MODELING AND SIMULATIONS OF THE 50TH PERCENTILE HYBRID III AND EUROSID-2RE DUMMIES ON OBLIQUE-FACING RIGID AIRCRAFT SEATS UNDER FAR TEST-2 DYNAMIC CONDITIONS

A Thesis by

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The following faculty members examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Mechanical Engineering.

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Hamid Lankarani, Committee Chair

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Dedication

To my amazing parents and sister
and
to my dear friends

ACKNOWLEDGEMENT

I am extremely grateful to my advisor Dr. Hamid Lankarani, professor of Mechanical Engineering at Wichita State University. His knowledge, guidance, wisdom, and dedication have been amazing in helping me complete this study. Without his directions, I would not be where I am today.

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Finally, I would like to thank my parents and sister. Without their constant support and encouragement, I would not have been able to begin and complete my studies at Wichita State University.

ABSTRACT

In the aircraft industry, as in most other industries, demand drives most of the change. This is true for all parts of the plane, including the seats. The constant demand for customization of seats in aircrafts has shifted focus to a new type, the oblique-facing aircraft seat. Although the Federal Aviation Administration (FAA) has requirements for front and side-facing seats, it is only recently focusing on development of guidelines for oblique-facing seats, which are defined by seats installed at angles between 18 to 45 degrees. When defining such criteria and guidelines, thoracic and lumbar forces are two important body parts to focus on for load conditions. These two areas, along with four partial injury criteria, namely the Thoracic Trauma Index (TTI), Viscous Criterion (VC), Pelvic Acceleration, and Chest Deflection, are addressed in this study. Using the MADYMO biodynamics software, three oblique-facing seat condition test cases are modeled and simulated with two types of dummies: Hybrid III Anthropomorphic Test Dummies (ATD), and EuroSID-2re. The variation of angles, belt attachments, along with the presence of an arm rest investigated, the results from which can be valuable in arriving at an optimum configuration of the oblique-facing seat for passenger protection. While the Hybrid III results show small variations with the criteria and injury types defined, the EuroSID-2re results show that that the addition of arm rest limits the lateral motion of the occupants in the seat, but could have a large adverse effect on the chest of the passenger on the oblique-facing seat. In the conclusions, injury criteria are explicitly suggested for certification of oblique-facing seats. Overall, it can be stated that the case 2 configuration (45 degrees, two belts, arm rest) would provide optimum protection for passengers on oblique-facing seats.

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LIST OF ABBREVIATIONS

ATD	Anthropomorphic Test Device
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FE	Finite Element
MADYMO	Mathematical Dynamic Model
SID	Side Impact Dummy
ELOS	Equivalent Level of Safety
TTI	Thoracic Trauma Index
FAR	Federal Aviation Regulation
NHTSA	National Highway Traffic Safety Administration

CHAPTER 1

INTRODUCTION

1.1 Background

The continuous demands for increased customization of private jets and commercial planes by the owners and the airlines have exponentially increased guidelines and regulations by the FAA. One of the most recent topics is oblique-facing seats on airplanes, which is technically defined by the FAA as “side-facing seats installed from 18° through 45° from the centerline of the airplane” [1]. As described by the code of federal regulation §25.562 and §25.785, “the seat and the restraint system be designed to protect each occupant when (1) proper use is made of the seats, safety belts, and shoulder harnesses; and (2) the occupant is exposed to loads resulting from the conditions prescribed in § 25.562(b)”[2]. Furthermore, it is required that “occupants of seats that are occupied during takeoff and landing not suffer serious injury as a result of the inertia forces specified in §25.561 and 25.562” [2]. Due to these rules, guidelines had to be created for any seats deviating from front and aft direction. The closest the FAA has come has been 2 different occurrences. First, a set of special criteria was created for fully side-facing seats (90°), which drew results partly applicable to oblique-facing seats, but not fully, due to the complexity of applied forces. The second occurrence was the granting of an equivalent level of safety (ELOS) by the FAA, which concluded that for seats installed obliquely at angles shallower than 18°, when a crash occurs, the occupant is predicted to align himself with the impact direction well enough that forward facing seat crash criteria are satisfactory [2]. However, this was later debunked, as the complexity of oblique seats proved to produce different results.

This brings the FAA to present time, where a new set of criteria, in addition to those derived for front facing seats, has been proposed, specifically for oblique-facing seats.

1.2 Overview of Current Regulations

Much of the current regulatory standards for forward-facing seats are based on the research efforts of the FAA and NASA conducted as early as the 1970's [3]. The FAA's requirements for regulatory standards for forward-facing seats are defined by the Federal Aviation Regulations (FARs) and divided into 2 distinct dynamic test conditions. Test 1 conditions require seat inclination of 60 degrees in the pitch and has requirements regarding velocity change and peak acceleration, which are shown in Table 1.1. Test 1 is intended to "evaluate the means provided to reduce the spinal loading…by combined vertical/horizontal load environment" [3]. Test 2 conditions require a 10-degree yaw angle and has velocity requirements shown in Table 1.1. Test 2 is intended to "provide an assessment of the seat structural performance and the occupant restraint system" [3]. Figure 1.1 shows the difference between these two test configurations.

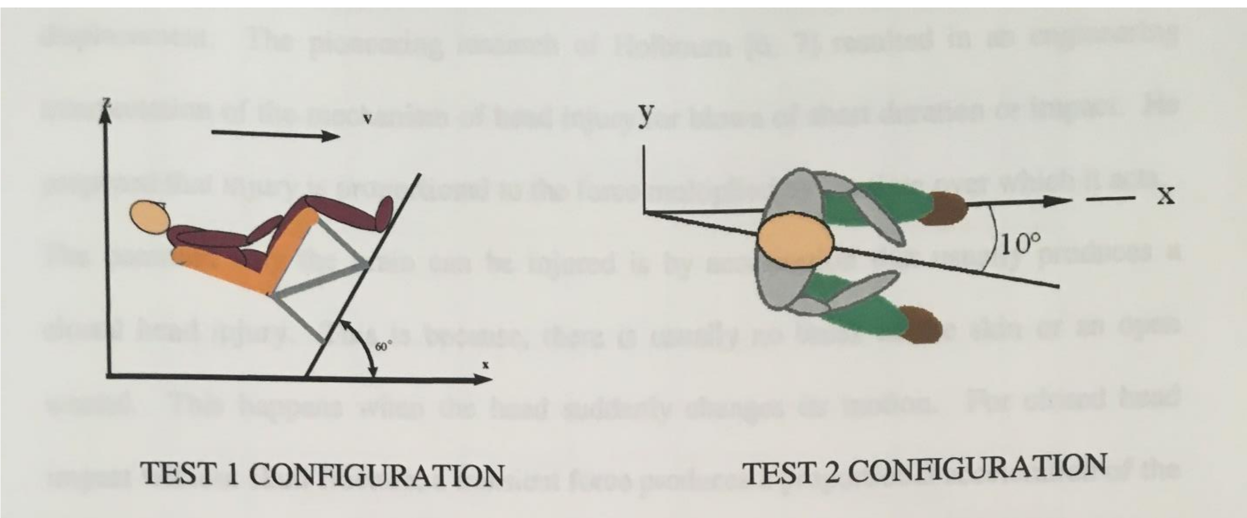


Figure 1.1: Federal Aviation Administration Test 1 and Test 2 configurations [4]

Table 1.1: Test 1 and Test 2 configurations, as required for Part 23, 25, and 27, as well as injury pass/fail criteria [4]

DYNAMIC TEST REQUIREMENTS	PART 23	PART 25	PART 27
Test 1			
Test Velocity – ft/sec	31 (9.5 m/sec)	35 (10.7 m/sec)	30 (9.2 m/sec)
Seat Pitch Angle - Degrees	60	60	60
Seat Yaw Angle - Degrees	0	0	0
Peak Deceleration – G's	19/15	14	30
Time to Peak - sec	0.05/0.06	0.08	0.031
Floor Deformation - Degrees	None	None	10 Pitch/10 Roll
Test 2			
Test Velocity – ft/sec	42 (12.8 m/sec)	44 (13.4 m/sec)	42 (12.8 m/sec)
Seat Pitch Angle - Degrees	0	0	0
Seat Yaw Angle - Degrees	±10	±10	±10
Peak Deceleration – G's	26/21	16	18.4
Time to Peak - sec	0.05/0.06	0.09	0.071
Floor Deformation - Degrees	10 Pitch/10 Roll	10 Pitch/10 Roll	10 Pitch/10 Roll
QUANTITATIVE COMPLIANCE CRITERIA			
HIC	1000	1000	1000
Lumbar Load – lb	1500 (6675 N)	1500 (6675 N)	1500 (6675 N)
Strap Loads – lb	1750[1]/2000[2] (7787N[1]/8900N[2])	1750[1]/2000[2] (7787N[1]/8900N[2])	1750[1]/2000[2] (7787N[1]/8900N[2])
Femur Load – lb	N/A	2250	N/A

[1] – Passenger
[2] – Pilot

Table 1.1 shows all the requirements for Test 1 and Test 2 dynamic conditions. The 3 different columns labeled part 23, 25, and 27, refer to general aviation aircraft, transport aircraft, and rotorcraft, respectively [3]. The final row of Table 1.1 describes the compliance criteria that each of the parts must comply to for that specific dynamic test.

It's important to note that all the requirements explained so far are for forward-facing seats. The FAA generally requires an "Equivalent Level of Safety" for other types of seats. However, currently, the FAA states that Equivalent Level of Safeties will not be issued solely based on similarity of oblique seats to front/aft seats. Therefore, in order to comply to the requirements set forth by §25.561 and §25.562, amendment 25-64, as well as §25.785 amendment 25-72, new special conditions are introduced, which reform the criteria for front/aft seats that can apply specifically to the oblique-facing seats. These special conditions are introduced in policy PS-

ANM- 25-27 and are as follows: Head Injury Criteria, Body-to-Wall/Furnishing Contact, Neck Injury Criteria, Spine and Torso Injury Criteria, Pelvis Criteria, Femur Criteria, and ATD and Test Conditions. It's important to remember that these special conditions are in addition to requirements of §25.562 and do not stand alone by themselves. Among the injuries listed, pelvis and lumbar were two that were focused on throughout this study. Others included thoracic injuries, and viscous criterion.

1.3 Injury Pass/Fail Criteria

The policies mentioned above provide the requirements for the FAA for forward-facing seats. The special requirements only apply to the oblique-facing seats. For a full list of refer to PS-ANM-25-27 [2].

Table 1.2 summarizes some important oblique-facing special requirements for the methods of injury related to this study. For a full list of refer to PS-ANM-25-27 [2].

Table 1.2: Injury criteria for forward-facing seats[2]

Condition	§25.562 Criteria (Current Forward-Facing)	Special Conditions in PS-ANM-25-27 (Oblique-Facing)
Pelvis Acceleration	The pelvic restraint remains on the ATD's pelvis during impact	Any part of the load-bearing portion of the bottom of the ATD pelvis must not translate beyond the edges of the bottom seat cushion supporting structure
Lumbar Loads	1500 lbs	The lumbar spine tension (F_z) cannot exceed 1200 lb_f
V*C	N/A	1.0

1.4 Literature Review

Crash testing history dates to 1950s, where it began with automobiles. Colonel John Paul Stapp, prominently known as the crash test pioneer, began a crash testing program. He began his research with dummies, putting them into out-of-cycled cars, and crashing them into heavy barriers. Later, he started to use himself as well as other human volunteers in order to gather better results. Tests with forces as high as 28 G's were conducted which resulted in a multitude of injuries [5]. Figure 1.2 shows Colonel Stapp in one of his 29 rocket sled tests.

Figure 1.2: Colonel John Paul Stapp during one of this high acceleration tests [5]

During these runs, he often broke various bones, fractured ribs, and suffered concussions. The results of his studies, and his manner of conducting them, lead to other crash test programs, with the main difference being the use of dummies rather than humans.

Before the wide use of dummies in crash tests, cadavers and various animals, along with human volunteers were used. This caused problems, both from an integrity standpoint, mainly in the volunteer tests, as well as difficulties correlating data between the models, animals, and humans. This lead to the first crash test dummy creation, designed in 1949 by Sierra Engineering Co. under a contract with the United States Air Force, named Sierra Sam. Sierra Sam, a 95th percentile male made of steel and rubber, was mostly used for seat ejection tests, but did not have a good enough resemblance to the human body to provide valuable results. In 1971, Hybrid I was created by General Motors, as compromise between two models that did not quite satisfy needed requirements. Hybrid I was an important step in the direction of durability [6]. Currently, the most popular dummy used by most automotive and aircraft companies, along with the National Highway Traffic administration—and one that has been used for half of the simulations in this study—is the 50th percentile Hybrid III dummy. This dummy represents the size of an average adult male, with a height of 5’9” and a weight of 173 pounds. It is the most complex one of the dummies created so far, representing the human body as closely as possible. Figure 1.3 shows the early Sierra Sam compared with the Hybrid III.

Figure 1.3: Sierra Sam (left) and Hybrid III (right) have many differences, including their shape and looks

Parallel to the advancement of the American dummies, Europeans created dummies focused on side impact. European Side Impact Dummy (EuroSID-1) was the first version developed, by making variations to the Hybrid II, as requested by the National Highway Traffic Safety Administration (NHTSA). The dummy was upgraded to EuroSID-2 in the early 2000s and was "used for [New Car Assessment Program] NCAP Mobile Deformable Barrier Test and the Car to Pole test" [7]. The 3rd version of this dummy, which is used for the second half of the simulations done in this study, is the ES-2re, which is much more sophisticated and resembling of the human body. Figure 1.4 shows the 50th percentile ES-2re dummy.

Figure 1.4: The EuroSID-2re dummy, especially made for side impacts

1.4.1 Previous Research

Although there has not been much research done specifically on oblique-facing seats, there has been a lot of relatable research done where correlations can be drawn to the topic of this study, including aircraft crashes, automobile crashes, and side-facing seat collisions. From the vehicle side, literature authored by Sasikumar was reviewed, where he compared the dynamic responses of human body models and crash dummy models in various frontal vehicle crashes. This included full frontal, small offset, and most relatable to this study, oblique impact configuration. He studied three cases for each of the above configurations: no airbag, no seatbelt; no airbag, seat belt; and airbag, seat belt. The results were compared to federal regulatory standards [8]. He concluded that oblique impacts can have large adverse effects on the body due to the absence of a crush zone. However, he did continue to say that values for injuries for an oblique configuration were smaller than the other two configurations. He also concluded that both airbags and seatbelts have very positive effects for the passenger, as they limit the bending of the spine, while thoracic and abdomen injuries fall considerably.

Furthermore, Hassan studied vehicle collisions with a pole and compared it with that of flat barriers. He measured the impact on both the vehicle and the dummy. He compared the data and concluded that pole crashes produced more severe results to both the vehicle and dummy [9]. Parallels were drawn from the pole crashes to side impacts into an arm rest for the purposes of this study, including a hypothesis that arm rest can increase the impact on the chest and the sides, even though it will protect the position of the passenger on the seat.

On airplane frontal crashes, an article by Lillehei was reviewed, where the author analyzed the "fatal injuries resulting from the Continental flight 1713 airline disaster: evidence in favor of improved passenger restraint system" [10]. He concluded that for passengers who suffered fatal blunt injuries, a simple use of a lap belt restraint alone is not adequate. He went on to suggest improvements to the design, such as securing "bolting of passenger seats to the airplane superstructure" or the introduction of "3-point lap and shoulder harness system.

Research was done on side impacts on planes. Deweese has conducted multiple researches on side crashes, two of which were reviewed closely, and the 3rd mimicked. The first article reviewed conducted a study for side-facing impacts, and had the following goals: force, displacement, and acceleration measurements, quantitative evaluation of kinematics, and qualitative evaluation of kinematics. The most important conclusion that he made pertaining to this study was that configurations permitting excessive lateral flail do not pass criteria defined by his study, and that those configurations that "limit [flailing] by combing effective restraint system geometry with a barrier or inflatable restraint pass readily" [11]. The second study conducted dynamic tests with typical aircraft side-facing seat configurations using the ES-2 Anthropomorphic Test Dummy. Deweese evaluated the potential for injury using current, proposed, and preliminary injury criteria and also evaluated the ES-2 ATD's functionality when used in the aviation environment. He investigated test methods unique to side-facing seats and evaluated the ability of inflatable restraint systems to mitigate injuries in these seating configurations. With regards to inflatable restraint evaluation, in most cases, he concluded that they were effective in reducing lateral flailing. These restraints also "significantly reduced the head acceleration, neck loads, chest acceleration, rib deflections…" [12].

The final piece of literature authored by Deweese is the chief source of literature for this study. It is an experiment conducted on a hybrid III dummy which seats the dummy at multiple angles with different restraint systems and studies the effects of acceleration [1]. This study is one that this thesis attempted to resemble by modeling on the computer.

1.5 Motivation

This study is motivated by the lack of existing research for oblique-facing aircraft seats, and their continuous demands by airlines and individual costumers. Rear and front facing seats are fully regulated by the FAA, and the existence of criteria for approval of such structures provides guidelines to safely build and transport people. The use of computer modeling and simulation techniques allows one to utilize these tools to simulate the dynamic responses of a person in various crash conditions including a passenger on an oblique-facing aircraft seat. These computer modeling and simulation tools can help in the identifying of the appropriate seating and restraint systems in protecting the occupants on side-facing aircraft seats. They can also be utilized in the selection of appropriate test procedure and pass-fail criteria for the passengers on side-facing aircraft seats. The dynamics of the simulation and injury data shown in this study research could provide valuable insight in the direction FAA can take in order to provide aerostructure companies with guidelines on how to correctly develop and install oblique-facing seats that best protect the occupant in the event of a crash.

CHAPTER 2

OBJECTIVES AND GENERAL METHODOLOGY

2.1 Objective

The goal of this study is to examine various configurations and arrive at configurations which best protect the passengers on oblique-facing aircraft seats. To achieve this goal, the following objectives are identified:

- To develop computer models of the passenger/restraint/oblique-seat
- To compare the results from the simulations with Hybrid III ATD in MADYMO with the ones from the experiments
- To utilize these simulations for comparisons of various other configurations and restraint systems
- To conduct the same simulations with the ES-2re dummies and to compare the results
- To evaluate appropriate injury criteria, including Viscous Criterion, Pelvic Acceleration, Chest Deflection, and Thoracic Trauma Index (TTI)
- To arrive at configurations which best protect the occupants in oblique-facing seats
- To propose a set of guidelines for testing of oblique-facing seats

2.2 General Methodology

To determine the progression of the research associated with this study, a flow chart was defined and utilized. After determining that both Hybrid III and EuroSID-2re dummies were going to be used, MADYMO was chosen as the software of choice for simulations. MADYMO is an important software for simulation of crashes both in the automobile and aviation industry. The efficiency with which it can simulate, as well as its user-friendly setup, makes MADYMO a reliable option for the purposes of this study. The next step was to define rigid seats as representation for aircraft seats, input acceleration pulses from the main literature review source, and select the right belts along with their properties. Most of the properties were taken from the literature review. For areas without clear explanation of the parameters, assumptions were made. The next steps involved defining the contacts that the dummy would have with the structure around it, namely the belt and the seat, and the creation of three cases for the simulations. Afterwards, an analysis and comparison assisted with drawing results and conclusions. Figure 2.1 gives a visual to the method followed in the modeling process.

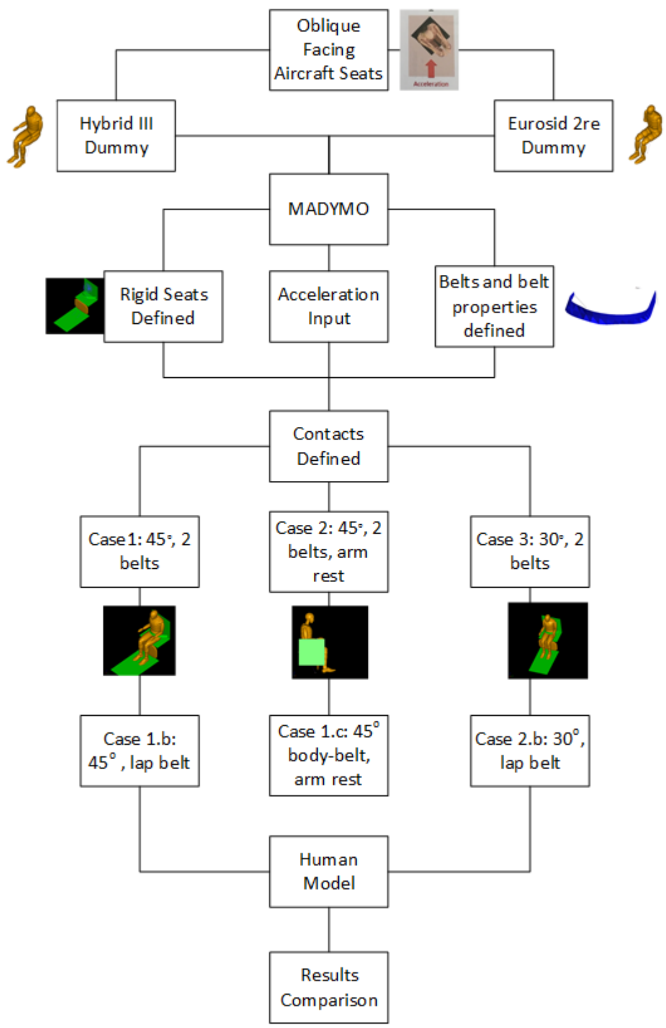


Figure 2.1: Progression of steps for simulations and analysis

2.3 Computational Tool

The most used software for this study was MADYMO. MADYMO is a widely used software across the aircraft and automotive industry that has optimized the process of designing safety features for both mediums of transportation. It is a flexible simulation engine that contains numerous, preloaded dummy, seat, belt, and other models, which makes designing very cost and time efficient.

To explain the extensive use of MADYMO, one must justify the need for numerical solutions. Numerical solutions are needed because of two important factors: cost and time. On the other hand, there are two major categories of aircrafts when it comes to certification; those include the commercial planes and the business jets. Testing and certification for commercial planes can be slightly easier, as various models and minor models differ only slightly from the base models created years ago. Certifications will only vary slightly as airlines make specific changes to their final products. Seats for business jets, on the other hand, are much more difficult to certify due to continuous customization of the consumer. Seats deviating from the norm are quite complex to certify. The following are a few factors that add to the complexity of calculations: angle, pitch, weight, cushion, arm rest, back rest, dimensions, proximity to other structures, flexibility, and location. Each slight variation of those factors require certification by FAA, which are difficult if the process is an aircraft impact test. Figure 2.2 shows the setup for one test.

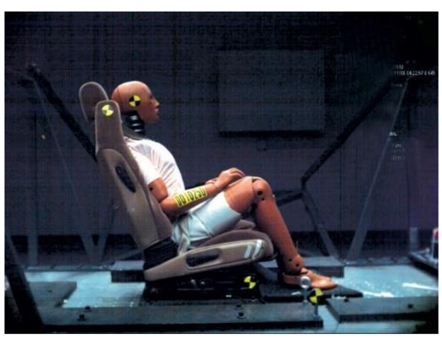


Figure 2.2: A setup of Hybrid III crash test [13]

Should the above testing be set up or conducted incorrectly in any way, the whole process must restart, costing hours of time and thousands of dollars for each repetition. It is, therefore, easy to see why numerical solutions are an important integration in the today's designing process, a solution with which MADYMO greatly assists.

CHAPTER 3

MODELING DEVELOPMENT

3.1 Aircraft Seat

The seats for this study were simplified to four MADYMO rigid planes, created by geometrical points. For a few particular tests, an arm rest was added, which was represented by a fifth plane in MADYMO. Figure 3.1 shows an example of one of the seats used, while Table 3.1 shows the dimensions of the planes.

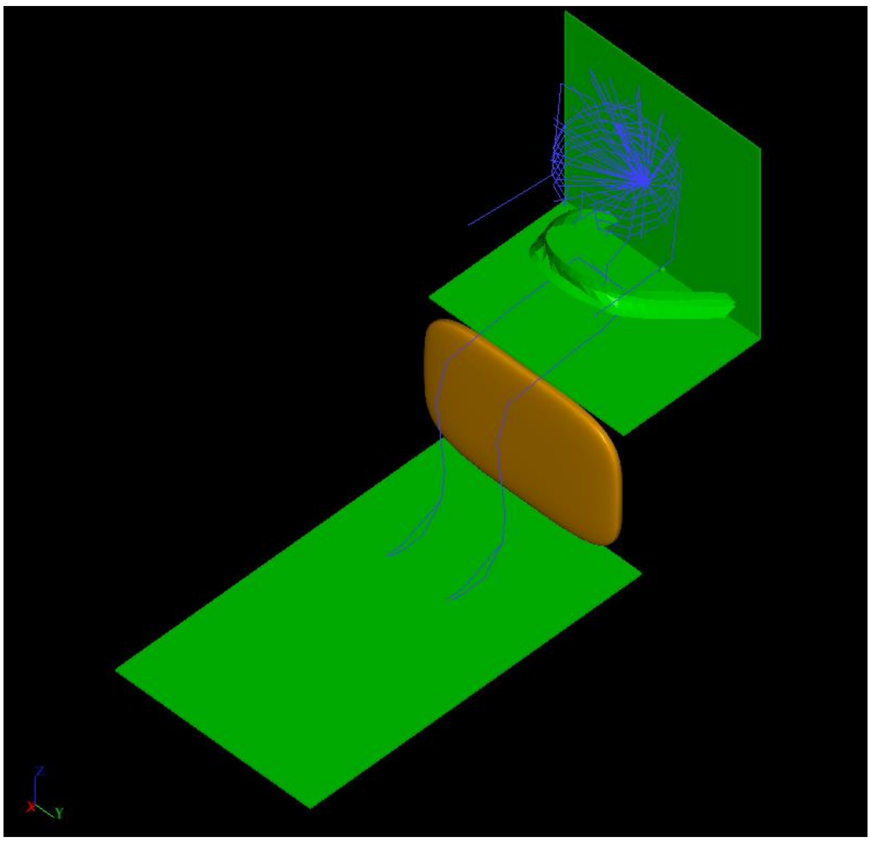


Figure 3.1: The aircraft seat, made up of four rigid planes, for the simulations in MADYMO

Table 3.1: The dimensions of the planes for the seat

	X (m)	Y (m)	Z (m)
Back-Seat	0	.596	.576
Bottom-Seat	.416	.593	0
Bottom Leg	0.08	.596	.389
Floor	1.00	.596	0
Arm Rest	.416	.593	0

3.2 Aircraft Belt

The type of belts used in this study are preloaded, finite element, nylon material belts. For certain types of simulations, two belts are used, one as a lap belt and the other as a body belt. The difference is visible only in the location and the points of attachment of the belts. With the belt fitting function available in MADYMO, the belts were fitted around the dummy and attached to 2 points in the seat back. Figure 3.2 shows visualizations of the belt setup for the lap belt. It is attached to the two sides of the seat. Figure 3.3 shows the body center belt, which has one attachment similar to the lap belt, and the other behind the dummy at the center of the seat. Figure 3.4 shows the attachment of the body center belt on the seat.

Figure 3.2: Lap belt has two attachments to the seat on both sides of the dummy

Figure 3.3: Body center belt has one attachment on the side and the other behind the dummy on the seat

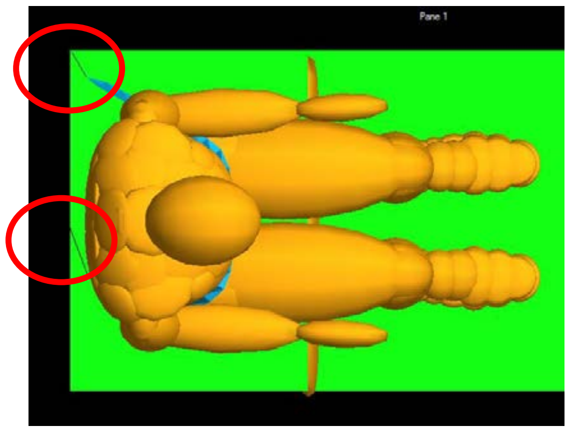


Figure 3.4: The attachment points of the body center belt

After attachment, loading and unloading conditions were applied to the belt, and frictional constraints were also applied.

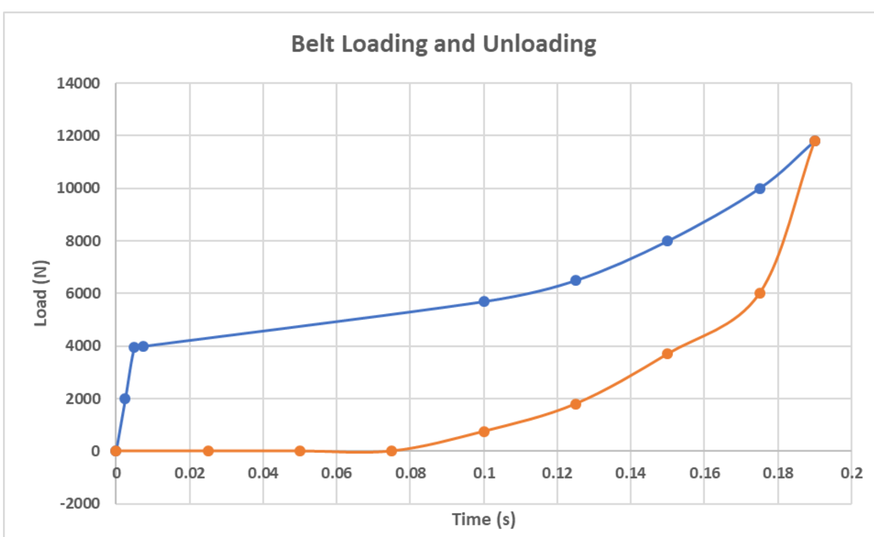


Figure 3.5: The loading and unloading conditions of the belts

3.3 Occupant Modeling

The dummies selected and used for this study were Hybrid III and EuroSID-2re. The Hybrid III was chosen to examine mostly the kinematics of the occupant motion as well as any injury potential corresponding to longitudinal loading of the dummy/passenger. The EuroSID-2re is utilized to examine the potential injury corresponding to the lateral component of the loading on the dummy/passenger. Both dummies are 50th percentile male, meaning they are 69.1" (175.5 cm) and weigh 172 lb. (78.4 kg). They were both selected from the provided database of MADYMO and were both set up similarly. The differences among the 2 are in their appearance, and their level of structure detail. The hybrid 3 dummy is designed for frontal crashes, while the EuroSID-2re dummy is sensitive to side impacts. This is clearly outlined and explained later in the study. Figure 3.6 shows the Hybrid III actual dummy as well as the model used in MADYMO. Figure 3.7shows the same comparison for EuroSID-2re dummy.

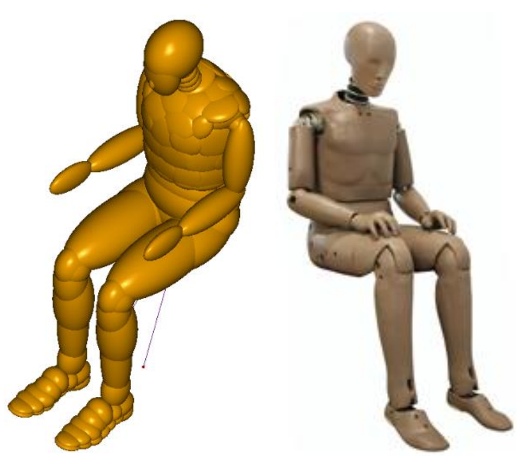


Figure 3.6: Hybrid III simulation dummy (left) and actual dummy (right) are mainly used for frontal impacts

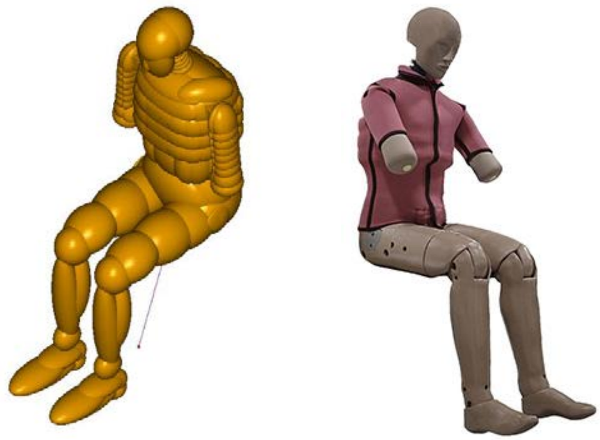


Figure 3.7: EuroSID-2re simulation dummy (left) and actual dummy (right) are mainly used for impacts with lateral components

3.4 Input Pulse Conditions

The main input parameter for various simulations was acceleration. The acceleration prescribed by the FAA, § 25.562, must reach a minimum of 16Gs, for an emergency landing condition for a horizontal impact. Figure 3.8 and Figure 3.9 show the change in acceleration for 180 milliseconds. It's important that this study is focused on the dynamic responses of occupants on oblique-facing seats under the FAR Test-2 (longitudinal dynamic test conditions). Test 1 conditions refer to the protection of the occupants in combined vertical-longitudinal direction. The nature of occupants' spinal loading does not seem to significantly change from frontal-facing to oblique-facing seats. However, in the Test-2 condition, the occupants in oblique-facing seats are exposed to both longitudinal as well as lateral G-forces. Hence, the dynamic responses are expected to have a combination of forward and side impact loading. This Test-2 dynamic condition is the focus of this study. Also, the aircraft seat is assumed to be entirely rigid to examine the worst-case scenario in terms of dynamics and potential injury to the occupant in the oblique-facing seats.

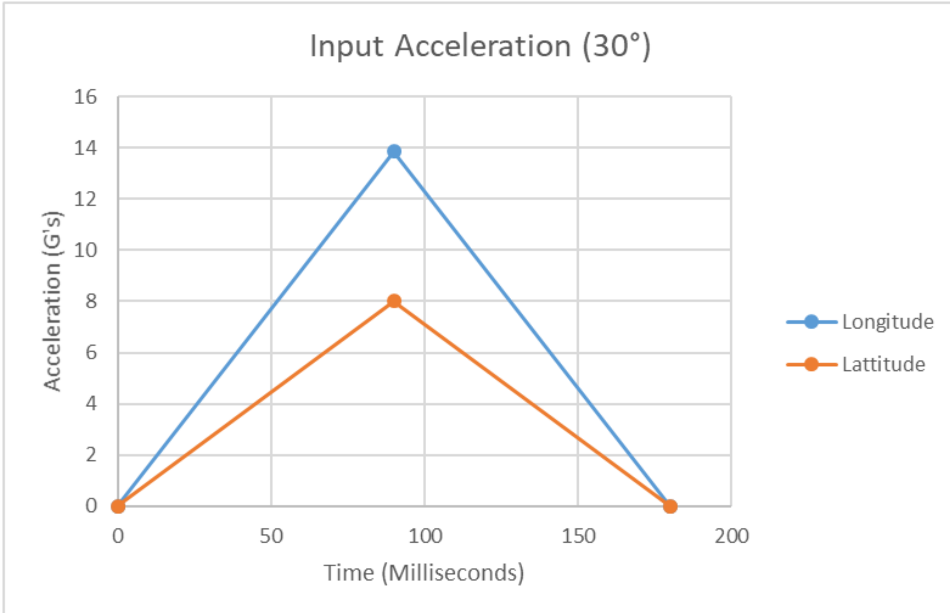


Figure 3.8: Input acceleration components at 30 degrees

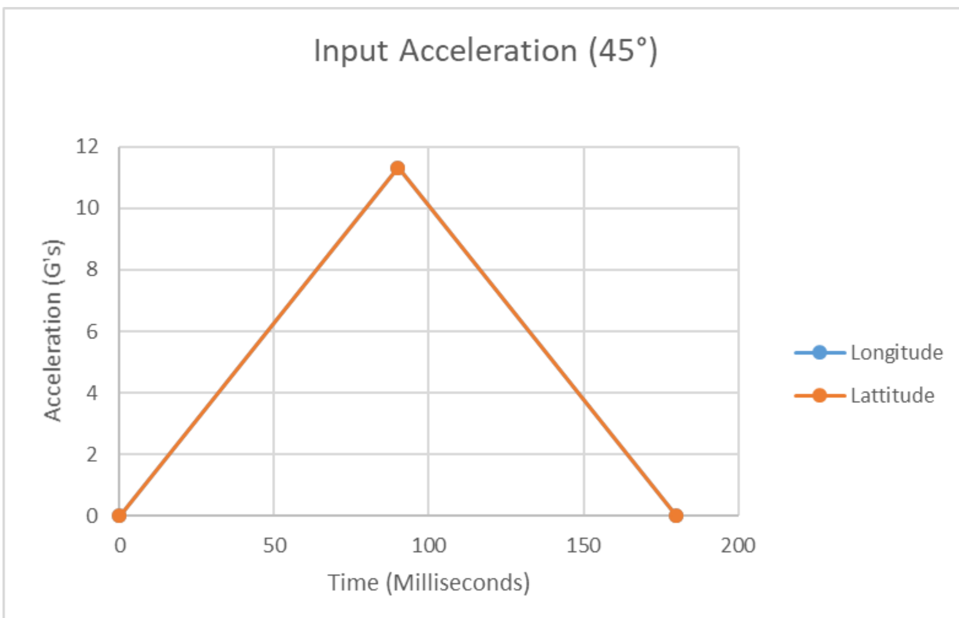


Figure 3.9: Input acceleration components at 45 degrees

To make the construction of multiple models at different angles more efficient, rather than positioning the dummy and the entire seat structure at various angles, the applied force was broken into sine and cosine components. Figure 3.10 visualizes the above explanation, and Table 2 provides the input acceleration values for each angle.

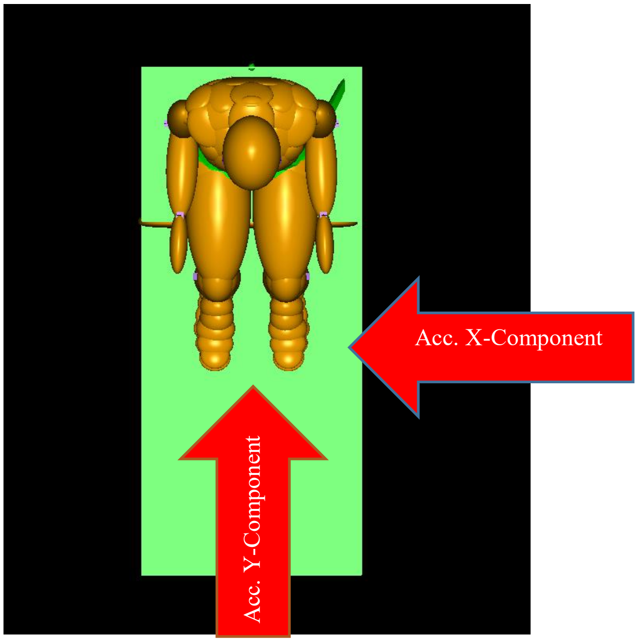


Figure 3.10: Method of application of the acceleration

Table 3.2: Acceleration input at 30 & 45 degrees

16G Acceleration	30 degrees	45 degrees
X component	135.9 m/s^2	111 m/s^2
Y component	78.5 m/s^2	111 m/s^2

The x-component of the accelerations above is positive because they are applied to the dummy. The sign of the y-component does not matter as it only changes the direction of the movement of the dummy. For the purposes of this study, the sign is negative, so the dummy moves to its right.

A simple horizontal friction function of .05 was applied to all the simulations. Among all contact points of the test, such as the feet and the ground, the back seat and the lumbar, and others, a friction coefficient of .3, and a damping coefficient of 100 was applied. The duration of each simulation was 200 milliseconds, and the time step was 1.0 x 10^{-5} milliseconds.

CHAPTER 4

SIMULATIONS OF VARIOUS TEST CASES

4.1 Hybrid III Cases

The Hybrid III cases are the most widely used dummies for frontal collisions. In this study, it was mainly used for the longitudinal component of the collision. The chest of this dummy is not as sensitive as the EuroSID-2re, which will result in smaller variations of data among the different cases.

4.1.1 Hybrid III Case 1

Case 1 was simulated with similar conditions as the literature review. The dummy was sitting on the same seat, strapped with 2 belts, a lap belt which had 2 connection points on the sides of the seat, and a body center belt, once again with 2 connection points, one of which was shared with the lap belt and the other behind the lower back of the passenger. For easier modeling purposes, the dummy was not at an angle; instead, the force was applied in components. The 16 G horizontal force was applied to the dummy with a 45-degree angle, which resembled that of a passenger sitting at 45 degrees and colliding with a 16G longitudinal force at 0 degrees. Figure 4.1 shows the setup.

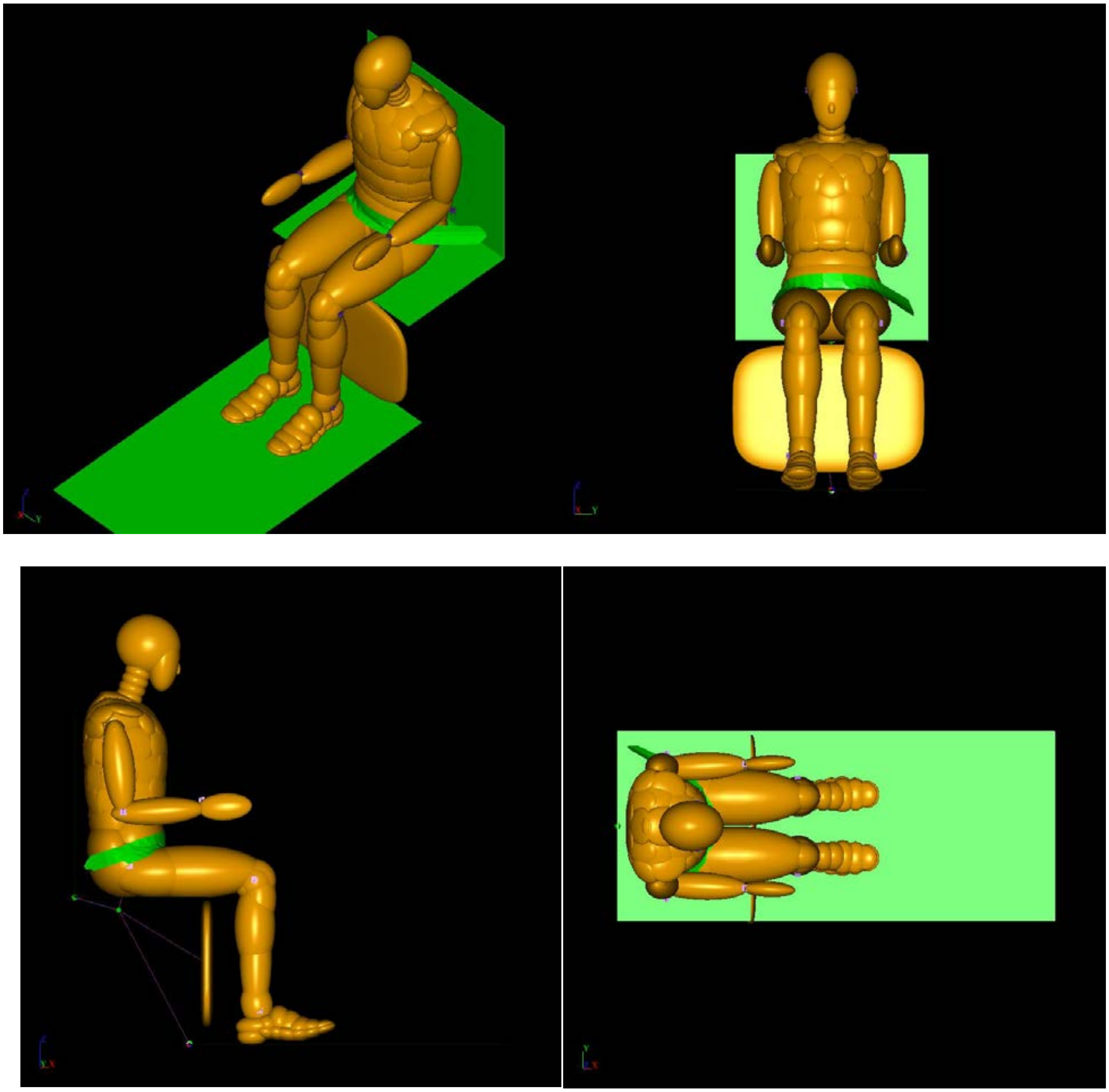


Figure 4.1: 4 different views of the Hybrid III dummy setup for case 1

The simulations are shown in Figure 4.2. For this case and all of the following cases, it's important to note that the input parameters were those explained earlier.

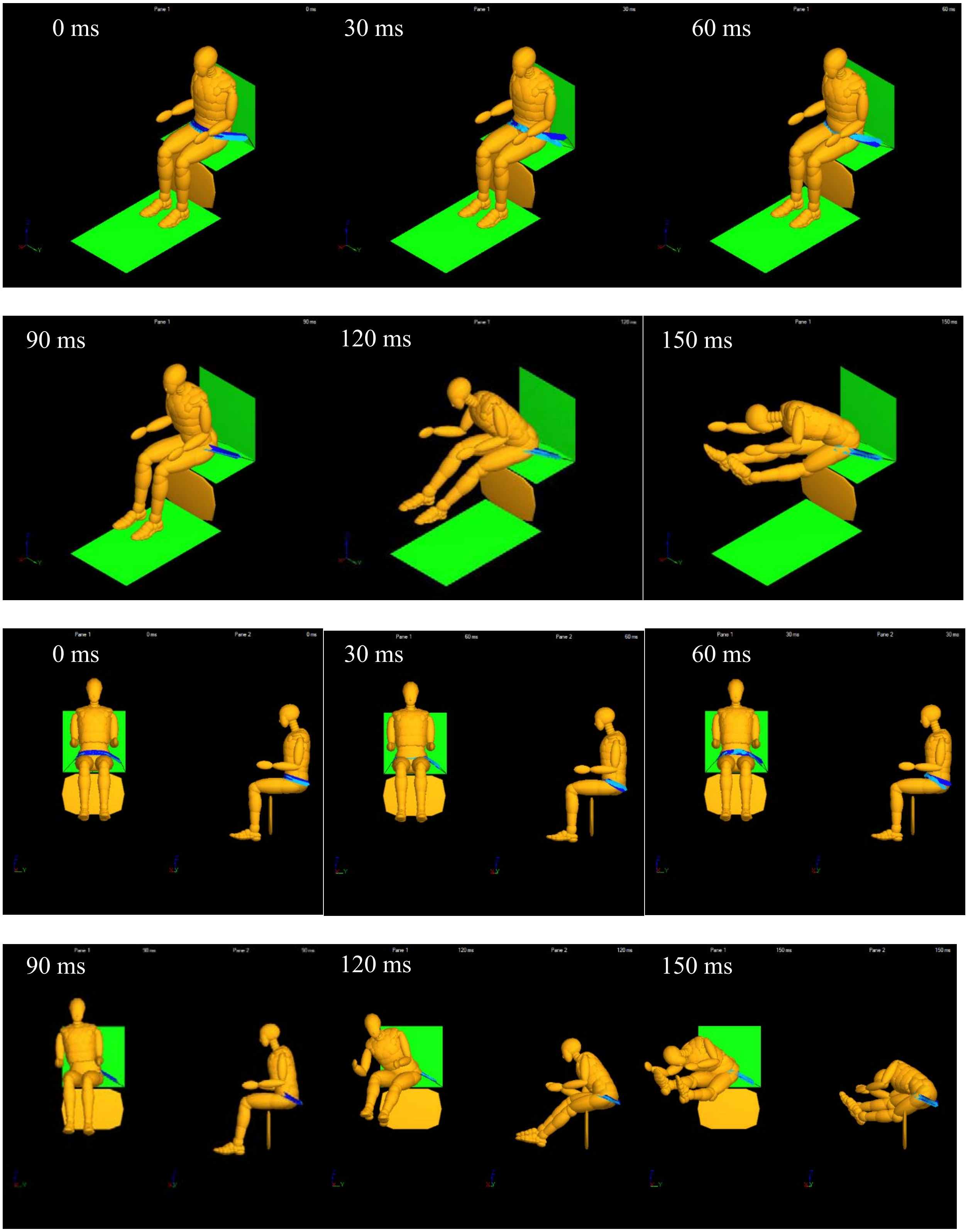


Figure 4.2: Hybrid III case 1 simulation snapshots from the front, side, and isometric view

4.1.2 Hybrid III Case 2

Case 2 has a very similar setup to case 1. The addition of the arm rest is the main difference, which is shown by the plane on the side of the dummy. The same force as case 1 is applied, and the dummy crashes into the arm rest. The setup is shown in Figure 4.3, and the simulations at 6 different steps are shown in Figure 4.4.

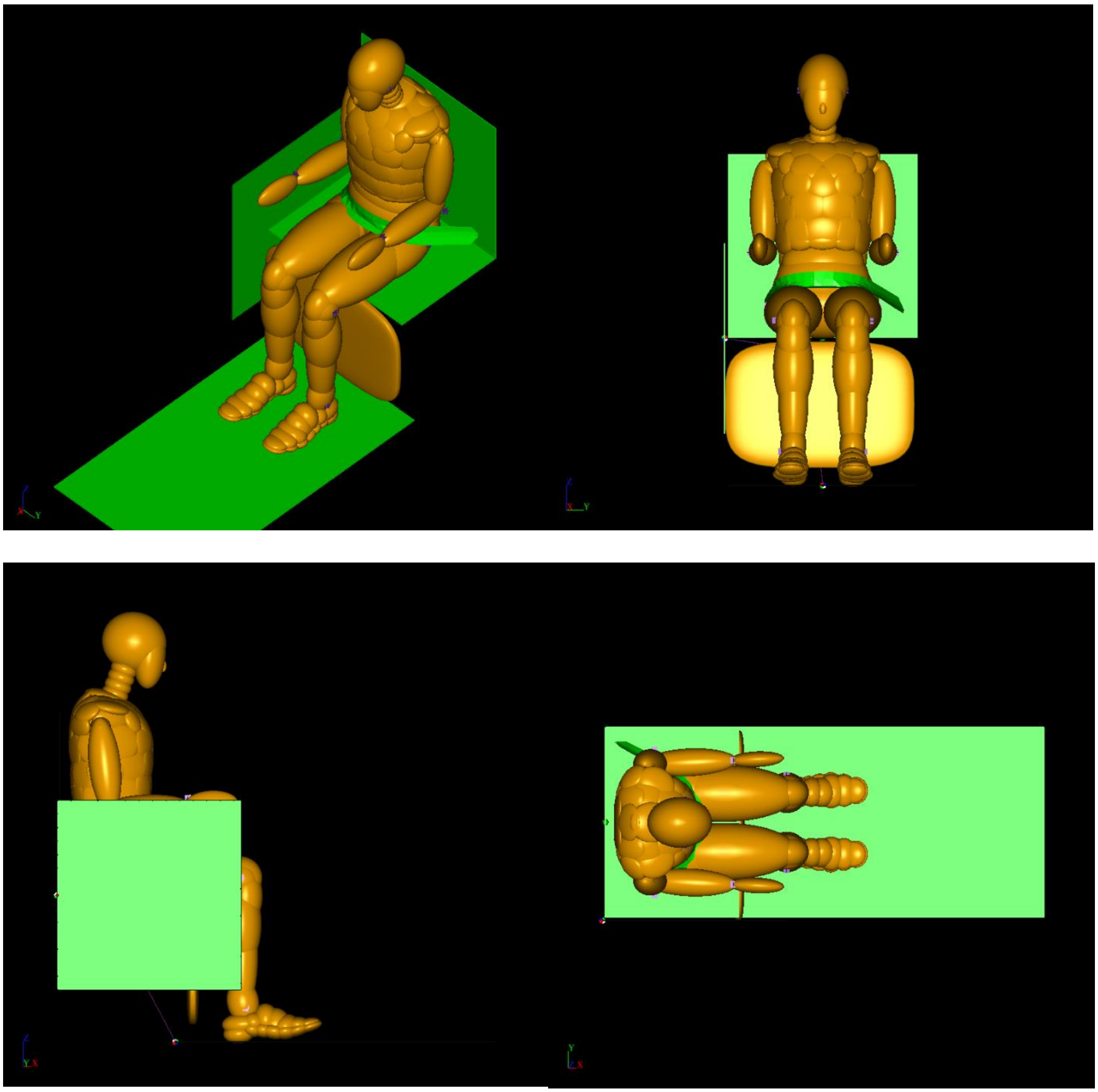


Figure 4.3: 4 different views of the Hybrid III dummy setup for case 2

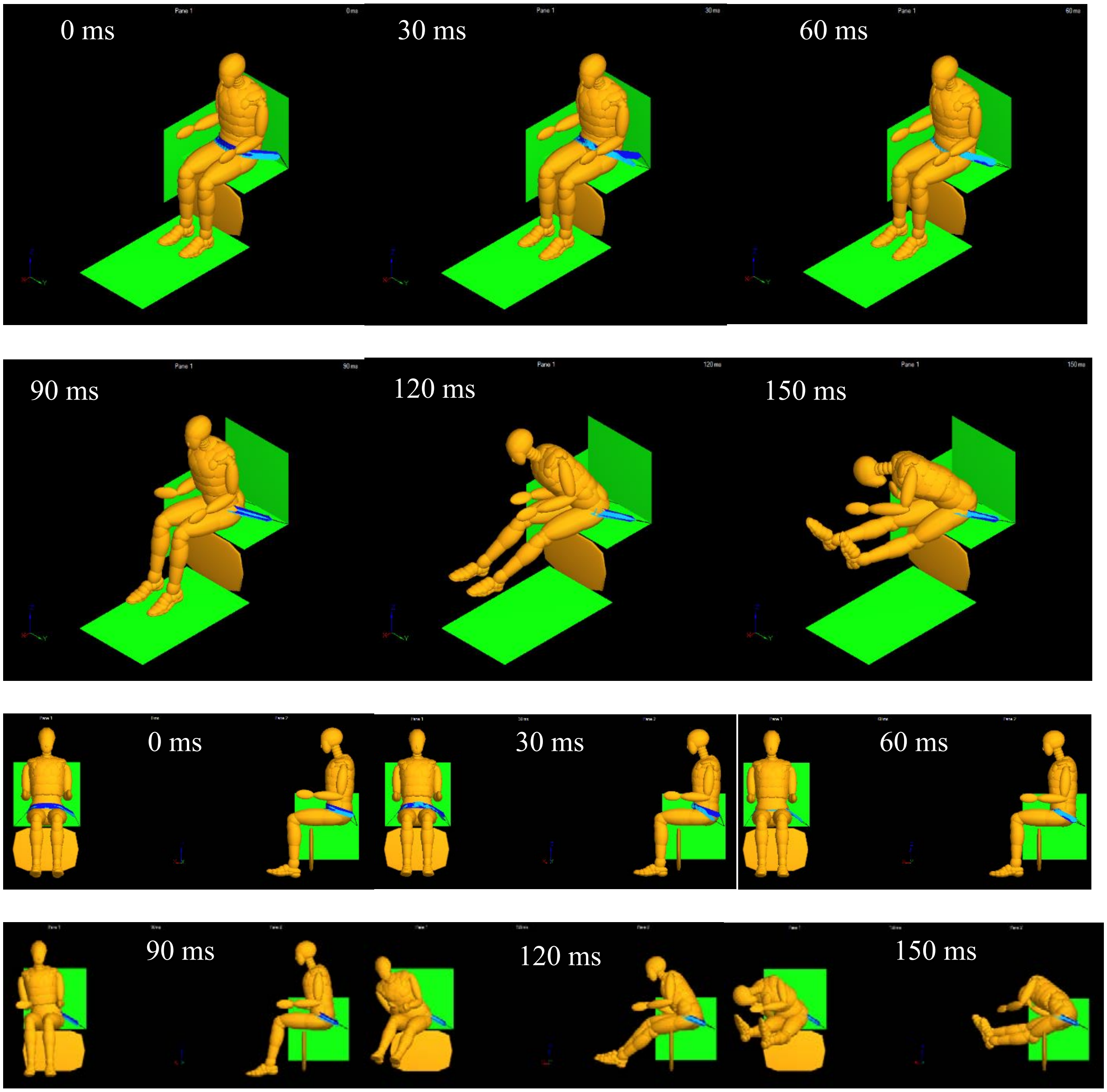


Figure 4.4: Hybrid III case 2 simulation snapshots from the front, side, and isometric view

4.1.3 Hybrid III Case 3

This case has a larger deviation. The same Hybrid III dummy is used for the simulation; however, the arm rest is taken out, and the 16G force is applied at a 30 degree angle. The effects are expected to be less severe, as the force aligns itself closer to the horizontal. The setup is shown in Figure 4.5 and the simulation steps are shown in Figure 4.6.

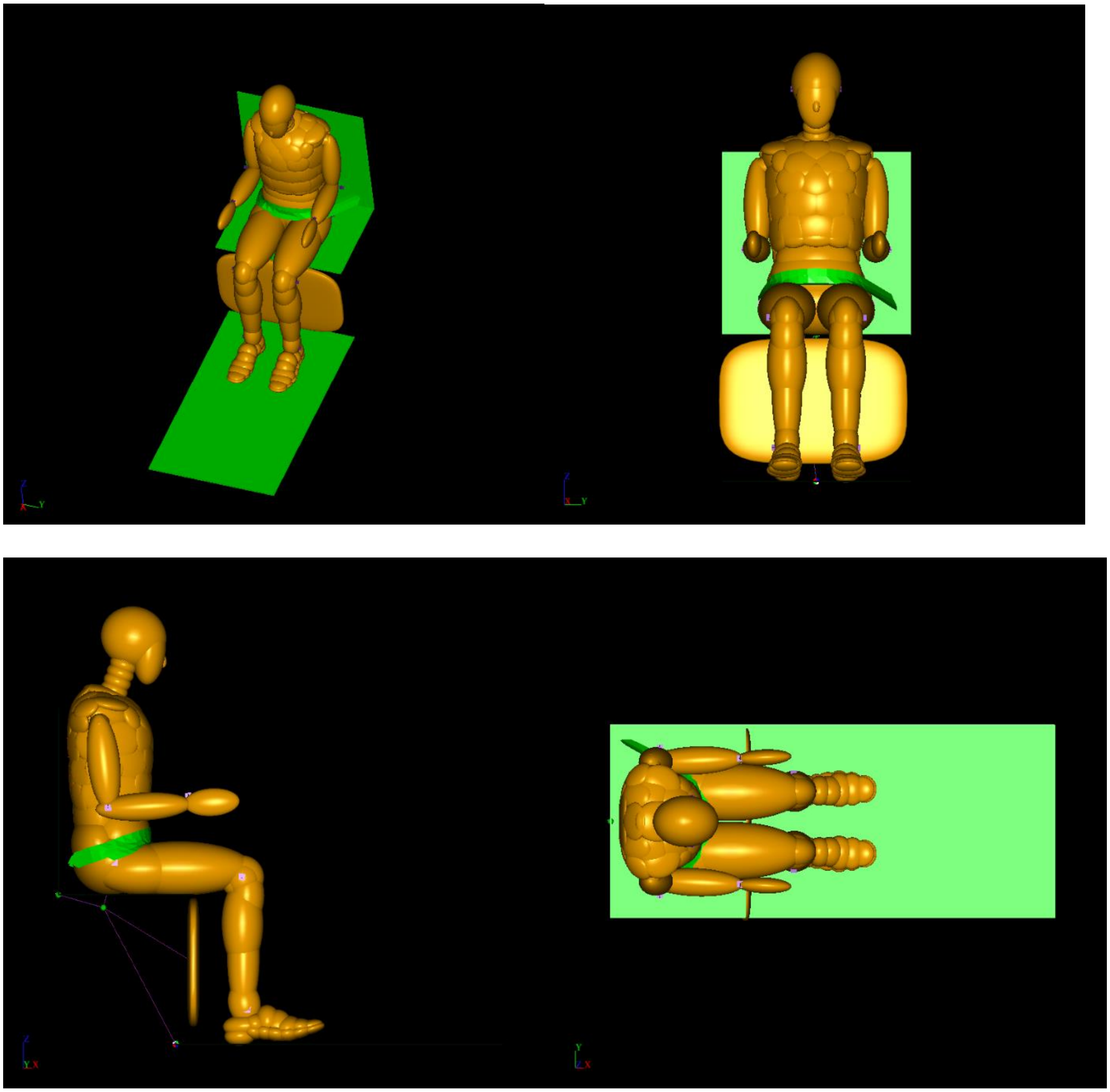


Figure 4.5: 4 different views of the Hybrid III dummy setup for case 3

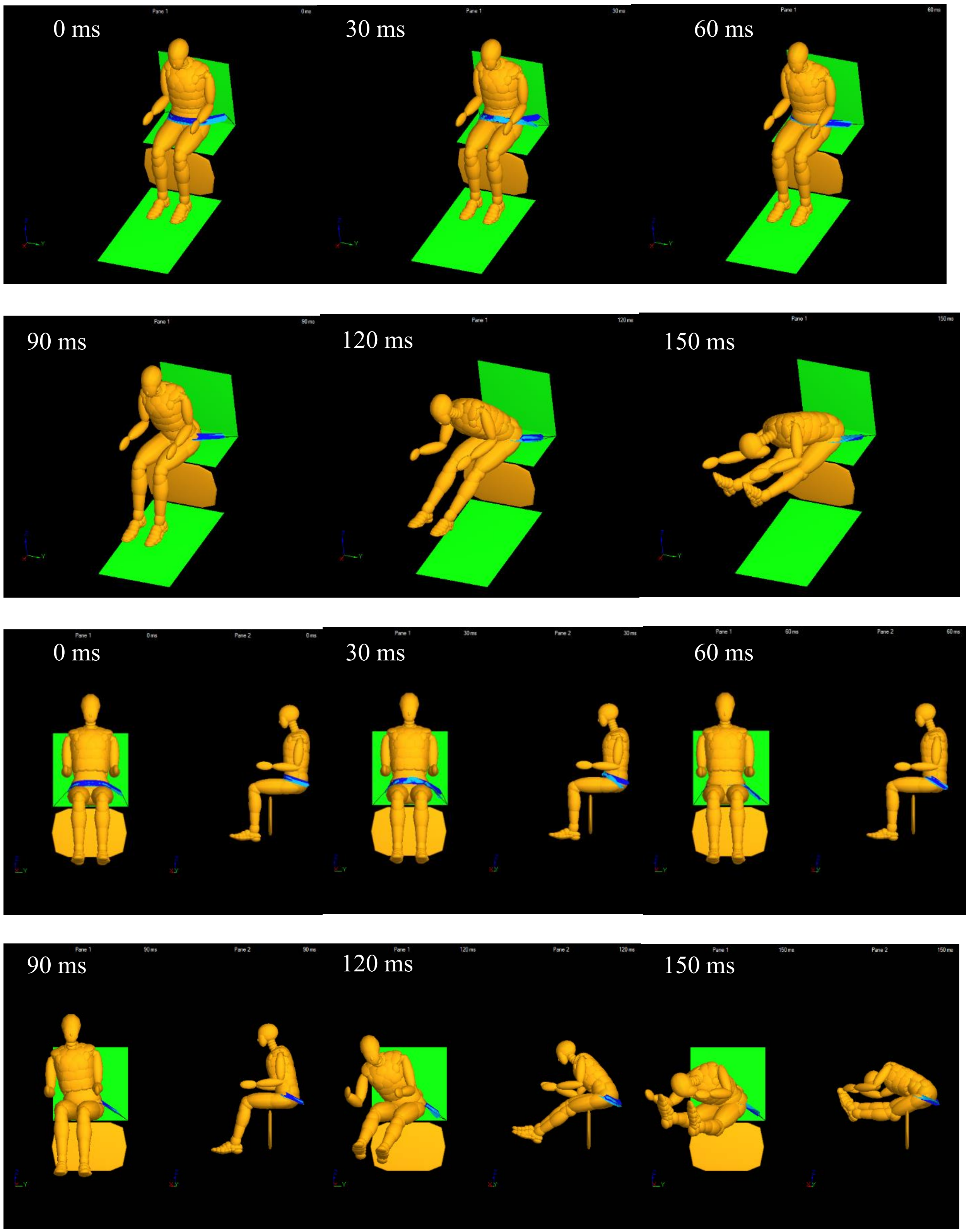


Figure 4.6: Hybrid III case 3 simulation snapshots from the front, side, and isometric view

4.2 ES2_RE Cases

All the above simulations were repeated with a EuroSID-2re Dummy, with all the parameters remaining the same. This was done so to better understand the effects of a side impact, as the EuroSID-2re is designed for such collisions. The setup for all 3 cases are explained below in a similar manner as the hybrid III dummy.

4.2.1 ES2_RE Case 1

Case 1 in Figure 4.7 was at 45 degrees, with 2 belts, and no side arm. Figure 4.8 shows the simulation snapshots for 150 milliseconds.

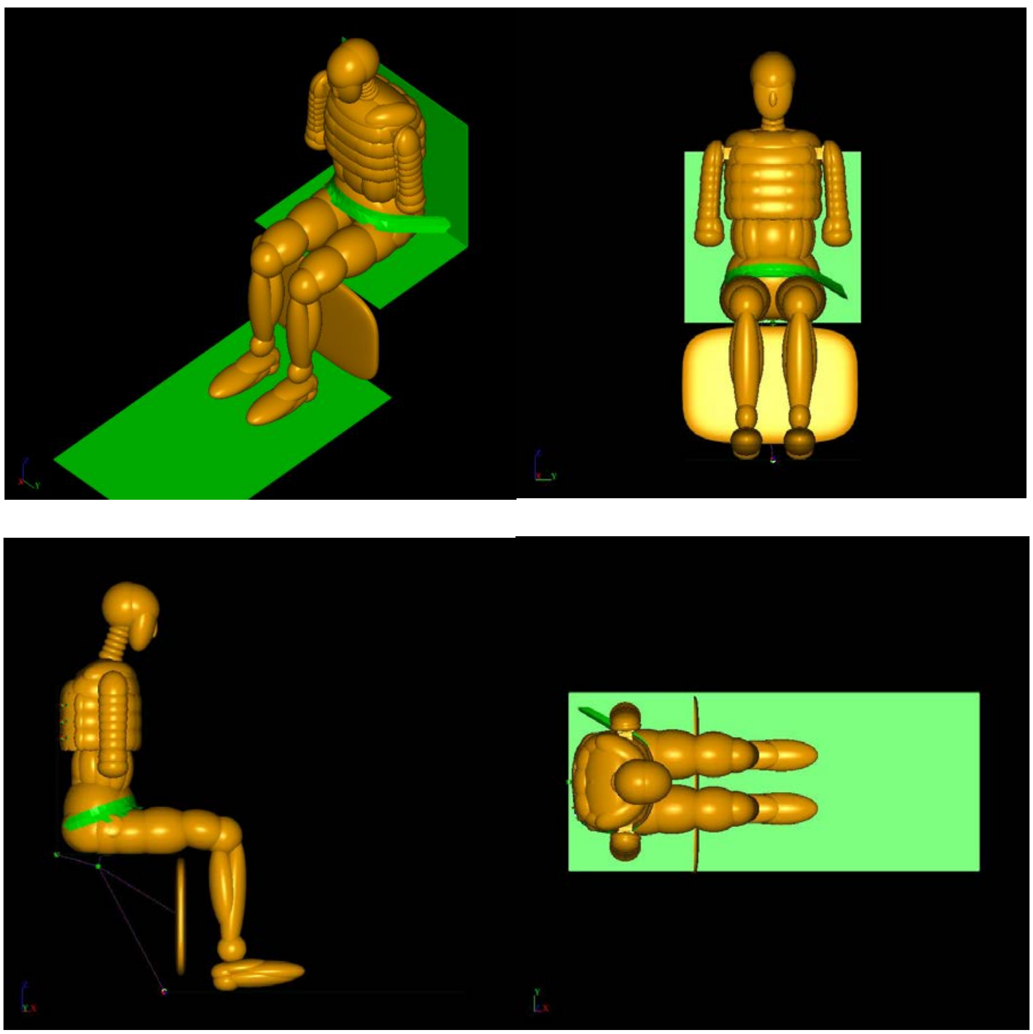


Figure 4.7: 4 different views of the ES-2re dummy setup for case 1

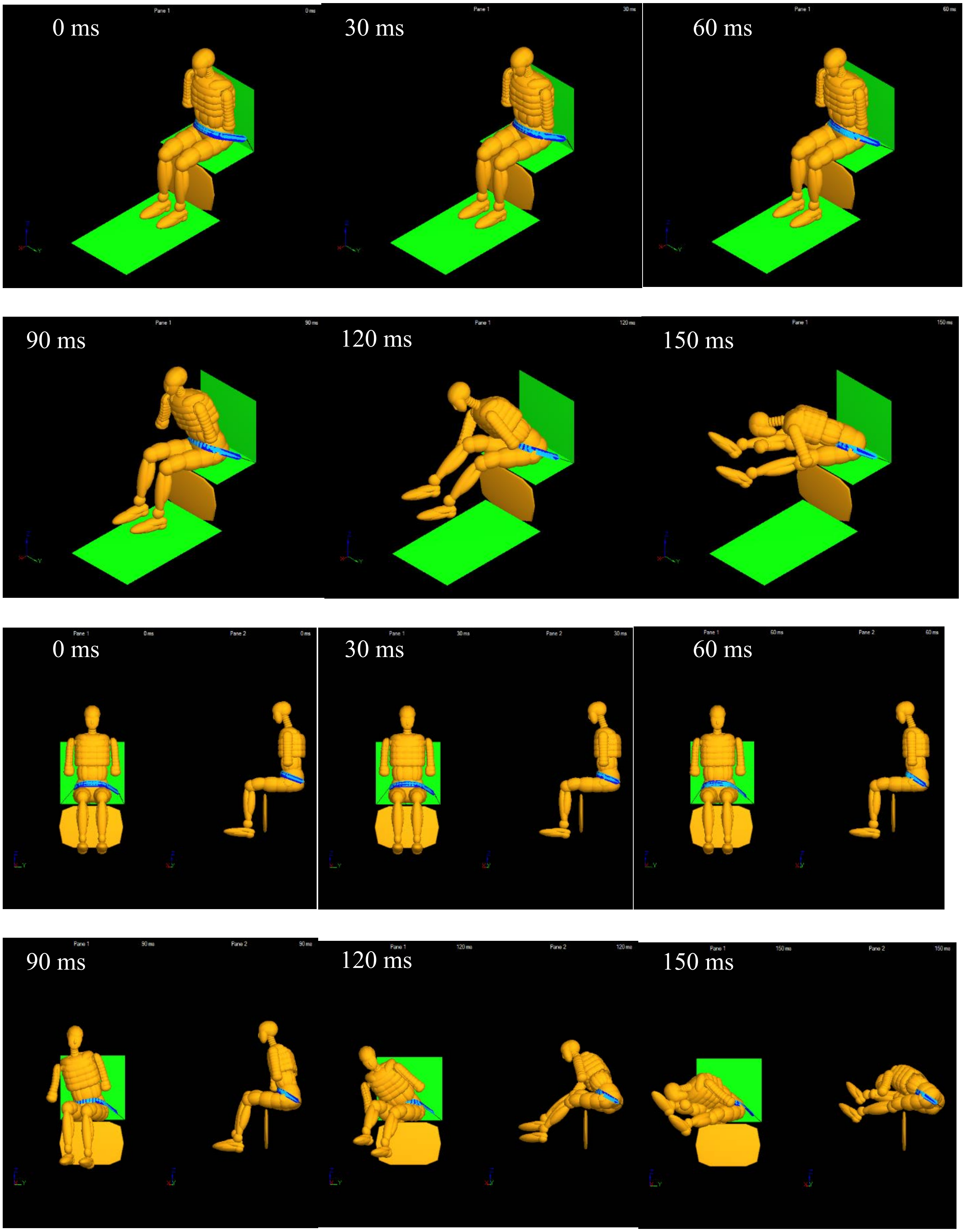


Figure 4.8: ES-2re case 1 simulation snapshots from the front, side, and isometric view

4.2.2 ES2_RE Case 2

The second case added the arm rest, and the angle remained the same 45 degrees. Expectations were that for this case, the side impact should be more severe. Figure 4.9 shows the setup, and Figure 4.10 shows the simulation snapshots.

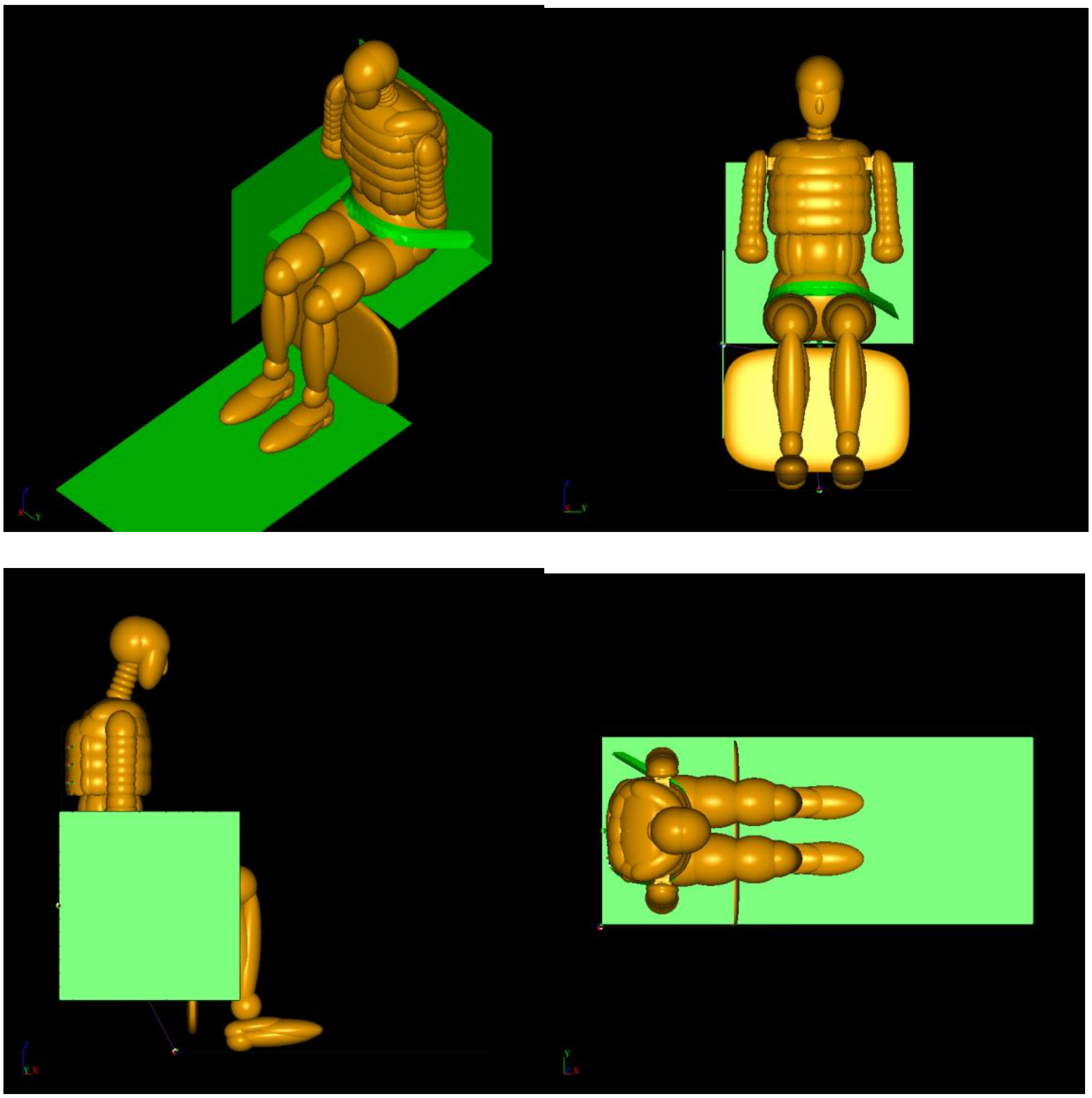


Figure 4.9: 4 different views of the ES-2re dummy setup for case 2

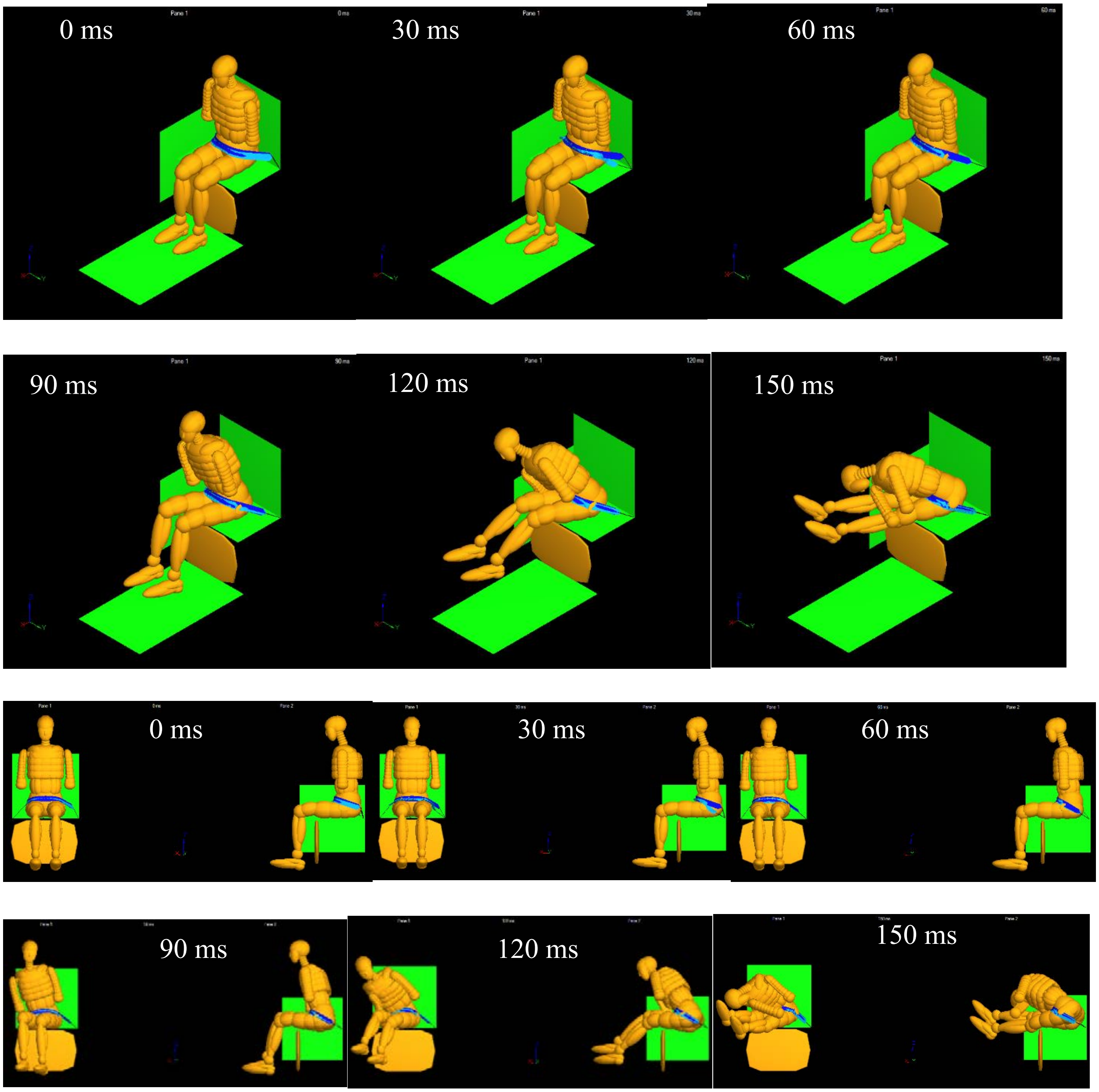


Figure 4.10: ES-2re case 2 simulation snapshots from the front, side, and isometric view

4.2.3 ES2_RE Case 3

The 3rd case was different in that the angle of the applied force varied. It reduced to 30 degrees, and the arm rest was taken away. Figure 4.11 shows the four different views of the setup, and Figure 4.12 shows the simulation snapshots.

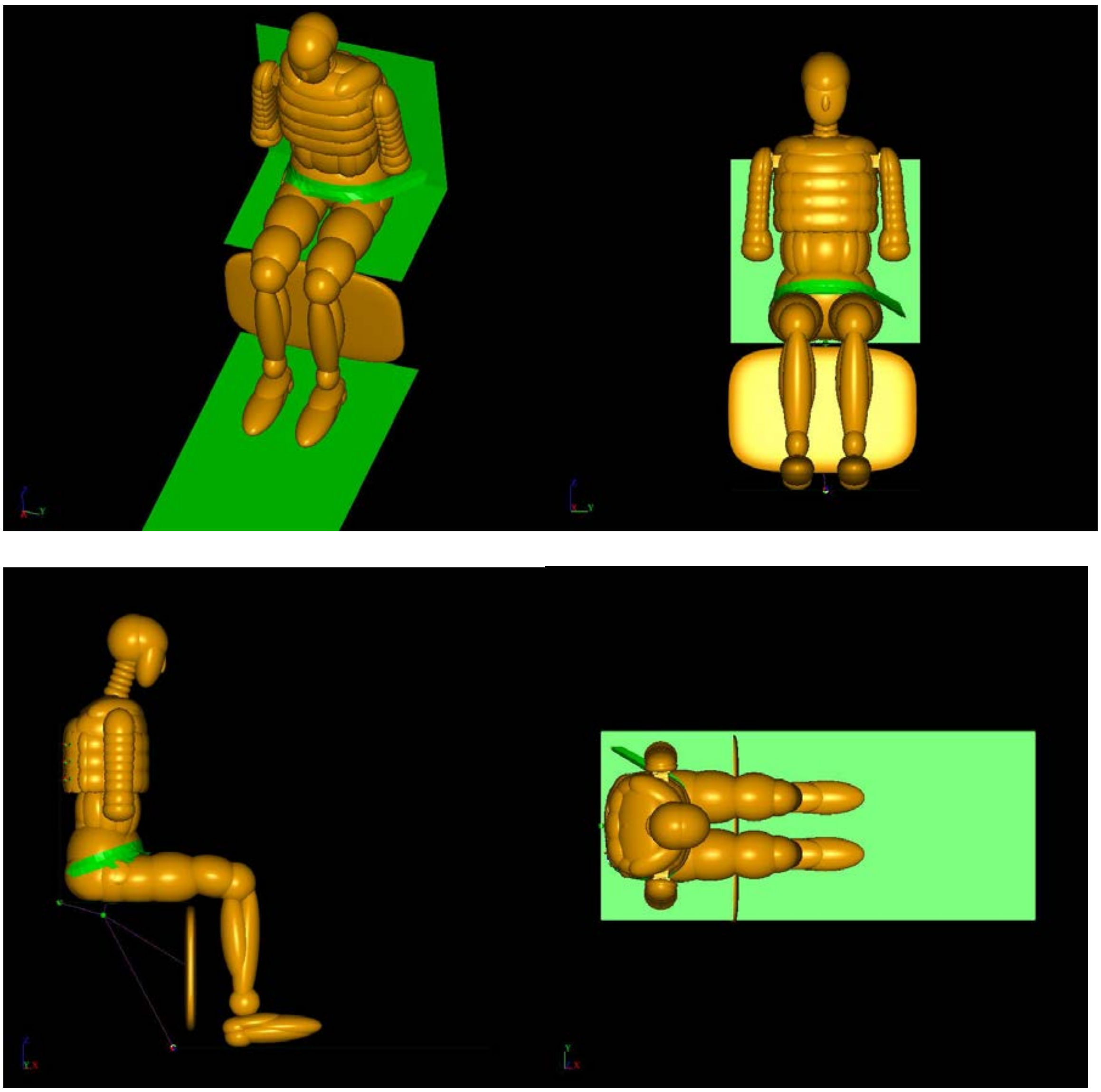


Figure 4.11: 4 different views of the ES-2re dummy setup for case 3

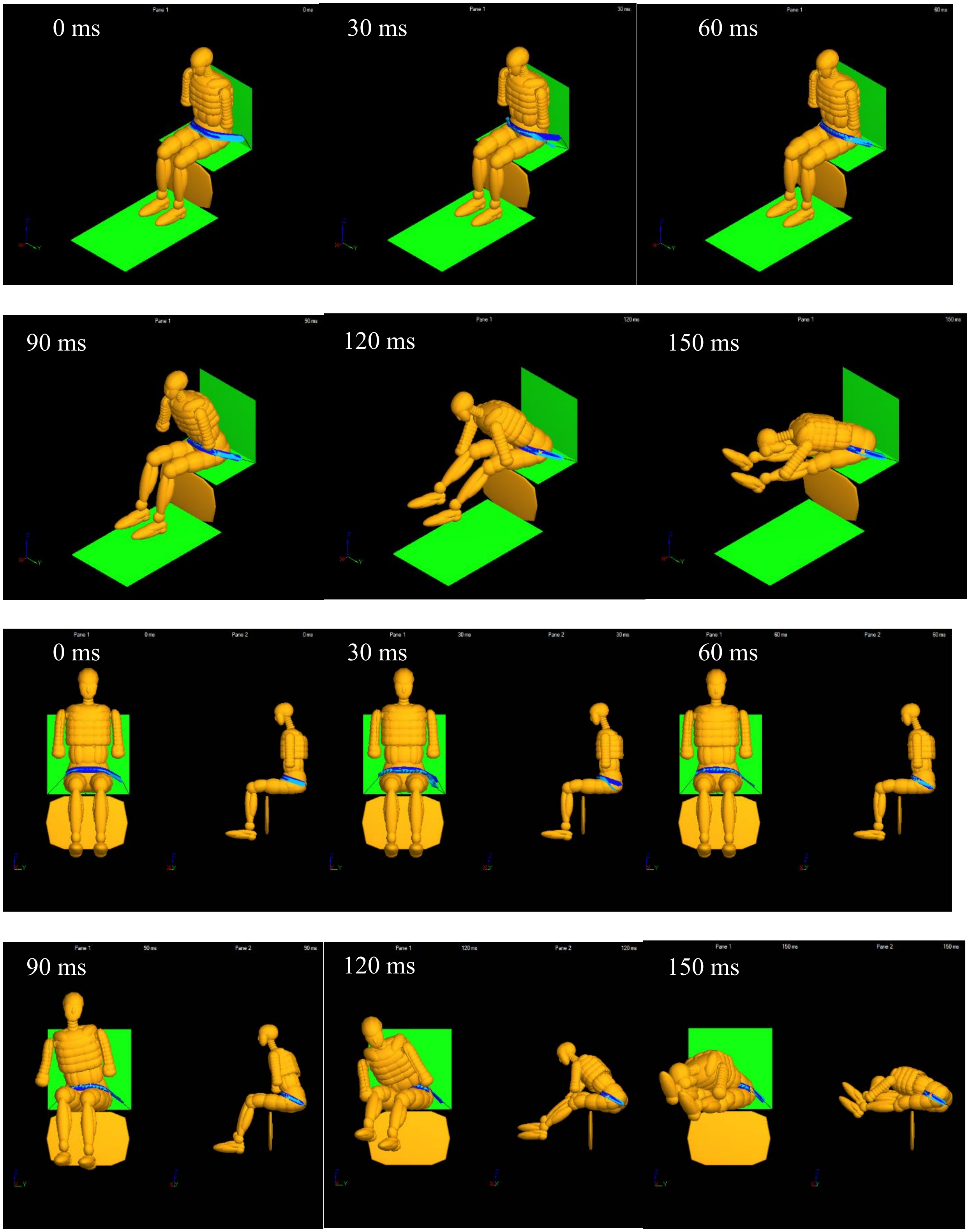


Figure 4.12: ES-2re case 3 simulation snapshots from the front, side, and isometric view

4.3 Other Cases

4.3.1 Case 1.b

In order to get a better perspective on the changes among the cases, 3 extra cases were introduced. The first is case 1.b, which is a variation of case 1. It remains at a 45 degree angle, but removes the body belt. This case can better serve to understand the effects of belts on the dummy. The setup looks similar to case 1, but the simulation snapshots vary slightly. Figure 4.13 shows the small difference between case 1 and case 1.b in the belt setup.

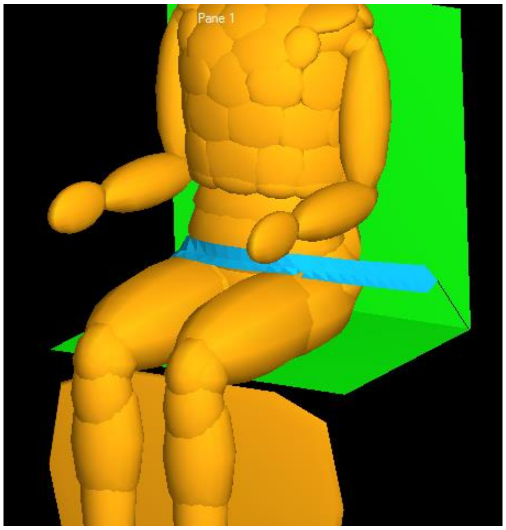


Figure 4.13: The setup for case 1.b, with no arm rest and lap belt only

4.3.2 4.3.2 Case 1.c

Case 1.c is a variation of case 2. It has the same setup, except it removes the lap belt. The differences in the belt setups can give better indications of how the belts affect the dummies when the arm rest is present. Figure 4.14 shows the setup.

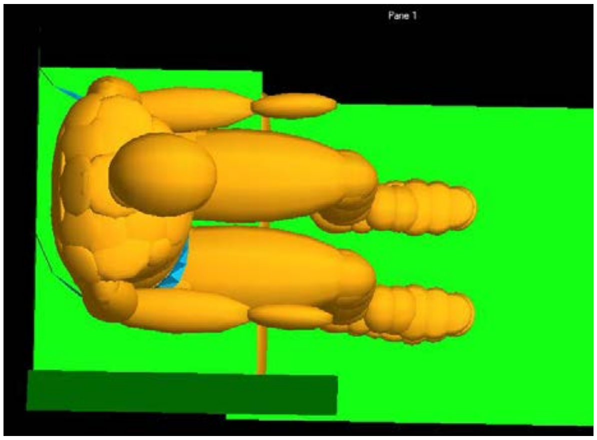


Figure 4.14: The setup for case 1.c, with body belt only and arm rest

4.3.3 Case 2.b

Case 2.b is a hybrid of case 2 and case 3. It has the arm rest, with only the lap belt, but it is set up at 30 degrees instead of 45. Figure 4.15 shows the setup for this case.

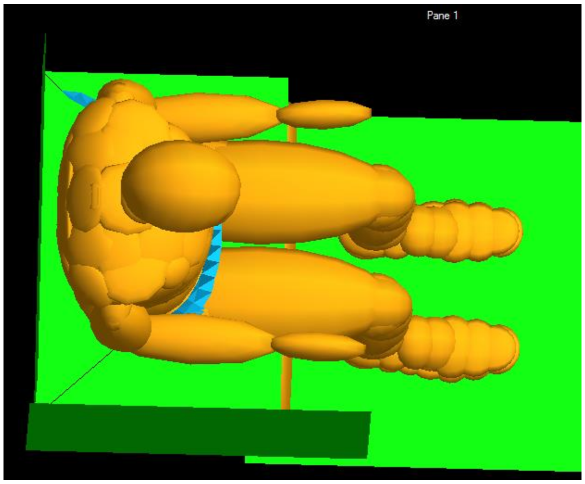


Figure 4.15: The setup for case 2.b, with lap belt only and arm rest

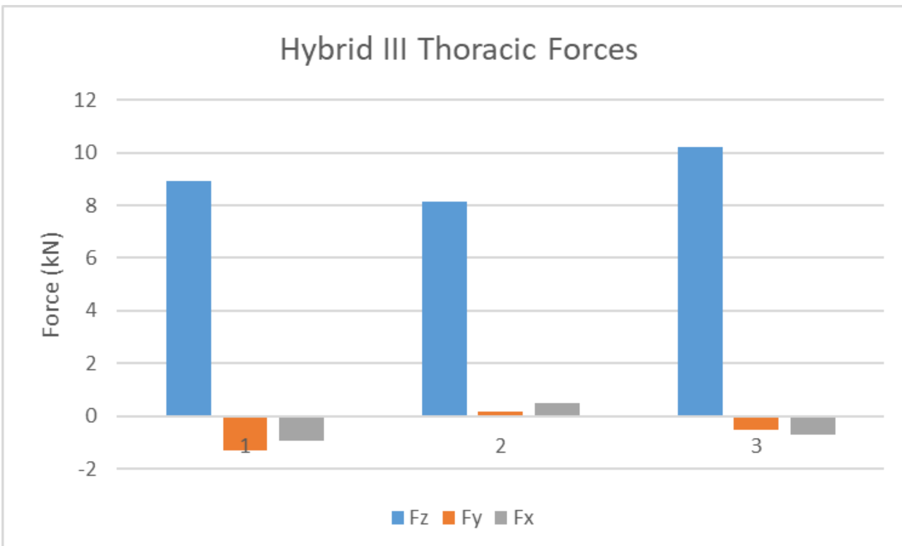
CHAPTER 5

COMPARISON OF RESULTS

5.1 Forces and Moments

5.1.1 Thoracic Region

After all the simulations were completed, the results were summarized and are shown below. Figure 5.1 and Table 3 are related to the thorax region of the body—the part of the body from the neck to the abdomen—for the Hybrid III dummy:



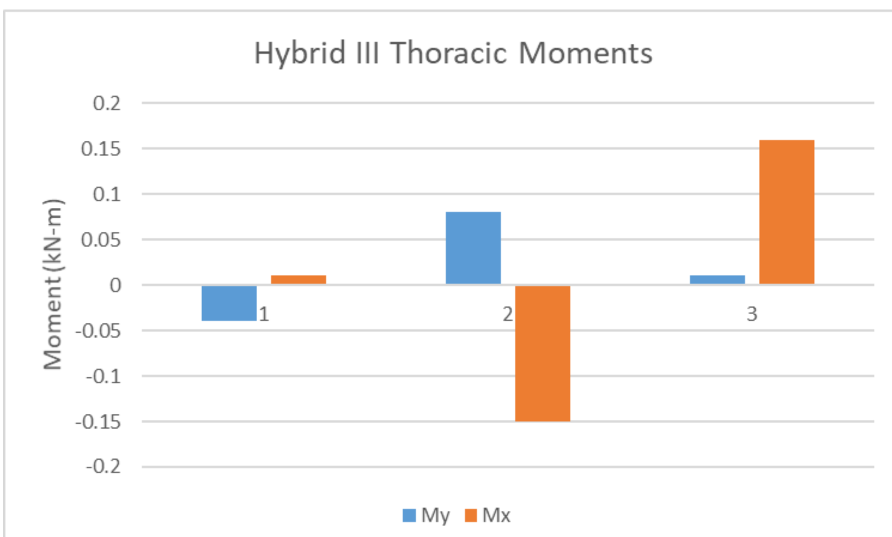


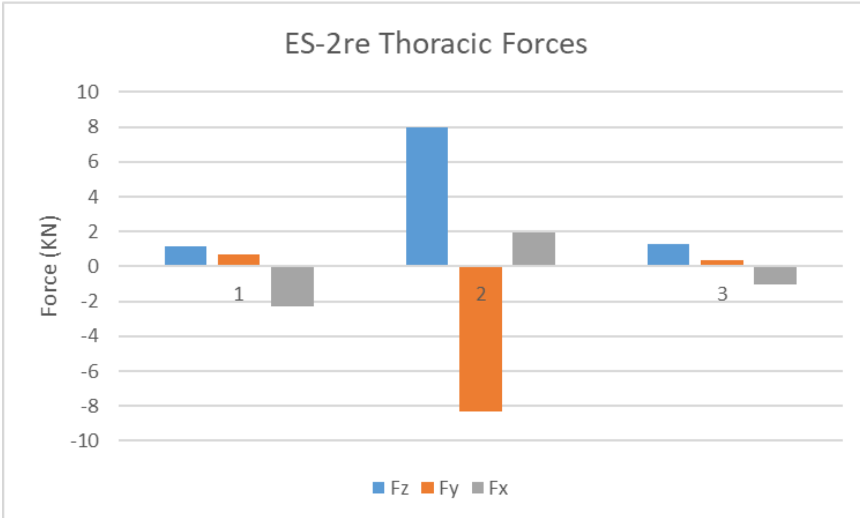
Figure 5.1: Hybrid III thoracic forces and moments for cases 1, 2, and 3 displayed graphically

Table 5.1: Tabulated thoracic forces for Hybrid III simulations

Output	Orientation	Hybrid III (Simulated Cases)		
		1	2	3
Thoracic Forces (kN)	Fz	8.95	8.13	10.2
	Fy	-1.32	0.19	-0.52
	Fx	-0.95	0.50	-0.70
Thoracic Moments (kN-m)	My	-0.04	0.08	0.01
	Mx	0.01	-0.15	0.16

From the plots and the table, there are important comparisons that can be noticed. The first is that there are far greater forces acting in the z direction, up and down through body of the dummy, than the latitude and longitude direction. Second, it is interesting to point out the slight change in the force from case 1 to case 2. The addition of arm rest shows to not impact the thoracic region of the body. Third, it is evident that case 3 produces the highest force in the z direction, a non-expected result, considering case 3 is the closest alignment with the horizontal. Finally, it's safe to assume that moments do not play a major role in comparisons, as the values are all very small.

The next two plots and table provide the same information as above, except for the EuroSID-2re dummy. They are organized and compared the same way by Figure 5.2 and Table 4.



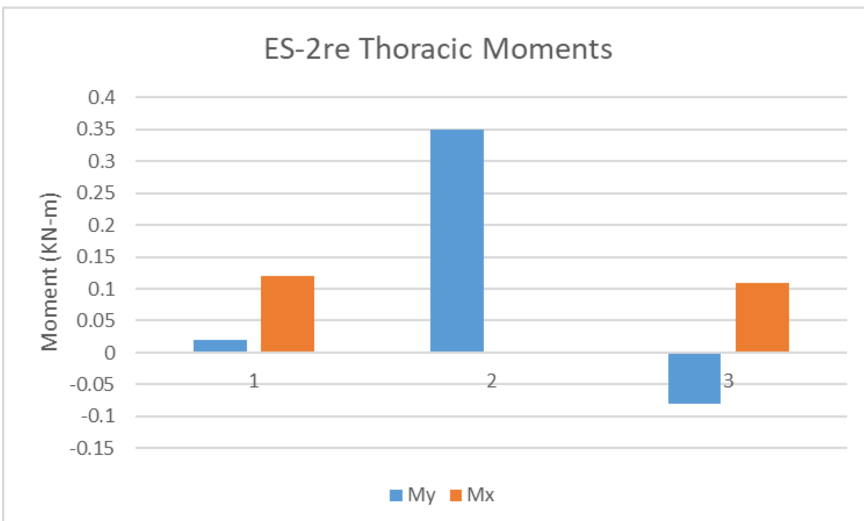


Figure 5.2: ES-2re thoracic forces and moments for cases 1, 2, and 3 displayed graphically

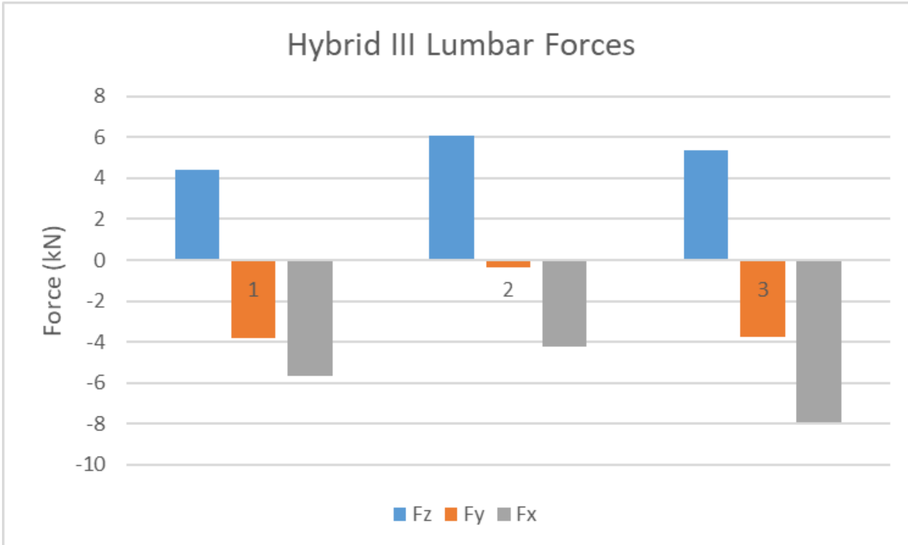
Table 5.2: Tabulated thoracic forces for ES-2re simulations

Output	Orientation	ES-2re (Simulated Cases)		
		1	2	3
Thoracic Forces (kN)	Fz	1.15	7.94	1.30
	Fy	0.66	-8.31	0.37
	Fx	-2.30	1.94	-1.04
Thoracic Moments (kN-m)	My	0.02	0.35	-0.08
	Mx	0.12	0.00	0.11

When comparing the forces for the ES-2re cases, the first fact that is noticeable is the significant difference between case 2 and the other cases. Case 2 thoracic force in the z direction is almost 7 times greater than case 1 and case 3. There is even a larger difference in the y or latitude direction. This is expected because of the addition of arm rest. Unlike the hybrid III case 2, EuroSID-2re dummy has more sensitivity in the thorax region, which clearly shows the effect of the addition of the arm rest. It is also evident once again that moments are non-factors, varying in an insignificant magnitude range of 0 to .35 kN-m

5.1.2 Lumbar Region

The next area of the body studied is the lumbar region. The lumbar is lower part of the spine and is significant in crash test. Figure 5.3 and Table 5 summarize the forces and moments on the lumbar region of the body for the Hybrid III dummy.



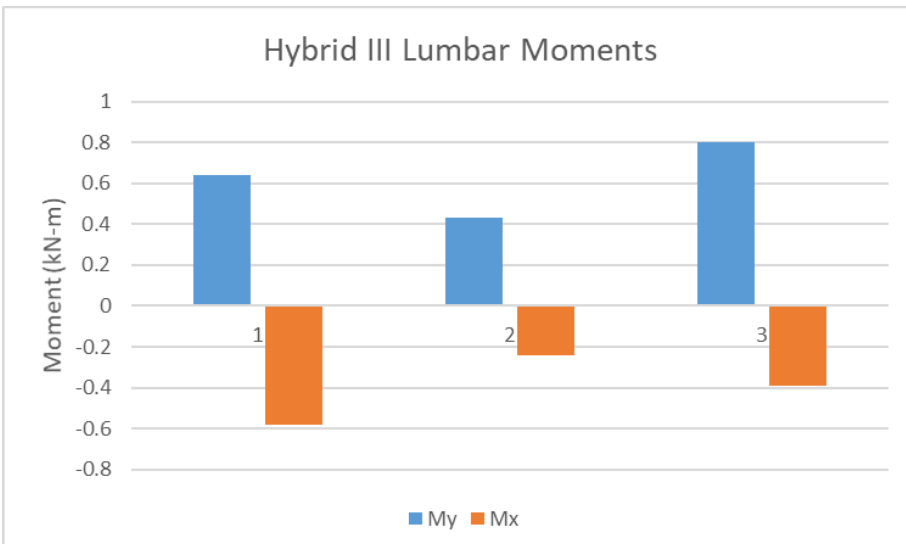


Figure 5.3: Hybrid III lumbar forces and moments for cases 1, 2, and 3 displayed graphically

Table 5.3: Lumbar forces for Hybrid III simulations

Output	Orientation	Threshold	Hybrid III (Simulated Cases)		
			1	2	3
Lumbar Forces (kN)	Fz	5.2 kN	4.42	6.09	5.36
	Fy		-3.82	-0.35	-3.75
	Fx		-5.64	-4.24	-7.93
Lumbar Moments (kN-m)	My		0.64	0.43	0.80
	Mx		-0.58	-0.24	-0.39

For the lumbar region, the variation of forces in the z direction is not large. Case 2 does produce the biggest value, while the largest magnitude of force produced in the y and x direction are from case 1 and case 3, respectively. Case 2 and case 3 exceed the 5.2 kN threshold suggested by the literature. The lumbar region, as oppose to the thoracic region, goes through roughly the same motion for all 3 cases. Therefore, large variations in the forces and the moments are not out of ordinary. Figure 5.4 and table 6 summarize these results.

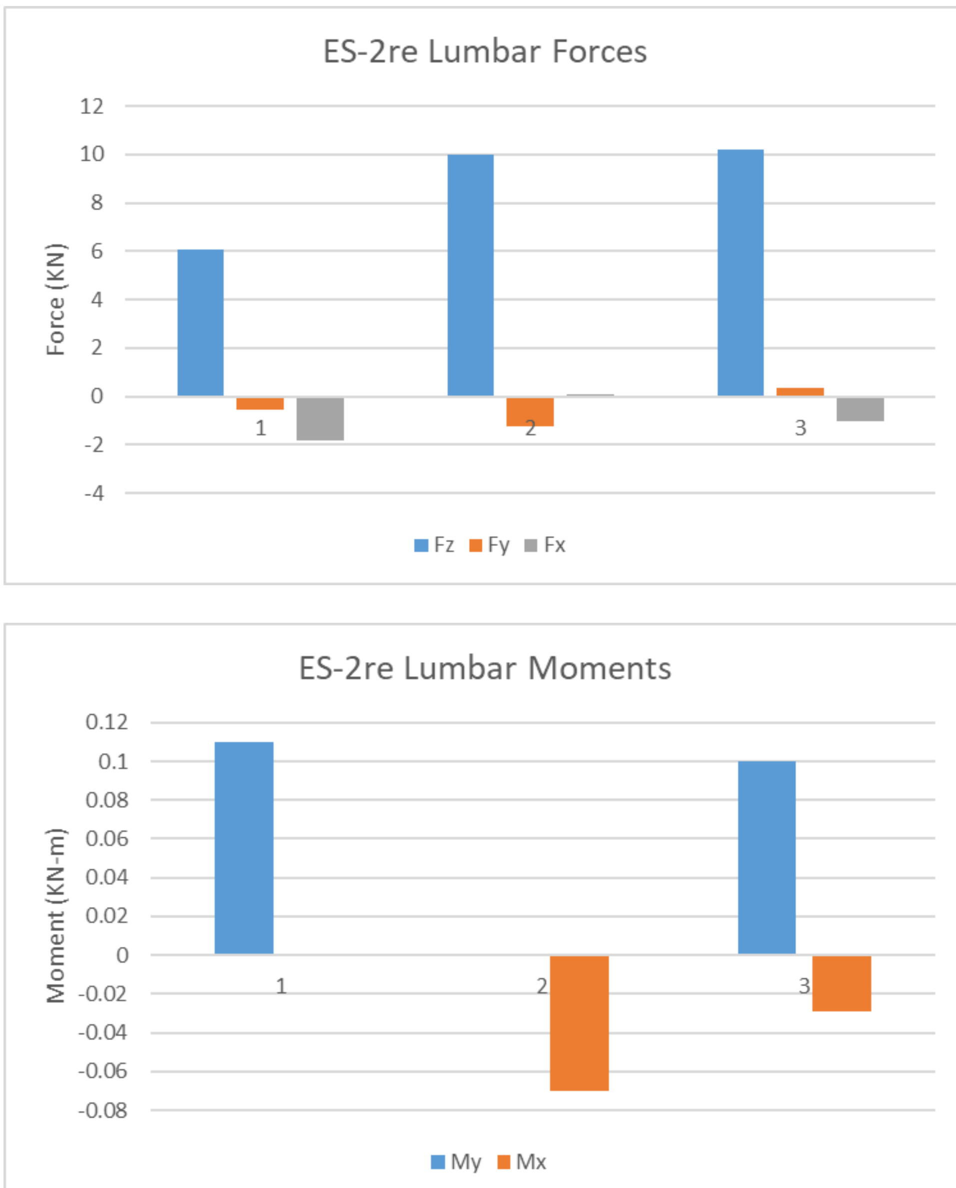


Figure 5.4: ES-2re lumbar forces and moments for cases 1, 2, and 3 displayed graphically

Table 5.4: Lumbar forces for ES-2re simulations

Output	Orientation	Threshold	ES-2re (Simulated Cases)		
			1	2	3
Lumbar Forces (kN)	Fz	5.2 kN	6.09	10.00	10.18
	Fy		-0.55	-1.22	0.34
	Fx		-1.83	0.08	-1.05
Lumbar Moments (kN-m)	My		0.10	0.00	0.10
	Mx		0.00	-0.07	-0.029

For the ES-2re model, the variation is larger. Case 2 shows an increase of roughly 4 kN in the z-direction, while case 3 remains to be close to case 2. All 3 cases cross the threshold of 5.2 kN suggested by the literature. In the y or lateral direction, case 2 produces the largest value, while case 1 is responsible for the largest force in the longitudinal direction. Moments in all direction remain to be insignificant.

5.2 Comparison with Literature Review

The comparison of data achieved with those provided by the literature is what solidifies the simulations. Table 5.5 is a comparison of data among the two models simulated by the author of this study and the data provided by reviewed literature.

Table 5.5: Comparisons of all simulated cases and literature provided results

Output	Orientation	Threshold	Hybrid III (Simulated Cases)			ES-2re (Simulated Cases)			Literature Cases (Experimental)		
			1	2	3	1	2	3	1	2	3
Thoracic Forces (kN)	Fz		8.95	8.13	10.2	1.15	7.94	1.30	11	11.5	13
	Fy		-1.32	0.19	-0.52	0.66	-8.31	0.37	-2	-3.5	-2
	Fx		-0.95	0.50	-0.70	-2.30	1.94	-1.04	-1	1	1.5
Lumbar Forces (kN)	Fz	5.2 kN	4.42	6.09	5.36	6.09	10.00	10.18	10	11	11
	Fy		-3.82	-0.35	-3.75	-0.55	-1.22	0.34	-5	-7	-5.2
	Fx		-5.64	-4.24	-7.93	-1.83	0.08	-1.05	-3	-0.5	-7
Thoracic Moments (kN-m)	My		-0.04	0.08	0.01	0.02	0.35	-0.08	-0.13	-0.4	-0.12
	Mx		0.01	-0.15	0.16	0.12	0.00	0.11	0.12	0.45	0.13
Lumbar Moments (kN-m)	My		0.64	0.43	0.80	0.10	0.00	0.10	0.17	0.02	0.3
	Mx		-0.58	-0.24	-0.39	0.00	-0.07	-0.029	-0.3	-0.4	-0.35

There are key facts to point out about the provided results above by the literature. The first is that these values are provided by plots. Therefore, a plot digitization tool had to be used to estimate the exact values. The second is the lack of exact information provided regarding the testing parameters. Examples include belt details, dummy details, and exact position of the dummy relative to the seat. The final fact to point out is that the research conducted by the literature is purely experimental with real dummies and not simulation. It's also important to point out that there are no reported results for ES-2re dummy.

Even with the above facts, the trends of the Hybrid III results resemble closely to what the literature provides. Looking at the Z direction forces for the thoracic region, the trend is similar to that of the literature. The difference in the values could be attributed to the differences in the seat structures, simulation vs. experimental research, and other various parameters. From the lumbar side, the provided values and the simulated values vary more. In the Z direction, for example, the lumbar force reported by the literature is almost twice the values calculated by the simulations. This is attributed to the limitations described above.

On the moment side, both the literature and simulated values show insignificance. They are very close to 0.

5.3 Injury Criteria

One of the main advantages of using a EuroSID dummy is the capability of injury evaluation. Aside from the forces and moments acting on the dummies, 4 injury criteria were used to compare the 3 cases. They include Viscous Criterion CFC180, Pelvic Acceleration, Chest deflection, and Thorax Trauma Index (TTI). Because these criteria do not provide meaningful results for Hybrid III dummies, ES-2re is used to add context to the injury side of these impacts. Table 5.6 shows the values for the injury criteria evaluated. The values in are red are those that exceed the threshold.

Table 5.6: Injury criteria values for ES-2re simulations

EuroSID-2re	Chest Def CFC180 Rib Up (mm)	Chest Def CFC180 Rib Mid (mm)	Chest Def CFC180 Rib Low (mm)	Pelvic Acceleration (G's)	VC (m/s)	TTI (Gs)
Injury Threshold	**43**			**130**	**1**	**85**
Case I	1.40	1.62	1.86	23.9	0.00	20.9
Case II	52.0	36.8	6.30	38.7	1.17	296.3
Case III	1.43	1.42	1.67	28.0	0.00	20.9

The viscous criterion derived above is a measurement of soft tissue injury induced by impact. It is the product of velocity of deformation and amount of compression. According to Lau, a VC of 1.0 corresponds to a 25% chance of sustaining severe thoracic injury [14].

The EuroSID-2re shows significant changes in the injury criteria when the arm rest is added. For the chest deflection, measured by the 3 ribs defined in the ES-2re dummy, it is easy to spot the significant difference. The deflection for Rib Up is the largest value among the 3, which makes sense, as the upper rib has the most significant contact with the top of the arm rest. The pelvic acceleration is also highest by case 2, as the arm rest makes a big contact with the pelvis region of the body. Figure 5.5 shows the pelvic acceleration of all 3 cases vs time. The largest value occurs at almost the height of the acceleration input. However, the arm rest causes a large disturbance in the pelvic acceleration, hence the multiple spikes throughout the simulation.

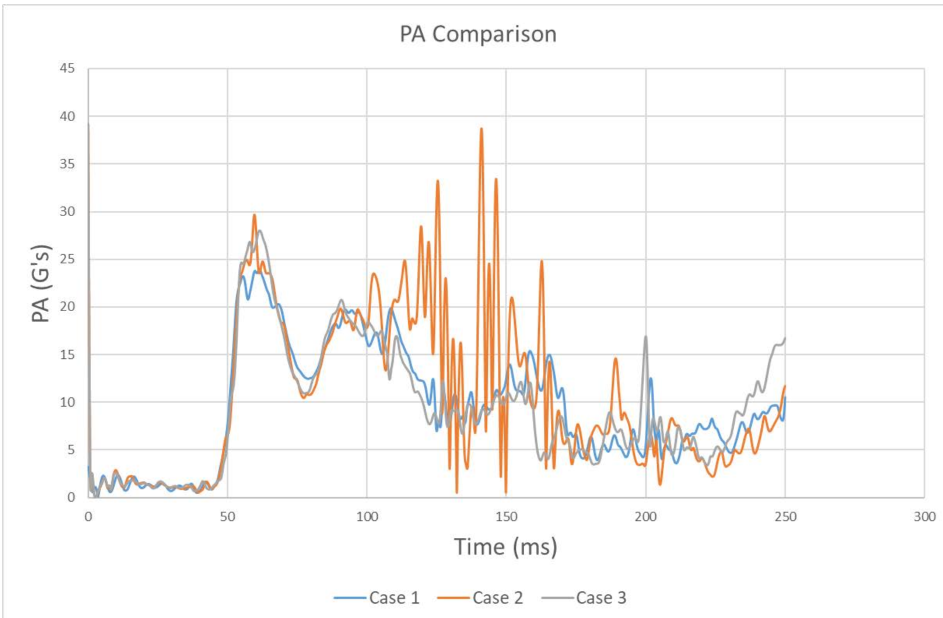


Figure 5.5: Pelvic acceleration of cases 1, 2, and 3 for ES-2re

The VC trend, shown for 250 milliseconds in Figure 5.6, for all 3 cases, shows expected results. The heavy impact on the chest from the arm rest was cause for a large value for the viscous criterion. A value of 1.17 for viscous criterion result in significant injuries. Case 1 and 3, on the other hand, show insignificant values for the viscous criterion.

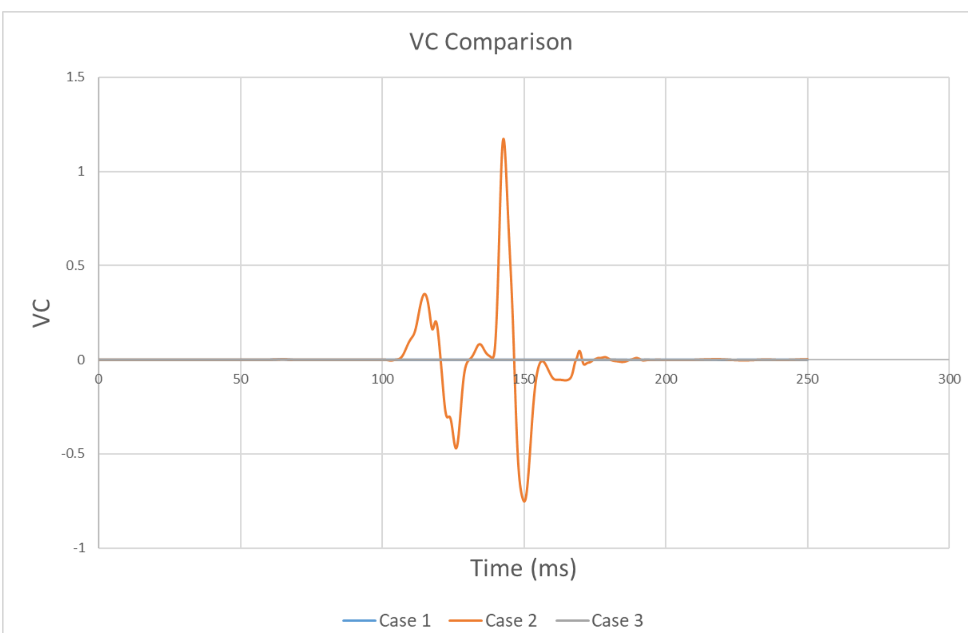


Figure 5.6: Viscous criterion behavior of cases 1,2, and 3 for ES-2re

Finally, the TTI for case 1 and 3 are almost the same, while case 2 is almost 15 times more, suggesting significant injury.

5.4 Belt Loads

Another method of comparison among the different simulations is belt anchor loads. These are the loads at the attachment point of the belts to the seat. Figure 5.7 and Figure 5.8 and Figure 5.9 show the anchor loads for the 3-different hybrid III cases for the lap belt. The ES-2re showed similar results, which are not published here. The left attachment of the lap belt is anchor point 1, and the right attachment is anchor point 2.

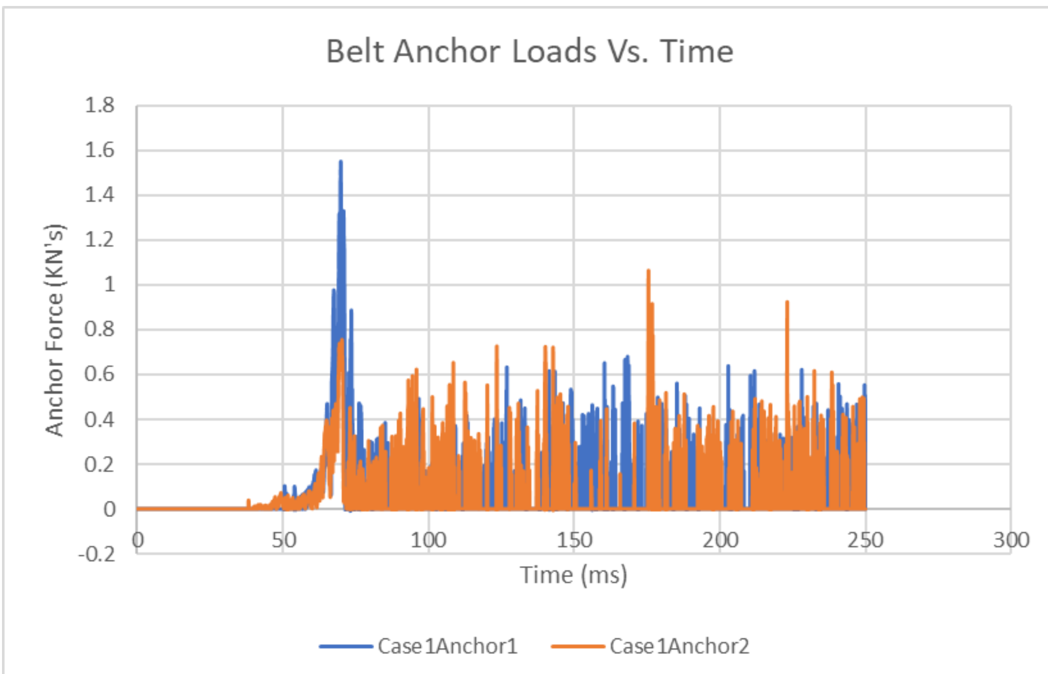


Figure 5.7: Lap belt anchor loads for the hybrid III case 1

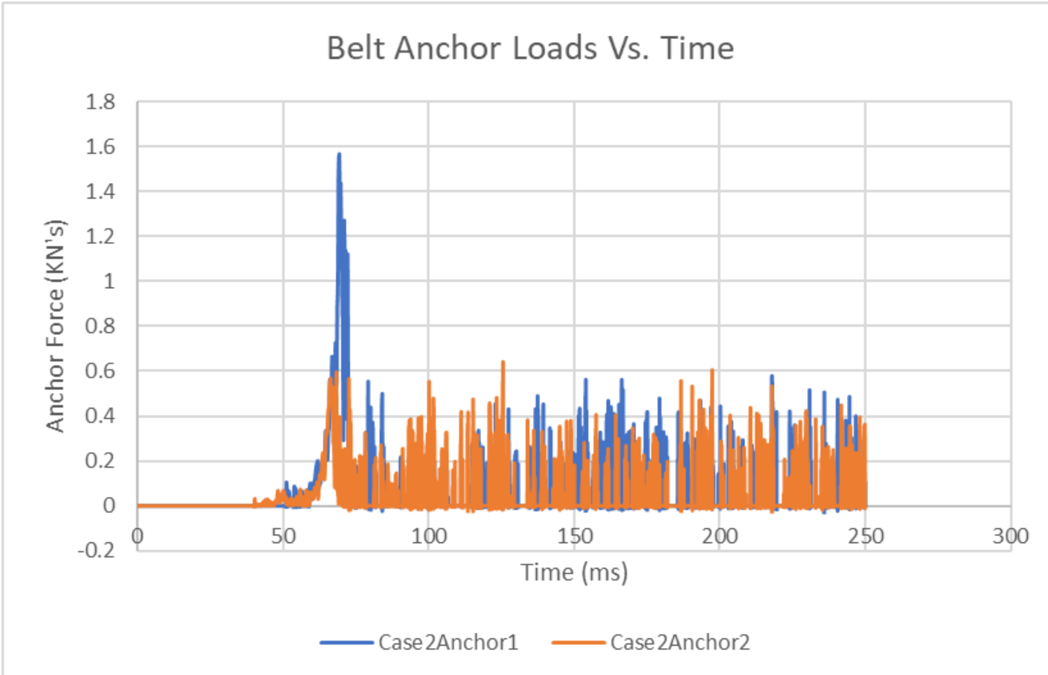


Figure 5.8: Lap belt anchor loads for the hybrid III case 2

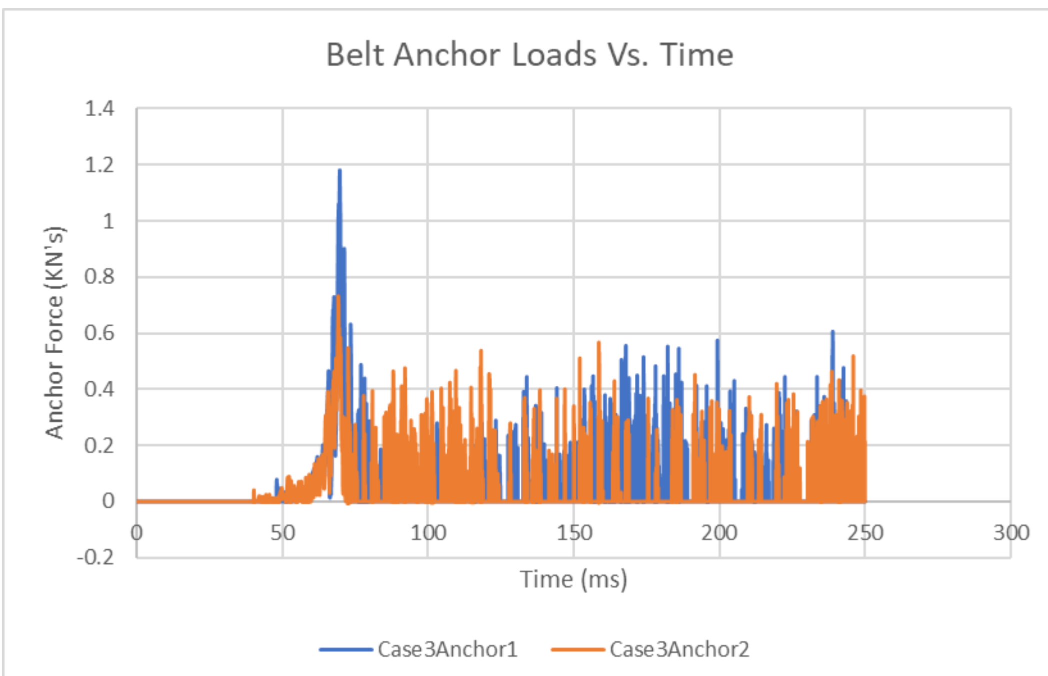


Figure 5.9: Lap belt anchor loads for the hybrid III case 3

It is evident that all 3 cases behave similarly. An exponential increase at the beginning where the acceleration is applied, and the maximum force resulting during the largest application of acceleration, which is at 90 milliseconds. Case 1 and 2 produce similar results, with the largest force of just below 1.6 kN. Case 3 produces a smaller maximum value of just less than 1.2 kN, which is due to the difference in the angle of the seat.

CHAPTER 6

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The objective of this study was to examine various oblique-facing aircraft seating configurations and to utilize computational modeling and simulation technique to arrive at configuration(s) that best protect the occupants in these seats. To achieve this goal, the Hybrid III was modeled for 3 different cases:

- 45°, Body Belt-Wrapping, No Arm Rest
- 45°, Body Belt-Wrapping, Arm Rest
- 30°, Body Belt-Wrapping , No Arm Rest

The setup included four simple planes as the seat (a 5th plane added for arm rest), 2 nylon belts with specific loading and unloading functions, and an ideal acceleration input with a maximum value of 16G's for 180 milliseconds. The results from the simulations were then compared to the experiment which show similar pattern, but smaller peak values.

The modeling was also done on the ES-2re dummy, because it has been designed for the lateral impact loading evaluation. The arm rest, although it protects the lateral moment of occupant, it has a large effect on EuroSID thorax, producing the largest values. It also showed that the oblique-facing seats could expose the passengers to significant potential injury.

From the simulations observed, including the thoracic and lumbar force and moment analysis, it is observed that the Hybrid III dummy doesn't show large variations in the forces. In the Z direction, the thoracic forces are within a 2 kN range. In the lumbar region, the variations are the same, but the overall magnitude of the forces is smaller, ranging from 4 to 6 kN.

The same simulations repeated with EuroSID-2re, however, provided different results. The effect of the arm rest crashing in the chest of the dummy was vast, creating large spikes in the forces. Case 2 thoracic forces in the Z and Y direction were 83.6% and 92% higher than the next highest value, respectively, solidifying the idea that the arm rest could have adverse effects on the chest. From the lumbar comparisons in the EuroSID dummy, the addition of the arm rest proved to have about the same effects as the change of angle from 45 to 30 degrees, increasing the force in the Z direction by about 4 kN.

The comparison of values calculated and those provided by the literature showed similar trends and values for thoracic forces, while lumbar forces were larger for the literature. The reasons for the differences were related but not limited to experiment vs. simulations, lack of belt properties from literature, and lack of exact dummy positioning with the seats.

From the injury criteria comparisons, the EuroSID-2re dummy shows valuable results. This model, once again, shows significant difference when the arm rest is added. The severity is large in all injury criteria for case 2 than the other two cases.

Overall, the configuration with body-belt wrapping and arm rest to limit lateral motion seems to provide best protection for passengers on oblique-facing seats. Furthermore, it is strongly recommended to utilize the EuroSID-2re dummy in certification of the oblique-facing aircraft seats. The EuroSID-2re dummy threshold values, including Viscous Criterion (1.0 m/s), Pelvic Acceleration (130G), Chest Deflection (43 mm), and TTI (85G), must be utilized in the evaluation of the certification of these seats. In addition, the lumbar load tension limit of 5.2 kN should also be utilized.

6.2 Recommendations

Based on multiple different simulations, results obtained from the study, and conclusions made on the comparisons of the mentioned results, the following are the recommendations for further study on the topic:

- An increase in the number of simulation scenarios, with different combinations of belts, arm rests, and angles should be investigated.
- The addition of a bulkhead representing or the back of a seat in front of the passenger can pose additional hazard to the occupant needs to be examined. Hence, the resulting HIC must be evaluated, and if needed, kept between the thresholds.
- The study is focused on the longitudinal (Test-2 configuration) aircraft crash certification configuration, and the up direction (Test-1 configuration) has not be studied here. The evaluation of this configuration, as required by the FAA, can lead to helpful results on the lumbar loads for certification of oblique facing aircraft seats.
- The arm rests and the seat in this thesis are represented by simple, rigid planes. A more accurate representation of an airplane seat, including cushions, can provide more useful results.
- The simulations on this thesis are performed on 50^{th} percentile adult male dummies. The evaluation on other size occupants will result in a complete set of data. This can be done both with the Hybrid III as well as EuroSID dummies of different sizes.
- The simulations for this study are done for 30 and 45 degrees only. Other angles from 18 to 45 degrees can provide additional results for a complete study

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