of exposure to COVID'19 and the possibility of contracting the virus. All Research Personnel are fully vaccinated and will be following Auburn University's guidelines to prevent the spread of COVID'19. Please review the information sheet on COVID'19 for research participants that is attached to this consent document.

Are there any benefits to yourself or others?
There are no direct benefits from participating in this study. However, this is a unique opportunity for most participants to experience being in a rolled over orientation and getting to unbuckle a seat belt while being in that rolled over position. To our knowledge this is the first study that will examine the capabilities of human subjects to unlatch a seat belt in a rolled over orientation. Your participation can provide the researchers with a greater understanding of this under-researched field.

Will you receive compensation for participating?
We will not be able to provide any type of compensation to you for participating.

Are there any costs? There is no cost for you to participate in this study. Any incurred medical costs are not covered through this research. Auburn University has not provided for any payment if you are harmed as a result of participating in this study.

If you change your mind about your participation, you can withdraw from the study at any time. Your participation is completely voluntary. Your decision about whether or not to participate or to stop participating will not jeopardize your future relations with Auburn University, or the Department of Industrial and Systems Engineering. You can request your data to be withdrawn as long as the data collection process is active (because all identifiers will be destroyed post data collection).

Your privacy will be protected. Any information obtained in connection with this study will remain confidential. Information obtained through your participation may be used to fulfill an educational requirement, published in a professional journal, used by general industry, and/or presented at a professional meeting. However, your identity will not be revealed, and your information will remain completely private. The confidential link between your personal information and the study data will be stored in a locked cabinet in a lab which only the PI and Faculty Advisor will have access to. Electronic data will be maintained on a password-protected computer and will be accessible only to the research team. Data will not be directly linked to any participant.

If you have questions about this study please ask now or contact Shiva Nageswaran at szn0043@auburn.edu, (334) 758-3504, or Dr. Jerry Davis at davisga@auburn.edu, (334) 332-7745. A copy of this document will be given to you to keep.

If you have questions about your rights as a research participant, you may contact the Auburn University Office of Human Subjects Research or the Institutional Review Board by phone (334)-844-5966 or e-mail at hsubjec@auburn.edu or IRBChair@auburn.edu.

HAVING READ THE INFORMATION PROVIDED, YOU MUST DECIDE WHETHER OR NOT YOU WISH TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES YOUR WILLINGNESS TO PARTICIPATE.

______________________	______________________
Participant's Signature	Investigator obtaining consent
______________________	______________________
Printed Name	Investigator Printed Name
______________________	
Date	

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Participant's initials ______________ Page 7 of 7

Information on COVID-19 For Research Participants (updated 05/27/2021)

Auburn University recognizes the essential role of research participants in the advancement of science and innovation for our university, community, state, nation, and beyond. Therefore, protection of those who volunteer to participate in Auburn University research is of utmost importance to our institution.

As you are likely aware, COVID-19 references the Coronavirus that is being spread around the world including in our country, state, and community. It is important that we provide you with basic information about COVID-19 and the risks associated with the virus so that you can determine if you wish to participate or continue your participation in human research.

How is COVID-19 spread? COVID-19 is a respiratory virus that is spread by respiratory droplets, mainly from person-to person. This can happen between people who are in close contact with one another. COVID-19 may also be spread by exposure to the virus in small droplets that can linger in the air. This kind of spread is referred to as airborne transmission. It is also possible that a person can get COVID-19 by touching a surface or object (such as a doorknob or counter surface) that has the virus on it, then touching their mouth, nose, or eyes.

Please visit the CDC's web page for more information on how COVID-19 spreads.

Can COVID-19 be prevented? Although there is no guarantee that infection from COVID-19 can be prevented, there are ways to minimize the risk of exposure to the virus. For instance, stay 6 feet apart from others who don't live with you; get a COVID-19 vaccine when it is available to you; avoid crowds and poorly ventilated indoor spaces; use effective barriers between persons; wear personal protective equipment like masks, gloves, etc.; wash hands with soap and water or use hand sanitizer after touching objects; disinfect objects touched by multiple individuals.

What are the risks of COVID-19? For most people, COVID-19 causes only mild or moderate symptoms, such as fever and cough. For some, especially older adults and people with existing health problems, it can cause more severe illness. While everyone is still learning about this virus, current information suggests that about 1-3% of people who are infected with COVID-19 might die as a result.

Who is most at risk? Individuals over age 65 and those with chronic conditions such as cancer, diabetes, heart or lung or liver disease, severe obesity, and conditions that cause a person to be immunocompromised have the highest rates of severe disease and serious complications from infection.

What precautions should be taken? Based on the proposed research, precautions for the risk of COVID-19 will be addressed on a project by project basis. You will be provided with information about precautions for the project in which you may participate. Any site where research activities will occur that are not a part of Auburn University (offsite location) are expected to have standard procedures for addressing the risk of COVID-19. It is important for participants to follow any precautions or procedures outlined by Auburn University and, when applicable, offsite locations. Further, participants will need to determine how best to address the risk of COVID-19 when traveling to and from research locations. The US Center for Disease Control and Prevention has issued recommendations on types of prevention measures you can use to reduce your risk of exposure and the spread of COVID-19.

Auburn University is continuing to monitor the latest information on COVID-19 to protect our students, employees, visitors, and community. Our research study teams will update participants as appropriate. *If you have specific questions or concerns about COVID-19 or your participation in research, please talk with your study team.* The name and contact information for the study team leader, along with contact information for the Auburn University Institutional Review Board for Protection of Human Research Participants, can be found in the consent document provided to you by the study team.

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DATE: ______________

COVID-19 SCREENING FORM

PLEASE READ EACH QUESTION CAREFULLY	PLEASE CIRCLE THE ANSWER THAT APPLIES TO YOU	
Have you experienced any of the following symptoms in the past 48 hours		
• fever or chills	yes	no
• cough	yes	no
• shortness of breath or difficulty breathing	yes	no
• fatigue	yes	no
• muscle or body aches	yes	no
• headache	yes	no
• new loss of taste or smell	yes	no
• sore throat	yes	no
• congestion or runny nose	yes	no
• nausea or vomiting	yes	no
• diarrhea	yes	no
Within the past 14 days, have you been in close physical contact (6 feet or closer for a cumulative total of 15 minutes) with:		
• Anyone who is known to have laboratory-confirmed COVID-19?	yes	no
OR		
• Anyone who has any symptoms consistent with COVID-19?	yes	no
Are you isolating or quarantining because you may have been exposed to a person with COVID-19 or are worried that you may be sick with COVID-19?	yes	no
Are you currently waiting on the results of a COVID-19 test?	yes	no

Did you answer **NO** to **ALL** the questions	You are **APPROVED** to participate in the study at this time.
Did you answer **YES** to ***ANY*** of the questions	You are **NOT APPROVED** to participate in the study at this time.

Thank you for helping us protect you and other during this pandemic

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Appendix D: Chapter 3 Subject Recruitment Data Sheet

Significance of seat belt buckle release force on a passenger vehicle rollover accident

Subject Recruitment Data Sheet

Subject Name: ________________________________ Subject Number: ______________

Height(cm): ___________ Sex: _________________

Weight(Kg): ____________ Birth Month and Year (mm/yyyy): ______________

Contact info: Phone: __________________________________

Email : __________________________________

For Research Associate only

Calculated BMI: ________________________________

Group Number Allotted:_____________________________

Trial Subject Number Allotted:_________________________

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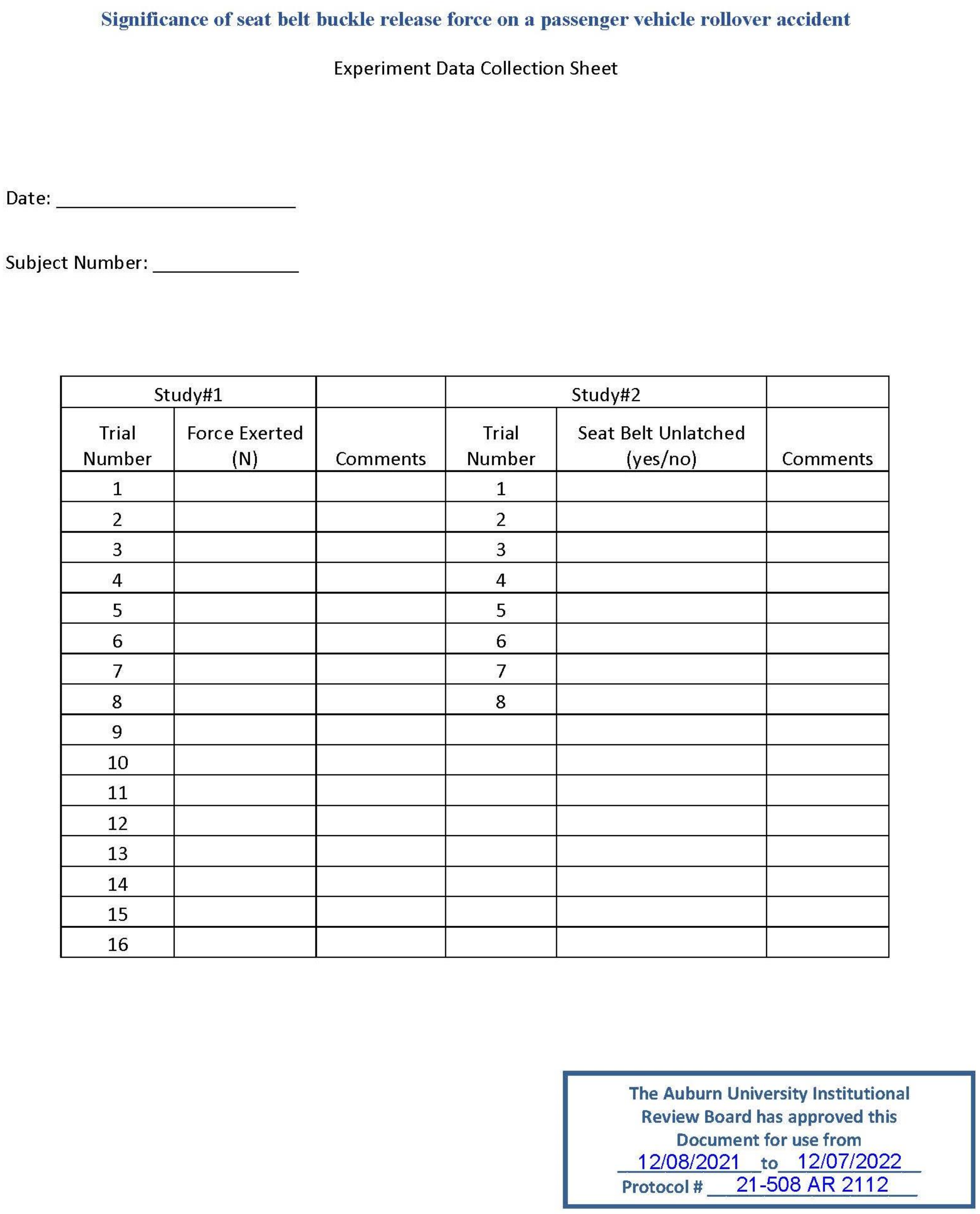
Appendix E: Chapter 3 Data Collection Sheet



Significance of seat belt buckle release force on a passenger vehicle rollover accident

Experiment Data Collection Sheet

Date: ________________________

Subject Number: _______________

Study#1			Study#2		
Trial Number	Force Exerted (N)	Comments	Trial Number	Seat Belt Unlatched (yes/no)	Comments
1			1		
2			2		
3			3		
4			4		
5			5		
6			6		
7			7		
8			8		
9					
10					
11					
12					
13					
14					
15					
16					

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Appendix F: Chapter 3 Video Release Form

VIDEO RELEASE

During your participation in this research study, “Significance of Seat Belt Buckles on a Passenger Vehicle Rollover Accident ”, you will be videotaped to evaluate your posture, measure the time taken to release the seat belt, and to observe what technique you use to release the seat belt. Your signature on the Stamped Informed Consent gives us the permission to do so.

Your permission:

I give my permission for videotapes produced in the study, “Significance of Seat Belt Buckles on a Passenger Vehicle Rollover Accident ”, which contain images of me, to be used only for the purpose of this study. When analysis is complete, the videos will be destroyed.

Participant’s Signature Date	Investigator’s Signature Date
Participant’s Printed Name	Investigator’s Printed Name

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Appendix G: Chapter 3 Covid Screening and Precautions

COVID Screening and Precautions

"Significance of Seat Belt Buckles on a Passenger Vehicle Rollover"

Health and Safety of the participants and the research personnel is at the highest priority. To cope with Data Collection during the Pandemic, the following procedures will be used:

Pre-Visit Screening:

- Call the participant and complete the Coronavirus Screening Form.
- All Key Personnel involved in the data collection complete Coronavirus Screening Form.

General Procedures:

- All research team members and the participant wash their hands upon arrival and after any physical contacts with other people.
- All research team members wear facemasks and face shields at all times. Participants will be required to wear facemasks at all times. Any participant who needs to briefly take off the mask (e.g., for drinking water) does so at least 6 ft away from others and in advance notifies a key personnel present at the experiment location to ensure adequate distancing during the break.
- During the study visit, only two designated study team members can make close contact (less than 6 ft apart) with the participant for all procedures that require close contact. Close contact will be minimized, and will only occur during the Rollover procedure to ensure the participant's safety.
- All materials are handled on a clean/sanitized surface, e.g. desks or benches.
- After every study visit, all non-disposable items used in the testing should be cleaned/sanitized and stored until next use.

  - Key Personnel sanitize their hands on a regular basis and after touching any testing surface.
  - Sanitizing Stations will be made available around the testing facility for everyone to use.

❖ *All Key Personnel on the team have been Fully Vaccinated.*

Operation

a) During Data Collection
   - One designated research personnel interacts with the participant. The subject is explained the procedure and is escorted to Station 1. Participant's age, height, weight is recorded here. The subject dons the PPE (Helmet) at this station. Participant will be assisted by the research personnel if required.
   - Participant is then escorted to station 2 which has the test device. The participant is asked to sit on the bucket seat and wear the appropriate restraint based on the trial order. The second designated research personnel is available to assist the participant with the restraint system if needed.

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  - For the *rollover procedure,* the research personnel rotates the lever connected to the device to rotate the participant to the desired orientation. The participant exerts force on a push-button for experiment 1 and unlatches the buckle at the rolled over orientation for experiment 2.
  - During the trials, the participant and two designated research personnel could be in close contact (within 6 feet) of each other for up to 30 minutes.

b) After Data Collection
  - The participant makes her/his way out of the test device and is out of the testing facility by the designated personnel.
  - Cleaning follows

c) Cleaning
  - While cleaning, all personnel will wear sterile gloves, face masks and face shields.
  - The test device bench seat and the rotating handles will be thoroughly wiped and sanitized using Lysol Disinfecting wipes and spray or equivalent.
  - The helmet will also be sanitized thoroughly after use and stored separately. We have enough helmets to be used only once per participant. The used helmet will be used after 24 hours if needed on a different participant, to mitigate any risk of contamination.
  - Disinfectant spray will be sprayed on the test device at the end of the day and an hour before the next participant starts the trial.

Appendix H: Emergency Action Plan for Chapter 3 Study

Emergency Action Plan

In Case of Emergency 911

Non-Emergency	On- Campus	Off- Campus
Ambulance (EMS)	9-749-8504	334-749-8504
Auburn Police	9-501-3100	334-501-3100
East Alabama Medical Center	9-705-1150	334-705-1105

Industrial and Systems Engineering Department Main Office 334-844-1404

Shiva Prasad Principal Investigator	cell: 334-758-3504	szn0043@auburn.edu
Dr. Jerry Davis Faculty Advisor	cell: 334-332-7745	davisga@auburn.edu
Dr. Richard Sesek Faculty Advisor	cell: 334-728-1438	sesek@auburn.edu
Dr. Mark Schall Associate Professor	cell: 708-539-8957	mcs0084@auburn.edu
Nathan Pool Graduate Student	cell: 571-344-4685	nwp0008@auburn.edu
Robert Sesek Graduate Student	cell: 334-844-4916	rms0082@auburn.edu

Lab Location:
Auburn University Biomechanics Lab, **Room # 3325**, Shelby Center, Third Floor,
Auburn University, Al 36849

Easy Access:
Elevator right next to the lab. Exit the lab door and turn left.

Alternate Access

Enter North Door. Turn right to the Hallway and take the right door at the end of the hallway to the stairs. Two Elevators at each corner of the building and 1 elevator in the middle. Exit at the 3rd floor.

Emergency Exits

Exit the lab and turn right, stairs are at the end of the hallway on your left. Stairs are located at the end of the hallway.

Emergency Equipment

A Portable First-Aid kit and fire extinguishers are available in the lab.

Emergency Procedures

If subject has an emergency on the equipment:

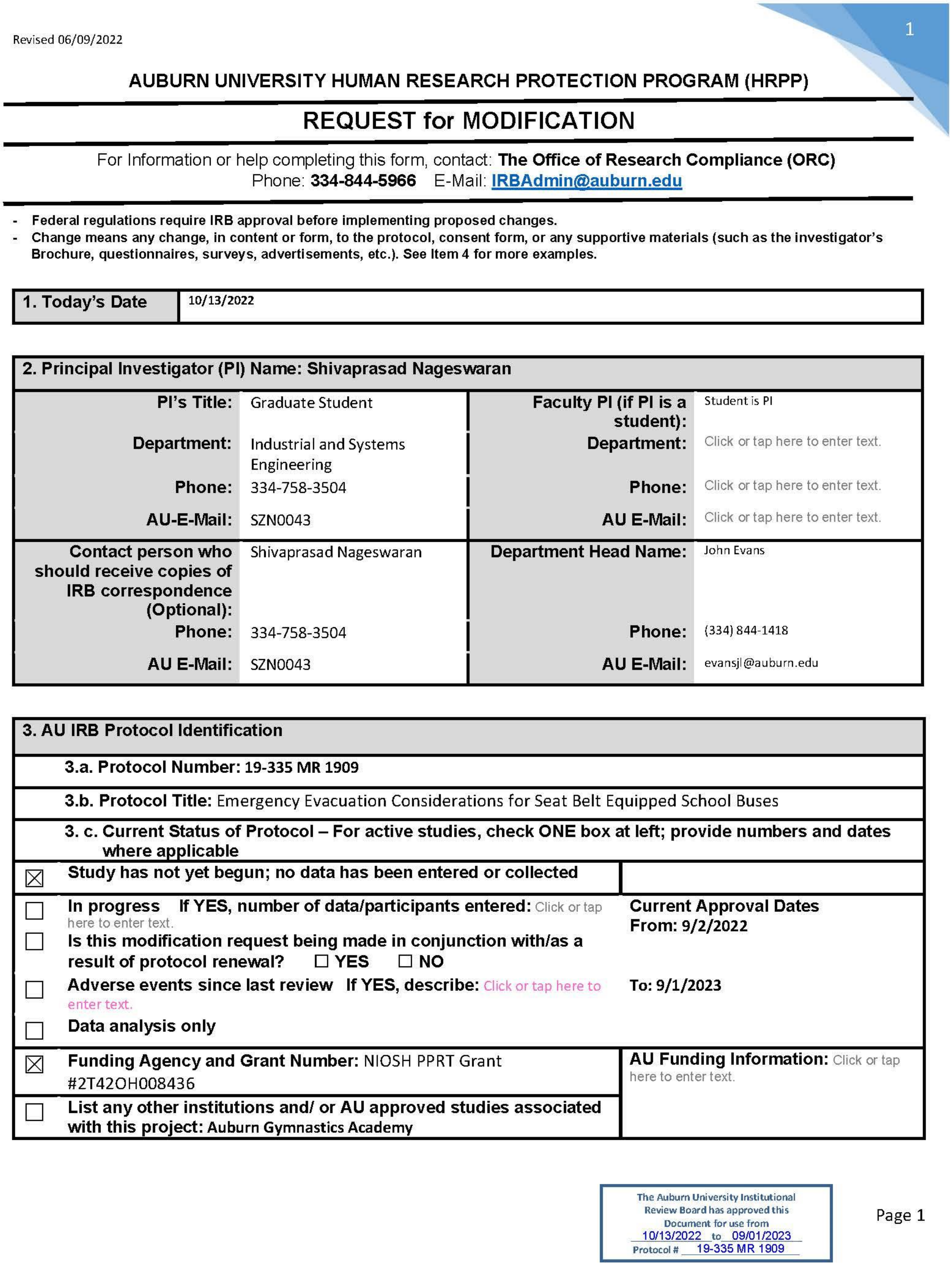
1. 1.Do NOT perform any emergency procedure on the Equipment.
2. If the subject is is at an angle, slowly bring him/her down.
3. Release the belt buckle and slowly help the subject step out of the device.
4. Assess the Situation – Use Emergency Equipment (if applicable). Perform First Aid and/or emergency CPR – if qualified to do so.
5. **Call 911** or EMS (Lee County EMS at 334-749-8504) if necessary and provide the required information:
    - *a)* *Location:* Auburn University Human Factors Lab, **Room # 3326**, Shelby Center, Third Floor, 345 W Magnolia Ave. In front of Chipotle on Magnolia. Next to Harbert School of Business.
    - *b)* Your Information
    - *c)* General information about the injury or the emergency
    - *d)* Any additional information if requested
    - *e)* BE THE LAST TO HANG UP!

6 Meet the ambulance and direct them to the site. Be sure to ask them which side they are coming and accordingly wait there.

7 Direct the emergency personnel to the site of emergency. If directed, assist emergency personnel with care of the injured subject.

- ❖ The primary research investigator must report the adverse event to the IRB via the office of Human Subject Research.

Appendix I: Chapter 4 Study IRB Approval



1

Revised 06/09/2022

AUBURN UNIVERSITY HUMAN RESEARCH PROTECTION PROGRAM (HRPP)

REQUEST for MODIFICATION

For Information or help completing this form, contact: **The Office of Research Compliance (ORC)**
Phone: **334-844-5966** E-Mail: **IRBAdmin@auburn.edu**

- **Federal regulations require IRB approval before implementing proposed changes.**
- **Change means any change, in content or form, to the protocol, consent form, or any supportive materials (such as the investigator's Brochure, questionnaires, surveys, advertisements, etc.). See Item 4 for more examples.**

1. Today's Date	10/13/2022

2. Principal Investigator (PI) Name: Shivaprasad Nageswaran

PI's Title:	Graduate Student	**Faculty PI (if PI is a student):**	Student is PI
Department:	Industrial and Systems Engineering	**Department:**	Click or tap here to enter text.
Phone:	334-758-3504	**Phone:**	Click or tap here to enter text.
AU-E-Mail:	SZN0043	**AU E-Mail:**	Click or tap here to enter text.
Contact person who should receive copies of IRB correspondence (Optional):	Shivaprasad Nageswaran	**Department Head Name:**	John Evans
Phone:	334-758-3504	**Phone:**	(334) 844-1418
AU E-Mail:	SZN0043	**AU E-Mail:**	evansjl@auburn.edu

3. AU IRB Protocol Identification

3.a. Protocol Number: 19-335 MR 1909

3.b. Protocol Title: Emergency Evacuation Considerations for Seat Belt Equipped School Buses

3. c. Current Status of Protocol – For active studies, check ONE box at left; provide numbers and dates where applicable

☒ **Study has not yet begun; no data has been entered or collected**

☐ **In progress If YES, number of data/participants entered:** Click or tap here to enter text.

☐ **Is this modification request being made in conjunction with/as a result of protocol renewal?** ☐ **YES** ☐ **NO**

☐ **Adverse events since last review If YES, describe:** Click or tap here to enter text.

☐ **Data analysis only**

Current Approval Dates
From: 9/2/2022
To: 9/1/2023

☒ **Funding Agency and Grant Number:** NIOSH PPRT Grant #2T42OH008436

AU Funding Information: Click or tap here to enter text.

☐ **List any other institutions and/ or AU approved studies associated with this project:** Auburn Gymnastics Academy

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Protocol # 19-335 MR 1909

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4. Types of Change **Mark all that apply, and describe the changes in item 5**	
☒	**Change in Key Personnel** List the name(s) of personnel being added to or removed from the study and attach a copy of the CITI documentation for personnel being added to the study.
☐	**Additional Sites or Change in Sites, including AU classrooms, etc.** Attach permission forms for new sites.
☐	**Change in methods for data storage/ protection or location of data/ consent documents**
☐	**Change in project purpose or project questions**
☐	**Change in population or recruitment** Attach new or revised recruitment materials as needed; both highlighted version & clean copy for IRB approval stamp
☐	**Change in study procedure(s)** Attach new or revised consent documents as needed; both highlighted revised copy & clean copy for IRB approval stamp
☒	**Change in data collection instruments/forms (surveys, data collection forms)** Attach new forms as needed; both highlighted version & clean copy for IRB approval stamp
☐	**Other** (BUAs, DUAs, etc.) Indicate the type of change in the space below, and provide details in the Item 5.c. or 5.d. as applicable. Include a copy of all affected documents, with revisions highlighted as applicable. Click or tap here to enter text.

5. Description and Rationale

5.a. For each item marked in Question #4 describe the requested change(s) to your research protocol, and the rationale for each.

Add the following Personnel to the Study

1) Savannah Maples
2) Yuqing Wang
3) Kristian Shumaker
4) Victoria Ballard

Accidentally forgot to add the Data Collection Sheet when requesting Renewal Approval. I have attached previously Stamped document and new Fresh Document for stamping

5.b. Briefly list (numbered or bulleted) **the activities that have occurred up to this point, particularly those that involved participants.**

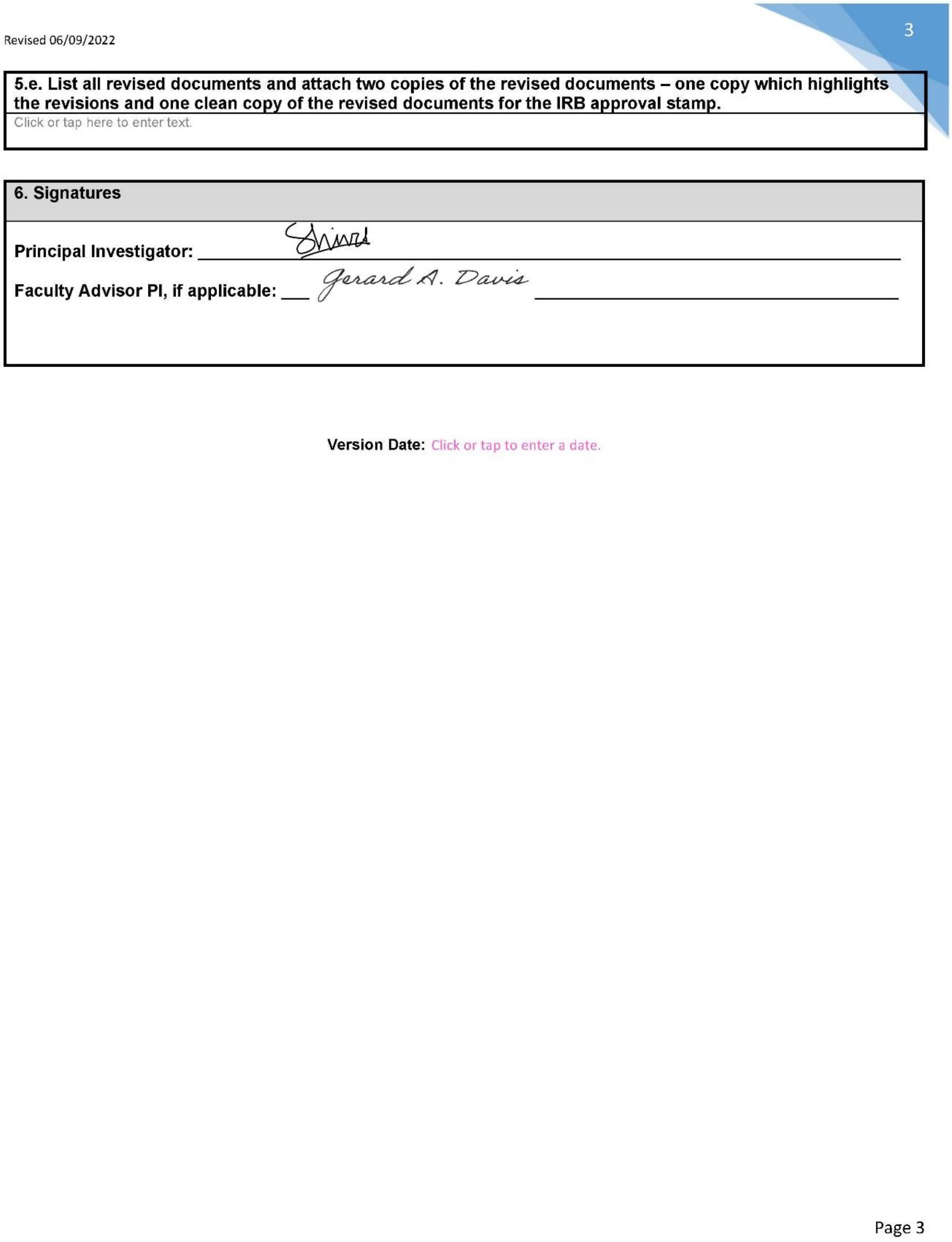
After receiving IRB approval in 2019, we acquired the funds from the grant to buy the required components.
We have built the test device and are awaiting to conduct the tests and perform data collection.

5.c. Does the requested change affect participants, such as procedures, risks, costs, benefits, etc.

NO

5.d. Attach a copy of all "IRB stamped" documents currently used. (Information letters, consent forms, flyers, etc.)

Click or tap here to enter text.



Revised 06/09/2022

3

5.e. List all revised documents and attach two copies of the revised documents – one copy which highlights the revisions and one clean copy of the revised documents for the IRB approval stamp.
Click or tap here to enter text.

6. Signatures
Principal Investigator: ______________________________
Faculty Advisor PI, if applicable: ___ Gerard A. Davis ______________________

Version Date: Click or tap to enter a date.

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AUBURN UNIVERSITY HUMAN RESEARCH PROTECTION PROGRAM (HRPP)

REQUEST for PROJECT RENEWAL

For assistance, contact: **The Office of Research Compliance (ORC)**
Phone: **334-844-5966** E-Mail: **IRBAdmin@auburn.edu**
Submit completed form and supporting materials as one PDF through the IRB Submission Page

1. **AU IRB Protocol Number: 19-335 MR 1909** **Today's Date: 8/23/2022**

2. **Dates of most recent IRB approval: From:** 9/15/2021 **To: 9/14/2022**

3. **Project Title:** : Emergency Evacuation Considerations for Seat Belt Equipped School Buses

4. **Principal Investigator (PI):** Shivaprasad Nageswaran Degree(s): **MISE, B. Tech**
   Rank/Title: **Graduate Student** Department/School: **Industrial and Systems Engineering**
   Role/responsibilities in this project: **Conduct Research**
   Preferred Phone Number: **334-758-3504** AU Email: **szn0043@auburn.edu**

   PI Signature: Shiva

   Faculty PI (if applicable): Gerard A Davis
   Rank/Title: **Professor** Department/School: **Industrial and Systems Engineering**
   Role/responsibilities in this project: **Supervise the research**
   Preferred Phone Number: **334-332-7745** AU Email: **davisga@auburn.edu**

   Faculty PI Signature: Gerard A. Davis

   Department Head: John Evans

   Department Head Signature:

5. **Funding Agency and Grant number:** NIOSH PPRT Grant #2T42OH008436

6. **List any contractors, sub-contractors, other entities associated with this project:**
   NA

7. **List any other institutions associated with this project:**
   Auburn Gymnastics Academy

8. **Describe why additional time to complete this research is required.**
   Due to the Covid'19 Pandemic, we have not been able to conduct any research and perform data collection till now. We have built the test device, but Auburn Gymnastics Academy (AGA) was closed since March 2020. We recently received approval to conduct research again from AGA. We plan to recruit participants and conduct research this semester after IRB approval.

9. **List activities that occurred over the past year, particularly those that involved participants.**

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After receiving IRB approval in 2019, we acquired the funds from the grant to buy the required components. We have built the test device and are awaiting to conduct the tests and perform data collection.

10. Will the project be changed/modified if the IRB approves the renewal request?
(e.g., research design, methodology, participant characteristics, authorized number of participants, etc.)

☐ **YES** ☒ **NO**
If "YES", briefly describe the intended change(s), list affected study documents, and separately submit a Protocol Modification Form. The Modification Form must describe the changes and include highlighted and clean copies of the revised documents.
Click or tap here to enter text.

11. PARTICIPANT INFORMATION

a. **How many participants/ records have enrolled in the study?**
NA

b. **Did participants withdraw from the study?**
☐ **YES** ☒ **NO**

  i. If YES, how many? Click or tap here to enter text.
  ii. If YES, reason(s) for withdrawals. Click or tap here to enter text.

c. **How many new participants/records do you intend to enroll during the renewal period?**
NA

d. **If participants will be recruited and enrolled or human subject data will be collected during the renewal period, attach a copy of the consent document, information letter, and any flyers that will be used.**

e. **During the next approval period, will any individual that has already participated in the research be continued?**
☐ **YES** ☒ **NO**

f. **Were there adverse events, unexpected difficulties, or unexpected benefits with the approved procedures?**
☐ **YES** ☒ **NO**
If YES describe.
Click or tap here to enter text.

If "YES", explain reason(s) and process for re-contacting participants. (If "YES" and the procedure to re-contact has not been previously approved, attach relevant materials.)
Click or tap here to enter text.

12. PROTECTION OF DATA

a. **Is the data being collected, stored, and protected as previously approved by the IRB?**
☒ **YES** ☐ **NO**

If NO explain. Click or tap here to enter text.

b. **Are there changes to key personnel?**

☐ **YES** ☒ **NO**

If YES list individual(s) and describe their role(s) in the research. Click or tap here to enter text.

c. **What is the latest date (month and year) you expect all identifiable data to be destroyed?** (Identifiable data includes videotapes, photographs, code lists, etc.)
DATE: Click or tap here to enter text.
☐ **Not Applicable – no identifiable data has been or will be collected.**
09/14/2023

13. **Attach a copy of all documents with the IRB approval stamp used during the previous review period. If requesting changes, submit a copy of revised documents highlighted and clean.** (Information letters, Informed Consents, Parental Permissions, flyers etc.)

COVID Screening and Precautions

“Emergency Evacuation Considerations for Seat Belt Equipped School Buses”

Health and Safety of the participants and the research personnel is at the highest priority. To cope with Data Collection during the Pandemic, the following procedures will be used:

Pre-Visit Screening:

- Call the participant’s parent/legal guardian and complete the Coronavirus Screening Form.
- All Key Personnel involved in the data collection complete Coronavirus Screening Form.

General Procedures:

- All research team members and the participant wash their hands upon arrival and after any physical contacts with other people.
- All research team members wear facemasks and face shields at all times. Participants will be required to wear facemasks at all times. Any participant who needs to briefly take off the mask (e.g., for drinking water) does so at least 6 ft away from others and in advance notifies a key personnel present at the experiment location to ensure adequate distancing during the break.
- During the study visit, only two designated study team members can make close contact (less than 6 ft apart) with the participant for all procedures that require close contact. Close contact will be minimized and will only occur during the Rollover test procedure (mentioned below) to ensure the participant’s safety.
- All materials are handled on a clean/sanitized surface, e.g. desks or benches.
- After every study visit, all non-disposable items used in the testing should be cleaned/sanitized and stored until next use.

➢ Key Personnel sanitize their hands on a regular basis and after touching any testing surface.
➢ Sanitizing Stations will be made available around the testing facility for everyone to use.
➢ *All Key Personnel on the team have been Fully Vaccinated.*

Operation

a) During Data Collection
  - One designated research personnel interacts with the participant. The subject is explained the procedure and is escorted to Station 1. Participant’s age, height, weight is recorded here. The subject dons the PPE (Helmet) at this station. Participant will be assisted by the research personnel if required.
  - Participant is then escorted to the test device. The participant is asked to be belted and the force at upright orientation is recorded.
  - The second designated research personnel arrives for the next procedure. For the *rollover procedure,* the two personnel help lift the device and the participant unlatches the buckle at

the rolled over orientation and gently descends into the foam pit. During the rollover procedure the participant and the two designated research personnel could be in close contact (within 6 feet) of each other for up to 2 minutes.

b) After Data Collection
  - The participant makes her/his way out of the foam pit and is escorted back to the camp by the designated personnel.
  - The test device is brought back to its original orientation.
  - Cleaning follows

c) Cleaning
  - While cleaning, all personnel will wear sterile gloves, face masks and face shields.
  - The test device bench seat and the lift handles will be thoroughly wiped and sanitized using Lysol Disinfecting wipes and spray or equivalent.
  - The helmet will also be sanitized thoroughly after use and stored separately. We have enough helmets to be used only once per participant. The used helmet will be used after 72 hours if needed on a different participant, to mitigate any risk of contamination.
  - The Foam pit will be sprayed with disinfectant spray once a day.

The highlighted are the two surface in contact during the rollover procedure.

TODAY'S DATE: ______________

CDC FACILITIES COVID-19 SCREENING

Accessible version available at *https://www.cdc.gov/screening/*

PLEASE READ EACH QUESTION CAREFULLY	**PLEASE CIRCLE THE ANSWER THAT APPLIES TO YOU**	
Have you experienced any of the following symptoms in the past 48 hours: • fever or chills • cough • shortness of breath or difficulty breathing • fatigue • muscle or body aches • headache • new loss of taste or smell • sore throat • congestion or runny nose • nausea or vomiting • diarrhea	**YES**	**NO**
Within the past 14 days, have you been in close physical contact (6 feet or closer for a cumulative total of 15 minutes) with: • Anyone who is known to have laboratory-confirmed COVID-19? OR • Anyone who has any symptoms consistent with COVID-19?	**YES**	**NO**
Are you isolating or quarantining because you may have been exposed to a person with COVID-19 or are worried that you may be sick with COVID-19?	**YES**	**NO**
Are you currently waiting on the results of a COVID-19 test?	**YES**	**NO**

Did you answer **NO** to **ALL QUESTIONS**?	Access to CDC facilities **APPROVED**. Please show this to security at the facility entrance. Thank you for helping us protect you and others during this time.
Did you answer **YES** to **ANY QUESTION**?	Access to CDC facilities **NOT APPROVED**. Please see Page 2 for further instructions. Thank you for helping us protect you and others during this time.

cdc.gov/screening

cdc.gov/screening/further-instructions.html

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1

THE SCREENING YOU COMPLETED INDICATES THAT YOU MAY BE AT INCREASED RISK FOR COVID-19

IF YOU ARE NOT FEELING WELL, WE HOPE THAT YOU FEEL BETTER SOON!

Here are instructions for what to do next

1

If you are not already at home, please avoid contact with others and go straight home immediately.

2

Call your primary care provider* for further instructions, including information about COVID-19 testing.

3

Contact your supervisor (if you are an employee) or your contracting company (if you are a contractor) to discuss options for telework and/or leave.

Before going to a healthcare facility, please call and let them know that you may have an increased risk for COVID-19.

In case of a life-threatening medical emergency, dial 911 immediately!

RETURNING TO THE WORKPLACE

If you have had symptoms consistent with COVID-19 or have tested positive for COVID-19, DO NOT physically return to work until you get a medical evaluation and are approved to return to a work setting by your primary care provider*. Please call your supervisor to discuss when to return to work. Read more about when it is safe to be around others at *https://www.cdc.gov/coronavirus/2019-ncov/if-you-are-sick/end-home-isolation.html.*

If you have a chronic medical condition that causes COVID-19-like symptoms and you need to access a CDC facility within the next few days, please call CDC's Occupational Health Clinic at 404-639-3385 to determine whether you can safely be granted access to a CDC facility.

If you have been in close contact with someone with COVID-19 you should stay home and self-quarantine for 14 days before returning to work. Read more about when you should be in isolation or quarantine at *https://www.cdc.gov/coronavirus/2019-ncov/if-you-are-sick/quarantine.html.*

If you are currently isolating or quarantining because of concerns about COVID-19 OR you have a COVID-19 test pending, please contact your primary care provider* for guidance on when you can return to work.

- If you have an urgent need to come to campus while waiting for a test result, call CDC's Occupational Health Clinic at 404-639-3385.
- If you have an urgent need to end your quarantine period early, please ask your CIO Management Officer to send an email request to eocevent106@cdc.gov and eocoht@cdc.gov.

If you have additional questions about when you can return to work, please email OSSAM@cdc.gov. For information about COVID-19 and basic instructions to prevent the spread of disease, visit CDC's COVID-19 website at *https://www.cdc.gov/covid19*.

*If you are assigned to the COVID-19, Ebola, or Polio responses, or work in a lab, call CDC's Occupational Health Clinic at 404-639-3385 instead of your primary care provider for next steps. DO NOT physically go to a CDC Occupational Health Clinic location.

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Appendix J: Chapter 4 Study Data Collection Sheet

Emergency Evacuation Considerations for Seat Belt Equipped School Buses

Data Collection Sheet (Individual Subject Data)

Date: ________________ Subject Number: ______________

Gender : __________________ Month & Year of Birth : ________________

Grade : ___________________ Weight : _________________ Height : ____________________

Neutral posture

Max. Force Applied :

LEFT RIGHT

Thumb : ____________ Thumb : _____________

Fingers : ____________ Fingers : ____________

Custom School Bus Bench Seat Testing

Upright Orientation

Max. Force Applied :

LEFT RIGHT

Thumb : ____________ Thumb : _____________

Fingers : ____________ Fingers : ____________

Evacuation Time : __________________________

Rolled Over Orientation

Max. Force Applied :

LEFT RIGHT

Thumb : ____________ Thumb : _____________

Fingers : ____________ Fingers : ____________

Evacuation Time : __________________________

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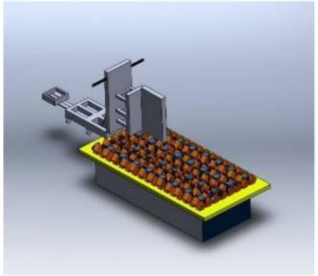
Appendix K: Chapter 4 Study Flyer

Research to Study the Effects of Seat Belts on Emergency Evacuation of a School Bus



Does your child ride a school bus?

Does your child wear a seatbelt while travelling in your car?

Do seatbelts make you feel safe?

Would you like school buses to be safer?

Are you willing to allow your child to participate in a study to help improve some safety aspects of school buses?

If you answered YES to these questions, your child may be eligible to participate in the following study:

Emergency Evacuation Considerations for Seat Belt Equipped School Buses

National Highway Traffic Safety Administration (NHTSA) states that in comparison to other vehicle transportation methods, students are about 70 times more likely to get to school safely when riding a school bus. School buses are an integral part of our education and transportation system, with almost half a million buses transporting 25.2 million children daily.

The purpose of our study is to determine whether children (5-16 years) can successfully evacuate a school bus that is equipped with seat belts. Seat belts have saved an estimated 255,000 lives in the US (1975-2008). It is important to study all aspects of seat belts in regards to school buses. We are trying to determine if wearing a seat belt has an effect on children during an emergency evacuation of a school bus.

This is a unique opportunity for your child to experience sitting on a school bus seat in different orientations. Participants will learn the importance of seat belts on school buses. They could potentially learn how it feels in a school bus rollover and how to eject themselves if the situation arises. There will be no monetary compensation for participation, and there is no direct benefit for participating in this study.

We will take all the possible precautions to prevent the spread of Covid 19 and will follow all the guidelines recommended by Auburn University to carry out safe research.

The study will be conducted at the Auburn Gymnastics Academy. Additional details of the study are mentioned in the Consent form.

If you have any questions or need more information, please feel free to contact:
Shiva Prasad (szn0043@auburn.edu, 334-758-3504) or
Dr. Jerry Davis (davisga@auburn.edu, 334-332-7745).

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Appendix L: Chapter 4 Study Assent Process for Subjects

AUBURN
UNIVERSITY
SAMUEL GINN
COLLEGE OF ENGINEERING

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Assent Process for Participants

Study Title: "Emergency Evacuation Considerations for Seat Belt Equipped School Buses"

1. What will happen to me in this study?

You will be asked for your age, and your height, you will be weighed in private. The Maximum force you can apply on a button using your fingers and thumb will be measured. You will be part of a test that will be conducted in two stages.

In Stage 1: You will be asked to sit on a school bus bench seat and wear a seat belt. You will then be asked to unlatch the seat belt, and the force and time required to unlatch a seat belt will be measured.

In Stage 2: You will be asked to sit on a school bus bench seat and wear a seat belt. You will be tilted 90 degrees, and from this position, you will be asked to get out of the seat (release the seat belt) and gently fall into a foam pit.

You will be required to wear bicycle helmet to eliminate any additional risks involved. Helmets of multiple sizes are available, and they will be sanitized by the research team before reuse. We will confirm with you post study if you experienced any injury.

You will be videoed during testing to record your escape time and your postures while wearing and releasing the seat belt. All video records are confidential and will be destroyed when the study is complete.

2. Can anything bad happen to me?

It is possible to trip, or fall, or get a minor irritation due to potential rubbing from the seat belt during the sliding phase. You will be falling into a foam pit. You may experience some level of discomfort as the bench seat is being tilted 90 degrees over a foam pit.

3. Can anything good happen to me?

This is a unique opportunity for you to experience sitting in a school bus seat in a different orientation other than the normal orientation. You could potentially learn how it feels in a school bus rollover and how to eject yourself if the situation arises

4. What happens if I get hurt?

There will be adults watching you the whole time to make sure you are as safe as possible.

5. Who can I talk to about the study?

If you have any questions about the study or any problems to do with the study, you can contact the Principal Investigator Shiva Prasad. You can call him at 334-758-3504. You can also call Dr. Jerry Davis at 334-332-7745.

Adopted from: http://humansubjects.stanford.edu/research/documents/ConsentProocolsChildrenConsentingMinors.pdf

If you have questions about the study but want to talk to someone else who is not a part of this study, you can call the Auburn University Institutional Review Board (IRB) at (334)-844- 5966.

6. What if I do not want to do this?

You can stop being in the study at any time without getting in trouble. Participants can stop at any time by simply telling us they do not want to participate any longer.

7. What are you doing to keep us safe from Covid'19?

We are taking all the recommended measures following the guidelines of Auburn University. We will all be wearing masks and gloves at all times and will be disinfecting all the frequently contacted surfaces at regular intervals. We have arranged for sanitization stations across the facility.

Images to be shown to the participants

Figure 1: Test Apparatus

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Figure 2: Measuring Maximum exerted push force with thumb and fingers

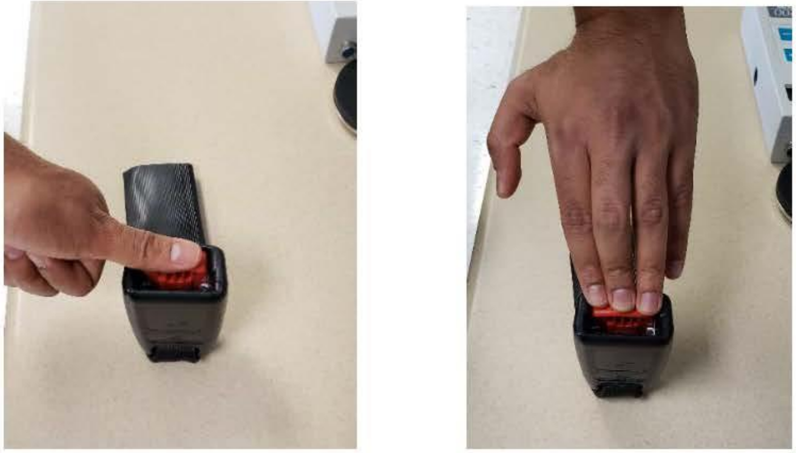

Figure 4: Exerting push force with thumb and fingers

Appendix M: Chapter 4 Parental Permission Document

AUBURN UNIVERSITY
SAMUEL GINN COLLEGE OF ENGINEERING

(NOTE: DO NOT AGREE TO PARTICIPATE UNLESS AN APPROVAL STAMP WITH CURRENT DATES HAS BEEN APPLIED TO THIS DOCUMENT.)

PARENTAL PERMISSION/MINOR ASSENT
for Research Study entitled

"*Emergency Evacuation Considerations for Seat Belt Equipped School Buses*"

School buses are an integral part of our education and transportation system, with almost half a million buses transporting 25.2 million children daily. The National Highway Traffic Safety Administration (NHTSA) states that in comparison to other vehicle transportation methods, students are about 70 times more likely to get to school safely when riding a school bus. The purpose of our study is to determine whether children (5-16 years) can successfully evacuate a school bus that is equipped with seat belts after rollover. We are trying to determine if wearing a seat belt influences children during an emergency evacuation. Participants will learn the importance of seat belts on school buses. They will also learn how to release a seat belt when a school bus is in the upright and rolled over (on its side) orientation simulating an after-accident event.

Your child is invited to participate in a research study to investigate the physical requirements needed to evacuate a school bus equipped with seat belts during an emergency evacuation. Shivaprasad Nageswaran, Principal Investigator, is conducting this research, under the supervision of Dr. Jerry Davis of the Auburn University, Department of Industrial and Systems Engineering. Your child was selected as a possible participant because he or she is a student at Auburn Gymnastics Academy. Since your child is age 19 or younger, we must have your permission to include him/her in the study.

What will be involved if your child participates?

If you decide to allow your child to participate in this research study, the following information will be recorded. 1) Height and weight (in private); 2) Age and gender; 3) Time to release the seat belt in upright and rolled-over orientations 4) Maximum finger force exerted on belt buckle (please see Figure 1,2,3,4)

They will be part of a test that will be conducted in two phases to simulate two orientations of a bus (during an accident)

Phase 1: *Upright Orientation:* your child will be asked to voluntarily buckle up on a school bus bench seat and, the force and the time required to unlatch a seat belt will be measured.

Phase 2: *Rolled Over Orientation:* your child will be asked to voluntarily buckle up on a school bus bench seat that will be tilted 90 degrees, and in that orientation, will be asked to release the belt and gently will fall into a foam pit. Again, the force and the time required to unlatch a seat belt will be measured

Your child will be videoed during testing to observe their escape time, and their postures while wearing and releasing the seat belt. All video records are confidential and will be destroyed when the study is complete.

Parent/Guardian Initials _______

The Auburn University Institutional Review Board has approved this Document for use from 09/02/2022 to 09/01/2023
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What are we doing to keep your child safe from Covid'19?

The health and safety of your child is our top priority. *All research team members are fully Vaccinated.* Surfaces will be regularly sprayed and wiped with disinfectants. a heightened focus will be on sanitizing and disinfecting high-touch surfaces. All associated in the area will be wearing the appropriate PPEs (face masks and gloves). We will maintain the recommended social distancing guidelines provided by Auburn University. Sanitizing stations will be provided in the testing area for all. Additional Covid Information sheet, screening procedures and precautions to be used are attached to this form.

Are there any risks or discomforts?

The risks associated with participating in this study are minimal and are limited to muscle strain or minor impact with equipment. Participants will be required to wear bicycle helmet to eliminate any additional risks involved. Helmets of multiple sizes are available, and they will be sanitized by the research team before reuse. Subjects may perceive some level of discomfort as the bench seat they are belted to is being tipped 90 degrees over a foam pit. We will not allow any horse play around the equipment Additionally; our research team and the Academy coaches and staff will be present throughout the test. Any incurred medical costs are not covered through this research and are the responsibility of the parents. *Auburn University has not provided for any payment if you are harmed as a result of participating in this study*

Are there any benefits to your child or others?

This is a unique opportunity for a child to experience sitting in a school bus seat in a different orientation other than the normal orientation. They could potentially learn how it feels in a school bus rollover and how to eject themselves if the situation arises. We cannot promise you that your child will receive any or all the benefits described.

Will you or your child receive compensation for participating?

We cannot provide any type of compensation to your child for participating.

Are there any costs? There is no cost for your child to participate in this study.

If you (or your child) change your mind about your child's participation, your child can withdraw from the study at any time. Your child's participation is completely voluntary, and you are welcome to observe your child during the study. Your decision about whether or not to allow your child to participate or to stop participating will not jeopardize your or your child's future relations with Auburn University, the Department of Industrial and Systems Engineering, or Auburn Gymnastics Academy.

Your child's privacy will be protected. Any information obtained in connection with this study will remain anonymous. All data/information is confidential. Information obtained through your child's participation may be used to fulfill an educational requirement, published in a professional journal, used by general industry, and/or presented at a professional meeting.

If you (or your child) have questions about this study please contact Mr. Shivaprasad at szn0043@auburn.edu, (334)-758-3504, or Dr. Jerry Davis at davisga@auburn.edu, (334)-332-7745. A copy of this document will be given to you to keep.

If you have questions about your child's rights as a research participant, you may contact the Auburn Univeristy Office of Human Subjects Research or the Institutional Review Board by phone at (334)-844-5966 or email at hsubjec@auburn.edu or IRBChair@auburn.edu

Parent/Guardian Initials ________

Reference Images

Figure 1: Test Apparatus

Figure 2: Measuring Maximum exerted push force with thumb and fingers

HAVING READ THE INFORMATION PROVIDED, YOU MUST DECIDE WHETHER OR NOT YOU WISH FOR YOUR CHILD TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES YOUR WILLINGNESS TO ALLOW YOUR CHILD TO PARTICIPATE.

____
Parent/Guardian Signature

____
Investigator obtaining consent

____
Printed Name

____
Investigator Printed Name

____
Date

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COVID Screening and Precautions

"Emergency Evacuation Considerations for Seat Belt Equipped School Buses"

Health and Safety of the participants and the research personnel is at the highest priority. To cope with Data Collection during the Pandemic, the following procedures will be used:

Pre-Visit Screening:

- Call the participant's parent/legal guardian and complete the Coronavirus Screening Form.
- All Key Personnel involved in the data collection complete Coronavirus Screening Form.

General Procedures:

- All research team members and the participant wash their hands upon arrival and after any physical contacts with other people.
- All research team members wear facemasks and face shields at all times. Participants will be required to wear facemasks at all times. Any participant who needs to briefly take off the mask (e.g., for drinking water) does so at least 6 ft away from others and in advance notifies a key personnel present at the experiment location to ensure adequate distancing during the break.
- During the study visit, only two designated study team members can make close contact (less than 6 ft apart) with the participant for all procedures that require close contact. Close contact will be minimized and will only occur during the Rollover test procedure (mentioned below) to ensure the participant's safety.
- All materials are handled on a clean/sanitized surface, e.g. desks or benches.
- After every study visit, all non-disposable items used in the testing should be cleaned/sanitized and stored until next use.

➢ Key Personnel sanitize their hands on a regular basis and after touching any testing surface.
➢ Sanitizing Stations will be made available around the testing facility for everyone to use.
➢ *All Key Personnel on the team have been Fully Vaccinated.*

Operation

a) During Data Collection
   - One designated research personnel interacts with the participant. The subject is explained the procedure and is escorted to Station 1. Participant's age, height, weight is recorded here. The subject dons the PPE (Helmet) at this station. Participant will be assisted by the research personnel if required.
   - Participant is then escorted to the test device. The participant is asked to be belted and the force at upright orientation is recorded.
   - The second designated research personnel arrives for the next procedure. For the *rollover procedure,* the two personnel help lift the device and the participant unlatches the buckle at

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the rolled over orientation and gently descends into the foam pit. During the rollover procedure the participant and the two designated research personnel could be in close contact (within 6 feet) of each other for up to 2 minutes.

b) After Data Collection
  - The participant makes her/his way out of the foam pit and is escorted back to the camp by the designated personnel.
  - The test device is brought back to its original orientation.
  - Cleaning follows

c) Cleaning
  - While cleaning, all personnel will wear sterile gloves, face masks and face shields.
  - The test device bench seat and the lift handles will be thoroughly wiped and sanitized using Lysol Disinfecting wipes and spray or equivalent.
  - The helmet will also be sanitized thoroughly after use and stored separately. We have enough helmets to be used only once per participant. The used helmet will be used after 72 hours if needed on a different participant, to mitigate any risk of contamination.
  - The Foam pit will be sprayed with disinfectant spray once a day

The highlighted are the two surface in contact during the rollover procedure.

Information on COVID-19 For Research Participants (updated 05/27/2021)

Auburn University recognizes the essential role of research participants in the advancement of science and innovation for our university, community, state, nation, and beyond. Therefore, protection of those who volunteer to participate in Auburn University research is of utmost importance to our institution.

As you are likely aware, COVID-19 references the Coronavirus that is being spread around the world including in our country, state, and community. It is important that we provide you with basic information about COVID-19 and the risks associated with the virus so that you can determine if you wish to participate or continue your participation in human research.

How is COVID-19 spread? COVID-19 is a respiratory virus that is spread by respiratory droplets, mainly from person-to person. This can happen between people who are in close contact with one another. COVID-19 may also be spread by exposure to the virus in small droplets that can linger in the air. This kind of spread is referred to as airborne transmission. It is also possible that a person can get COVID-19 by touching a surface or object (such as a doorknob or counter surface) that has the virus on it, then touching their mouth, nose, or eyes.

Please visit the CDC's web page for more information on how COVID-19 spreads.

Can COVID-19 be prevented? Although there is no guarantee that infection from COVID-19 can be prevented, there are ways to minimize the risk of exposure to the virus. For instance, stay 6 feet apart from others who don't live with you; get a COVID-19 vaccine when it is available to you; avoid crowds and poorly ventilated indoor spaces; use effective barriers between persons; wear personal protective equipment like masks, gloves, etc.; wash hands with soap and water or use hand sanitizer after touching objects; disinfect objects touched by multiple individuals.

What are the risks of COVID-19? For most people, COVID-19 causes only mild or moderate symptoms, such as fever and cough. For some, especially older adults and people with existing health problems, it can cause more severe illness. While everyone is still learning about this virus, current information suggests that about 1-3% of people who are infected with COVID-19 might die as a result.

Who is most at risk? Individuals over age 65 and those with chronic conditions such as cancer, diabetes, heart or lung or liver disease, severe obesity, and conditions that cause a person to be immunocompromised have the highest rates of severe disease and serious complications from infection.

What precautions should be taken? Based on the proposed research, precautions for the risk of COVID-19 will be addressed on a project by project basis. You will be provided with information about precautions for the project in which you may participate. Any site where research activities will occur that are not a part of Auburn University (offsite location) are expected to have standard procedures for addressing the risk of COVID-19. It is important for participants to follow any precautions or procedures outlined by Auburn University and, when applicable, offsite locations. Further, participants will need to determine how best to address the risk of COVID-19 when traveling to and from research locations. The US Center for Disease Control and Prevention has issued recommendations on types of prevention measures you can use to reduce your risk of exposure and the spread of COVID-19.

Auburn University is continuing to monitor the latest information on COVID-19 to protect our students, employees, visitors, and community. Our research study teams will update participants as appropriate. *If you have specific questions or concerns about COVID-19 or your participation in research, please talk with your study team.* The name and contact information for the study team leader, along with contact information for the Auburn University Institutional Review Board for Protection of Human Research Participants, can be found in the consent document provided to you by the study team.

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TODAY'S DATE: ______________

CDC FACILITIES COVID-19 SCREENING

Accessible version available at *https://www.cdc.gov/screening/*

PLEASE READ EACH QUESTION CAREFULLY	**PLEASE CIRCLE THE ANSWER THAT APPLIES TO YOU**	
Have you experienced any of the following symptoms in the past 48 hours: • fever or chills • cough • shortness of breath or difficulty breathing • fatigue • muscle or body aches • headache • new loss of taste or smell • sore throat • congestion or runny nose • nausea or vomiting • diarrhea	**YES**	**NO**
Within the past 14 days, have you been in close physical contact (6 feet or closer for a cumulative total of 15 minutes) with: • Anyone who is known to have laboratory-confirmed COVID-19? OR • Anyone who has any symptoms consistent with COVID-19?	**YES**	**NO**
Are you isolating or quarantining because you may have been exposed to a person with COVID-19 or are worried that you may be sick with COVID-19?	**YES**	**NO**
Are you currently waiting on the results of a COVID-19 test?	**YES**	**NO**

Did you answer **NO** to **ALL QUESTIONS**?	Access to CDC facilities **APPROVED**. Please show this to security at the facility entrance. Thank you for helping us protect you and others during this time.
Did you answer **YES** to **ANY QUESTION**?	Access to CDC facilities **NOT APPROVED**. Please see Page 2 for further instructions. Thank you for helping us protect you and others during this time.

cdc.gov/screening

cdc.gov/screening/further-instructions.html

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THE SCREENING YOU COMPLETED INDICATES THAT YOU MAY BE AT INCREASED RISK FOR COVID-19

IF YOU ARE NOT FEELING WELL, WE HOPE THAT YOU FEEL BETTER SOON!

Here are instructions for what to do next

1	2	3
If you are not already at home, please avoid contact with others and go straight home immediately.	Call your primary care provider* for further instructions, including information about COVID-19 testing.	Contact your supervisor (if you are an employee) or your contracting company (if you are a contractor) to discuss options for telework and/or leave.

Before going to a healthcare facility, please call and let them know that you may have an increased risk for COVID-19.

In case of a life-threatening medical emergency, dial 911 immediately!

RETURNING TO THE WORKPLACE

If you have had symptoms consistent with COVID-19 or have tested positive for COVID-19, DO NOT physically return to work until you get a medical evaluation and are approved to return to a work setting by your primary care provider*. Please call your supervisor to discuss when to return to work. Read more about when it is safe to be around others at *https://www.cdc.gov/coronavirus/2019-ncov/if-you-are-sick/end-home-isolation.html.*

If you have a chronic medical condition that causes COVID-19-like symptoms and you need to access a CDC facility within the next few days, please call CDC's Occupational Health Clinic at 404-639-3385 to determine whether you can safely be granted access to a CDC facility.

If you have been in close contact with someone with COVID-19 you should stay home and self-quarantine for 14 days before returning to work. Read more about when you should be in isolation or quarantine at *https://www.cdc.gov/coronavirus/2019-ncov/if-you-are-sick/quarantine.html.*

If you are currently isolating or quarantining because of concerns about COVID-19 OR you have a COVID-19 test pending, please contact your primary care provider* for guidance on when you can return to work.

- If you have an urgent need to come to campus while waiting for a test result, call CDC's Occupational Health Clinic at 404-639-3385.
- If you have an urgent need to end your quarantine period early, please ask your CIO Management Officer to send an email request to eocevent106@cdc.gov and eocoht@cdc.gov.

If you have additional questions about when you can return to work, please email OSSAM@cdc.gov. For information about COVID-19 and basic instructions to prevent the spread of disease, visit CDC's COVID-19 website at *https://www.cdc.gov/covid19*.

*If you are assigned to the COVID-19, Ebola, or Polio responses, or work in a lab, call CDC's Occupational Health Clinic at 404-639-3385 instead of your primary care provider for next steps. DO NOT physically go to a CDC Occupational Health Clinic location.

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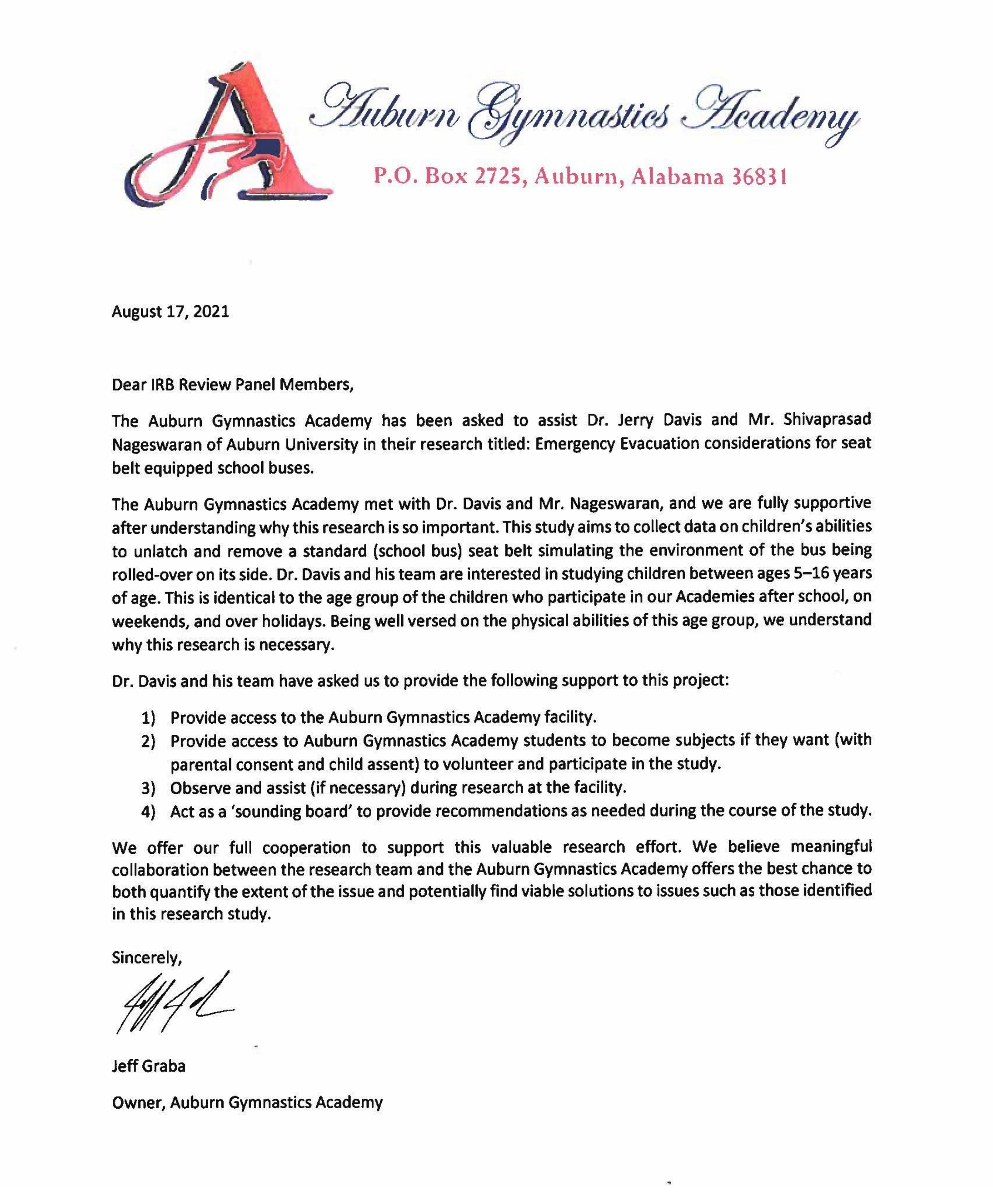
Appendix N: Auburn Gymnastics Academy Letter of Support



Auburn Gymnastics Academy
P.O. Box 2725, Auburn, Alabama 36831

August 17, 2021

Dear IRB Review Panel Members,

The Auburn Gymnastics Academy has been asked to assist Dr. Jerry Davis and Mr. Shivaprasad Nageswaran of Auburn University in their research titled: Emergency Evacuation considerations for seat belt equipped school buses.

The Auburn Gymnastics Academy met with Dr. Davis and Mr. Nageswaran, and we are fully supportive after understanding why this research is so important. This study aims to collect data on children's abilities to unlatch and remove a standard (school bus) seat belt simulating the environment of the bus being rolled-over on its side. Dr. Davis and his team are interested in studying children between ages 5–16 years of age. This is identical to the age group of the children who participate in our Academies after school, on weekends, and over holidays. Being well versed on the physical abilities of this age group, we understand why this research is necessary.

Dr. Davis and his team have asked us to provide the following support to this project:

1) Provide access to the Auburn Gymnastics Academy facility.
2) Provide access to Auburn Gymnastics Academy students to become subjects if they want (with parental consent and child assent) to volunteer and participate in the study.
3) Observe and assist (if necessary) during research at the facility.
4) Act as a 'sounding board' to provide recommendations as needed during the course of the study.

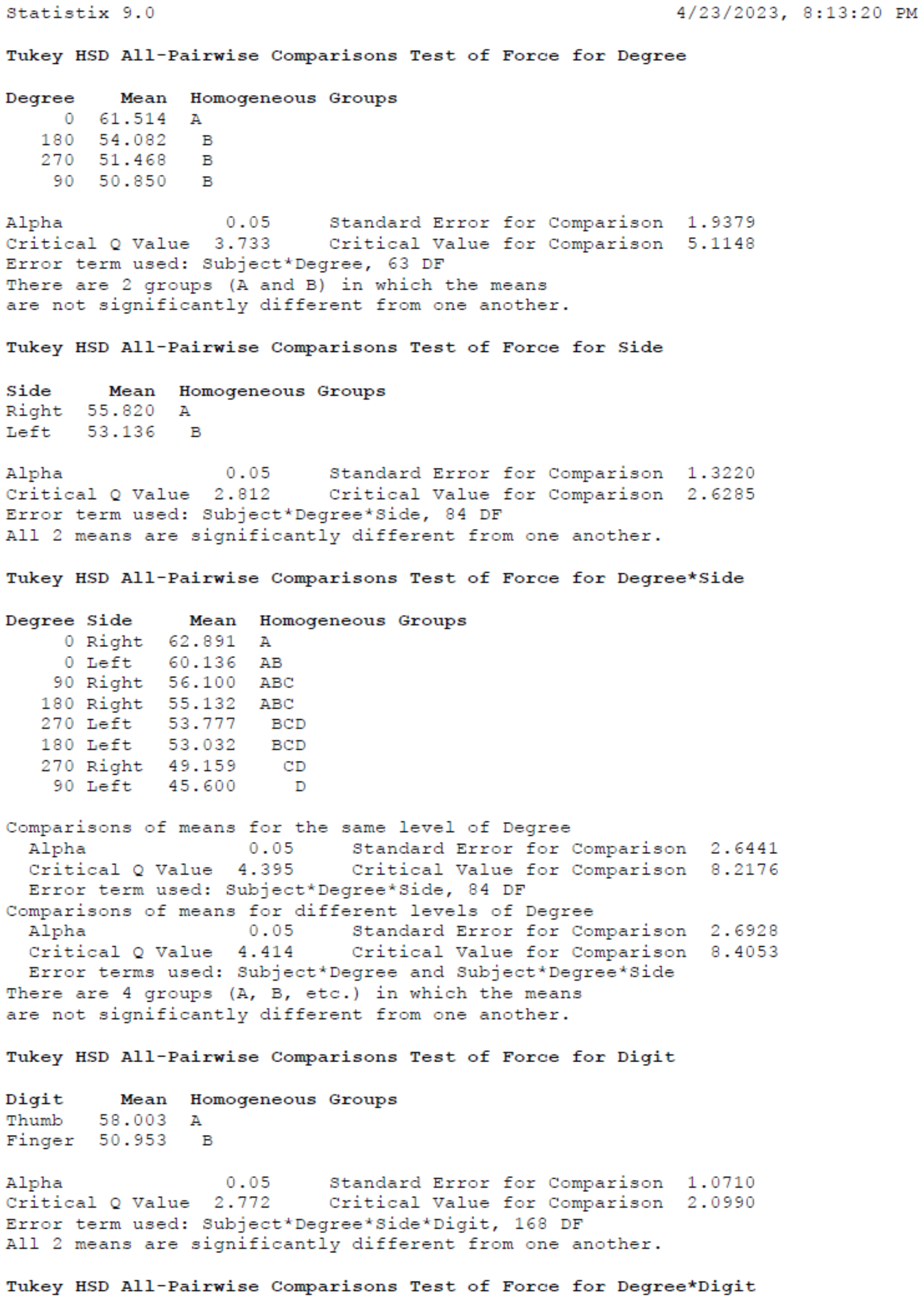
We offer our full cooperation to support this valuable research effort. We believe meaningful collaboration between the research team and the Auburn Gymnastics Academy offers the best chance to both quantify the extent of the issue and potentially find viable solutions to issues such as those identified in this research study.

Sincerely,

Jeff Graba

Owner, Auburn Gymnastics Academy

Appendix O: Results of Tukey HSD Tests for Females for Chapter 3 Study



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Tukey HSD All-Pairwise Comparisons Test of Force for Degree

Degree    Mean  Homogeneous Groups
     0  61.514  A
   180  54.082   B
   270  51.468   B
    90  50.850   B

Alpha              0.05     Standard Error for Comparison  1.9379
Critical Q Value  3.733     Critical Value for Comparison  5.1148
Error term used: Subject*Degree, 63 DF
There are 2 groups (A and B) in which the means
are not significantly different from one another.

Tukey HSD All-Pairwise Comparisons Test of Force for Side

Side     Mean  Homogeneous Groups
Right  55.820  A
Left   53.136   B

Alpha              0.05     Standard Error for Comparison  1.3220
Critical Q Value  2.812     Critical Value for Comparison  2.6285
Error term used: Subject*Degree*Side, 84 DF
All 2 means are significantly different from one another.

Tukey HSD All-Pairwise Comparisons Test of Force for Degree*Side

Degree Side     Mean  Homogeneous Groups
     0 Right  62.891  A
     0 Left   60.136  AB
    90 Right  56.100  ABC
   180 Right  55.132  ABC
   270 Left   53.777   BCD
   180 Left   53.032   BCD
   270 Right  49.159    CD
    90 Left   45.600     D

Comparisons of means for the same level of Degree
  Alpha              0.05     Standard Error for Comparison  2.6441
  Critical Q Value  4.395     Critical Value for Comparison  8.2176
  Error term used: Subject*Degree*Side, 84 DF
Comparisons of means for different levels of Degree
  Alpha              0.05     Standard Error for Comparison  2.6928
  Critical Q Value  4.414     Critical Value for Comparison  8.4053
  Error terms used: Subject*Degree and Subject*Degree*Side
There are 4 groups (A, B, etc.) in which the means
are not significantly different from one another.

Tukey HSD All-Pairwise Comparisons Test of Force for Digit

Digit     Mean  Homogeneous Groups
Thumb   58.003  A
Finger  50.953   B

Alpha              0.05     Standard Error for Comparison  1.0710
Critical Q Value  2.772     Critical Value for Comparison  2.0990
Error term used: Subject*Degree*Side*Digit, 168 DF
All 2 means are significantly different from one another.

Tukey HSD All-Pairwise Comparisons Test of Force for Degree*Digit
```

```
Degree Digit     Mean   0,Finger     0,Thumb   90,Finger    90,Thumb
     0 Finger  55.227
     0 Thumb   67.800    12.573*
    90 Finger  50.268     4.959      17.532*
    90 Thumb   51.432     3.795      16.368*      1.164
   180 Finger  50.573     4.655      17.227*      0.305       0.859
   180 Thumb   57.591     2.364      10.209*      7.323       6.159
   270 Finger  47.745     7.482      20.055*      2.523       3.686
   270 Thumb   55.191     0.036      12.609*      4.923       3.759
Degree Digit     Mean 180,Finger   180,Thumb  270,Finger
   180 Finger  50.573
   180 Thumb   57.591     7.018*
   270 Finger  47.745     2.827       9.845*
   270 Thumb   55.191     4.618       2.400       7.445*

Comparisons of means for the same level of Degree
  Alpha             0.05     Standard Error for Comparison  2.1419
  Critical Q Value  4.285    Critical Value for Comparison  6.4901
  Error term used: Subject*Degree*Side*Digit, 168 DF
Comparisons of means for different levels of Degree
  Alpha             0.05     Standard Error for Comparison  2.4596
  Critical Q Value  4.376    Critical Value for Comparison  7.6113
  Error terms used: Subject*Degree and Subject*Degree*Side*Digit
The homogeneous group format can't be used
because of the pattern of significant differences.

Tukey HSD All-Pairwise Comparisons Test of Force for Side*Digit

Side  Digit     Mean  Homogeneous Groups
Right Thumb   59.223  A
Left  Thumb   56.784  AB
Right Finger  52.418   BC
Left  Finger  49.489    C

Comparisons of means for the same level of Side
  Alpha             0.05     Standard Error for Comparison  1.5146
  Critical Q Value  3.632    Critical Value for Comparison  3.8899
  Error term used: Subject*Degree*Side*Digit, 168 DF
Comparisons of means for different levels of Side
  Alpha             0.05     Standard Error for Comparison  1.7014
  Critical Q Value  3.678    Critical Value for Comparison  4.4244
  Error terms used: Subject*Degree*Side and Subject*Degree*Side*Digit
There are 3 groups (A, B, etc.) in which the means
are not significantly different from one another.

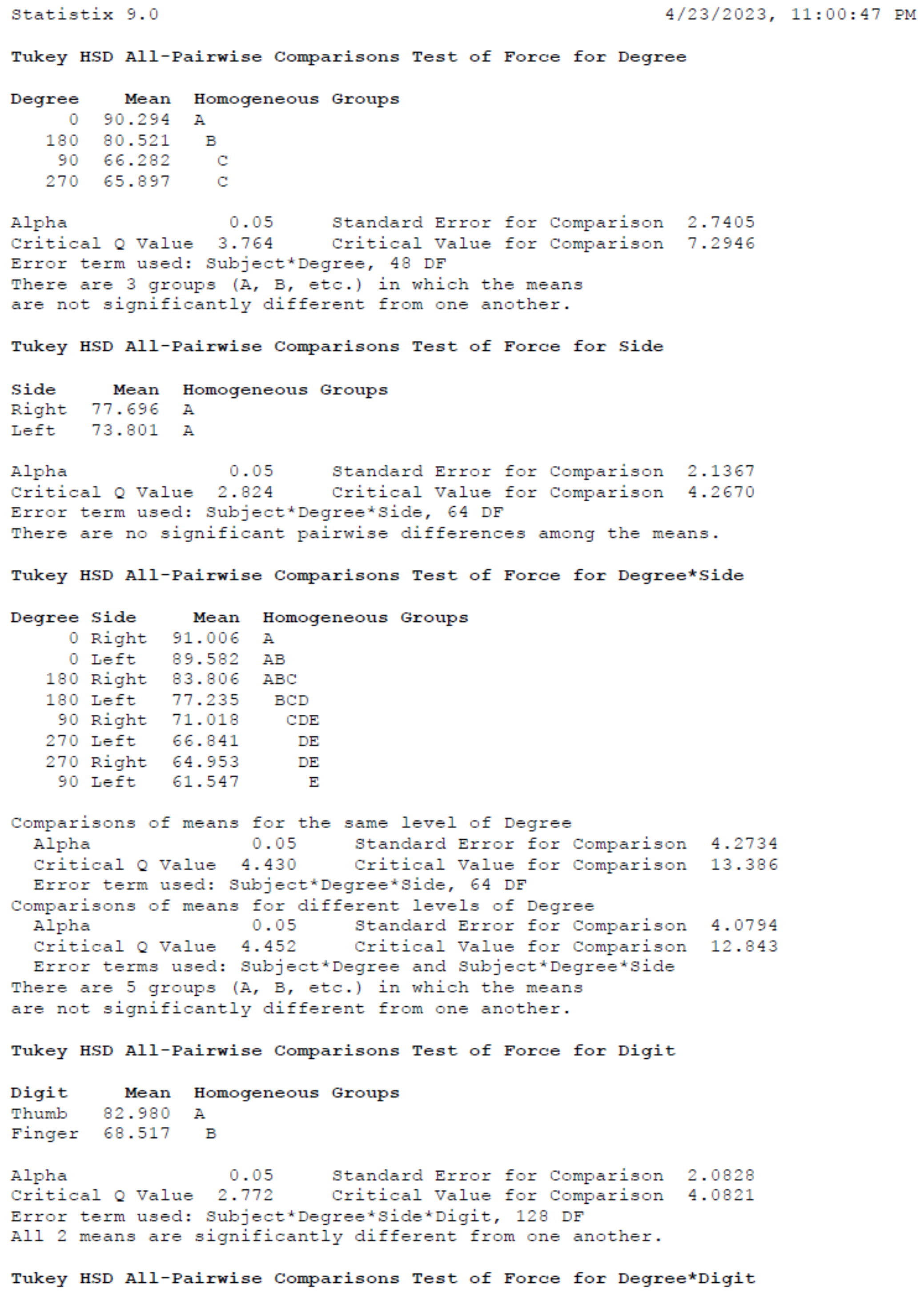
Tukey HSD All-Pairwise Comparisons Test of Force for Degree*Side*Digit

Degree Side  Digit     Mean  Homogeneous Groups
     0 Left  Thumb   68.127  A
     0 Right Thumb   67.473  AB
   270 Left  Thumb   60.664  ABC
    90 Right Thumb   60.045  ABCD
   180 Right Thumb   59.655  ABCD
     0 Right Finger  58.309  ABCDE
   180 Left  Thumb   55.527   BCDE
    90 Right Finger  52.155    CDEF
     0 Left  Finger  52.145    CDEF
   180 Right Finger  50.609    CDEF
   180 Left  Finger  50.536    CDEF
   270 Right Thumb   49.718    CDEF
   270 Right Finger  48.600     DEF
    90 Left  Finger  48.382     DEF
   270 Left  Finger  46.891      EF
```

```
    90 Left  Thumb   42.818       F

Comparisons of means for the same levels of Degree and Side
  Alpha              0.05     Standard Error for Comparison  3.0291
  Critical Q Value  4.843     Critical Value for Comparison  10.374
  Error term used: Subject*Degree*Side*Digit, 168 DF
Comparisons of means for the same levels of Degree
  Alpha              0.05     Standard Error for Comparison  3.4028
  Critical Q Value  4.931     Critical Value for Comparison  11.865
  Error terms used: Subject*Degree*Side and Subject*Degree*Side*Digit
Comparisons of means for different levels of Degree
  Alpha              0.05     Standard Error for Comparison  3.4408
  Critical Q Value  5.014     Critical Value for Comparison  12.200
  Error terms used: Subject*Degree and Subject*Degree*Side and Subject*Degree*Side*Digit
There are 6 groups (A, B, etc.) in which the means
are not significantly different from one another.
```

Appendix P: Results of Tukey HSD Tests for Males for Chapter 3 Study



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Tukey HSD All-Pairwise Comparisons Test of Force for Degree

Degree    Mean  Homogeneous Groups
     0  90.294  A
   180  80.521   B
    90  66.282    C
   270  65.897    C

Alpha              0.05     Standard Error for Comparison  2.7405
Critical Q Value  3.764     Critical Value for Comparison  7.2946
Error term used: Subject*Degree, 48 DF
There are 3 groups (A, B, etc.) in which the means
are not significantly different from one another.

Tukey HSD All-Pairwise Comparisons Test of Force for Side

Side     Mean  Homogeneous Groups
Right  77.696  A
Left   73.801  A

Alpha              0.05     Standard Error for Comparison  2.1367
Critical Q Value  2.824     Critical Value for Comparison  4.2670
Error term used: Subject*Degree*Side, 64 DF
There are no significant pairwise differences among the means.

Tukey HSD All-Pairwise Comparisons Test of Force for Degree*Side

Degree Side     Mean  Homogeneous Groups
     0 Right  91.006  A
     0 Left   89.582  AB
   180 Right  83.806  ABC
   180 Left   77.235   BCD
    90 Right  71.018    CDE
   270 Left   66.841     DE
   270 Right  64.953     DE
    90 Left   61.547      E

Comparisons of means for the same level of Degree
  Alpha              0.05     Standard Error for Comparison  4.2734
  Critical Q Value  4.430     Critical Value for Comparison  13.386
  Error term used: Subject*Degree*Side, 64 DF
Comparisons of means for different levels of Degree
  Alpha              0.05     Standard Error for Comparison  4.0794
  Critical Q Value  4.452     Critical Value for Comparison  12.843
  Error terms used: Subject*Degree and Subject*Degree*Side
There are 5 groups (A, B, etc.) in which the means
are not significantly different from one another.

Tukey HSD All-Pairwise Comparisons Test of Force for Digit

Digit     Mean  Homogeneous Groups
Thumb   82.980  A
Finger  68.517   B

Alpha              0.05     Standard Error for Comparison  2.0828
Critical Q Value  2.772     Critical Value for Comparison  4.0821
Error term used: Subject*Degree*Side*Digit, 128 DF
All 2 means are significantly different from one another.

Tukey HSD All-Pairwise Comparisons Test of Force for Degree*Digit
```

```
Degree Digit      Mean  Homogeneous Groups
     0 Thumb    105.29  A
   180 Thumb     87.28   B
     0 Finger    75.30   BC
   180 Finger    73.76    CD
   270 Thumb     70.10    CD
    90 Thumb     69.26    CD
    90 Finger    63.31    CD
   270 Finger    61.69     D

Comparisons of means for the same level of Degree
  Alpha              0.05     Standard Error for Comparison  4.1655
  Critical Q Value  4.285     Critical Value for Comparison  12.622
  Error term used: Subject*Degree*Side*Digit, 128 DF
Comparisons of means for different levels of Degree
  Alpha              0.05     Standard Error for Comparison  4.0232
  Critical Q Value  4.375     Critical Value for Comparison  12.447
  Error terms used: Subject*Degree and Subject*Degree*Side*Digit
There are 4 groups (A, B, etc.) in which the means
are not significantly different from one another.

Tukey HSD All-Pairwise Comparisons Test of Force for Side*Digit

Side  Digit      Mean  Homogeneous Groups
Right Thumb   84.041  A
Left  Thumb   81.919  A
Right Finger  71.350   B
Left  Finger  65.684   B

Comparisons of means for the same level of Side
  Alpha              0.05     Standard Error for Comparison  2.9455
  Critical Q Value  3.632     Critical Value for Comparison  7.5649
  Error term used: Subject*Degree*Side*Digit, 128 DF
Comparisons of means for different levels of Side
  Alpha              0.05     Standard Error for Comparison  2.9839
  Critical Q Value  3.683     Critical Value for Comparison  7.7704
  Error terms used: Subject*Degree*Side and Subject*Degree*Side*Digit
There are 2 groups (A and B) in which the means
are not significantly different from one another.

Tukey HSD All-Pairwise Comparisons Test of Force for Degree*Side*Digit

Degree Side  Digit      Mean  Homogeneous Groups
     0 Right Thumb    105.78  A
     0 Left  Thumb    104.79  A
   180 Right Thumb     90.98  AB
   180 Left  Thumb     83.58   BC
   180 Right Finger    76.64   BCD
     0 Right Finger    76.24   BCD
   270 Left  Thumb     75.32   BCD
    90 Right Thumb     74.53   BCD
     0 Left  Finger    74.37   BCD
   180 Left  Finger    70.89   BCD
    90 Right Finger    67.51    CD
   270 Right Finger    65.02    CD
   270 Right Thumb     64.88    CD
    90 Left  Thumb     63.99    CD
    90 Left  Finger    59.11     D
   270 Left  Finger    58.36     D

Comparisons of means for the same levels of Degree and Side
  Alpha              0.05     Standard Error for Comparison  5.8910
  Critical Q Value  4.843     Critical Value for Comparison  20.175
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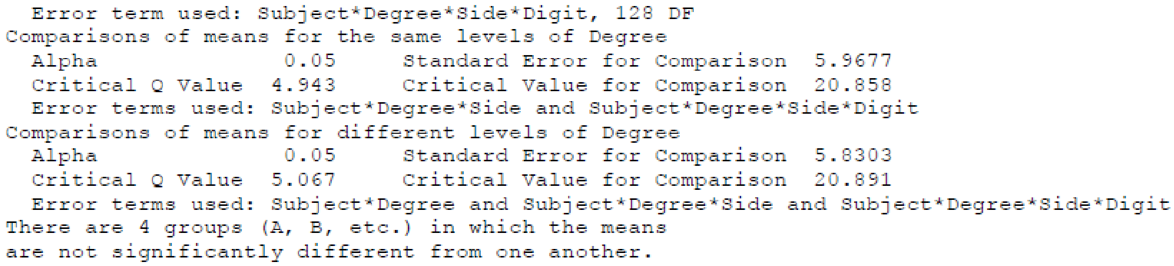

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  Error term used: Subject*Degree*Side*Digit, 128 DF
Comparisons of means for the same levels of Degree
  Alpha              0.05     Standard Error for Comparison  5.9677
  Critical Q Value  4.943     Critical Value for Comparison  20.858
  Error terms used: Subject*Degree*Side and Subject*Degree*Side*Digit
Comparisons of means for different levels of Degree
  Alpha              0.05     Standard Error for Comparison  5.8303
  Critical Q Value  5.067     Critical Value for Comparison  20.891
  Error terms used: Subject*Degree and Subject*Degree*Side and Subject*Degree*Side*Digit
There are 4 groups (A, B, etc.) in which the means
are not significantly different from one another.
```

Appendix Q: Results of Tukey HSD Tests for Females for Chapter 4 Study

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Tukey HSD All-Pairwise Comparisons Test of Force for Degree

Degree    Mean  Homogeneous Groups
     0  43.852  A
    90  37.852   B

Alpha              0.05     Standard Error for Comparison  1.4380
Critical Q Value  2.877     Critical Value for Comparison  2.9250
Error term used: Subject*Degree, 32 DF
All 2 means are significantly different from one another.

Tukey HSD All-Pairwise Comparisons Test of Force for Side

Side     Mean  Homogeneous Groups
Right  40.855  A
Left   40.849  A

Alpha              0.05     Standard Error for Comparison  0.9846
Critical Q Value  2.824     Critical Value for Comparison  1.9663
Error term used: Subject*Degree*Side, 64 DF
There are no significant pairwise differences among the means.

Tukey HSD All-Pairwise Comparisons Test of Force for Degree*Side

Degree Side     Mean  Homogeneous Groups
     0 Right  44.618  A
     0 Left   43.086  AB
    90 Left   38.612   BC
    90 Right  37.091    C

Comparisons of means for the same level of Degree
  Alpha              0.05     Standard Error for Comparison  1.3925
  Critical Q Value  3.731     Critical Value for Comparison  3.6736
  Error term used: Subject*Degree*Side, 64 DF
Comparisons of means for different levels of Degree
  Alpha              0.05     Standard Error for Comparison  1.7428
  Critical Q Value  3.800     Critical Value for Comparison  4.6830
  Error terms used: Subject*Degree and Subject*Degree*Side
There are 3 groups (A, B, etc.) in which the means
are not significantly different from one another.

Tukey HSD All-Pairwise Comparisons Test of Force for Digit

Digit     Mean  Homogeneous Groups
Thumb   43.407  A
Finger  38.297   B

Alpha              0.05     Standard Error for Comparison  1.0158
Critical Q Value  2.772     Critical Value for Comparison  1.9908
Error term used: Subject*Degree*Side*Digit, 128 DF
All 2 means are significantly different from one another.

Tukey HSD All-Pairwise Comparisons Test of Force for Degree*Digit

Degree Digit     Mean  Homogeneous Groups
     0 Thumb   46.738  A
     0 Finger  40.967   B
    90 Thumb   40.076   B
    90 Finger  35.627    C

Comparisons of means for the same level of Degree
  Alpha              0.05     Standard Error for Comparison  1.4365
```

```
  Critical Q Value  3.632     Critical Value for Comparison  3.6894
  Error term used: Subject*Degree*Side*Digit, 128 DF
Comparisons of means for different levels of Degree
  Alpha              0.05     Standard Error for Comparison  1.7606
  Critical Q Value  3.766     Critical Value for Comparison  4.6881
  Error terms used: Subject*Degree and Subject*Degree*Side*Digit
There are 3 groups (A, B, etc.) in which the means
are not significantly different from one another.
```

Tukey HSD All-Pairwise Comparisons Test of Force for Side*Digit

```
Side  Digit     Mean  Homogeneous Groups
Right Thumb   43.909  A
Left  Thumb   42.905  A
Left  Finger  38.794   B
Right Finger  37.800   B

Comparisons of means for the same level of Side
  Alpha              0.05     Standard Error for Comparison  1.4365
  Critical Q Value  3.632     Critical Value for Comparison  3.6894
  Error term used: Subject*Degree*Side*Digit, 128 DF
Comparisons of means for different levels of Side
  Alpha              0.05     Standard Error for Comparison  1.4146
  Critical Q Value  3.680     Critical Value for Comparison  3.6811
  Error terms used: Subject*Degree*Side and Subject*Degree*Side*Digit
There are 2 groups (A and B) in which the means
are not significantly different from one another.
```

Tukey HSD All-Pairwise Comparisons Test of Force for Degree*Side*Digit

```
Degree Side  Digit     Mean  Homogeneous Groups
     0 Right Thumb   47.970  A
     0 Left  Thumb   45.506  AB
     0 Right Finger  41.267   BC
     0 Left  Finger  40.667   BC
    90 Left  Thumb   40.303   BC
    90 Right Thumb   39.848   BC
    90 Left  Finger  36.921    C
    90 Right Finger  34.333    C

Comparisons of means for the same levels of Degree and Side
  Alpha              0.05     Standard Error for Comparison  2.0315
  Critical Q Value  4.285     Critical Value for Comparison  6.1555
  Error term used: Subject*Degree*Side*Digit, 128 DF
Comparisons of means for the same levels of Degree
  Alpha              0.05     Standard Error for Comparison  2.0006
  Critical Q Value  4.355     Critical Value for Comparison  6.1610
  Error terms used: Subject*Degree*Side and Subject*Degree*Side*Digit
Comparisons of means for different levels of Degree
  Alpha              0.05     Standard Error for Comparison  2.2585
  Critical Q Value  4.530     Critical Value for Comparison  7.2343
  Error terms used: Subject*Degree and Subject*Degree*Side and Subject*Degree*Side*Digit
There are 3 groups (A, B, etc.) in which the means
are not significantly different from one another.
```

Appendix R: Results of Tukey HSD Tests for Males for Chapter 4 Study

```
Statistix 9.0                                             2/9/2023, 10:35:01 PM

Tukey HSD All-Pairwise Comparisons Test of Force for Degree

Degree    Mean  Homogeneous Groups
     0  51.550  A
    90  46.637   B

Alpha              0.05     Standard Error for Comparison  2.0009
Critical Q Value  3.035     Critical Value for Comparison  4.2938
Error term used: Subject*Degree, 14 DF
All 2 means are significantly different from one another.

Tukey HSD All-Pairwise Comparisons Test of Force for Side

Side     Mean  Homogeneous Groups
Right  52.092  A
Left   46.095   B

Alpha              0.05     Standard Error for Comparison  1.8112
Critical Q Value  2.892     Critical Value for Comparison  3.7033
Error term used: Subject*Degree*Side, 28 DF
All 2 means are significantly different from one another.

Tukey HSD All-Pairwise Comparisons Test of Force for Degree*Side

Degree Side     Mean  Homogeneous Groups
     0 Right  53.563  A
    90 Right  50.620  A
     0 Left   49.537  AB
    90 Left   42.653   B

Comparisons of means for the same level of Degree
  Alpha              0.05     Standard Error for Comparison  2.5614
  Critical Q Value  3.862     Critical Value for Comparison  6.9955
  Error term used: Subject*Degree*Side, 28 DF
Comparisons of means for different levels of Degree
  Alpha              0.05     Standard Error for Comparison  2.6989
  Critical Q Value  3.999     Critical Value for Comparison  7.6319
  Error terms used: Subject*Degree and Subject*Degree*Side
There are 2 groups (A and B) in which the means
are not significantly different from one another.

Tukey HSD All-Pairwise Comparisons Test of Force for Digit

Digit     Mean  Homogeneous Groups
Thumb   54.015  A
Finger  44.172   B

Alpha              0.05     Standard Error for Comparison  1.7054
Critical Q Value  2.832     Critical Value for Comparison  3.4146
Error term used: Subject*Degree*Side*Digit, 56 DF
All 2 means are significantly different from one another.

Tukey HSD All-Pairwise Comparisons Test of Force for Degree*Digit

Degree Digit     Mean  Homogeneous Groups
     0 Thumb   57.330  A
    90 Thumb   50.700  AB
     0 Finger  45.770   BC
    90 Finger  42.573    C

Comparisons of means for the same level of Degree
  Alpha              0.05     Standard Error for Comparison  2.4117
```

```
  Critical Q Value  3.745     Critical Value for Comparison  6.3865
  Error term used: Subject*Degree*Side*Digit, 56 DF
Comparisons of means for different levels of Degree
  Alpha              0.05     Standard Error for Comparison  2.6290
  Critical Q Value  3.957     Critical Value for Comparison  7.3563
  Error terms used: Subject*Degree and Subject*Degree*Side*Digit
There are 3 groups (A, B, etc.) in which the means
are not significantly different from one another.
```

Tukey HSD All-Pairwise Comparisons Test of Force for Side*Digit

```
Side  Digit     Mean  Homogeneous Groups
Right Thumb   57.180  A
Left  Thumb   50.850  AB
Right Finger  47.003   BC
Left  Finger  41.340    C

Comparisons of means for the same level of Side
  Alpha              0.05     Standard Error for Comparison  2.4117
  Critical Q Value  3.745     Critical Value for Comparison  6.3865
  Error term used: Subject*Degree*Side*Digit, 56 DF
Comparisons of means for different levels of Side
  Alpha              0.05     Standard Error for Comparison  2.4877
  Critical Q Value  3.807     Critical Value for Comparison  6.6971
  Error terms used: Subject*Degree*Side and Subject*Degree*Side*Digit
There are 3 groups (A, B, etc.) in which the means
are not significantly different from one another.
```

Tukey HSD All-Pairwise Comparisons Test of Force for Degree*Side*Digit

```
Degree Side  Digit     Mean  Homogeneous Groups
     0 Right Thumb   59.973  A
     0 Left  Thumb   54.687  AB
    90 Right Thumb   54.387  AB
     0 Right Finger  47.153   BC
    90 Left  Thumb   47.013   BC
    90 Right Finger  46.853   BC
     0 Left  Finger  44.387   BC
    90 Left  Finger  38.293    C

Comparisons of means for the same levels of Degree and Side
  Alpha              0.05     Standard Error for Comparison  3.4107
  Critical Q Value  4.451     Critical Value for Comparison  10.735
  Error term used: Subject*Degree*Side*Digit, 56 DF
Comparisons of means for the same levels of Degree
  Alpha              0.05     Standard Error for Comparison  3.5181
  Critical Q Value  4.543     Critical Value for Comparison  11.302
  Error terms used: Subject*Degree*Side and Subject*Degree*Side*Digit
Comparisons of means for different levels of Degree
  Alpha              0.05     Standard Error for Comparison  3.6194
  Critical Q Value  4.821     Critical Value for Comparison  12.339
  Error terms used: Subject*Degree and Subject*Degree*Side and Subject*Degree*Side*Digit
There are 3 groups (A, B, etc.) in which the means
are not significantly different from one another.
```

Appendix S: Regression Equations for Regression Analysis in Chapter 3

Sex	Degree	Side	Digit		
F	0	Left	Finger	Force	= -85.2 + 5.73 BMI + 3.689 Age - 0.1511 BMI*Age
F	0	Left	Thumb	Force	= -68.3 + 5.73 BMI + 3.689 Age - 0.1511 BMI*Age
F	0	Right	Finger	Force	= -83.0 + 5.73 BMI + 3.689 Age - 0.1511 BMI*Age
F	0	Right	Thumb	Force	= -66.1 + 5.73 BMI + 3.689 Age - 0.1511 BMI*Age
F	90	Left	Finger	Force	= -91.3 + 5.73 BMI + 3.689 Age - 0.1511 BMI*Age
F	90	Left	Thumb	Force	= -91.3 + 5.73 BMI + 3.689 Age - 0.1511 BMI*Age
F	90	Right	Finger	Force	= -81.3 + 5.73 BMI + 3.689 Age - 0.1511 BMI*Age
F	90	Right	Thumb	Force	= -81.3 + 5.73 BMI + 3.689 Age - 0.1511 BMI*Age
F	180	Left	Finger	Force	= -88.4 + 5.73 BMI + 3.689 Age - 0.1511 BMI*Age
F	180	Left	Thumb	Force	= -81.8 + 5.73 BMI + 3.689 Age - 0.1511 BMI*Age
F	180	Right	Finger	Force	= -84.4 + 5.73 BMI + 3.689 Age - 0.1511 BMI*Age
F	180	Right	Thumb	Force	= -77.7 + 5.73 BMI + 3.689 Age - 0.1511 BMI*Age
F	270	Left	Finger	Force	= -86.3 + 5.73 BMI + 3.689 Age - 0.1511 BMI*Age
F	270	Left	Thumb	Force	= -81.7 + 5.73 BMI + 3.689 Age - 0.1511 BMI*Age
F	270	Right	Finger	Force	= -89.7 + 5.73 BMI + 3.689 Age - 0.1511 BMI*Age
F	270	Right	Thumb	Force	= -85.1 + 5.73 BMI + 3.689 Age - 0.1511 BMI*Age
M	0	Left	Finger	Force	= -2.6 + 5.73 BMI + 1.41 Age - 0.1511 BMI*Age
M	0	Left	Thumb	Force	= 21.7 + 5.73 BMI + 1.41 Age - 0.1511 BMI*Age
M	0	Right	Finger	Force	= -0.4 + 5.73 BMI + 1.41 Age - 0.1511 BMI*Age
M	0	Right	Thumb	Force	= 23.9 + 5.73 BMI + 1.41 Age - 0.1511 BMI*Age

M 90 Left Finger Force = -22.1 + 5.73 BMI + 1.41 Age - 0.1511 BMI*Age

M 90 Left Thumb Force = -14.7 + 5.73 BMI + 1.41 Age - 0.1511 BMI*Age

M 90 Right Finger Force = -12.1 + 5.73 BMI + 1.41 Age - 0.1511 BMI*Age

M 90 Right Thumb Force = -4.6 + 5.73 BMI + 1.41 Age - 0.1511 BMI*Age

M 180 Left Finger Force = -8.2 + 5.73 BMI + 1.41 Age - 0.1511 BMI*Age

M 180 Left Thumb Force = 5.9 + 5.73 BMI + 1.41 Age - 0.1511 BMI*Age

M 180 Right Finger Force = -4.1 + 5.73 BMI + 1.41 Age - 0.1511 BMI*Age

M 180 Right Thumb Force = 9.9 + 5.73 BMI + 1.41 Age - 0.1511 BMI*Age

M 270 Left Finger Force = -18.1 + 5.73 BMI + 1.41 Age - 0.1511 BMI*Age

M 270 Left Thumb Force = -6.0 + 5.73 BMI + 1.41 Age - 0.1511 BMI*Age

M 270 Right Finger Force = -21.5 + 5.73 BMI + 1.41 Age - 0.1511 BMI*Age

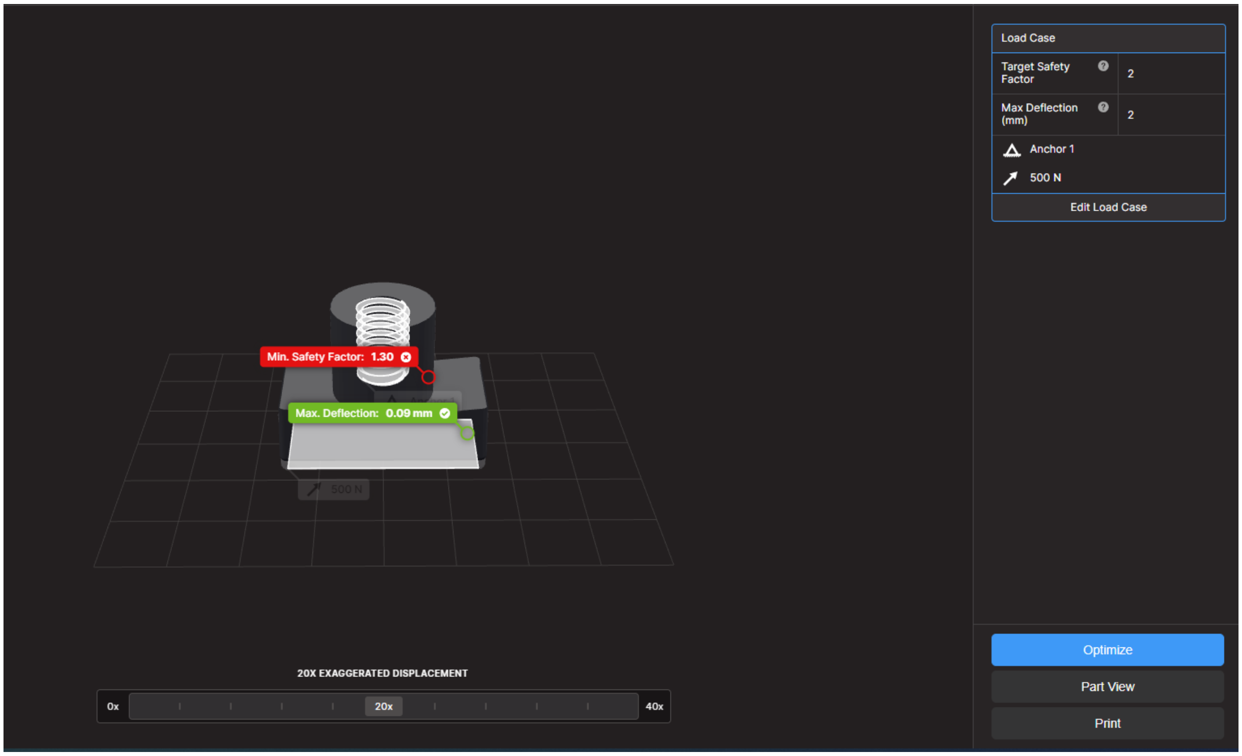
M 270 Right Thumb Force = -9.4 + 5.73 BMI + 1.41 Age - 0.1511 BMI*Age

Appendix T: Regression Equations for Regression Analysis in Chapter 4

Sex	Degree	Side	Digit		
F	0	Left	Finger	Force	= -90.4 + 15.3 Age - 13.7 Grade + 8.49 BMI + 1.29 Age*Grade - 1.32 Age*BMI + 1.41 Grade*BMI - 0.069 Age*Grade*BMI
F	0	Left	Thumb	Force	= -83.8 + 15.3 Age - 13.7 Grade + 8.49 BMI + 1.29 Age*Grade - 1.32 Age*BMI + 1.41 Grade*BMI - 0.069 Age*Grade*BMI
F	0	Right	Finger	Force	= -90.4 + 15.3 Age - 13.7 Grade + 8.49 BMI + 1.29 Age*Grade - 1.32 Age*BMI + 1.41 Grade*BMI - 0.069 Age*Grade*BMI
F	0	Right	Thumb	Force	= -83.8 + 15.3 Age - 13.7 Grade + 8.49 BMI + 1.29 Age*Grade - 1.32 Age*BMI + 1.41 Grade*BMI - 0.069 Age*Grade*BMI
F	90	Left	Finger	Force	= -96.1 + 15.3 Age - 13.7 Grade + 8.49 BMI + 1.29 Age*Grade - 1.32 Age*BMI + 1.41 Grade*BMI - 0.069 Age*Grade*BMI
F	90	Left	Thumb	Force	= -89.5 + 15.3 Age - 13.7 Grade + 8.49 BMI + 1.29 Age*Grade - 1.32 Age*BMI + 1.41 Grade*BMI - 0.069 Age*Grade*BMI
F	90	Right	Finger	Force	= -96.1 + 15.3 Age - 13.7 Grade + 8.49 BMI + 1.29 Age*Grade - 1.32 Age*BMI + 1.41 Grade*BMI - 0.069 Age*Grade*BMI
F	90	Right	Thumb	Force	= -89.5 + 15.3 Age - 13.7 Grade + 8.49 BMI + 1.29 Age*Grade - 1.32 Age*BMI + 1.41 Grade*BMI - 0.069 Age*Grade*BMI
M	0	Left	Finger	Force	= 748 - 108.6 Age - 152.8 Grade - 47.4 BMI + 22.87 Age*Grade + 7.08 Age*BMI + 9.22 Grade*BMI - 1.366 Age*Grade*BMI
M	0	Left	Thumb	Force	= 755 - 108.6 Age - 152.8 Grade - 47.4 BMI + 22.87 Age*Grade + 7.08 Age*BMI + 9.22 Grade*BMI - 1.366 Age*Grade*BMI

M	0	Right	Finger	Force	= 754 - 108.6 Age - 152.8 Grade - 47.4 BMI + 22.87 Age*Grade + 7.08 Age*BMI + 9.22 Grade*BMI - 1.366 Age*Grade*BMI
M	0	Right	Thumb	Force	= 761 - 108.6 Age - 152.8 Grade - 47.4 BMI + 22.87 Age*Grade + 7.08 Age*BMI + 9.22 Grade*BMI - 1.366 Age*Grade*BMI
M	90	Left	Finger	Force	= 742 - 108.6 Age - 152.8 Grade - 47.4 BMI + 22.87 Age*Grade + 7.08 Age*BMI + 9.22 Grade*BMI - 1.366 Age*Grade*BMI
M	90	Left	Thumb	Force	= 749 - 108.6 Age - 152.8 Grade - 47.4 BMI + 22.87 Age*Grade + 7.08 Age*BMI + 9.22 Grade*BMI - 1.366 Age*Grade*BMI
M	90	Right	Finger	Force	= 748 - 108.6 Age - 152.8 Grade - 47.4 BMI + 22.87 Age*Grade + 7.08 Age*BMI + 9.22 Grade*BMI - 1.366 Age*Grade*BMI
M	90	Right	Thumb	Force	= 755 - 108.6 Age - 152.8 Grade - 47.4 BMI + 22.87 Age*Grade + 7.08 Age*BMI + 9.22 Grade*BMI - 1.366 Age*Grade*BMI

Appendix U: Push Button Prototype Deformation Simulation Test



Load Case

Target Safety Factor	2
Max Deflection (mm)	2

Anchor 1

500 N

Min. Safety Factor: 1.30

Max. Deflection: 0.09 mm

Appendix V: Chapter 3 Phase Order

	Study 1	Study 2
Subject 1	Force	Unlatching
Subject 2	Force	Unlatching
Subject 3	Force	Unlatching
Subject 4	Unlatching	Force
Subject 5	Force	Unlatching
Subject 6	Force	Unlatching
Subject 7	Force	Unlatching
Subject 8	Force	Unlatching
Subject 9	Unlatching	Force
Subject 10	Unlatching	Force
Subject 11	Force	Unlatching
Subject 12	Unlatching	Force
Subject 13	Force	Unlatching
Subject 14	Force	Unlatching
Subject 15	Unlatching	Force
Subject 16	Force	Unlatching
Subject 17	Force	Unlatching
Subject 18	Unlatching	Force
Subject 19	Unlatching	Force
Subject 20	Force	Unlatching
Subject 21	Unlatching	Force
Subject 22	Unlatching	Force
Subject 23	Unlatching	Force
Subject 24	Unlatching	Force
Subject 25	Force	Unlatching
Subject 26	Unlatching	Force
Subject 27	Force	Unlatching
Subject 28	Unlatching	Force
Subject 29	Unlatching	Force
Subject 30	Force	Unlatching

	Study 1	Study 2
Subject 31	Force	Unlatching
Subject 32	Unlatching	Force
Subject 33	Force	Unlatching
Subject 34	Unlatching	Force
Subject 35	Unlatching	Force
Subject 36	Force	Unlatching
Subject 37	Force	Unlatching
Subject 38	Unlatching	Force
Subject 39	Force	Unlatching
Subject 40	Unlatching	Force
Subject 41	Unlatching	Force
Subject 42	Force	Unlatching
Subject 43	Unlatching	Force
Subject 44	Force	Unlatching
Subject 45	Force	Unlatching
Subject 46	Unlatching	Force
Subject 47	Force	Unlatching
Subject 48	Force	Unlatching
Subject 49	Force	Unlatching
Subject 50	Force	Unlatching
Subject 51	Unlatching	Force
Subject 52	Force	Unlatching
Subject 53	Unlatching	Force
Subject 54	Force	Unlatching
Subject 55	Force	Unlatching
Subject 56	Unlatching	Force
Subject 57	Force	Unlatching
Subject 58	Force	Unlatching
Subject 59	Unlatching	Force
Subject 60	Force	Unlatching

Appendix W: Chapter 3 Force Exertion Trial Order

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8	Trial 9	Trial 10	Trial 11	Trial 12	Trial 13	Trial 14	Trial 15	Trial 16
Subject 1	180LT	180LF	180RT	180RF	0LF	0LT	0RF	0RT	90RT	90RF	90LF	90LT	270RT	270RF	270LT	270LF
Subject 2	270RF	270RT	270LT	270LF	180RT	180RF	180LT	180LF	90LF	90LT	90RF	90RT	0RT	0RF	0LT	0LF
Subject 3	90RF	90RT	90LT	90LF	270LT	270LF	270RT	270RF	0RF	0RT	0LT	0LF	180LF	180LT	180RF	180RT
Subject 4	0RF	0RT	0LT	0LF	180RT	180RF	180LT	180LF	270RF	270RT	270LT	270LF	90LF	90LT	90RF	90RT
Subject 5	0LT	0LF	0RF	0RT	180RF	180RT	180LT	180LF	90LF	90LT	90RT	90RF	270RF	270RT	270LT	270LF
Subject 6	180RT	180RF	180LF	180LT	270LF	270LT	270RF	270RT	90RF	90RT	90LF	90LT	0RT	0RF	0LT	0LF
Subject 7	180RF	180RT	180LT	180LF	90RT	90RF	90LT	90LF	270RT	270RF	270LF	270LT	0RF	0RT	0LT	0LF
Subject 8	0LF	0LT	0RF	0RT	180LT	180LF	180RT	180RF	90RF	90RT	90LF	90LT	270LF	270LT	270RT	270RF
Subject 9	270RF	270RT	270LT	270LF	0RT	0RF	0LF	0LT	90LT	90LF	90RT	90RF	180LT	180LF	180RT	180RF
Subject 10	0RF	0RT	0LT	0LF	90LT	90LF	90RT	90RF	270RT	270RF	270LF	270LT	180RT	180RF	180LT	180LF
Subject 11	180LT	180LF	180RT	180RF	90LT	90LF	90RT	90RF	270RT	270RF	270LT	270LF	0RF	0RT	0LF	0LT
Subject 12	180LF	180LT	180RF	180RT	90RT	90RF	90LT	90LF	0RF	0RT	0LT	0LF	270LF	270LT	270RT	270RF
Subject 13	90RT	90RF	90LF	90LT	180LF	180LT	180RF	180RT	270LF	270LT	270RT	270RF	0LF	0LT	0RT	0RF
Subject 14	0LT	0LF	0RF	0RT	270LT	270LF	270RF	270RT	180LT	180LF	180RT	180RF	90RT	90RF	90LF	90LT
Subject 15	270LF	270LT	270RF	270RT	180LF	180LT	180RF	180RT	90RT	90RF	90LF	90LT	0RF	0RT	0LT	0LF
Subject 16	0RT	0RF	0LT	0LF	270RT	270RF	270LT	270LF	90RT	90RF	90LT	90LF	180LT	180LF	180RF	180RT
Subject 17	0RT	0RF	0LT	0LF	270RT	270RF	270LT	270LF	90LT	90LF	90RF	90RT	180LT	180LF	180RT	180RF
Subject 18	90LT	90LF	90RF	90RT	0LF	0LT	0RT	0RF	270LT	270LF	270RT	270RF	180LT	180LF	180RT	180RF
Subject 19	90LF	90LT	90RF	90RT	180RF	180RT	180LT	180LF	270LF	270LT	270RT	270RF	0LT	0LF	0RT	0RF
Subject 20	0RF	0RT	0LF	0LT	270RF	270RT	270LF	270LT	90RT	90RF	90LF	90LT	180LT	180LF	180RT	180RF
Subject 21	180LT	180LF	180RF	180RT	0RT	0RF	0LF	0LT	90RT	90RF	90LT	90LF	270LF	270LT	270RF	270RT
Subject 22	180RF	180RT	180LF	180LT	270RF	270RT	270LF	270LT	0RT	0RF	0LT	0LF	90RF	90RT	90LT	90LF

Subject 23	90LF	90LT	90RF	90RT	0RT	0RF	0LT	0LF	180RF	180RT	180LT	180LF	270RT	270RF	270LF	270LT
Subject 24	90LF	90LT	90RF	90RT	270RF	270RT	270LF	270LT	0LF	0LT	0RT	0RF	180LT	180LF	180RT	180RF
Subject 25	180RT	180RF	180LF	180LT	0RT	0RF	0LF	0LT	270RT	270RF	270LT	270LF	90RF	90RT	90LT	90LF
Subject 26	180LF	180LT	180RT	180RF	0LT	0LF	0RF	0RT	90LF	90LT	90RF	90RT	270LF	270LT	270RT	270RF
Subject 27	270LT	270LF	270RF	270RT	90LF	90LT	90RT	90RF	0RF	0RT	0LF	0LT	180RF	180RT	180LF	180LT
Subject 28	0RF	0RT	0LF	0LT	90LF	90LT	90RF	90RT	270RT	270RF	270LT	270LF	180LF	180LT	180RF	180RT
Subject 29	180LT	180LF	180RT	180RF	90RT	90RF	90LF	90LT	0LF	0LT	0RT	0RF	270LF	270LT	270RF	270RT
Subject 30	180RT	180RF	180LT	180LF	0LF	0LT	0RT	0RF	90LT	90LF	90RT	90RF	270RF	270RT	270LF	270LT
Subject 31	180RF	180RT	180LT	180LF	0LT	0LF	0RF	0RT	90LF	90LT	90RF	90RT	270LF	270LT	270RF	270RT
Subject 32	270RF	270RT	270LT	270LF	180LT	180LF	180RT	180RF	0LT	0LF	0RT	0RF	90LT	90LF	90RF	90RT
Subject 33	90RT	90RF	90LF	90LT	270LF	270LT	270RT	270RF	180LF	180LT	180RF	180RT	0RF	0RT	0LF	0LT
Subject 34	270LF	270LT	270RT	270RF	90LF	90LT	90RF	90RT	0RF	0RT	0LF	0LT	180RT	180RF	180LF	180LT
Subject 35	270LT	270LF	270RT	270RF	0LF	0LT	0RF	0RT	90LT	90LF	90RF	90RT	180LT	180LF	180RT	180RF
Subject 36	90RF	90RT	90LT	90LF	180LF	180LT	180RT	180RF	270LT	270LF	270RF	270RT	0LF	0LT	0RF	0RT
Subject 37	180LT	180LF	180RT	180RF	0LF	0LT	0RT	0RF	90LF	90LT	90RT	90RF	270LF	270LT	270RT	270RF
Subject 38	270LT	270LF	270RT	270RF	180LF	180LT	180RF	180RT	0LT	0LF	0RT	0RF	90LF	90LT	90RF	90RT
Subject 39	90LT	90LF	90RF	90RT	0LT	0LF	0RT	0RF	180LT	180LF	180RF	180RT	270LT	270LF	270RT	270RF
Subject 40	180RF	180RT	180LF	180LT	270RT	270RF	270LT	270LF	0RT	0RF	0LF	0LT	90LF	90LT	90RF	90RT
Subject 41	90RT	90RF	90LT	90LF	0LT	0LF	0RF	0RT	270LT	270LF	270RT	270RF	180RF	180RT	180LF	180LT
Subject 42	90LF	90LT	90RF	90RT	270LF	270LT	270RT	270RF	0LT	0LF	0RF	0RT	180RF	180RT	180LF	180LT
Subject 43	180RF	180RT	180LT	180LF	90RF	90RT	90LF	90LT	270LF	270LT	270RT	270RF	0LT	0LF	0RF	0RT
Subject 44	180RT	180RF	180LF	180LT	90LF	90LT	90RF	90RT	0LT	0LF	0RF	0RT	270LT	270LF	270RF	270RT
Subject 45	180RT	180RF	180LT	180LF	90RT	90RF	90LF	90LT	270LF	270LT	270RF	270RT	0LT	0LF	0RT	0RF
Subject 46	270LF	270LT	270RF	270RT	180RF	180RT	180LF	180LT	0RF	0RT	0LT	0LF	90LT	90LF	90RF	90RT
Subject 47	270RT	270RF	270LF	270LT	0RT	0RF	0LF	0LT	90LT	90LF	90RF	90RT	180RT	180RF	180LT	180LF
Subject 48	270LF	270LT	270RT	270RF	180RT	180RF	180LF	180LT	90LT	90LF	90RT	90RF	0LF	0LT	0RF	0RT
Subject 49	270LT	270LF	270RF	270RT	0RF	0RT	0LT	0LF	90RT	90RF	90LF	90LT	180LT	180LF	180RF	180RT
Subject 50	270LF	270LT	270RT	270RF	0LT	0LF	0RT	0RF	180RF	180RT	180LF	180LT	90LF	90LT	90RF	90RT

Subject 51	180RT	180RF	180LF	180LT	270LF	270LT	270RT	270RF	0LT	0LF	0RT	0RF	90RF	90RT	90LT	90LF
Subject 52	180LT	180LF	180RF	180RT	90RT	90RF	90LT	90LF	270RF	270RT	270LT	270LF	0LT	0LF	0RT	0RF
Subject 53	180RF	180RT	180LF	180LT	270RF	270RT	270LF	270LT	0RF	0RT	0LT	0LF	90LT	90LF	90RF	90RT
Subject 54	0LF	0LT	0RF	0RT	90LF	90LT	90RT	90RF	180RT	180RF	180LT	180LF	270LT	270LF	270RT	270RF
Subject 55	0LT	0LF	0RT	0RF	90LF	90LT	90RT	90RF	270LT	270LF	270RF	270RT	180RT	180RF	180LT	180LF
Subject 56	270LF	270LT	270RF	270RT	90LF	90LT	90RT	90RF	0RF	0RT	0LT	0LF	180LT	180LF	180RF	180RT
Subject 57	180RF	180RT	180LF	180LT	270RF	270RT	270LF	270LT	0LF	0LT	0RF	0RT	90LF	90LT	90RT	90RF
Subject 58	90LT	90LF	90RF	90RT	180LF	180LT	180RT	180RF	270RT	270RF	270LF	270LT	0LT	0LF	0RT	0RF
Subject 59	180RF	180RT	180LF	180LT	270LT	270LF	270RT	270RF	90LT	90LF	90RF	90RT	0LT	0LF	0RF	0RT
Subject 60	270RF	270RT	270LF	270LT	0RF	0RT	0LF	0LT	180LF	180LT	180RT	180RF	90RF	90RT	90LT	90LF

Appendix X: Chapter 3 Unlatching Trial Order

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
Subject 1	180 R	90 L	180 L	270 R	270 L	90 R
Subject 2	270 L	90 L	90 R	180 L	270 R	180 R
Subject 3	180 R	90 L	90 R	270 L	270 R	180 L
Subject 4	270 L	90 R	90 L	180 L	180 R	270 R
Subject 5	90 R	90 L	270 R	180 R	270 L	180 L
Subject 6	90 R	180 L	90 L	270 R	270 L	180 R
Subject 7	270 R	180 R	90 R	90 L	270 L	180 L
Subject 8	180 R	90 L	90 R	270 L	270 R	180 L
Subject 9	180 R	270 L	270 R	180 L	90 R	90 L
Subject 10	90 R	270 L	270 R	90 L	180 R	180 L
Subject 11	90 R	270 R	180 R	90 L	270 L	180 L
Subject 12	270 L	270 R	180 R	90 R	180 L	90 L
Subject 13	180 R	180 L	270 R	270 L	90 L	90 R
Subject 14	270 R	180 L	270 L	90 R	90 L	180 R
Subject 15	90 L	270 R	180 R	90 R	270 L	180 L
Subject 16	270 L	270 R	90 L	180 R	90 R	180 L
Subject 17	90 R	180 R	270 R	270 L	180 L	90 L
Subject 18	270 R	90 R	90 L	180 L	270 L	180 R
Subject 19	90 L	90 R	180 L	270 L	270 R	180 R
Subject 20	180 R	270 R	90 L	180 L	90 R	270 L
Subject 21	180 L	90 R	270 R	270 L	90 L	180 R
Subject 22	180 R	270 R	90 R	180 L	90 L	270 L
Subject 23	270 R	180 R	180 L	90 R	90 L	270 L
Subject 24	180 L	180 R	270 R	270 L	90 L	90 R
Subject 25	180 R	90 R	180 L	270 R	90 L	270 L
Subject 26	270 L	270 R	90 R	90 L	180 L	180 R
Subject 27	90 L	180 R	270 R	90 R	180 L	270 L
Subject 28	90 R	270 R	180 L	270 L	180 R	90 L
Subject 29	270 L	180 R	90 L	270 R	180 L	90 R
Subject 30	270 R	270 L	180 L	90 R	90 L	180 R

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
Subject 31	90 L	180 L	270 L	270 R	180 R	90 R
Subject 32	180 R	270 R	90 L	180 L	270 L	90 R
Subject 33	90 L	180 L	90 R	270 R	270 L	180 R
Subject 34	270 L	180 L	90 L	180 R	270 R	90 R
Subject 35	180 L	90 R	270 R	270 L	180 R	90 L
Subject 36	180 R	90 R	90 L	270 R	180 L	270 L
Subject 37	270 L	180 R	90 L	90 R	270 R	180 L
Subject 38	90 L	270 R	270 L	180 L	90 R	180 R
Subject 39	270 R	270 L	180 L	90 R	90 L	180 R
Subject 40	90 L	270 L	180 R	90 R	180 L	270 R
Subject 41	90 R	90 L	270 L	180 L	270 R	180 R
Subject 42	90 L	270 R	270 L	180 R	90 R	180 L
Subject 43	90 R	270 L	90 L	180 L	180 R	270 R
Subject 44	90 L	270 L	180 R	180 L	270 R	90 R
Subject 45	180 L	180 R	90 L	270 L	90 R	270 R
Subject 46	90 R	270 R	90 L	180 L	270 L	180 R
Subject 47	180 L	180 R	90 R	90 L	270 L	270 R
Subject 48	270 L	90 R	90 L	270 R	180 R	180 L
Subject 49	90 R	180 R	270 R	270 L	180 L	90 L
Subject 50	270 R	90 R	180 R	270 L	90 L	180 L
Subject 51	180 R	270 R	180 L	90 R	90 L	270 L
Subject 52	90 R	270 L	90 L	270 R	180 L	180 R
Subject 53	90 R	180 L	180 R	270 R	270 L	90 L
Subject 54	270 R	90 L	270 L	180 L	90 R	180 R
Subject 55	270 L	90 L	90 R	180 R	270 R	180 L
Subject 56	90 R	180 L	270 L	90 L	270 R	180 R
Subject 57	270 R	90 L	180 L	90 R	180 R	270 L
Subject 58	270 R	90 R	180 R	270 L	90 L	180 L
Subject 59	180 L	270 R	270 L	90 R	180 R	90 L
Subject 60	180 L	90 L	180 R	90 R	270 L	

Appendix Y: Chapter 4 Phase Order

Force Exertion or Unlatching

	Study 1	Study 2		Study 1	Study 2
Subject 1	Force	Unlatching	Subject 31	Force	Unlatching
Subject 2	Force	Unlatching	Subject 32	Force	Unlatching
Subject 3	Unlatching	Force	Subject 33	Force	Unlatching
Subject 4	Force	Unlatching	Subject 34	Force	Unlatching
Subject 5	Unlatching	Force	Subject 35	Unlatching	Force
Subject 6	Unlatching	Force	Subject 36	Unlatching	Force
Subject 7	Unlatching	Force	Subject 37	Force	Unlatching
Subject 8	Unlatching	Force	Subject 38	Unlatching	Force
Subject 9	Force	Unlatching	Subject 39	Force	Unlatching
Subject 10	Unlatching	Force	Subject 40	Force	Unlatching
Subject 11	Unlatching	Force	Subject 41	Unlatching	Force
Subject 12	Unlatching	Force	Subject 42	Force	Unlatching
Subject 13	Force	Unlatching	Subject 43	Force	Unlatching
Subject 14	Unlatching	Force	Subject 44	Unlatching	Force
Subject 15	Unlatching	Force	Subject 45	Force	Unlatching
Subject 16	Unlatching	Force	Subject 46	Unlatching	Force
Subject 17	Unlatching	Force	Subject 47	Unlatching	Force
Subject 18	Force	Unlatching	Subject 48	Unlatching	Force
Subject 19	Unlatching	Force	Subject 49	Unlatching	Force
Subject 20	Unlatching	Force	Subject 50	Force	Unlatching
Subject 21	Unlatching	Force	Subject 51	Unlatching	Force
Subject 22	Force	Unlatching	Subject 52	Unlatching	Force
Subject 23	Force	Unlatching	Subject 53	Force	Unlatching
Subject 24	Unlatching	Force	Subject 54	Force	Unlatching
Subject 25	Unlatching	Force	Subject 55	Unlatching	Force
Subject 26	Force	Unlatching	Subject 56	Force	Unlatching
Subject 27	Unlatching	Force	Subject 57	Force	Unlatching
Subject 28	Unlatching	Force	Subject 58	Unlatching	Force
Subject 29	Unlatching	Force	Subject 59	Force	Unlatching
Subject 30	Unlatching	Force	Subject 60	Force	Unlatching

Appendix Z: Chapter 4 Force Exertion Trial Order

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8
Subject 1	0LF	0LT	0RT	0RF	90LF	90LT	90RT	90RF
Subject 2	0RF	0RT	0LT	0LF	90LT	90LF	90RF	90RT
Subject 3	0LF	0LT	0RT	0RF	90LF	90LT	90RT	90RF
Subject 4	90RF	90RT	90LF	90LT	0RT	0RF	0LT	0LF
Subject 5	90RT	90RF	90LF	90LT	0RF	0RT	0LT	0LF
Subject 6	0LF	0LT	0RF	0RT	90RT	90RF	90LT	90LF
Subject 7	0LT	0LF	0RT	0RF	90RF	90RT	90LF	90LT
Subject 8	90RF	90RT	90LF	90LT	0LT	0LF	0RF	0RT
Subject 9	0LF	0LT	0RT	0RF	90LF	90LT	90RT	90RF
Subject 10	90LF	90LT	90RF	90RT	0LF	0LT	0RT	0RF
Subject 11	90RT	90RF	90LF	90LT	0RT	0RF	0LF	0LT
Subject 12	0RF	0RT	0LT	0LF	90LF	90LT	90RF	90RT
Subject 13	0RF	0RT	0LF	0LT	90RF	90RT	90LF	90LT
Subject 14	0LT	0LF	0RT	0RF	90LF	90LT	90RT	90RF
Subject 15	0LF	0LT	0RF	0RT	90RT	90RF	90LT	90LF
Subject 16	0LF	0LT	0RT	0RF	90LF	90LT	90RF	90RT
Subject 17	0RT	0RF	0LT	0LF	90RF	90RT	90LF	90LT
Subject 18	0LT	0LF	0RF	0RT	90RF	90RT	90LT	90LF
Subject 19	0RF	0RT	0LT	0LF	90RT	90RF	90LT	90LF
Subject 20	0LT	0LF	0RT	0RF	90RT	90RF	90LF	90LT
Subject 21	90RT	90RF	90LT	90LF	0RF	0RT	0LF	0LT
Subject 22	0LF	0LT	0RF	0RT	90RF	90RT	90LT	90LF
Subject 23	90LF	90LT	90RF	90RT	0LT	0LF	0RT	0RF
Subject 24	90LT	90LF	90RT	90RF	0LT	0LF	0RT	0RF
Subject 25	90LT	90LF	90RF	90RT	0LT	0LF	0RT	0RF
Subject 26	0LF	0LT	0RF	0RT	90RF	90RT	90LT	90LF
Subject 27	0LT	0LF	0RF	0RT	90RF	90RT	90LT	90LF
Subject 28	0RF	0RT	0LF	0LT	90RF	90RT	90LF	90LT
Subject 29	0LT	0LF	0RF	0RT	90LF	90LT	90RF	90RT
Subject 30	0LT	0LF	0RF	0RT	90LT	90LF	90RT	90RF
Subject 31	90RF	90RT	90LF	90LT	0RF	0RT	0LF	0LT
Subject 32	0LT	0LF	0RT	0RF	90RT	90RF	90LT	90LF
Subject 33	90LT	90LF	90RT	90RF	0LF	0LT	0RF	0RT
Subject 34	90RF	90RT	90LT	90LF	0LF	0LT	0RT	0RF
Subject 35	90LT	90LF	90RF	90RT	0RT	0RF	0LT	0LF
Subject 36	0LF	0LT	0RT	0RF	90RT	90RF	90LF	90LT
Subject 37	90LF	90LT	90RT	90RF	0LT	0LF	0RT	0RF

Subject 38	90LF	90LT	90RT	90RF	0LT	0LF	0RT	0RF
Subject 39	0LF	0LT	0RT	0RF	90LT	90LF	90RF	90RT
Subject 40	0LT	0LF	0RT	0RF	90RF	90RT	90LF	90LT
Subject 41	90RT	90RF	90LT	90LF	0LT	0LF	0RT	0RF
Subject 42	0RF	0RT	0LT	0LF	90RT	90RF	90LT	90LF
Subject 43	90LT	90LF	90RT	90RF	0RT	0RF	0LT	0LF
Subject 44	90LT	90LF	90RT	90RF	0RT	0RF	0LT	0LF
Subject 45	90RT	90RF	90LT	90LF	0RT	0RF	0LT	0LF
Subject 46	0LF	0LT	0RF	0RT	90RF	90RT	90LT	90LF
Subject 47	0RF	0RT	0LT	0LF	90LT	90LF	90RF	90RT
Subject 48	90LT	90LF	90RT	90RF	0LT	0LF	0RF	0RT
Subject 49	0RF	0RT	0LF	0LT	90RT	90RF	90LT	90LF
Subject 50	90LF	90LT	90RT	90RF	0LT	0LF	0RT	0RF
Subject 51	0RF	0RT	0LF	0LT	90RT	90RF	90LT	90LF
Subject 52	0LT	0LF	0RF	0RT	90RF	90RT	90LT	90LF
Subject 53	90LF	90LT	90RF	90RT	0RT	0RF	0LF	0LT
Subject 54	0LT	0LF	0RF	0RT	90LT	90LF	90RT	90RF
Subject 55	0RT	0RF	0LF	0LT	90LF	90LT	90RT	90RF
Subject 56	90RT	90RF	90LT	90LF	0LF	0LT	0RT	0RF
Subject 57	0LF	0LT	0RT	0RF	90RT	90RF	90LF	90LT
Subject 58	0RT	0RF	0LF	0LT	90RF	90RT	90LT	90LF
Subject 59	90LF	90LT	90RF	90RT	0RF	0RT	0LT	0LF
Subject 60	90RT	90RF	90LT	90LF	0LF	0LT	0RT	0RF

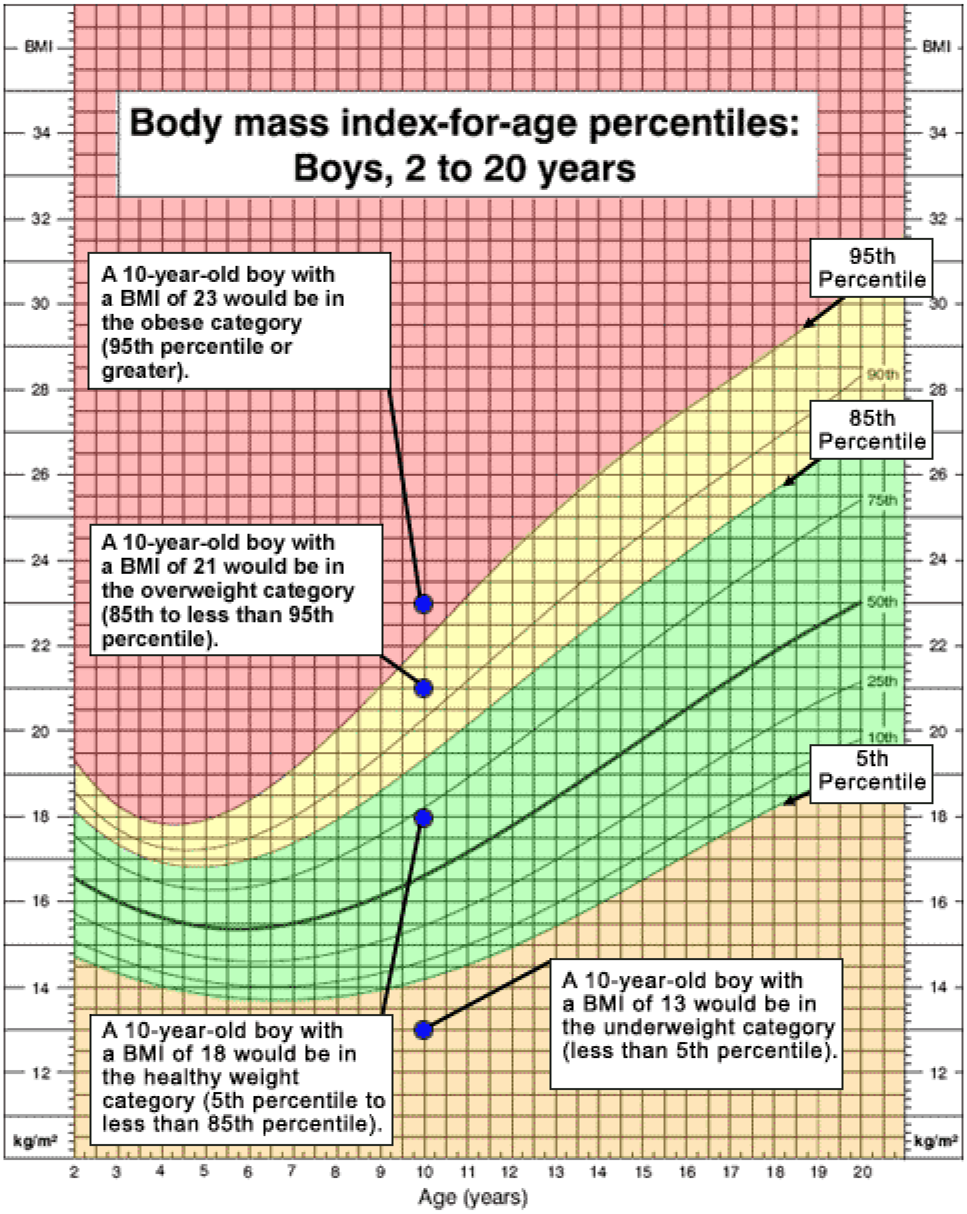
Appendix AA: Chapter 4 Unlatching Trial Order

	Trial 1	Trial 2	Trial 3	Trial 4
Subject 1	90R	0R	0L	90L
Subject 2	0R	0L	90L	90R
Subject 3	0R	90R	0L	90L
Subject 4	0L	0R	90L	90R
Subject 5	90R	0R	90L	0L
Subject 6	90L	0L	90R	0R
Subject 7	90R	0R	90L	0L
Subject 8	90L	0L	90R	0R
Subject 9	0L	0R	90R	90L
Subject 10	0R	90L	0L	90R
Subject 11	0R	90L	90R	0L
Subject 12	0R	0L	90R	90L
Subject 13	0L	90L	90R	0R
Subject 14	90L	0L	90R	0R
Subject 15	90L	0L	90R	0R
Subject 16	90L	0L	0R	90R
Subject 17	0L	90R	90L	0R
Subject 18	90R	90L	0R	0L
Subject 19	90R	0L	90L	0R
Subject 20	90R	0L	0R	90L
Subject 21	0L	0R	90L	90R
Subject 22	0L	0R	90L	90R
Subject 23	90L	0R	0L	90R
Subject 24	90R	0R	0L	90L
Subject 25	0L	90L	0R	90R
Subject 26	90R	90L	0R	0L
Subject 27	0L	90R	0R	90L
Subject 28	90L	90R	0R	0L
Subject 29	90L	0L	90R	0R
Subject 30	0L	0R	90L	90R

	Trial 1	Trial 2	Trial 3	Trial 4
Subject 31	0R	90L	90R	0L
Subject 32	0R	90L	0L	90R
Subject 33	90L	0L	0R	90R
Subject 34	90L	90R	0L	0R
Subject 35	90L	90R	0R	0L
Subject 36	0L	90L	0R	90R
Subject 37	90L	0L	0R	90R
Subject 38	0L	90R	0R	90L
Subject 39	90L	0R	90R	0L
Subject 40	0L	90L	90R	0R
Subject 41	0L	90R	90L	0R
Subject 42	90R	90L	0L	0R
Subject 43	0L	90L	0R	90R
Subject 44	0L	90R	90L	0R
Subject 45	90R	90L	0L	0R
Subject 46	0L	90L	90R	0R
Subject 47	0L	0R	90R	90L
Subject 48	0L	90L	0R	90R
Subject 49	90L	0L	90R	0R
Subject 50	90L	0R	0L	90R
Subject 51	90L	0L	90R	0R
Subject 52	0L	90L	90R	0R
Subject 53	90R	0L	0R	90L
Subject 54	0R	0L	90L	90R
Subject 55	90L	0R	90R	0L
Subject 56	0L	90L	90R	0R
Subject 57	0R	90R	90L	0L
Subject 58	90L	0L	90R	0R
Subject 59	90R	90L	0R	0L
Subject 60	0R	0L	90R	90L

Appendix AB: CDC BMI-for-age Growth Chart

Following is an example for the interpretation of BMI for a 10-year-old boy using the CDC's BMI-for-age growth chart for boys 2-20 years [210], [211].



A 10-year-old boy with a BMI of 23 would be in the obese category (95th percentile or greater).

A 10-year-old boy with a BMI of 21 would be in the overweight category (85th to less than 95th percentile).

A 10-year-old boy with a BMI of 18 would be in the healthy weight category (5th percentile to less than 85th percentile).

A 10-year-old boy with a BMI of 13 would be in the underweight category (less than 5th percentile).

Appendix AC: Permission to Reprint Images

The following table describes the details of documentation related to the Permission to Reprint (PTR) images on this Dissertation. For this section, here is a list of abbreviations:

CCC	Copyright Clearance Center
CDC	Centers for Disease Control and Prevention
Euro NCAP	European New Car Assessment Programme
FARS	Fatality Analysis Reporting System
FMVSS	Federal Motor Vehicle Safety Standards
IEEE	Institute of Electrical and Electronics Engineers
NCAP	New Car Assessment Program
NCSA	National Center for Statistics and Analysis
NCSL	National Conference of State Legislatures
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers

Figure	Page No.	PTR Documentation	Source Organization
Chapter 2			
Figure 2.1: First Patented Seat Belt by Edward J Claghorn in 1885 [33]	7	Patent in Public Domain	Historygarage.com
Figure 2.2: Seat Belt Used in the 1907 Thomas Flyer [34]	8	Creative Commons Attribution 2.0 Generic License	Wikimedia.org
Figure 2.3: Nils Bohlin: Inventor of the Original Seat Belts in 1959 [35]	8	Permission received via E-Mail	Volvo cars
Figure 2.4: FMVSS Related to Seat Belt Assemblies	9	Self-Created	
Figure 2.5: Adult Seat Belt Laws in the U.S. [37]	11	Permission received via E-Mail	NCSL
Figure 2.6: National Seat Belt Use Rate (Data Source: [14])	13	Self-Created	NCSA - NHTSA (Data)
Figure 2.7: Fatal Work Injuries in U.S.by Major Event or Exposure, 2016-19 [52]	16	Government Document	Bureau of Labor Statistics - US Department of Labor
Figure 2.8: Motor Vehicle Crash Deaths vs Population MVC Death Rates from 1915 – 2020 in the U.S. (Data Source: [8])	17	Self-Created	NHTSA (Data)
Figure 2.9: Passenger Vehicles Involved in Fatal Crashes [61]	19	Government Document	NHTSA
Figure 2.10: SUV Occupant Fatalities by Crash Type [61]	21	Government Document	NHTSA
Figure 2.11: Light Trucks Involved in Fatal Rollover Crashes [61]	21	Government Document	NHTSA
Figure 2.12: Vehicle Sales (in Thousands) in the U.S. (Data Source: [69])	22	Self-Created	Bureau of Labor Statistics - US Department of Labor (Data)
Figure 2.13: NHTSA Star Rating vs Roll Over Risk vs SSF (Data Source: [72])	23	Self-Created	
Figure 2.14: Weighted Average of SSF for MY 1975-2013 (Data Source: [71], [73])	24	Self-Created	NHTSA (Data)
Figure 2.15: Percentage Rollover Occurrence by Vehicle Type and Crash Severity [16]	25	Government Document	NCSA - NHTSA
Figure 2.16: Passenger Vehicle Occupants in Fatal Crashes by Injury Severity and Ejection Status [74]	26	Government Document	NHTSA
Figure 2.17: Passenger Vehicle Occupants in Fatal Crashes by Injury Status and Restraint Use [74]	27	Government Document	NHTSA
Figure 2.18: Injury Risk as a Function of Seat Belt Use for All Occupants [75]	28	Permission License Letter	Elsevier License
Figure 2.19: Injury Risk to Belted Occupants in a Rollover [75]	28	Permission License Letter	Elsevier License
Figure 2.20: Injury Distribution (AIS≥2) for PV Occupants in Side and Front Impact Collision [66]	29	Permission License Letter	Elsevier License
Figure 2.21: Occupant Fatality Percent by Restraint Use for Passenger Cars and Light Trucks:1990-2018 (Data Source: [16])	30	Self-Created	NCSA - NHTSA (Data)
Figure 2.22: End-Release Push-Button Buckles	33	Educational License	Adobe Stock Photos
Figure 2.23: Illustration of Seat Belt Release Force [80]	35	Permission Acquired - CCC Marketplace	SAE
Figure 2.24: Distribution of Maximum Exerted Force Using Side and Top-Release Buckles [63]	36	Permission Acquired - CCC Marketplace	SAE
Figure 2.25: Cumulative Force Distribution for Males and Females Using Top-Release Buckles [63]	37	Permission Acquired - CCC Marketplace	SAE
Figure 2.26: Average Buckle Release Forces for Different Seat Belt Buckles [94]	38	Permission Statement	IEEE

Figure 2.27: Push-Button Force Release Data and FMVSS and EU Requirements [80]	39	Permission Acquired - CCC Marketplace	SAE
Figure 2.28: Rollover Test Rig Setup for the Hare et al., Study [93]	40	Permission Acquired - CCC Marketplace	SAE
Figure 2.29: Shoulder Belt Loads for Driver vs Roll Angle for Non-Pretensioner Tests [93]	41	Permission Acquired - CCC Marketplace	SAE
Figure 2.30: Shoulder Belt Loads for Right Front Passenger vs Roll Angle for Non-Pretensioner Tests [93]	41	Permission Acquired - CCC Marketplace	SAE
Figure 2.31: 1984 Chevrolet S-10 Blazer on the Rollover Dolly [91]	42	Permission Acquired - CCC Marketplace	SAE
Figure 2.32: Left Front Lap Belt Tension vs Position of Vehicle Rear View [91]	43	Permission Acquired - CCC Marketplace	SAE
Figure 2.33: Right Front Lap Belt Tension vs Position of Vehicle Front View [91]	43	Permission Acquired - CCC Marketplace	SAE
Figure 2.34: Dynamic Rollover Component Test System used by McCoy and Chou [95]	44	Permission Acquired - CCC Marketplace	SAE
Figure 2.35: Prevalence of Age Adjusted Obesity and Severe Obesity Among Adults Aged 20 and Over in the U.S. [106]	47	Government Document	CDC.gov
Figure 2.36: MVC Fatality Distribution Considering Miles Traveled and Population: Urban vs Rural 2018 [55]	58	Government Document	NHTSA
Figure 2.37: Yearly MVC Fatality Distribution: Urban vs Rural - 2009 – 2018 [145]	58	Government Document	NCSA - NHTSA
Figure 2.38: Occupants Involved in Fatal Rollovers with Fire Occurrences (Data Source: [49])	59	Self-Created	FARS Database
Figure 2.39: Evolution of School Buses	61		
Figure 2.39: Evolution of School Buses - Image 1 - [148]	61	Creative Commons Attribution 2.0 Generic License	Wikimedia.org
Figure 2.39: Evolution of School Buses - Image 2 - [149]	61	Government Website	Library of congress
Figure 2.39: Evolution of School Buses - Image 3 - [150]	61	Permission received via E-Mail	Thomas built buses
Figure 2.39: Evolution of School Buses - Image 4 - [151]	61	Creative Commons Attribution 2.0 Generic License	Wikimedia.org
Figure 2.39: Evolution of School Buses - Image 5 - [152]	61	Creative Commons Attribution 2.0 Generic License	Wikimedia.org
Figure 2.39: Evolution of School Buses - Image 6 - [153]	61	Educational License	Adobe Stock Photos
Figure 2.40: Federal Restraint Standards Associated with School Buses	63	Self-Created	
Figure 2.41: State Wise School Bus Safety Laws in 2021 [162]	64	Government Document	NCSL
Figure 2.42: Experimental Setup for (a) Circular Force Plate (20mm) by the DTI Study [169]	66	Permission received via E-Mail	Govt of UK / National Archives/ Department of Trade and Industry
Figure 2.43: Experimental Setup for (b) Plastic Cube (50mm) by the DTI Study [170]	66	Permission received via E-Mail	Govt of UK / National Archives/ Department of Trade and Industry

Figure 2.44: Mean Finger Push Force for Children Aged 2-15 Years (Data Source: [169], [170])	67	Self-Created	
Chapter 3			
Figure 3.1: Number and Rate of Road Traffic Deaths from 2000 to 2020 (Data Source: [15], [177])	71	Self-Created	
Figure 3.2: Passenger Vehicle Occupant Fatalities from FARS Data 1999-2019 (Data Source: [15])	71	Self-Created	
Figure 3.3: Seca 700 Physician Scale	74	Self-Clicked	
Figure 3.4: Rubbermaid Pelouze P250SS Weight Scale	74	Self-Clicked	
Figure 3.5: 3D Model of the Rollover Device Built in Solidworks	77	Self-Created	
Figure 3.6: Summit Racing 1,000 lb. Engine Stand [178]	77	Permission received via E-Mail	Summit Racing
Figure 3.7: Worm Gear Assembly Used in Engine Stand [179]	78	Educational License	Adobe Photos
Figure 3.8: Racequip 6-Point Racing Harness [180]	78	Permission received via E-Mail	Summit Racing
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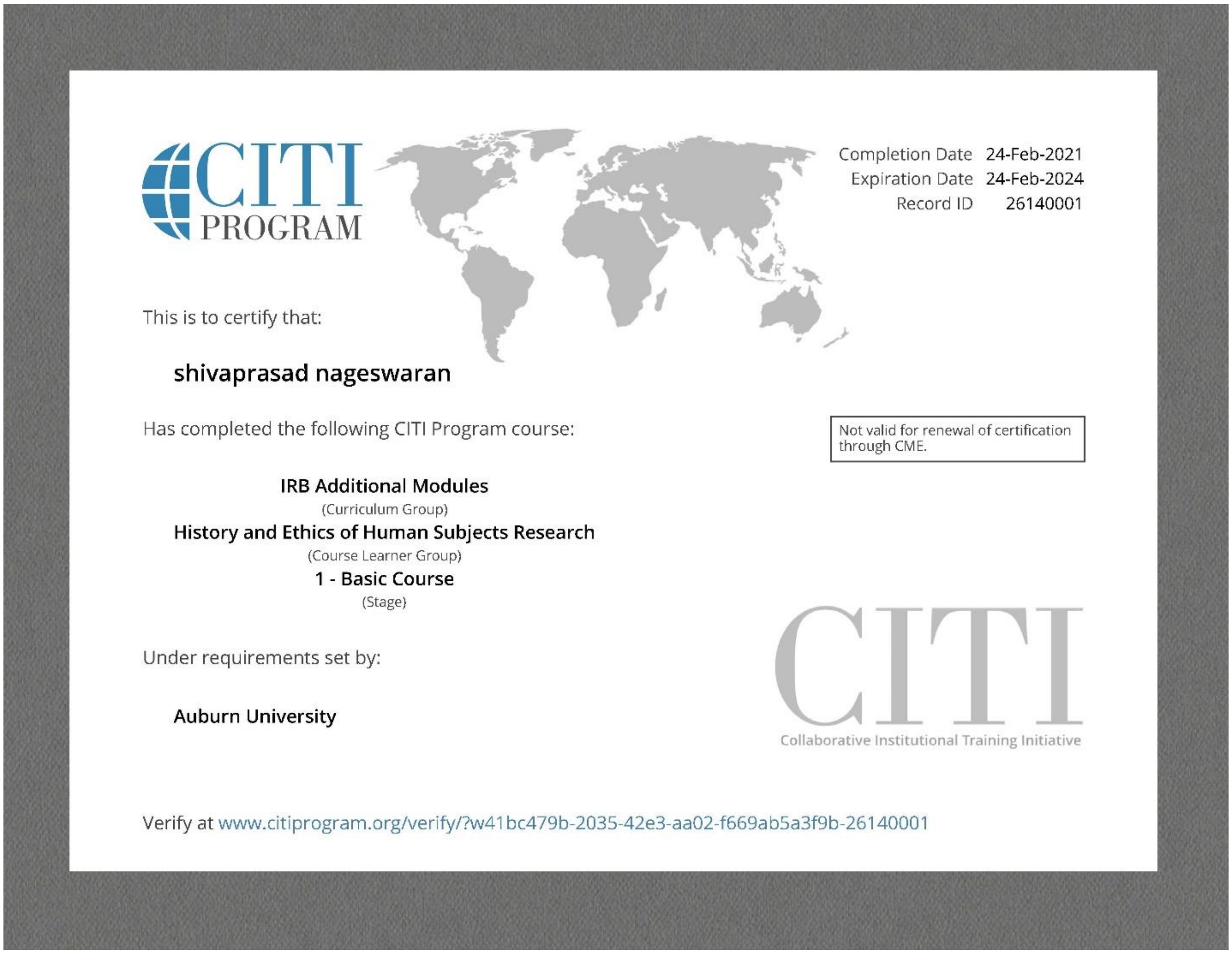

Completion Date 24-Feb-2021
Expiration Date 24-Feb-2024
Record ID 26140001

This is to certify that:

shivaprasad nageswaran

Has completed the following CITI Program course:

Not valid for renewal of certification through CME.

IRB Additional Modules
(Curriculum Group)
History and Ethics of Human Subjects Research
(Course Learner Group)
1 - Basic Course
(Stage)

Under requirements set by:

Auburn University

CITI
Collaborative Institutional Training Initiative

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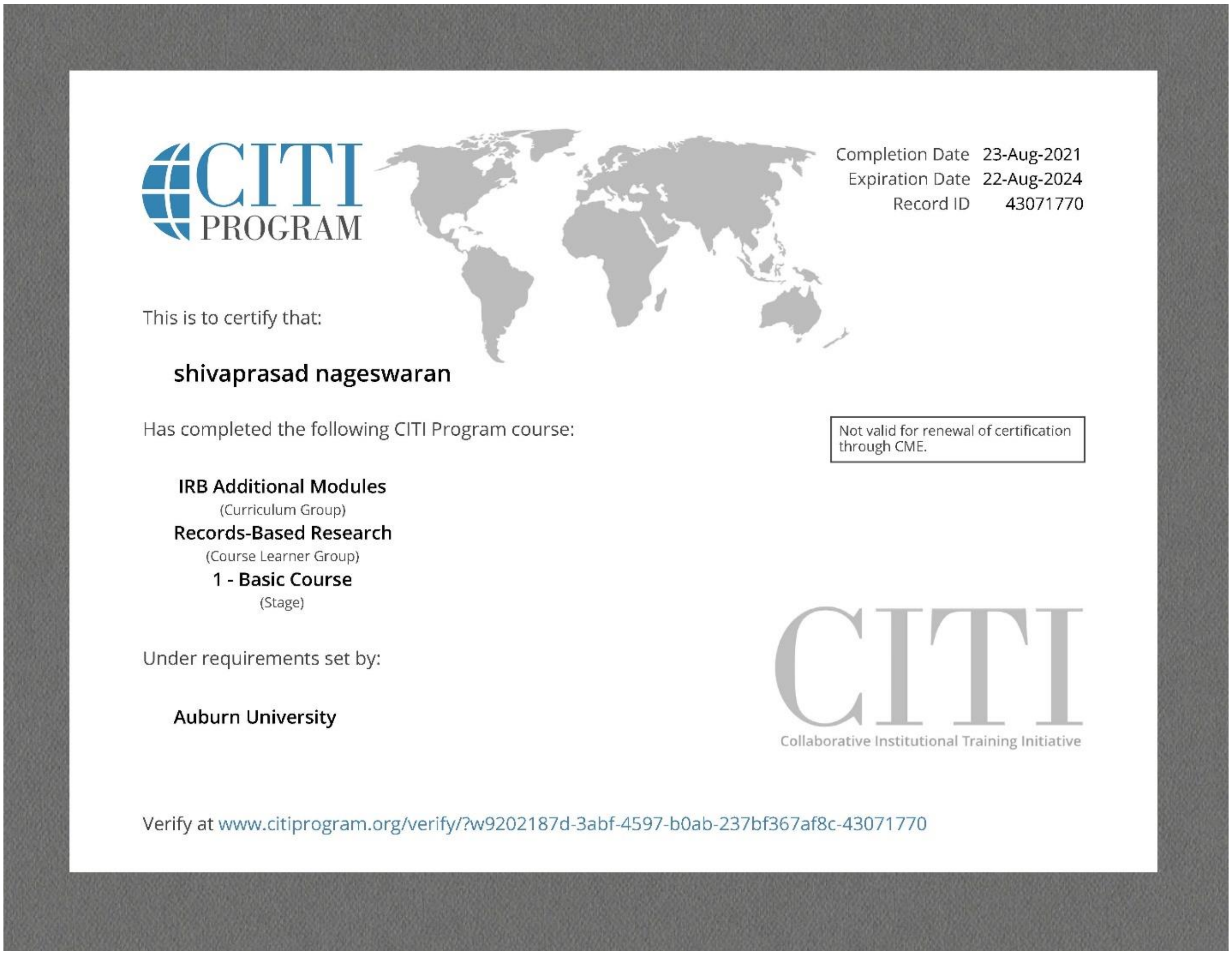


CITI PROGRAM

Completion Date 23-Aug-2021
Expiration Date 22-Aug-2024
Record ID 43071770

This is to certify that:

shivaprasad nageswaran

Has completed the following CITI Program course:

Not valid for renewal of certification through CME.

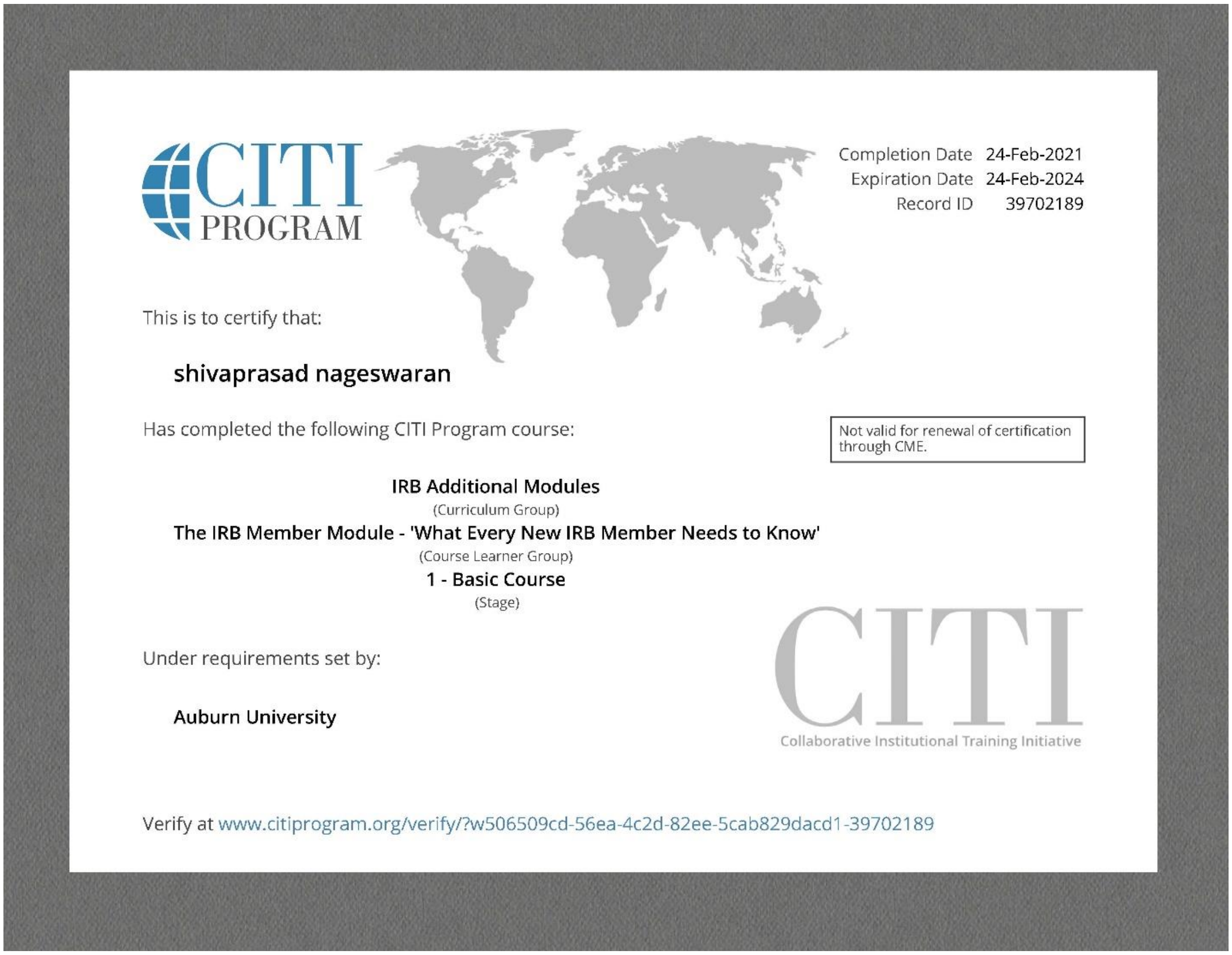
IRB Additional Modules
(Curriculum Group)
Records-Based Research
(Course Learner Group)
1 - Basic Course
(Stage)

Under requirements set by:

Auburn University

CITI
Collaborative Institutional Training Initiative

Verify at www.citiprogram.org/verify/?w9202187d-3abf-4597-b0ab-237bf367af8c-43071770



CITI PROGRAM

Completion Date 24-Feb-2021
Expiration Date 24-Feb-2024
Record ID 39702189

This is to certify that:

shivaprasad nageswaran

Has completed the following CITI Program course:

Not valid for renewal of certification through CME.

IRB Additional Modules
(Curriculum Group)
The IRB Member Module - 'What Every New IRB Member Needs to Know'
(Course Learner Group)
1 - Basic Course
(Stage)

Under requirements set by:

Auburn University

CITI
Collaborative Institutional Training Initiative

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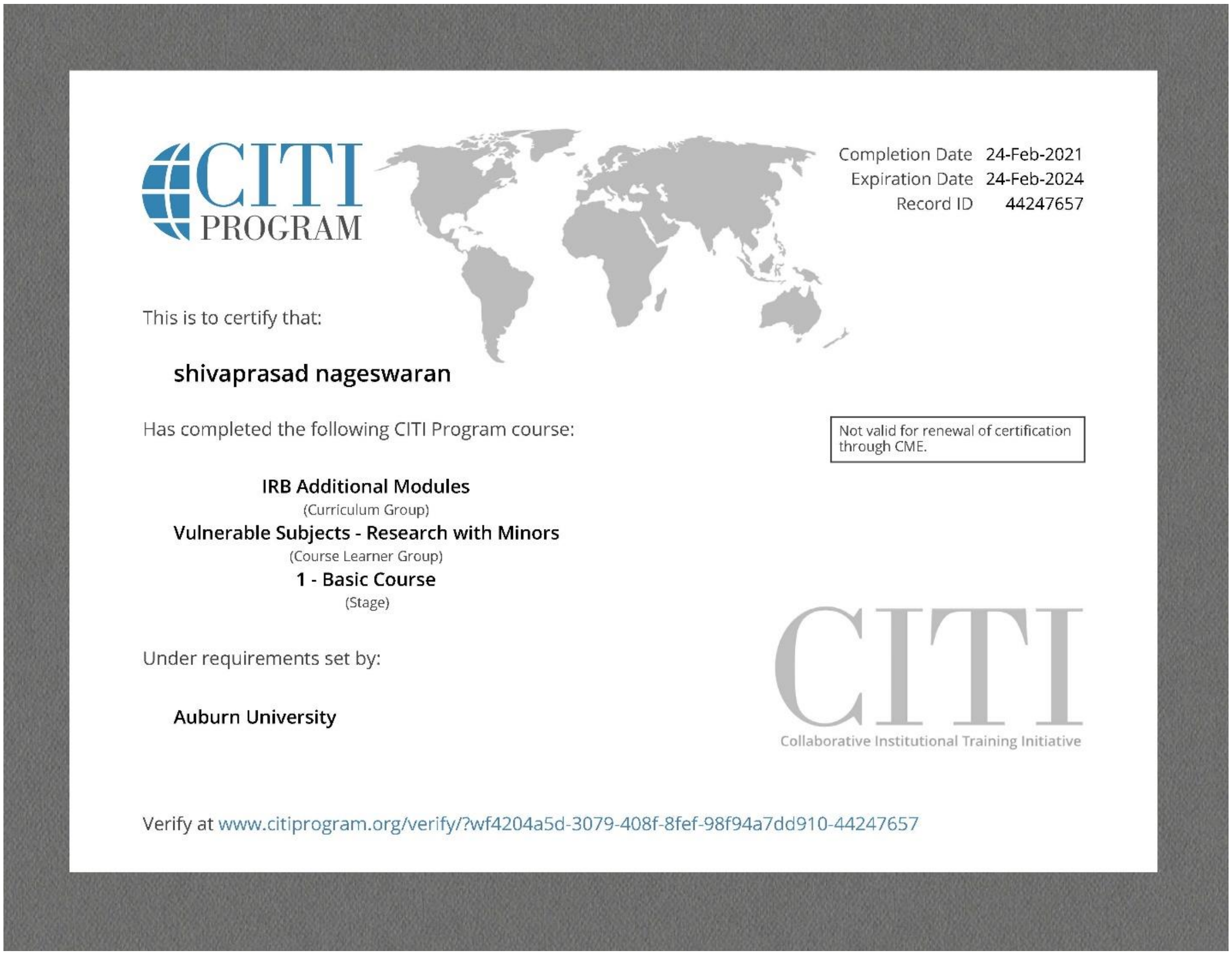

CITI PROGRAM

Completion Date 24-Feb-2021
Expiration Date 24-Feb-2024
Record ID 44247657

This is to certify that:

shivaprasad nageswaran

Has completed the following CITI Program course:

Not valid for renewal of certification through CME.

IRB Additional Modules
(Curriculum Group)
Vulnerable Subjects - Research with Minors
(Course Learner Group)
1 - Basic Course
(Stage)

Under requirements set by:

Auburn University

CITI
Collaborative Institutional Training Initiative

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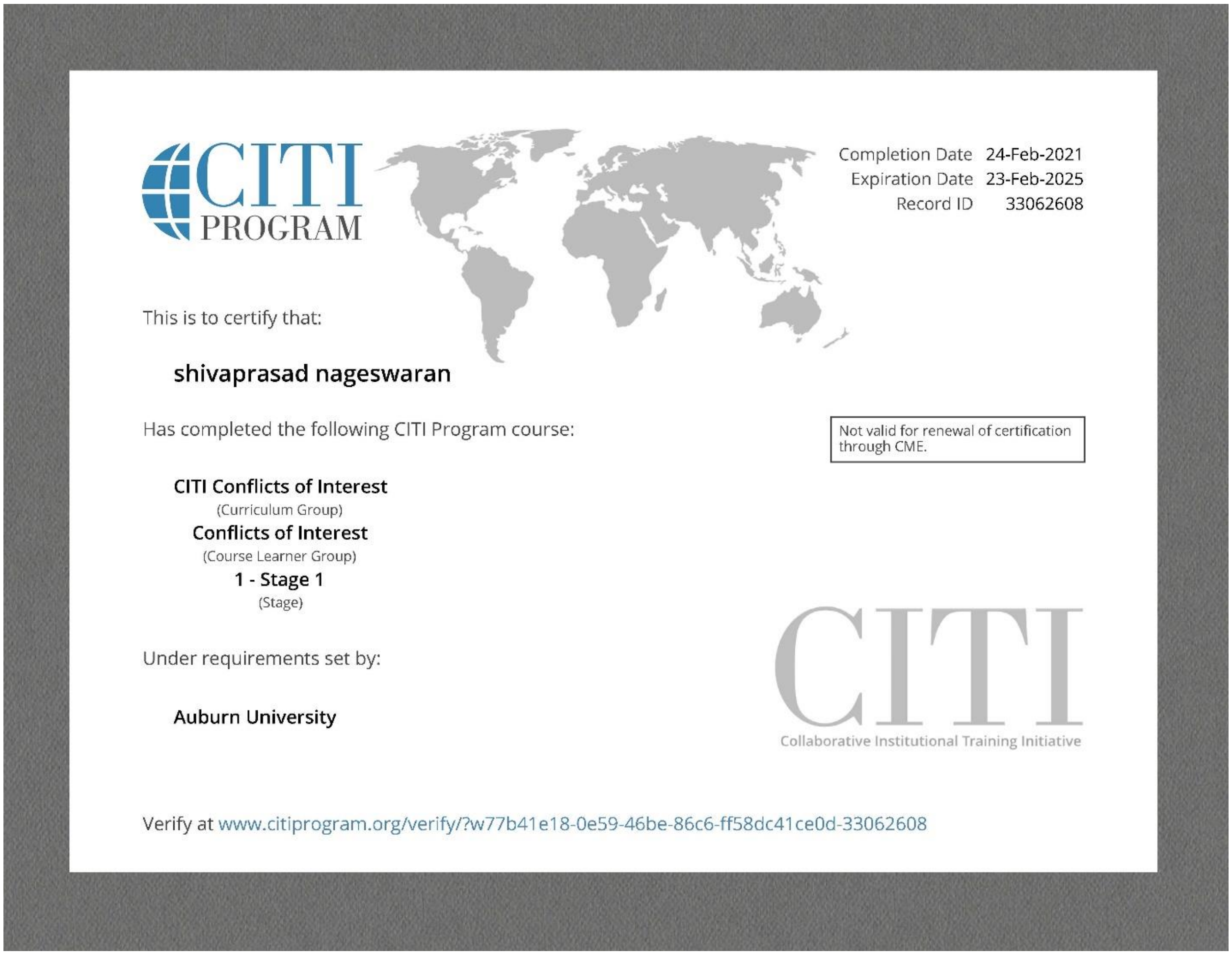


CITI PROGRAM

Completion Date 24-Feb-2021
Expiration Date 23-Feb-2025
Record ID 33062608

This is to certify that:

shivaprasad nageswaran

Has completed the following CITI Program course:

Not valid for renewal of certification through CME.

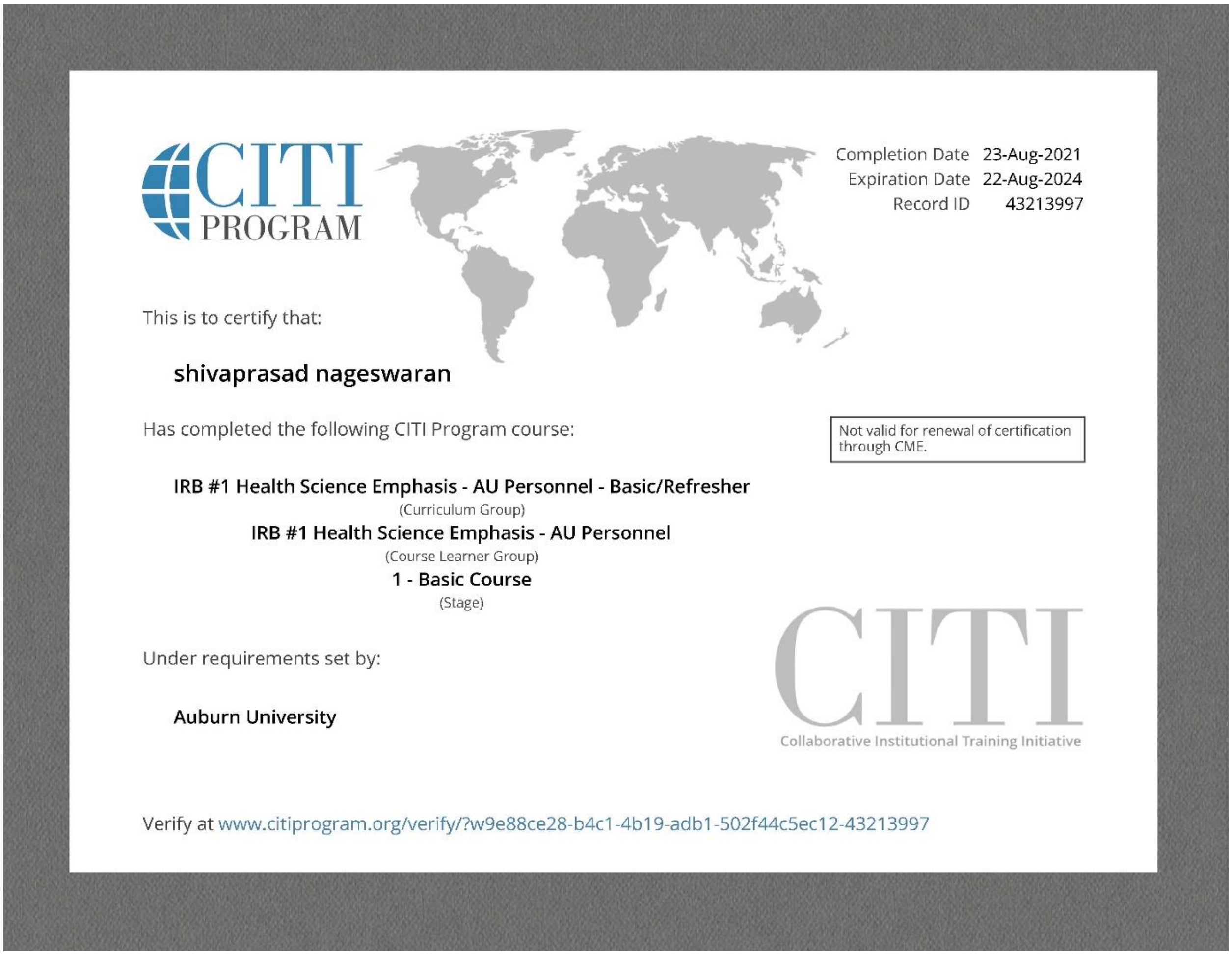
CITI Conflicts of Interest
(Curriculum Group)
Conflicts of Interest
(Course Learner Group)
1 - Stage 1
(Stage)

Under requirements set by:

Auburn University

CITI
Collaborative Institutional Training Initiative

Verify at www.citiprogram.org/verify/?w77b41e18-0e59-46be-86c6-ff58dc41ce0d-33062608



CITI PROGRAM

Completion Date 23-Aug-2021
Expiration Date 22-Aug-2024
Record ID 43213997

This is to certify that:

shivaprasad nageswaran

Has completed the following CITI Program course:

Not valid for renewal of certification through CME.

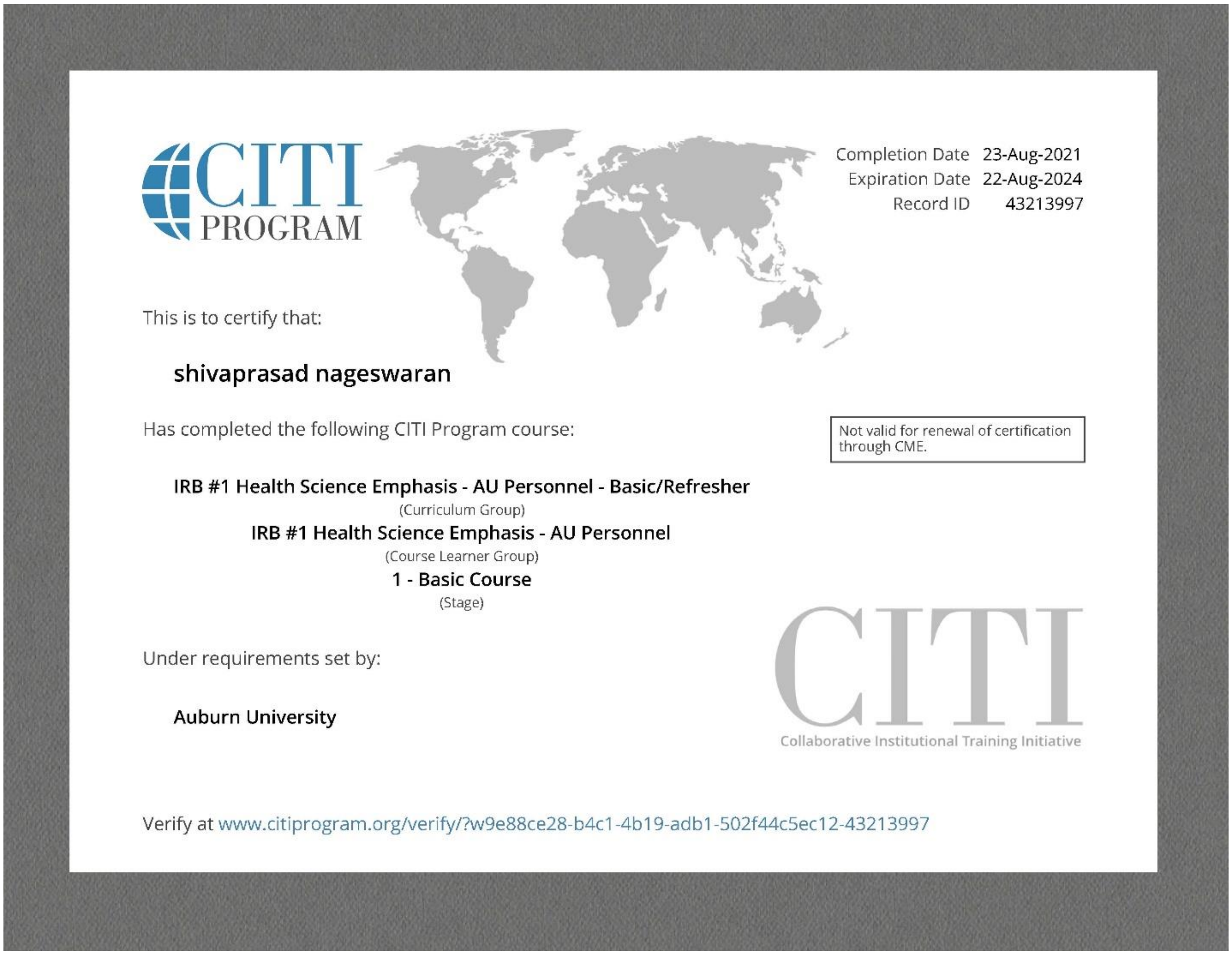
IRB #1 Health Science Emphasis - AU Personnel - Basic/Refresher
(Curriculum Group)
IRB #1 Health Science Emphasis - AU Personnel
(Course Learner Group)
1 - Basic Course
(Stage)

Under requirements set by:

Auburn University

CITI
Collaborative Institutional Training Initiative

Verify at www.citiprogram.org/verify/?w9e88ce28-b4c1-4b19-adb1-502f44c5ec12-43213997



CITI PROGRAM

Completion Date 23-Aug-2021
Expiration Date 22-Aug-2024
Record ID 43213997

This is to certify that:

shivaprasad nageswaran

Has completed the following CITI Program course:

Not valid for renewal of certification through CME.

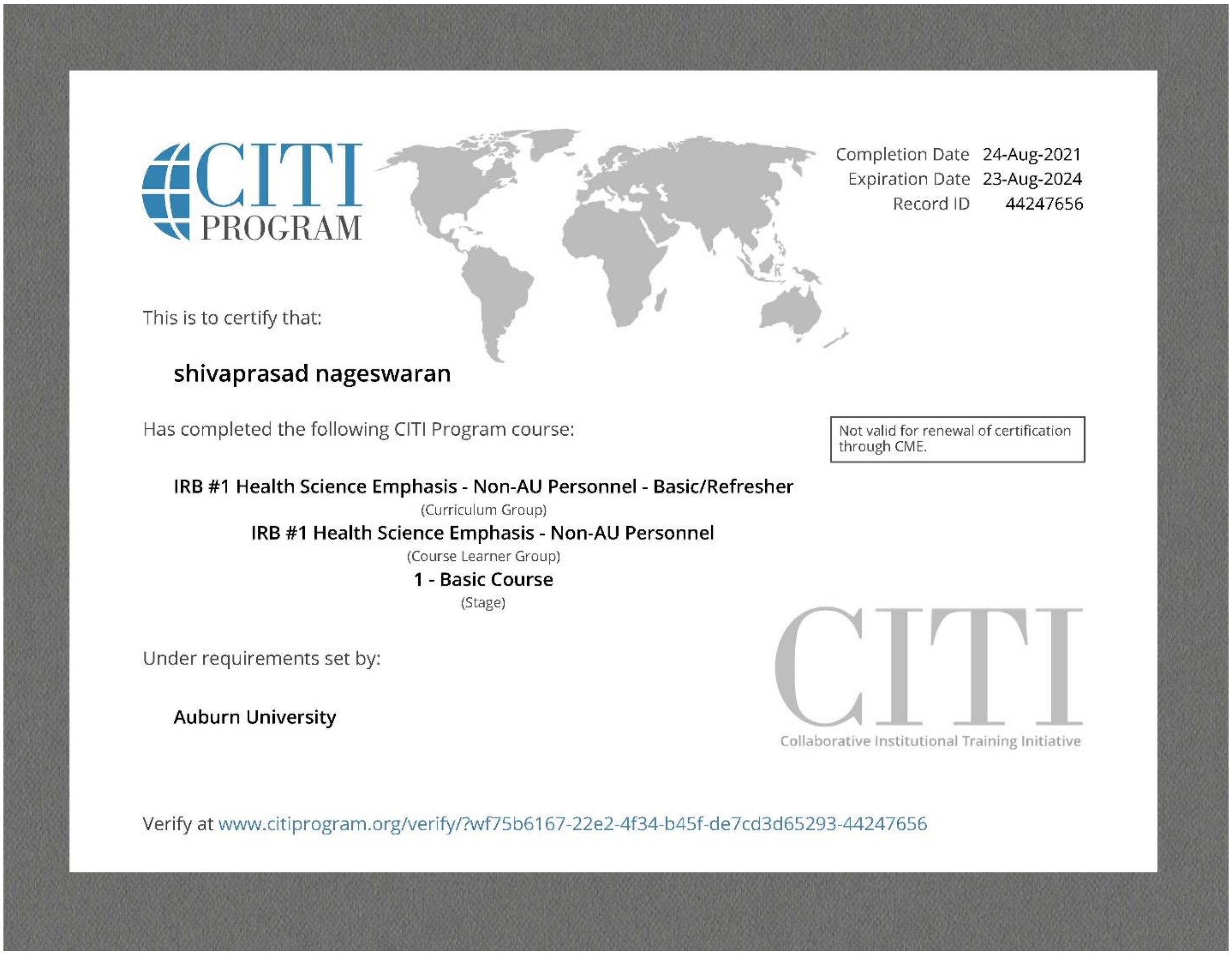
IRB #1 Health Science Emphasis - AU Personnel - Basic/Refresher
(Curriculum Group)
IRB #1 Health Science Emphasis - AU Personnel
(Course Learner Group)
1 - Basic Course
(Stage)

Under requirements set by:

Auburn University

CITI
Collaborative Institutional Training Initiative

Verify at www.citiprogram.org/verify/?w9e88ce28-b4c1-4b19-adb1-502f44c5ec12-43213997



CITI PROGRAM

Completion Date 24-Aug-2021
Expiration Date 23-Aug-2024
Record ID 44247656

This is to certify that:

shivaprasad nageswaran

Has completed the following CITI Program course:

Not valid for renewal of certification through CME.

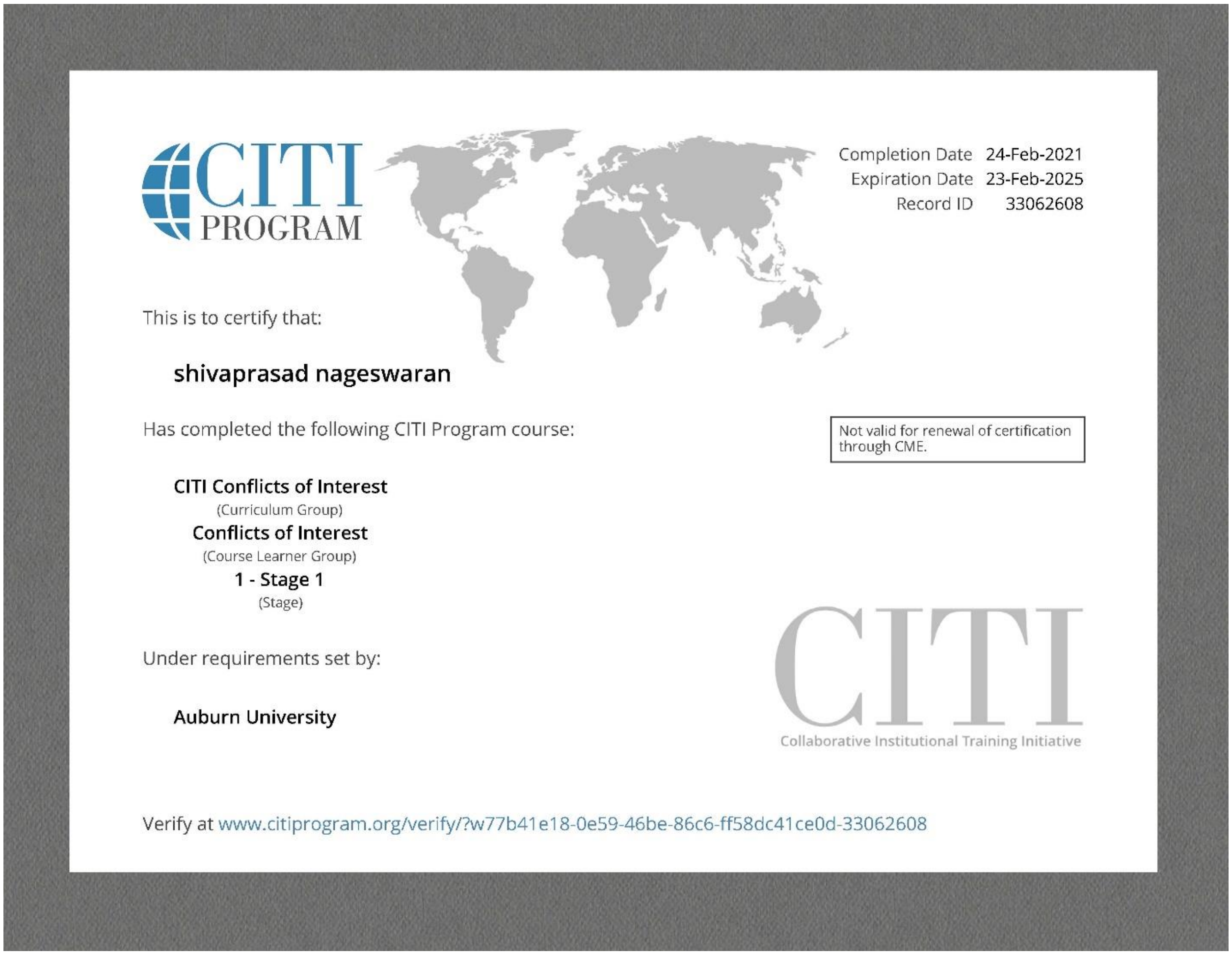
IRB #1 Health Science Emphasis - Non-AU Personnel - Basic/Refresher
(Curriculum Group)
IRB #1 Health Science Emphasis - Non-AU Personnel
(Course Learner Group)
1 - Basic Course
(Stage)

Under requirements set by:

Auburn University

CITI
Collaborative Institutional Training Initiative

Verify at www.citiprogram.org/verify/?wf75b6167-22e2-4f34-b45f-de7cd3d65293-44247656



CITI PROGRAM

Completion Date 24-Feb-2021
Expiration Date 23-Feb-2025
Record ID 33062608

This is to certify that:

shivaprasad nageswaran

Has completed the following CITI Program course:

Not valid for renewal of certification through CME.

CITI Conflicts of Interest
(Curriculum Group)
Conflicts of Interest
(Course Learner Group)
1 - Stage 1
(Stage)

Under requirements set by:

Auburn University

CITI
Collaborative Institutional Training Initiative

Verify at www.citiprogram.org/verify/?w77b41e18-0e59-46be-86c6-ff58dc41ce0d-33062608