

DESIGN, ANALYSIS AND EXPERIMENTAL STUDY OF A NOVEL SIDE
THORAX IMPACTOR TO BE USED IN PEDESTRIAN PROTECTION TESTS
FOR FLAT FRONT VEHICLES

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THORAX IMPACTOR TO BE USED IN PEDESTRIAN PROTECTION
TESTS FOR FLAT FRONT VEHICLES**

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ABSTRACT

DESIGN, ANALYSIS AND EXPERIMENTAL STUDY OF A NOVEL SIDE THORAX IMPACTOR TO BE USED IN PEDESTRIAN PROTECTION TESTS FOR FLAT FRONT VEHICLES

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Pedestrian protection is crucial and the vehicle manufacturers put more and more effort to make vehicles safer for pedestrians in case of pedestrian involved accidents. Injuries and fatalities are very frequent and severe in pedestrian involved accidents because the pedestrians are much more vulnerable when compared to the vehicle occupants as they do not have any protection like airbags or seatbelts. The current pedestrian protection regulations focus on the tests of bonnet type passenger cars for the head, upper leg and lower leg regions that are performed by using the headform and legform impactors. However, no tests are defined to evaluate thorax injuries. The number of flat front vehicles is increasing within the cities. Additionally, the number of Sports Utility Vehicles (SUVs) and Light Truck Vehicles (LTVs) which are bonnet type vehicles but with relatively high bonnets and bumpers is increasing. Thorax impacts and thorax injuries are more frequently encountered in pedestrian involved accidents with these types of vehicles.

Furthermore, thorax region injuries become almost as severe as head injuries for especially flat front vehicles.

In this study, a novel patentable thorax impactor has been designed to evaluate thorax injuries in pedestrian involved accidents. The design has been firstly validated with Finite Element Analysis (FEA). Prototype of the thorax impactor has been manufactured and physical pendulum tests have been performed for the biofidelity validation. The test results have shown that ThImp-PED has an acceptable biofidelity.

A novel pedestrian protection test procedure for thorax impact with for flat-front vehicles has been proposed. Pedestrian tests have been performed with the Linear Impactor Test System by using the novel thorax impactor and the proposed test procedure. The pedestrian test results have shown that the thorax impactor can be used as the impactor in pedestrian protection tests to evaluate the vehicle's performance in pedestrian safety in terms of the thorax injury criterion. A patentable design of the pedestrian thorax impactor has been achieved.

Keywords: Vehicle Safety, Pedestrian Protection, Pedestrian Protection Tests, Thorax Impactor, Test Regulations, Flat Front Vehicles, Finite Element Analysis

ÖZ

ÖNÜ DÜZ ARAÇLAR İÇİN YAYA GÜVENLİĞİ TESTLERİNDE KULLANILMAK ÜZERE ÖZGÜN BİR GÖĞÜS YAN FİZİKSEL MODELİNİN TASARIMI, ANALİZİ VE DENEYSEL ÇALIŞMASI

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Yaya güvenliği hayati öneme sahiptir ve araç üreticileri kaza sırasında araçları yayalar için daha güvenli yapabilmek için gittikçe daha çok çaba sarfetmektedir. Yayaların karıştığı kazalarda yaralanma ve ölümler çok sık ve şiddetlidir çünkü yayalar araç içi sürücü ve yolculara kıyasla çok daha savunmasızdır ve havayastığı, emniyet kemeri gibi korumaları yoktur. Güncel yaya güvenliği regülasyonları, burunlu binek araçlar için kafa formu ve bacak formlarıyla gerçekleştirilen kafa, alt bacak ve üst bacak testlerine odaklanmıştır. Ancak göğüs yaralanmalarını değerlendirmek için herhangi bir test tanımlanmamıştır. Şehirlerdeki önü düz araçların sayıları artmaktadır. Ayrıca, jip ve kamyonet gibi burunlu olmasına rağmen göreceli olarak yüksek kaput ve tampona sahip araçların sayıları da artmaktadır. Bu tip araçlarla yayaların karşılaştığı kazalarda göğüs darbeleri ve yaralanmalarına daha sık rastlanmaktadır. Bununla birlikte, özellikle önü düz

araçlarda göğüs bölgesi yaralanmaları hemen hemen kafa yaralanmaları kadar şiddetli görülmektedir.

Bu çalışmada, yayaların karıştığı kazalardaki göğüs yaralanmalarını değerlendirmek üzere özgün ve patentlenebilir bir göğüs modeli tasarlanmıştır. Tasarım öncelikle Sonlu Elemanlar Analizi (SEA) ile doğrulanmıştır. Göğüs modelinin prototipi üretilmiş ve biofidelite doğrulaması için fiziksel pendulum testleri gerçekleştirilmiştir. Testler sonucunda göğüs modelinin kabul edilebilir biofidelitesi olduğu görülmüştür.

Önü düz araçlarla yaya göğüs kısmının çarpışmasını test etmek üzere özgün bir yaya güvenliği test prosedürü ortaya konmuştur. Önerilen test prosedürü ve özgün göğüs bloğu kullanılarak Doğrusal Darbe Test Sisteminde yaya güvenliği testleri gerçekleştirilmiştir. Yaya güvenliği testleri sonucunda göğüs modelinin yaya güvenliği testlerinde göğüs yaralanma kriteri açısından aracın yaya güvenliği performansını değerlendirmek üzere bir model olarak kullanılabileceği görülmüştür. Patentlenebilir yaya göğüs modeli tasarımı başarıyla gerçekleştirilmiştir.

Anahtar Kelimeler: Taşıt Güvenliği, Yaya Güvenliği, Yaya Güvenliği Testleri, Göğüs Modeli, Test Regülasyonları, Önü Düz Araçlar, Sonlu Elemanlar Analizi



To my Father

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LIST OF ABBREVIATIONS

ABS	Antilock Braking System
ACL	Anterior Collateral Ligament
AIS	Abbreviated Injury Scale
ATD	Anthropomorphic Test Device
CFC	Channel Frequency Class
COG	Center of gravity
EEVC	European Enhanced Vehicle-safety Committee
ES-2	EuroSID-2
EU	European Union
FEA	Finite Element Analysis
Flex-PLI	Flexible Pedestrian Legform Impactor
FMH	Free Motion Headform
FMVSS	Federal Motor Vehicle Safety Standards
HIC	Head Injury Criterion
Hybrid III	Hybrid III
ISO/TR	International Organization for Standardization / Technical Report
LDW	Lane Departure Warning
LTV	Light Trucks and Vans
MCL	Medial Collateral Ligament

NCAP	New Car Assessment Program
NHTSA	National Highway Traffic Safety Administration
PCL	Posterior Collateral Ligament
PMHS	Post Mortem Human Surrogate
RDC	Rib Deflection Criterion
SUV	Sport Utility Vehicle
ThImp-PED	Thorax Impactor-PEDESTRIAN
TRL	Transport Research Laboratory
TTI	Thoracic Trauma Index
UN ECE	United Nations Economic Commission for Europe
VC	Soft Tissue Criterion / Viscous Criterion
WAD	Wrap Around Distance
WHO	World Health Organization
WorldSID	Worldwide Harmonized Side Impact Dummy

CHAPTER 1

INTRODUCTION

In 2018, World Health Organization (WHO) published the third Global Status Report on Road Safety based on 2016 data. In this report, it is stated that the number of deaths on the world's roads remains unacceptably high with 1.35 million people dying each year. According to the same report, road traffic injury is now the leading cause of death for children and young adults aged 5–29 years, and the eighth leading cause of death for all age groups [1]. There are several national and international initiatives aiming to reduce the injuries and fatalities resulting from traffic accidents. In August 2020, the United Nations General Assembly announced the Decade of Action for Road Safety 2021-2030, with the target of preventing at least 50% of road traffic deaths and injuries by 2030. To achieve this target, the action plan covers all aspects like design of safer vehicles; design of safer roads; enhancement of laws and regulations and arrangement of immediate life-saving emergency care for the injured [2]. In this thesis, design of safer vehicles, automotive safety regulations and tests to evaluate the safety of the vehicles focusing on pedestrians will be addressed. Other aspects of the action plan will not be taken into account as they are not related to this study.

1.1 Introduction to Vehicle Safety

Vehicle safety studies focus on minimizing the occurrence and results of traffic collisions involving motor vehicles. The systems and technologies used for vehicle safety can be grouped under four categories as given below [3]:

a- Passive Safety Measures: These measures aim to reduce the results of an accident. It is closely related to the term “crashworthiness”. Crashworthiness can

be defined as the ability of a vehicle to protect its occupants and pedestrians from serious injury or death in case of accidents. Examples of passive safety measures are using of airbags, seatbelts, head restraints, energy absorbing steering system, anti-whiplash seats, deployable bonnets for pedestrian protection, etc. Interior design of the vehicle also affects passive safety.

b- Active Safety Measures: These measures aim to reduce the possibility of accidents to occur by taking preventative measures. Examples of active safety measures are ABS (Antilock Braking System), Automated Headlights, Adaptive Cruise Control, LDW (Lane Departure Warning), Collision Avoidance and Automatic Emergency Braking, etc.

c- Integrated Safety Measures: These measures aim to integrate active and passive safety systems within a vehicle to allow the vehicle to adapt to a pre-crash situation and either stop the crash from occurring or reducing the crash consequences by reacting to the crash appropriately.

d-Tertiary Safety Measures: These measures aim to optimize the rescue phase after an accident by providing information on severity and location of the crash to the related services. Tertiary safety measures are relatively new compared to others and different systems are still being developed. One example of tertiary safety measures is eCall which contacts the emergency services in case of an accident.

1.2 Vehicle Safety Regulations

Vehicle safety regulations are obligatory standards that vehicle manufacturers should follow. There are regional and international vehicle safety regulations. Additionally there are safety programs that inform and guide the consumers for the safety of the cars in the market. For example, New Car Assessment Program (NCAP) is a government or an institutional car safety program whose task is to evaluate the safety performance of new car designs. Two well known NCAP are

United States New Car Assessment Program (USNCAP) since 1978 and European New Car Assessment Program (EuroNCAP) since 1997. There are also other NCAPs like Japanese (JNCAP), Australian (ANCAP), Korean (KNCAP), Chinese (CNCAP), South American (Latin NCAP) and Asean (ASEAN NCAP).

Vehicle safety in European Union countries is regulated mainly by international standards and regulations prepared by the European Union (EU) and the United Nations Economic Commission for Europe (UN ECE).

European vehicle crash tests and pedestrian sub-system tests have been developed by the European Enhanced Vehicle-safety Committee (EEVC) which brings together experts and governmental representatives from several countries [4]. Such tests aim to reflect the types, impact speeds of the most common types of crashes. Crash test dummies and pedestrian impactors are used in these tests to evaluate the injuries and fatalities that are observed in these crashes. The list and full text of the global UN ECE regulations can be found on the UN ECE website [5]. In recent years, the most important vehicle safety regulations include crash tests for frontal impact protection and side impact protection to car occupants and sub-system tests for pedestrian protection.

In the United States of America (USA), National Highway Traffic Safety Administration (NHTSA) regulates the safety of motor vehicles and related equipment as a Federal agency. NHTSA issues Federal Motor Vehicle Safety Standards (FMVSS) to implement laws. The list and full text of FMVSS standards can be found on the NHTSA website [6]. Current overview of rules and regulations worldwide on occupant and pedestrian protection can be found in Table 1.1. Detailed information on regulations and safety programs related to pedestrian protection will be given in detail in Chapter 2.

Table 1.1 Rules and Regulations on Occupant & Pedestrian Protection [7]

	USA	EUROPE	JAPAN	CHINA
Full Width Frontal	FMVSS 208	ECE R137	Art.18&Att.23	GB 11551-2014
Offset Frontal	FMVSS 208	ECE R94	Article 18	GB/T 20913-2007
Side Barrier	FMVSS 214	ECE R95	Art.18&Att.24	GB 20071-2006
Side Pole	FMVSS 214	ECE R135	ECE R135	-
Pedestrian	-	ECE R127	Art.18&Att.99	GB/T 24550-2009 QC/T 938-2013
Rear	FMVSS 202a FMVSS 301	ECE R32	Art.18&Att.34	GB 20072-2006
Head Impact	FMVSS 201U	ECE R21	-	GB 11551-2009

1.3 Pedestrian Safety

A detailed description of “pedestrian” can be given as follows; a pedestrian is any person who is travelling by walking for at least part of his or her journey. In addition to the ordinary form of walking, a pedestrian may be using wheelchairs, walkers, canes, motorized scooters, skateboards and roller blades.

According to the third Global Status Report on Road Safety by WHO, globally pedestrians constitute 23% of all road deaths which means that each year, more than 310.000 pedestrians lose their lives on the world’s roads [1]. In Figure 1.1, distribution of road traffic deaths by type of road user globally can be found.

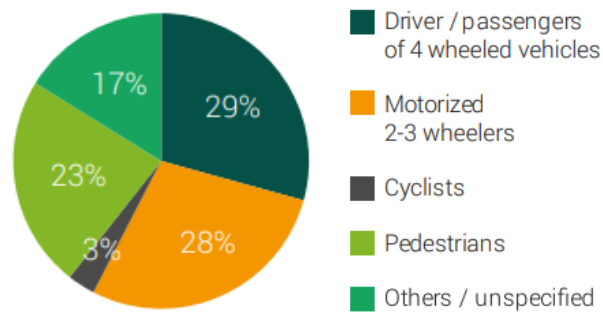


Figure 1.1. Global Distribution of Deaths by Road User Type [1]

Traffic accidents where pedestrians are involved and pedestrian fatalities are major issues in Turkey similar to the global case. Reported road traffic fatalities in Turkey in 2016 is 7.300 [1]. In Figure 1.2, it can be seen that pedestrians constitute 23% of road deaths in Turkey, so by a rough calculation, it can be concluded that 1.680 pedestrians lost their lives in 2016 in Turkey.

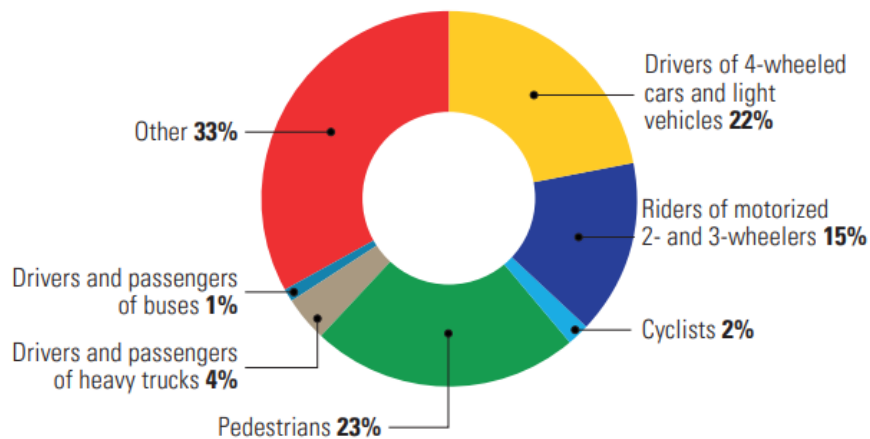


Figure 1.2. Distribution of Deaths by Road User Type in Turkey, 2016 [1]

Also it should be noted that, in many countries, crashes involving pedestrians are poorly reported in official road traffic injury statistics. The actual number of pedestrian fatalities and injuries is probably higher than what the official statistics show.

As the statistics show, pedestrian injuries continue to be a major public health problem in Turkey and worldwide. Therefore, the vehicle manufacturers are putting more and more effort on designing vehicles that are safer for the pedestrians in case of pedestrian involved accidents.

The pedestrian protection tests are performed with pedestrian impactors instead of crash test dummies. There are several reasons for this; test repeatability and reproducibility is increased by performing sub-system impactor tests, the pedestrians have a greater whole body motion compared to vehicle occupants during an accident which makes the validation requirements of a pedestrian dummy more difficult to achieve and finally biofidelity of the commercially available pedestrian dummy is not good enough to evaluate the pedestrian kinematics and injuries during a collision. Adult and child headform impactors, upper legform impactor and Flex PLI legform impactor are used for the pedestrian safety tests. The details of these impactors in terms of their usage, structure, dimensions and instrumentation will be given in Chapter 2.

Adult and child headform impactors, upper legform impactor and Flex PLI legform impactor enable to evaluate the fatalities resulting from the injuries observed on the head, pelvis, upper and lower leg regions of a pedestrian during an accident. The reason that the test standards focus on head and leg regions is that according to the post accident reports and statistics, head and legs are the most frequently injured parts during pedestrian involved accidents with passenger cars. However, it should be noted that pedestrian kinematics during impact is different when accidents with passenger cars and flat front vehicles are compared as the shape and dimensions of the front of the vehicle determine the kinematics of the pedestrian during the accident and the body parts that are impacted by the vehicle. In many studies [8]–[14] it is shown that “wrap projection” occurs in case of accidents with passenger cars as the vehicle impact force is applied at a location below the centre of gravity of the pedestrian. This is the most common sequence for pedestrians struck by passenger bonnet type vehicle fronts. The sequence of events during wrap

projection simulated in a test using a Post Mortem Human Surrogate (PMHS) and a passenger car is given in Figure 1.3 [8]. Typically, the first contact occurs between the bumper and either the leg or knee-joint area, followed by thigh-to-bonnet edge contact. The lower extremity of the body is accelerated forwards and the upper body is rotated relative to the car. Consequently, the pelvis is impacted by the bonnet edge and the thorax is impacted by the bonnet top. The head will hit the bonnet or windscreen at a velocity that is at, or close to, that of the striking car [8].

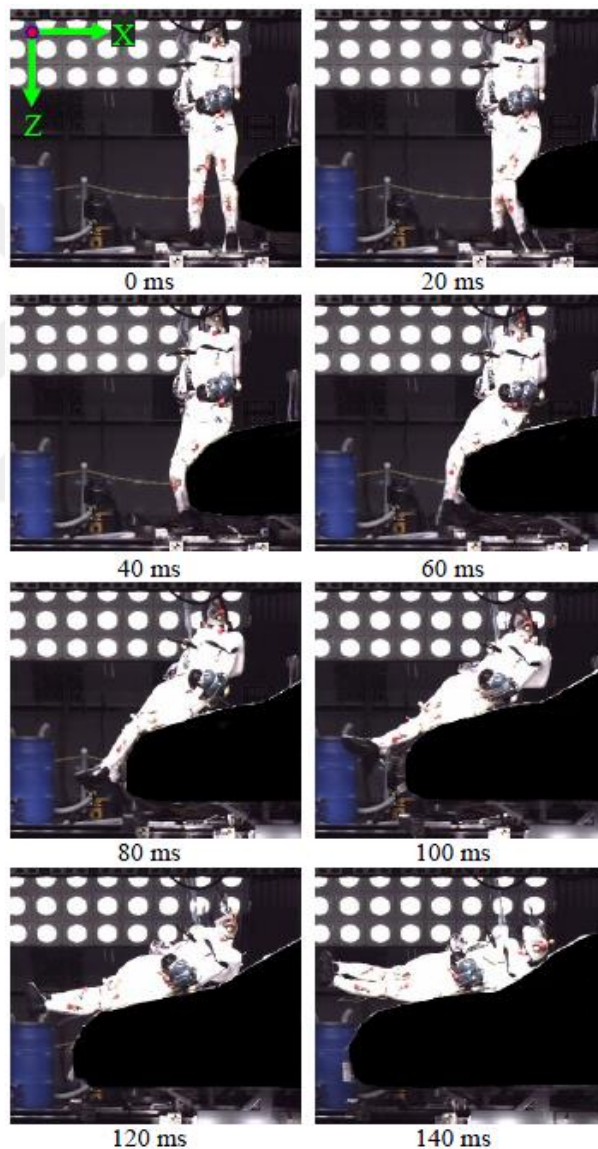


Figure 1.3. High Speed Video Images of a PMHS Test with a Passenger Car [8]

Although research on pedestrian protection currently is focusing mainly on passenger cars, impacts with flat front vehicles like trucks and buses are also important, especially in urban areas and in developing countries. There are studies [15]–[18] that focus on accidents with flat front vehicles. The kinematics of the pedestrian during accidents with flat front vehicles is simulated with numerical methods and experiments in these studies. It is shown that “forward projection” occurs in case of accidents with flat front vehicles as the vehicle’s front leading edge height is above the pedestrian’s center of gravity. This typically occurs where an adult is struck by a bus, minivan or a truck, a small adult is struck by a large Sport Utility Vehicle (SUV) or a child is struck by a passenger car, van, truck or an SUV. The location of the first contact depends on the size of the pedestrian relative to the vehicle front, but subsequent contacts follow in very quick succession since the pedestrian is struck by an almost flat and vertical surface. As a result, the mid-body region is rapidly accelerated in the direction of vehicle travel with very little rotation so that the mid-body region and the vehicle attain an almost common post impact velocity. In Figure 1.4, pedestrian forward projection kinematics at an impact speed of 16,9 km/h against a stationary dummy is given [19]. The sequence shows the typical kinematics of a pedestrian resulting from a flat front vehicle collision.

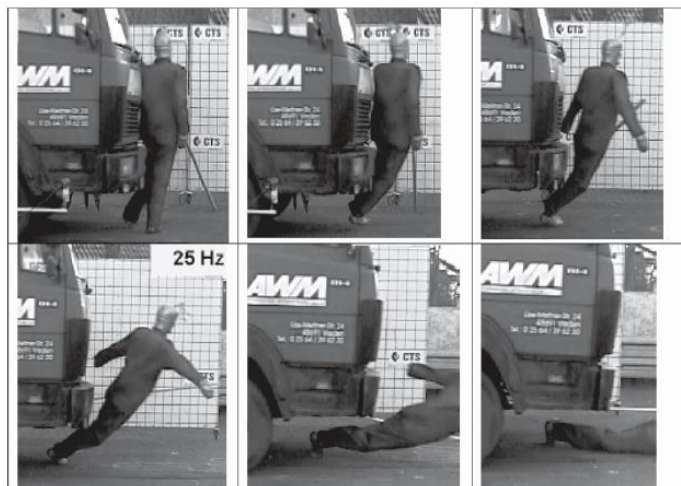


Figure 1.4. Pedestrian Forward Projection Kinematics [19]

Studies [18]–[22] show that the distribution of frequency and severity of injuries in pedestrian involved accidents is highly dependent on vehicle type (passenger cars, buses, trucks, Sport Utility Vehicles, Light Trucks and Vans (LTVs), etc.) as the front shape and dimensions change with vehicle type. The distribution of injuries observed on the body regions during pedestrian involved accidents with passenger cars is given in Table 1.2 [23].

Table 1.2 The Distribution of Injuries on the Body Regions in Pedestrian Involved Accidents with Passenger Cars [23]

Body Region	% Injuries
Head	31,4
Face	4,2
Neck	1,4
Chest	10,3
Abdomen	5,4
Pelvis	6,3
Arms	8,2
Legs	32,6

The body parts that are impacted by the vehicle and the severity of the impact is different in flat front vehicles when compared to passenger cars. Thorax region injuries become almost as frequent and as severe as head injuries for flat front vehicles. Injuries caused by a passenger car front on the thorax region is 24% whereas injuries caused by a LTV front is 60% in case of an accident, as given in Figure 1.5 [20].

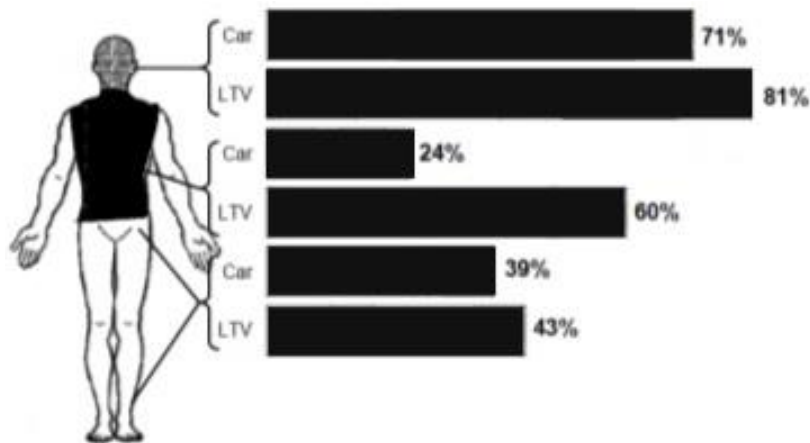


Figure 1.5. Distribution of Injuries by Body Region and Vehicle Type [20]

1.4 Scope of the Thesis

It is summarised in the previous sections that the standard tests for pedestrian protection are well defined for head, upper leg and lower leg impacts with passenger cars. These tests are performed with adult and child headforms, upper leg form and lower legform. However, there have been no pedestrian protection standard tests and no impactors that are used for the thorax regions of pedestrians yet. Additionally, there is no standard test for pedestrian protection that is defined for other vehicle types than passenger cars such as SUVs, buses and trucks.

Scope of the current study is to propose a novel thorax impactor which will be used to evaluate thorax injuries in pedestrian involved accidents. The study covers the design, Finite Element Analysis (FEA), manufacturing of the prototype, validation with physical tests steps. Additionally, proposing a test procedure to evaluate thorax injuries in case of pedestrian accidents with flat-front vehicles is in the scope of the study. Determination of impact points, angle and speed of impact, evaluation criteria, etc will be covered in the proposed test procedure.

In Chapter 2, information on crash test dummies, pedestrian protection test standards and impactors used for the tests is given. In Chapter 3, human thorax,

thorax injury criteria and design of the novel thorax impactor are explained. In Chapter 4, FEA studies that have been performed for the biofidelity validation of the thorax impactor are given in detail. In Chapter 5, manufacturing of the thorax impactor and pendulum tests that have been performed for the biofidelity validation are explained. In Chapter 6, the proposed novel test procedure is given and pedestrian protection tests that have been performed with the novel thorax impactor on the Linear Impactor Test System by using the proposed procedure are shown. Finally, in Chapter 7 conclusions of the study and studies that can be performed as future work are given.



CHAPTER 2

CRASH TEST DUMMIES, TEST STANDARDS AND IMPACTORS FOR PEDESTRIAN PROTECTION

In this chapter, detailed information on crash test dummies will be given. Pedestrian protection test regulations and safety programs which is in the scope of this study will also be summarized. Human body bones are frequently referred to in the description of crash test dummies, impactors and test regulations, therefore the schematic description of the major human body bones related to this study are given in Appendix A.

2.1 Crash Test Dummies

Crash Test Dummies are mechanical surrogates of the human body and they are also called Anthropomorphic Test Devices (ATDs). ATDs are calibrated test devices used to measure human injury potential by simulating human response to impacts, accelerations, deflections, forces and moments generated during a crash [24]. Starting from the 1950s, researchers began to study the injury biomechanics of occupants in car collisions in order to investigate the human injuries caused by collisions and correctly assess the actual injuries experienced by occupants in car collisions. Researchers used human surrogates (i.e. human cadavers) to collect data on human injuries caused by accidents in crash experiments and subsequently adopted animals and volunteers as crash surrogates. Although these experiments provided valuable data for collision safety, they were gradually abandoned due to restrictions such as ethical and moral constraints, physiological function differences, experimental risks, and experimental irreproducibility. With the development of science and technology, crash test dummies were developed [25].

Adult crash test dummies and child crash test dummies were developed in order to represent adults and children involved in crashes.

Dummy development is a continuing process. With the development of the technology, new materials, new manufacturing methods and new sensor technologies are becoming available which enables new generation of dummies to be developed. Also, as the car manufacturers are designing safer, more complex and customized cars, they are demanding these new generation dummies which have higher biofidelity and instrumented with more sensors to provide more data.

The parameters that are used in general during the design of ATDs are given below:

a. Anthropometry: Anthropometry involves the systematic measurement of the physical properties of the human body. In terms of anthropometry, ATDs should have similar mass distribution to that of a living human and have a similar shape and similar limb dimensions to that of a living human.

b. Biofidelity: In general, biofidelity is defined as the degree of faithfulness of a model to the real biological system it is based on [26]. ATDs should duplicate the biomechanical response behaviour of a living human exposed to the same impact conditions. Biofidelity is verified by comparison with corridors responses of human surrogate (i.e. human cadaver) tests. Biofidelity of the crash test dummies are evaluated and biofidelity scores or ratings are calculated. The dummy and human surrogate are tested in an environment similar to the crash and the response of the human cadaver and dummy are compared quantitatively. Then the quantitative response comparison from each test is combined into a meaningful score.

c. Percentile: In statistics, percentile is a score below which a given percentage of scores in its frequency distribution falls. Considering crash test dummies, percentile refers to the size of the ATD. It shows the stature and mass of the ATD compared to the normal distribution of the population. Three percentiles are used for the ATDs which are 5th, 50th, and 95th percentile. 50th percentile ATD represents

an average adult male. 5th percentile ATD indicates that 5% of the adult population is smaller than that ATD and 95th percentile ATD indicates that 5% of the adult population is larger than that ATD. The normal distribution curve showing the 5th, 50th and 95th percentile is given in Figure 2.1.

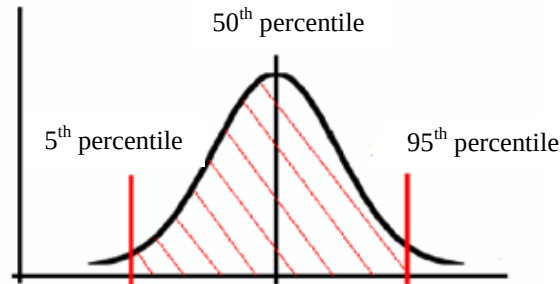


Figure 2.1. Normal Distribution Curve

d. Measuring Capability: The ATD should have the required instrumentation to measure the accelerations, forces, moments and deflections. Typically accelerometers, loadcells and different types of displacement sensors are used for the measurements. The types, locations and quantities of sensors on the ATD differs according to the purpose that the ATD is designed for like frontal, side and rear crash test dummies. Also with the development of new sensor technologies, measuring capability of the ATDs is increasing continuously.

e. Repeatability and Reproducibility: Repeatability and reproducibility are among the major parameters during ATD design. Different Crash Test Dummies of same design should receive the same response (output) to the same impact conditions (input). To assess the repeatability of a Crash Test Dummy, responses to tests with the same dummy are evaluated [27]. For example a predefined number of tests are performed in a controlled manner with the same Crash Test Dummy and the same test set-up and a defined set of measurement are taken and compared between these tests. Finally the coefficient of variation is calculated and evaluated by using the results of this test series. To assess the reproducibility of a Crash Test Dummy, responses to tests with different dummies of the same design are evaluated [27]. A

test program is defined so that it includes a predefined number of tests with different dummies of the same design. The same test parameters and test set-up are used for the tests. The defined measurements are taken and compared between these tests and the coefficient of variation is calculated for the evaluation of reproducibility.

f. Durability: The ATD durability implies that the crash test dummy should be structurally intact following an impact and it should have responses that remain repeatable between tests. Additionally, for cost reasons it is desirable that a crash test dummy be sufficiently durable to be used for many years in many tests with only a reasonable level of maintenance and repair. During dummy development, it is one of the major challenges to design a dummy which is both durable and sensitive to variations in crash loading ranging from low energy levels to high energy levels.

g. Simplicity and Ease of Use: Simplicity and ease of use of a Crash Test Dummy refers to many aspects of the dummy like calibration, maintenance and repair during its lifetime. In terms of calibration, the ATD should be easy to calibrate, have defined and clear calibration procedures. In terms of maintenance, it should have parts that are easy to change and replace and minimal external support equipment should be necessary for the maintenance and/or repair of the dummy.

There are many types and many generations of adult crash test dummies that are developed for different crash scenarios like frontal, side and rear. The structures and instrumentation of these dummies are different from each other which enables the dummies to be sensitive to the direction of impact and collect the relevant data through sensors. These crash test dummies are being used by the automotive industry and crash test facilities for development and legislative tests.

Typically, ATDs consist of several sub-assemblies representing the body regions as given in Figure 2.2 [28].

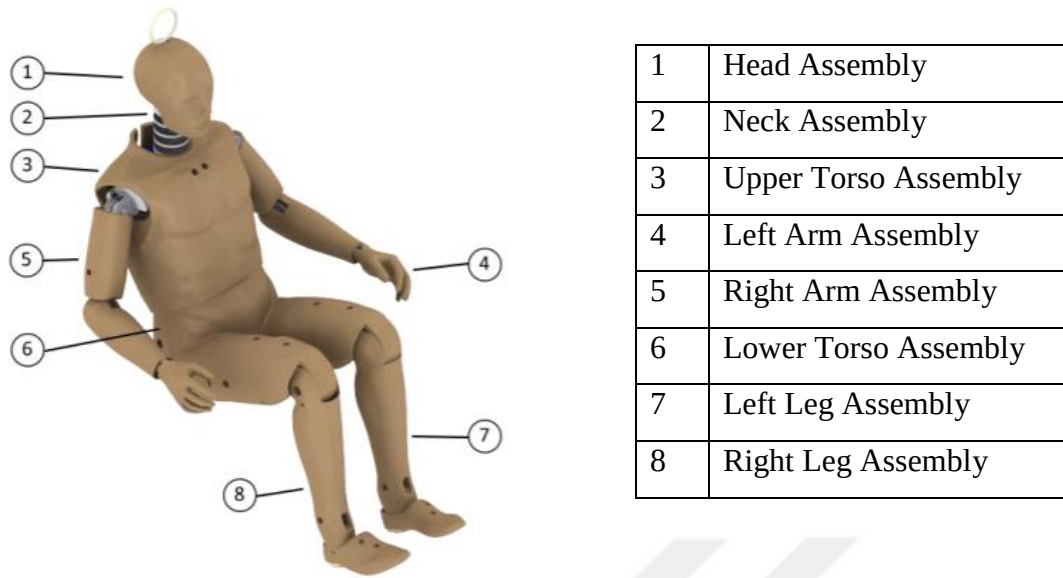


Figure 2.2. Body Regions of ATDs [28]

Details of the mostly used commercially available crash test dummies will be given with special emphasis on their thorax regions as this study focuses on the thorax region. The part lists corresponding to the part numbers given in the figures below for the exploded thorax regions of the crash test dummies will be given in Appendix B.

2.1.1 Hybrid III (HIII) Crash Test Dummy

The Hybrid III 50th Percentile Male Crash Test Dummy is the most widely used crash test dummy in the world for the evaluation of automotive safety restraint systems in frontal crash testing [24]. In Hybrid III family, there are also 5th and 95th percentile dummies which are very similar to 50th percentile dummy but with different dimensions and masses to represent smaller and larger persons, respectively. General photographs of the dummy are given in Figure 2.3.



Figure 2.3. Hybrid III 50th Percentile Male Crash Test Dummy [24]

Typically, the HIII dummy is instrumented with accelerometers in head, thorax and pelvis regions; loadcells in neck, spine, femur, tibia regions and displacement transducers in thorax and knee regions. The single axis linear displacement transducer in the thorax region measures the overall frontal deflection of the ribs resulting from contact with seatbelt, airbag or vehicle interior parts during crash tests.

The ribcage is represented with 6 steel ribs each having bonded damping material. The ribs are connected to the sternum at the front of the dummy. Detailed exploded assembly of the thorax region is given in Figure 2.4.

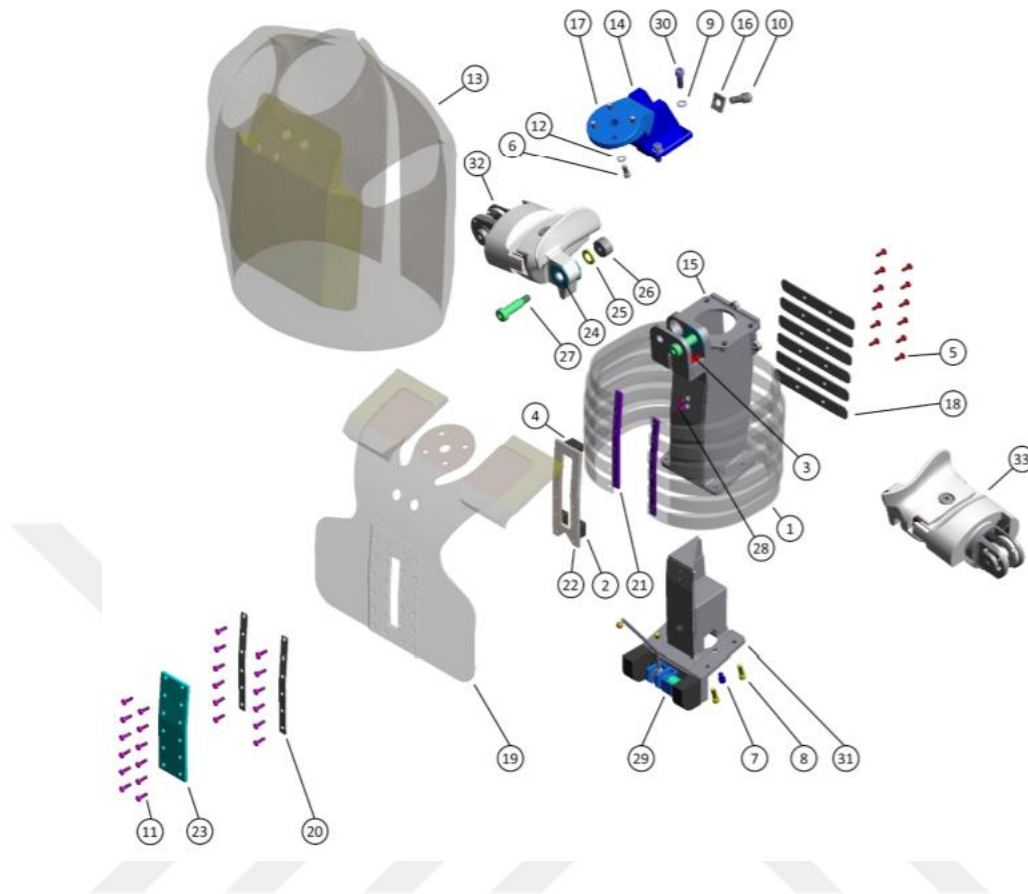


Figure 2.4. Hybrid III 50th Percentile Male Exploded Thorax Assembly [28]

2.1.2 THOR Crash Test Dummy

THOR dummy is the new generation frontal impact crash test dummy for the evaluation of automotive safety restraint systems in frontal crashes. It integrates major advancements in biofidelity and sensing with improved user handling. THOR dummy is available in 50th percentile male and 5th percentile female models. It is currently the most sophisticated ATD for assessing whole-body trauma in a variety of occupant restraint environments. General photographs of the dummy are given in Figure 2.5.



Figure 2.5. THOR 50th Percentile Male Crash Test Dummy [24]

Typically, the THOR dummy is instrumented with accelerometers in head, spine, pelvis and foot regions; loadcells in face, skull, neck, shoulder, arm, spine, femur, tibia and foot regions; tilt sensor in head region and displacement transducers in thorax, abdomen, knee and ankle regions. Typically, there are in total six 3D IR-TRACC displacement transducers in the upper and lower thorax regions. The 3D IR-TRACC is a complex and advanced displacement transducer which is an assembly consisting of 2 angle transducers and 1 displacement transducer. It gives a very detailed measurement of frontal deflection of the ribs resulting from contact with seatbelt, airbag or vehicle interior parts during crash tests.

The ribcage is represented with 7 steel ribs each having bonded damping material. The thorax region of THOR is much more complicated and detailed compared to the HIII thorax. Detailed exploded assembly of the thorax region is given in Figure 2.6.

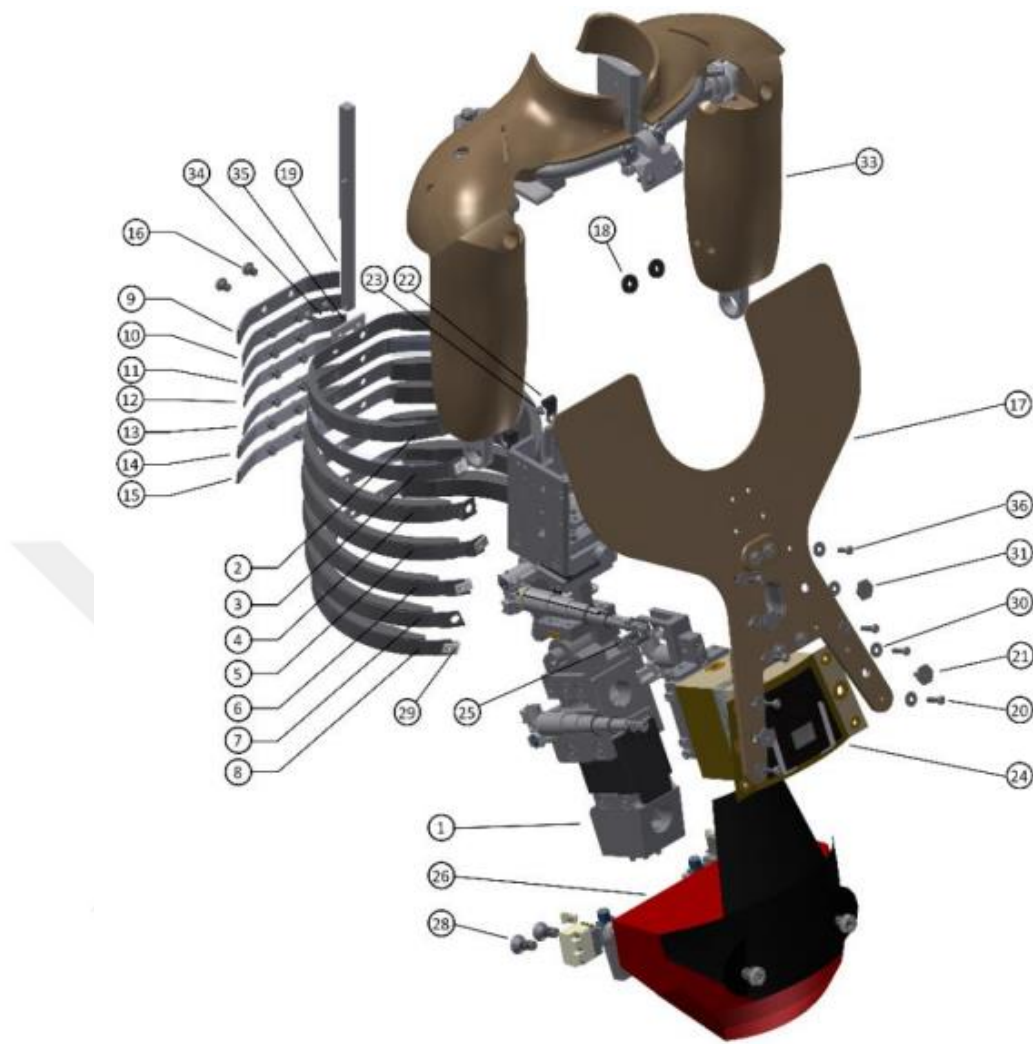


Figure 2.6. THOR 50th Percentile Male Exploded Thorax Assembly [29]

2.1.3 EuroSID-2 Dummy

The EuroSID-2 Side Impact Dummy (ES-2) represents a 50th percentile adult male, and it is a standard dummy used in vehicle side impact testing. The ES-2 was developed by the SID-2000 program which was a consortium of European researchers, automotive manufacturers and dummy manufacturers [24]. ES-2 dummy is only available in 50th percentile male model. General photographs of the dummy are given in Figure 2.7.



Figure 2.7. ES-2 Crash Test Dummy [24]

Typically, the ES-2 dummy is instrumented with accelerometers in head, shoulders, spine, lumbar and pelvis regions; loadcells in neck, shoulder, spine, rib slides, abdomen and femur regions and displacement transducers in ribs in the thorax region. There are in total three single axis linear potentiometers on the ribs. The linear potentiometer in each rib unit measures the lateral rib displacement resulting from contact with airbag or vehicle interior parts during side crash tests.

The ribcage is represented with 3 rib units. The rib units are individually mounted to the spine box at the back of the dummy. The ES-2 thorax assembly is given in Figure 2.8. A rib module consists of the following parts:

- A steel rib bow which is covered with flesh representing foam. The whole flesh system is held to the rib by a sleeve.
- A linear guidance assembly in the Y (impact) direction of the dummy which attaches to the impacted side and the none-impacted side of the rib to limit the deflection mode to purely lateral. The non-impacted side of the rib is rigidly attached to the spine box.

- A tuning spring located in the cylinder which is used to tune the performance of the rib module. Springs with different spring rates are available.
- A hydraulic damper, working parallel to the linear guidance assembly.
- A stiff damper spring, connecting the damper piston to the impacted side of the rib.
- A displacement transducer on each rib to measure rib deformation between struck side and non-struck side [30].

The rib modules are sensitive to impact from only one direction. The three rib modules can be reversed to change the impact direction of the dummy from the left hand to right hand side.

ES-2 rib unit details are given in Figure 2.9.

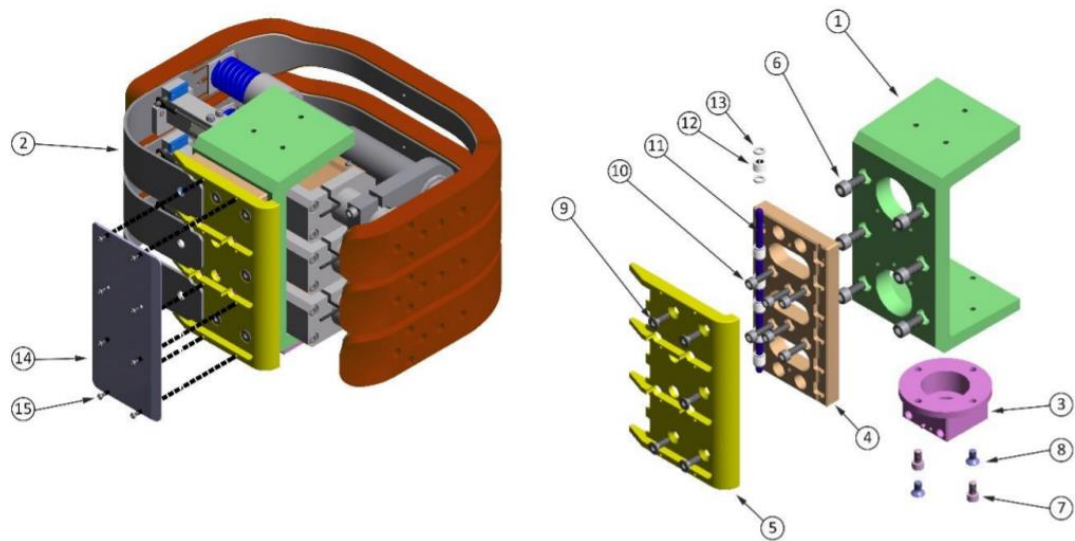


Figure 2.8. ES-2 Thorax Assembly [30]

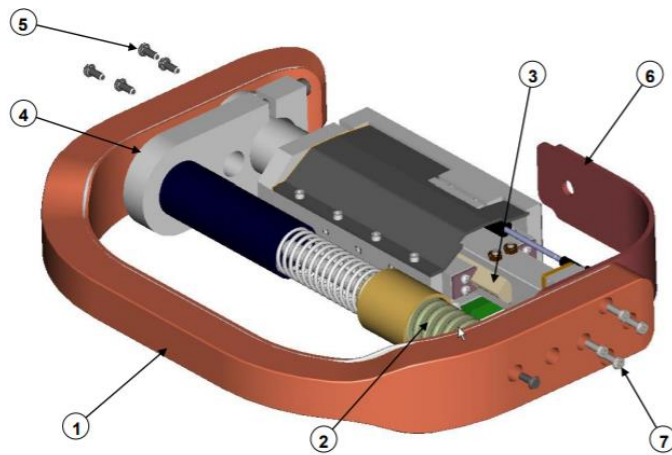


Figure 2.9. ES-2 Rib Unit [30]

2.1.4 WorldSID Dummy

WorldSID (Worldwide Harmonized Side Impact Dummy) is an advanced crash test dummy which was designed in collaboration with industry and government experts with the goal to simulate human reactions in side impact crashes. WorldSID-50M represents the a 50th percentile male and is designed to be used worldwide as a regulatory and research test tool. WorldSID dummy is also available as 5th percentile female. General photographs of the dummy are given in Figure 2.10.



Figure 2.10. WorldSID Crash Test Dummy [24]

Typically, the WorldSID dummy is instrumented with linear accelerometers in head, thorax, ribs and pelvis regions; rotational accelerometers and tilt sensors in thorax and pelvis regions; loadcells in neck, shoulder, elbow, spine, femur, knee and tibia regions and displacement transducers in knee region. Typically, there are in total six 2D IR-TRACC displacement transducers mounted to the ribs. The 2D IR-TRACC in each rib measures the lateral rib displacement resulting from contact with airbag or vehicle interior parts during side crash tests.

The ribcage is represented with 6 ribs. The WorldSID thorax assembly is given in Figure 2.11. The ribs of the WorldSID are very detailed and complex compared to the HIII and ES-2 dummies ribs as can be seen from the figure. The rib assemblies consist of an inner band and the rib.

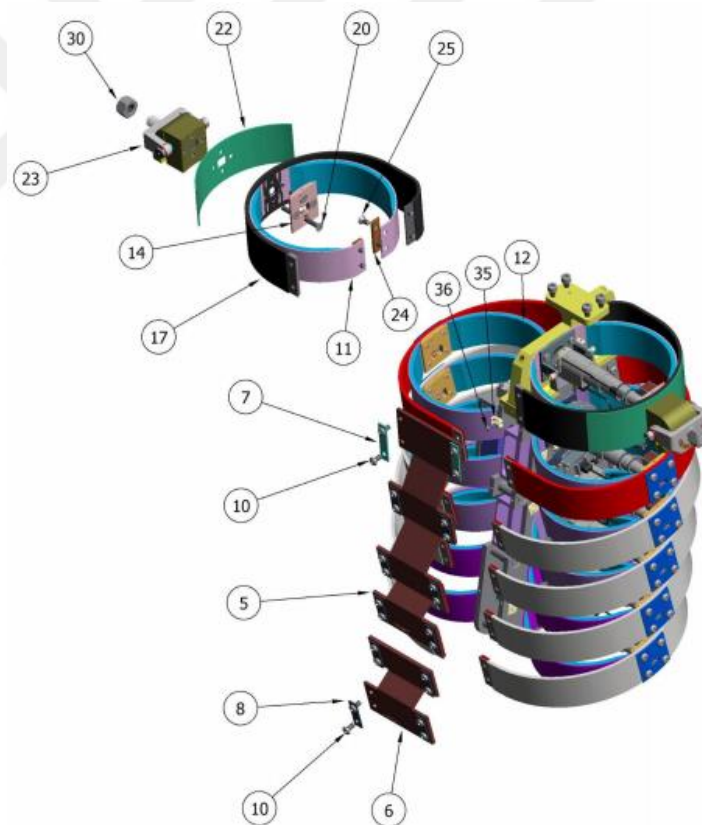


Figure 2.11. WorldSID 50th Percentile Male Exploded Thorax Assembly [31]

2.1.5 SID-IIs

Small Side Impact Dummy (SID-IIs) was designed to meet the needs of side impact vehicle protection. Hybrid III 5th Female ATD as taken as a reference for the design of the dummy. SID-IIs is instrumented with over 100 data channels to measure injuries to the head, neck, arm, thorax, abdomen, pelvis and leg regions. General photographs of the dummy are given in Figure 2.12.

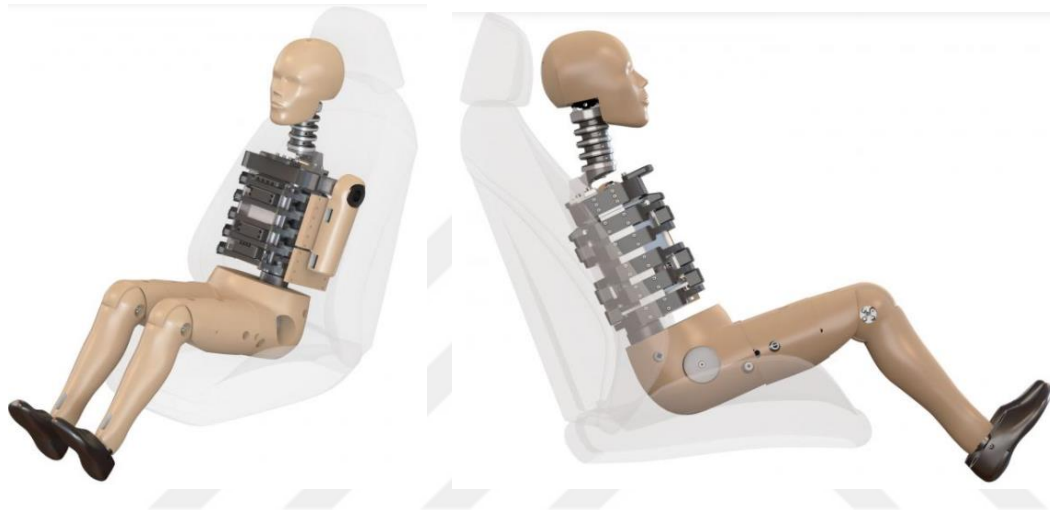


Figure 2.12. SID IIs Crash Test Dummy [24]

Typically, the SID-IIs dummy is instrumented with linear accelerometers in head, shoulder, arm, spine, ribs and pelvis regions; loadcells in neck, shoulder, ribs, elbow, lumbar, femur, knee and tibia regions and displacement transducers in shoulder and ribs regions. Typically, there are in total six linear potentiometers mounted to the ribs.

The ribcage is represented with 5 ribs. The SID-IIs thorax assembly is given in Figure 2.13. The ribs are bolted to the spine box from the non-impact side. The dummy can be used for the test from right or left sides, the ribs and the torso needs to be adjusted to be used in each orientation.

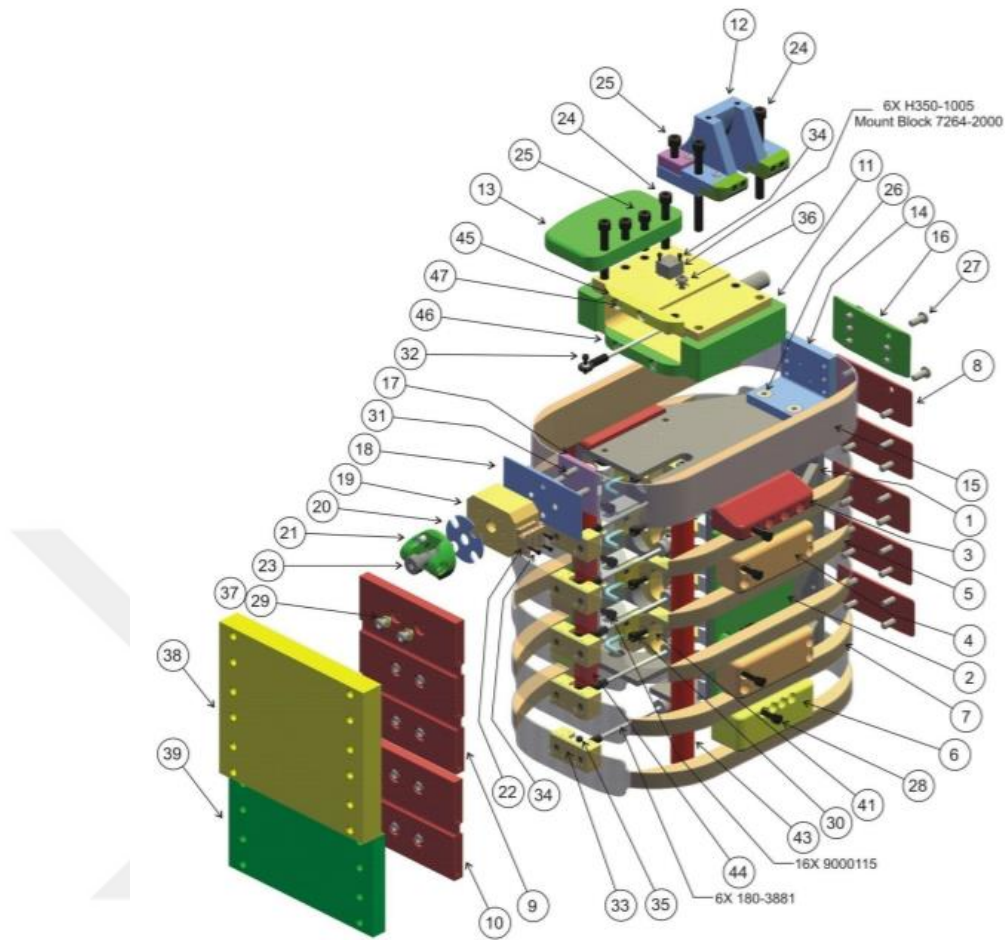


Figure 2.13. SID IIs Exploded Thorax Assembly [32]

2.1.6 BioRID-II Dummy

BioRID-II dummy is an advanced biofidelic rear impact dummy, which is used to test the effectiveness of seat headrests in preventing excess motion of the head and neck and occurrence of whiplash injuries during low-speed rear impacts. BioRID-II dummy is only available in 50th percentile male model. General photographs of the dummy are given in Figure 2.14.



Figure 2.14. BioRID-II Crash Test Dummy [24]

Head, pelvis, legs and arms of the BioRID-II dummy are same as or modified versions of HIII parts. The BioRID-II's distinguishing part is its neck, thorax and abdomen region. Washers, bumpers, and muscle-simulating springs provide biofidelic performance of the dummy.

Typically, the BioRID-II dummy is instrumented with linear accelerometers in head, neck, spine and pelvis regions; loadcells in skull cap, neck, thorax and lumbar regions.

2.1.7 HIII-50M PED Pedestrian Dummy

The Hybrid III 50th Male Pedestrian dummy was developed to test vehicle-to-pedestrian interactions. It is based on the Hybrid III 50th male crash test dummy with modifications to the lower torso, upper legs and knees. There are also 5th and 95th percentile pedestrian dummies which are very similar to 50th percentile dummy but with different dimensions and masses to represent smaller and larger persons, respectively. General photographs of the dummy are given in Figure 2.15.



Figure 2.15. 50th Pedestrian Test Dummy [24]

Typically, the HIII-50M PED dummy instrumentation is very similar to the HIII frontal dummy instrumentation. It is instrumented with accelerometers in head, upper and lower torso regions; loadcells in neck, thorax, spine, femur, knee and tibia regions and displacement transducers in thorax region. The single axis linear displacement transducer in the thorax region measures the overall frontal deflection of the ribs during tests. The dummy thorax does not have any sensors that are capable of measuring lateral rib deflections that would be caused by impacts from the side of the dummy. The HIII-50M PED is not being used in any regulations. It is mostly used for research purposes. The dummy is set free standing or supported by a rope or other means in the path of the car. During the vehicle-dummy interaction the dummies head strikes the hood and windshield so that head injury potential may be measured. Lower limb injury may be evaluated by using force and moment sensors [33].

The HIII dummy upper torso and ribcage is used in the HIII-50M PED dummy. The ribcage is represented with 6 steel ribs each having bonded damping material. The ribs are connected to the sternum at the front of the dummy. Detailed exploded assembly of the thorax region of HIII dummy is already given in Figure 2.4.

2.1.8 POLAR Pedestrian Dummy

POLAR is a pedestrian dummy designed to be used as a research tool to investigate the mechanism of pedestrian involved accidents. Its knee region and tibias are designed flexible similar to the humans to simulate the kinematics of a pedestrian in an accident more precisely. The dummy is not used in regulatory tests, it is used by the automotive manufacturers for research purposes. Photograph of POLAR pedestrian dummy is given in Figure 2.16.



Figure 2.16. POLAR Pedestrian Test Dummy [34]

2.2 Impactors Used for Occupant Safety

Crash test dummies are used to represent the occupants in most of the vehicle standards, however there are some standards that require the use of impactors instead of dummies.

2.2.1 UN ECE R12 Body Block

Driver against the steering mechanism impact is simulated with this bodyblock given in Figure 2.17. Accelerations are measured with a 3-axis accelerometer that is located inside the bodyblock and evaluation is done.



Figure 2.17. Bodyblock Used for ECE R12 Tests [33]

The body block is a very simplified model which consists of a half shape rubber body front mounted on a wooden base. The wooden base has slots which set the position of the rubber body block. A leather sheet is attached to the front of the body block with cords around the back to distribute the load and prevent damage to

the rubber body during impact. The head, neck and torso are fixed to the rubber body with tapes.

2.2.2 FMVSS 201U Free Motion Headform (FMH)

The FMH is a simplified version of a HIII 50% dummy head and it is used to evaluate occupant protection in interior impact for certain regions of the vehicle like pillar, side rail, etc. Photographs of the FMH are given in Figure 2.18.



Figure 2.18. Free Motion Headform Used for FMVSS 201U Tests [24]

The FMH has accelerometers at the center of gravity to measure head accelerations during the impact. These measurements are used to calculate specified Head Injury Criterion (HIC). The definition of HIC and other related injury criterion will be given in Appendix C.

2.3 Impactors Used in Pedestrian Safety Tests

As mentioned before, in all test and evaluation procedures, pedestrian sub-system impactor tests are proposed instead of tests with a pedestrian dummy. Adult and child headform impactors, upper legform impactor and Flex PLI legform impactor are used for the pedestrian safety tests. In this Section, these impactors will be given in detail in terms of their usage, structure, dimensions and instrumentation.

2.3.1 Pedestrian Adult and Child Head Forms

The pedestrian headform impactors are partial spheres designed to be launched at the windshields and hoods of cars to simulate the head impact during a vehicle to pedestrian accident. The impactors have tri-axial accelerometers at the center of gravity (cog) of the impactor which enable to measure accelerations for calculating the HIC. The adult head form impactor and the child head form impactor both consist of a spherical skull and flexible elastomer cap skin with a removable flat cap plate at the back. The impactors are same in structure but the child head form impactor is lighter. The outer diameter of the pedestrian adult and child head form impactors including the skin is 165 ± 1 mm. The thickness of the skin is 14 ± 0.5 mm. The weight of a complete assembly including accelerometers is $4,50 \pm 0,10$ kg for the adult and $3,50 \pm 0,07$ kg for the child pedestrian head form [35]. General photograph of the head form impactor is given in Figure 2.19.



Figure 2.19. Pedestrian Headform Impactor [24]

2.3.2 Upper Legform

The upper legform impactor was designed by Transport Research Laboratory (TRL) to evaluate the injuries to the upper leg and pelvis of a pedestrian in an accident. The upper legform has sensors to measure bending moment and force which are the two principal modes of injury to pedestrians impacted by a vehicle. The upper legform is currently used by the Euro NCAP and ECE R127.

The TRL upper legform impactor consists of a front member and a rear member with a torque limiting joint. The entire upper legform assembly is attached to the launcher by the two clutch plates on the rear member as shown in Figure 2.20. Two 25,4 mm (1 inch) thick sheets of blue CONFOR foam (Type CF-45) and an outer rubber sheet to represent flesh are attached to the rear member and wrapped around the front member as can be seen in Figure 2.21. Bending moment is calculated by three full-bridge strain gages mounted at the centerline as well as 50 mm above and below the centerline. Force is measured between the front and rear members with two load transducers, one at the top and one at the bottom.

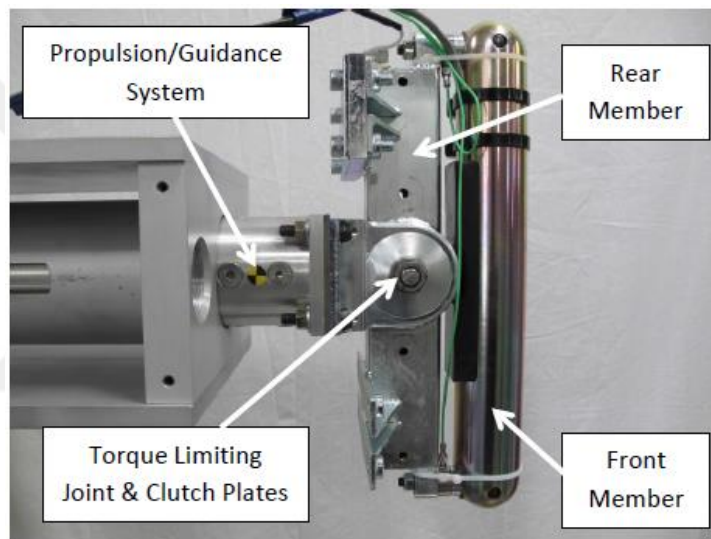


Figure 2.20. TRL Upper Legform with Attachment to Propulsion System [36]

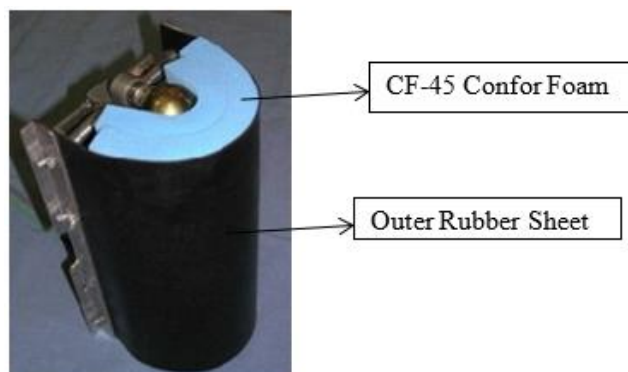


Figure 2.21. TRL Upper Legform

2.3.3 Flex PLI Legform

The Flex-PLI (Flexible Pedestrian Legform Impactor) simulates the flexible nature of the human leg bones. The impactor represents a 50th percentile male leg which is struck from the right side. It is fired from a launcher to the bumper of a vehicle for the assessment of pedestrian lower leg and knee injuries.

The tibia and femur are designed as a segmented assembly made from high strength plastic and a fiber reinforced bone on the inside. The knee is designed as two parts and it is flexible at the knee joint. Springs and stainless steel wires are used in the knee to simulate ligaments. The flesh is a combination of rubber and neoprene foam sheets. Total weight of the Flex-PLI impactor is 12,95 kg [24]. General photograph of the Flex-PLI impactor is given in Figure 2.22.



Figure 2.22. Flex-PLI Legform [24]

Strain gauges are bonded to the bones to measure bending moments. Standard leg instrumentation has 12 channels including accelerometers, loadcells and strain gauges.

2.4 Regulations Related to Pedestrian Safety

A summary of the automotive safety regulations was given in Section 1.2. In this section, regulations related to pedestrian safety will be given in detail.

There are many bodies and formal groups that define test and evaluation procedures for pedestrian protection. The types of tests proposed by these bodies are very similar. The objective of all pedestrian safety standards is protecting pedestrians hit from the side by a vehicle at speeds up to 40 km/h. 40 km/h is judged to be the upper limit at which pedestrian protection could reasonably be provided and over 80% of pedestrian accident cases happen within this speed.

In all test and evaluation procedures pedestrian sub-system impactor tests are proposed instead of tests with a pedestrian dummy, as mentioned before. There are several reasons for this: test repeatability and reproducibility is increased by performing sub-system impactor tests; the pedestrians have a greater whole body motion compared to vehicle occupants during an accident, which makes the validation requirements of a pedestrian dummy more difficult to achieve and finally biofidelity of the commercially available pedestrian dummy is not good enough to evaluate the pedestrian kinematics and injuries during a collision.

Figure 2.23 shows the summary of the pedestrian sub-system impactor tests in terms of impactors and test areas on the vehicle [37].

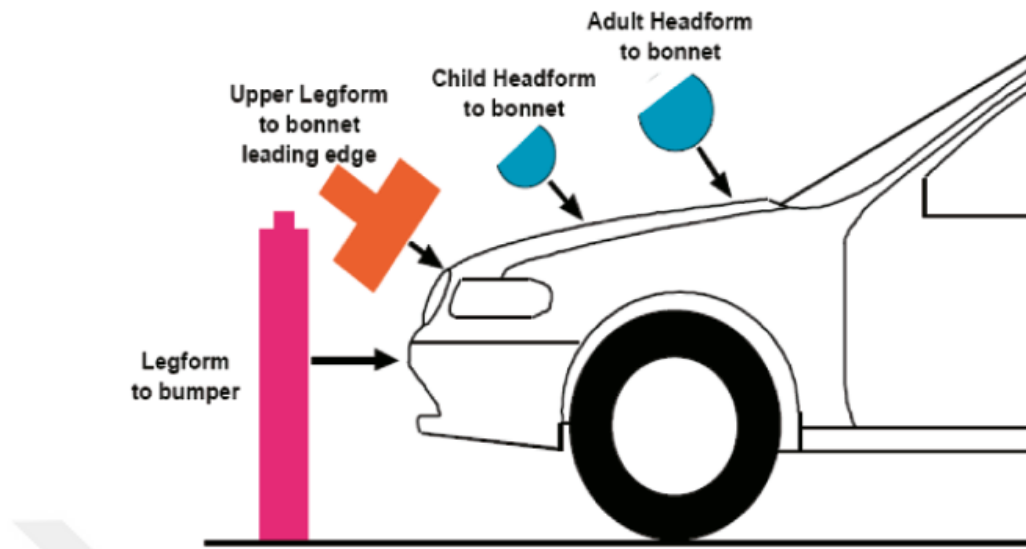


Figure 2.23. Summary of Pedestrian Sub-System Impactor Tests [37]

2.4.1 UNECE R127

The UNECE R127 “Uniform Provisions Concerning the Approval of Motor Vehicles with Regard to their Pedestrian Safety Performance” is the United Nations Regulation for pedestrian safety [38]. The impactors used for the tests, the injury criteria and the vehicle body measurement which are used as reference during the tests are described in the regulation. The preparations that need to be done on the vehicle body are also described. Additionally, the impactors that are used for the tests are given. Flex-PLI, upper legform impactor, adult and child headform impactors are used in these C. The details of the tests will be given in the following subsections.

2.4.1.1 Flexible Lower Legform Impactor Tests

The test procedure for the flexible lower legform impactor is summarised below:

- For each test the impactor shall be covered by flesh and skin composed of rubber and neoprene sheets.
- A minimum of three lower legform to bumper tests shall be carried out. Bumper test area is divided to 3 regions and the tests are performed for these 3 regions at positions judged to be most likely to cause injury. Tests shall be to different types of structure, where they vary throughout the area to be assessed.
- The direction of the impact velocity vector shall be parallel to the longitudinal vertical plane of the vehicle and in the horizontal plane. The tolerance for the direction of the velocity vector in the horizontal and longitudinal planes shall be $\pm 2^\circ$ at the time of first contact.
- The bottom of the impactor shall be at 75 mm ± 10 mm above ground reference plane at the time of first contact with the bumper. When setting the height of the propulsion system, the influence of gravity during the period of free flight of the impactor shall be taken into account.
- The lower legform impactor for the bumper tests shall be in "free flight" at the moment of impact.
- The impact velocity of the impactor when striking the bumper shall be 11,1 m/s $\pm 0,2$ m/s.
- To evaluate the test results it should be checked that the maximum dynamic knee bending angle shall not exceed 19° , the maximum dynamic knee shearing displacement shall not exceed 6,0 mm, and the acceleration measured at the upper end of the tibia shall not exceed 170 g [38].

2.4.1.2 Upper Legform to Bumper Tests

The upper legform to bumper test procedure is summarised below:

- For each test the foam flesh shall be two new sheets of 25 mm thick foam type CF-45 or equivalent. The skin shall be a 1,5 mm thick rubber sheet.

- A minimum of three upper legform to bumper tests shall be carried out. Bumper test area is divided to 3 regions and the tests are performed for these 3 regions at positions judged to be most likely to cause injury. Tests shall be to different types of structure, where they vary throughout the area to be assessed.
- The direction of impact shall be parallel to the longitudinal axis of the vehicle. The tolerance to this direction is $\pm 2^\circ$.
- The impact velocity of the upper legform impactor when striking the bumper shall be $11,1 \text{ m/s} \pm 0,2 \text{ m/s}$.
- To evaluate the test results it should be checked that the instantaneous sum of the impact forces with respect to time shall not exceed 7,5 kN and the bending moment on the test impactor shall not exceed 510 Nm [38].

2.4.1.3 Adult and Child Headform Tests

Test specifications for the adult and child headform impactors are summarised below:

- The headform impactors shall be in "free flight" at the moment of impact, at the required impact velocity and the required direction of impact.
- The acceleration values shall be recorded, and Head Injury Criterion (HIC) shall be calculated.
- The manufacturer shall identify the zones of the bonnet top test area where the HIC shall not exceed 1000 (HIC1000 zone) or 1700 (HIC1700 zone). An example for identification of these zones is given in Figure 2.24.

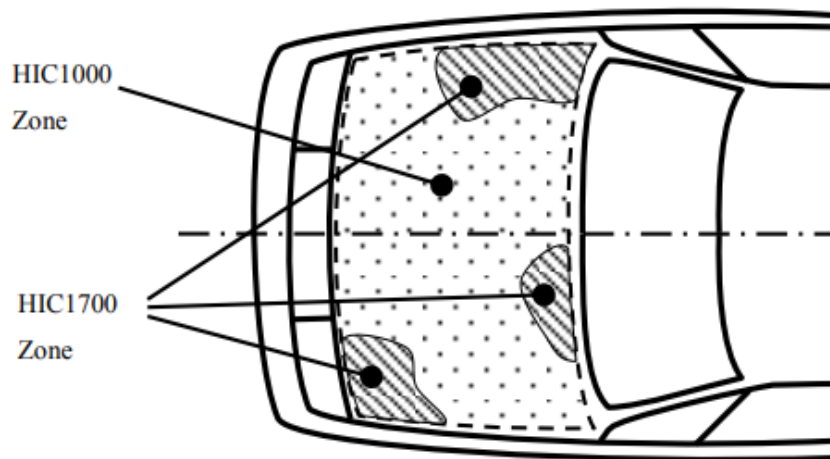


Figure 2.24. Example of Marking of HIC1000 Zone and HIC1700 Zone [38]

- The technical services conducting the tests shall perform as many tests as necessary to assure that the vehicle satisfies the HIC limit values of 1000 for the HIC1000 zone and 1700 for the HIC1700 zone.
- To evaluate the test results it should be checked that the HIC recorded shall not exceed 1000 over two thirds of the combined child and adult headform test areas. The HIC for the remaining areas shall not exceed 1700 for both headforms [38].

2.4.2 EURO NCAP Pedestrian Testing Protocol

The European New Car Assessment Program (Euro NCAP) “Pedestrian Testing Protocol” defines how the pedestrian protection tests should be performed when requested by the manufacturer [39]. In the protocol, firstly it is described how the vehicles should be prepared for the tests. Then it is described that the vehicle shall be marked with a grid. The marking procedures divide the front of the car into zones which are then assessed using appropriate impactors. Then the definitions of reference lines, edges and corners on the vehicle are given in detail. Using these reference lines, edges and corners, test areas for the child and adult headform,

upper legform and lower legform are identified. Grid points are marked on the test areas following the procedure given in the protocol. Headform test area and grid points are given in Figure 2.25. The bumper test zone and legform grid points are given in Figure 2.26.

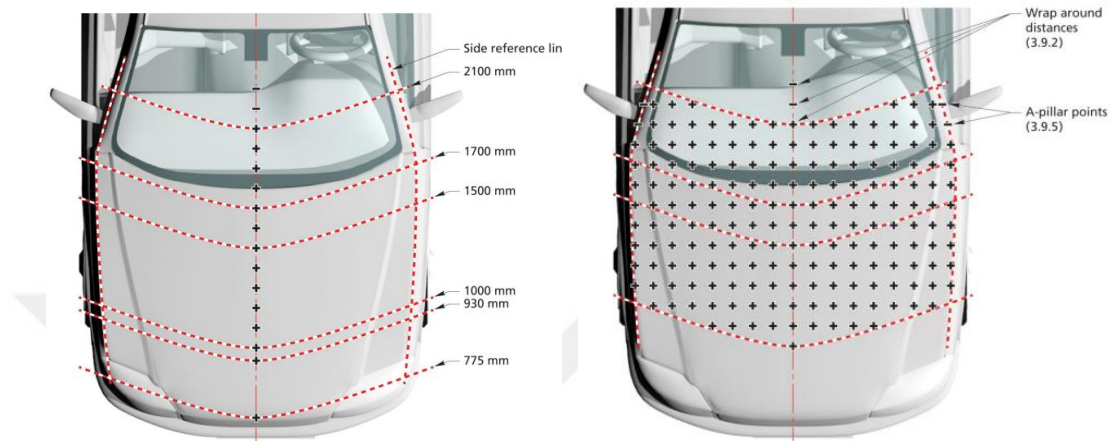


Figure 2.25. Headform Test Area and Grid Points [39]

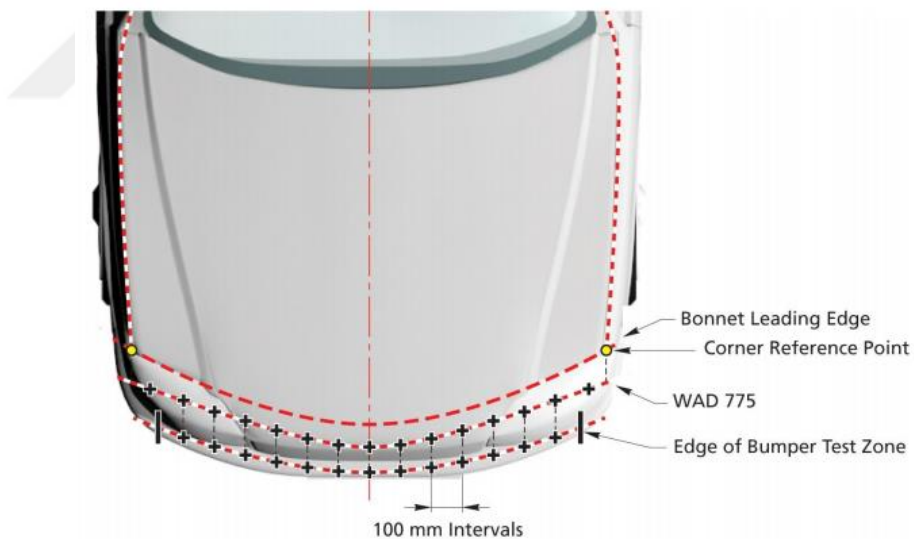


Figure 2.26. Bumper Test Zone and Legform Grid Points [39]

Similar to ECE R127, the test procedures are defined for the impactors. The details of the tests are given in the following subsections.

2.4.2.1 Flexible Lower Legform Impactor Tests

The flexible lower legform to bumper test procedure is summarised below:

- The launching speed is adjusted to give $11,1\text{m/s} \pm 0,2\text{m/s}$ at the point of first contact.
- The direction of impact at the point of first contact shall be in the horizontal plane and parallel to the longitudinal vertical plane of the vehicle. The axis of the legform shall be vertical at the time of first contact. The tolerance to these directions is $\pm 2^\circ$.
- At the time of first contact the centreline of the legform impactor shall be within $\pm 10\text{ mm}$ of the selected impact point.
- At the time of first contact the bottom of the legform shall be $75\text{mm} \pm 10\text{mm}$ above Ground Reference Level as can be seen in Figure 2.27.

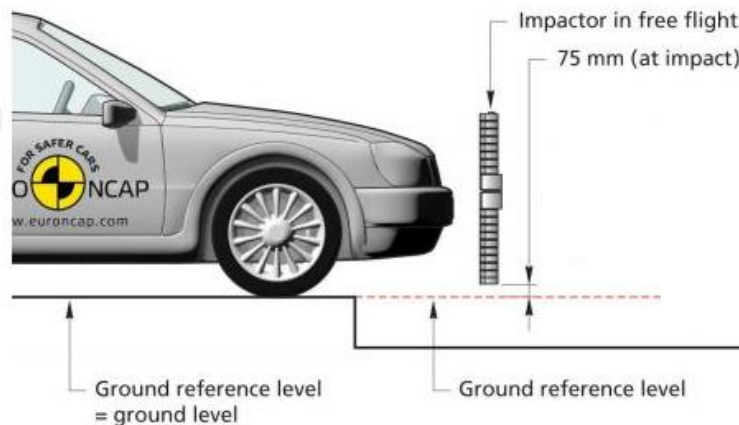


Figure 2.27. Legform to Bumper Tests [39]

- For the evaluation of flexible lower legform tests, the moments and elongations measured with the impactor shall be compared to the performance limits given below in Table 2.1. Each of the grid points can be awarded up to one point resulting in a maximum total of points equal to the number of grid points. The total score for the legform area will be

calculated out of 6,00 points by scaling down the sum of grid points scores by the relevant number of grid points.

Table 2.1 Performance Limits in Euro NCAP Flexible Lower Legform Tests [39]

	Higher Performance Limit	Lower Performance Limit
Tibia Bending Moment	282 Nm	340 Nm
Medial Collateral Ligament (MCL) Elongation	19 mm	22 mm
Anterior Collateral Ligament (ACL) / Posterior Collateral Ligament (PCL) Elongation	10 mm	10 mm

2.4.2.2 Upper Legform Impactor Tests

The upper legform to bumper test procedure is summarised below:

- New pieces of certified foam is fitted to the upper legform before each test.
- The total mass of the upper legform impactor including the propulsion and guidance components shall be adjusted for the upper legform to bumper tests and upper legform to Wrap Around Distance (WAD) 775mm tests.
- The vehicle is aligned so that the test system can aim at the impact position and can accelerate and guide the upper legform in a direction that is parallel to the vehicle centre line $\pm 2^\circ$.
- The impact velocity of the upper legform impactor when striking the bumper shall be 11,1 m/s $\pm 0,2$ m/s.
- The direction of impact shall be in the horizontal plane and parallel to the longitudinal vertical plane of the vehicle. The axis of the upper legform shall be vertical at the time of first contact. The tolerance to these directions is $\pm 2^\circ$.

The sample test set-up is given in Figure 2.28.

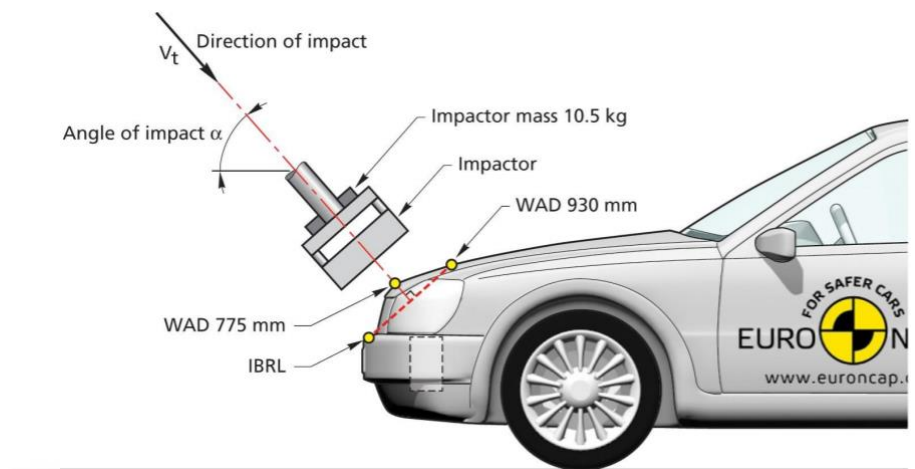


Figure 2.28. Upper Legform to WAD775mm Test [39]

- For the evaluation of upper legform tests, the moments and forces measured with the impactor shall be compared to the performance limits given below in Table 2.2. Each of the grid points can be awarded up to one point resulting in a maximum total of points equal to the number of grid points. The upper legform performance for each grid point is based upon the worst performing parameter. The total score for the upper legform area will be calculated out of 6,00 points by scaling the sum of grid points score by the relevant number of grid points.

Table 2.2 Performance Limits in Euro NCAP Upper Legform Tests [39]

	Higher Performance Limit	Lower Performance Limit
Bending Moment	285 Nm	350 Nm
Sum of Forces	5,0 kN	6,0 kN

2.4.2.3 Adult and Child Headform Impactor Tests

- A child headform impactor shall be used for tests to the forward section of the bonnet top, A-pillars, windscreen, roof, for the test locations between boundaries described by WAD1000mm and WAD1500mm as can be seen in Figure 2.25 . An adult headform impactor shall be used for tests to the rearward section of the bonnet top with the test locations between boundaries described by WAD1700 mm and WAD2100 mm.
- The test system shall be adjusted so that it can launch the headform at the grid point with the correct angle of incidence. The angle of impact shall be $50^{\circ} \pm 2^{\circ}$ for child headform impactor tests and $65^{\circ} \pm 2^{\circ}$ for adult headform impactor tests.
- The centreline of the headform impactor shall be within a ± 10 mm tolerance to the selected grid point.
- The test system shall be adjusted to give a velocity of $11,1 \pm 0,2$ m/s at the point of first contact.
- For the evaluation of headform impactor tests, HIC_{15} values are calculated and reported as a colour according to the corresponding colour boundaries given below in Table 2.3. Then each of the grid points are awarded up to one point, resulting in a maximum total amount of points equal to the number of grid points. A maximum of 24 points is available for the headform test zone. The total score for all grid points is calculated as a percentage of the maximum achievable score, which is then multiplied by 24 points.

Table 2.3 Evaluation of Impactor Tests [39]

Green	$HIC_{15} < 650$	1,00 point
Yellow	$650 \leq HIC_{15} < 1000$	0,75 points
Orange	$1000 \leq HIC_{15} < 1350$	0,50 points
Brown	$1350 \leq HIC_{15} < 1700$	0,25 points
Red	$1700 \leq HIC_{15}$	0 points

2.4.3 Comparison of UN ECE R127 and EURO NCAP Pedestrian Protection Standards

UN ECE R127 tests are legislative tests that are obligatory for the vehicle manufacturers. However, Euro NCAP tests are not obligatory and they are performed when requested by the vehicle manufacturer.

The test zones are determined for the related impactors in both standards. In UNECE R127 the impact points are determined within these zones by the technical service but in Euro NCAP grids are formed to define the impact points within the impact zones and the related impactors are launched to these impact points.

CHAPTER 3

DESIGN OF THE NOVEL THORAX IMPACTOR

Pedestrian sub-system impactors and pedestrian dummies were described in Chapter 2. As explained before, pedestrian dummies are mostly used to evaluate the general kinematics of the pedestrian during impact and they are used for research purposes. On the other hand, pedestrian sub-system impactors are used in the standard tests only for head and leg regions. Consequently, it has come out that a new impactor is needed to evaluate thorax region injuries during pedestrian involved accidents.

A novel thorax impactor, which will be used to evaluate the thorax injuries in pedestrian sub-system impactor tests, is designed in this study. Firstly, brief information about human thorax and the thorax injury criteria will be given for providing background for the design of the particular impactor. Later, details of the design, analysis, validation and prototype stages for the novel thorax impactor will be given in this chapter.

3.1 Human Thorax

There are twelve pairs of ribs, accounting for 24 total rib bones in human thorax. The ribs are flat, thin bones that form the ribcage together with the sternum. The ribs provide protection for vital organs in the upper body, including the heart and lungs. The ribs also help to protect major vessels in the upper body. In addition to protecting vital organs, such as the heart and lungs, the ribs give shape and support to the chest, they protect parts of other organs, including the stomach, spleen and kidneys. The ribs also help humans to breathe.

The ribs are divided into three categories: true ribs, false ribs, and floating ribs. The primary differences are size and how they connect to the front of the skeleton. The first seven pairs of rib bones beginning at the top of the sternum are called "true ribs." They connect to the spine by ligaments at the back, and to the sternum by costal cartilage in the front. Costal cartilage is elastic and allows the ribcage to expand during respiration. The next three pairs of rib bones (8, 9 and 10) are called "false ribs". Like the true ribs, false ribs are connected to the spine at the back. The primary difference between true ribs and false ribs is that false ribs connect to the lowest true ribs instead of connecting to the sternum at the front. The last two pairs of ribs (11 and 12) are the smallest of all of the rib bones, and are called "floating ribs." They are called "floating rib" because they are connected to the spine at the back, but are not connected to anything at the front [40]. In Figure 3.1 human thoracic cage can be seen.

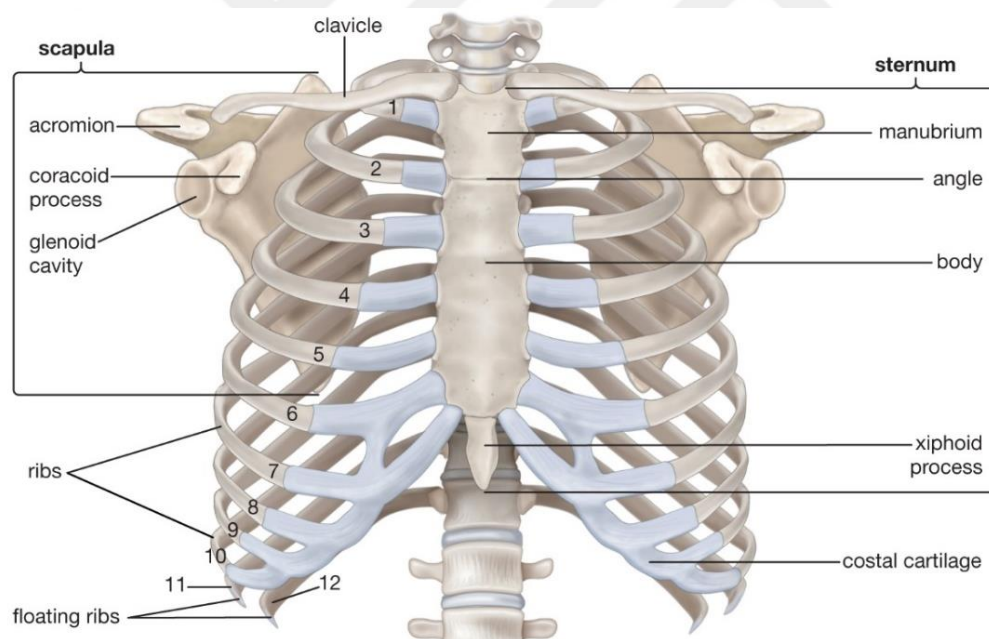


Figure 3.1. Human Thoracic Cage [41]

3.2 Thorax Injury Criteria

Several injury criteria have been used to evaluate the thorax injuries from 1960s to today. These injury criteria are derived from experiments conducted with PMHS (i.e. cadavers) or via the reconstruction of well-documented real world accidents by the different research groups [42]. Some of these criteria are applicable to thorax injuries resulting from frontal impacts [43]–[46] and some are applicable to thorax injuries resulting from side impacts [47]–[53].

For defining the severity of the injuries, the commonly used scaling system is the Abbreviated Injury Scale (AIS). AIS provides an internationally accepted tool for ranking injury severity. The AIS is an anatomically based global severity scoring system that classifies an individual injury by body region according to its relative severity on a 6 point scale [54]. In Table 3.1, AIS scores for corresponding injuries are given [55].

Table 3.1 Summary of AIS Codes [55]

AIS Score	Injury
AIS0	None
AIS1	Minor
AIS2	Moderate
AIS3	Serious
AIS4	Severe
AIS5	Critical
AIS6	Unsurvivable

Forces, accelerations and rib deflections are being used to evaluate the frontal impact tolerances of the thorax. Forces, accelerations, rib deflections and criteria obtained by using a combination of these measurements are being used to evaluate the side impact tolerances of the thorax. The side impact tolerances of the thorax that are mostly used for dummy development and determination of injury criteria in

the current standards are defined by researchers like Viano [47], Sacresté et al. [48], Tarriere et al. [49], Cavanaugh et al. [50], Chung et al. [51], Eppinger et al. [52]. The expected level of injuries based on AIS scores corresponding to the determined tolerances are also defined by these researchers.

Side impact criteria that are used in the current side impact regulations and safety programs are summarised in Table 3.2.

Table 3.2 Side Impact Injury Criteria Commonly Used in Side Impact Regulations

<u>Regulation</u>	<u>Dummy Used</u>	<u>Injury Criteria for Thorax Region</u>	<u>Required Instrumentation</u>
UN ECE R95 [56]	ES-2	(a) RDC ≤ 42 mm (b) VC $\leq 1,0$ m/s	Rib displacement potentiometers (upper, middle, lower rib)
FMVSS 214 [57]	SID	TTI $< 85g$	Accelerometers
	ES-2re	The deflection of any of the upper, middle, lower ribs ≤ 44 mm	Rib displacement potentiometers (upper, middle, lower rib)
EuroNCAP Side Impact Mobile Deformable Barrier Test [58]	WorldSID	(a) Peak deflection of each rib between 28 mm and 50 mm (b) VC $\leq 1,0$ m/s	Rib displacement 2D IR-TRACC sensors

Details of the Rib Deflection Criterion (RDC), Thoracic Trauma Index (TTI) and Viscous Criterion (VC) are given in Appendix C.

3.3 Novel Thorax Impactor Design

Several design alternatives have been considered during this study. The alternatives have been analysed by using Finite Element Analysis Method as described in

Chapter 4. The design of the particular impactor has been improved iteratively. The finalised impactor is named as “**Thorax Impactor-PEDESTRIAN**” and will be referred as “**ThImp-PED**”. General view of ThImp-PED can be seen in Figure 3.2.

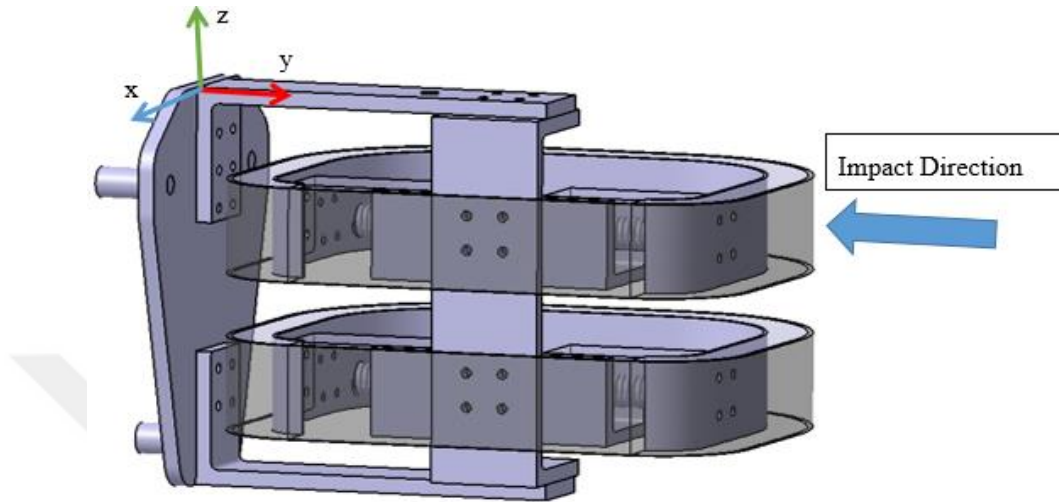


Figure 3.2. ThImp-PED General View

3.3.1 Main Considerations During Design of ThImp-PED

During the design of the thorax impactor alternatives, the following factors and parameters have been taken into account:

- Mass distribution and center of gravity (cog): Statistics on human body mass distribution and thorax masses of some of the available crash test dummies have been taken into consideration for determining the mass of ThImp-PED. The geometry and dimensioning of the parts have been designed so that the cog of the impactor lies at the middle in z direction ($\pm 5\text{mm}$) and along the centerline of the pins in x direction ($\pm 5\text{mm}$).
- Biofidelity: Rib displacement measurement has been used to compare the biofidelity of ThImp-PED with ES-2 dummy. Details will be given in Chapter 4 and Chapter 5.

- Measuring capability: Linear potentiometers have been used to measure the rib deflections.
- Simplicity and ease of use: ThImp-PED has been designed in such a way that it is less complex than available dummy thorax regions. It includes less number of parts and that it is easy to be assembled and handled.
- Selection of commercially available materials: Commercially available steel materials (i.e. SAE/AISI 4140 and SAE/AISI 1070) have been used for the steel parts. CF-45 foam and neoprene material which are also used in current pedestrian impactors and crash test dummies have been used for the non-metallic parts.
- Producibility and Interchangeability of the parts: The parts of ThImp-PED have been designed such that they are as simple as possible and easy to manufacture using conventional manufacturing methods. Additionally, identical parts have been used in different locations to increase the interchangeability of the parts.
- Maintainability: ThImp-PED assembly has been designed in such a way that it is easy to disassemble, maintain and reassemble. All the parts are accessible and can be easily dismantled from the assembly by the use of conventional tools.
- Durability: The crash test dummies are designed durable to enable them to be used in many tests. Durability is even more critical for the pedestrian sub-system impactors, as they are launched directly to the vehicle and there are no parts like seatbelts and airbags that restrain the impactor or reduce the severity of the impact during the tests. Therefore, durability has been taken into account during the design of ThImp-PED such as high Carbon steel materials have been used to increase the strength of the parts and bolt connections have been utilized in the assembly.
- Modular Design: During the design of the mounting parts (i.e. mounting plate and mounting pins) that are used to mount ThImp-PED to the test

system, the interface dimensions of the Linear Impactor Test System in METU-BILTIR Center have been taken into account. However, these mounting parts can easily be modified without changing the rest of the ThImp-PED assembly so that the impactor can be fit to other test systems as well.

3.3.2 Overall Dimensions of ThImp-PED

To determine the dimensions of the thorax impactor, the anthropomorphic data of human body on which crash test dummies dimensions are based on, and the dimensions of the EuroSID-2 dummy given in Figure 3.3 [30] and Table 3.3 have been examined.

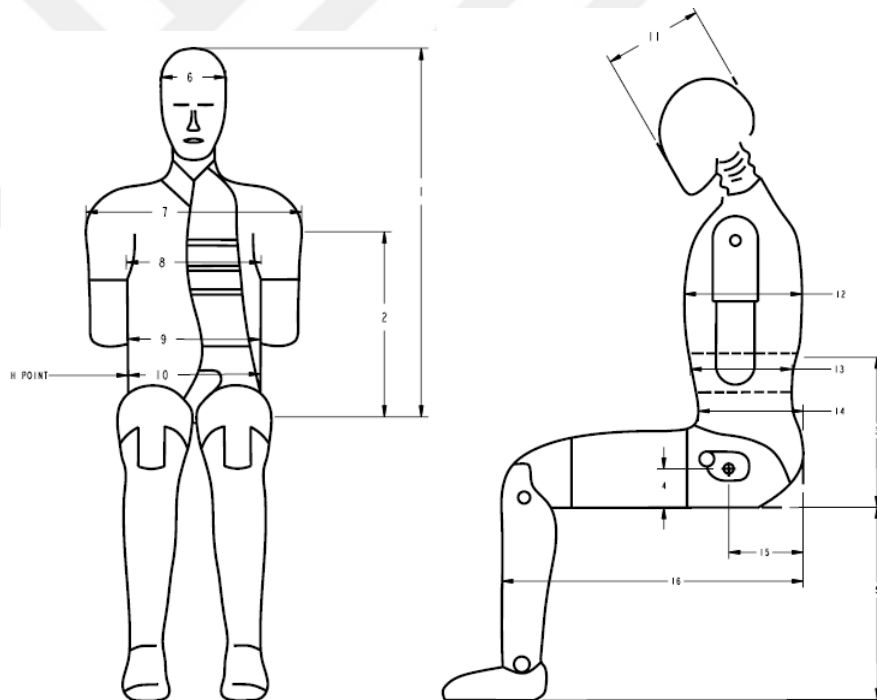


Figure 3.3. Dimensions of the ES-2 Dummy [30]

Table 3.3 Related Dimensions of ES-2 Dummy [30]

No	Dimension	Value (mm)
1	Sitting Height	909 ± 9
2	Seat to Shoulder Joint	565 ± 7
3	Seat to Lower Face of Thoracic Spine Box	351 ± 5
4	Seat to Hip Joint	100 ± 3
5	Sole to Seat, Sitting	442 ± 9
6	Head Width	155 ± 3
7	Shoulder / Arm Width	470 ± 9
8	Thorax Width	327 ± 5
9	Abdomen Width	280 ± 7
10	Pelvis Lap Width	366 ± 7
11	Head Depth	201 ± 5
12	Thorax Depth	267 ± 5
13	Abdomen Depth	199 ± 5
14	Pelvis Depth	240 ± 5
15	Back of Buttocks to Hip Joint	155 ± 5
16	Back of Buttocks to Front Knee	606 ± 9

The outer dimensions of ThImp-PED can be seen in Figure 3.4. Width of ThImp-PED from inner to inner surface (d1) of the ribs is designed as 280 mm. The overall width (d2) becomes 342 mm with ribs having a thickness of 2,5 mm, the flesh representing foam having a thickness of 25 mm and neoprene skin having a thickness of 3,5 mm. Depth of ThImp-PED (d3) is designed as 267 mm.

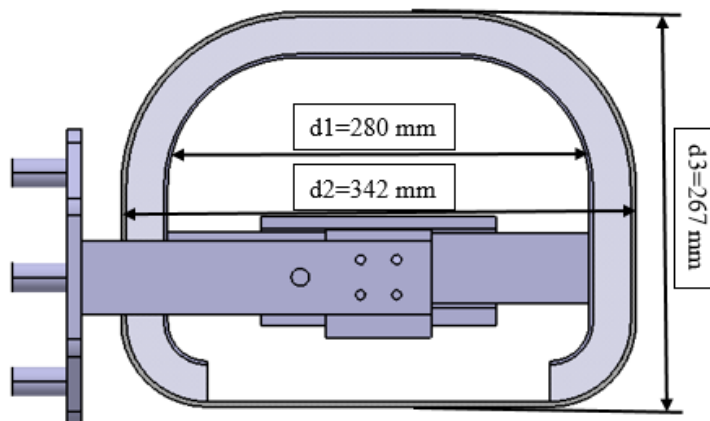


Figure 3.4. Overall Dimensions of ThImp-PED

The mass of ThImp-PED has been designed to be 22,4 +/- 1,0 kg.

3.3.3 Parts of ThImp-PED

As explained in Section 2.4, in the pedestrian protection standards, the tests are performed to simulate a pedestrian struck from the side by a vehicle due to the fact that statistically 80% of pedestrian accidents occur when the pedestrian is walking across the road and struck from the side by the front of a vehicle. ThImp-PED is designed such that it will be impacted by the vehicle front from the side during the tests as shown in Figure 3.5.

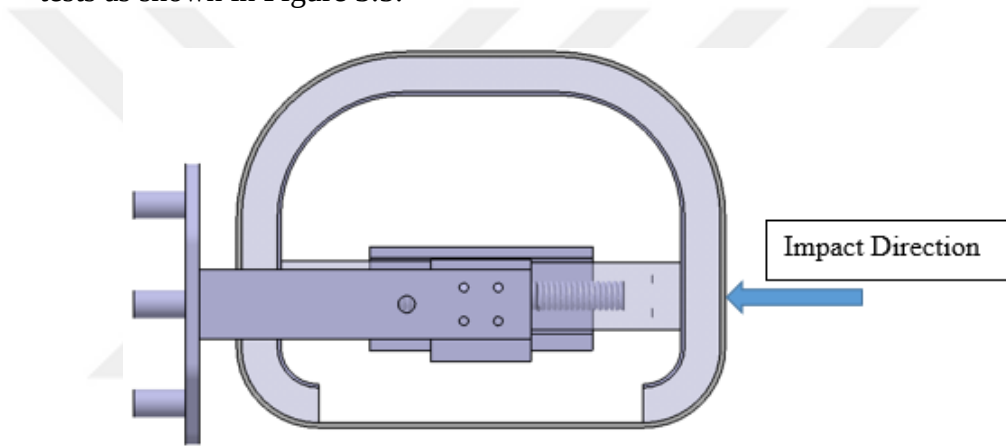


Figure 3.5. ThImp-PED Top View

The back view of ThImp-PED is given in Figure 3.6.

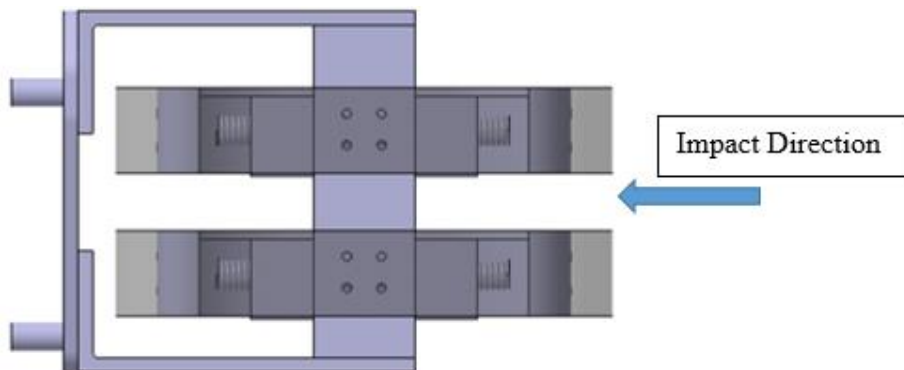


Figure 3.6. ThImp-PED Back View

ThImp-PED assembly consists of 25 parts in total. It includes 2 subassemblies called “Upper Rib Set” and “Lower Rib Set” which are the major critical sections of the design. These subassemblies are connected to the “Rear Plate” with bolt-nut connections. “Rear Plate” is connected to the “Upper Plate” and “Lower Plate” with bolt-nut connections. Finally, “Mounting Bracket” is connected to the whole assembly via “Upper Plate” and “Lower Plate”. The “Mounting Bracket” has the “Mounting Pins” on it and its function is to fit ThImp-PED to the Linear Impactor Test System in METU-BILTIR Center. The “Mounting Bracket” design is based on the interface dimensions of particular test system as seen in Figure 3.7 and it can be easily modified to be compatible with other test systems in other test laboratories.

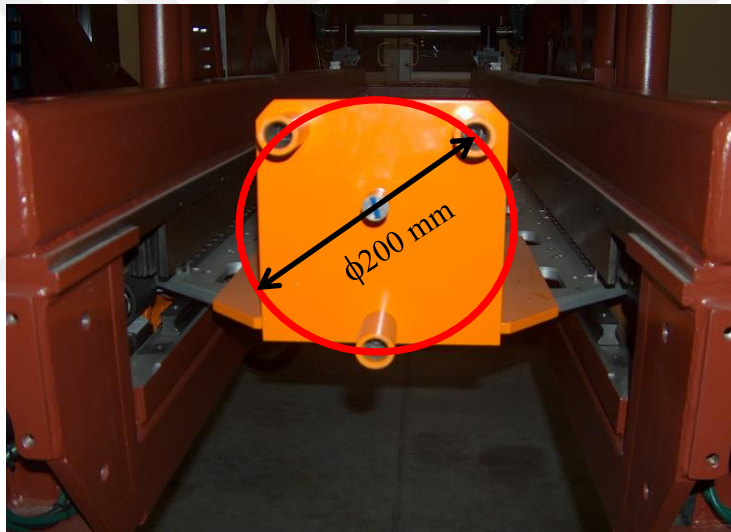


Figure 3.7. Interface Dimensions of the Particular Linear Impactor Test System

The “Upper Rib Set” and “Lower Rib Set” subassemblies include 9 parts. “Left Piston” and “Right Piston” are positioned on “Rails” which support their mass and also restrict their motion to be uniaxial. The “Left Pistons” are fixed to the “Rails” with bolts and the “Right Pistons” are free to slide. The pistons have cylindrical holes and in these holes the springs are located. The end parts of the “Pins” are positioned in these holes and it provides the alignment of the pistons during the sliding motion observed at the time of impact. 4 identical ISO 10243 compression

springs [59] are used in ThImp-PED. “Upper Rib” and “Lower Rib” are fixed to the pistons from the sides. Finally, each rib set subassembly is covered by “Upper Flesh”, “Lower Flesh” and “Skin” parts. Views of ThImp-PED assembly and “Rib Set Subassembly” with part numbers are given in Figure 3.8 and Figure 3.9. The part list is given in Table 3.4.

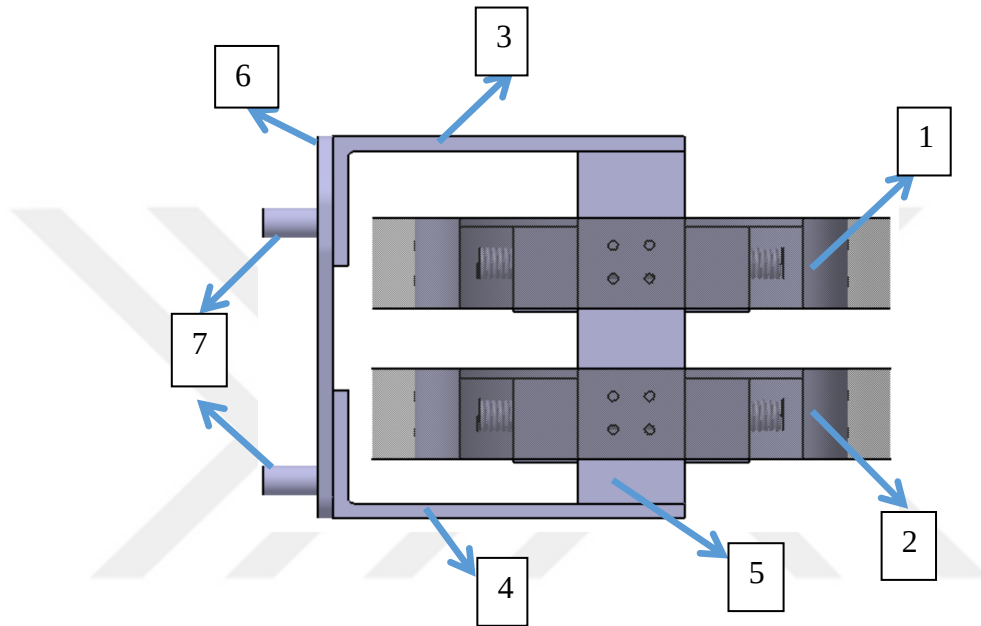


Figure 3.8. ThImp-PED Back View with Part Numbers

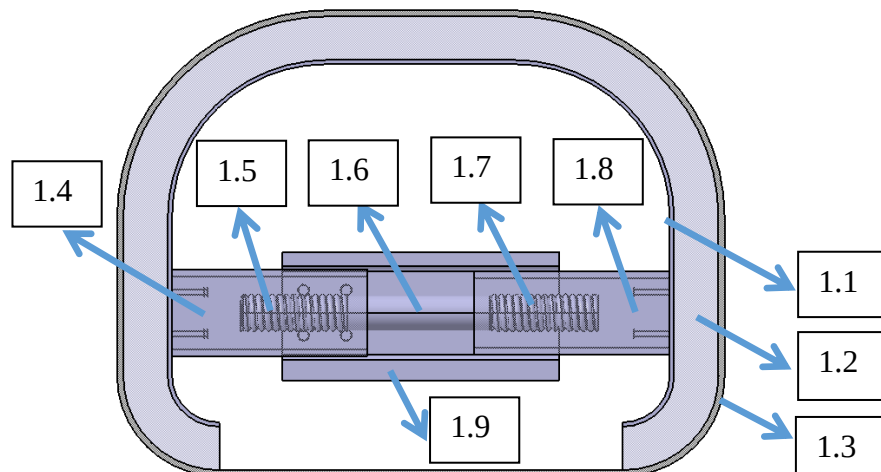


Figure 3.9. ThImp-PED Rib Set Subassembly with Part Numbers

Table 3.4 ThImp-PED Parts List

Part No	Part Name	Quantity	Material
1	Upper Rib Set Assy	1	NA
2	Lower Rib Set Assy	1	NA
3	Upper Bracket	1	AISI/SAE 4140
4	Lower Bracket	1	AISI/SAE 4140
5	Rear Bracket	1	AISI/SAE 4140
6	Mounting Bracket	1	AISI/SAE 4140
7	Mounting Pins	3	AISI/SAE 4140
1.1	Upper Rib	1	AISI/SAE 1070
1.2	Upper Flesh	1	CF-45 Foam
1.3	Upper Skin	1	Neoprene
1.4	Upper Left Piston	1	AISI/SAE 4140
1.5	Upper Left Spring	1	Chrome Silicone Steel
1.6	Upper Pin	1	AISI/SAE 4140
1.7	Upper Right Spring	1	Chrome Silicone Steel
1.8	Upper Right Piston	1	AISI/SAE 4140
1.9	Upper Rail	1	AISI/SAE 4140
2.1	Lower Rib	1	AISI/SAE 1070
2.2	Lower Flesh	1	CF-45 Foam
2.3	Lower Skin	1	Neoprene
2.4	Lower Left Piston	1	AISI/SAE 4140
2.5	Lower Left Spring	1	Chrome Silicone Steel
2.6	Lower Pin	1	AISI/SAE 4140
2.7	Lower Right Spring	1	Chrome Silicone Steel
2.8	Lower Right Piston	1	AISI/SAE 4140
2.9	Lower Rail	1	AISI/SAE 4140

CHAPTER 4

FINITE ELEMENT ANALYSIS

As soon as the thorax impactor initial conceptual design is finalized, several Finite Element Analysis attempts have been performed during the study to improve and justify the design of the thorax impactor iteratively. After the satisfactory results of FEA, the dimensions and materials of ThImp-PED impactor have been finalized. The details are given in the following sections.

4.1 General Remarks Regarding the FEA Modeling of ThImp-PED

LS-DYNA R10.0 [60] has been used as the solver for the FEA. LS-DYNA is a general purpose FEA program which enables to simulate complex real world problems. It is widely used by the industries such as automotive, aerospace, defence and manufacturing. The program performs highly nonlinear, transient dynamic finite element analysis using explicit time integration.

LS-DYNA is adequate to analyze high speed, short duration events where inertial forces are important, so automotive crash (deformation of car body, airbag inflation, etc) can be analysed with LS-DYNA as it involves "Transient dynamic" characteristics.

LS-PrePost version 4.3 [61] has been used for preparing the FEA models and also for post processing of the results. As LS-PrePost is also provided by the same company which supplies LS-DYNA, it is perfectly compatible with LS-DYNA. However, the meshing capability of LS-PrePost is not sufficient for complex 3D geometries. Therefore, MSC Apex Modeler [62], which is a very effective and user friendly pre-post processor for preparing FEA models has been used for creating the mesh of the parts in this study.

The types and number of elements, types of materials and contacts are given in the following subsections.

4.1.1 Types of Elements

The FEA Model (FEM) of ThImp-PED (impactor) is given in Figure 4.1.

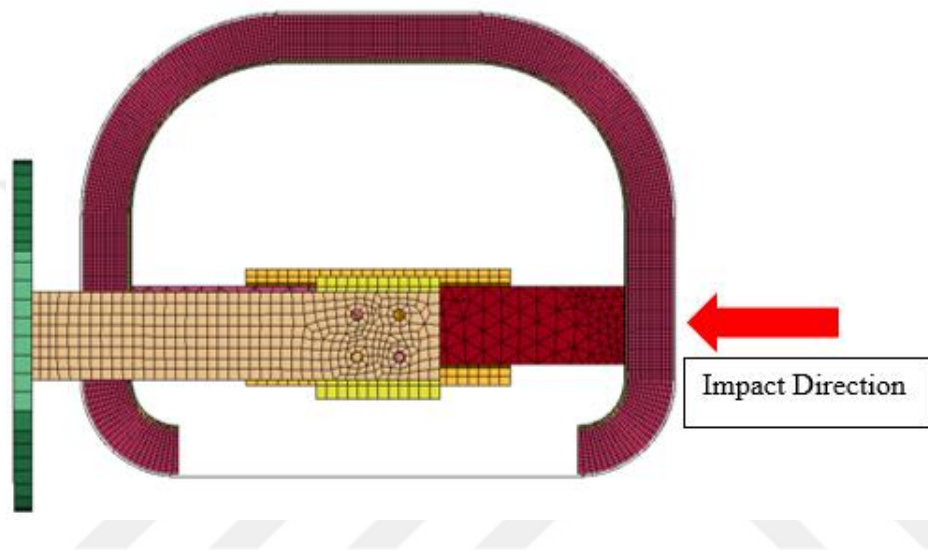


Figure 4.1. ThImp-PED FEM

In the model, solid steel parts except the right and left piston parts have been meshed with “Solid Hexahedron Elements”. This element type is more accurate compared to “Solid Tetrahedral Elements”. However, as the piston parts have features like holes on different orientations, it was not possible to use “Solid Hexahedron Elements” and they have been meshed with “Solid Tetrahedral Elements”. The ribs have also been meshed with “Solid Hexahedron Elements” although they are thin and could be meshed with “2D Shell Quadratic Elements”. The reason is, they are critical parts and stresses are obtained through their thicknesses during the analyses.

The skin has been meshed with “2D Shell Quadratic Elements”.

“Beam Elements” have been used to model the springs.

In the model, there are 379.303 “Solid Hexahedron Elements” (Solid Hex), 57.944 “Solid Tetrahedral Elements” (Solid Tet), 7982 “2D Shell Quadratic Elements” and 4 “Beam Elements”. The summary of the element types, element numbers and material types is given in Table 4.1.

Table 4.1 Summary of Element Types, Element Numbers, Material Types

Part Type	Material	Element Type	# of Elements	Material Model
Brackets	AISI 4140	Solid Hex	3.837	MAT 024
Rails	AISI 4140	Solid Hex	1.862	MAT 024
Pistons	AISI 4140	Solid Tet	57.944	MAT 024
Pins	AISI 4140	Solid Hex	56.480	MAT 024
Ribs	AISI 1070	Solid Hex	58.164	MAT 024
Springs	Chrome Silicone Steel	Beam	4	MAT 066
Fleshes	CF-45 Foam	Solid Hex	258.960	MAT 083
Skin	Neoprene	2D Shell	7.982	MAT 001

4.1.2 Description of the Materials

As the model consists of parts with different materials like steel, rubber and foam, different material cards have been used in the model. Material properties have been obtained from available dummy FEMs and the literature [63], [64].

a- MAT001 Elastic Material for Defining the Skin

The skin material which is neoprene, has been modeled with “MAT001 Elastic Material Card”. In this study the following values have been used for the required parameters, which have been obtained from FEM of ES-2 Dummy provided by LS-DYNA supplier company [65].

Density (RO) = 5,998 10⁻⁷ kg/mm³

Elastic Modulus (E) = 0,05 GPa

Poissons Ratio (PR) = 0,2

b- MAT083 Fu Chang Foam for Defining the Flesh Representing Foam

The flesh representing foam has been modeled with “MAT083 Fu Chang Foam Material Card”. With this material type, rate effects can be modeled in low and medium density foams. Unloading behavior in this model is a function of the rate sensitivity with the most rate sensitive foams providing the largest hysteresis and vice versa. This material type has been selected because the foam material used in ThImp-PED is CF45 Confor Foam which is a highly rate dependent, medium to high density foam. In the pedestrian upper legform impactor, CF45 Confor Foam is used. It is difficult to find rate dependent properties of foam materials, therefore the following parameter values that are obtained from FEM of Legform Model provided by LS-DYNA supplier company [66] have been used.

Density (RO) = $9,905 \cdot 10^{-8} \text{ kg/mm}^3$

Elastic Modulus (E) = 0,09807 GPa

Viscous Coefficient (DAMP) = 0,05

“Optional Elastic Modulus” is different than the standard “Elastic Modulus” and it is used in the computation of sound speed (KCON) which influences the time step, contact forces, hourglass stabilization forces, and numerical damping [67] and it is taken as 0,1961 GPa in this study.

Stress-strain values at different strain rates for the particular foam are given in Figure 4.2. Curve 1 (Blue Curve) shows the stress-strain values at $0,02 \text{ s}^{-1}$ strain rate, Curve 2 (Orange Curve) shows the stress-strain values at $0,05 \text{ s}^{-1}$ strain rate, Curve 3 (Green Curve) shows the stress-strain values at $0,1 \text{ s}^{-1}$ strain rate.

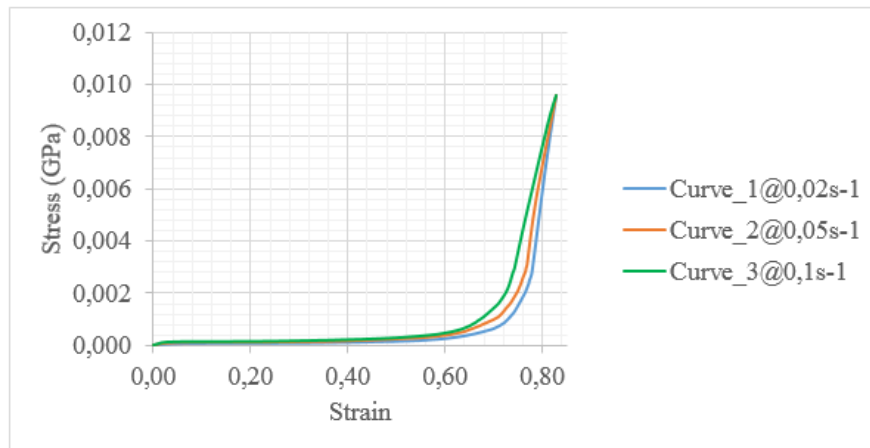


Figure 4.2. Stress-Strain Curves at Different Strain Rates for CF45 Foam [66]

c- MAT024 Piecewise Linear Plasticity for Defining the Steel Parts

The AISI 4140 Steel parts have been modeled with “MAT024 Piecewise Linear Plasticity Card”. MAT024 material is an elasto-plastic material. It enables to define stress versus strain curve with strain rate dependency. Also failure based on a plastic strain value can be defined.

For defining the 4140 steel, True Stress-True Strain after the yield curve for AISI 4140 Steel has been found from the literature at a strain rate of 500 s^{-1} as shown in Figure 4.3 [63].

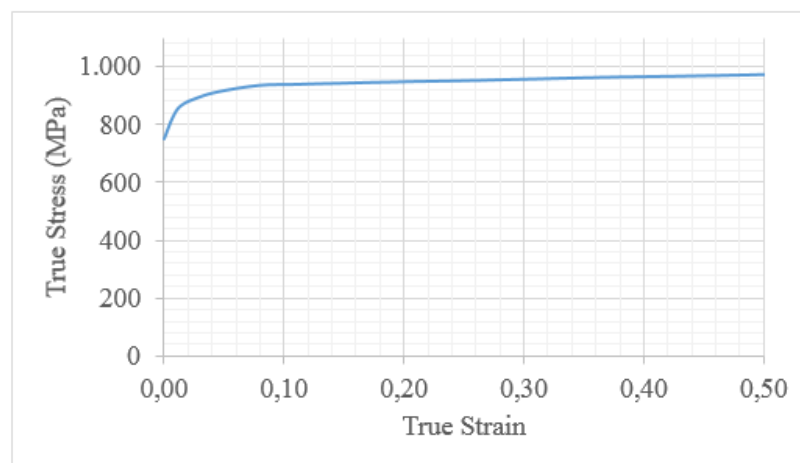


Figure 4.3. True Stress-True Strain Curve of AISI 4140 Steel at 500 s^{-1} [63]

Additionally, the following values have been used:

$$\rho = 7,85 \cdot 10^{-6} \text{ kg/mm}^3$$

$$E = 200 \text{ GPa}$$

$$\nu = 0,29$$

$$\sigma_y = 0,750 \text{ GPa}$$

For defining the 1070 steel, True Stress-True Strain after the yield curve for AISI 1070 Steel has been found from the literature as shown in Figure 4.4 [64].

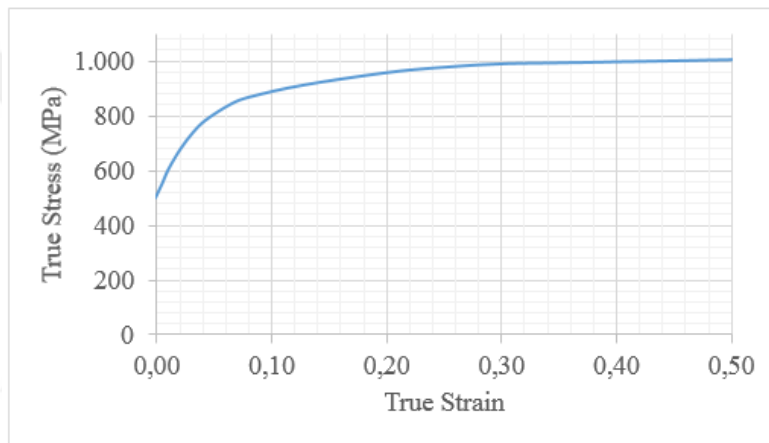


Figure 4.4. True Stress-True Strain Curve of AISI 1070 Steel [64]

Additionally the following values have been used:

$$\rho = 7,85 \cdot 10^{-6} \text{ kg/mm}^3$$

$$E = 200 \text{ GPa}$$

$$\nu = 0,3$$

$$\sigma_y = 0,500 \text{ GPa}$$

d- MAT066 Linear Discrete Elastic Beam Material for Defining the Springs

The spring parts have been modeled with “MAT066 Linear Discrete Elastic Beam Card”. MAT066 material model is defined for simulating the effects of a linear

elastic beam. The beam is oriented by defining a local coordinate system for the directional springs.

The spring definition has been achieved by entering the values to the Material and Section cards of the spring as follows:

$$RO = 2,50 \cdot 10^{-6} \text{ kg/mm}^3$$

Translational Stiffness about Local r-axis (TKR) has been defined as 0,072 kN/mm where r-axis is defined through the centerline of the pins and piston holes.

Volume of the beams (VOL) has been defined as: $2,0 \cdot 10^4 \text{ mm}^3$. Mass of the springs are calculated by multiplying RO and VOL values.

4.1.3 Contact and Constraints

- Three different contact cards have been used for contact definitions between the parts. “Automatic_Surface_To_Surface_Contact” card has been defined between the parts which come into contact during the analysis. In this type of contact, the software does the penetration check for the surfaces of the both parts that come into contact. In crash analysis, this type of contact is recommended since the orientation of parts relative to each other cannot always be predicted in crash simulations as the model undergoes large deformations [68]. “Tied_Nodes_To_Surface_Offset” card has been defined between the flesh and skin parts. In the model, the middle surface of the skin has been used and meshed with shell elements. Its thickness has been defined in the “Section” card of the skin part. “Tied_Nodes_To_Surface_Offset” has been defined between the middle surface of the skin and outer surfaces of the fleshes and the offset definition has been used to introduce the gap resulting from the skin thickness. “Tied_Surface_To_Surface” card has been defined between the ribs and the

flesh parts. The outer surfaces of the ribs and the inner surfaces of the fleshes are in contact during the analyses.

- All bolts have been modeled with “Constrained Rigid Nodal Body (CRNB)” by defining the nodes around the fastener holes in connecting parts tied to each other. In this type of connection, it is assumed that there can be no deformation or failure in the bolts.

4.2 Finite Element Analyses of Pendulum Tests for ES-2 and ThImp-PED

It should be verified that ThImp-PED is biofidelic and represent a pedestrian thorax in case of pedestrian involved accidents. This is one of the major concerns during this PhD study and the details of biofidelity validation tests will be given in Section 5.2. In this study, biofidelity of ThImp-PED has been validated by comparing with ES-2 dummy as it is a standard commercially available side impact crash test dummy with an accepted level of biofidelity. Firstly, the certification pendulum test of the ES-2 dummy [69] has been simulated by FEA for ES-2 dummy. Secondly, by using the same parameters described in the particular certification pendulum test, FEA of ThImp-PED has also been conducted. The results have been compared in terms of the rib deflections and the pendulum force during pendulum impact. In the following subsections, FEA of each one will be given in detail.

4.2.1 FEA of Pendulum Tests for the Certification of ES-2

ES-2 Dummy FEM is given in Figure 4.5.

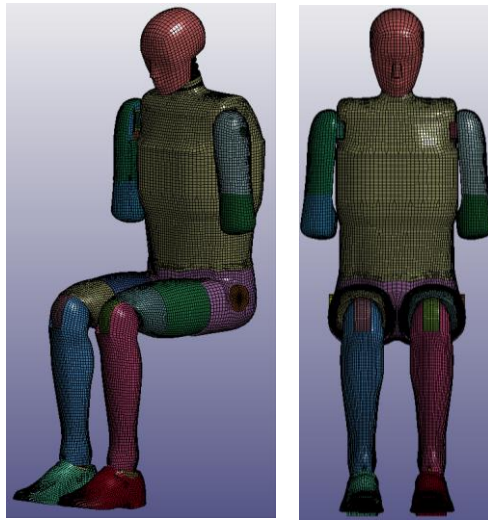


Figure 4.5. ES-2 FEM [65]

It is a very complex and detailed model to enable the researchers and engineers to simulate side impact crashes. It includes 333.582 elements, 424.430 nodes and 310 parts as shown in Table 4.2 [65].

Table 4.2 Types and Numbers of Components in ES-2 Dummy FEM [65]

Component	Total Number
Nodes	424.430
Solid Elements	313.363
Shell Elements	79
Beam Elements	20.111
Discrete Elements	12
Accelerometer Elements	17
Parts	310
Materials	62
Joints	19
Contacts	7
Load Curves / Tables	26

For the FEA of certification tests, a rigid pendulum of 23,4 kg has been modeled such as it impacts the ES-2 dummy from the side with a velocity of 4,3 m/s and 5,5 m/s as shown in Figure 4.6. The pendulum impact location has been obtained from

ES-2 standard certification procedure [69]. The arm has been rotated around the shoulder joint to enable direct impact of the pendulum with the thorax as it is the defined scenario for the certification tests. Although, ES-2 dummy can be adjusted to be sensitive to impacts from either left or right side by changing the orientation of the internal components of the particular dummy, ES-2 has been impacted by the rigid pendulum from the left of the dummy in the analyses since the FEM of the dummy is sensitive to impacts from the left. To evaluate the results of the analyses, rib deflections and pendulum forces have been measured and compared with the results in the standards. Rib deflections and pendulum forces given in the standards are not dependent on the impact side.

The pendulum has been modeled with “MAT020 Rigid Material Card” for the analyses as it is a rigid body which is made of high strength steel and which is assumed to be undeformable during the certification tests. The velocity values of 4,3 m/s and 5,5 m/s have been defined with “Initial Velocity” option in LS-DYNA to all nodes of the pendulum. The impact velocities have been considered as the initial velocities because the analysis is defined to start just before the impact and there is no loss in velocity before the impact.

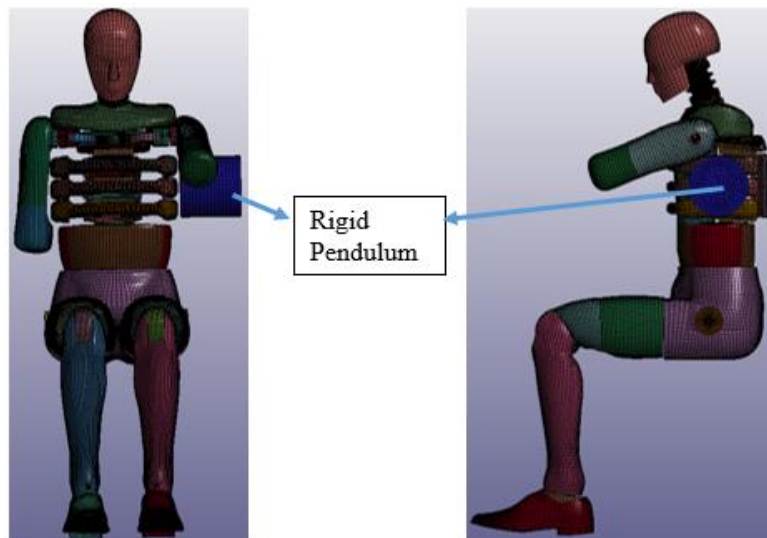


Figure 4.6. ES-2 FEM with Pendulum

4.2.1.1 **Thorax Pendulum Test at 4,3 m/s for ES-2 Dummy According to ISO/TR 9790**

According to the Technical Report ISO/TR 9790 Test 1 [70], the thorax of the ES-2 dummy has been impacted laterally at 4,3 m/s. After the test, the pendulum force has been calculated and checked if it fits to the upper and lower limits of the corridor.

The same scenario has been modeled in FEA. The pendulum acceleration has been measured and it has been filtered with Channel Frequency Class (CFC) 60 filter [71] as specified in ISO/TR 9790. Then the pendulum acceleration has been multiplied by the pendulum mass of 23,4 kg and pendulum force has been found. The pendulum force fits to the corridor specified in the standard as shown in Figure 4.7. In the figure, UL represents the “Upper Limit” and LL represents the “Lower Limit”.

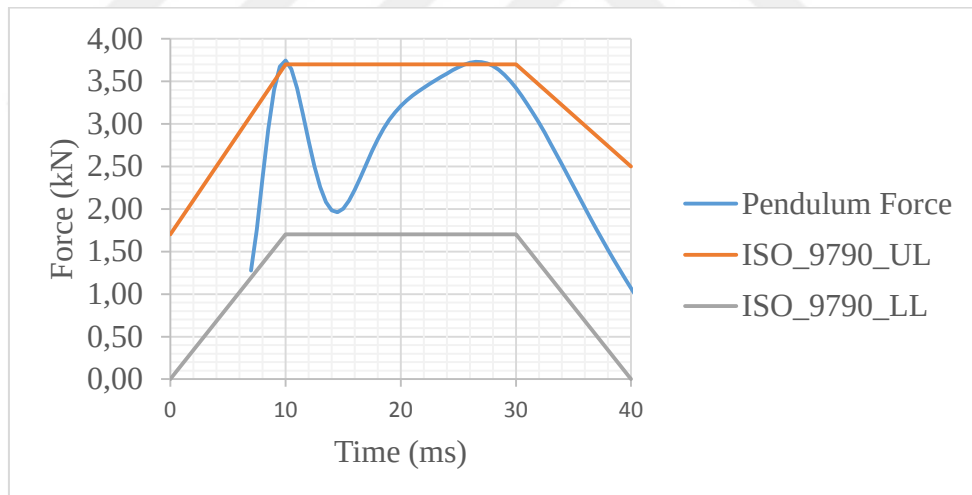


Figure 4.7. ES-2 Pendulum Force for 4,3 m/s Pendulum Test

4.2.1.2 Thorax Pendulum Test at 5,5 m/s for Certification of ES-2 Dummy

According to the certification procedure of ES-2 dummy [69], the thorax of the ES-2 dummy has been impacted laterally at 5,5 m/s. The rib deflections and pendulum acceleration have been measured during the test. After the test, the rib deflections have been compared with the specified values. Also the pendulum force has been calculated and checked if it lies between the lower and upper limits which are 5.100 N and 6.200 N respectively.

The same scenario has been modeled in FEA. The rib deflections and the pendulum acceleration have been measured. The rib deflections have been filtered with CFC 180 filter [71] as specified in the certification procedure. The pendulum acceleration has been filtered with CFC 60 filter as specified in ISO/TR 9790. Then it has been multiplied by the pendulum mass of 23,4 kg and pendulum force is found.

The maximum pendulum force lies between the lower and upper limits as shown in Figure 4.8.

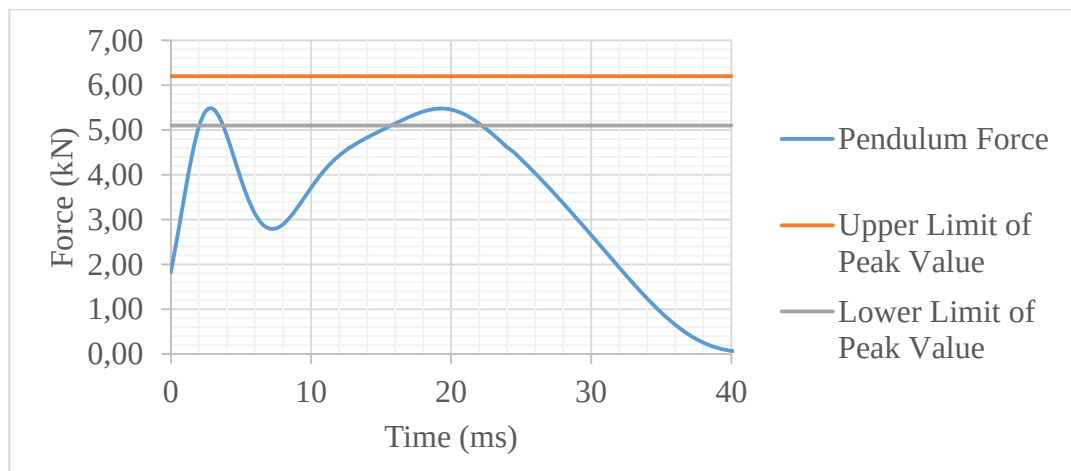


Figure 4.8. ES-2 Pendulum Force for 5,5 m/s Pendulum Test

The FEM of ES-2 at time 19 ms when the rib deflections are maximum is given in Figure 4.9. The rib deflections are given in Figure 4.10, Figure 4.11 and Figure 4.12.

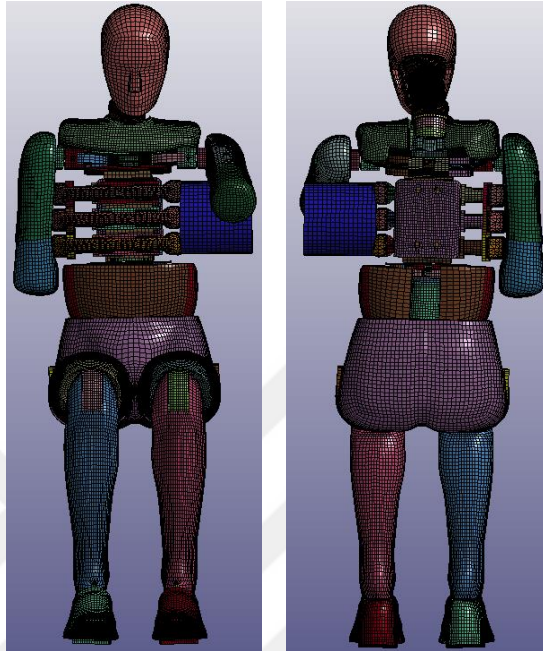


Figure 4.9. ES-2 FEM from Front and Back in FEA at 19 ms

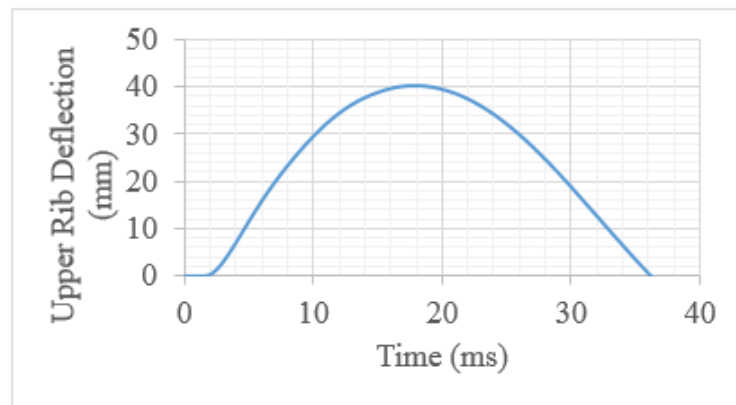


Figure 4.10. ES-2 Upper Rib Deflection for 5,5 m/s Pendulum Test

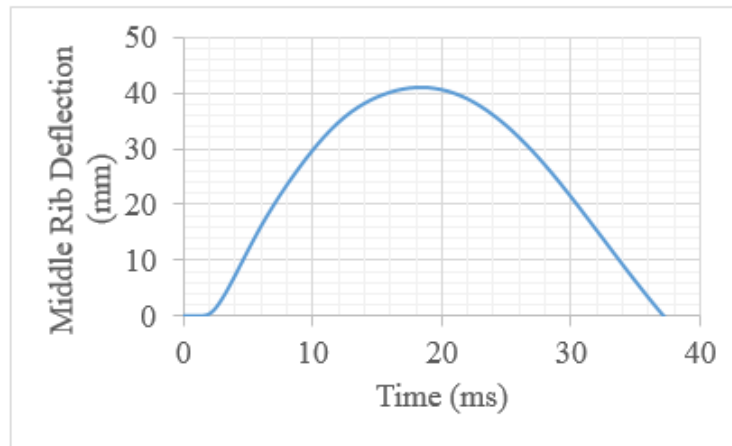


Figure 4.11. ES-2 Middle Rib Deflection for 5,5 m/s Pendulum Test

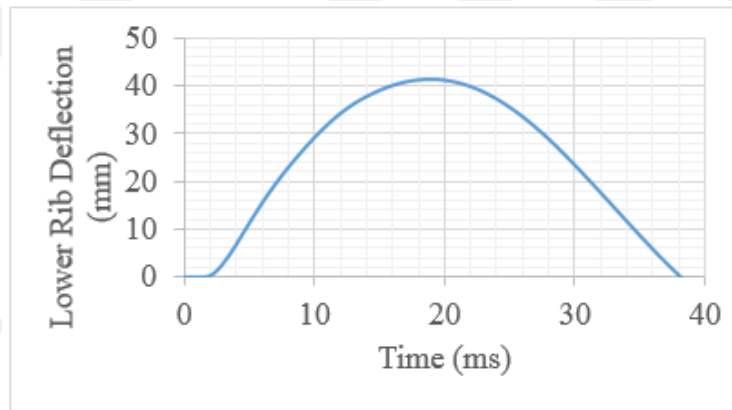


Figure 4.12. ES-2 Lower Rib Deflection for 5,5 m/s Pendulum Test

The rib deflections for the upper, middle and lower ribs are very close to each other and they meet the specifications as shown in Table 4.3.

Table 4.3 ES-2 Rib Deflections Comparison

ES-2 Rib Deflections Defined in the Standard (mm) [68]			FEA Results of ES-2 Rib Deflections in the Current Study (mm)		
Upper Rib	Middle Rib	Lower Rib	Upper Rib	Middle Rib	Lower Rib
34-41	37-45	37-44	40,1	41,0	41,5

4.2.2 FEA of Pendulum Tests for Biofidelity Validation of ThImp-PED

For the FEA of pendulum tests with ThImp-PED, a rigid pendulum of 23,4 kg has been modeled such that it impacts ThImp-PED from the side with a velocity of 4,3 m/s and 5,5 m/s.

The FEA of ES-2 pendulum tests are performed with full body of the dummy. ThImp-PED includes only the thorax region. To compare the results, it is required to add representative masses of the other body parts (i.e. head, neck, abdomen, arms, pelvis, legs and feet) to ThImp-PED FEM to include their effects. The “Inertia Elements” in LS-DYNA have been preferred for the particular application to include the effects of both the masses and the inertias of these body parts [72]. The inertia elements have been assigned to the top of ThImp-PED to represent neck, head and arms masses. Additionally, the inertia elements have been assigned to the bottom of ThImp-PED to represent abdomen, pelvis, legs and feet masses. The ThImp-PED FEM with the inertia elements is given in Figure 4.13. ThImp-PED and the pendulum can be seen on left and right of the figure, respectively. The inertia elements added to the top and bottom of the model at particular distances are marked with red circles. The calculations performed for determining the location, mass and inertia of these elements are given in Appendix D. The orange dashed line in the figure, shows the extension of the pendulum centerline which is aligned to the middle of upper and lower ribs in z direction.

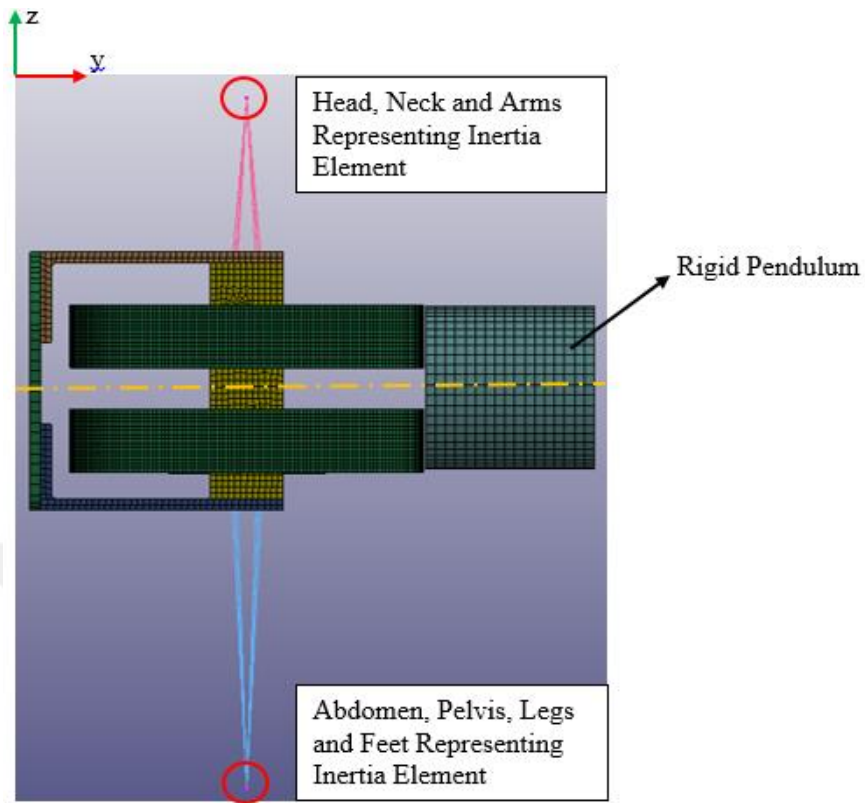


Figure 4.13. FEM of ThImp-PED with Inertia Elements and Rigid Pendulum

During the FEA, the centerline of the pendulum is coincident with the x coordinate of cog of ThImp-PED as seen in Figure 4.14. The orange dashed line in the figure shows the extension of the centerline of the pendulum and it intersects with the cog of ThImp-PED which is shown with a yellow plus mark.

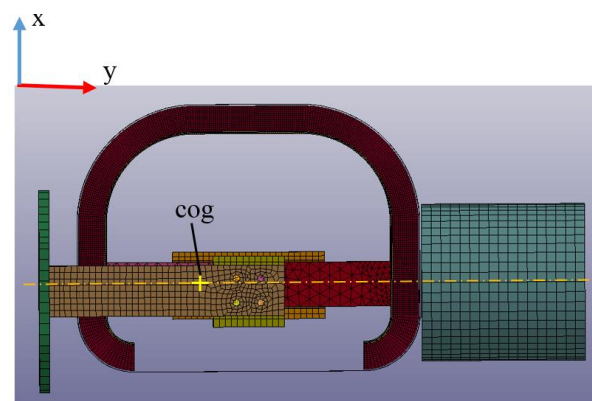


Figure 4.14. Cog of ThImp-PED and Positioning of the Pendulum

To evaluate the results of the analyses, rib deflections have been measured for the upper and lower ribs and pendulum forces have been calculated by using the pendulum acceleration in y direction. Then the results have been compared with the specifications in the standards. In Subsections 4.2.2.1 and 4.2.2.2, the FEA results will be given in terms of pendulum forces and rib deflections and the FEA results will be given in terms of stresses and strains in Appendix E.

4.2.2.1 FEA of Thorax Pendulum Test at 4,3 m/s for ThImp-PED According to ISO/TR 9790

ThImp-PED has been impacted laterally at 4,3 m/s according to ISO/TR 9790 Test 1 [70]. The pendulum acceleration has been measured and it is filtered with CFC 60 filter as specified in ISO/TR 9790. Then the pendulum acceleration has been multiplied by the pendulum mass of 23,4 kg and pendulum force has been found and checked if it fits to the upper and lower limits of the corridor. The pendulum force with the corridors is shown in Figure 4.15.

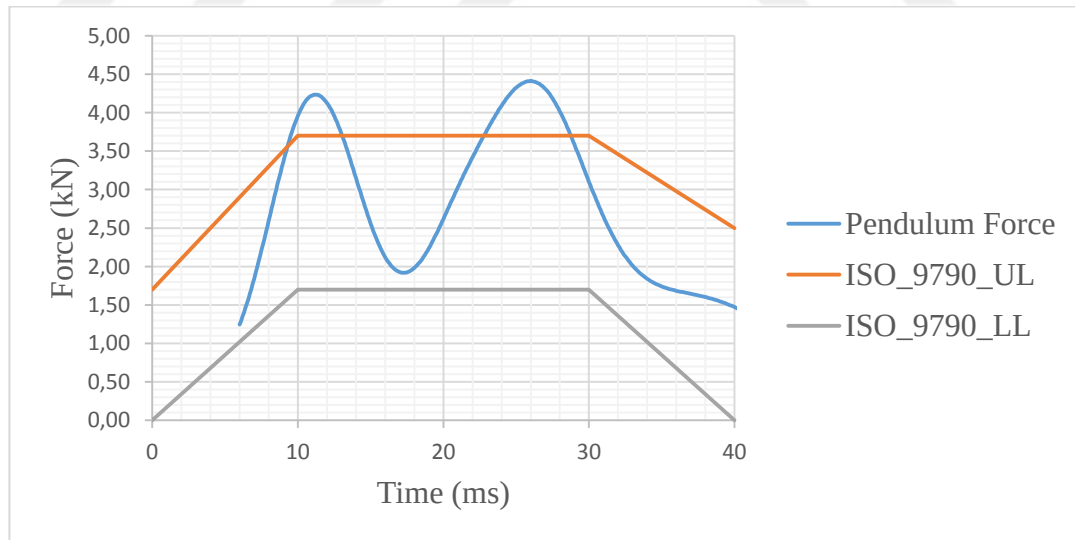


Figure 4.15. ThImp-PED Pendulum Force for 4,3 m/s Pendulum Test

Although, the values are mostly within the upper and lower limits, the peak pendulum force is 4,41 kN which is higher than the upper limit of the corridor. There are many assumptions done during the FEA for the material properties, contacts, joints and using of inertia elements to represent the parts. The reasons for getting high pendulum force values are evaluated as follows:

- ThImp-PED FEM used in the FEA of pendulum tests for biofidelity validation is a simplified model since inertia elements have been assigned to represent the masses of the particular body parts (i.e. head, neck, abdomen, arms, pelvis, legs and feet) to include their effects as discussed in Appendix D.
- ThImp-PED assembly consists of various materials (i.e. steel, foam, neoprene). The mechanical properties of these materials have been found from the literature and used in the analyses. There may be deviations caused from these material data and the real material properties.
- As defined in Section 4.1.3, the bolts have been modeled with “Constrained Rigid Nodal Body (CRNB)” in which the the nodes around the fastener holes in connecting parts are tied to each other and it is assumed that there can be no deformation or failure in the bolts. This is an assumption that may result in stiffer behaviour of ThImp-PED.
- As defined in Section 4.1.3, three different contact cards have been used to define the relations of the parts in ThImp-PED assembly with respect to each other during impact. The definition of “Tied_Surface_To_Surface” contact between the ribs and flesh parts may create extra stiffness in the behaviour of the flesh foam compared to the double sided tapes used in real life application. Additionally, the definition of “Tied_Nodes_To_Surface_Offset” contact between the flesh and skin parts may create extra stiffness in the behaviour of the flesh and skin surfaces during the analyses.

To sum up, each assumption done for the FEA has a certain effect in the results. However, the results of FEA can be acceptable since the impactor designed in the scope of this study has been validated not only with FEA but also with physical tests. As it will be given in detail in Chapter 5, the results of the ThImp-PED physical validation tests with pendulum satisfy the target values in the standards.

4.2.2.2 **FEA of Thorax Pendulum Test at 5,5 m/s for ThImp-PED**

ThImp-PED has been impacted laterally at 5,5 m/s according to the certification procedure of ES-2 dummy [69]. The rib deflections and pendulum acceleration have been measured. The rib deflections have been filtered with CFC 180 as specified in the certification procedure. The pendulum acceleration has been filtered with CFC 60 filter as specified in ISO/TR 9790. Then it has been multiplied by the pendulum mass of 23,4 kg and pendulum force has been found. The rib deflections and the pendulum force have been compared with the specified values in the standard.

The pendulum force with the upper and lower limits specified in the standard is shown in Figure 4.16.

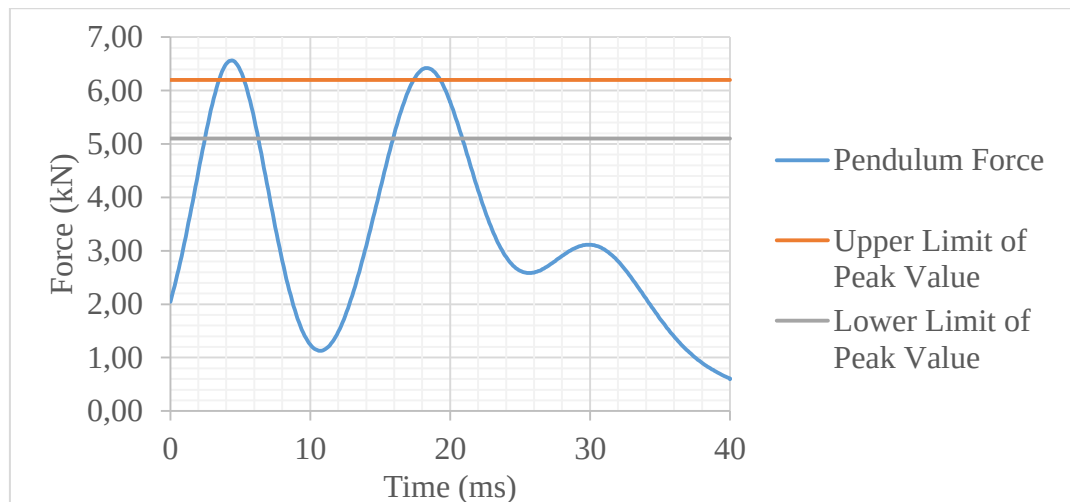


Figure 4.16. ThImp-PED Pendulum Force for 5,5 m/s Pendulum Test

Although, the peak values are mostly within the upper and lower limits, the peak pendulum force is 6,56 kN which is slightly higher than the upper limit of the corridor. However, the results of FEA can be acceptable since the impactor designed in the scope of this study is validated not only with FEA but also with physical tests. As it will be given in detail in Chapter 5, the results of the ThImp-PED physical validation tests with pendulum satisfy the target values in the standards.

FEA of ThImp-PED at time zero and at 21 ms is given in Figure 4.19. The model on the left is at time zero, the red arrow show the initial gap between the left and right pistons which is 60 mm. The model on the right is at time 21 ms where the upper and lower rib deflections are maximum and the gap between the left and right pistons is shown with a yellow arrow.

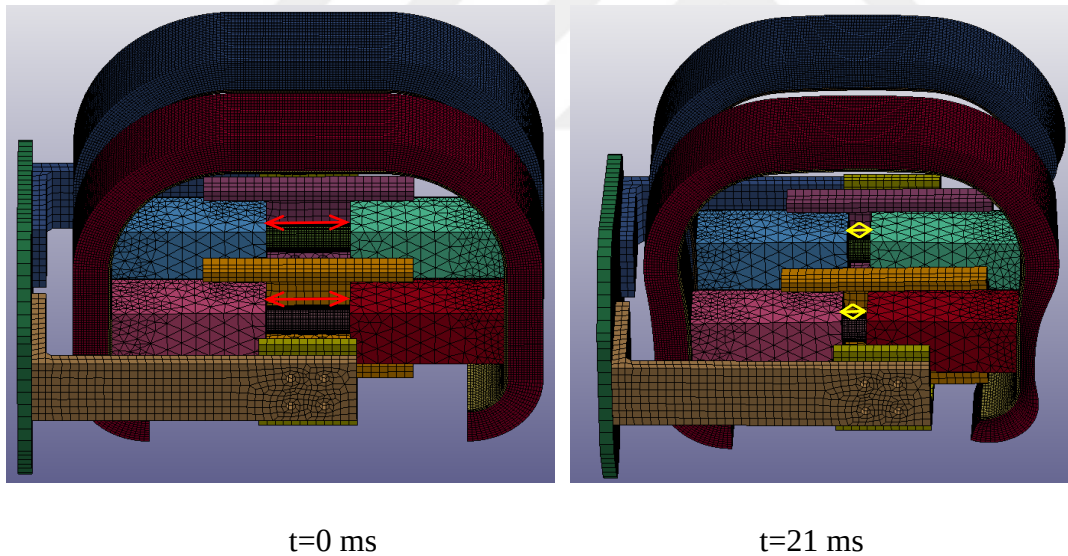


Figure 4.17. FEA of ThImp-PED at $t=0$ ms and $t=21$ ms

The rib deflection for the upper rib is given in Figure 4.18 and for the lower rib given in Figure 4.19.

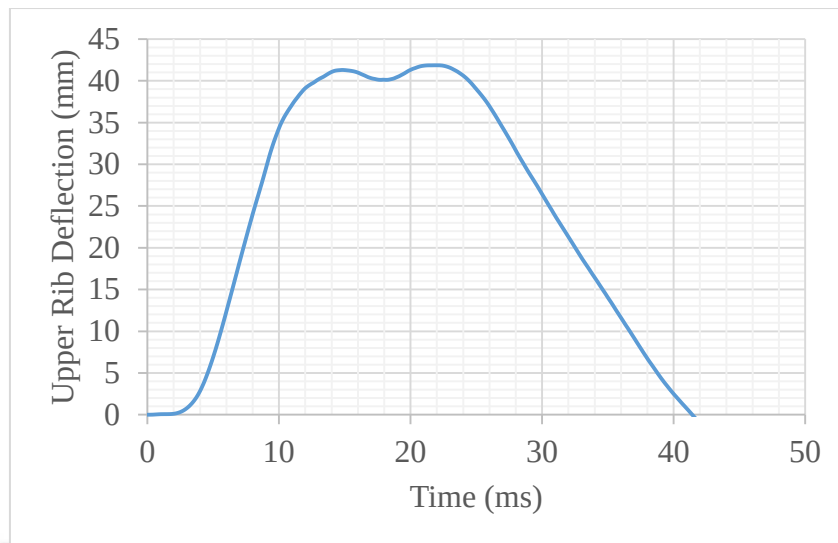


Figure 4.18. ThImp-PED Upper Rib Deflection for 5,5 m/s Pendulum Test

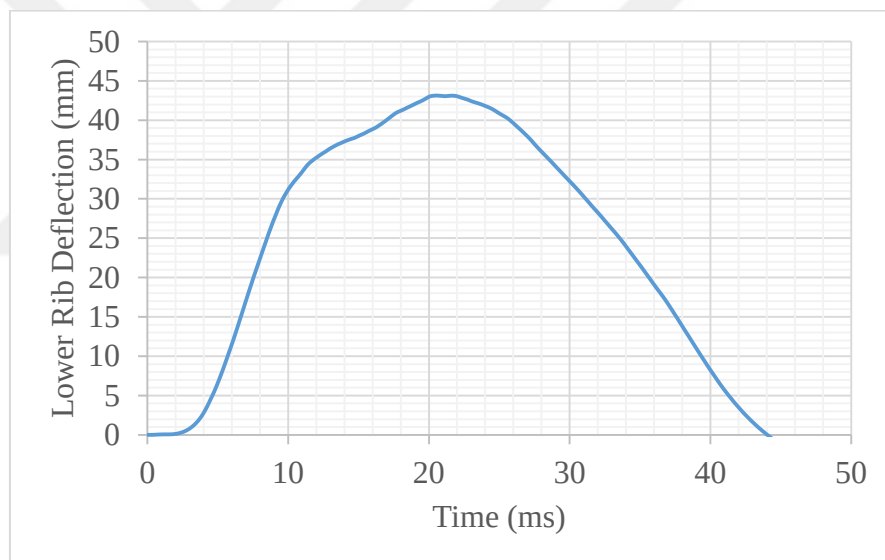


Figure 4.19. ThImp-PED Lower Rib Deflection for 5,5 m/s Pendulum Test

The maximum upper rib deflection is 41.9 mm and the maximum lower rib deflection is 43.1 mm. These values are within the limits given in the standard as shown in Table 4.4.

Table 4.4 ES-2 Rib Deflection Limits in Pendulum Test [69]

ES-2 Rib Deflections Defined in the Standard (mm) [68]			FEA Results of ThImp-PED Rib Deflections in the Current Study (mm)	
Upper Rib	Middle Rib	Lower Rib	Upper Rib	Lower Rib
34-41	37-45	37-44	41,9	43,1

Note that, ES-2 dummy has 3 ribs, so the limits are given on the left side of the table for these 3 ribs. However, ThImp-PED has 2 ribs and the rib deflections have been found for these 2 ribs in the FEA as given on the right side of the table.

FEA results of the pendulum tests performed with ES-2 dummy FEM and ThImp-PED FEM have been summarized in this chapter.

CHAPTER 5

MANUFACTURING OF THIMP-PED AND VALIDATION TESTS

After finalization of the design of ThImp-PED, the parts have been manufactured by a company in Ankara. Details of the manufacturing will be given in the following section. After manufacturing, the validation tests have been performed with ThImp-PED using the pendulum test system in METU-BILTIR Center.

5.1 ThImp-PED Manufacturing

CNC milling, drilling and boring operations have been used for manufacturing of the pistons, rails and brackets. Turning operation has been used for manufacturing of the pins. Sheet metal forming operations like shearing and bending have been used for manufacturing of the ribs. Appropriate dies have been manufactured and the ribs have been formed using these dies. Heat treatment process has also been applied to the ribs; after bending operation, the ribs have been tempered to increase the hardness to RC 45-49. After the steel parts are manufactured and assembled, non-metalic parts like the flesh representing foam and the skin representing neoprene have been added to the assembly. The photographs of ThImp-PED from 3D view are given in Figure 5.1. The photographs of ThImp-PED from front and back are given in Figure 5.2. The photographs of ThImp-PED from left and right are given in Figure 5.3. The photographs of ThImp-PED from top are given in Figure 5.4.



Figure 5.1. Photographs of ThImp-PED from 3D view



Figure 5.2. Photographs of ThImp-PED from front and back

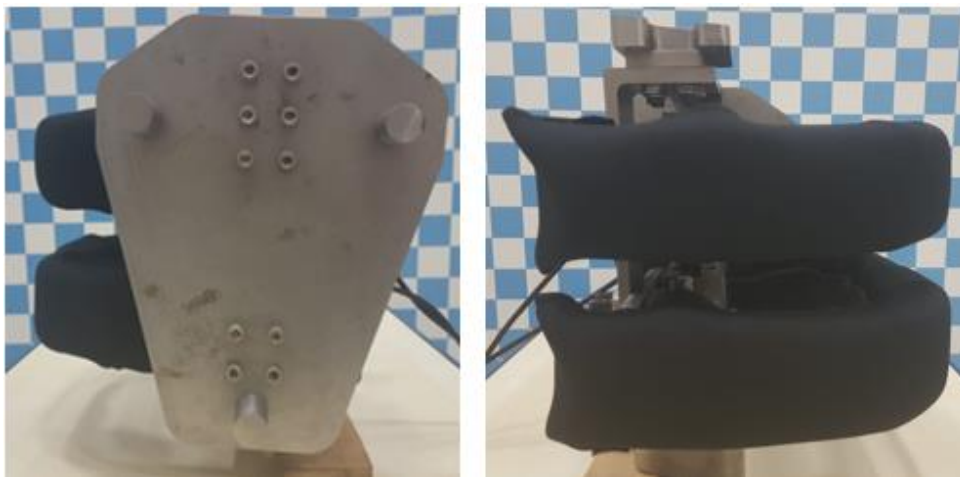


Figure 5.3. Photographs of ThImp-PED from left and right



Figure 5.4. Photographs of ThImp-PED from top

The flesh representing foams for the upper and lower ribs have been fixed by using 2-sided adhesive tapes as shown in Figure 5.5.



Figure 5.5. Adhesive Tapes for Foam Fixation

Two neoprene covers have been prepared to represent the skin and to cover the upper and lower ribs properly. Special cutouts as shown in Figure 5.6 have been designed on the neoprene material to enable access to the fasteners that are used to fasten the ribs to the assembly. Also the hook and loop bands have been used to enable quick and easy assembly of the neoprene material and to enable repeated times of usage.

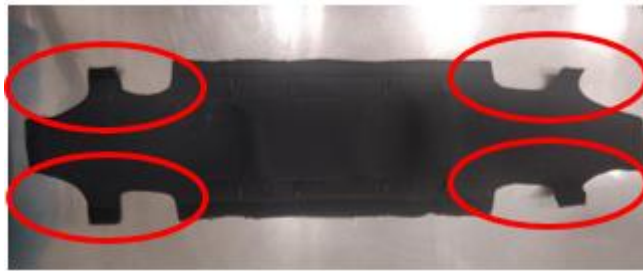


Figure 5.6. Photograph of Skin Representing Neoprene

5.2 Pendulum Tests for Biofidelity Validation of ThImp-PED

As already mentioned in Section 4.2, pendulum tests defined in the technical report ISO/TR 9790 and the standard certification procedure of ES-2 dummy have been used to compare and validate the biofidelity of ThImp-PED.

5.2.1 Summary of the Pendulum Test Procedures

The Technical Report ISO/TR 9790 [70] released by ISO is used to assess the biofidelity of side impact dummies like ES-2, WorldSID, etc by researchers and dummy developers [73]–[76]. In the technical report, different test procedures using drop tests, pendulum tests, sled tests are described to assess the biofidelity of head, neck, shoulder, thorax, abdomen and pelvis regions of side impact dummies. In this study Thorax Test 1 which is performed with pendulum has been used for the assessment. For the tests, the dummy is seated upright with its arm raised so that the side of its thorax can be impacted. The dummy's thorax is impacted at 4,3 m/s laterally with a rigid pendulum of 23,4 kg mass and 155 mm diameter [70]. To find the pendulum force during impact, the pendulum acceleration is measured, filtered with CFC 60 and multiplied by the pendulum mass. The calculated pendulum force must lie within the corridor defined by upper and lower limits as given in Figure 5.7 [70].

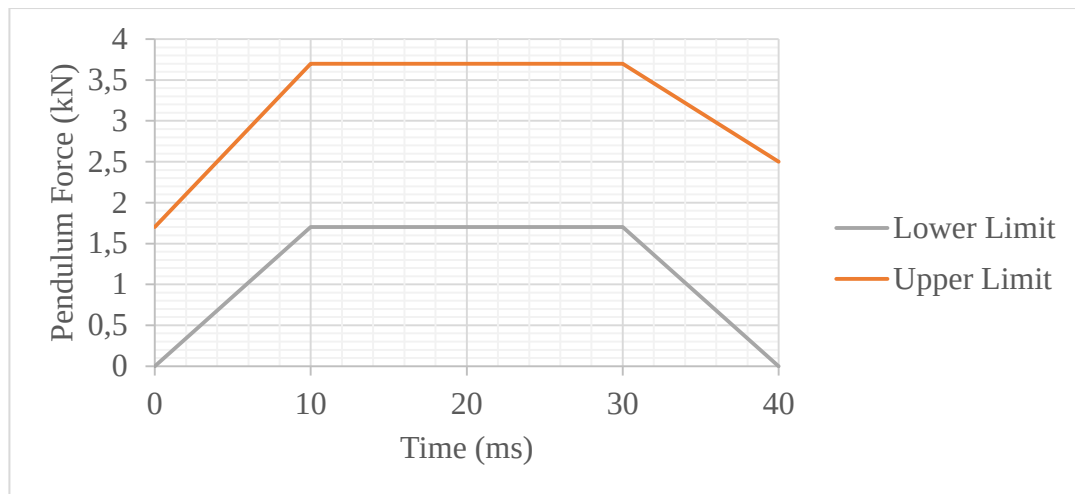


Figure 5.7. ISO/TR 9790 Thorax Test 1 Pendulum Force Corridor [70]

Thorax pendulum test is defined as “Full-Body Thorax Impact Test” in the certification procedure of ES-2 dummy [69]. The dummy is seated on a flat, horizontal, rigid surface as shown in Figure 5.8. In this figure, “Part 572 Subpart E Pendulum” represents the pendulum to be used in the test. The dummy’s thorax is vertical within ± 2 degrees and midsagittal plane of thorax is positioned perpendicular to the direction of motion of the pendulum so that the pendulum surface impacts the thorax perpendicularly. The dummy’s legs are horizontal and symmetrical about the midsagittal plane. The pendulum is guided, its mass is 23,4 kg and the pendulum diameter is 155 mm. Pendulum center is aligned with the middle rib as shown in Figure 5.8 [69]. The impact velocity is $5,5 \pm 0,1$ m/s.

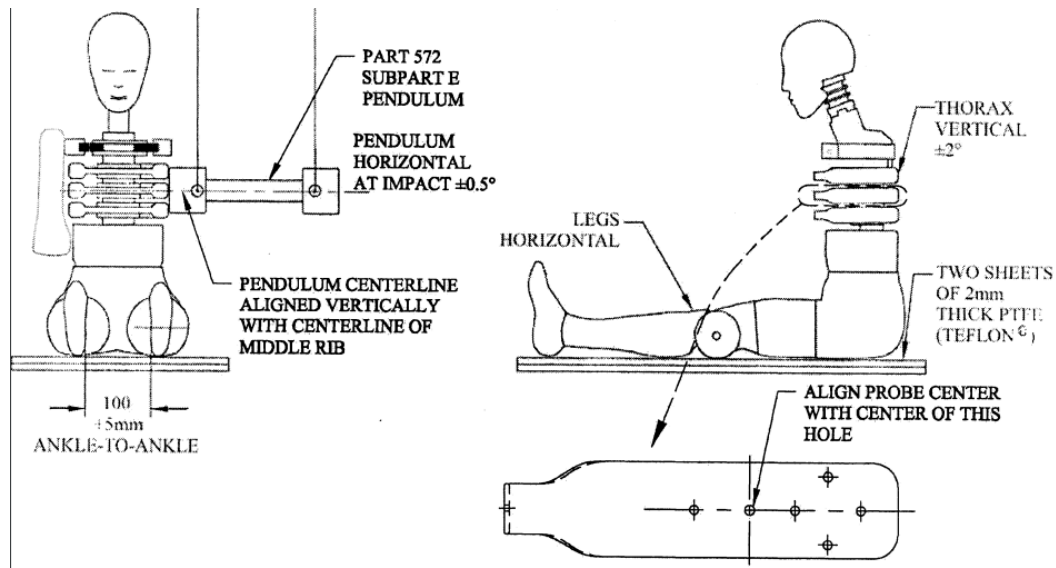


Figure 5.8. ES-2 Dummy Certification Pendulum Test Set-Up [69]

The rib deflections should lie within the limits given in Table 5.1 after they are filtered with CFC 180 filter. Peak pendulum force should be between 5.100 N and 6.200 N.

Table 5.1 ES-2 Rib Deflection Limits in Pendulum Test [69]

Component	Deflection Limits
Upper Rib	34-41 mm
Middle Rib	37-45 mm
Lower Rib	37-44 mm

5.2.2 Pendulum Test System and Test Set-Up

Thorax certification test system that is used for the HIII dummy's standard thorax certification procedure in METU-BILTIR Center has been used for the tests in this study. The photograph of the system is shown in Figure 5.9. This particular test system can be used for HIII dummy thorax certification as well as ES-2 thorax certification.

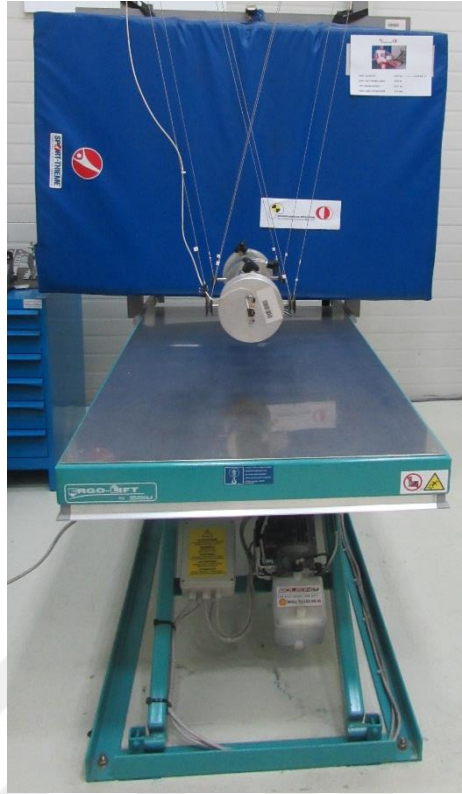


Figure 5.9. Thorax Certification Pendulum in METU-BILTIR Center

The pendulum is guided by cables so that its direction of impact is controlled. It is lifted to a certain height by a mechanism and released from that height so that it hits the dummy's thorax at the target velocity. Pendulum acceleration and the sensor measurements on the related dummy are recorded during the test.

The smooth, flat, horizontal surface that the dummy is seated is height adjustable so that the dummy thorax height can be adjusted and the pendulum impacts to the target location on the dummy.

For the pendulum tests, the thorax region of a 50th percentile HIII dummy has been replaced with ThImp-PED as shown in Figure 5.10. The same approach has been used and the head, neck, arms, abdomen, pelvis, legs and feet masses have been represented during Finite Element Analyses with inertia elements as described in Section 4.2.2.



Figure 5.10. ThImp-PED Pendulum Test Set-Up

For this particular purpose, 2 adapter parts called “Neck Bracket” and “Pelvis Bracket” have been designed and manufactured. Photographs of the neck bracket are given in Figure 5.11 and photographs of the pelvis bracket are given in Figure 5.12. The adapter parts connected to ThImp-PED are shown in Figure 5.13. During the design of the adapter parts, connection interfaces on the neck and pelvis regions of HIII 50th percentile dummy have been taken into account. Dummy mass distribution, dummy total mass, dummy sitting height, angular alignment of pelvis and neck with respect to thorax and machinability of parts have also been taken into account.

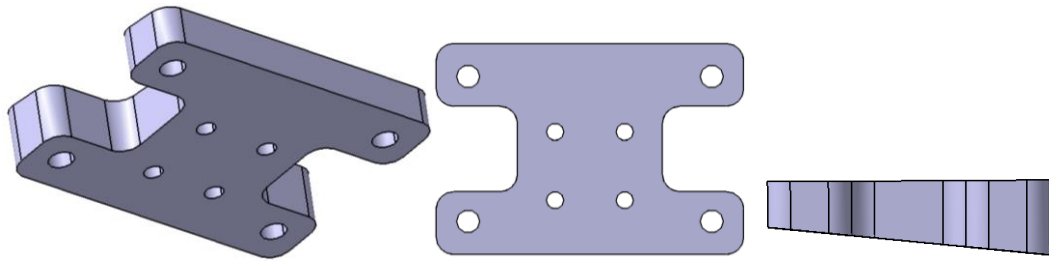


Figure 5.11. ThImp-PED Neck Bracket

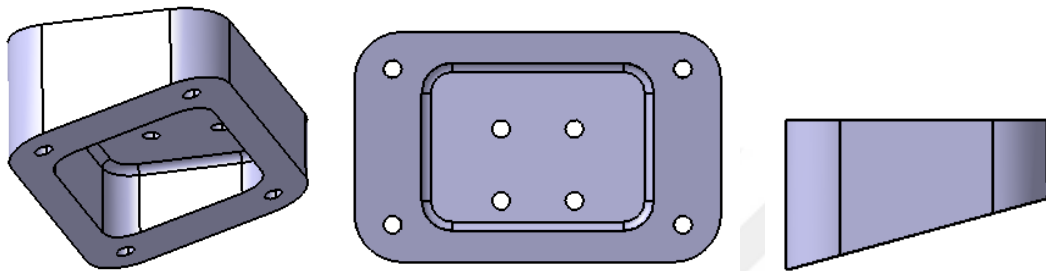


Figure 5.12. ThImp-PED Pelvis Bracket

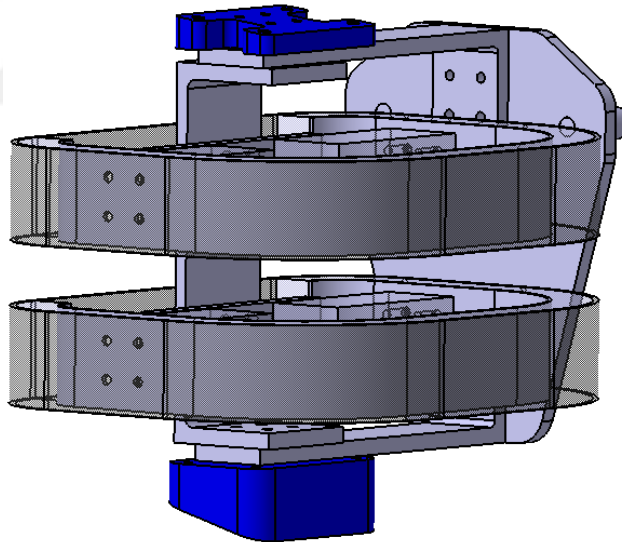


Figure 5.13. ThImp-PED with Neck and Pelvis Bracket

Before each test, the pendulum impact location has been adjusted such that it impacts the ThImp from the middle of the upper and lower ribs in z direction as can be seen in Figure 5.14. The pendulum impact location has been adjusted such

that the centerline of the pendulum is coincident with the centerline of the pistons of ThImp-PED as seen in Figure 5.15. For this purpose, centerlines of the pendulum and the pistons have been marked and aligned before the tests. Additionally, the ThImp-PED upper bracket surface has been adjusted to be parallel to xy plane by using a water gauge which is marked with a red circle in Figure 5.15.



Figure 5.14. Pendulum Positioning in z-Axis

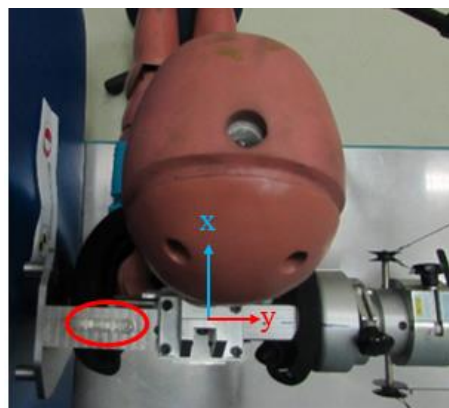


Figure 5.15. Pendulum Positioning in y-Axis

5.2.3 Pendulum Test Results at 4,3 m/s for ThImp-PED

3 pendulum tests have been performed with $4,3 \pm 0,1$ m/s according to ISO/TR 9790 and the results are given below.

Pendulum Test-1 at 4,3 m/s:

The impact speed is 4,28 m/s. The maximum pendulum force has been calculated as 3.809 N. The pendulum force curve fits into the corridor as shown in Figure 5.16.

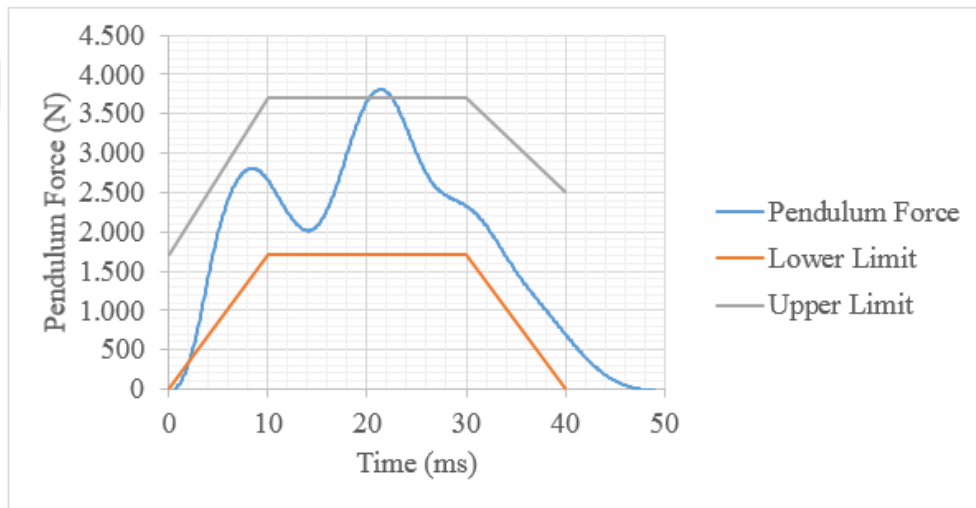


Figure 5.16. Pendulum Force for 4,3 m/s Pendulum Test 1

Pendulum Test-2 at 4,3 m/s:

The impact speed is 4,26 m/s. The maximum pendulum force has been calculated as 3.790 N. The pendulum force curve fits into the corridor as shown in Figure 5.17.

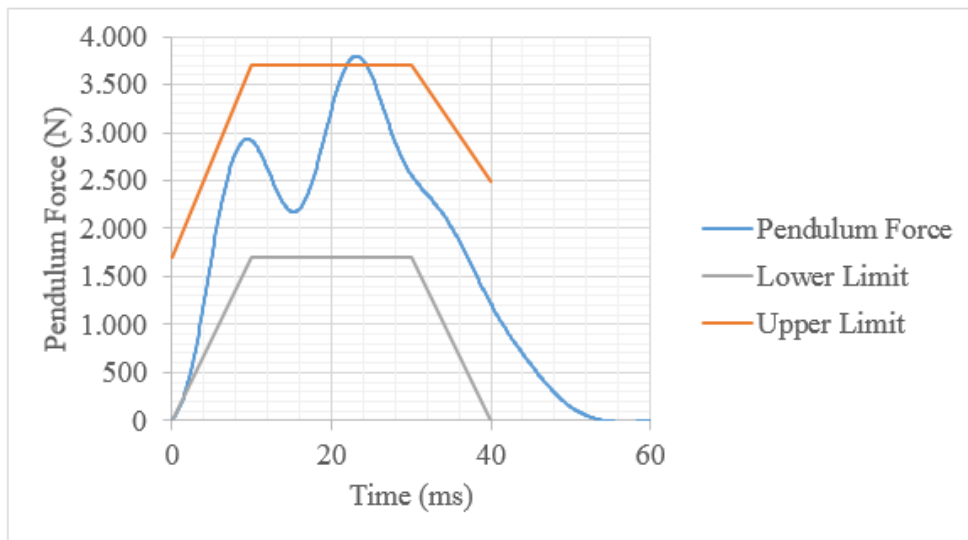


Figure 5.17. Pendulum Force for 4,3 m/s Pendulum Test 2

Pendulum Test-3 at 4,3 m/s:

The impact speed is 4,23 m/s. The maximum pendulum force has been calculated as 3.630 N. The pendulum force curve fits into the corridor as shown in Figure 5.18.

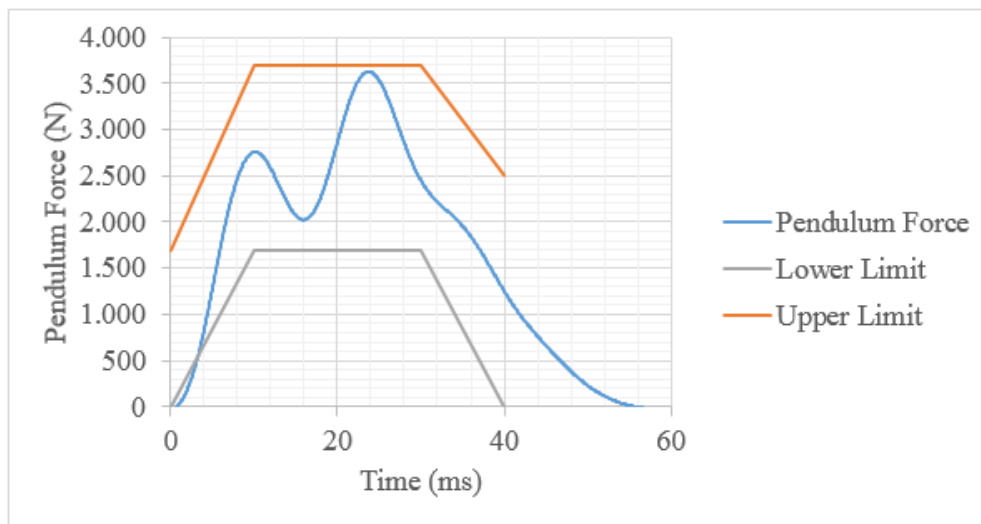


Figure 5.18. Pendulum Force for 4,3 m/s Pendulum Test 3

5.2.4 Pendulum Test Results at 5,5 m/s for ThImp-PED

3 pendulum tests have been performed with $5,5 \pm 0,1$ m/s by using the same parameters described in the ES-2 certification pendulum test and the results are given below.

Pendulum Test-1 at 5,5 m/s:

The impact speed is 5,47 m/s. The maximum pendulum force has been calculated as 5.970 N. The peak pendulum force fits into the corridor as shown in Figure 5.19.

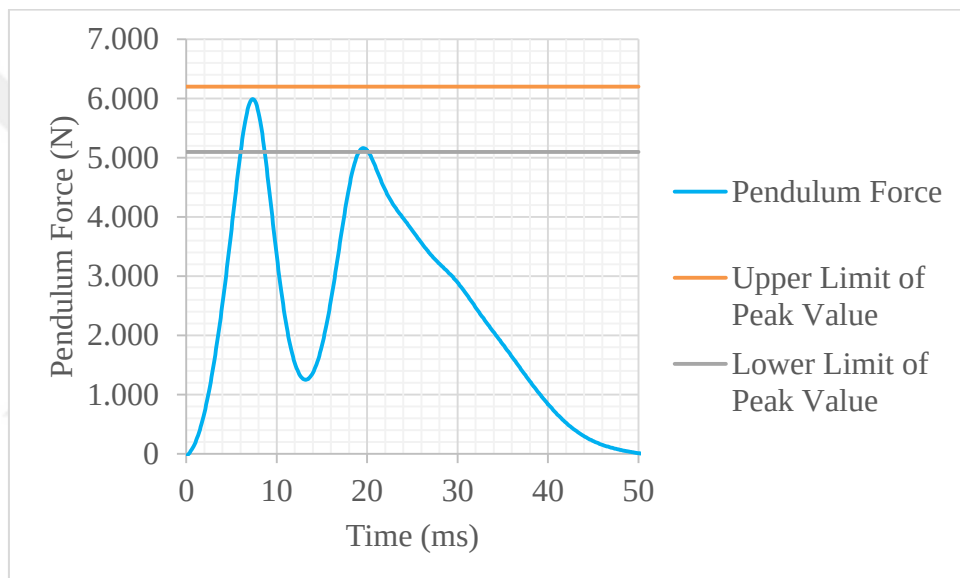


Figure 5.19. ThImp-PED Pendulum Force for 5,5 m/s Pendulum Test 1

The rib deflection for the upper rib is given in Figure 5.20 and for the lower rib in Figure 5.21.

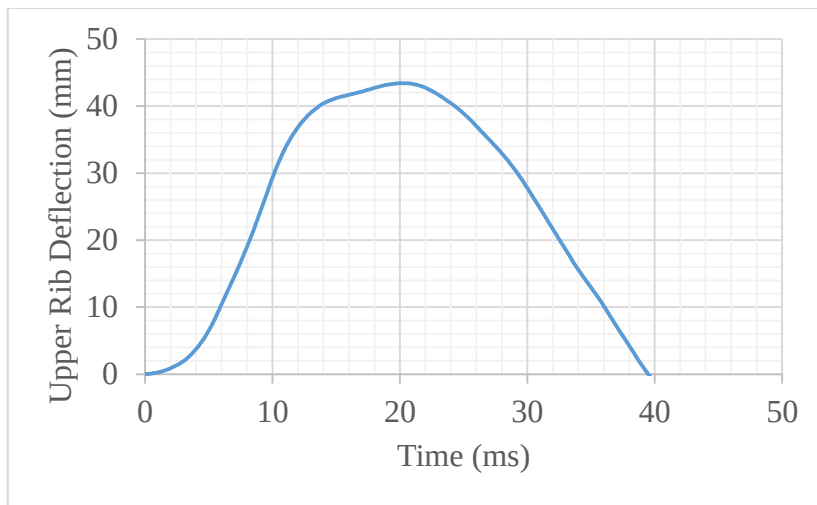


Figure 5.20. ThImp-PED Upper Rib Deflection for 5,5 m/s Pendulum Test 1

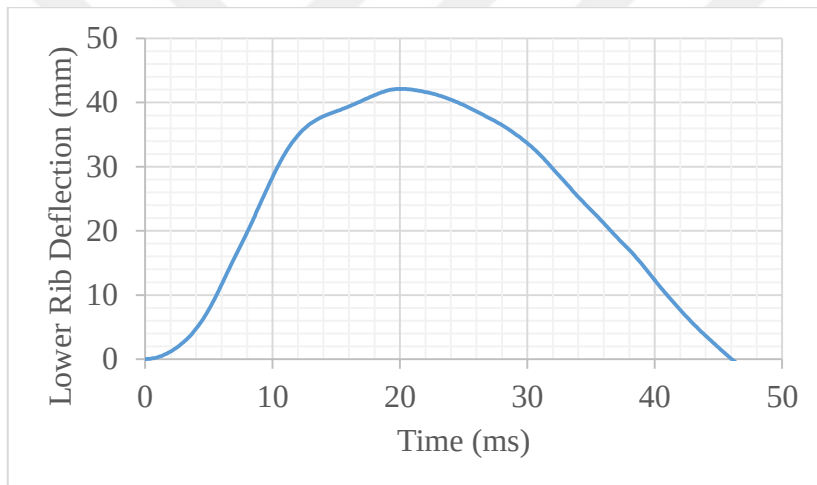


Figure 5.21. ThImp-PED Lower Rib Deflection for 5,5 m/s Pendulum Test 1

Pendulum Test-2 at 5,5 m/s:

The impact speed is 5,43 m/s. The maximum pendulum force has been calculated as 5.440 N. The peak pendulum force fits into the corridor as shown in Figure 5.22.

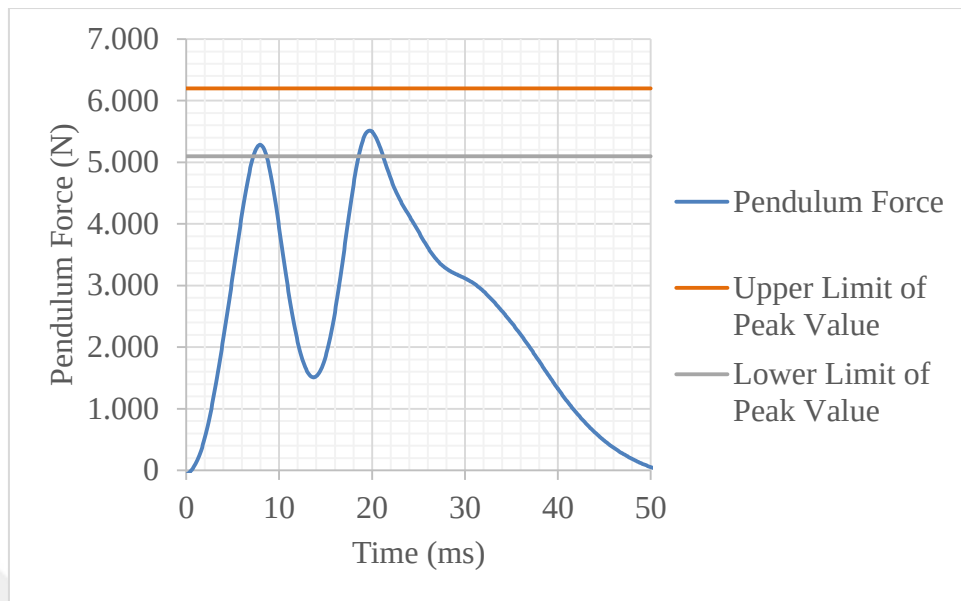


Figure 5.22. ThImp-PED Pendulum Force for 5,5 m/s Pendulum Test 2

The rib deflection for the upper rib is given in Figure 5.23 and for the lower rib in Figure 5.24.

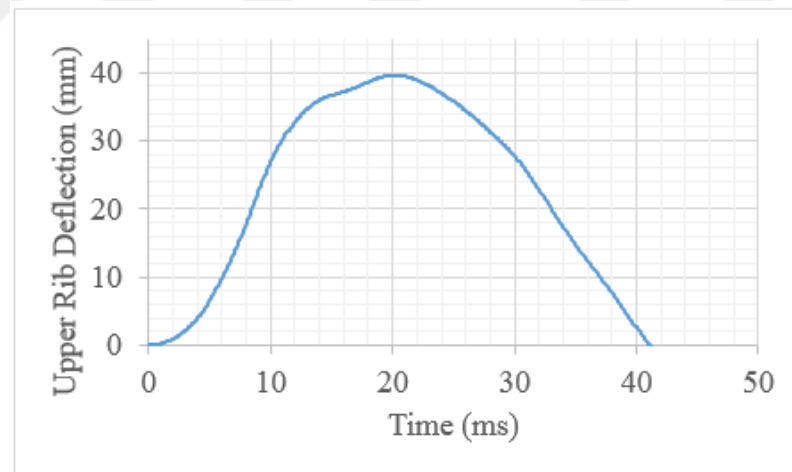


Figure 5.23. ThImp-PED Upper Rib Deflection for 5,5 m/s Pendulum Test 2

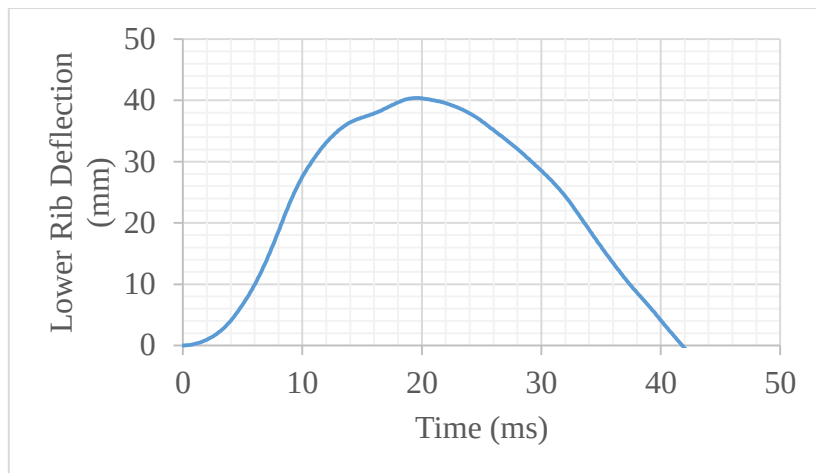


Figure 5.24. ThImp-PED Lower Rib Deflection for 5,5 m/s Pendulum Test 2

Pendulum Test-3 at 5,5 m/s:

The impact speed is 5,43 m/s. The maximum pendulum force has been calculated as 5.420 N. The peak pendulum force fits into the corridor as shown in Figure 5.25.

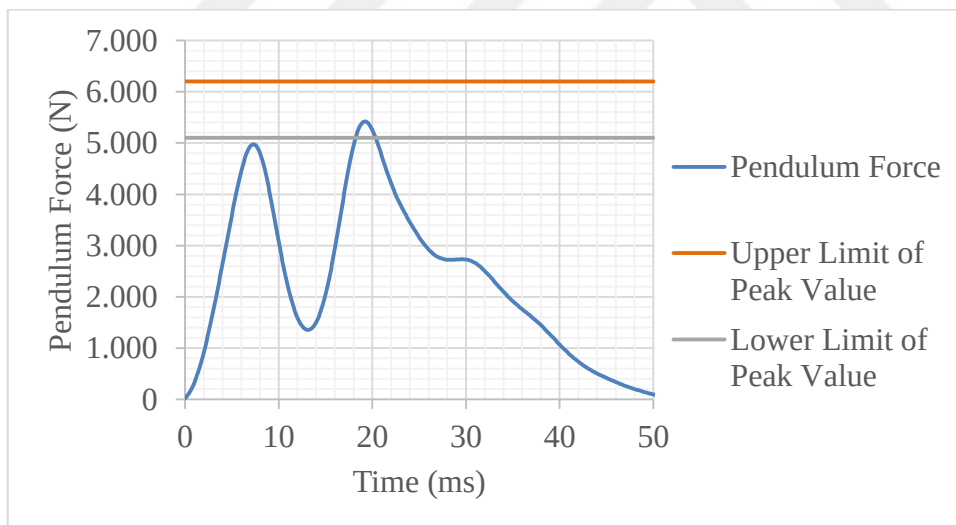


Figure 5.25. ThImp-PED Pendulum Force for 5,5 m/s Pendulum Test 3

The rib deflections for the upper rib is given in Figure 5.26 and for the lower rib in Figure 5.27.

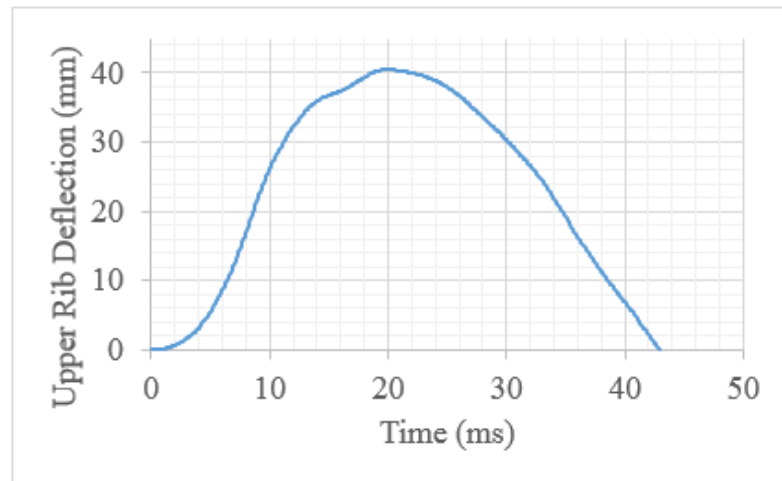


Figure 5.26. ThImp-PED Upper Rib Deflection for 5,5 m/s Pendulum Test 3

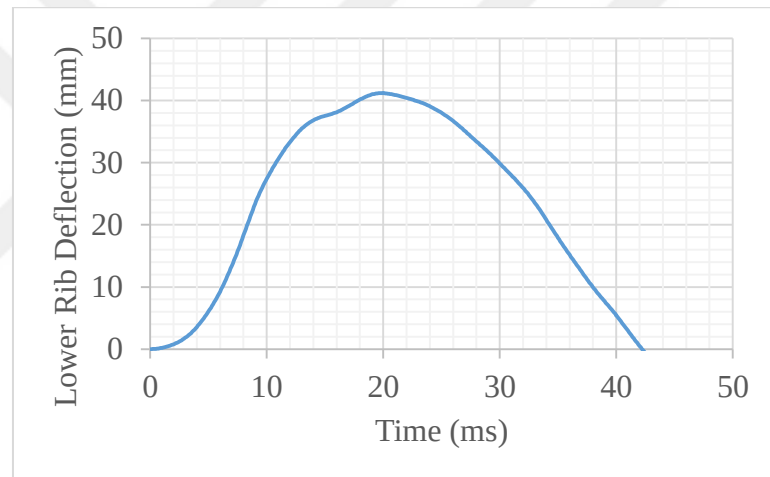


Figure 5.27. ThImp-PED Lower Rib Deflection for 5,5 m/s Pendulum Test 3

The upper and lower rib deflections in Pendulum Test-1, Pendulum Test-2 and Pendulum Test-3 satisfy the limits specified in the standard as given in Table 5.2.

Table 5.2 ThImp-PED Rib Deflections for 5,5 m/s Pendulum Tests

ES-2 Rib Deflections Defined in the Standard (mm) [68]			Pendulum Test Results of ThImp-PED Rib Deflections in the Current Study (mm)		
Upper Rib	Middle Rib	Lower Rib		Upper Rib	Lower Rib
34-41	37-45	37-44	Test 1	42,5	42,1
			Test 2	39,6	40,4
			Test 3	40,5	41,2

Note that, ES-2 dummy has 3 ribs, so the limits are given on the left side of the table for these 3 ribs. However, ThImp-PED has 2 ribs and the rib deflections have been measured for these 2 ribs in the pendulum tests as given on the right side of the table.

The pendulum tests performed at 4,3 m/s and 5,5 m/s with ThImp-PED show that the pendulum forces and the rib deflections satisfy the specifications in the related standards. Therefore, ThImp-PED has an acceptable level of biofidelity.

CHAPTER 6

PROPOSED NOVEL TEST PROCEDURE AND PEDESTRIAN PROTECTION TESTS WITH THIMP-PED ON LINEAR IMPACTOR TEST SYSTEM

The pedestrian protection regulations and standards define the tests for head, upper leg and lower leg regions of the pedestrians as mentioned in Section 2.4. However, there is no test procedure defined for the thorax region of the pedestrians. In this study, a novel test procedure has been developed and proposed for the flat front vehicle impact to the thorax region of pedestrian. In the following section, this procedure is given.

In this chapter, the pedestrian protection tests with ThImp-PED on Linear Impactor Test System will also be presented.

6.1 Novel Test Procedure

The available test procedures about pedestrian safety [38], [39] have been examined and it is decided that the novel test procedure should cover the following main parts:

- Test specimen preparation
- Test specimen marking
- Impactor specifications and certification of the impactors
- Definition of test conditions
- Performing the tests
- Evaluation of the test results

Reasoning and details of each part of the proposed procedure will be given in the following subsections and the steps of application of the proposed procedure are

presented in “Instructions Document for the Proposed Test Procedure” is given in Appendix F.

6.1.1 Test Specimen Preparation

The test specimen may be a full vehicle or a vehicle front that is prepared for the tests. The test specimen should include all parts of the vehicle front structure that may be involved in an impact with a pedestrian to demonstrate the performance and interactions of all the related vehicle components.

When a full vehicle is the test specimen, the vehicle should be at rest on a flat horizontal surface with the parking brake applied. In the available pedestrian protection regulations [38], [39], the test position of the vehicle is defined in terms of its height, orientation and suspension. Similar parameters and values have been used in this proposed test procedure and the vehicle’s test position has been defined as follows:

- a. The vehicle attitude should be in running order positioned on the ground
- b. The tyres should be inflated to the recommended pressures
- c. The suspension should be set for a driving speed of 40km/h in normal running conditions specified by the manufacturer
- d. The front wheels should be in the straight-ahead position
- e. The vehicle should be equipped with all standard equipment as provided by the vehicle manufacturer.

When a vehicle front is the test specimen, it should be secured firmly to the floor of the test laboratory. The height of the vehicle front with respect to the ground should be specified by the manufacturer of the test specimen by considering the parameters and values defined in “a-e” steps given above for the full vehicle case.

The vehicle’s reference system is given in Figure 6.1. In the figure, yz plane represents the “vertical transverse plane” of the vehicle and xz plane represents the

“vertical longitudinal plane” of the vehicle. The test specimen should be positioned with respect to the test system such that its vertical transverse plane is perpendicular to the impactor axis within $\pm 2^\circ$ which is the accepted tolerance in the pedestrian protection regulations.

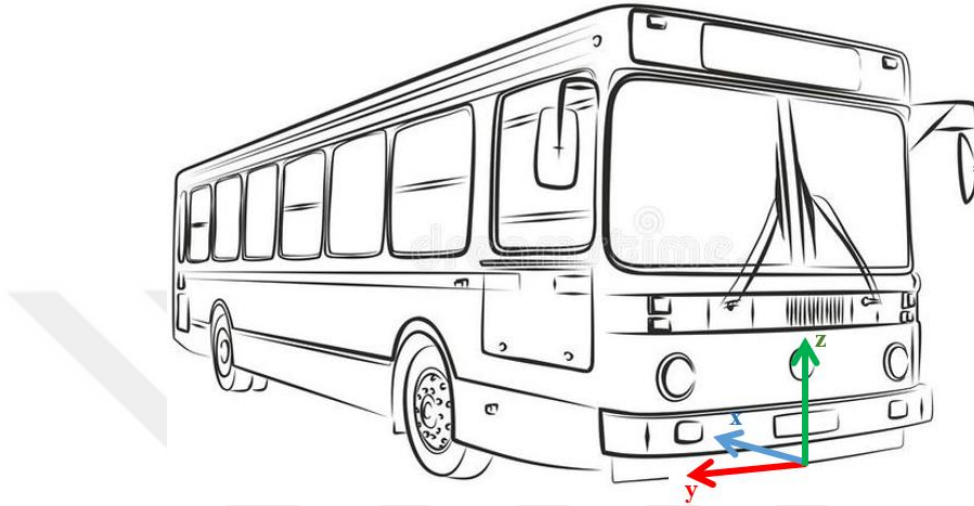


Figure 6.1. Vehicle Reference System

6.1.2 Marking of Test Specimen

It is assumed that the vehicle hits the pedestrian from the side and the pedestrian has a walking stance. Firstly, the region of the vehicle front that comes in contact with the pedestrian thorax in case of an accident should be specified.

To determine the particular region, the manufacturer of the test specimen could analyse the potential impact region. For example, the 50th Percentile Male CAD model has been considered together with CAD Model of an available commercial bus front. For this case, it is seen that upper body of the manikin (i.e. thorax, shoulders, upper arms and head) contacts the windshield of the bus in case of an accident. Abdomen and elbows contact the transition region between the front cover and the windshield including the wipers. Pelvis, upper legs and lower legs contact the front cover of the bus. These are the impact regions for this particular

bus front. However, different impact regions can be determined for different vehicle fronts.

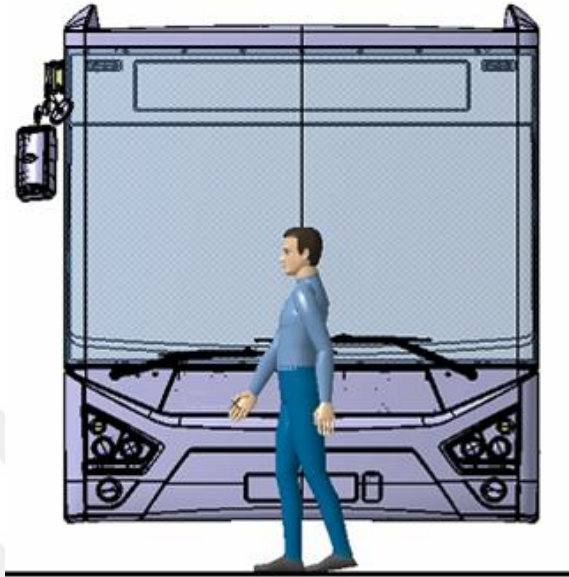


Figure 6.2. 50th Percentile Male and Bus Front

In this study, thorax height of a 50th percentile male has been used to determine the impact zone in this proposed procedure. “2012 Anthropometric Survey Of U.S. Army Personnel” [77] has been used as a reference for the related standard dimensions of the pedestrian. The report presents results of a comprehensive anthropometric survey of U.S. Army Soldiers completed in 2012. In total, 94 dimensions of 7435 male and 3922 female soldiers of different percentiles were measured. Total height, shoulder height and ribcage height of the 50th percentile male are given in Figure 6.3 [77]. Shoulder height and ribcage height have been used to determine the impact zone in this proposed procedure.

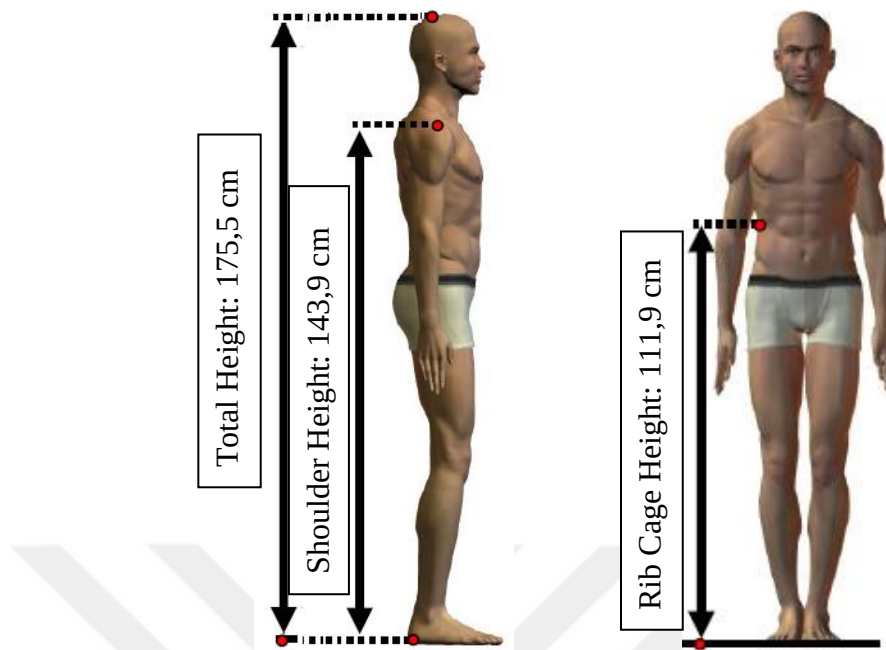


Figure 6.3. Anthropometric Dimensions of 50th Percentile Male [77]

The lower boundary of the impact zone is determined by taking the projection of the “rib cage height” on the test specimen from the ground. The upper boundary of the impact zone is determined by taking the projection of the “shoulder height” on the test specimen from the ground. These boundaries should be marked on the vehicle front from the leftmost to the rightmost of the vehicle. Then this area (i.e. impact zone) should be investigated in terms of parts, geometries and materials. At least one set of impact points corresponding to the upper and lower rib impact locations should be marked on each region (i.e. test zone) that is different from its surroundings in terms of geometries and materials within the impact zone. During the marking, trackers should be used and each impact point should be given a unique name. The impact point names should be “U1” and “L1” for the first test where “U1” represents the upper rib impact point and “L1” represents the lower rib impact point. The impact point names for the following tests should be “U2”, “L2”, “U3”, “L3” and so on.

6.1.3 Impactor Specifications and Certification of the Impactor

In this study, ThImp-PED has been designed to be used for pedestrian protection tests on the thorax region of pedestrian. ThImp-PED is a side impact thorax impactor as described in Section 3.3. ThImp-PED will be used in this proposed test procedure.

For the certification of ThImp-PED, thorax pendulum tests should be performed at 5,5 m/s by using the parts of a 50th percentile HIII dummy as defined in Section 5.2. ThImp-PED should be certified after a test in case damage is observed and parts of the impactor need to be replaced. Additionally, periodical certification should be performed after every 10 tests.

6.1.4 Definition of Test Conditions

The tests will be performed with a test system having a launcher. The impactor will be mounted on the launcher of the test system and launched to the test specimen. At the time of testing, the test facility where the test system is located shall have a stabilized temperature of $20\text{ }^{\circ}\text{C} \pm 4\text{ }^{\circ}\text{C}$ and relative humidity of $40\% \pm 30\%$.

The test site floor shall be flat, smooth and hard surface with a slope not exceeding 1%.

The direction of the impact velocity vector shall be parallel to the horizontal plane within ± 2 degrees and it should be parallel to the vertical longitudinal plane of the vehicle within ± 2 degrees. Flight distance of the impactor should be between 600 mm to 700 mm measured between the first contact points on the impactor and the impact points on the test specimen prior to impact.

Impact velocity is $40\text{ km/h} \pm 0,7\text{ km/h}$ ($11,1\text{ m/s} \pm 0,2\text{ m/s}$) and it should be measured with a measuring system such as a laser speed trap sensor at a location just prior to first contact of the impactor with the impact points.

6.1.5 Performing the Tests

The test specimen should be prepared according to Section 6.1.1 and the impact points should be marked on the test zone according to Section 6.1.2.

Detailed photographs of the test specimen and the related impact points should be taken from different angles before each test.

At least 2 high speed cameras should be positioned to record the test. One of the camera views (i.e. the general view) should be taken from the side. It should include the trajectory of the impactor starting from the time at it leaves the test system to the time it hits the test specimen. The second camera view (i.e. the detail view) should be taken either from the side or from the top. It should include a close view of the moment that the impactor hits the test specimen. The cameras should record at least 500 frames per second (fps).

The impact points on ThImp-PED that are expected to make the first contact with the test specimen should be marked with trackers. Coloured paint should be applied on these trackers to check if there is any deviation from the target impact points after the test.

The impactor defined in Section 6.1.3 should be launched to each impact point with an impact velocity of $40 \text{ km/h} \pm 0,7 \text{ km/h}$. The impact velocity should be measured with a measuring system such as a laser speed trap sensor at a location just prior to first contact of the impactor with the test specimen.

Rib deflections should be measured by using the linear potentiometers mounted on the upper and lower rib sets and they should be recorded by using the Data Acquisition System (DAS).

Detailed photographs of the test specimen and the related impact points should be taken from different angles after each test. The photographs should include detailed views of the damaged or deformed parts on the test specimen.

The impactor should be examined visually after each test to see if any damage occurred on its parts during or after the impact.

The flesh representing foams should be removed and replaced with new sheets so that each test is performed with a new set of foams.

6.1.6 Evaluation of Test Results and Assessment of Injury Criterion

The high speed videos that are taken during the test, impact speed measurement and rib deflections that are recorded by the DAS should be examined in detail to evaluate the test results. It should be checked from the high speed videos if the impactor hits the target impact point in the target position and with the target angle. Impact velocity measurement should be checked and verified that it is $40 \text{ km/h} \pm 0,7 \text{ km/h}$.

Rib deflections for the upper and lower ribs should be filtered with CFC 180 [69] and it should be checked if the Rib Deflection Criterion (RDC) is less than or equal to 42 mm [56]. RDC is the maximum of the rib deflections measured from the upper and lower rib sets.

6.2 Tests with ThImp-PED and Linear Impactor System According to the Proposed Novel Test Procedure

6.2.1 Performing the Tests

Four tests with ThImp-PED have been performed according to the proposed novel test procedure. The Linear Impactor System in METU-BILTIR Center has been used for the tests. The photograph of the system is given in Figure 6.4. It is an electrically driven system with accurate velocity and position control. The launcher can move in up/down, left/right directions and can be angled so that the position

and angle of impact can be adjusted accurately. Technical details of the system are given in Appendix G.



Figure 6.4. The Linear Impactor Test System in METU-BILTIR Center

In this study, a flat front vehicle shown in Figure 6.5, has been used as the test specimen. The logo and identifying parts on the front are camouflaged in the photograph for the commercial confidentiality of the related vehicle manufacturer.

Firstly, the test vehicle has been positioned relative to the Linear Impactor Test System according to the requirements defined in the proposed novel test procedure.

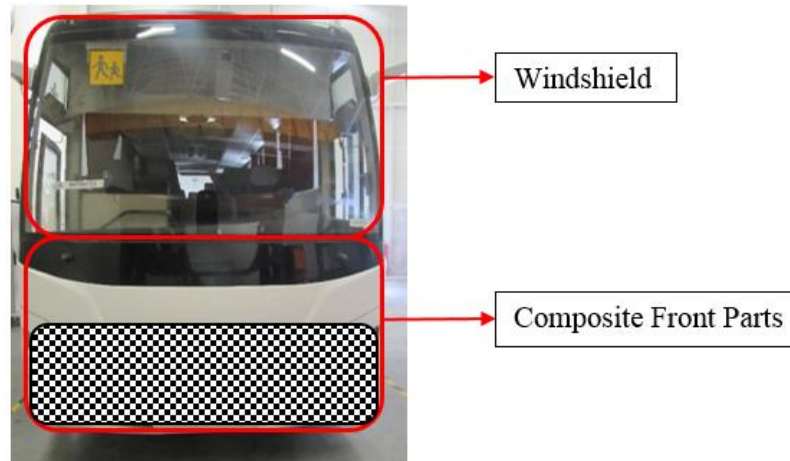


Figure 6.5. Test Vehicle

According to the proposed novel test procedure, the lower boundary of the impact zone has been determined by taking the projection of the “rib cage height” which is 111,9 mm [77] on the test specimen from the ground. The upper boundary of the impact zone has been determined by taking the projection of the “shoulder height” which is 143,9 mm [77] on the test specimen from the ground. These boundaries have been marked on the vehicle front from the leftmost to the rightmost of the vehicle as shown in Figure 6.6.

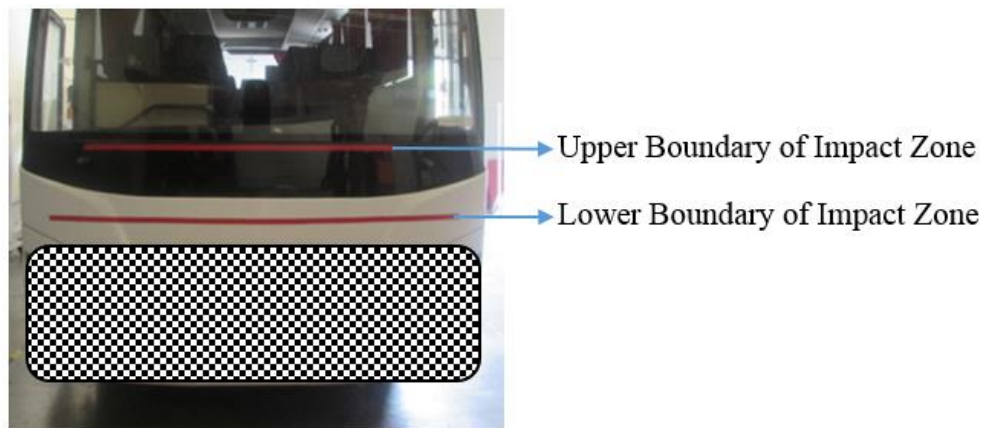


Figure 6.6. Upper and Lower Boundaries of the Impact Zone

For this particular vehicle, the impact zone includes the composite parts on the front of the vehicle.

Pedestrian Test-1:

The target impact points “U1” and “L1” have been marked with trackers on the vehicle front as seen in Figure 6.7. The vertical distance between the target points is same as the distance between centerlines of upper and lower ribs of ThImp-PED.

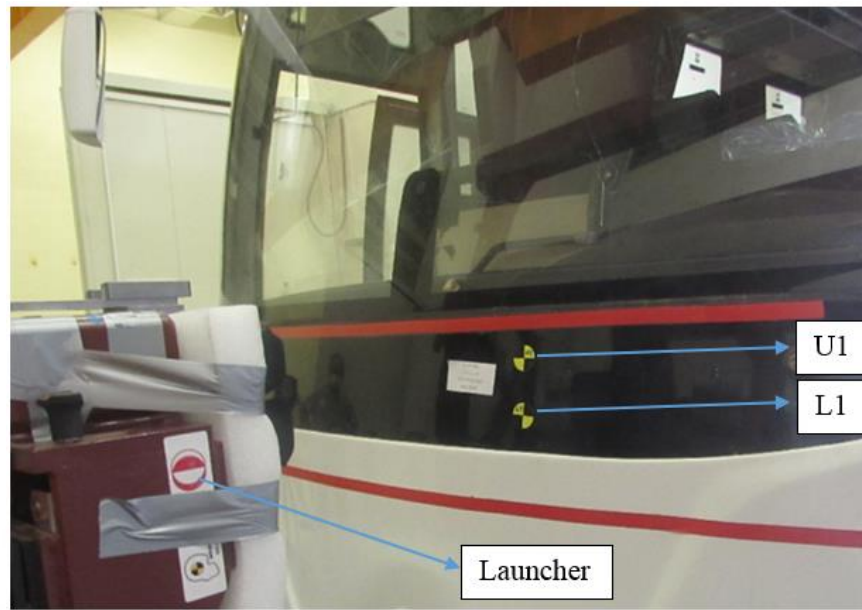


Figure 6.7. U1 and L1 Impact Points in Pedestrian Test-1

The corresponding impact points on ThImp-PED that are expected to make the first contact with the test specimen have also been marked with trackers as seen in Figure 6.8. Red coloured paint has been applied on these trackers to check if there is any deviation from the target impact points after the test.

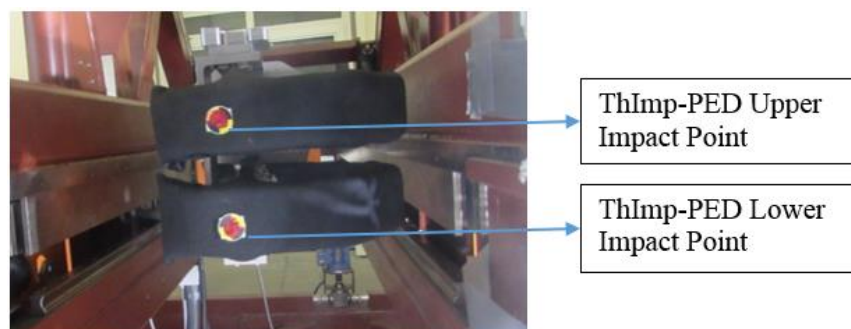


Figure 6.8. ThImp-PED Expected Impact Points in Pedestrian Test-1

The launcher has been adjusted so that ThImp-PED is launched parallel to the ground (at zero degrees) and vertical to the vehicle front.

Target speed has been adjusted to 40,7 km/h from the Linear Impactor System to compensate the speed drop during free flight of ThImp-PED.

Two high speed cameras have been positioned so that one view (i.e. general view) will include the trajectory of the impactor starting from the time at it leaves the test system to the time it hits the test specimen as seen in Figure 6.9 and the other view (i.e. detail view) includes a close view of the moment that the impactor hits the test specimen as seen in Figure 6.10. Both cameras have recorded at 500 fps.



Figure 6.9. Camera General View at Time Zero for Pedestrian Test-1



Figure 6.10. Camera Detail View at Time Zero for Pedestrian Test-1

Data Acquisition System (DAS) has been adjusted so that the rib deflections during impact could be measured by the linear potentiometers.

Pre test photographs have been taken from different views.

The test has been performed as seen in Figure 6.11 and Figure 6.12.



Figure 6.11. Camera General View at Time of Impact for Pedestrian Test-1

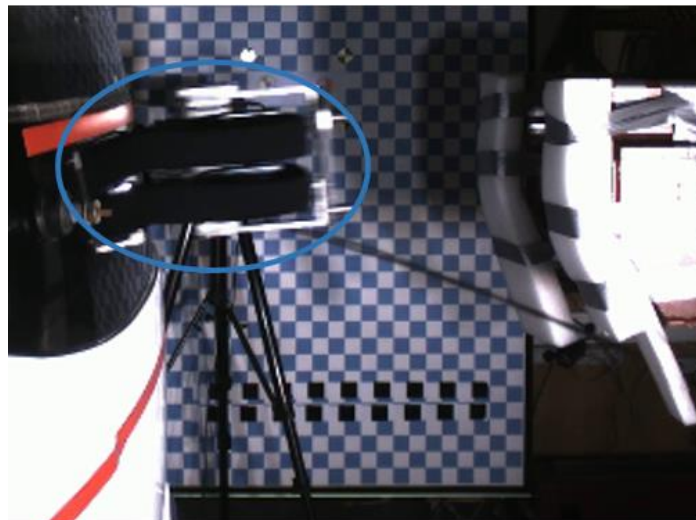


Figure 6.12. Camera Detail View at Time of Impact for Pedestrian Test-1

Post test photographs have been taken from different views and the high speed videos have been downloaded and analysed. After the test, the red paint marks on the vehicle front have been checked and it has been evaluated that ThImp-PED impacted the vehicle front accurately in correct position as seen in Figure 6.13.



Figure 6.13. Post Test Photograph for Pedestrian Test-1

The impact speed has been measured by means of the laser speed trap sensor as 39,8 km/h which is within the tolerances of the target speed ($40,0 \pm 0,7$ km/h).

The upper and rib deflection measurements have been obtained from the DAS. The maximum upper rib deflection has been measured as 52,4 mm as shown in Figure 6.14.

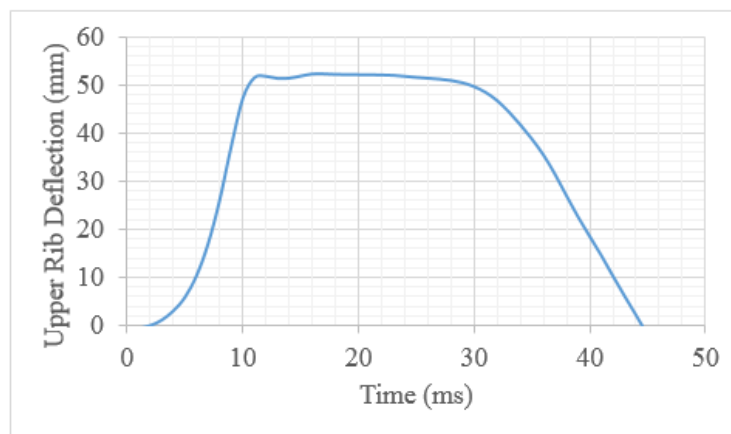


Figure 6.14. Upper Rib Deflection in Pedestrian Test-1

Upper rib deflection is higher than 42,0 mm therefore the vehicle front does not satisfy the RDC injury criterion according to the proposed novel procedure at these impact points.

Lower rib deflection could not be measured in Pedestrian Test-1 due to a connection fault in the lower rib linear potentiometer. To see the lower rib deflection as well, test has been repeated as described in Pedestrian Test-3.

Pedestrian Test-2:

Pedestrian Test-2 has been performed similar to Pedestrian Test-1 by following the same steps defined in the proposed novel test procedure. The target impact points “U2” and “L2” are seen in Figure 6.15.

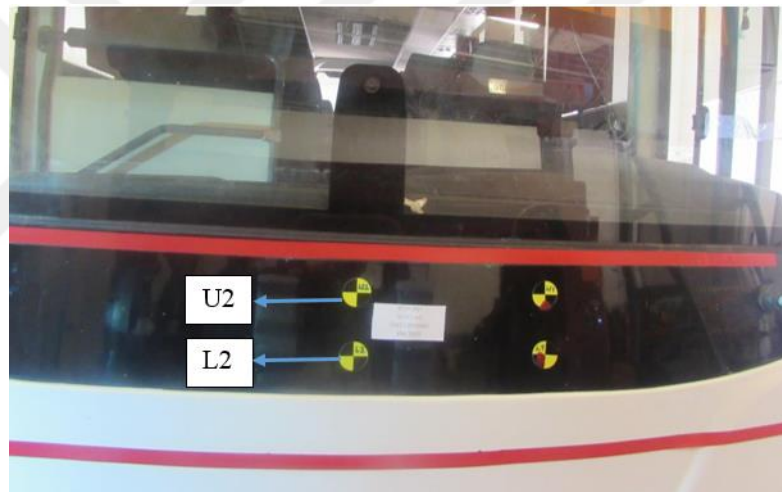


Figure 6.15. U2 and L2 Impact Points in Vehicle Test-2

Marking and painting of the corresponding impact points on ThImp-PED, adjustment of the launcher position and impact speed, positioning of the high speed cameras, adjustment of the DAS and taking the pre test photos have been performed similar to Pedestrian Test-1.

The test has been performed as seen in Figure 6.16 and Figure 6.17.

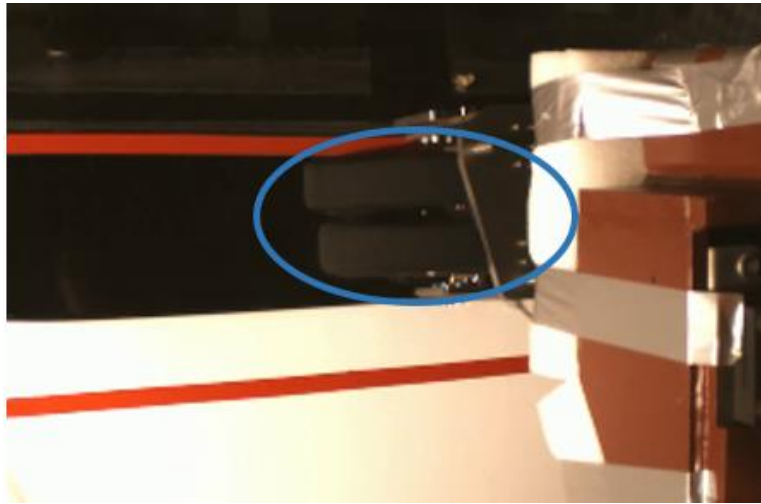


Figure 6.16. Camera General View at Time of Impact for Pedestrian Test-2

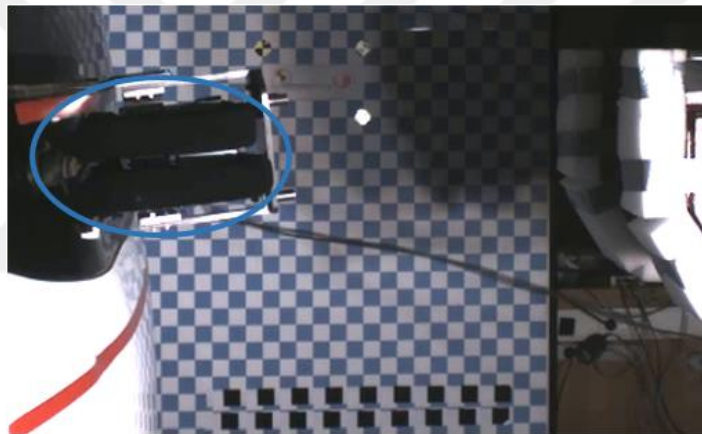


Figure 6.17. Camera Detail View at Time of Impact for Pedestrian Test-2

Post test photographs have been taken from different views and the high speed videos have been downloaded and analysed. After the test, the red paint marks on the vehicle front have been checked and it is evaluated that ThImp-PED impacted the vehicle front accurately in correct position as seen in Figure 6.18. The impact speed has been measured as 39,6 km/h which is within the tolerances of the target speed ($40,0 \pm 0,7$ km/h).



Figure 6.18. Post Test Photograph for Pedestrian Test-2

As can be seen in Figure 6.19, it is observed that, crack has been formed on the composite part that is impacted by ThImp-PED. Additionally, cracks have been observed on the windshield after the test.

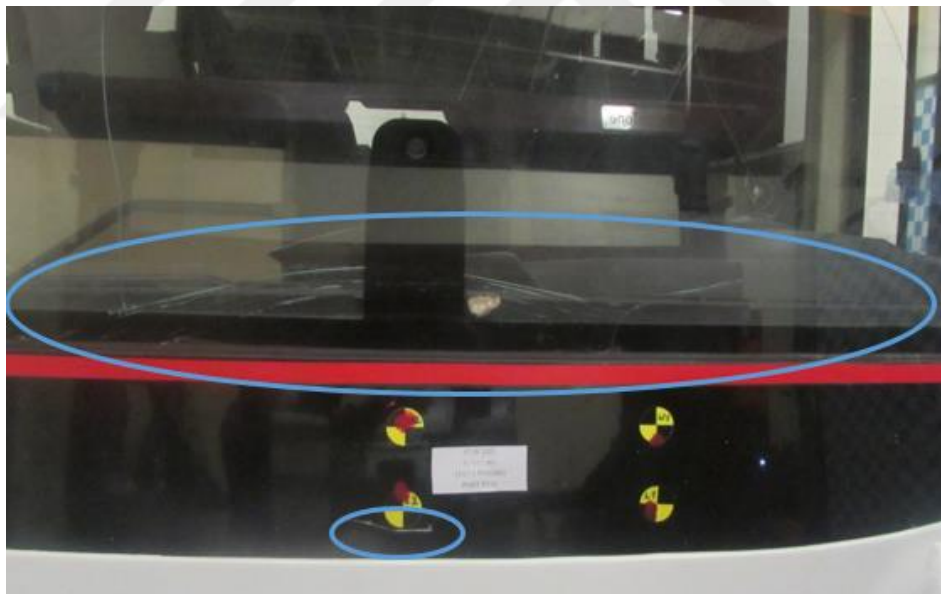


Figure 6.19. Post Test Photograph for Pedestrian Test-2 Showing the Cracks

The upper and rib deflection measurements have been obtained from the DAS. The maximum upper rib deflection has been measured as 43,7 mm as shown in Figure

6.20. The maximum lower rib deflection has been measured as 49,1 mm as shown in Figure 6.21.

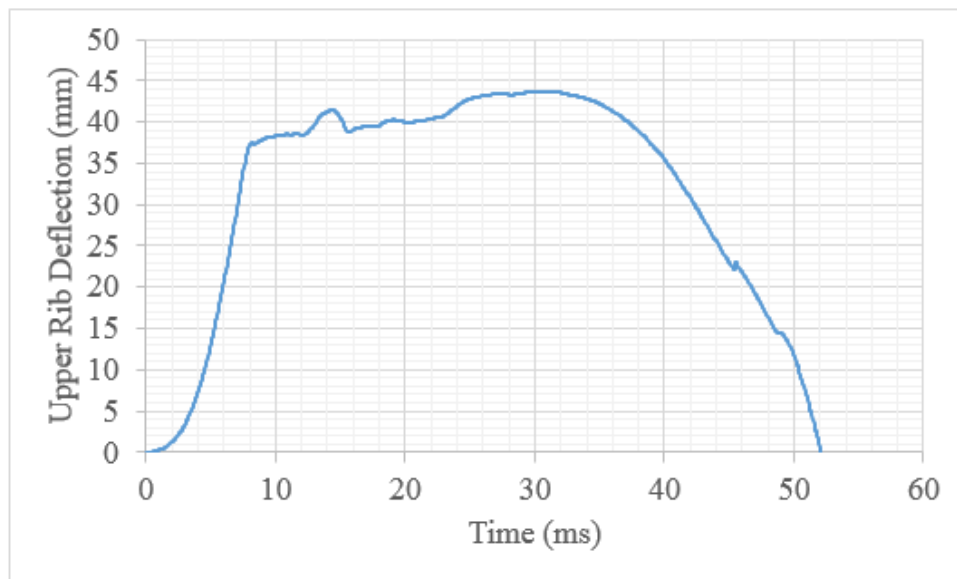


Figure 6.20. Upper Rib Deflection in Pedestrian Test-2

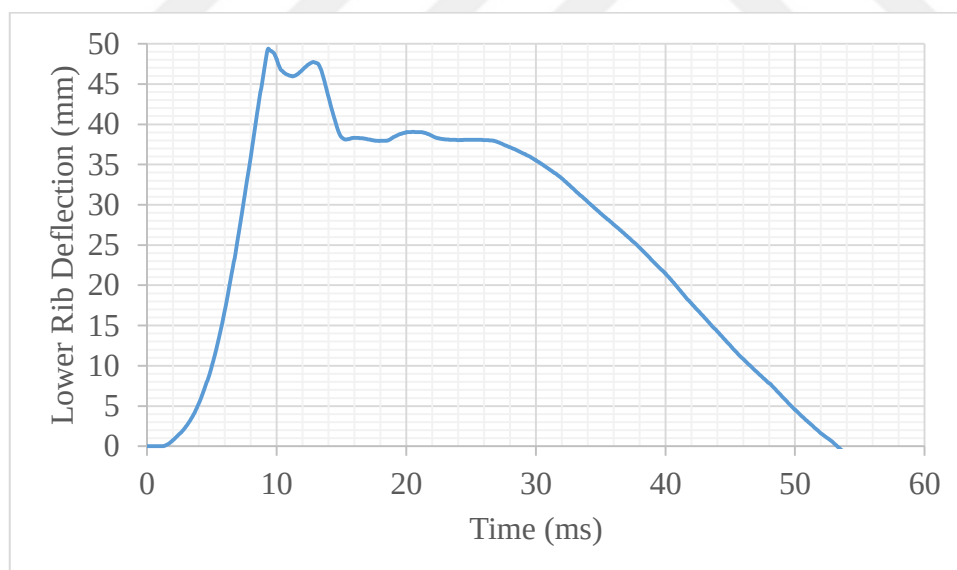


Figure 6.21. Lower Rib Deflection in Pedestrian Test-2

Upper rib and lower rib deflections are higher than 42,0 mm therefore the vehicle front does not satisfy the RDC injury criterion according to the proposed novel procedure at these impact points.

Pedestrian Test-3:

Pedestrian Test-3 has been performed similar to Pedestrian Test-1 by following the same steps defined in the proposed novel test procedure. The target impact points “U3” and “L3” are seen in Figure 6.22. “U3” and “L3” have been marked very close to “U1” and “L1” since Pedestrian Test-3 is considered as the repetition of Pedestrian Test-1 in which the lower rib deflection could not be measured.

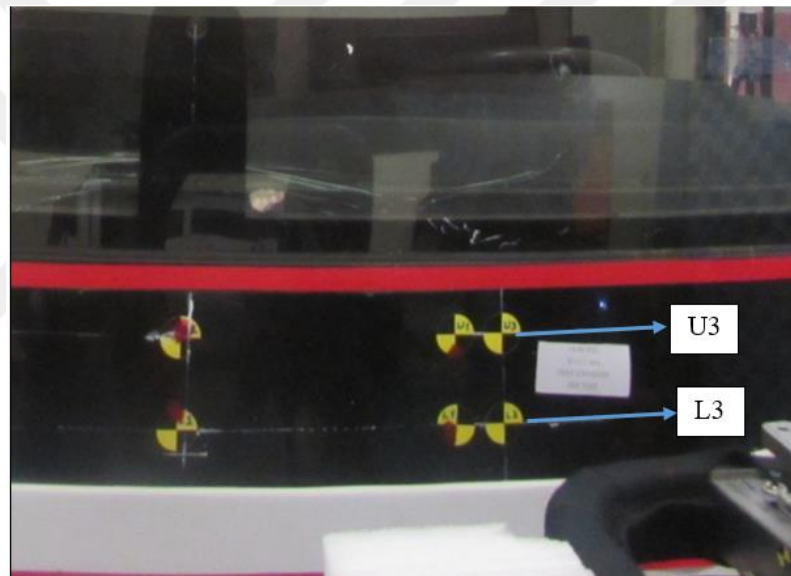


Figure 6.22. U3 and L3 Impact Points in Pedestrian Test-3

Marking and painting of the corresponding impact points on ThImp-PED, adjustment of the launcher position and impact speed, positioning of the high speed cameras, adjustment of the DAS and taking the pre test photos have been performed similar to Pedestrian Test-1.

The test has been performed as seen in Figure 6.23.

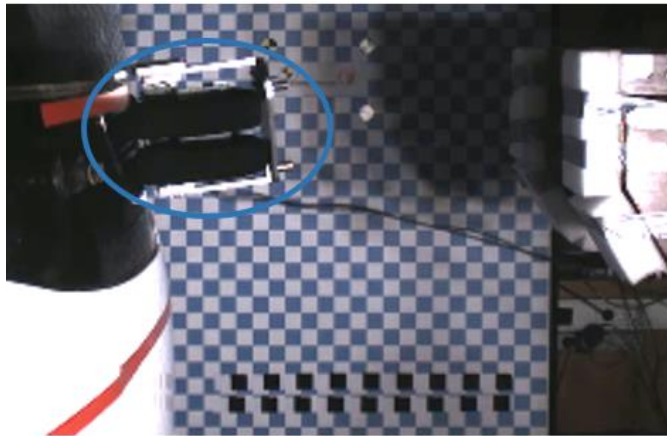


Figure 6.23. Camera Detail View at Time of Impact for Pedestrian Test-3

Post test photographs have been taken from different views and the high speed videos have been downloaded and analysed. After the test, the red paint marks on the vehicle front have been checked and it is evaluated that ThImp-PED impacted the vehicle front accurately in correct position as seen in Figure 6.24. The impact speed has been measured as 39,6 km/h which is within the tolerances of the target speed ($40,0 \pm 0,7$ km/h).



Figure 6.24. Post Test Photograph for Pedestrian Test-3

The upper and lower rib deflection measurements have been obtained from the DAS. The maximum upper rib deflection has been measured as 52,9 mm as shown in Figure 6.25. The maximum lower rib deflection has been measured as 50,9 mm as shown in Figure 6.26.

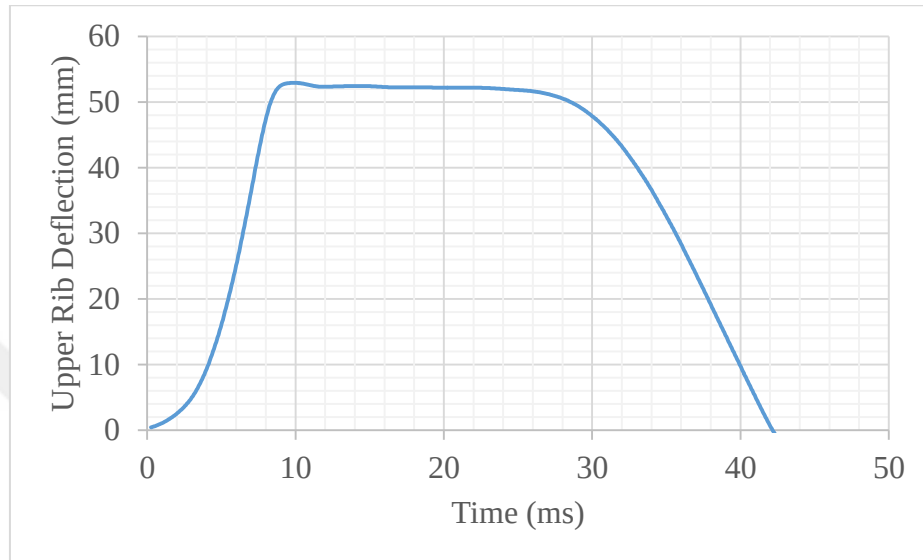


Figure 6.25. Upper Rib Deflection in Pedestrian Test-3

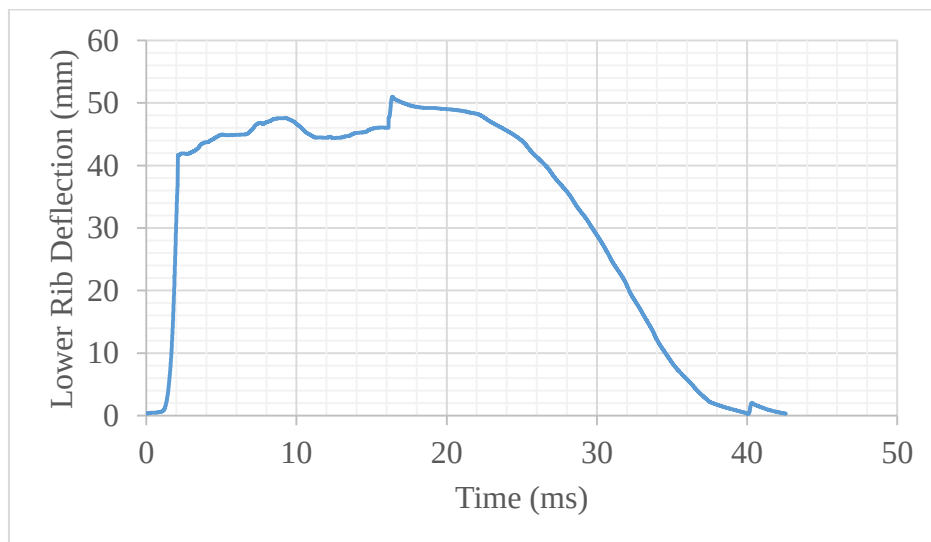


Figure 6.26. Lower Rib Deflection in Pedestrian Test-3

Upper rib and lower rib deflections are higher than 42,0 mm therefore the vehicle front does not satisfy the RDC injury criterion according to the proposed novel procedure at these impact points.

Pedestrian Test-4:

Pedestrian Test-4 has been performed similar to Pedestrian Test-1 by following the same steps defined in the proposed novel test procedure. The target impact points “U4” and “L4” are seen in Figure 6.27.

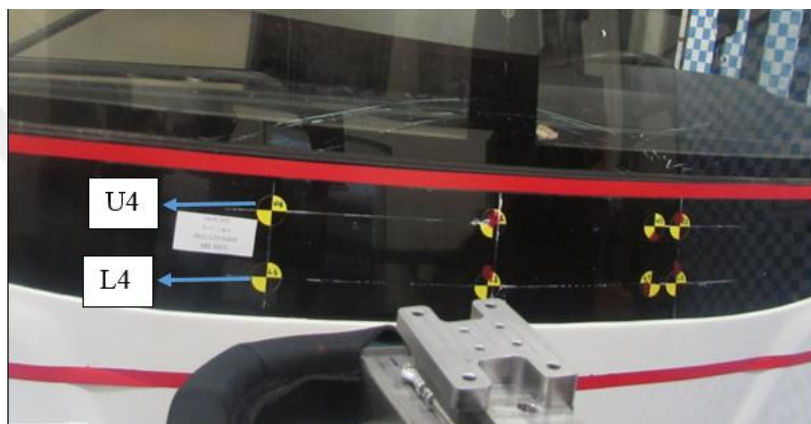


Figure 6.27. U4 and L4 Impact Points in Pedestrian Test-4

Marking and painting of the corresponding impact points on ThImp-PED, adjustment of the launcher position and impact speed, positioning of the high speed cameras, adjustment of the DAS and taking the pre test photos have been performed similar to Pedestrian Test-1.

The test has been performed as seen in Figure 6.28.

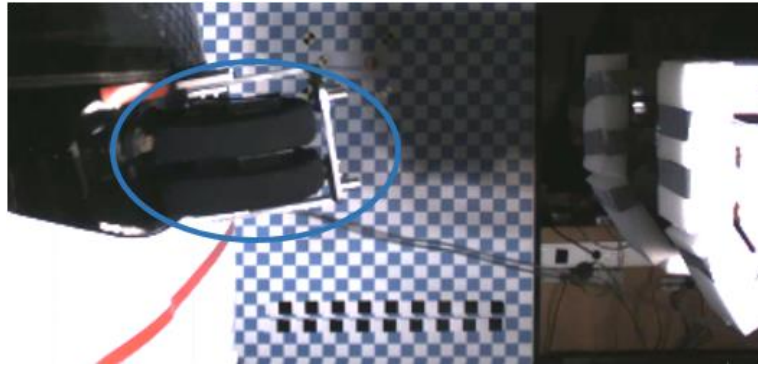


Figure 6.28. Camera Detail View at Time of Impact for Pedestrian Test-4

Post test photographs have been taken from different views and the high speed videos have been downloaded and analysed. After the test, the red paint marks on the vehicle front have been checked and it is evaluated that ThImp-PED impacted the vehicle front accurately in correct position as seen in Figure 6.29. The impact speed has been measured as 39,5 km/h which is within the tolerances of the target speed ($40,0 \pm 0,7$ km/h).



Figure 6.29. Post Test Photograph for Pedestrian Test-4

As can be seen in Figure 6.30, it is observed that, additional cracks have occurred and propagated all through the windshield after the test.



Figure 6.30. Post Test Photograph for Pedestrian Test-4 Showing the Cracks

The upper and rib deflection measurements have been obtained from the DAS. The maximum upper rib deflection has been measured as 40,7 mm as shown in Figure 6.31. The maximum lower rib deflection has been measured as 37,8 mm as shown in Figure 6.32.

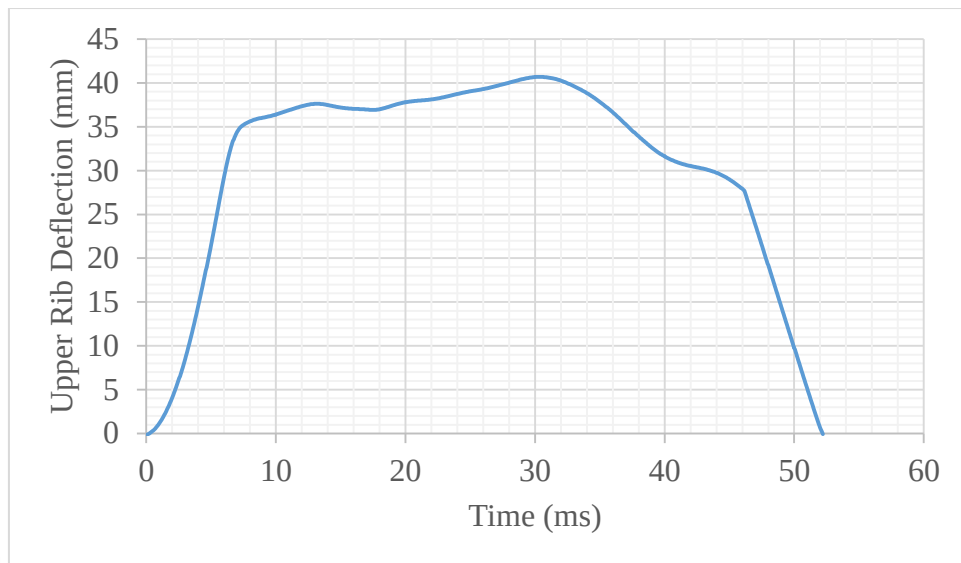


Figure 6.31. Upper Rib Deflection in Pedestrian Test-4

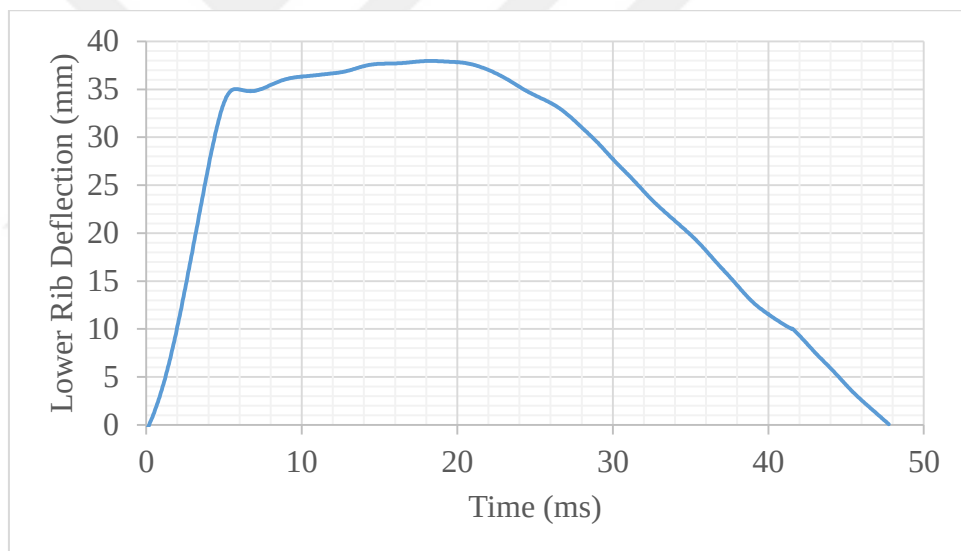


Figure 6.32. Lower Rib Deflection in Pedestrian Test-4

Upper rib and lower rib deflections are both lower than 42,0 mm therefore the vehicle front satisfies the RDC injury criterion according to the proposed novel procedure at these impact points.

6.2.2 Discussion of the Test Results

The impact points that are impacted in Pedestrian Tests 1-4 are shown in Figure 6.33.

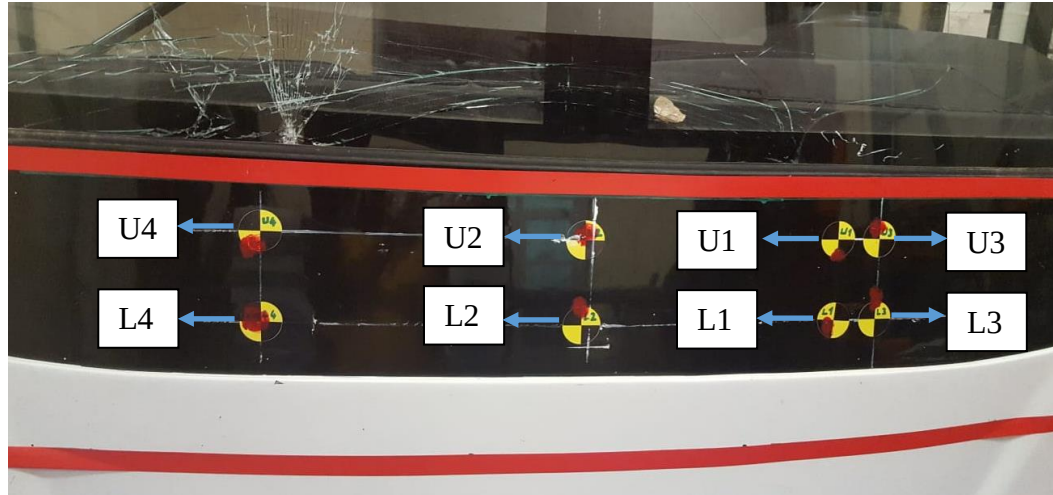


Figure 6.33. Impact Points in Pedestrian Tests

The rib deflections measured in Pedestrian Tests 1-4 are summarized in Table 6.1.

Table 6.1 Rib Deflections in Pedestrian Tests

Pedestrian Test No	Upper Rib Deflection (mm)	Lower Rib Deflection (mm)	Average Rib Deflection (mm)
1	52,4	-	52,4
2	43,7	49,1	46,4
3	52,9	50,9	51,9
4	40,7	37,8	39,3

Upper rib deflections and lower rib deflections are very close to each other in all the tests as can be seen in Table 6.1. This is an expected result for ThImp-PED impact to a flat front vehicle since similar forces are applied for similar durations by the vehicle front to the ThImp-PED upper and lower ribs during impact for a flat front vehicle.

The rib deflections are higher than 42,0 mm for the first three tests which have been performed at the driver side and center of the vehicle. The initial interpretation could be that the zones that are impacted by the ThImp-PED may be stiff and there may not be sufficient energy absorbing material behind these particular zones. This may be the cause of high rib deflections. Detailed study on the design, materials and inner structure of the particular vehicle front is required to interpret the reasons for the high rib deflections.

The lower rib deflection could not be measured due to a connection fault with the linear potentiometer in Pedestrian Test-1. The test has been repeated as Pedestrian Test-3 by impacting to very close points to those in Pedestrian Test-1. Lower rib deflection in Pedestrian Test-3 has been measured very close to the upper rib deflection as seen in Table 6.1. It is also noted that, the upper rib deflections in Pedestrian Test-1 and Pedestrian Test-3 are very close to each other. This shows that even single rib deflection measurement may be sufficient to provide necessary information.

In Pedestrian Test-4, upper and lower rib deflections are below the RDC criterion of 42,0 mm. As discussed above, this may be due to material and inner structure at that zone of the vehicle.

6.3 Research and Development Tests with Fixture

Research and development tests may also be performed for vehicle fronts by using ThImp-PED. Components of vehicle front made of different materials (i.e. glass, steel, aluminum, composite, etc) with different properties can be tested at different impact velocities to see their behavior during pedestrian involved accidents.

In this study, a simple fixture has been designed and plexiglass has been used to perform two sample development tests at 18 km/h and 40 km/h.

Steel profiles have been used to construct the frame of the fixture. The profiles have been connected to each other by welding and bolt connections. The fixture has been firmly secured to the ground with bolt connections. Plexiglass with the thickness of 5 mm has been used as a sample component to be used in the vehicle front. Photograph of the fixture is given in Figure 6.34.

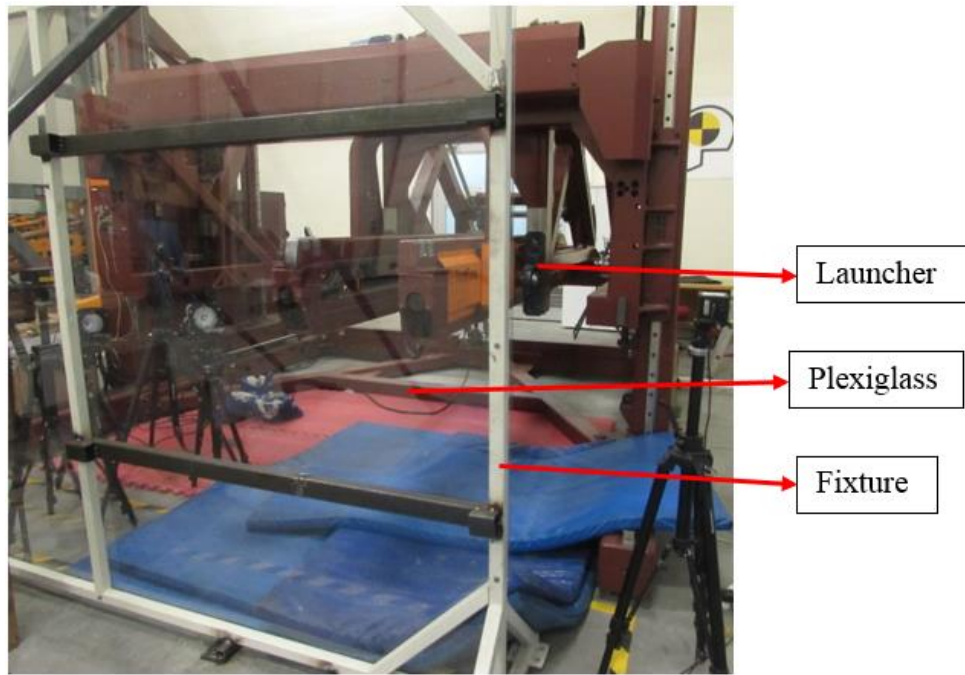


Figure 6.34. Fixture Used for the Sample Development Tests

The results of the tests are given below.

Development Test at 18 km/h

Firstly, low speed test has been performed. Camera view showing ThImp-PED at the time of impact is given in Figure 6.35.

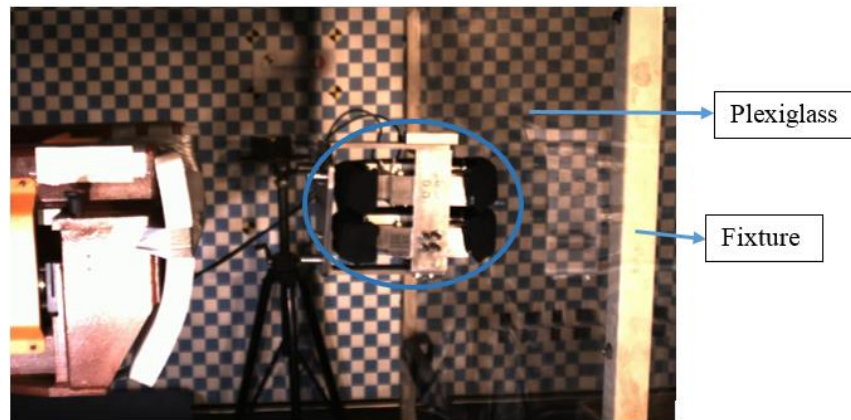


Figure 6.35. Camera View at Time of Impact in Test at 18 km/h

The upper rib deflection has been measured as 26,3 mm and the lower rib deflection has been measured as 26,5 mm. It is observed that the maximum rib deflections for the upper and lower ribs are very close to each other as expected. The rib deflection graphs are given in Figure 6.36 and Figure 6.37.

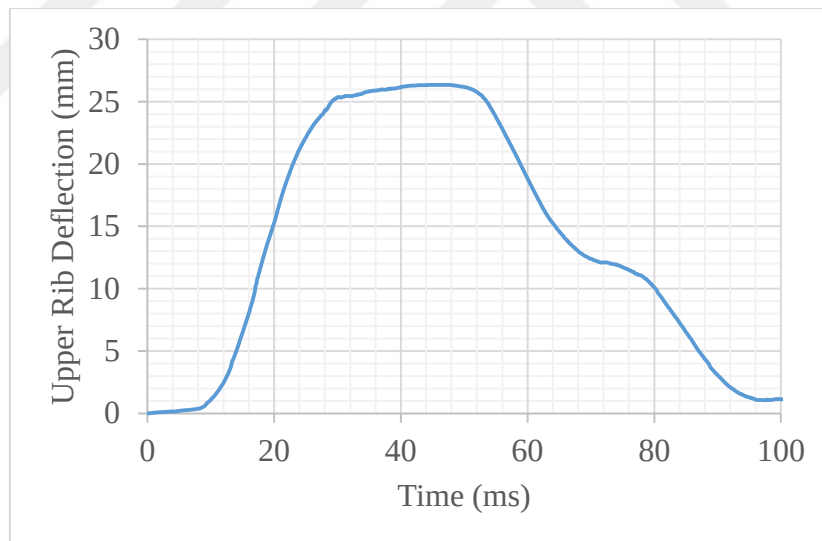


Figure 6.36. Upper Rib Deflection in Test at 18 km/h

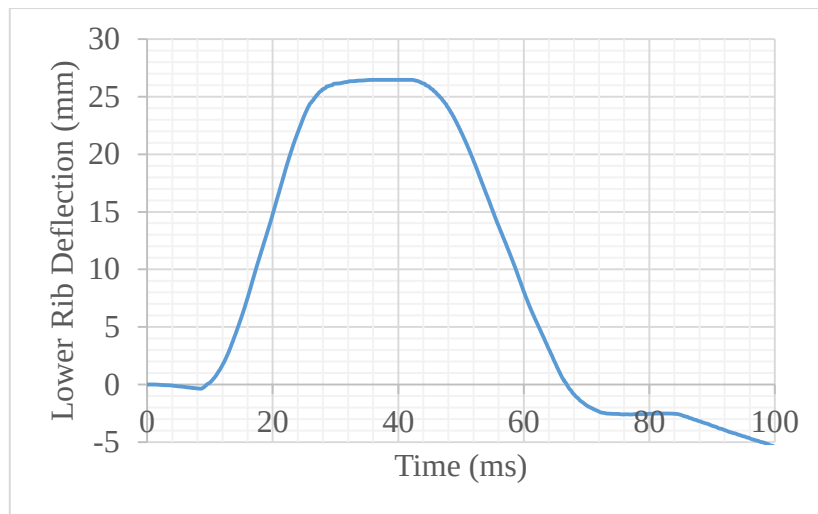


Figure 6.37. Lower Rib Deflection in Test at 18 km/h

Development Test at 40 km/h

Pedestrian protection tests are performed at 40 km/h. In this development test, the impact speed is adjusted as 40 km/h accordingly. Camera view showing ThImp-PED at the time of impact is given in Figure 6.38.

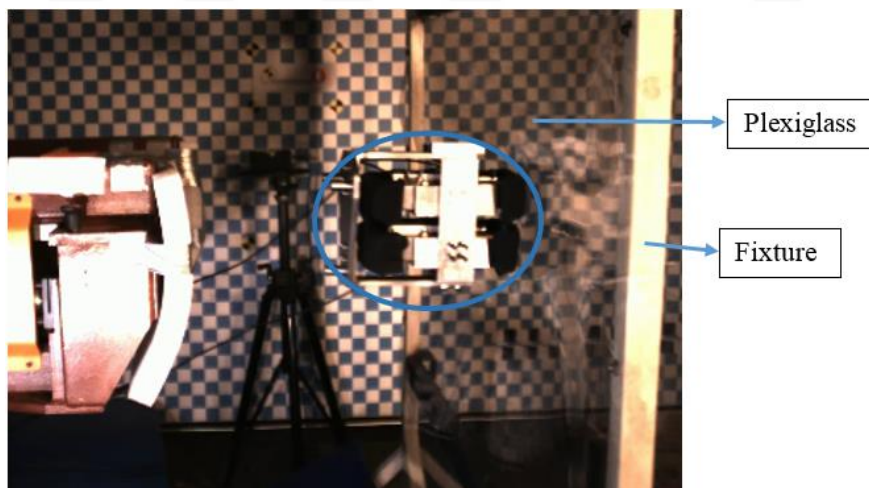


Figure 6.38. Camera View at Time of Impact in Test at 40 km/h

The upper rib deflection and the lower rib deflection have been measured as 38,2 mm and 34,1 mm respectively. It is evaluated that RDC injury criterion is satisfied

according to the proposed test procedure, since the maximum of the upper and lower rib deflections is less than 42,0 mm. The rib deflection graphs are given in Figure 6.39 and Figure 6.40.

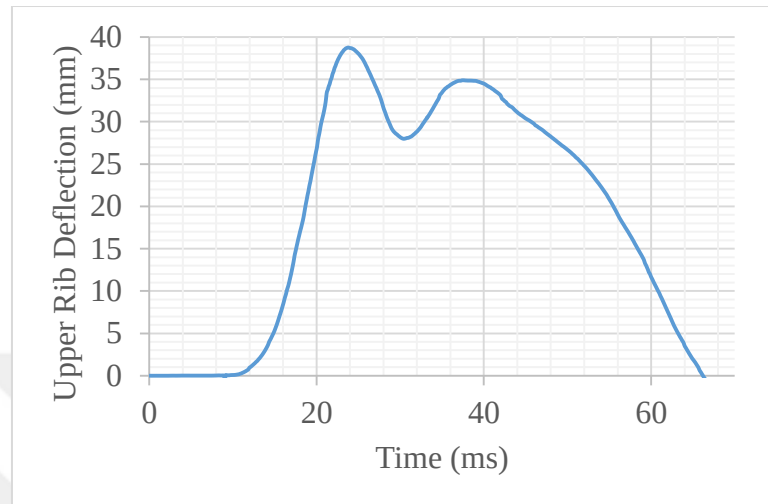


Figure 6.39. Upper Rib Deflection in Test at 40 km/h

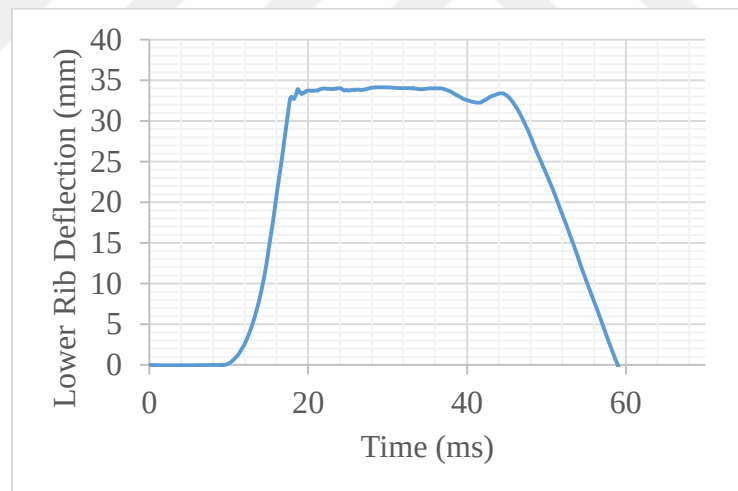


Figure 6.40. Lower Rib Deflection in Test at 40 km/h

Similar research and development tests may be conducted by using adequate fixtures for other materials for the vehicle manufacturers.

CHAPTER 7

CONCLUSION

General conclusions of the study and the proposed further studies are presented in the following sections.

7.1 Conclusions

One of the main contributions of this study is proposition of the novel patentable thorax impactor (i.e. ThImp-PED) that can be used in the pedestrian protection tests. Other main contribution is proposition of the novel test procedure to be used in the pedestrian protection tests for thorax region of pedestrians in case of accidents with flat front vehicles.

ThImp-PED is a low cost, modular, biofidelic impactor to be used in pedestrian protection tests and it represents the thorax region of a 50th percentile male. Currently available pedestrian protection tests are only defined for the head and legs regions of the pedestrians that impact with passenger cars. There are no standard tests to evaluate the injuries in the thorax region of pedestrians in case of an accident. With the proposed novel thorax impactor it is possible to evaluate the thorax injuries of pedestrians in case of an accident with a vehicle. Most of the passenger cars are bonnet type vehicles, however, there are several other types of vehicles having flat front such as buses, minibuses, trucks, etc. ThImp-PED can be used for pedestrian impacts with flat front vehicles.

ThImp-PED has been analysed with Finite Element Analysis (FEA) and its biofidelity has been validated by comparing it with ES-2 which is a commercially available side impact crash test dummy used as a driver or passenger in standard tests. FEA of pendulum tests at 4,3 m/s and 5,5 m/s have been conducted for ES-2

and ThImp-PED and the results have been compared in terms of rib deflections and pendulum force during impact. A good correlation has been found in terms of biofidelity between the FEA results of ES-2 and ThImp-PED.

ThImp-PED has been manufactured and physical pendulum tests have been performed in METU-BILTIR Center to validate the biofidelity of ThImp-PED. For this purpose, the thorax region of a 50th percentile HIII crash test dummy has been replaced with ThImp-PED by using adapter parts which have been designed during this study. Then ThImp-PED has been impacted laterally at 4,3 m/s and 5,5 m/s with a rigid pendulum. The rib deflections and pendulum forces during impact have been measured and compared with the defined values in the standards. The pendulum tests have shown that ThImp-PED has an acceptable biofidelity.

A novel test procedure has been proposed to be used in the pedestrian protection tests for thorax region of pedestrians in case of accidents with flat front vehicles. The proposed test procedure describes the preparation of the test specimen, determination of impact points, impact speed and angle, evaluation criteria, etc. The tests have been performed with the Linear Impactor Test System in METU-BILTIR Center by using the proposed test procedure. In the tests, ThImp-PED having the designed mounting bracket for the particular Linear Impactor Test System and a commercial flat front vehicle have been used. The results of the tests have been evaluated. Upper rib deflections and lower rib deflections are very close to each other in all the tests as expected for ThImp-PED impact to a flat front vehicle. The rib deflections are higher than 42,0 mm for the first three tests which have been performed at the driver side and center of the vehicle. The initial interpretation could be that the zones that have been impacted by the ThImp-PED may be stiff and there may not be sufficient energy absorbing material behind these particular zones. This may be the cause of high rib deflections. Detailed study on the design, materials and inner structure of the particular vehicle front is required to interpret the reasons for the high rib deflections. In Pedestrian Test-4, upper and

lower rib deflections are below the RDC criterion of 42,0 mm which may be due to material and inner structure at that zone of the vehicle, as discussed before.

Development tests have been performed by using a designed sample fixture to show that ThImp-PED can also be used for research and development tests for vehicle fronts. The tests have been performed with plexiglass material. However, components of vehicle front made of different materials and with different properties can also be tested by using similar fixtures to see their behavior during pedestrian involved accidents.

ThImp-PED has been designed, analysed, manufactured and experimentally tested. The METU authorities have approved to start the patent application procedures by acknowledging that ThImp-PED is a patentable invention.

7.2 Future Studies

The study can be extended to the following studies:

- ThImp-PED can be scaled to propose new thorax impactors that represent pedestrians with different percentiles such as 5th percentile adult, 95th percentile adult and children at different ages.
- Tests can be performed with ThImp-PED for different vehicle fronts like buses and trucks by using the proposed test procedure.
- Tests can be performed with ThImp-PED for different bonnet type vehicle fronts to see the effects of the impact on pedestrian thorax.
- Different material models can be studied for the components of ThImp-PED in FEA. Sensitivity analysis on the minimum number of elements, which should be used for the predictions to be mesh-independent, can also be performed for FEA.
- FEA by using ThImp-PED FEM can be performed with different vehicle front parts having different structure, materials and geometries.

- Research and development tests by using ThImp-PED can be performed with different vehicle front parts having different structure, materials and geometries.
- ThImp-PED can be used with different Launching Systems by designing different mounting brackets.
- Additional sensors can be added to ThImp-PED and additional thorax injury criteria like “Viscous Criterion” and “Thoracic Trauma Index” can be calculated.
- Additional applicable injury criteria can be studied in collaboration with the experts from medicine and biomechanics.

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APPENDICES

A. Some of the Human Body Bones

The major human body bones referred frequently in this study are shown in Figure A.1.

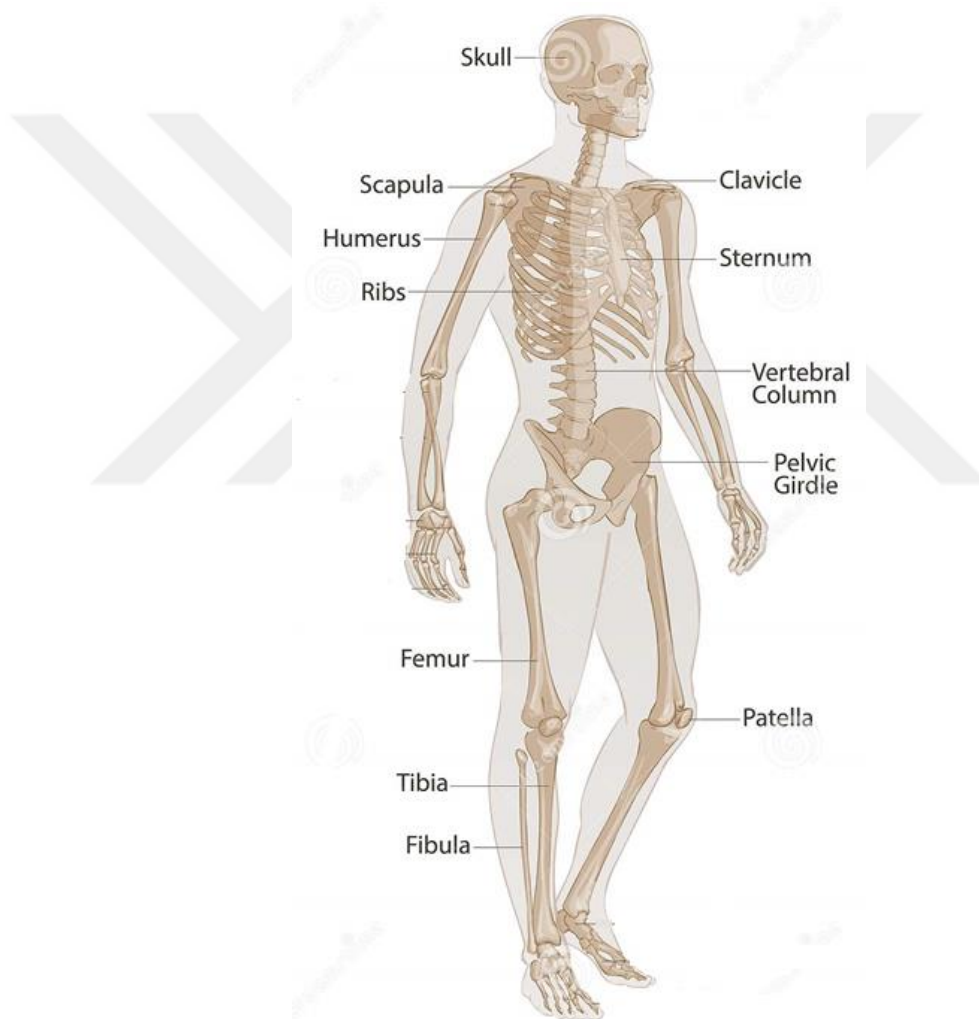


Figure A.1. Some of the Human Body Bones [78]

B. Details of Crash Test Dummies Thorax Regions

Details of the mostly used commercially available crash test dummies have been given with special emphasis on their thorax regions in Section 2.1. The part lists for the exploded thorax regions of the crash test dummies are given below.

a. Hybrid III 50th Percentile Male

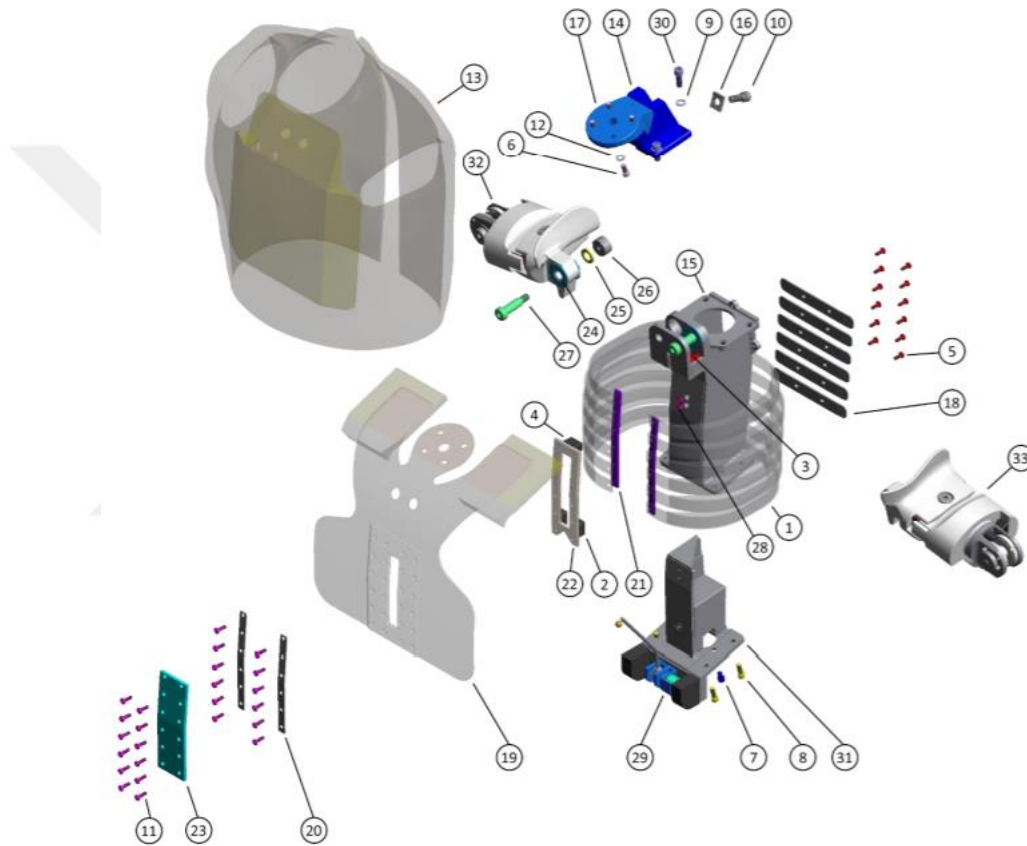


Figure B.1. Hybrid III 50th Percentile Male Exploded Thorax Assembly [28]

Table B.1 Hybrid III 50th Percentile Male Exploded Thorax Parts List [28]

Item	Quantity	Description
1	1	Rib Set, Complete
2	2	Stop, Sternum
3	2	Bumper, Shoulder
4	1	Stop, Sternum
5	12	Screw
6	4	Screw
7	2	Screw
8	4	Screw
9	4	Washer
10	1	Screw
11	24	Screw
12	4	Washer
13	1	Chest Flesh and Skin Assembly
14	1	Bracket, Neck, Adjusting Lower
15	1	Thoracic Spine Assembly
16	1	Washer, Clamping
17	1	Bracket Assembly, Neck Adjusting
18	6	Support, Rib, Rear
19	1	Bib Assembly, Sternum to Rib
20	2	Plate, Front End Stiffener
21	2	Strip, Front End
22	1	Sternum
23	1	Slider, Chest Deflector
24	4	Washer, Clavicular Link
25	2	Washer, Nut Clavicular
26	2	Nut, Clavicle Link Pivot
27	2	Clavicular Link, Pivot Screw
28	2	Screw
29	1	Transducer Assembly
30	4	Screw
31	1	Adapter Assembly
32	1	Shoulder Assembly, Right
33	1	Shoulder Assembly, Left

b. THOR 50th Percentile Male

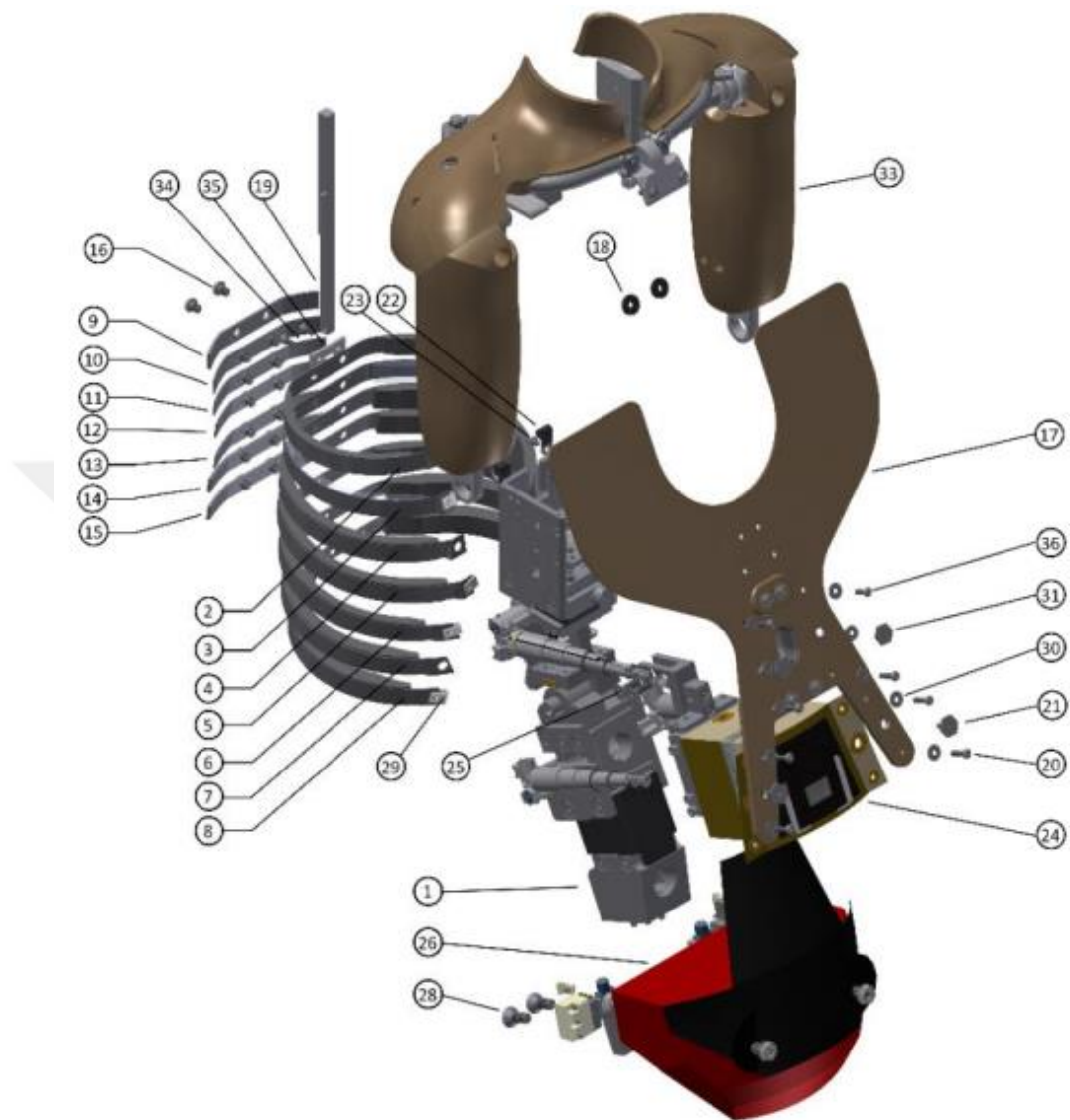


Figure B.2. THOR 50th Percentile Male Exploded Thorax Assembly [29]

Table B.2 THOR 50th Percentile Male Exploded Thorax Parts List [29]

Item	Quantity	Description
1	1	SPINE MECHANICAL ASSEMBLY
2	1	THORAX ELLIPTICAL RIB #1 – ASSEMBLY
3	1	THORAX ELLIPTICAL RIB #2 – ASSEMBLY
4	1	THORAX ELLIPTICAL RIB #3 – ASSEMBLY
5	1	THORAX ELLIPTICAL RIB #4 – ASSEMBLY
6	1	THORAX ELLIPTICAL RIB #5 – ASSEMBLY
7	1	THORAX ELLIPTICAL RIB #6 – ASSEMBLY
8	1	THORAX ELLIPTICAL RIB #7 – ASSEMBLY
9	1	THORAX ELLIPTICAL RIB STIFFENER #1
10	1	THORAX ELLIPTICAL RIB STIFFENER #2
11	1	THORAX ELLIPTICAL RIB STIFFENER #3
12	1	THORAX ELLIPTICAL RIB STIFFENER #4
13	1	THORAX ELLIPTICAL RIB STIFFENER #5
14	1	THORAX ELLIPTICAL RIB STIFFENER #6
15	1	THORAX ELLIPTICAL RIB STIFFENER #7
16	14	SCREW
17	1	THORAX BIB ASSEMBLY
18	2	WASHER
19	1	THOR LIFT STRAP
20	6	SCREW
21	2	IRTRACC CONNECTING BOLT, LOWER
22	2	1/4 COATED CABLE CLAMP
23	2	SCREW
24	1	UPPER ABDOMEN ASSEMBLY
25	2	SCREW
26	1	LOWER ABDOMEN MECHANICAL ASSEMBLY
27-28	6	SCREW
29-30	20	CLIP NUT & WASHER
31	2	IRTRACC CONNECTING BOLT, UPPER
32	4	SCREW
33	1	SD3 SHOULDER AND ARMS ASSEMBLY
34	2	SCREW
35	1	BRACKET, LIFTING STRAP
36	2	SCREW

c. ES-2 Side Dummy

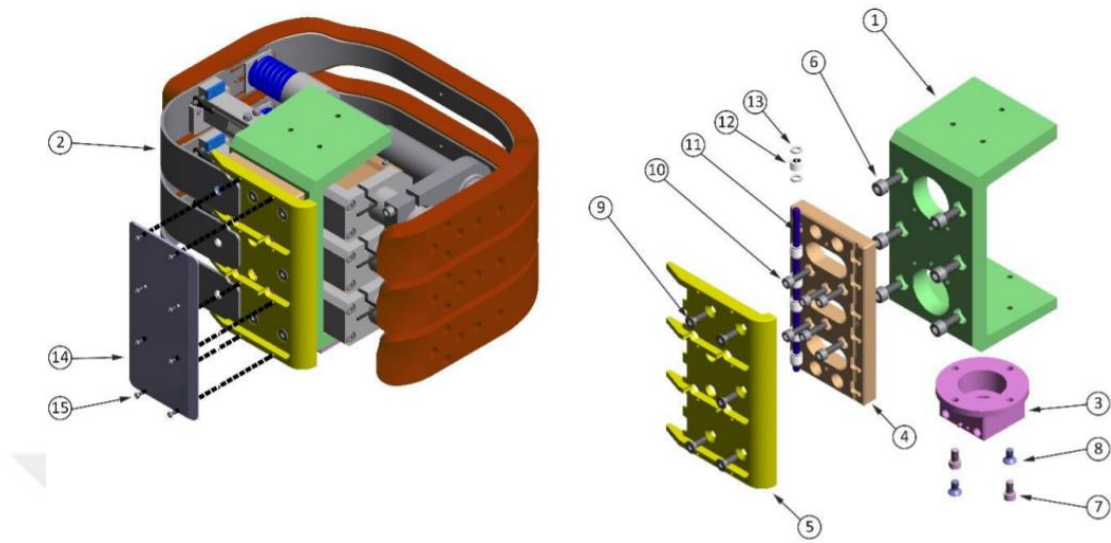


Figure B.3. ES-2 Exploded Thorax Assembly [30]

Table B.3 ES-2 Exploded Thorax Parts List [30]

Item	Quantity	Description
1	1	Spine Box, Rib Extension
2	3	Complete Rib Module with Rib Extensions
3	1	T12 Structural Replacement
4	1	Back plate, Load Cell Replacement, Rib Extensions
5	1	Rib Extension Guide
6	6	Screw
7	2	Screw
8	2	Screw
9	5	Screw
10	6	Screw
11	1	Rib Extension Shaft
12	6	Needle Roller Bearing
13	12	Rib Extension Spacer
14	1	Rib Extension Cover
15	8	Screw

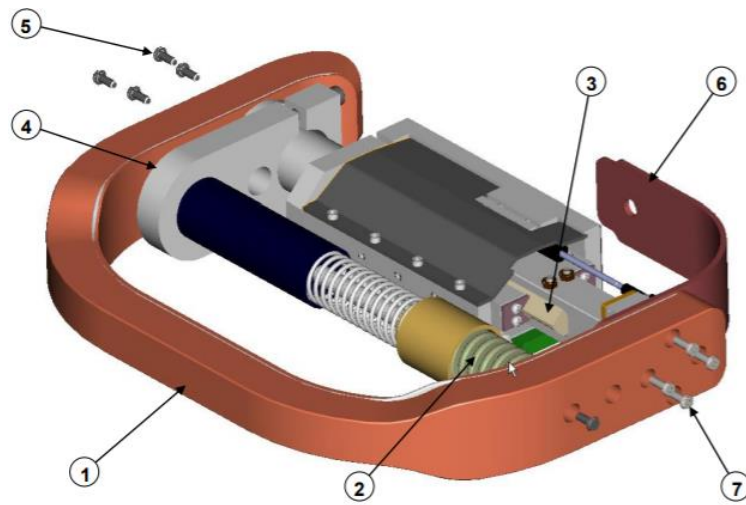


Figure B.4. ES-2 Exploded Rib Unit Assembly [30]

Table B.4 ES-2 Exploded Rib Unit Parts List [30]

Item	Quantity	Description
1	1	Rib Assembly
2	3	Damper Spring Locator
3	1	Rib Rail Assembly
4	1	Damper Spring Assembly
5	5	Screw
6	1	Rib Extension Rear Bracket
7	4	Screw

d. WorldSID 50th Percentile Male Side Dummy

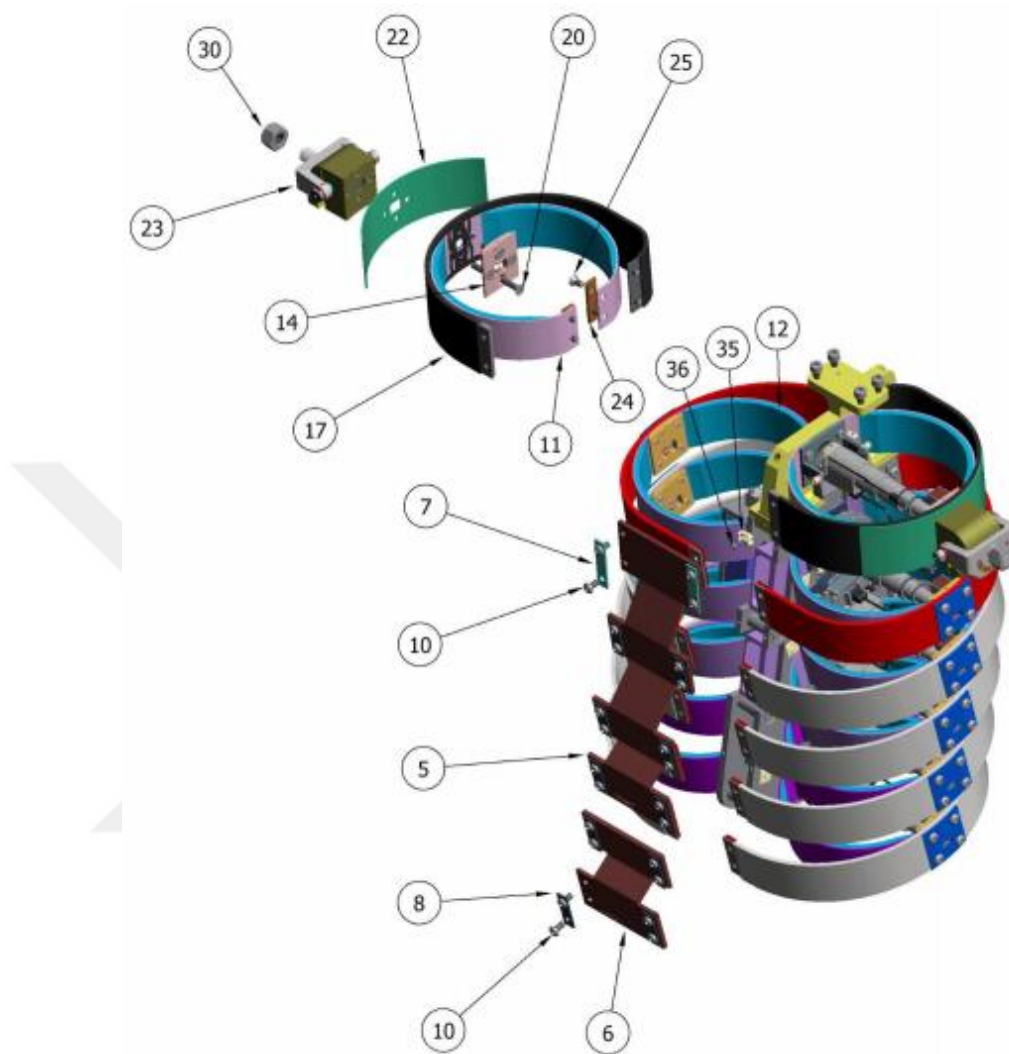


Figure B.5. WorldSID 50th Percentile Male Exploded Thorax Assembly [31]

Table B.5 WorldSID 50th Percentile Male Exploded Thorax Parts List [31]

Item	Quantity	Description
5	1	STERNUM, THORAX RIB
6	1	RIB COUPLER, ABDOMINAL
7	2	SHOULDER RIB STERNUM MOUNTING STRIP
8	10	THORAX AND ABDOMINAL RIB STERNUM MOUNTING STRIP
10	24	SCREW
11	2	SHOULDER RIB ASSEMBLY, INNER BAND
12	6	THORAX RIB ASSEMBLY, INNER BAND
14	2	SHOULDER RIB MOUNTING BRACKET
17	2	RIB ASSEMBLY, SHOULDER
20	8	SCREW
22	2	RIB DOUBLER, SHOULDER
23	2	SHOULDER ASSEMBLY, L.C. STRUCTURAL
24	12	CLAMP, DAMPING
25	24	SCREW
30	2	NUT
35	1	CABLE TIE MOUNT, #4 SCREW
36	1	SCREW

e. SID-IIs Side Dummy

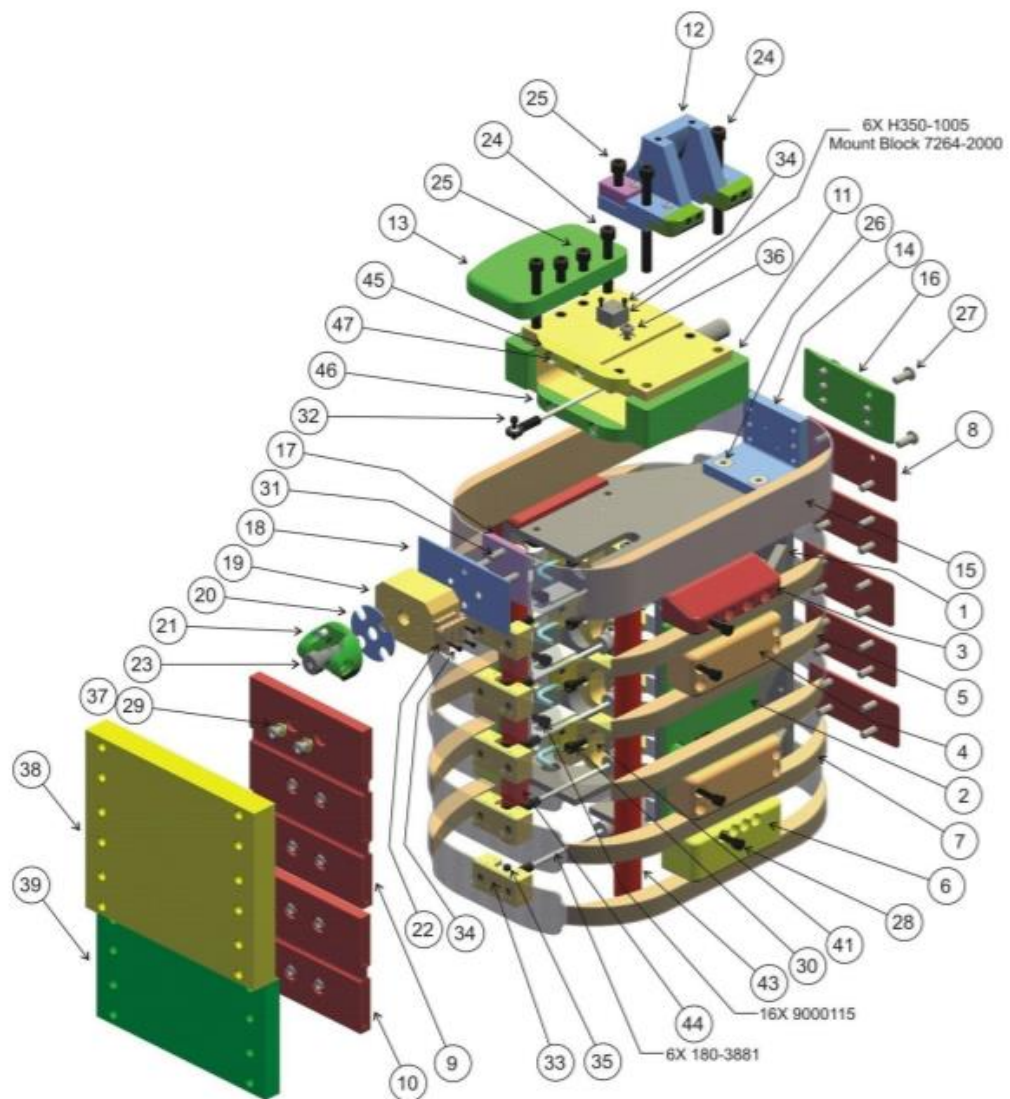


Figure B.6. SID IIs Exploded Thorax Assembly [32]

Table B.6 SID IIs Exploded Thorax Parts List [32]

Item	Quantity	Description
1	1	WELDMENT, SPINE BOX
2	2	LOWER RIB PAD-UPPER TORSO
3	2	UPPER RIB STOP-UPPER TORSO
4	4	MIDDLE RIB STOP-UPPER TORSO
5	3	THORAX RIB & DAMPING MATERIAL ASSEMBLY
6	2	LOWER RIB STOP-UPPER TORSO
7	2	ABDOMEN RIB & DAMPING MATERIAL ASSEMBLY
8	5	RIB STIFFENER LOWER
9	1	UPPER BIB-RIBS
10	1	LOWER BIB-RIBS
11	1	NECK MOUNT BLOCK ASSEMBLY
12	1	LOWER HALF NECK ASSEMBLY, LC REPLACEMENT
13	1	STERNUM
14	1	RIB MOUNT, SHOULDER
15	1	SHOULDER RIB & DAMPING MATERIAL ASSEMBLY
16	1	RIB STIFFENER SHOULDER
17	1	LINEAR POT HOOK SHOULDER RIB
18	1	SHOULDER RIB STIFFENER
19	1	SHOULDER LOADCELL SIMULATOR, ASSEMBLY
20	1	WASHER-SHOULDER
21	1	SHOULDER YOKE ASSEMBLY
22	1	ACCEL MOUNT SHOULDER LOAD CELL
23-32	96	SCREWS
33	5	LINEAR POT HOOK ASSY-LOWER RIBS, ENHANCED
34-35	20	SCREWS
36	10	LINEAR POT BEARING PIVOT SCREW, MODIFIED
37	10	WASHER, #10 LOCK SPRING
38	1	THORAX PAD, SID-IIs
39	1	ABDOMINAL PAD, SID-IIs
40	1	CHEST JACKET SIDIIS
41	4	LINEAR POT FRAME ASS'Y
42	10	CABLE TIE, 7.4 INCH
43-44	2	RIB STOP ASSEMBLY, A & B
45-46	2	UPPER & LOWER SHOULDER RIB STOP
47	4	SCREW

C. Injury Criteria in Detail

The definition and formulation of the injury criteria that are referred in this study are summarized below.

a. Head Injury Criteria

HIC is the “Head Injury Criterion” and it is calculated with Equation C.1 [38] by using the acceleration time histories measured during the tests.

$$HIC = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a \, dt \right]^{2.5} (t_2 - t_1) \quad (C.1)$$

where:

a is the resultant acceleration measured in units of gravity "g"

" t_1 " and " t_2 " are the two time instants (expressed in seconds) during the impact, defining an interval between the beginning and the end of the recording period for which the value of HIC is the maximum. HIC_{15} is the head injury criterion where this time period is limited to 15 ms and HIC_{36} is the head injury criterion where this time period is limited to 36 ms.

b. Thorax Injury Criteria

Three of the Thorax Injury Criteria that are most commonly used in side impact tests are given as follows:

- i. “Rib Deflection Criterion (RDC)” is the maximum value of deflection on any rib as determined by the thorax displacement transducers [56].
- ii. “Viscous Criterion (VC)” is also known as “Soft Tissue Criterion” and it is the instantaneous product of the compression (D) and the rate of deflection (dD/dt) of

the rib as given in Equation C.2 [56]. “0,14” in the formula represents the half width of the ES-2 chest, measured at the metal ribs.

$$VC = \max \left(\frac{D}{0.14} \cdot \frac{dD}{dt} \right) \quad (C.2)$$

iii. “Thoracic Trauma Index (TTI)” is calculated by using the greater of the peak accelerations of either the upper or lower rib, expressed in g’s (GR) and the lower spine “T12” peak acceleration, expressed in g’s (GLS) as given in Equation C.3 [57].

$$TTI (d) = \frac{1}{2} (GR + GLS) \quad (C.3)$$

D. Inertia Elements in FEA of Pendulum Tests for Biofidelity Validation

“Inertia Element” option in LS Dyna has been used to include the effects of the masses and inertias of the particular parts in the FEM of ThImp-PED in FEA of biofidelity validation pendulum tests as defined in Section 4.2.2.

2 inertia elements (i.e. Inertia Element-1 and Inertia Element-2) have been created at defined distances (i.e. d_1 and d_2) from the top and bottom of ThImp-PED as shown with red circles in Figure D.2. “Inertia Element-1” represents the mass and inertia of head, neck and arms parts. “Inertia Element-2” represents the mass and inertia of abdomen, pelvis, legs and feet parts. Mass and inertia values have been calculated and assigned to each of these inertia elements accordingly.

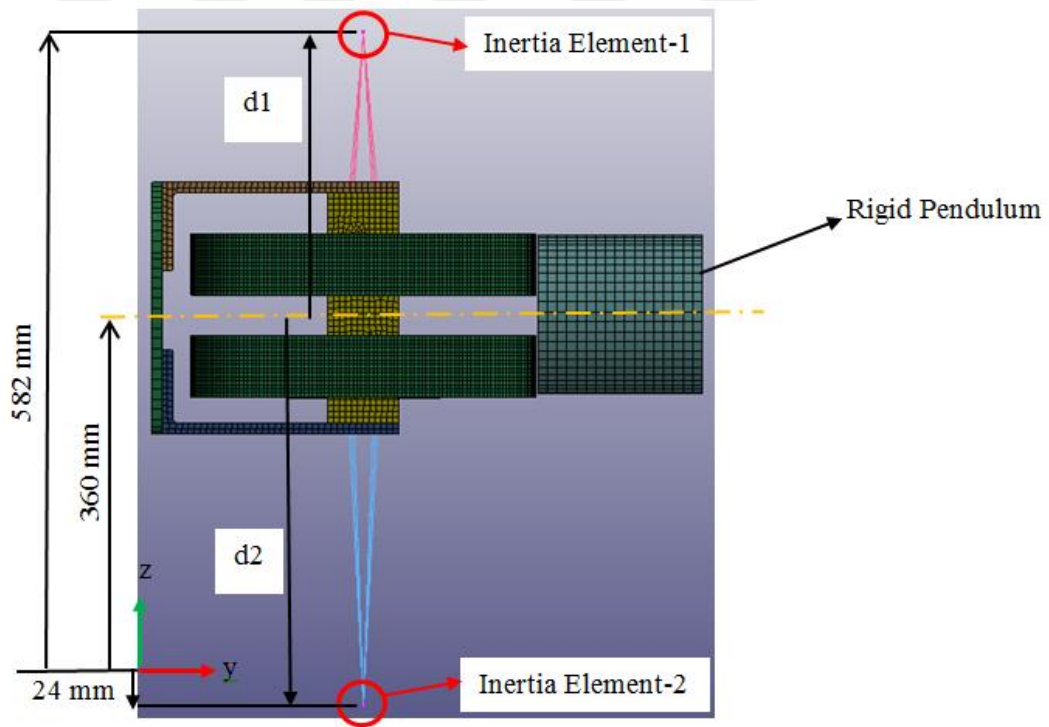


Figure D.1. Inertia Elements in FEA of Pendulum Tests for Biofidelity Validation

To determine the d1 value and mass and inertia values of “Inertia Element-1”, related parts of the ES-2 dummy FEM (i.e. ES-2 Upper FEM) have been used. ES-2 Upper FEM consisting of the head, neck and arms parts is shown in Figure D.2.

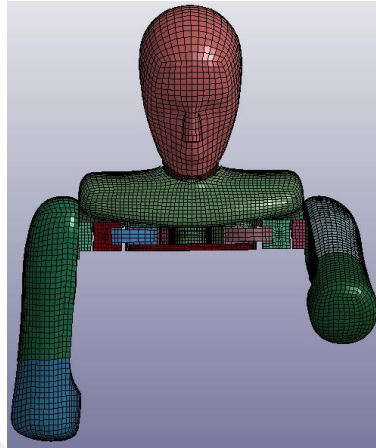


Figure D.2. FEM of Head, Neck and Arms Parts of ES-2 Dummy [65]

Total mass, cog in the z direction (cog z) and inertia values of the part group shown in Figure D.2 have been calculated by LS Dyna and given in Table D.1.

Table D.1 Mass, Cog and Inertia Values of ES-2 Upper FEM

Mass (kg)	8
Cog z	582
Ixx (kg.mm ²)	375274
Iyy (kg.mm ²)	316124
Izz (kg.mm ²)	207876
Ixy (kg.mm ²)	-32364
Iyz (kg.mm ²)	-22971
Ixz (kg.mm ²)	-21402

“d1” value has been calculated as 222 mm by taking the difference of the cog z values of ThImp-PED and ES-2 upper FEM.

To determine the d2 value and mass and inertia values of “Inertia Element-2”, related parts of the ES-2 dummy FEM (i.e. ES-2 Lower FEM) has been used. ES-2

Lower FEM consisting of the abdomen, pelvis, legs and feet parts is shown in Figure D.3.

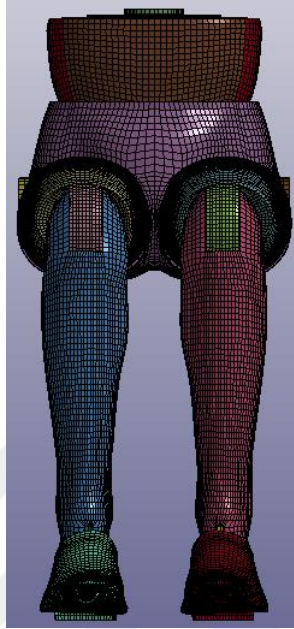


Figure D.3. FEM of Abdomen, Pelvis, Legs and Feet Parts of ES-2 Dummy [65]

Total mass, cog and inertia values of the part group shown in Figure D.3 have been calculated by LS Dyna and given in Table D.2Table D.1.

Table D.2 Mass, Cog and Inertia Values of ES-2 Lower FEM

Mass (kg)	48
Cog z	-24
Ixx (kg.mm ²)	1,89 10 ⁶
Iyy (kg.mm ²)	3,16 10 ⁶
Izz (kg.mm ²)	2,02 10 ⁶
Ixy (kg.mm ²)	-77,08
Iyz (kg.mm ²)	46,25
Ixz (kg.mm ²)	1,07 10 ⁶

“d2” value has been calculated as 384 mm by taking the difference of cog z values of ThImp-PED and ES-2 upper FEM.

E. FEA Results in Terms of Stresses and Strains in Pendulum Tests for Biofidelity Validation

The upper rib and the lower rib are considered as the critical parts since they are directly impacted by the pendulum and/or the vehicle front. During the FEA of pendulum tests for biofidelity validation, the stresses and strains observed on these critical parts of ThImp-PED assembly have been evaluated. The distribution of the Von Mises stress values at time 17,5 ms, when maximum stress is observed, is given in Figure E.4 for the upper and lower ribs in the 4,3 m/s pendulum test. The Yield Stress of AISI 1070, which is the material of the ribs, is 500 MPa as given in Section 4.1.2. The von Mises Stress values are below the Yield Strength of the material through the majority of the ribs. However, the maximum stress slightly exceeds the Yield Strength in a very limited zone for a short duration. The maximum von Mises stress around the fastener holes is 535,5 MPa and it can be interpreted that stress concentration around the holes is the reason for the high stress values. Plastic strain distribution is given in Figure E.5. No plastic strains have been observed on the ribs except that particular region.

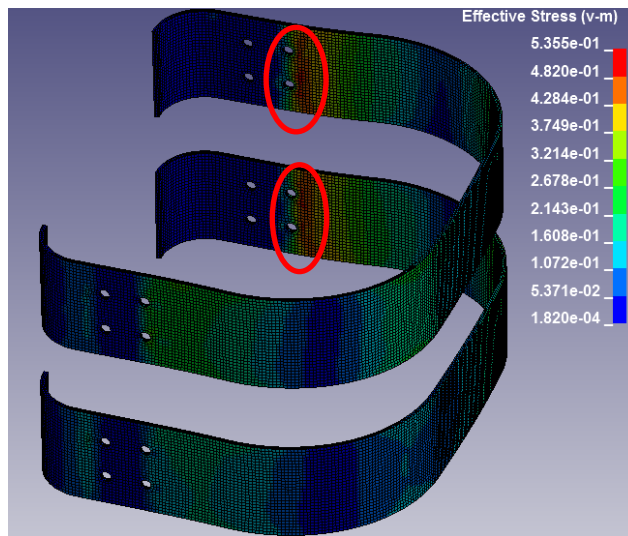


Figure E.4. Upper & Lower Ribs von Mises Stress Distribution in 4,3 m/s Test

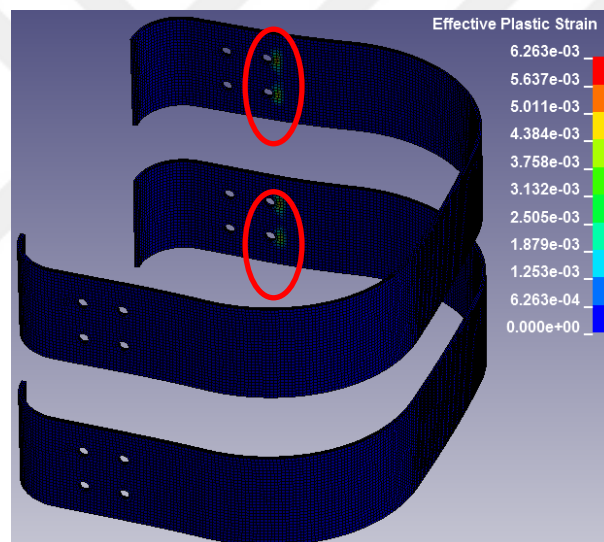


Figure E.5. Upper & Lower Ribs Plastic Strain Distribution in 4,3 m/s Test

The distribution of the Von Mises stress values at time 15,0 ms, when maximum stress is observed, is given in Figure E.6 for the upper and lower ribs in the 5,5 m/s pendulum test. The von Mises Stress values are below the Yield Strength of the material through the majority of the ribs. However, the maximum stress exceeds the Yield Strength in a very limited zone for a short duration. The maximum von

Mises Stress around the fastener holes is 594,8 MPa and it can be interpreted that stress concentration around the holes is the reason for the high stress values. Plastic strain distribution is given in Figure E.7. No plastic strains have been observed throughout the ribs except that particular zone.

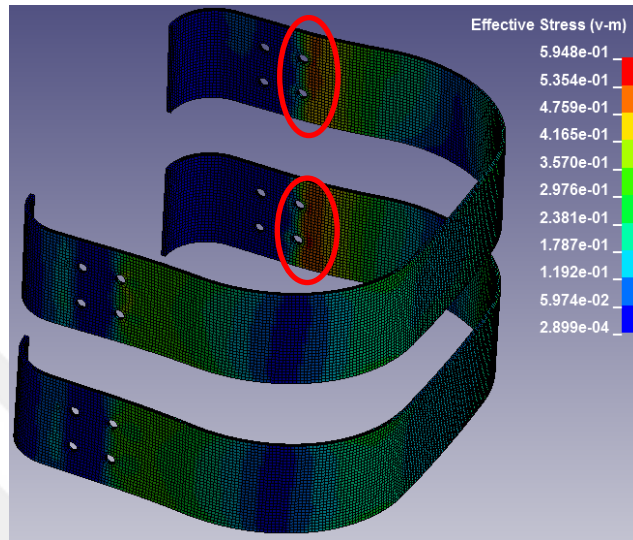


Figure E.6. Upper & Lower Ribs von Mises Stress Distribution in 5,5 m/s Test

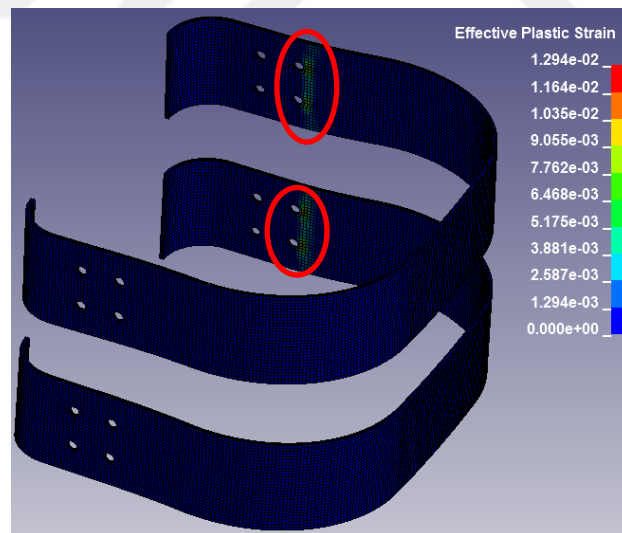


Figure E.7. Upper & Lower Ribs Plastic Strain Distribution in 5,5 m/s Test

F. Instructions Document for the Proposed Novel Test Procedure

The following steps will be applied:

1. Test Specimen Preparation

1.1. The test specimen may be a full vehicle or a vehicle front that is prepared for the tests. The test specimen should include all parts of the vehicle front structure that may be involved in an impact with a pedestrian to demonstrate the performance and interactions of all the related vehicle components.

1.2. When a full vehicle is the test specimen, the vehicle should be at rest on a flat horizontal surface with the parking brake applied.

- a. The vehicle attitude should be in running order positioned on the ground
- b. The tyres should be inflated to the recommended pressures
- c. The suspension should be set for a driving speed of 40km/h in normal running conditions specified by the manufacturer
- d. The front wheels should be in the straight-ahead position
- e. The vehicle should be equipped with all standard equipment as provided by the vehicle manufacturer.

1.3. When a vehicle front is the test specimen, it should be secured firmly to the floor of the test laboratory. The height of the vehicle front with respect to the ground should be specified by the manufacturer of the test specimen by considering the parameters and values defined in “a-e” steps given above for the full vehicle case.

1.4. The vehicle’s reference system is given in Figure F.. In the figure, yz plane represents the “vertical transverse plane” of the vehicle and xz plane represents the “vertical longitudinal plane” of the vehicle. The test specimen should be positioned

with respect to the test system such that its vertical transverse plane is perpendicular to the impactor axis within $\pm 2^\circ$.

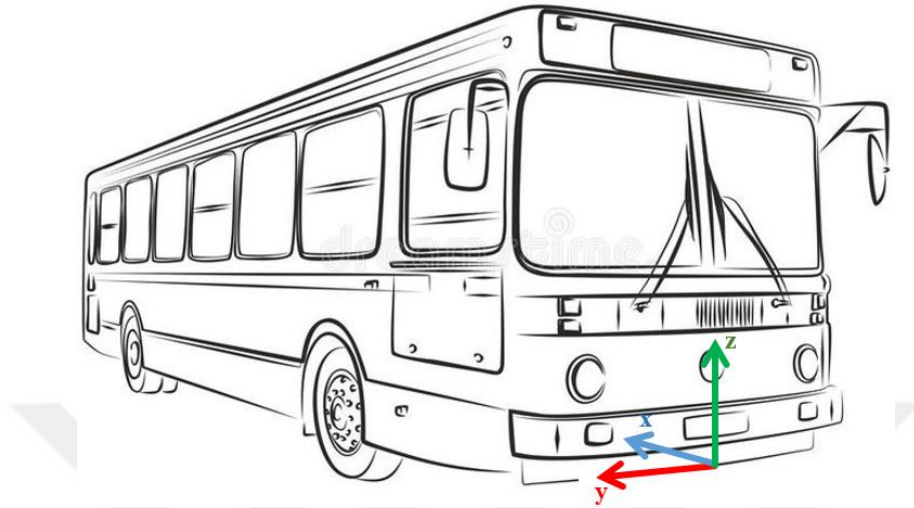


Figure F.1. Vehicle Reference System

2. Marking of Test Specimen

2.1. Determine the lower boundary of the impact zone by taking the projection of the “rib cage height” of a 50th percentile male, which is 111,9 cm, on the test specimen from the ground.

2.2. Determine the upper boundary of the impact zone by taking the projection of the “shoulder height” of a 50th percentile male, which is 143,9 cm, on the test specimen from the ground.

2.3. Mark these boundaries on the vehicle front from the leftmost to the rightmost of the vehicle.

2.4. Investigate then this area (i.e. impact zone) in terms of parts, geometries and materials.

2.5. Mark at least one set of impact points corresponding to the upper and lower rib impact locations on each region (i.e. test zone) that is different from its

surroundings in terms of geometries and materials within the impact zone. During the marking, use trackers and give a unique name to each impact point. The impact point names should be “U1” and “L1” for the first test where “U1” represents the upper rib impact point and “L1” represents the lower rib impact point. The impact point names for the following tests should be “U2”, “L2”, “U3”, “L3” and so on.

3. Impactor Specifications and Certification of the Impactor

3.1. Use ThImp-PED as the impactor.

3.2. Perform thorax pendulum tests at 5,5 m/s by using the parts of a 50th percentile HIII dummy for the certification of ThImp-PED.

3.3. Certify ThImp-PED after a test in case damage is observed and parts of the impactor need to be replaced.

3.4. Additionally, perform periodical certification after every 10 tests.

4. Definition of Test Conditions

4.1. Perform the tests with a test system having a launcher.

4.2. Mount the impactor on the launcher of the test system and launch to the test specimen.

4.3. At the time of testing, the test facility where the test system is located shall have a stabilized temperature of $20\text{ °C} \pm 4\text{ °C}$ and relative humidity of $40\% \pm 30\%$.

4.4. The test site floor shall be flat, smooth and hard surface with a slope not exceeding 1%.

4.5. The direction of the impact velocity vector shall be parallel to the horizontal plane within ± 2 degrees and it should be parallel to the vertical longitudinal plane of the vehicle within ± 2 degrees.

4.6. Flight distance of the impactor should be between 600 mm to 700 mm measured between the first contact points on the impactor and the impact points on the test specimen prior to impact.

4.7. Impact velocity is $40 \text{ km/h} \pm 0,7 \text{ km/h}$ ($11,1 \text{ m/s} \pm 0,2 \text{ m/s}$) and it should be measured with a measuring system such as a laser speed trap sensor at a location just prior to first contact of the impactor with the impact points.

5. Performing the Tests

5.1. Ensure that the the test specimen is prepared and the impact points are marked on the test zone.

5.2. Take detailed photographs of the test specimen and the related impact points from different angles before each test.

5.3. Position at least 2 high speed cameras to record the test. One of the camera views (i.e. the general view) should be taken from the side. It should include the trajectory of the impactor starting from the time at it leaves the test system to the time it hits the test specimen. The second camera view (i.e. the detail view) should be taken either from the side or from the top. It should include a close view of the moment that the impactor hits the test specimen. The cameras should record at least 500 frames per second (fps).

5.4. Mark the impact points on ThImp-PED that are expected to make the first contact with the test specimen with trackers. Apply coloured paint on these trackers to check if there is any deviation from the target impact points after the test.

5.5. Launch ThImp-PED to each impact point with an impact velocity of $40 \text{ km/h} \pm 0,7 \text{ km/h}$. Measure the impact velocity with a measuring system such as a laser speed trap sensor at a location just prior to first contact of the impactor with the test specimen.

5.6. Measure the rib deflections by using the linear potentiometers mounted on the upper and lower rib sets and they should be recorded by using the DAS.

5.7. Take detailed photographs of the test specimen and the related impact points from different angles after each test. The photographs should include detailed views of the damaged or deformed parts on the test specimen.

5.8. Examine the impactor visually after each test to see if any damage occurred on its parts during or after the impact.

5.9. Remove the flesh representing foams and replace with new sheets so that each test is performed with a new set of foams.

6. Evaluation of Test Results and Assessment of Injury Criterion

6.1. Examine the high speed videos that are taken during the test, impact speed measurement and rib deflections that are recorded by the DAS in detail to evaluate the test results.

6.2. Check from the high speed videos if the impactor hits the target impact point in the target position and with the target angle.

6.3. Check the impact velocity measurement and verify that it is $40 \text{ km/h} \pm 0,7 \text{ km/h}$.

6.4. Filter the rib deflections for the upper and lower ribs with CFC 180 and check if the Rib Deflection Criterion (RDC) is less than or equal to 42 mm. RDC is the maximum of the rib deflections measured from the upper and lower rib sets.

G. Linear Impactor Test System in METU-BILTIR Center

The Linear Impactor Test System in METU-BILTIR Center has been shown in Figure 6.4 and some technical data are given in Table G.3.

Table G.3 Some Technical Data of the Linear Impactor Test System in METU-BILTIR Center

Power	Solely electrically driven
Acceleration	Up to 120 m/s ²
Speed	Up to 42,0 km/h
Speed Accuracy	± 0,1 km/h
Repeatability	± 0,1 km/h
Targeting Precision	Within a radius of 5 mm
Max. Impactor Mass at 42,0 km/h	13,5 kg at +5 ⁰ vertical

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