MARMARA UNIVERSITY
FACULTY OF ENGINEERING

KINEMATIC AND DYNAMIC STRUCTURAL ANALYSES OF AN EXOSKELETON STRUCTURE DESIGNED FOR INCREASING THE LOAD BEARİNG CAPACITY OF AN AVERAGE SOLDİER

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GRADUATION PROJECT REPORT

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ISTANBUL, 2020

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by

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July 8, 2020, Istanbul

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

OF

BACHELOR OF SCIENCE

AT

MARMARA UNIVERSITY

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ACKNOWLEDGEMENT

First of all, I would like to thank my supervisor Res. Asst. PhD Ömer Haluk Bayraktar, for the valuable guidance and advice on preparing this thesis and giving me moral and material support.

July, 2020 Sinan Özcan

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ABSTRACT

Kinematic And Dynamic Structural Analyses Of An Exoskeleton Structure Designed For Increasing The Load Bearing Capacity Of An Average Soldier

Exoskeleton is a wearable device that used in many different areas, facilitating the movement and increasing the mobility of the human body. In this study, the exoskeleton design made for military use was made to support the joints with actuators to increase the load bearing capacity and less fatigue of the soldier. Solidworks were used for the design. The torque values required for actuators to support the joints were calculated by analytical method firstly. Afterwards, Gait Analysis was studied to simulate human walking analysis, and by using this study, human walking was simulated in MATLAB/Simmechanics. In order to select the right material for this Gait Analysis, dynamic and static analyzes were carried out using ANSYS. In the actuator selection, FHA-25C model actuator for the hip, FHA-17C model actuator for the knee and FHA-25C model actuator for the ankle were considered suitable. In the material selection, Low Alloy Steel (4140) was considered suitable by keeping the high safety factor criterion in the foreground.

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1. INTRODUCTION

Exoskeleton is a wearable device that used in many different areas, facilitating the movement and increasing the mobility of the human body. It supports shoulders, back, thigh, waist, shinbone, thighbone and ankle. That suit aims assist walking, runnin, carrying heavy backpacks and lifting heavy loads.

Exoskeletons has more than 100 years of historical background. First known exoskeleton developed by Russian engineer Nicolas Yagin in 1889. But until the 2000s, despite many attempts, the exoskeletons could not be designed and manufactured efficiently. These exoskeletons were heavy and bulky.

1.1 Literature Review

Shaari N. L. A., Isa I. S. And Jun T. C. (2015,), their article titled Torque Analysis of the Lower Limb Exoskeleton Robot Design, is the study of choosing the appropriate electric actuator for an exoskeleton robot. In this study, DC servomotor, linear actuator and series elastic actuator were compared for actuator selection and DC servomotor was selected. Range of motion, more compact size and less prone to wear to the other alternatives of DC servomotor are stated as the reason for selection.

	DC Servomotor	Linear Actuator	Series Elastic Actuator
Advantages	-Compact -Easy To Control- -Accurate Positioning -High Energy Efficiency -Silent -Can Be Coupled With Drives To Produce High Torque	-Cheap -High Load Capability	-Low Impedance -Accurate Force Feedback -Shock Tolerance -Energy Storage
Disadvantages	-Expensive -Size Could Be Large	-Large And Bulky -Wear And Tear Of The Ball Screw(Friction)	-Bulky -Custom Built, Not Available On Market
Range Of Motion	Wide	Limited by the length of leadscrew	Limited by the length of leadscrew

Table 1 : The Comparison Between Actuator Types[1]

Harmonic drive, chain drive and cable-pulley drive comparisons were made for the drive system selection and harmonic drive was selected. Most compact size, possess high accuracy and high reduction capability to the other alternatives of harmonic drive are stated as the reason for selection.

	Harmonic Drive	Chain Drive	Cable-Pulley Drive
Features	-short distance power transmission -speed reduction	-transmit power over long distance -speed reduction	-transmit power over long distance -speed reduction
Advantages	-compact -no backlash -excellent positional accuracy -high reduction ratio	-simple to use -any length can be achieved	-no backlash -no friction
Disadvantages	-expensive	-takes space	-limited range of motion -takes space

Table 2 : The Comparison Between Drive Types[1]

In material selection, aluminum was chosen as the main material and Duralumin (Aluminum 2024), Aluminum 7075 and Prosthetic Aluminum (Aluminum 7068) were compared. The Prosthetic Aluminum (Aluminum 7068) selection was deemed suitable, but Aluminum 7075 was chosen due to Aluminum 7068's low availability. Aluminum 7075 has high availability but it has lower yield strength as well as density.

	Duralumin (Aluminium 2024)	Aluminium 7075	Prosthetic Aluminium (Aluminium 7068)
Yield strength (MPa)	393	503	683
Density (g/cc)	2.77	2.80	2.85
Machinability	High	Medium	Medium
Availability	High	High	Low

Table 3 : The Comparison Between Material Types[1]

Kinematic analysis and Denavit-Hartenberg method were used to establish the relationship between joint angles and positions in the exoskeleton.

	Joint	α_{i-1}	a_{i-1}	d_i	θ_i
Hip	1	0	0	0	θ_1
Knee	2	0	l_1	0	θ_2
Ankle	3	0	l_2	0	θ_3

$$x = l_1 c_1 + l_2 c_{12}$$

$$y = l_1 s_1 + l_2 s_{12}$$

$$^{0}_{3}T = \begin{bmatrix} c_{123} & -s_{123} & 0 & l_1 c_1 + l_2 c_{12} \\ s_{123} & c_{123} & 0 & l_1 s_1 + l_2 s_{12} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\theta_2 = \frac{\pm\sqrt{(2l_1 l_2)^2 - [x^2 + y^2 - (l_1^2 + l_2^2)^2]}}{x^2 + y^2 - (l_1^2 + l_2^2)}$$

$$\theta_1 = \tan^{-1}\left(\frac{y}{x}\right) - \tan^{-1}\left(\frac{l_2 s_2}{l_1 + l_2 c_2}\right)$$

Figure 1 : Denavit-Hartenberg Parameters and Position-Joint Angle Equations

The weight and the heigth of the Exoskeleton user considered as 100 kg 1.85 m. Joint torque values were calculated. The calculated required hip joint torque was 47.56 N.m, knee joint torque was 21.68 N.m, and ankle joint torque was 2.10 N.m.

According to these values, actuator motors and reducers are selected as follows;

	Hip	Knee	Ankle
Model	MAXON EC90 FLAT	MAXON EC60 FLAT	MAXON EC45 FLAT
Voltage	36V	24V	24V
Weight	600g	471g	141g
Max. Continuous Torque	560mNm	289mNm	128mNm

	Hip	Knee	Ankle
Model	HARMONIC DRIVE CSD-25-100	HARMONIC DRIVE CSD-17-100	HARMONIC DRIVE CSD-14-100
Weight	240g	100g	60g
Reduction Ratio	100:1	100:1	100:1

Table 4 : Selected Actuator Motors and Reducers Specifications

These selected actuators with selected reducers produce maximum torque as 56 N.m, 28.9 N.m and 12.8 N.m, respectively.

The design was made with CAD program Solidworks. Exoskeleton is designed for maximum 100 kg weight and for 1.85 m length. The linls for all limbs are connected by joints. Link weights with actuators are total 6.44 kg.

Figure 2 : The Designed Exoskeleton

Motion analysis is simulated using Solidworks Motion Analysis and the results are discussed. For one leg swing motion, it was observed that there was maximum 21.32 N.m torque for the hip joint, maximum 9.39 N.m torque for the knee joint and maximum 1.21 N.m torque for the ankle joint. All of these values are lower than the maximum torque values that the selected actuators can provide. For two complete cycle walking motion, the hip and knee joint torque values are maximum 130 N.m and 42 N.m, respectively. These actuators need to be overdriven. The torque value for ankle joint is maximum 4 N.m and the selected actuator is suitable.

In the 2000s, there was a breakthrough in the DARPA's Exoskeletons for Human Performance Augmentation Program with Dr. John Main's lead. DARPA started its first project with Sarcos Research Corporation, University of California, Berkeley, and the Oak Ridge National Laboratory. In the second phase of the program, DARPA worked with University of California, Berkeley and Sarcos Research Corporation; in the final phase of the program worked with Sarcos Research Corporation for fast movement, light weight and efficiency. [2]

In May 2013, DARPA announced a new exoskeleton project called TALOS. TALOS served as and armor suit as well as helping physical movements and carrying heavy loads. It designed to be bulletproof, resistant to shrapnel and weaponized. Many prototypes were built in the 5 years, but these prototypes were not suitable and effective for combat scenarios. At the end of 5 years, the project evolved into another defense system research project.

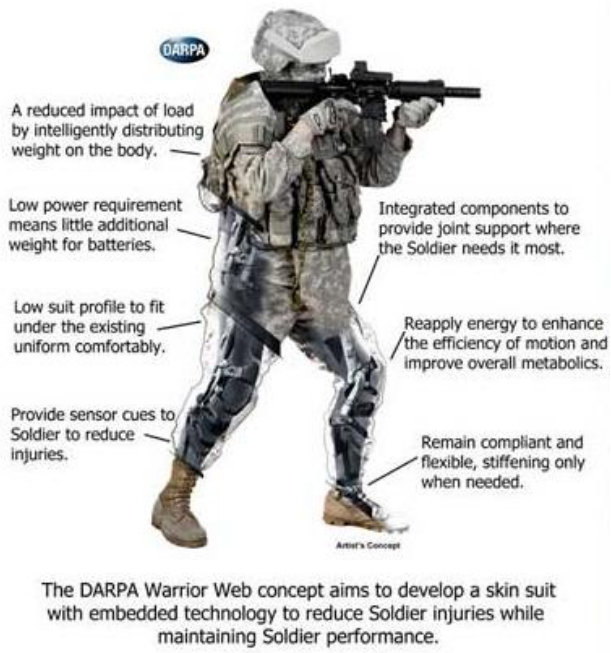


Figure 3 :The TALOS Developed by DARPA

Onyx is a reinforced lower body exoskeleton with artificial intelligence technology that supports the physical strength and endurance of soldiers. This exoskeleton damps and compansates overstress in the legs and back with electro-mechanical actuators, sensors and artificial intelligence computers. Onyx's artificial intelligence learns to give the right torque at the right time form soldier's movements and applies the appropriate torque when walking up on hills, in rough road conditions and lifting heavy loads. An independent study at the University of Michigan has confirmed that Onyx users spend less energy on hill climbing with a 40-pound(18.14 kg) backpack. In 2018, Onyx won Best of What New 2018 Award which that Popular Science Magazine's Grand Award in the Security category.[3]

Figure 4 :The Exoskeleton Developed by ONYX - 1

Figure 5 : The Exoskeleton Developed by ONYX - 2

The Human Universal Load Carrier(HULC) is an exoskeleton developed for soldiers by Lockheed Martin. Originally, HULC is an exoskeleton developed by Berkeley Bionics in 2008. In 2009, Lockheed Martin purchased this exoskeleton design lisence from Berkeley. Hydraulically-powered HULC helps soldiers carry heavy backpack loads and reduces stresses on their body. This allows soldiers to lift heavy loads and reduce muscle and skeletal injuries. HULC helps soldiers to carry backpack loads up to 91 kg. The weight of this load is transmitted to the feets by the exoskeleton, the soldier’s legs and back are less tired and the soldier can easily walk in uneven and rough road conditions. This exoskeleton design is designed for squatting, drifting and weight lifting. Except batteries, HULC’s weight is 24 kg. Although this system is controlled by micro-computer; it can work without any control mechanism.[4]

Figure 6 : The HULC Developed by Lockheed Martin – 1

Figure 7 : The HULC Developed by Lockheed Martin – 2

The first XOS system was developed with Wearable Energetically Autonomous Robot(WEAR) name as a biomechanical robot with Sorcos Research in Salt Lake City, Utah in 2000. The project purchased by Raytheon in 2007. The first prototype(XOS 1) announced in 2008.XOS 2 is a 2nd generation exoskeleton suite developed by Raytheon for the US Army. Raytheon first announced the capabilities of the exoskeleton in 2010. XOS 2 is designed to increase the strength, agility and endurance of the soldier. This exoskeleton is an apparatus for lifting heavy loads using high-pressure hydraulic actuators. The soldier can lift a 17 kg load like as 1 kg. This means that soldiear can lift and carry heavy loads repeatedly without getting tired or injured. XOS 2 is lighter that XOS 1 and works 50% more efficiently. With its controllers, sensors, aluminum and steel material and actuators, it is approximately 95 kg. The flexible hydraulic hoses allow the fluid to move easily and the soldier can easily move, run and crawl.[5]

Figure 8 :The XOS Developed by Raytheon - 1

Figure 9 : The XOS Developed by Raytheon - 2

The Twenty Knots Plus(20 KTS+) has designed a new exoskeleton called Marine Mojo. Marine Mojo is an exoskeleton that absorbs the shocks and vibrations exposed in fast and small water boats. These speedboats which used in military, coast guard and police are higly exposed to shock and vibration, which restricts or prevents soldier's movement in operations. Marine Mojo is designed to avoid these obstacles. It reduces tension and injuries to the legs when standing condition. Marine Mojo is a passive exoskeleton – does not use and contain any electronics, sensors or motors. For this reason, its production and mainenance are very easy and inexpensive. Marine Mojo is approximately only 1 kg.[6] Marine Mojo absorbs 20% of the shock in the lower body that reducing vibration in the body. In adddition, tests at the Chichester University have shown that it improves endurance 3 times and reduces leg muscle strength by 60%.[7]

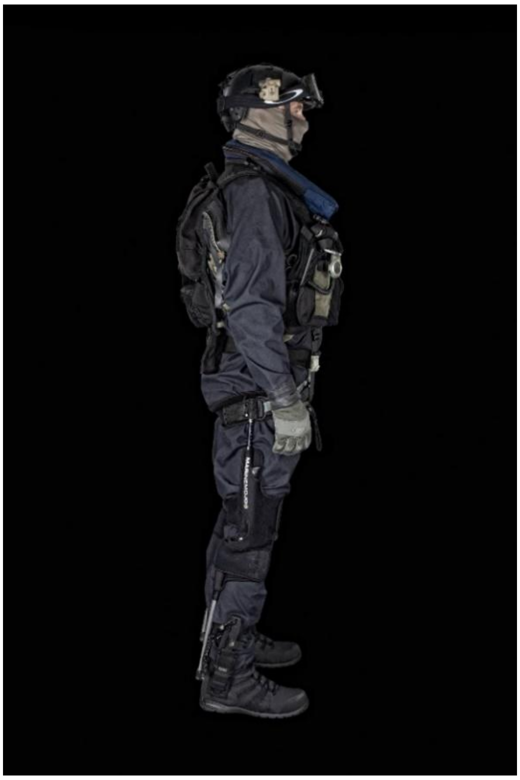


Figure 10 : The Marine Mojo Developed by 20KTS+ - 1 [8]

Figure 11 : The Marine Mojo Developed by 20KTS+ - 2 [8]

OX-Operational Exoskeleton is an innovative soft(non-rigid) exoskeleton design made by the DST Group. Its main purpose is to increase the durability of soldiers by transferring heavy loads to the ground and to reduce the injuries of soldiers. OX is a passive and unpowered exoskeleton. Its weight is approximately 3-4 kg. Because of its light weight, it is easy to carry and wear and remove. Also it has high mobility and it is inexpensive.[9]

Figure 12 :The OX- Operational Exoskeleton Developed by DST Group

PowerWalk Kinetic Energy Harvester is a power collector exoskeleton made by Bionic PowerInc. PowerWalk does not apply and support or force to the limbs. The main purpose of this exoskeleton is to charge rechargeable batteries. The batteries that a soldier must carry in a 72-hour operation for GPS, night vision and communication devies are approximately 16-20 lbs. As the PowerWalk intended, the exoskeleton’s weight can be reduced considerably with small, rechargeable batteries. In this way, the solder can carry less load and can charge the electonic devices.[10] Inherently, PowerWalk generates and stores electricity from the natural movement of walking.[11]

Figure 13 : The PowerWalk Developed by Bionic PowerInc. - 1

Figure 14 : The PowerWalk Developed by Bionic PowerInc. - 2

2. KINEMATIC ANALYSIS

Kinematic analysis allows us to analyze the movements of a body or a robot; calculate position, velocity and acceleration without using the forces providing motion.[12]

In order to control the actuators of the exoskeleton, we need to know the nstantaneous angle values in the joints and the instantaneous positions of the limbs. This can be done by establishing a geometric relationship between angle values and position. This relationship can be made by applying forward kinematic.

2.1 Forward Kinematic

The position analysis of the exoskeleton which made with using the Denavit-Hartenberg method is shown below.

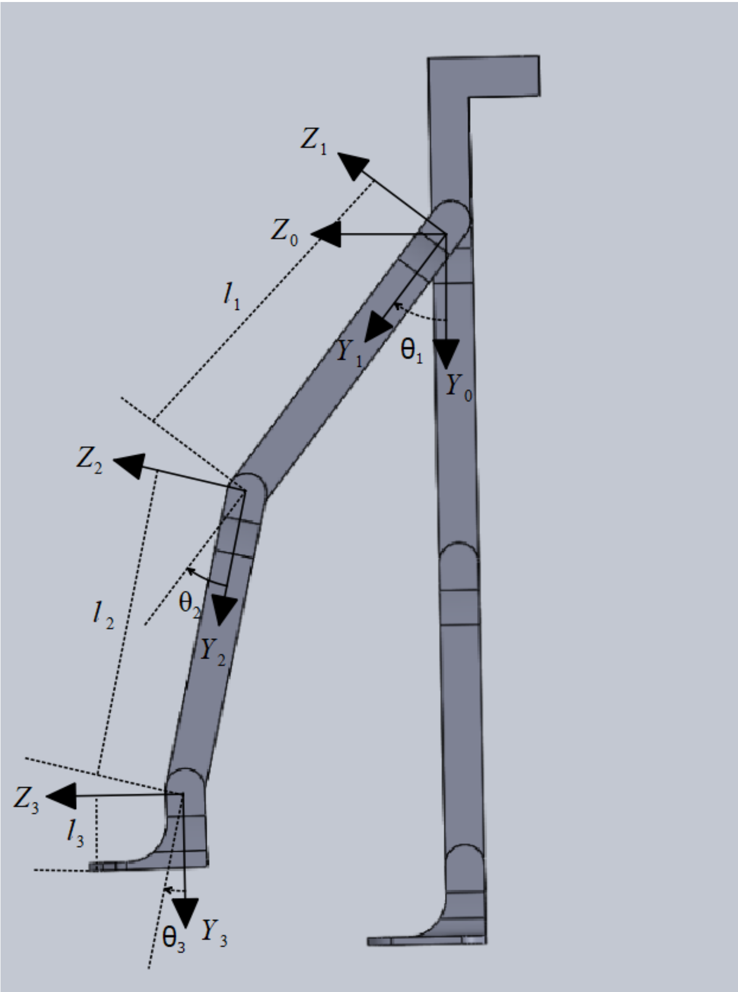


Figure 15 : Free Body Diagram of 3 Link

Denavit-Hartenberg Representation

Link	α_i	a_i	d_i	θ_i
1	0	l_1	0	θ_1
2	0	l_2	0	θ_2
3	0	l_3	0	θ_3

a_i : distance along z_i from O_i to the intersection of the z_i and x_{i-1} axes.

d_i : distance along x_{i-1} from O_{i-1} to the intersection of the z_i and x_{i-1} axes. d_i is variable if joint i is prismatic.

α_i : the angle between x_{i-1} and x_i measured about z_i.

θ_i : the angle between z_{i-1} and z_i measured about x_{i-1}. θ_i is variable if joint i is revolute.

$$H_n^{n-1} = \begin{bmatrix} cos(\theta_n) & -sin(\theta_n)\,cos(\alpha_n) & sin(\theta_n)\,sin(\alpha_n) & a_n\,cos(\theta_n) \\ sin(\theta_n) & cos(\theta_n)\,cos(\alpha_n) & -cos(\theta_n)\,sin(\alpha_n) & a_n\,sin(\theta_n) \\ 0 & sin(\alpha_n) & cos(\alpha_n) & d_n \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$H_1^0 = \begin{bmatrix} cos(\theta_1) & -sin(\theta_1) & 0 & l_1\,cos(\theta_1) \\ sin(\theta_1) & cos(\theta_1) & 0 & l_1\,sin(\theta_1) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$H_2^1 = \begin{bmatrix} cos(\theta_2) & -sin(\theta_2) & 0 & l_2\,cos(\theta_2) \\ sin(\theta_2) & cos(\theta_2) & 0 & l_2\,sin(\theta_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$H_3^2 = \begin{bmatrix} cos(\theta_3) & -sin(\theta_3) & 0 & l_3\,cos(\theta_3) \\ sin(\theta_3) & cos(\theta_3) & 0 & l_3\,sin(\theta_3) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The T matrix for foot joint:

$$T_2^0 = H_1^0 H_2^1 = \begin{bmatrix} cos(\theta_1+\theta_2) & -sin(\theta_1+\theta_2) & 0 & l_1\,cos(\theta_1)+l_2\,cos(\theta_1+\theta_2) \\ sin(\theta_1+\theta_2) & cos(\theta_1+\theta_2) & 0 & l_1\,sin(\theta_1)+l_2\,sin(\theta_1+\theta_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

y = $l_1\,cos(\theta_1)+l_2\,cos(\theta_1+\theta_2)$

z = $l_1\,sin(\theta_1)+l_2\,sin(\theta_1+\theta_2)$

2.2 Inverse Kinematic

Inverse kinematic application for foot joint:

$$\theta_1 = \text{arctan}\left(\frac{z}{y}\right) - \text{arctan}\left(\frac{l_2\,sin(\theta_2)}{l_1+l_2\,cos(\theta_2)}\right)$$

$$\theta_2 = \text{arccos}\left(\frac{y^2+z^2-{l_1}^2-{l_2}^2}{2l_1l_2}\right)$$

The T matrix for soles of foot:

$$T_3^0 = H_1^0 H_2^1 H_3^2 =$$

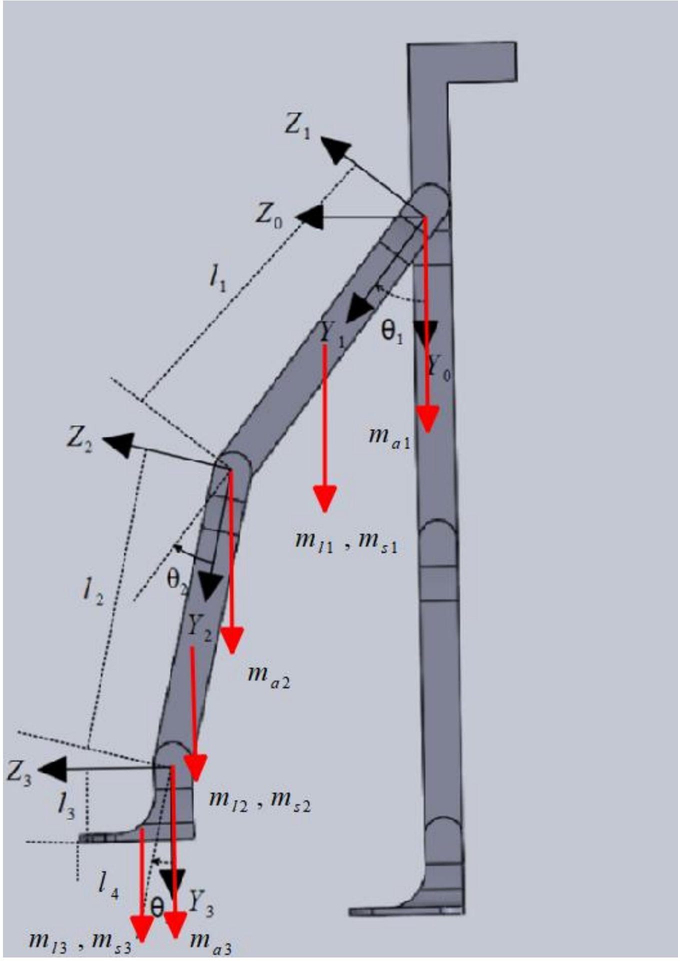
$$\begin{bmatrix} cos(\theta_1+\theta_2+\theta_3) & -sin(\theta_1+\theta_2+\theta_3) & 0 & l_1\,cos(\theta_1)+l_2\,cos(\theta_1+\theta_2)+l_3\,cos(\theta_1+\theta_2+\theta_3) \\ sin(\theta_1+\theta_2+\theta_3) & cos(\theta_1+\theta_2+\theta_3) & 0 & l_1\,sin(\theta_1)+l_2\,sin(\theta_1+\theta_2)+l_3\,sin(\theta_1+\theta_2+\theta_3) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

y = $l_1\,cos(\theta_1)+l_2\,cos(\theta_1+\theta_2)+l_3\,cos(\theta_1+\theta_2+\theta_3)$

z = $l_1\,sin(\theta_1)+l_2\,sin(\theta_1+\theta_2)+l_3\,sin(\theta_1+\theta_2+\theta_3)$

2.3 Joint Torque Equation

The required torque values in the joints can be achieved with the torque formulas below by using the free body diagram shown in the figure below.



m_{a1} : actuator mass at hip joint

m_{a2} :actuator mass at knee joint

m_{a3} :actuator mass at knee joint

m_{l1} : thigh(femur) link mass

m_{l2} : shank(fibula) link mass

m_{l3} : foot link mass

m_{s1} : thigh(femur) mass

m_{s2} : shank(fibula) mass

m_{s3} : foot mass

l_1 : thigh(femur) length

l_2 : shank(fibula) length

l_3 : ankle length

l_4 : foot length

T_1 : Torque required at hip joint

T_2 : Torque required at knee joint

T_3 : Torque required at ankle joint

$$T_1 = (m_{l1} + m_{s1}) \times \sin(\theta_1) \times g \times \left(\frac{l_1}{2}\right) + m_{a2} \times \sin(\theta_1) \times g \times l_1$$

$$+ (m_{l2} + m_{s2}) \times \sin(\theta_1 - \theta_2) \times g \times \left(\frac{l_2}{2}\right) + m_{a3} \times \sin(\theta_1 - \theta_2) \times g \times l_1$$

$$+ (m_{l3} + m_{s3}) \times \sin(\theta_1 - \theta_2 - \theta_3) \times g \times l_3$$

$$+ (m_{l3} + m_{s3}) \times \cos(\theta_1 - \theta_2 - \theta_3) \times g \times \left(\frac{l_4}{3}\right)$$

$$T_2 = (m_{l2} + m_{s2}) \times \sin(\theta_1 - \theta_2) \times \mathrm{g} \times \left(\frac{l_2}{2}\right) + m_{a3} \times \sin(\theta_1 - \theta_2) \times \mathrm{g} \times l_1$$

$$+ (m_{l3} + m_{s3}) \times \sin(\theta_1 - \theta_2 - \theta_3) \times \mathrm{g} \times l_3$$

$$+ (m_{l3} + m_{s3}) \times \cos(\theta_1 - \theta_2 - \theta_3) \times \mathrm{g} \times \left(\frac{l_4}{3}\right)$$

$$T_3 = (m_{l3} + m_{s3}) \times \sin(\theta_1 - \theta_2 - \theta_3) \times \mathrm{g} \times l_3$$

$$+ (m_{l3} + m_{s3}) \times \cos(\theta_1 - \theta_2 - \theta_3) \times \mathrm{g} \times \left(\frac{l_4}{3}\right)$$

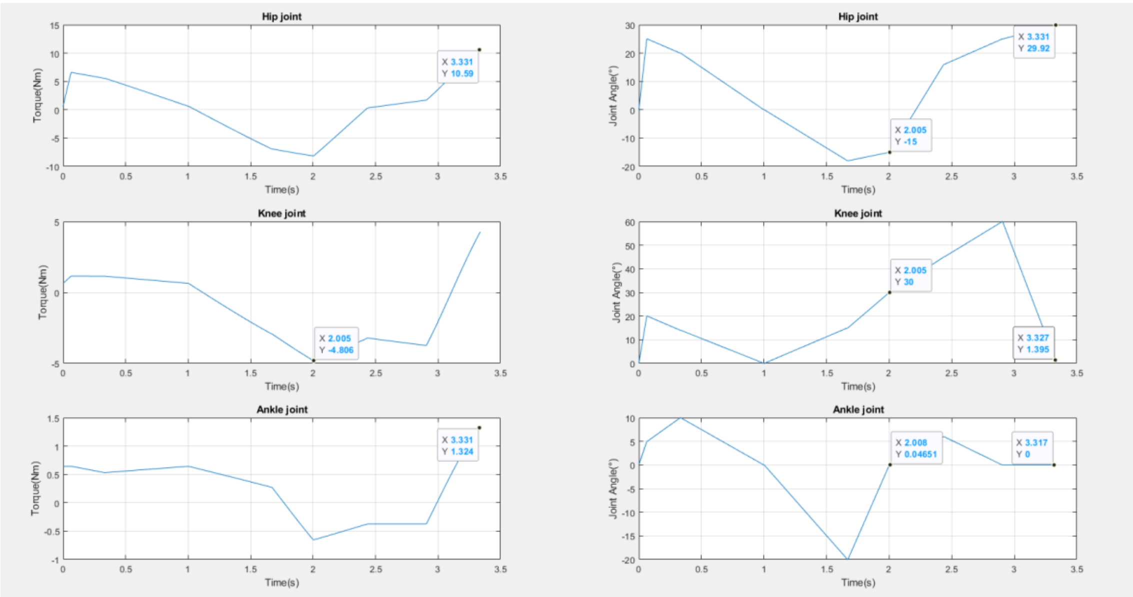


Figure 16 : Torque – Time and Joint Angle - Time Graphics for Hip, Knee and Ankle Joints with Joint Torque Equations (Appendix A)

Torque-time and joint angle-time graphs in kinematic analysis are given above. The maximum torque values for each joint is marked. The maximum required torque value for Hip Joint is 10.59 N.m in 3.33 seconds. The joint angle values of the exoskeleton at this moment are 29.92 ° for Hip, 1.4 ° for Knee and 0 ° for ankle. The maximum required torque value for Knee Joint is 4.81 N.m in 2 seconds. The joint angle values of the exoskeleton at this moment are -15 ° for Hip, 30 ° for Knee and 0 ° for ankle. The maximum required torque value for Ankle Joint is 1.32 N.m in 3.33 seconds. The joint angle values of the exoskeleton at this moment are 29.92 ° for Hip, 1.4 ° for Knee and 0 ° for ankle.

3. MECHANICAL DESIGN OF EXOSKELETON

The design of the exoskeleton was made with CAD program Solidworks. The exoskeleton designed in 7 parts as waist, two upper legs, two lower legs and two feet. It is designed to be a male with a height of 175 cm and a weight of 75 kg; the thighbone(Femur) is 43 cm, the calfbone(Tibia) is 38 cm, and the ankle is 10 cm height.

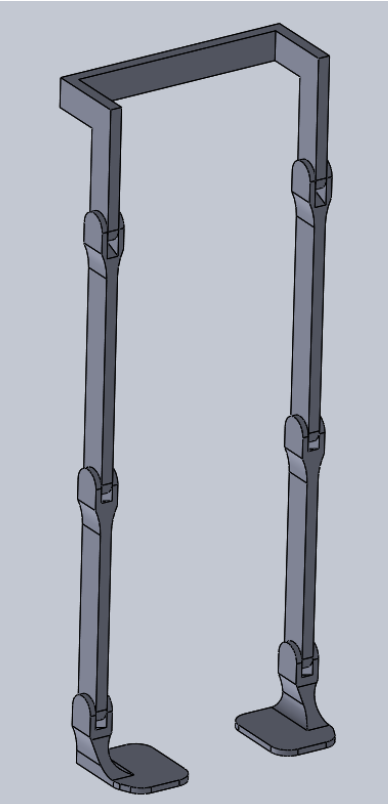


Figure 17 : The Assembly Drawing of the Exoskeleton

Figure 18 : Human Model Used in Design and Designed Exoskeleton

3.1 Waist Design

The waist is designed that the solid can support the pelvic bone. For the revolute movement of the thighbone(Femur) to the part of the pelvis bone that called Femoral Head, joints are designed as shown in the Figure. Because of some difficulties in walking analysis and structural analysis, the design of the waist is simplified.

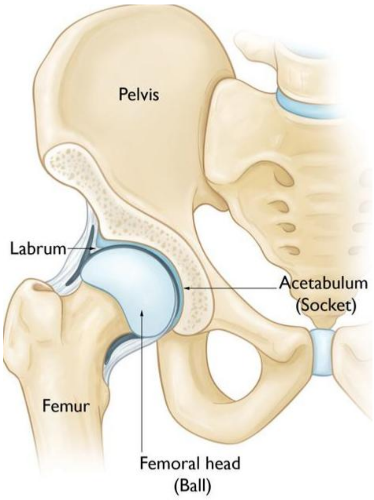


Figure 19 : Pelvis and Femoral Head View [13]

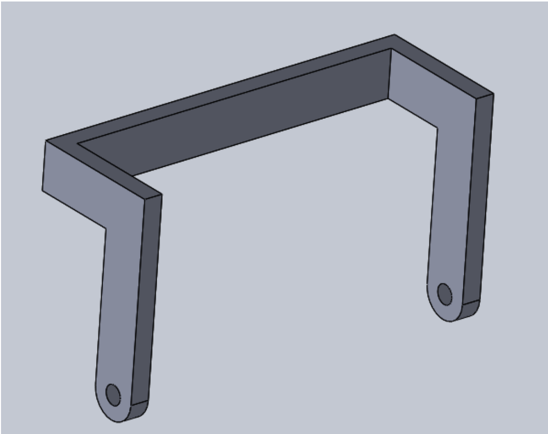


Figure 20 : The Waist Drawing of the Exoskeleton

3.2 Upper Leg Design

The upper leg design is made in accordance with the human anatomy to support the thighbone(femur). For both legs, the joints are designed to fit the upper part of the thighbone(Head) and the lower part of the thighbone(Patella).

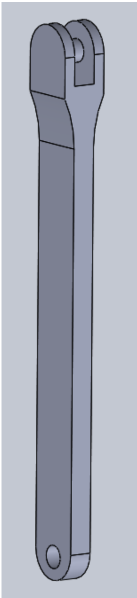


Figure 21 : The Upper Leg Drawing of the Exoskeleton

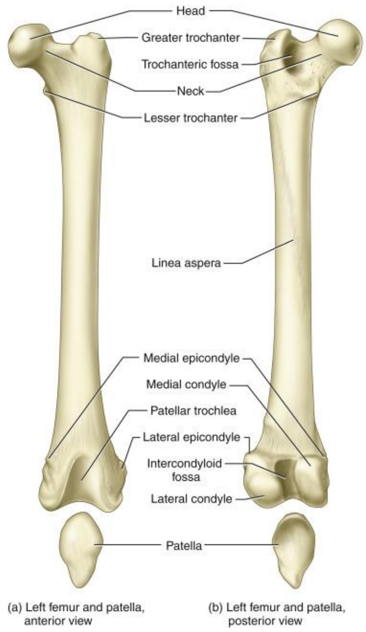


Figure 22 : Femur and Patella Views [14]

3.3 Lower Leg Design

The lower leg design is made to support the shinbone(tibia and fibula) in accordance with the human anatomy. For both legs, the joints were designed to correspond to the the upper part of the shinbone(lateral candyle) and the lower part(medial malleolus).

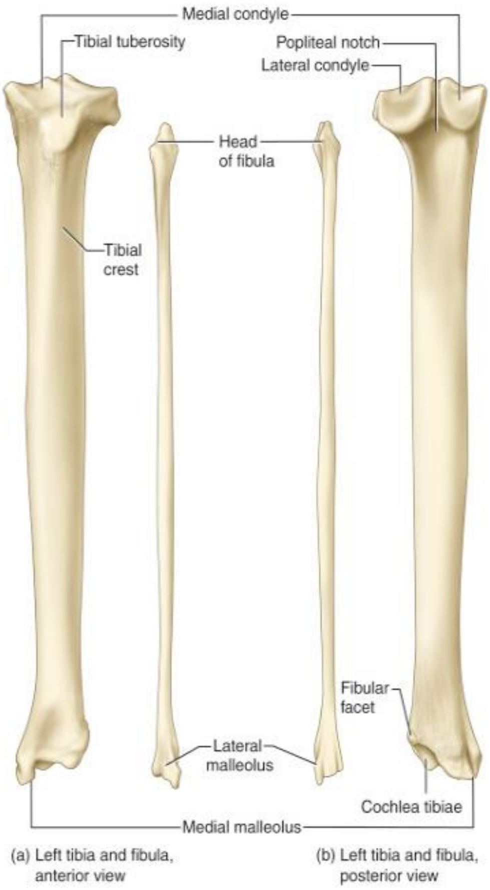


Figure 23 : Fibula and Tibia Views [14]

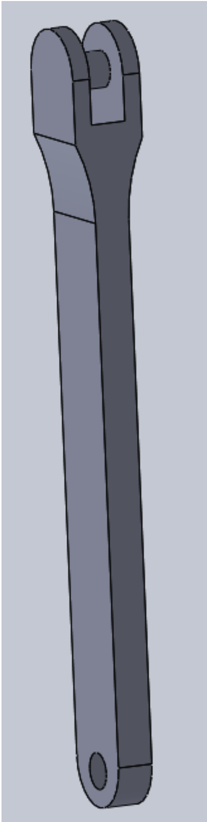


Figure 24 : The Lower Leg Drawing of the Exoskeleton

3.4 Foot Design

The foot design is made by designing a joint in accordance with the human anatomy, which corresponds to the lower part of the fibula. The sole of the foot is designed from calcaneal bone to the metatarsals as seen be low.

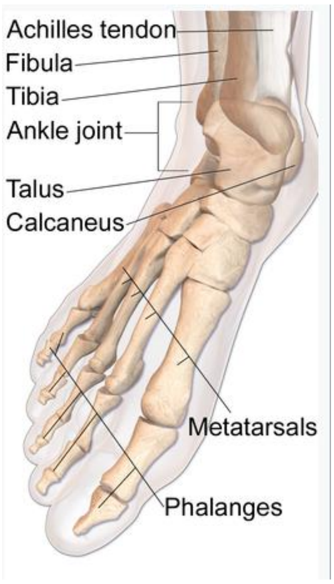


Figure 25 : Lower Leg and Foot View [15]

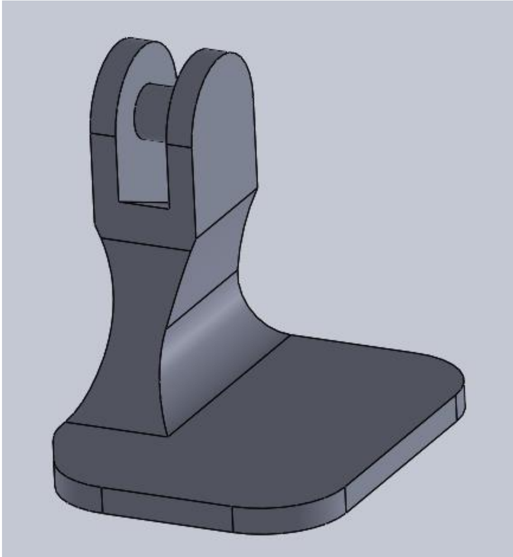


Figure 26 : The Foot Drawing of the Exoskeleton

4. WALKING ANALYSIS OF A HUMAN BODY

In order to make the walking analysis of the designed exoskeleton in computer, the walking(gait) analysis of the human anatomy has been researched and studied. With the information obtained from these studies, the gait cycle was understood and walking analysis was done using MATLAB/Simulink/Simmechanics.

4.1 The Gait Cycle

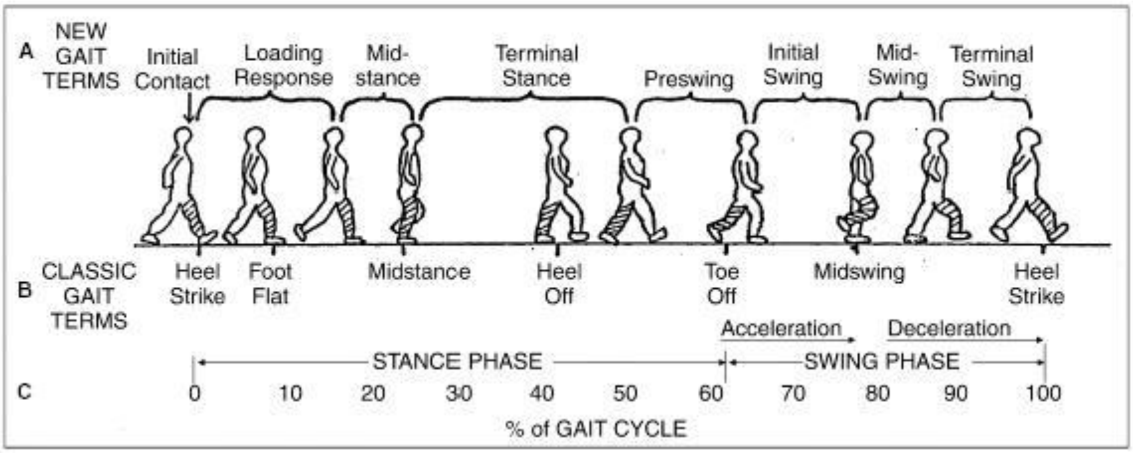


Figure 27 : Gait Cycle Phases (Dr. Sara J. Cuccurullo, MD, Physical Medicine and Rehabilitation Board Review)

Figure 29 : Simulink Block Diagram of Right LegFigure 27 : Gait Cycle Phases (Dr. Sara J. Cuccurullo, MD, Physical Medicine and Rehabilitation Board Review)

The gait cycle is a medical term that examines repetitive cycle of human steps. A step is called between the heel hit of one foot and the heel hit of the other foot. The elapsed time is called as step time.[16]

The gait cycle involves 8 phases;

1- Initial Contact

2- Loading Response

3- Midstance

4- Terminal Stance

5- Pre Swing

6- Initial Swing

7- Mid Swing

8- Late Swing

1- Initial Contact

This phase is the first stage of the step where both feet are in contact with the ground. The angle between the hip and the upper leg is about 30°, the angle between lower leg and the upper leg is 180°, that is, the knee is not bent, but straight. The angle between the lower leg and the foot is about 95°, and this angle decreases towards the next phase.

2- Loading Response

At this phase, the sole of the foot is in full contact with the ground and the hip moves forward slowly. The knee joint between the upper leg and the lower leg bents at about 15 to 20 degrees. The ankle angle drops from 95° to between 80°-85°.

3- Midstance

At this phase, the hip reaches the upper point of the leg that is contact with ground, and body weight is on the leg that is contact with ground. The swinging leg comes alignment to the leg that is contact with the ground by bending the leg from the knee.

4- Terminal Stance

At this phase, the swinging leg continues swinging forward as it will be in contact with ground in the next phase and the knee angle approaches close to 180°. The heel of the foot that is alread contact with the ground leaves the ground.

5- Pre Swing

At this phase, the heel of the in contact with the ground in the previous phases is now in the swing, and the heel of the foot that was previously swing, begins to contact with the ground. The hip slowly moves forward and the foot which heel is not contact from the ground is now completely in swing. The other foot steps to the ground with its entire sole. Now, the foot that was in swing in the previous phases, is literally on the ground and the other foot begins swinging.

6- Initial Swing

At this phase, the foot that starts to swing rises with the increase of the angle of the joint in the knee and comes to the leg in contact with the ground. Now all the body's weight is on the leg in contact with the ground.

7- Mid Swing

At this phase, the leg in swing continyes to swing to contact the ground in the future, and the angle at the knee gradually approaches 180°. The engle in the ankle joint which between the foot and lower leg in contact with the ground decreases, and therefore the hip moves forward.

8- Late Swing

At this phase, the heel of the foot on the swing touches the ground and the heel of the foot which is already in contact with the ground rises from the ground. Now, both legs' knee joints are straight(close to 180°).[16][17]

5. WALKING SIMULATION OF THE EXOSKELETON

The walking analysis was done on computer, using Simulink/Simmechanics extensions of the MATLAB R2019. The design that made in Solidworks was exported from Solidworks for Simmechanics and run in MATLAB with code **smimport (‘Filename.xml’).**

In simmechanics, firstly, the automatically assigned revolute joints between the links have been corrected(Figure 28 and Figure 29), and the connection with the ground for both feet was created using Spherical Solid and Spatial Contact Force elements and assigned Frames to 4 different corners of the feet soles.

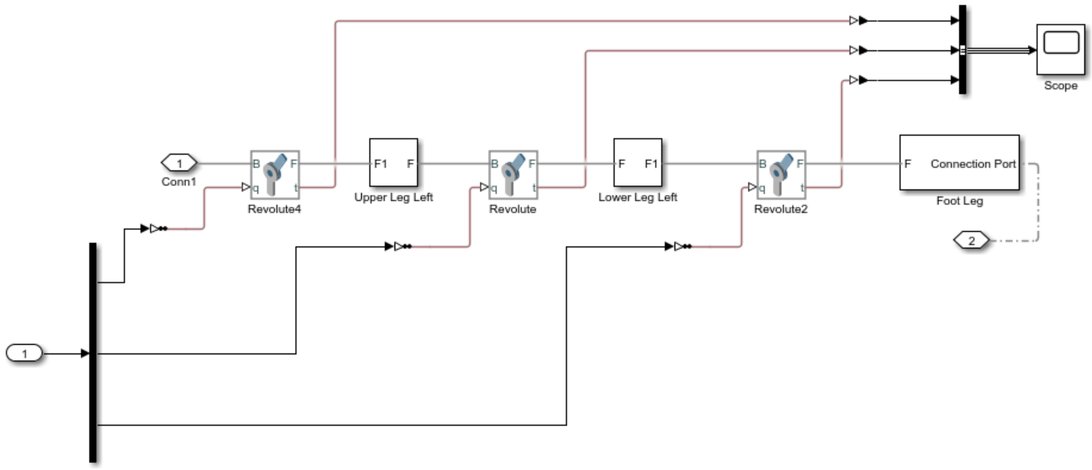


Figure 28 : Simulink Block Diagram of Left Leg

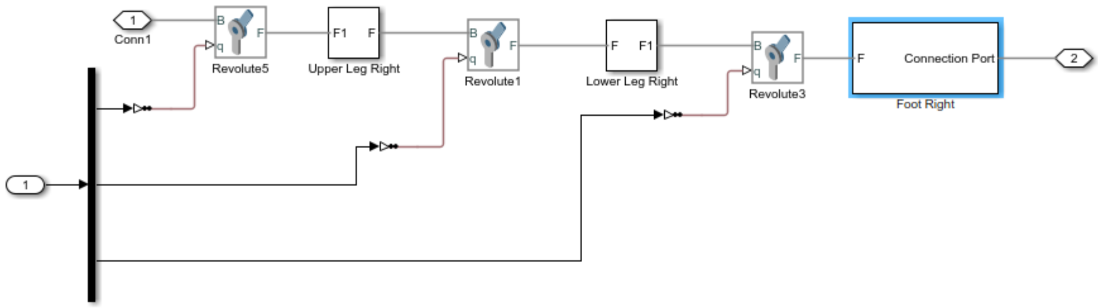


Figure 29 : Simulink Block Diagram of Right Leg

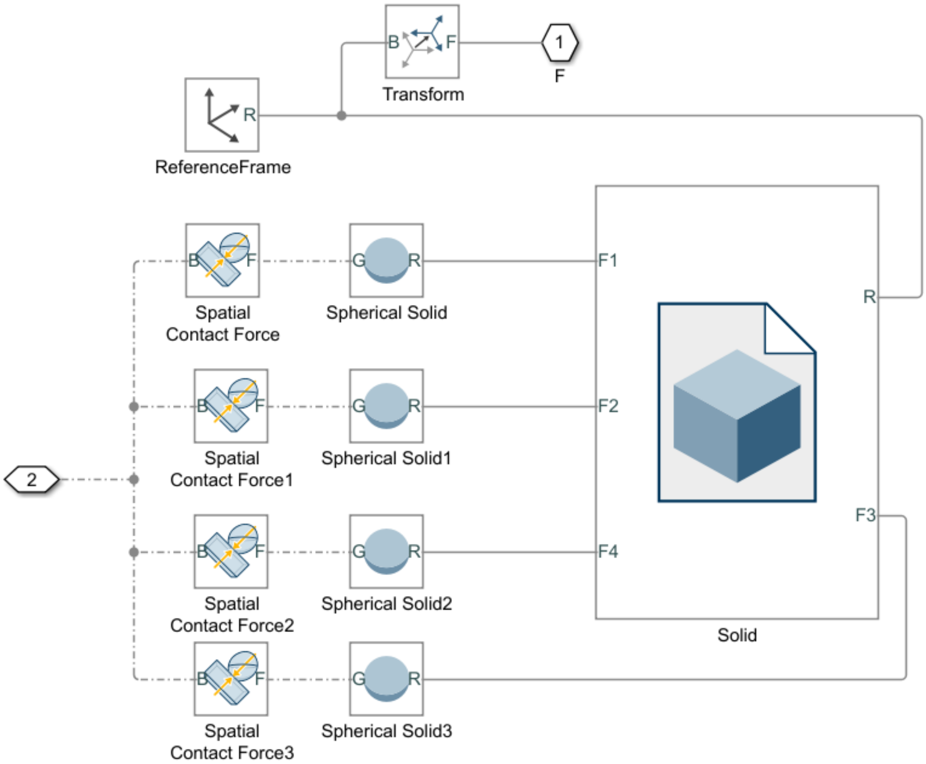


Figure 30 : Contact Force Connections Block Diagram of Foot

Gravity has been assigned as 9.81 m/s^2 on (-y) axis.

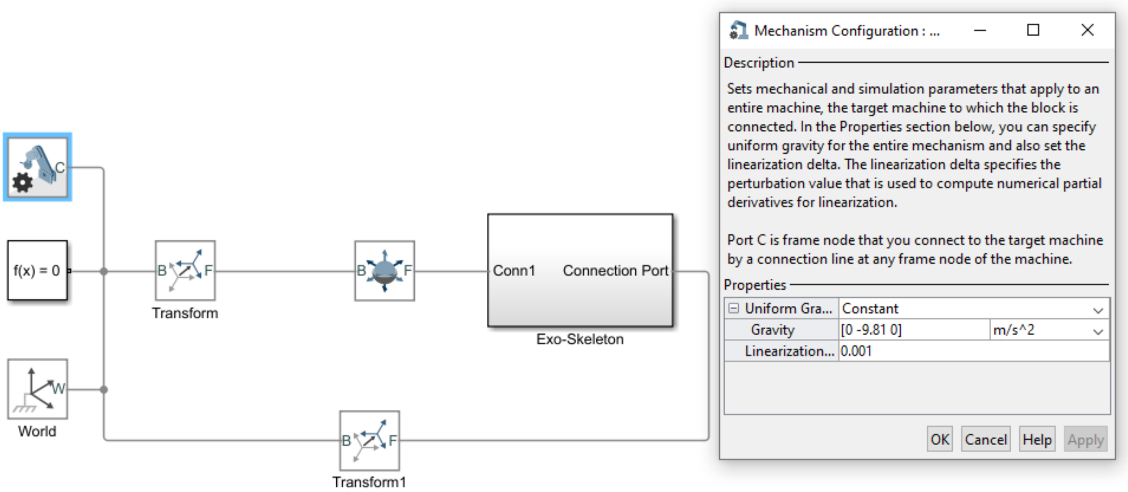


Figure 31 : Block Diagram of Exoskeleton and Assigned Gravity

The time – joint angle relationships that required for motion analysis of the exoskeleton are created based on the studies in the Gait Analysis section and are defined for each joint.

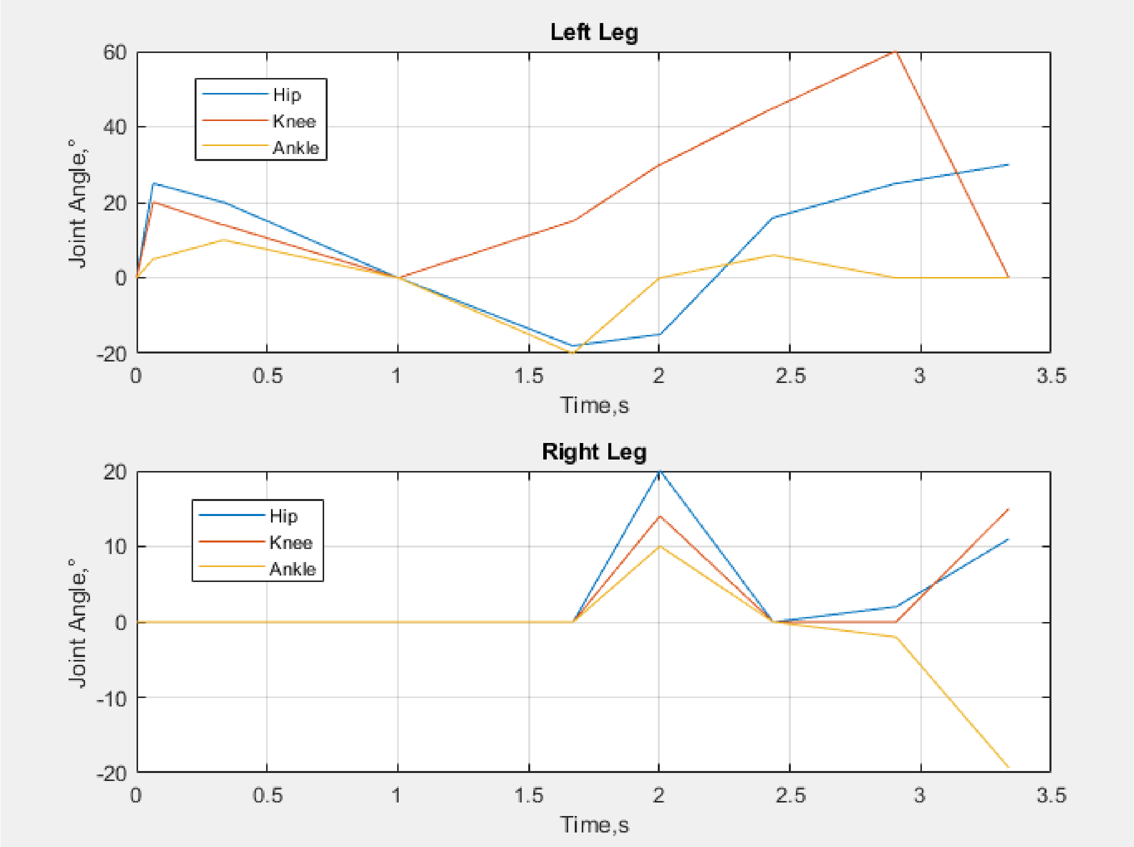


Figure 32 :Time – Joint Angle Graph for Each Joint as Simulation Input

Motion analysis in which both legs can take steps has been tried but the left foot has been fixed to the ground due to the movement defects. The step starts at 2 s. Between 0-2 s is preparation for the step.

Motion analysis simulation for one step is shown in below step by step(2 - 3.34s).

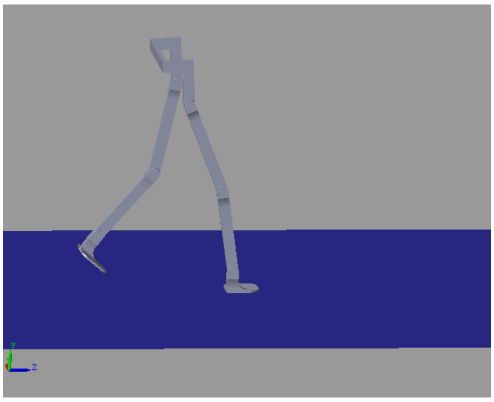


Figure 33 : Motion Analysis Simulation at 2 s.

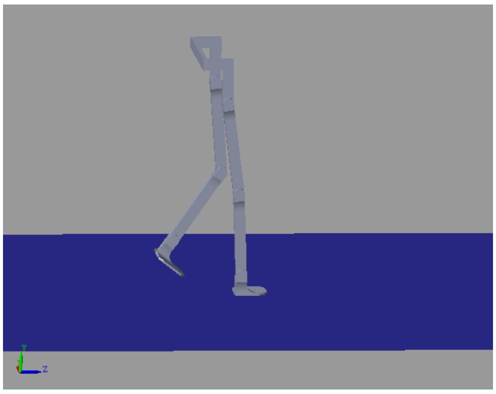


Figure 34 : Motion Analysis Simulation at 2.25 s.

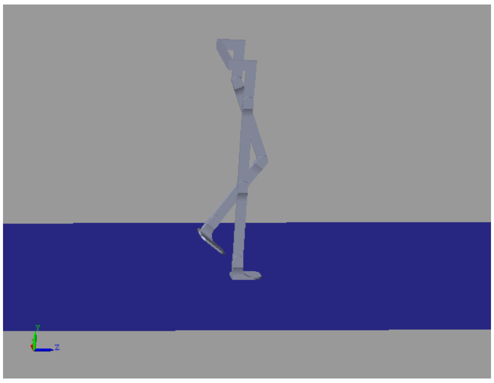


Figure 35 : Motion Analysis Simulation at 2.45 s.

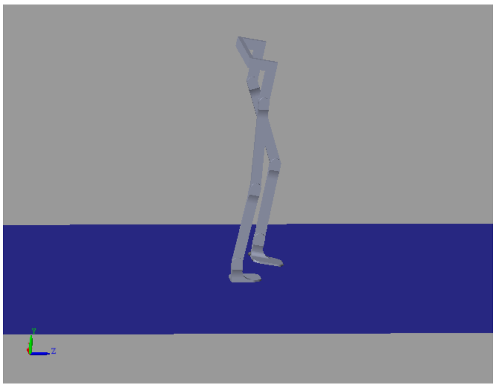


Figure 36 : Motion Analysis Simulation at 3.1 s.

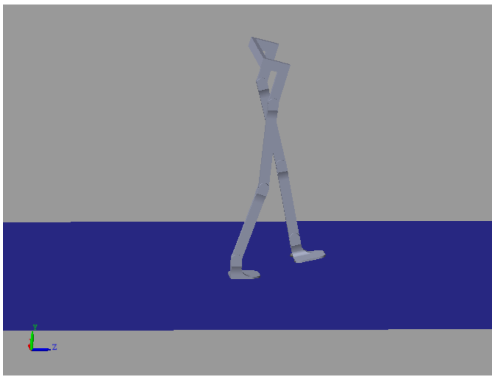


Figure 37 : Motion Analysis Simulation at 3.34 s.

The walking motion in the mechanical simulation was created on the basis of the studied Gait Cycle phases. Simulation begins with the left foot off the ground. The angles between joints entered as input are as specified in the table below. Also Exoskeleton user, joints and actuators weights are as shown below. The lateral opening of the legs is not taken into account.

	Angles(°)								
Time(s)	0	0.0635	0.3307	0.9989	1.6671	2.0012	2.4355	2.9032	3.3375
Right Leg									
Hip	0	0	0	0	0	20	0	2	11
Knee	0	0	0	0	0	14	0	0	15
Ankle	0	0	0	0	0	10	0	-2	-19.33
Left Leg									
Hip	0	25	20	0	-18	-15	16	25	30
Knee	0	20	14	0	15	30	45	60	0
Ankle	0	5	10	0	-20	0	6	0	0

Table 5: The Angles Between Joints as Input in Simulink Simulation

	Weights(kg)
Exoskeleton User	
Upper Body, Backpack and Waist	85.1
Upper Leg	4.8
Lower Leg	1.95
Foot	0.7
Exoskeleton	
Waist	2.7
Upper Leg	1.33
Lower Leg	1.19
Foot	0.89
Actuators	
FHA-25C (For Hip and Ankle)	4
FHA-17C (For Knee)	2.5

Table 6: Exoskeleton User, Exoskeleton and Actuator Weights

With the relation of time-angle values assigned to all joints as input; actuator torque values for each joint were examined by adding scope to the block diagram.

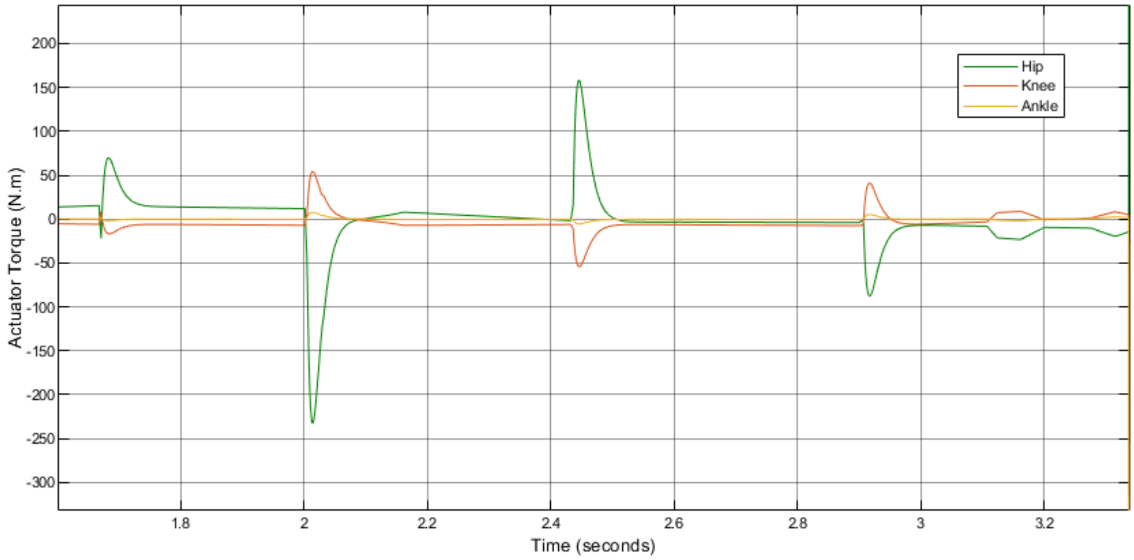


Figure 38 : Left Leg(Swing) Hip, Knee and Ankle Actuator Torque Scope

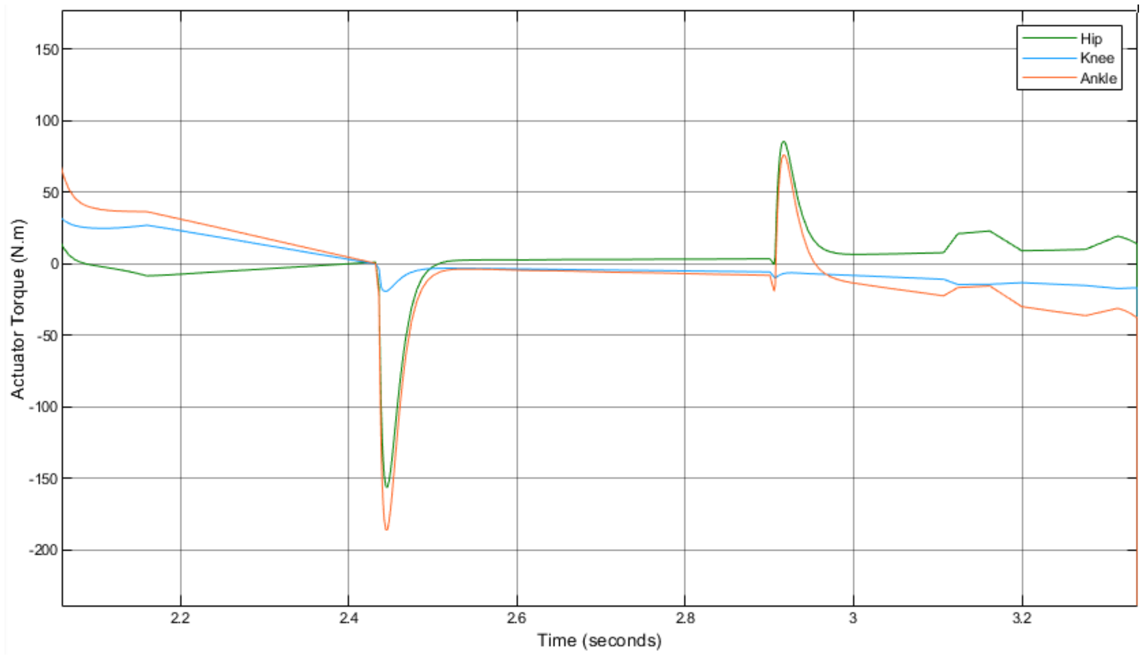


Figure 39 : Right Leg(Contact with the Ground) Hip, Knee and Ankle Actuator Torque Scope

As a result of the motion analysis, for the left leg(swinging), for the hip, the maximum peak torque is 231.1 N.m, the maximum continuous torque is 14 N.m. For the knee, the maximum peak torque is 54.4 N.m, the maximum continuous torque is 6.9 N.m. For the ankle, the maximum peak torque is 7.74 N.m, the maximum continuous torque is 0.35 N.m.

For the right leg(contact with the ground), for the hip, the maximum peak torque is 156 N.m, the maximum continuous torque is 22.9 N.m. For the knee, the maximum peak torque is 19.1 N.m, the maximum continuous torque is 15 N.m. For the ankle, the maximum peak torque is 185 N.m, the maximum continuous torque is 36 N.m.

In addition, the model of the motion analysis and its subsystems are shown at the end of the thesis.

6. DYNAMIC AND STATIC ANALYSIS OF THE EXOSKELETON

6.1 Gait Cycle

6.1.1 Dynamic Analysis

Dynamic and static analysis of the designed exoskeleton in Solidworks was done using ANSYS 2019 R3. Designs in Solidworks have been saved with the extension STEP AP203(.step) and assigned to Geometry using the Transient Structural analysis system in ANSYS Workbench (Figure 40).

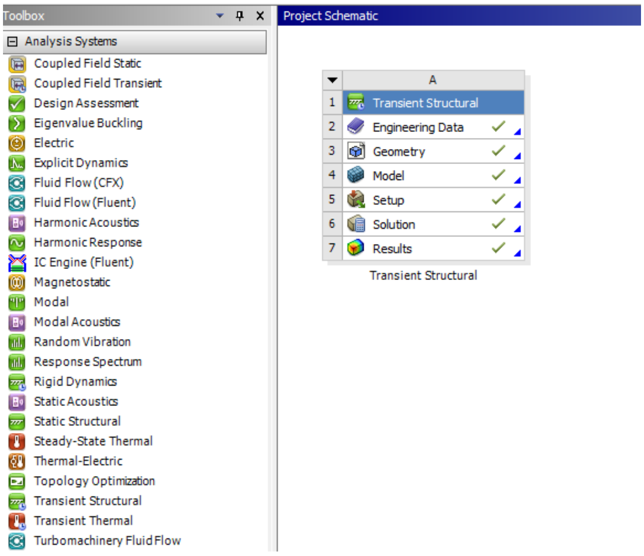


Figure 40 : Transient Structural Analysis System for Dynamic Analysis

Afterwards, 7 point masses were assigned to the model as shown in Figure 41 for the exoskeleton user weights. These are respectively, upper body 60.1 kg + backpack weight 25 kg, each of the upper legs 4.8 kg, each of the upper legs 4.8 kg, each of the lower legs 1.95 kg, each of the feet 0.7 kg.

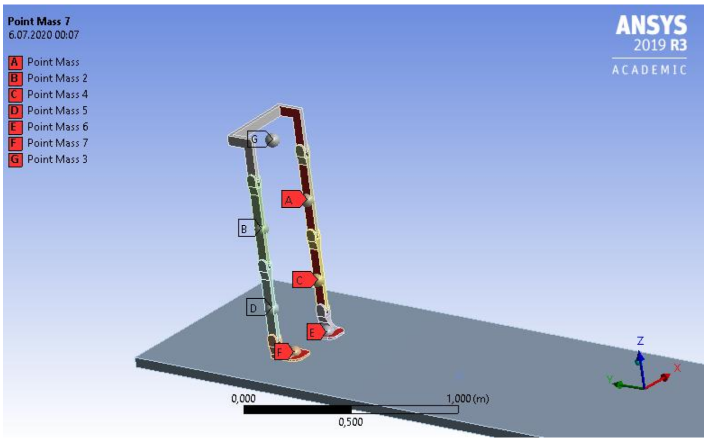


Figure 41 : Assigned Point Masses for the Exoskeleton User Weights

As the material, structural steel was used in the analyzes shown below. Later, analyzes were made with different materials and material selection was discussed in the optimization section.

In the model, the contacts that automatically assigned to the Connections are disabled. For the connected limbs, no separation type and asymmetric behavior contacts are assigned to the contacting surfaces(Figure 42).

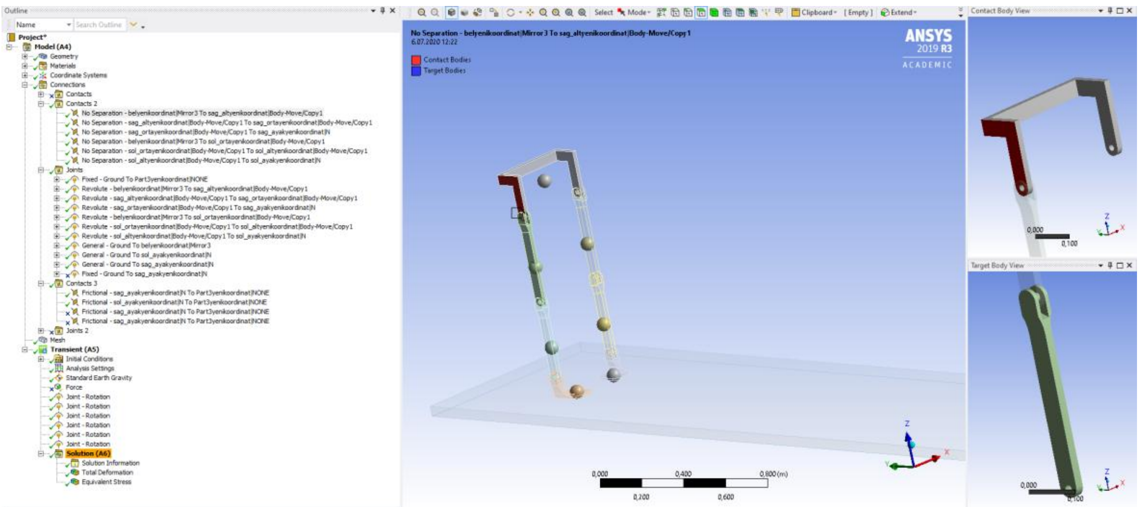


Figure 42 : Connections of the Dynamic Analysis in ANSYS

Subsequently, the bottom of the floor used as the base in walking analysis is defineed as Fixed type Body-Ground connection. For each joint, Body-Body, Revolute joints are assigned. General type Body-Ground translations free rotations fix contacts are assigned for the contact of the feet with the floor. Contacts between the feet and the ground is assigned as Frictional and friction coefficient 0.1.

Meshing section is assigned with Mechanical Physics Preference and Linear Element Order, also mesh statistics are as seen in the Figure 43. The reason for determining the number of mesh is too low is that the process time of dynamic analysis is too long and the number of mesh in ANSYS student version is limited.

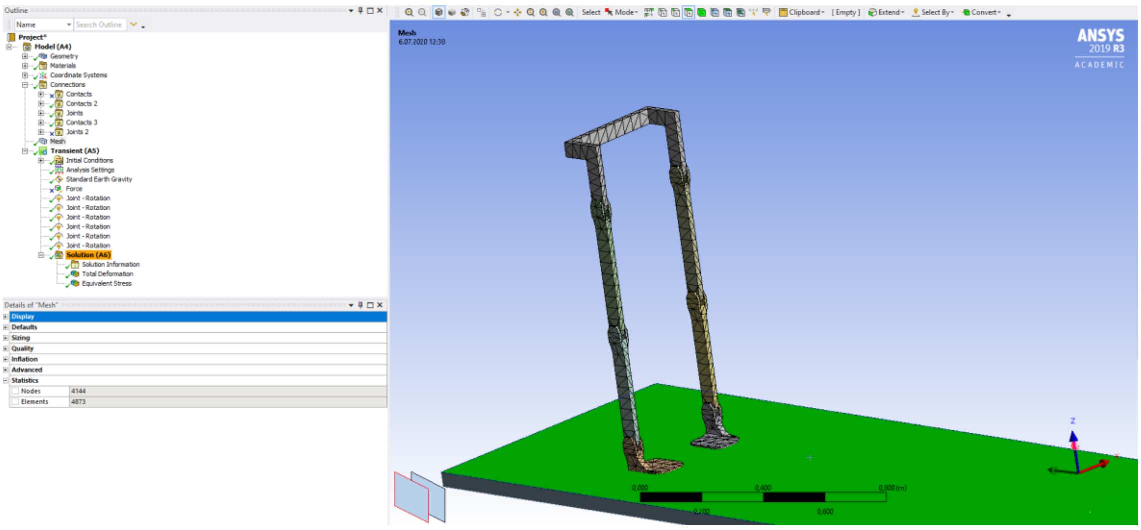


Figure 43 : Meshing for Dynamic Analysis in ANSYS

For the Transient, firstly Standard Earth Gravity was assigned in (-z) direction. Afterwards, joint-rotations were assigned using revolute joint contacts using time-rotation angles tabular datas.

In the solution, equivalent (von-Mises) stress for all bodies is examined. As can be seen in the figure 44, maximum von-Mises stress is 175.46 Mpa in the left ankle for dynamic gait analysis.

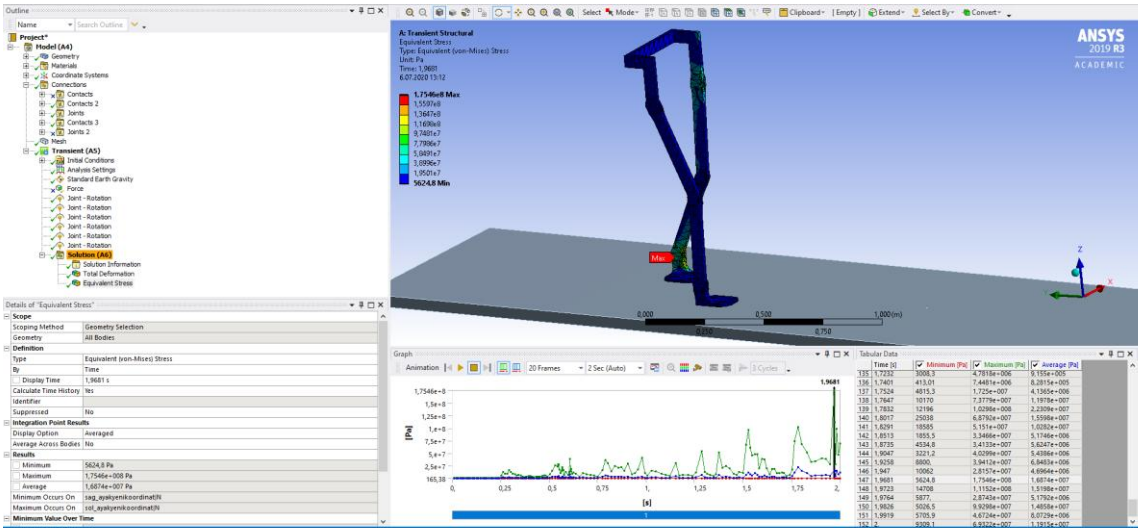


Figure 44 : Equivalent (von-Mises) Stress Solution for Dynamic Analysis in ANSYS

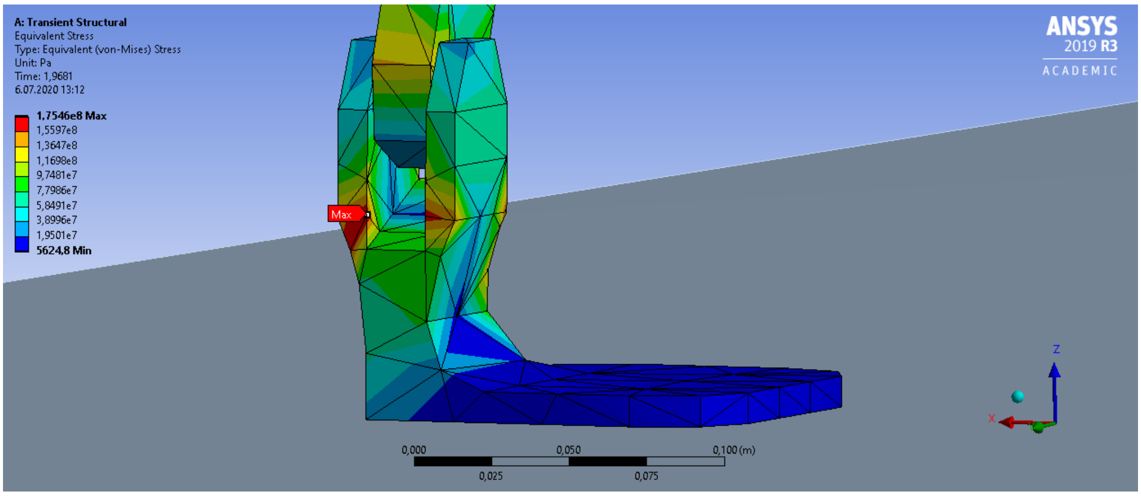
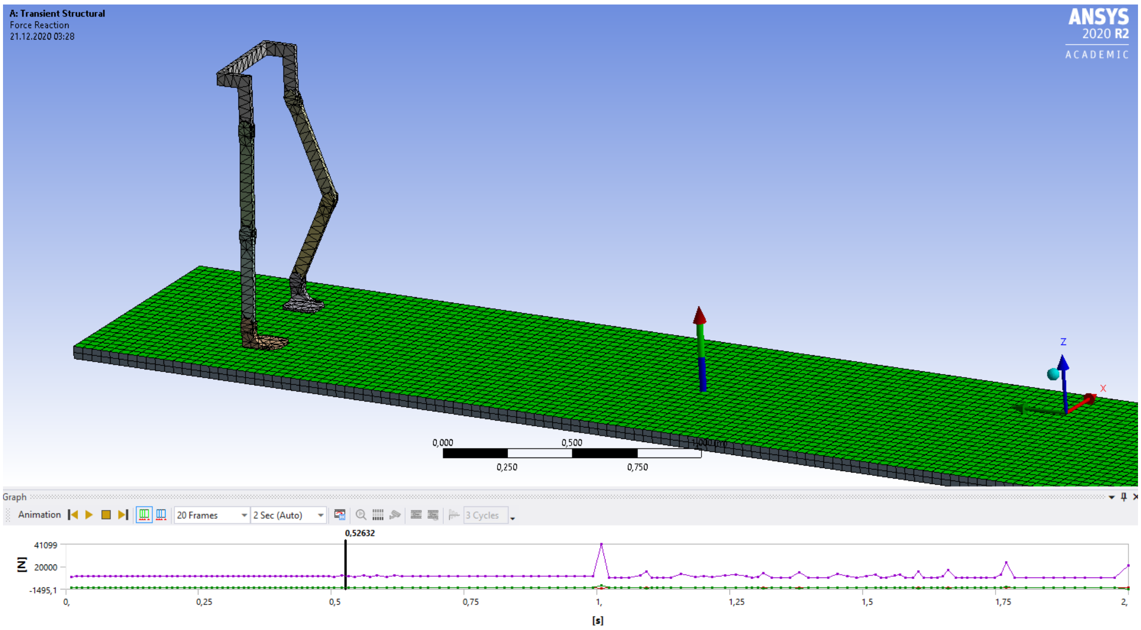


Figure 45 : Maximum Equivalent (von-Mises) Stress for Left Ankle in ANSYS

Ground's reaction force during walking analysis was examined. The reaction force when one foot touches the ground is 10.8 kN in the + Z direction throughout the simulation.

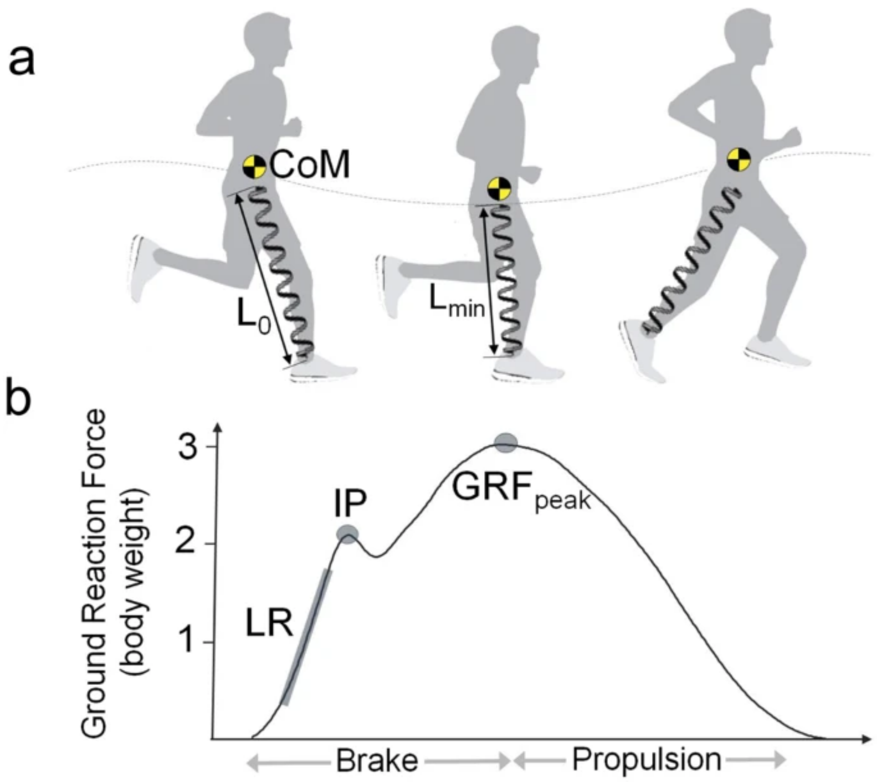


Tabular Data

	Time [s]	Force Reaction (X) [N]	Force Reaction (Y) [N]	Force Reaction (Z) [N]	Force Reaction (Total) [N]
23	0,24325	6,1318e-002	-0,37982	10868	10868
24	0,25431	-7,6822	-163,49	10850	10851
25	0,26431	-7,7445	-176,63	10949	10950
26	0,27431	-4,5842	-155,57	10792	10793
27	0,28431	-2,3063	-177,36	10958	10959
28	0,29431	-7,2466	-159,83	10823	10824
29	0,30431	1,5958	-170,26	10907	10909
30	0,31431	20,967	-162,22	10877	10879
31	0,32431	-17,436	83,04	10865	10865
32	0,33431	19,639	-168,22	10919	10921
33	0,34431	28,983	73,011	10831	10831

Figure 46: Reaction Force in Ground for Foot in ANSYS

In the article named **Running in highly cushioned shoes increases leg stiffness and amplifies impact loading**[19], the ground reaction forces of an athlete running at 10 km / h were examined. As can be seen in the graph below, the reaction force is 3 times body weight at the point where the reaction force is maximum. (For the exoskeleton we examined, if we assume a total weight of 120 kg with the backpack load, this reaction force is approximately 3x120x9.81 = 3531.6 N.) Although the exoskeleton user in our simulation is walking, the reaction force is about 3 times that in this article.



Spring-mass mechanics of running. (**a**) The mechanical energy during the braking phase of running is absorbed by compression of the leg-spring from initial length (L_o) to minimal length (L_{min}). The body's centre of mass (CoM) reaches its highest position during the aerial phase, whereas the lowest position, L_{min} and the (**b**) peak ground reaction force (GRF_{peak}) occur at the mid-stance. Leg stiffness can be calculated as a ratio of GRF_{peak} to the change in leg length. During heel running, a visible GRF impact peak (IP) and a relatively high impact loading rate (LR) occur after the heel collides with the ground.

Figure 47: Ground Reaction Force for Running at 10 km/h [https://doi.org/10.1038/s41598-018-35980-6][19]

6.1.2 Static Analysis

The 8 phases that examined in Gait Analysis for static analysis were saved separately in Solidworks as STEP AP203 (.step) extension and imported into ANSYS Workbench using Static Structural Analysis System.

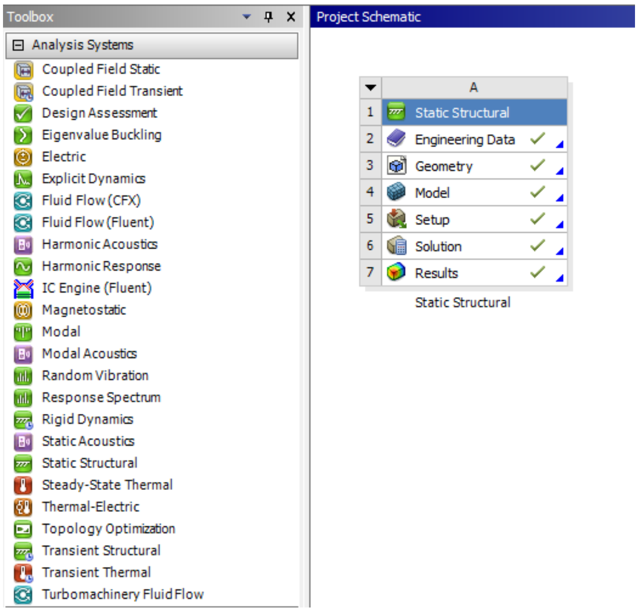


Figure 48 : Static Structural Analysis System for Static Analysis

In the model, 7 Point Mass have been assigned for exoskeleton user weights as in the dynamic analysis. These are respectively, upper body 60.1 kg + backpack weight 25 kg, each of the upper legs 4.8 kg, each of the upper legs 4.8 kg, each of the lower legs 1.95 kg, each of the feet 0.7 kg. As the material, structural steel was used in the analyzes shown below. Later, analyzes were made with different materials and material selection was discussed in the optimization section. Automatically assigned contacts are used in the connections section. Meshing and statistics are as in the Figure 47.

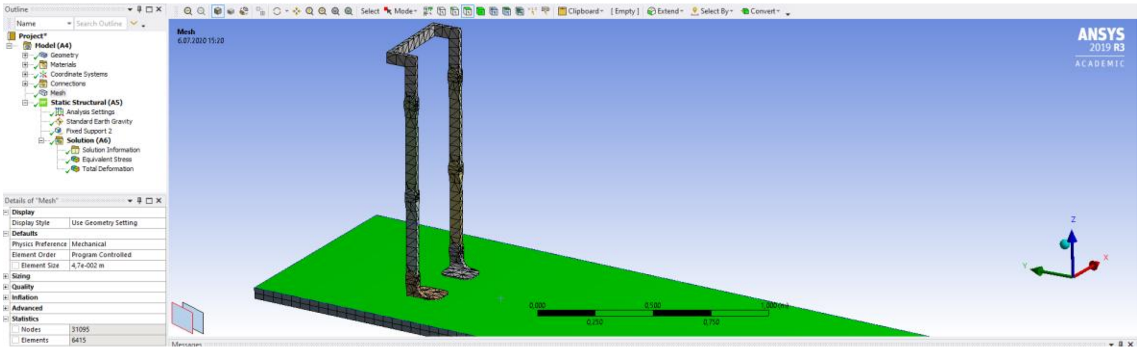


Figure 49 : Meshing for Static Analysis in ANSYS

For the Structural, Standard Earth Gravity was assigned in (-z) direction. Fixed support is defined under the floor used as the base in walking analysis.

In the first phase, static analysis is examined in case both feet are in contact with the ground and the body is upright. As seen in the figure 48, maximum von-Mises stress is 2.52 MPa in the ankle.

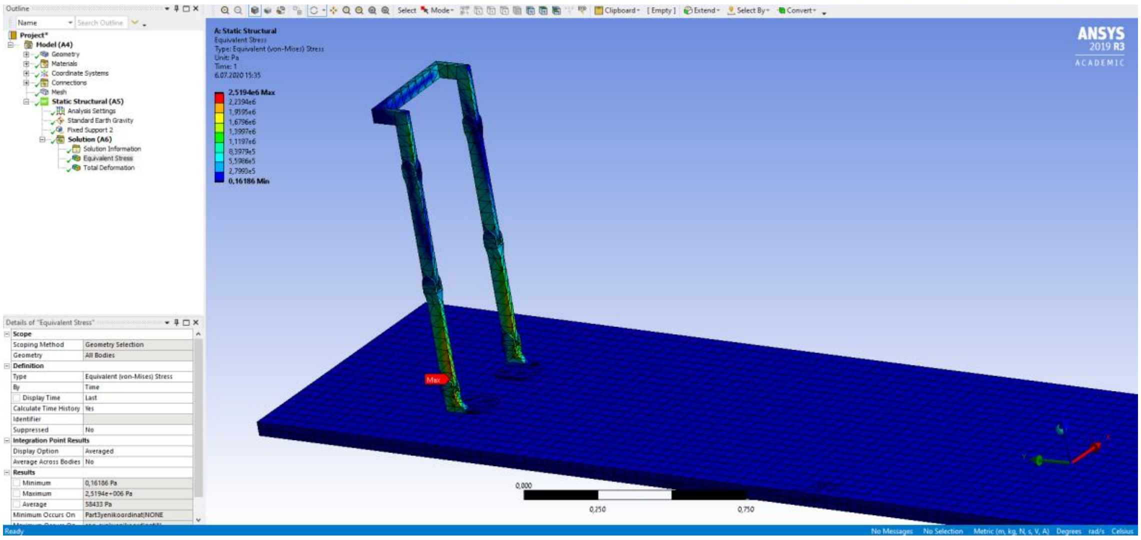


Figure 50 : Equivalent (von-Mises) Stress Solution Phase 1 for Static Analysis in ANSYS

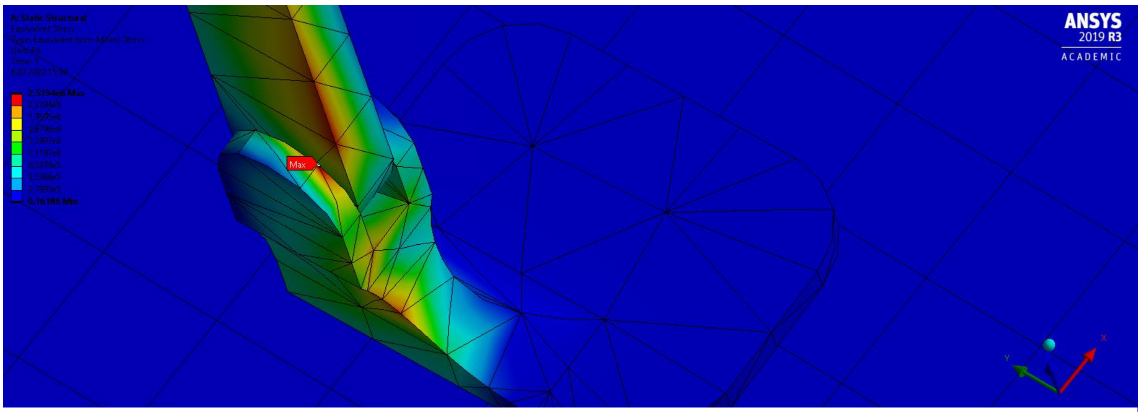


Figure 51 : Maximum Equivalent (von-Mises) Stress Phase 1 for Ankle in ANSYS

In the second phase as seen in the Figure 50, the right foot is contact with the ground and the angles in left leg joints are 27° on the left hip, 57.2° on the knee and 29° on the ankle. Static analysis results in this case were examined. As can be seen in the figure 51, maximum equivalent von-Mises stress is 156.05 MPa in the left ankle.

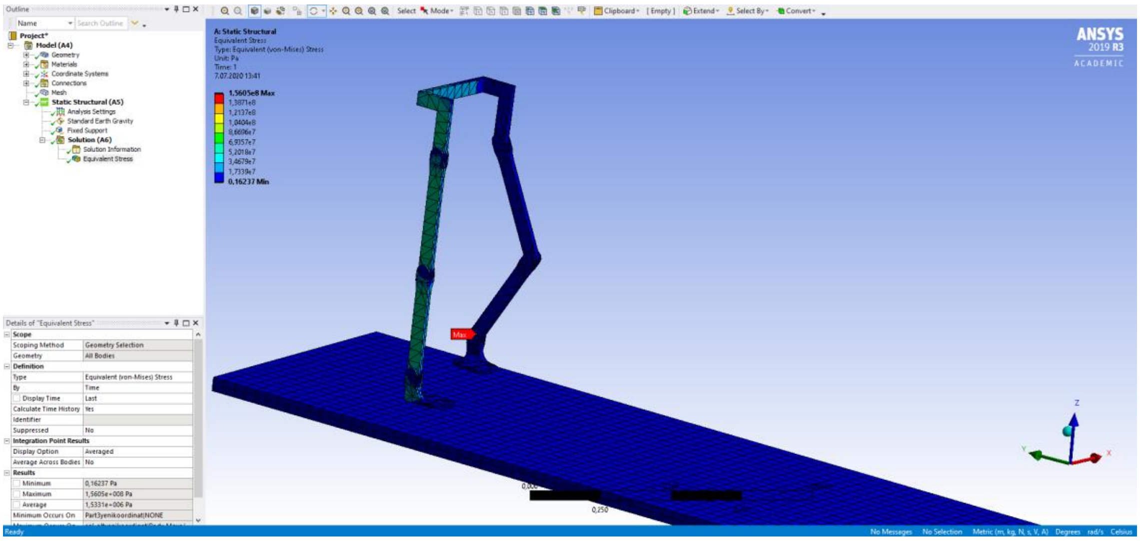


Figure 52 : Equivalent (von-Mises) Stress Solution Phase 2 for Static Analysis in ANSYS

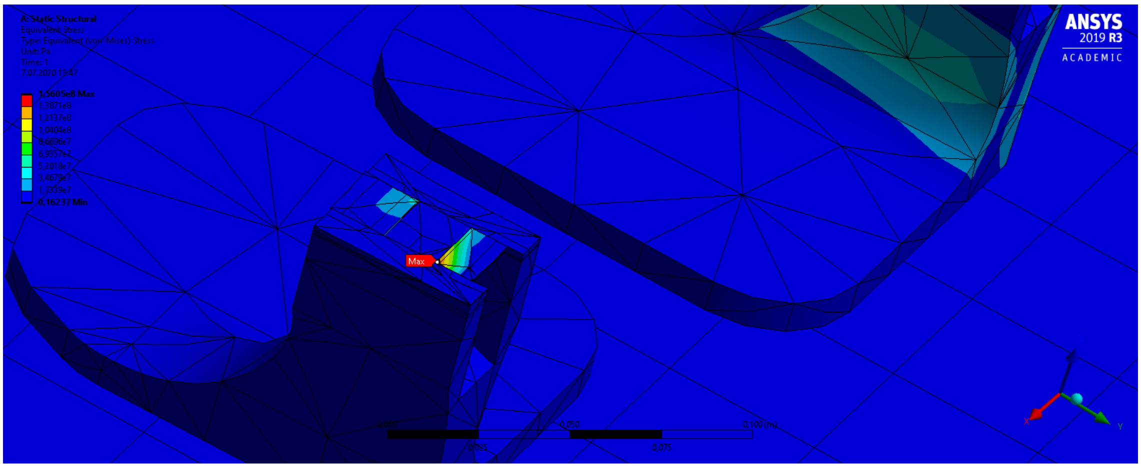


Figure 53 : Maximum Equivalent (von-Mises) Stress Phase 2 for left Ankle Section view in ANSYS

In the third phase, the right foot is in contact with the ground and the angles in right leg joints are 5.6° on the hip, 1.3° on the knee and 6.9° on the ankle; the angles in left leg joints are 33.35° on the hip, 41.8° on the knee and 8.3° on the ankle. Static analysis results in this case were examined. As can be seen in the figure 52, maximum equivaletn von-Mises stress is 334.17 MPa in the left ankle.

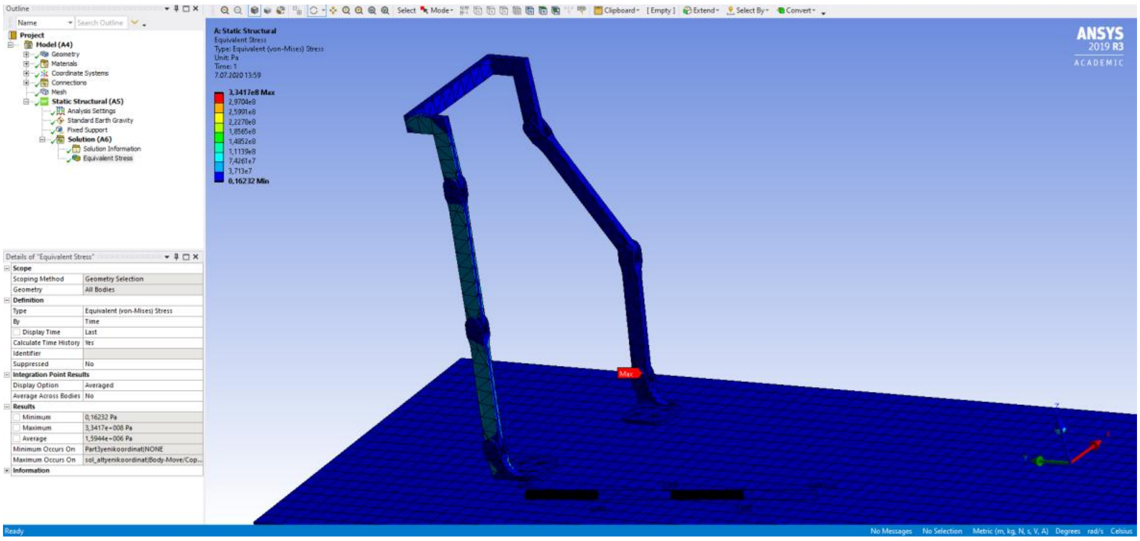


Figure 54 : Equivalent (von-Mises) Stress Solution Phase 3 for Static Analysis in ANSYS

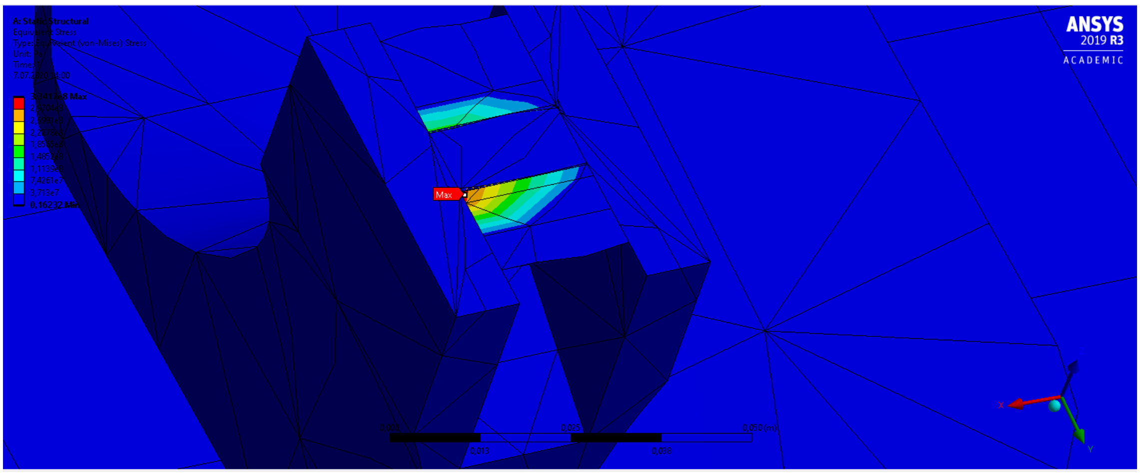


Figure 55 : Maximum Equivalent (von-Mises) Stress Phase 3 for left Ankle Section view in ANSYS

In the fourth phase, both feet are in contact with the ground. The angles in right leg joints are 11° on the hip, 10.9° on the knee and 21.9° on the ankle; the angles in left leg joints are 22.5° on the hip, 16° on the knee and 6.6° on the ankle. Static analysis results in this case were examined. As can be seen in the Figure 54, maximum equivalent von-Mises stress is 10.064 MPa in the right ankle.

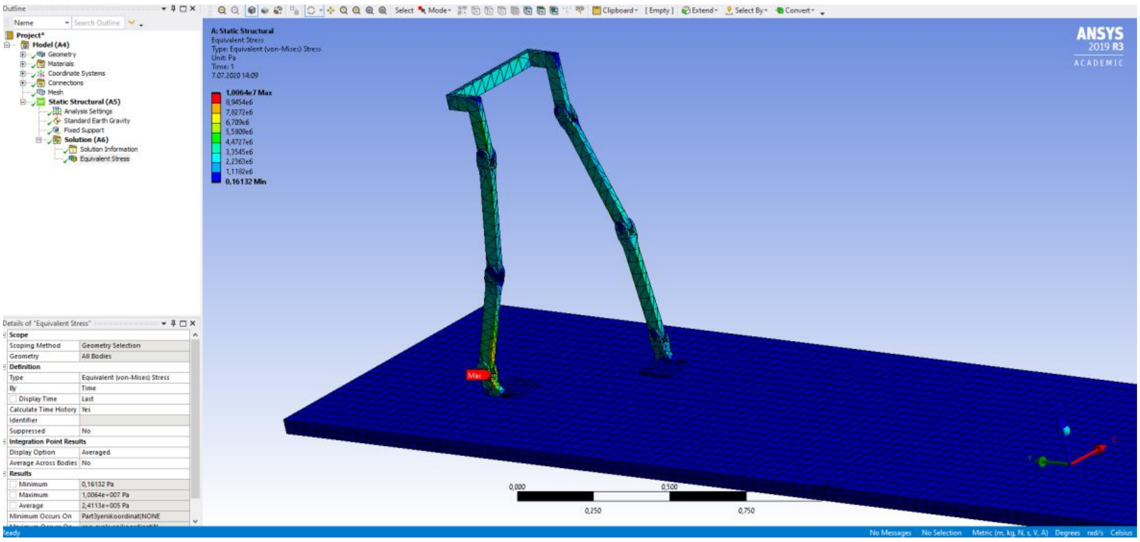


Figure 56 : Equivalent (von-Mises) Stress Solution Phase 4 for Static Analysis in ANSYS

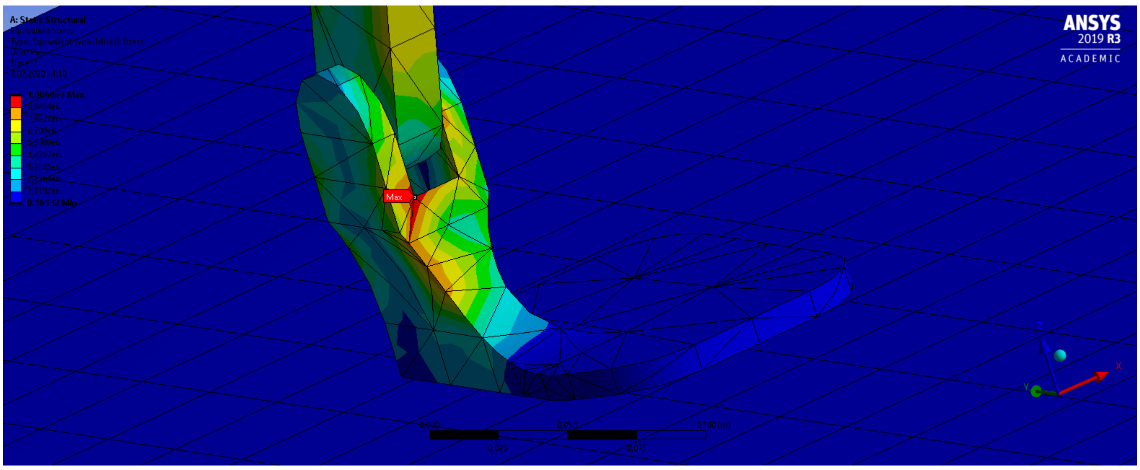


Figure 57 : Maximum Equivalent (von-Mises) Stress Phase 4 for Right Ankle in ANSYS

In the fifth phase, the angles in right leg joints are 0.6° on the hip, 27.1° on the knee and 27.7° on the ankle; the left foot is in contact with the ground and the angles in left leg joints are 19.5° on the hip, 19.75° on the knee and 0.23° on the ankle. Static analysis results in this case were examined. As can be seen in the Figure 56, maximum equivalent von-Mises stress is 264.01 MPa in the right ankle.

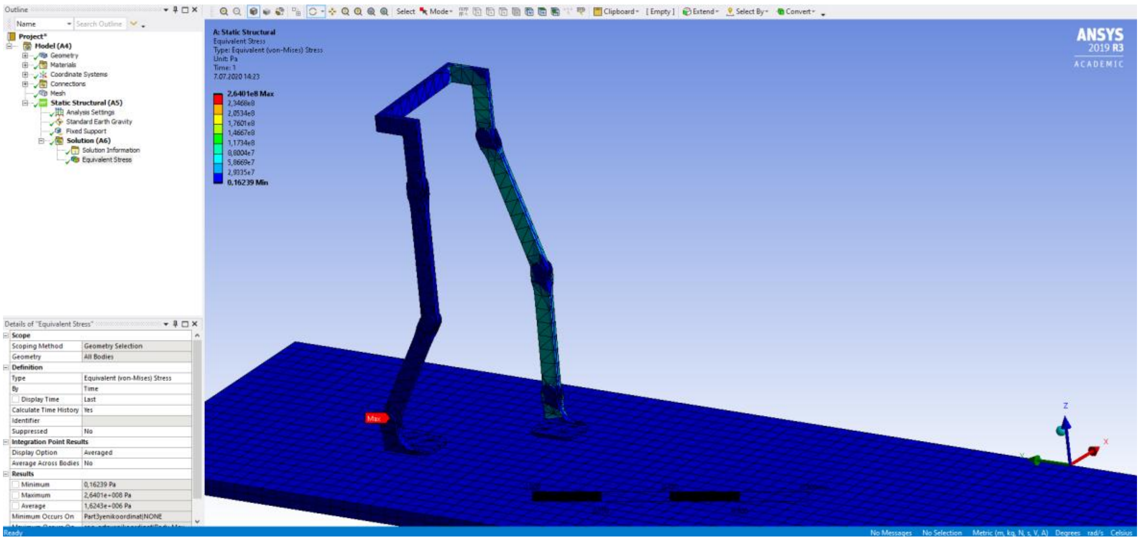


Figure 58 : Equivalent (von-Mises) Stress Solution Phase 5 for Static Analysis in ANSYS

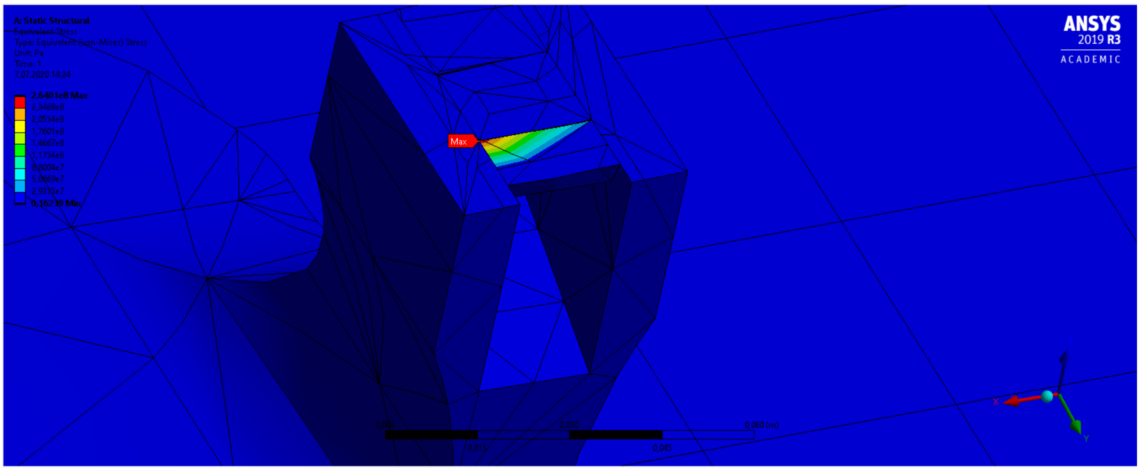


Figure 59 : Maximum Equivalent (von-Mises) Stress Phase 5 for Right Ankle Section View in ANSYS

In the sixth phase, , the angles in right leg joints are 11.5° on the hip, 57.3° on the knee and 45.8° on the ankle and the left foot is in contact with the ground. Static analysis results in this case were examined. As can be seen in the Figure 58, maximum equivalent von-Mises stress is 248.36 MPa in the right ankle.

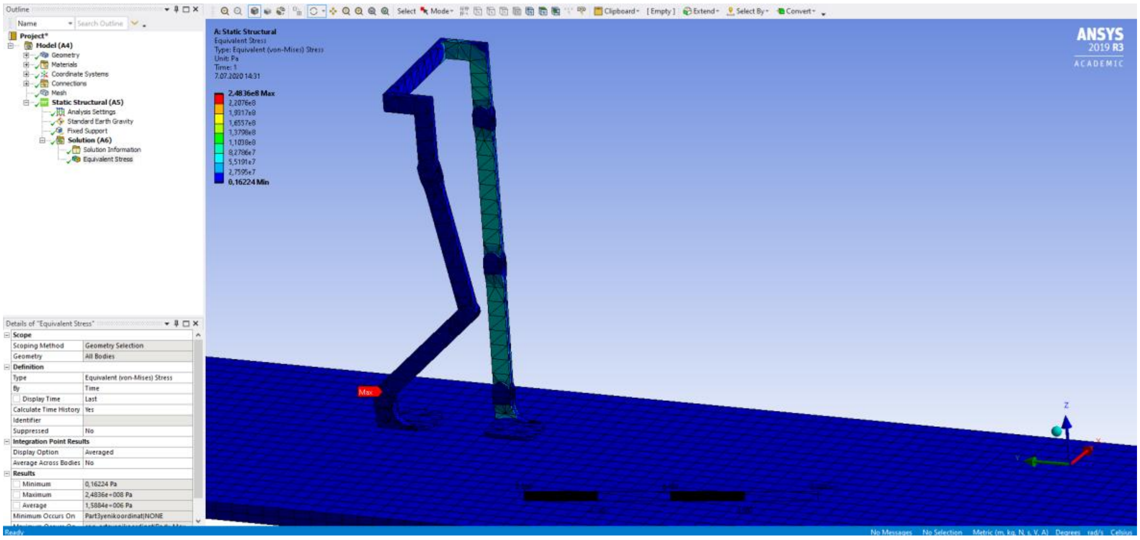


Figure 60 : Equivalent (von-Mises) Stress Solution Phase 6 for Static Analysis in ANSYS

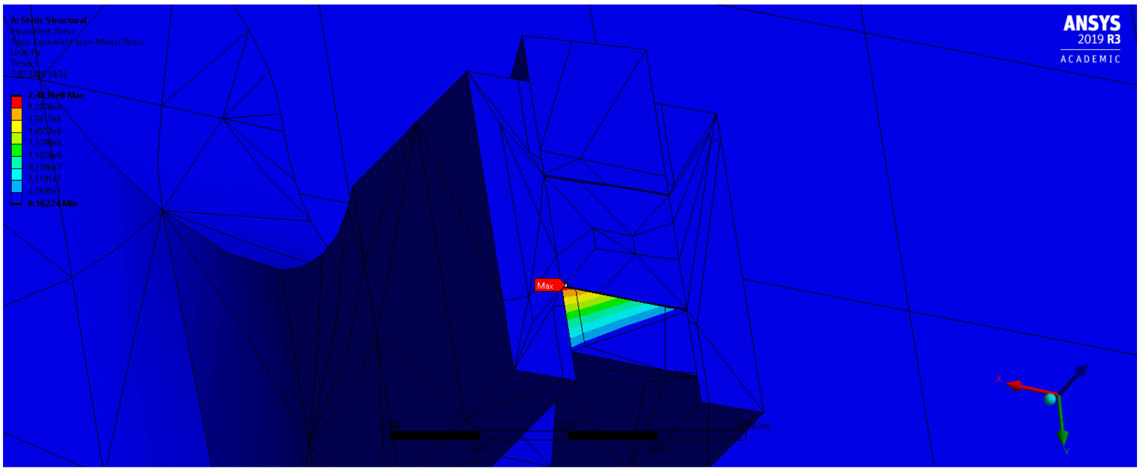


Figure 61 : Maximum Equivalent (von-Mises) Stress Phase 6 for Right Ankle Section View in ANSYS

In the seventh phase, the angles in right leg joints are 39° on the hip, 48.5° on the knee and 9.5° on the ankle; the left foot is in contact with the ground and the angles in left leg joints are 10.8° on the hip, 1.4° on the knee and 9.4° on the ankle. Static analysis results in this case were examined. As can be seen in the Figure 60, maximum equivalent von-Mises stress is 276.21 MPa in the right ankle.

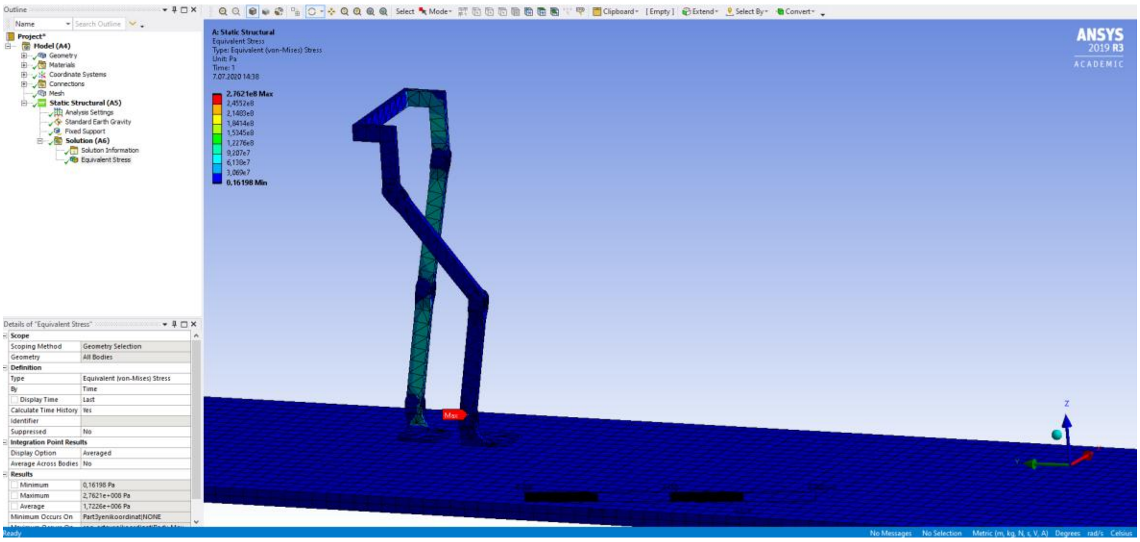


Figure 62 : Equivalent (von-Mises) Stress Solution Phase 7 for Static Analysis in ANSYS

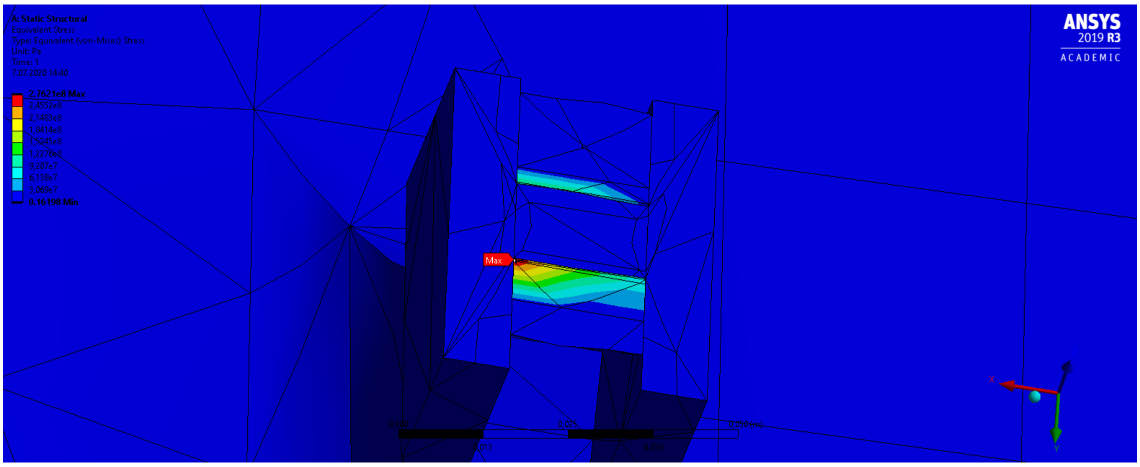


Figure 63 : Maximum Equivalent (von-Mises) Stress Phase 7 for Right Ankle Section View in ANSYS

In the eighth phase, both feet are in contact with the ground. The angles in right leg joints are 24.3° on the hip, 25.5° on the knee and 1.2° on the ankle; the angles in left leg joints are 0.7° on the hip, 26.6° on the knee and 25.9° on the ankle. Static analysis results in this case were examined. As can be seen in the Figure 62, maximum equivalent von-Mises stress is 10.45 MPa in the right knee.

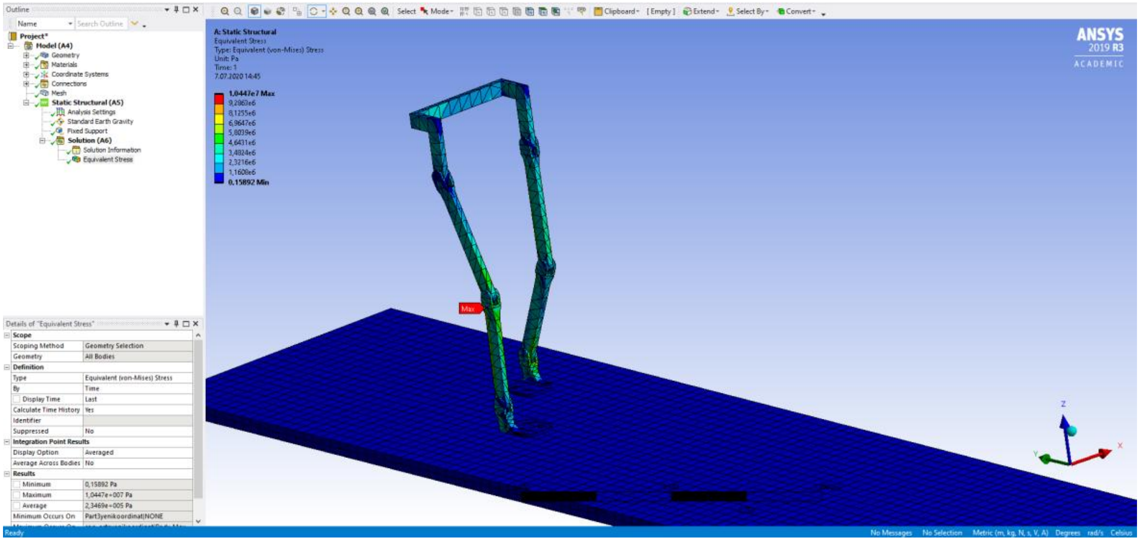


Figure 64 : Equivalent (von-Mises) Stress Solution Phase 8 for Static Analysis in ANSYS

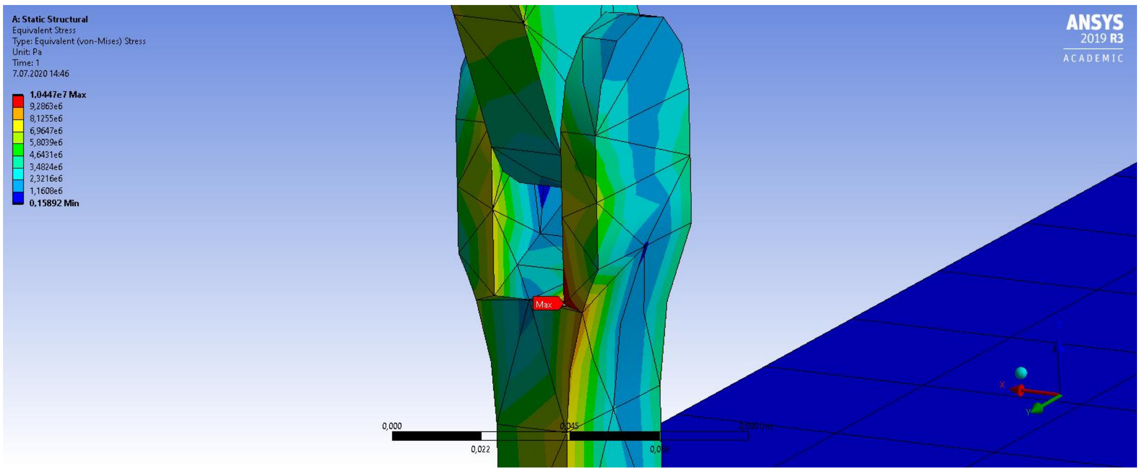


Figure 65 : Maximum Equivalent (von-Mises) Stress Phase 8 for Right Knee in ANSYS

6.2 Stair Gait Cycle

Stair Gate Cycle Analysis was done with the angles shown in the table below.[20]

	Angles(°)								
Time(s)	0	0.5	1	1.5	2	2.5	3	3.5	4
Right Leg									
Hip	0	36.56	44.02	32	16.73	16.73	16.73	1.21	0
Knee	0	68.51	57.76	35.41	17.45	17.45	17.45	1.97	0
Ankle	0	-3.55	-9.47	3.42	0.72	0.72	0.72	0.72	0
Left Leg									
Hip	0	0	0	0	10.84	32.05	47.82	38.92	32.51
Knee	0	0	0	0	29.94	61.17	59.78	46.3	36.99
Ankle	0	0	0	0	-9.46	-16.11	-7.97	-1	5.2

Table 7: The Angles Between Joints as Input in Stair Gait Cycle Analysis

6.2.1 Dynamic Analysis

Dynamic and static analysis of the designed exoskeleton in Solidworks was done using ANSYS 2020 R2. Designs in Solidworks have been saved with the extension STEP AP203(.step) and assigned to Geometry using the Transient Structural analysis system in ANSYS Workbench.

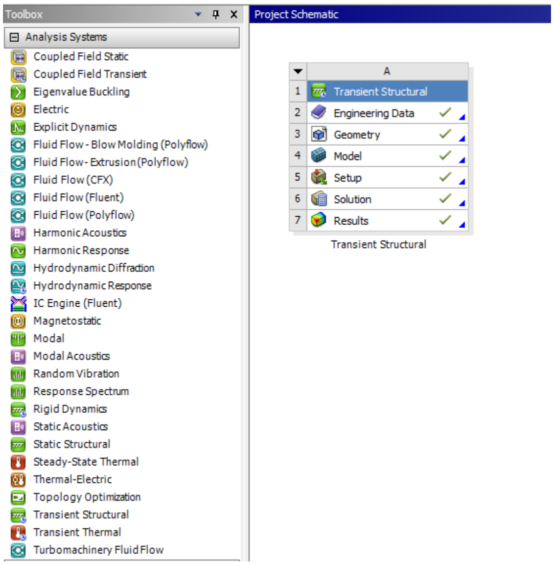


Figure 66 : Transient Structural Analysis System for Stair Gait Cycle for Dynamic Analysis

Afterwards, 7 point masses were assigned to the model as shown in Figure 41 for the exoskeleton user weights. These are respectively, upper body 60.1 kg + backpack weight 25 kg, each of the upper legs 4.8 kg, each of the lower legs 1.95 kg, each of the feet 0.7 kg.

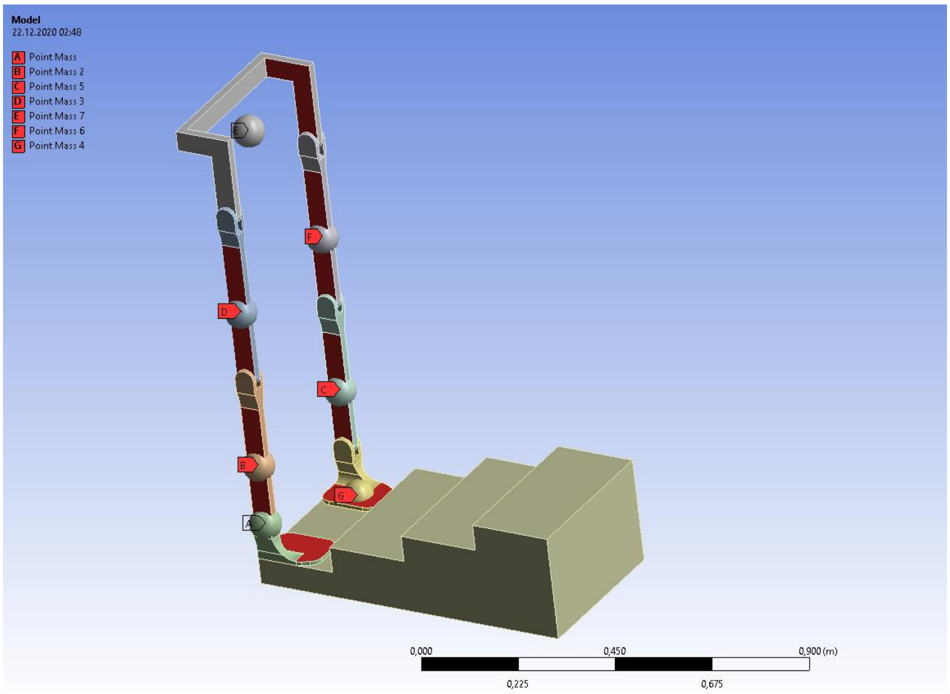


Figure 67: Assigned Point Masses for the Exoskeleton User Weights

As the material, structural steel was used in the analyzes shown below. Later, analyzes were made with different materials and material selection was discussed in the optimization section.

In the model, the contacts that automatically assigned to the Connections are disabled. For the connected limbs, no separation type and asymmetric behavior contacts are assigned to the contacting surfaces.

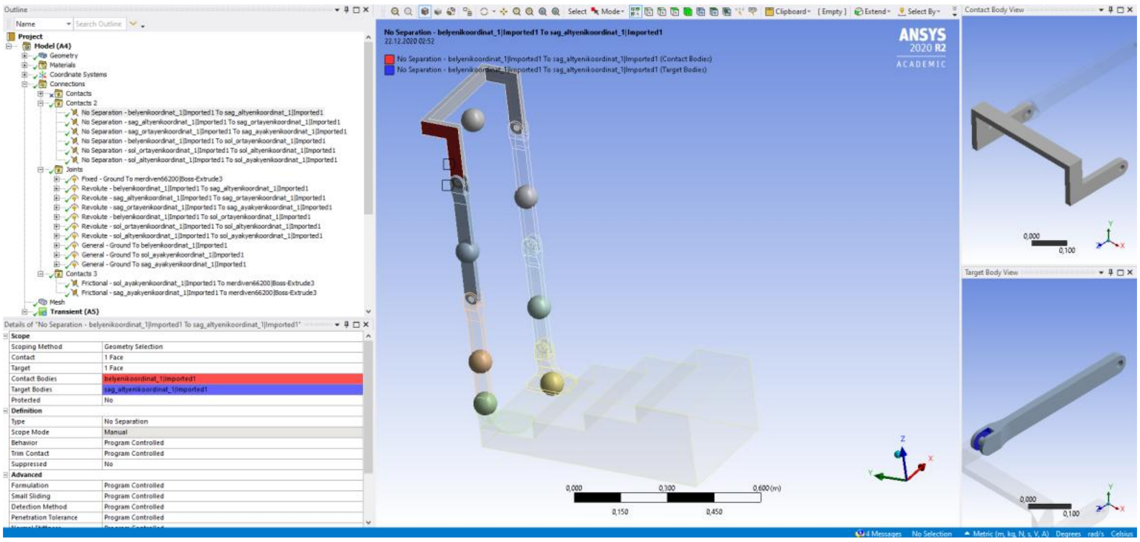


Figure 68 : Connections of the Dynamic Analysis of Stair Gait Cycle in ANSYS

Subsequently, the bottom of the floor used as the base in walking analysis is defineed as Fixed type Body-Ground connection. For each joint, Body-Body, Revolute joints are assigned. General type Body-Ground translations free rotations fix contacts are assigned for the contact of the feet with the floor. Contacts between the feet and the ground is assigned as Frictional and friction coefficient 0.2.

Meshing section is assigned with Mechanical Physics Preference and Linear Element Order, also mesh statistics are as seen in the Figure 69. The reason for determining the number of mesh is too low is that the process time of dynamic analysis is too long and the number of mesh in ANSYS student version is limited.

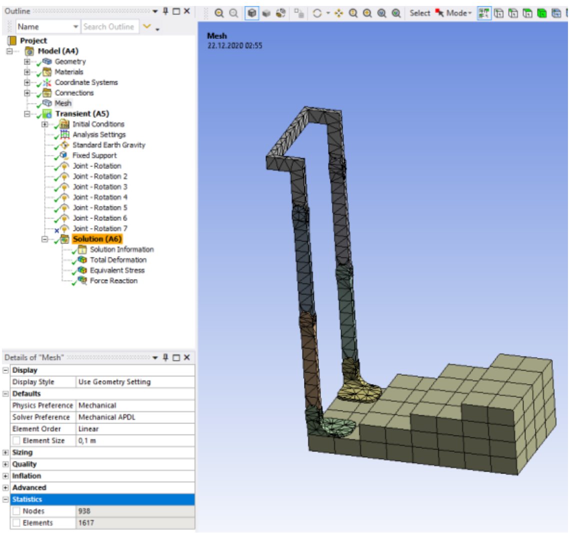


Figure 69 : Meshing for Dynamic Analysis of Stair Gait Cycle in ANSYS

For the Transient, firstly Standard Earth Gravity was assigned in (-z) direction. Afterwards, joint-rotations were assigned using revolute joint contacts using time-rotation angles tabular datas.

In the solution, equivalent (von-Mises) stress for all bodies is examined. As can be seen in the figure ?, maximum von-Mises stress is 175.46 Mpa in the left ankle for dynamic stair gait analysis.

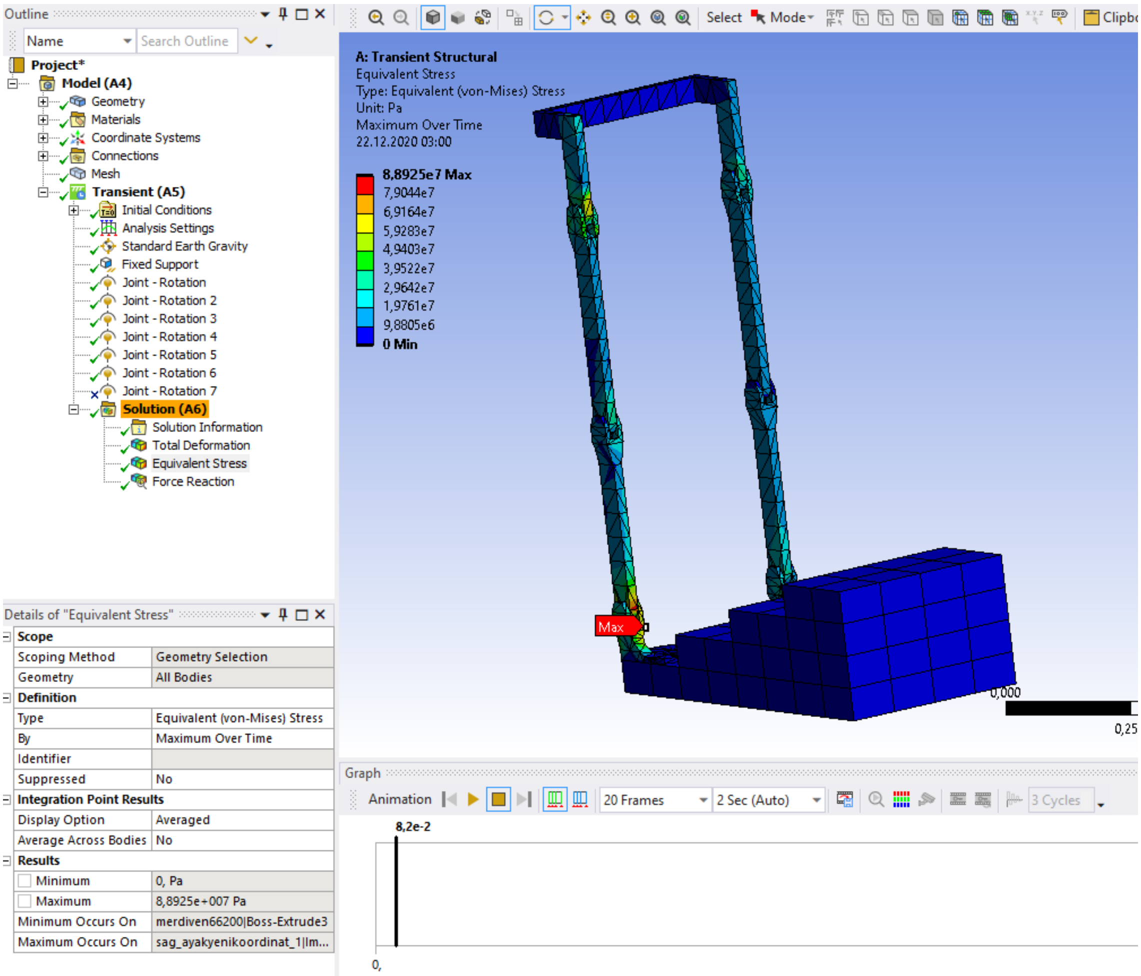


Figure 70 : Equivalent (von-Mises) Stress Solution for Dynamic Analysis of Stair Gait Anlysis in ANSYS

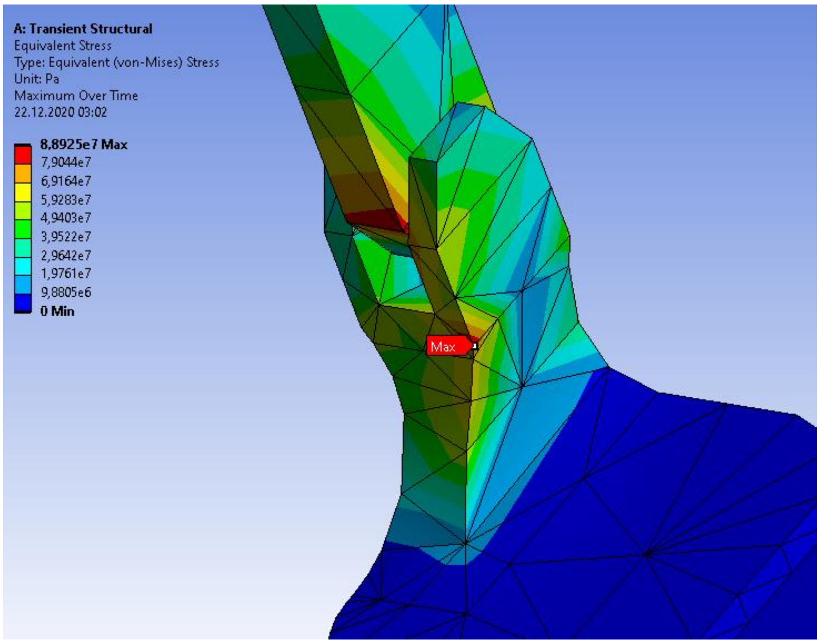


Figure 71 : Maximum Equivalent (von-Mises) Stress for Left Ankle in ANSYS

Ground's reaction force during walking analysis was examined. The reaction force when one foot touches the ground is 3.4 kN in the + Z direction throughout the simulation.

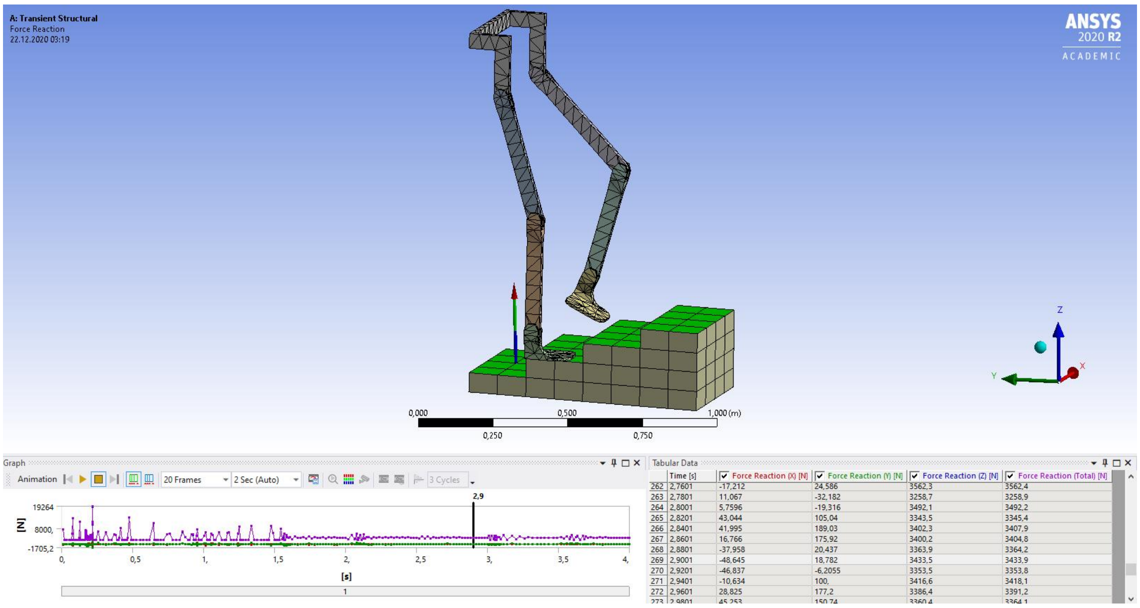


Figure 72 : Reaction Forces for Stair Gait Cycle Analysis in ANSYS

In the article named **Running in highly cushioned shoes increases leg stiffness and amplifies impact loading**[19], the ground reaction forces of an athlete running at 10 km / h were examined. As can be seen in the graph below, the reaction force is 3 times body weight at the point where the reaction force is maximum. (For the exoskeleton we examined, if we assume a total weight of 120 kg with the backpack load, this reaction force is approximately 3x120x9.81 = 3531.6 N.) Although the exoskeleton user in our simulation is climbing stairs, the reaction force is approximately equal that in this article.

6.2.2 Static Analysis

The 9 phases of 4 seconds that examined in Stair Gait Analysis for static analysis were saved separately in Solidworks as STEP AP203 (.step) extension and imported into ANSYS Workbench using Static Structural Analysis System.

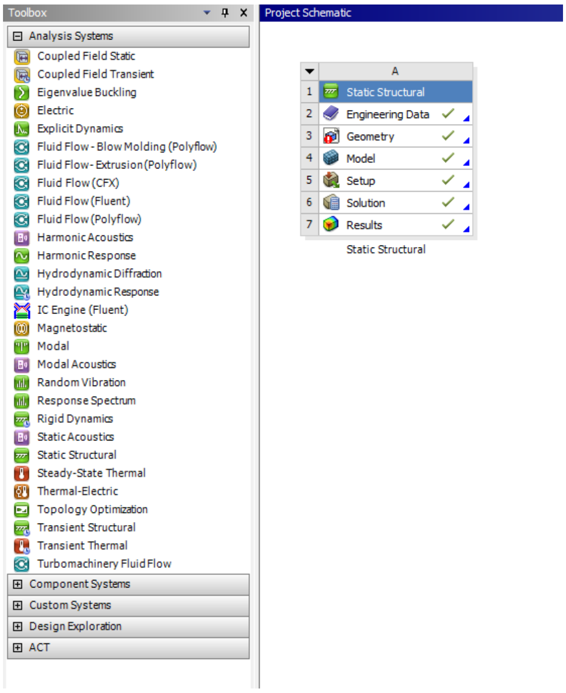


Figure 73 : Static Structural Analysis System for Static Analysis of Stair Gait Cycle

In the model, 7 Point Mass have been assigned for exoskeleton user weights as in the dynamic analysis. These are respectively, upper body 60.1 kg + backpack weight 25 kg, each of the upper legs 4.8 kg, each of the lower legs 1.95 kg, each of the feet 0.7 kg. As the material, structural steel was used in the analyzes shown below. Later, analyzes were made with different materials and material selection was discussed in the optimization section. Automatically assigned contacts are used in the connections section.

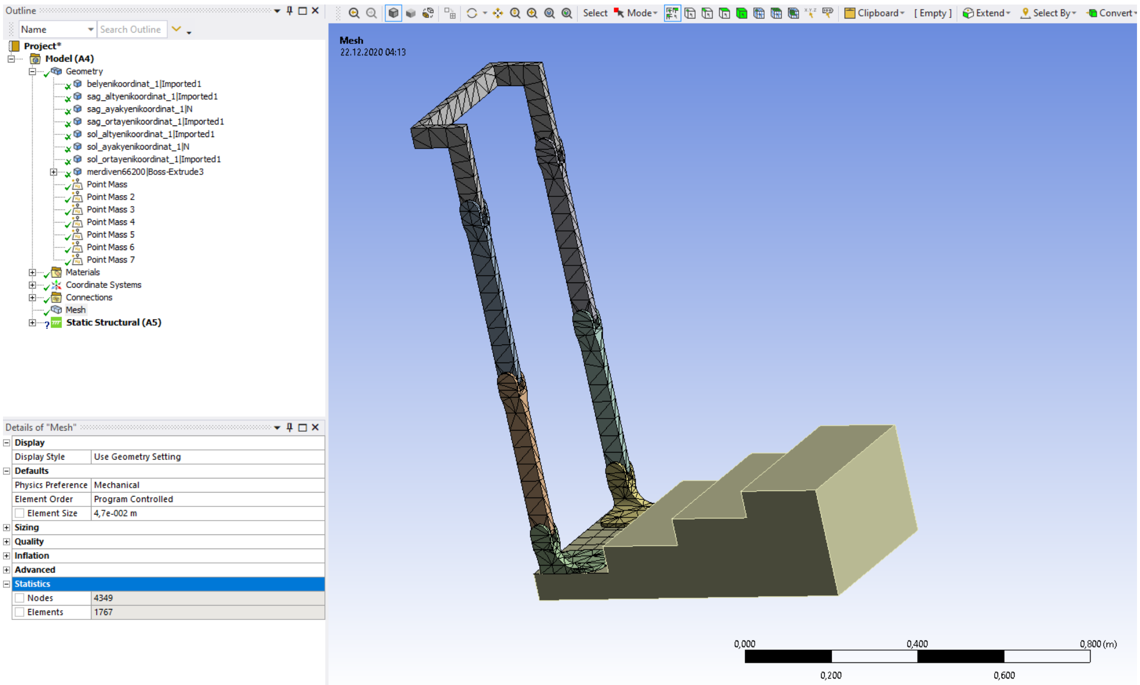


Figure 74 : Meshing for Static Analysis in ANSYS

For the Structural, Standard Earth Gravity was assigned in (-z) direction. Fixed support is defined under the floor used as the base in walking analysis.

In the 0 s., static analysis is examined in case both feet are in contact with the ground and the body is upright. As seen in the figure, maximum von-Mises stress is 2.33 MPa in the ankle.

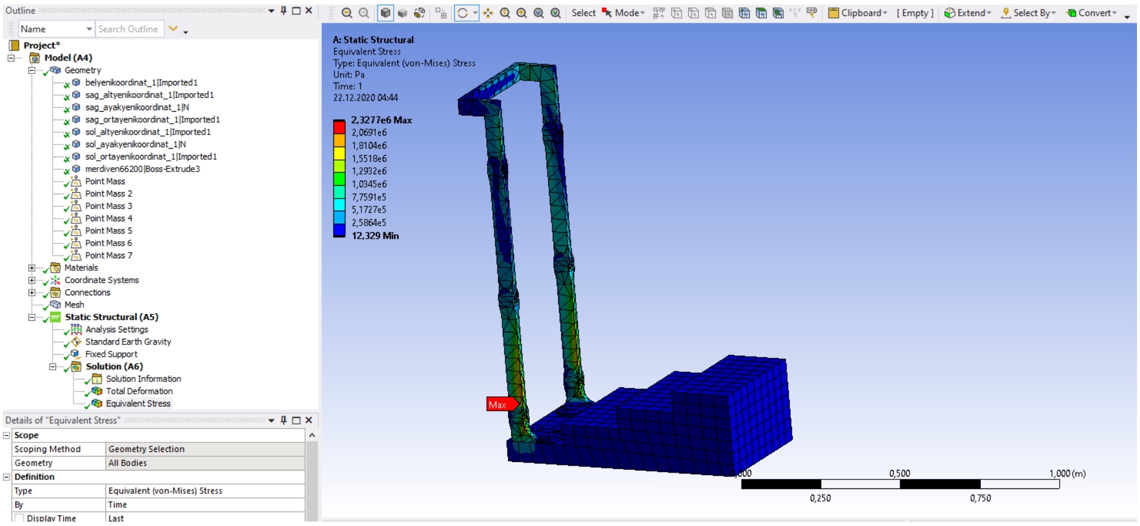


Figure 75 : Equivalent (von-Mises) Stress Solution at 0 s. for Static Analysis in ANSYS

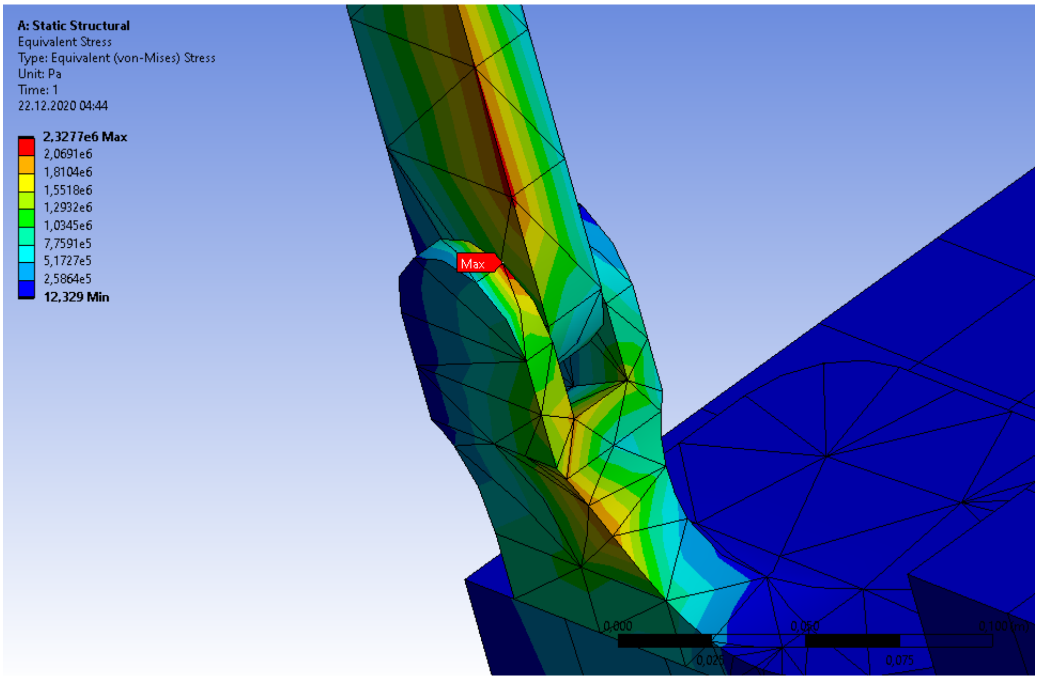


Figure 76 : Maximum Equivalent (von-Mises) Stress at 0 s. for Right Ankle in ANSYS

At the 0.5 s. as seen in the Figure, the left foot is contact with the ground and the angles in right leg joints are 36.56° on the left hip, 68.51° on the knee and 3.55° on the ankle. Static analysis results in this case were examined. As can be seen in the figure, maximum equivalent von-Mises stress is 306.26 MPa in the left ankle.

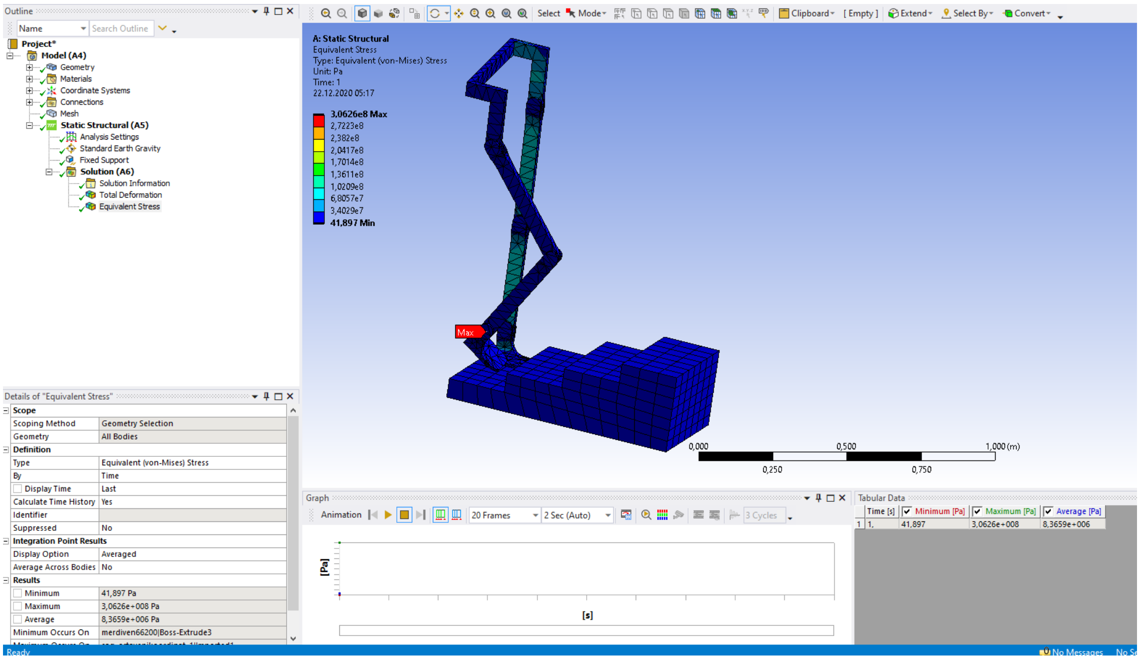


Figure 77 : Equivalent (von-Mises) Stress Solution at 0.5 s. for Static Analysis in ANSYS

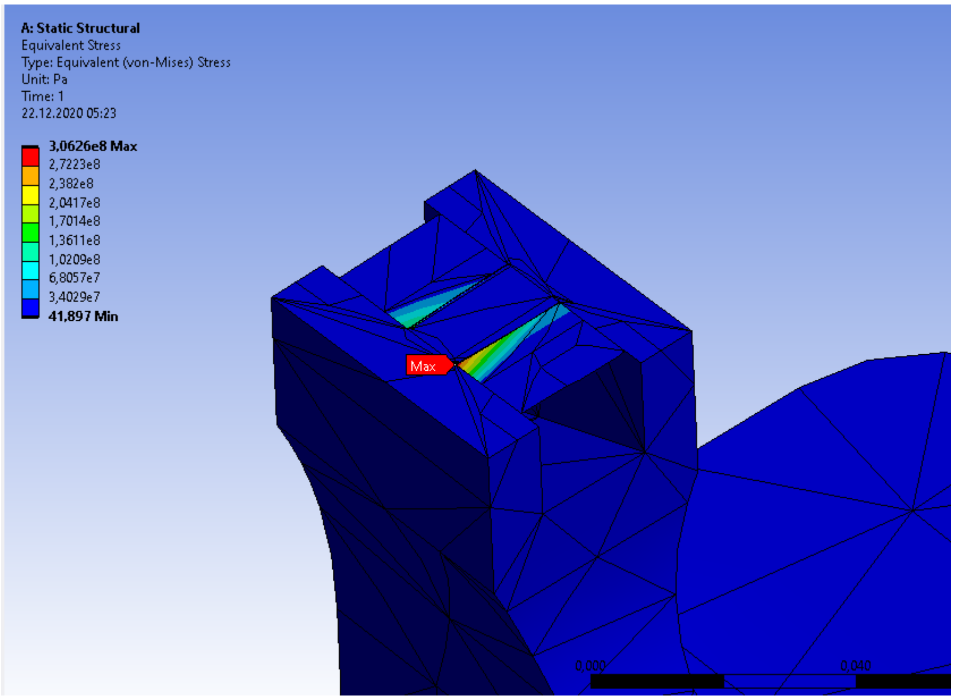


Figure 78 : Maximum Equivalent (von-Mises) Stress at 0.5 s. for left Ankle Section view in ANSYS

At the 1 s., the left foot is in contact with the ground and the angles in right leg joints are 44.02° on the hip, 57.76° on the knee and 9.47° on the ankle. Static analysis results in this case were examined. As can be seen in the figure, maximum equivalent von-Mises stress is 301.73 MPa in the right ankle.

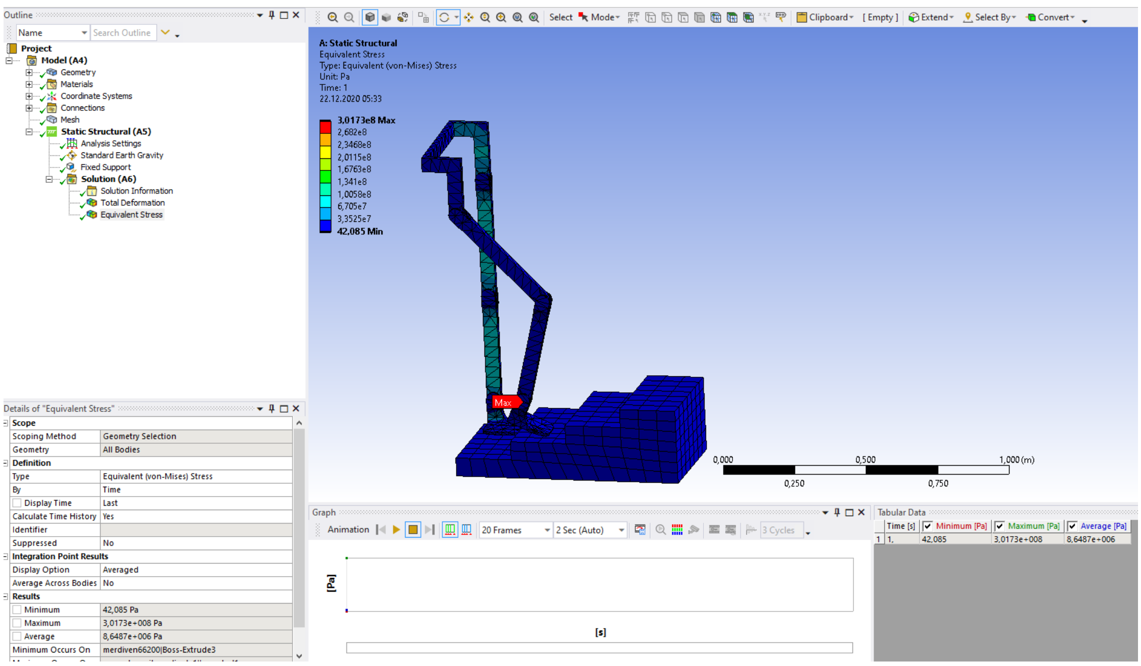


Figure 79 : Equivalent (von-Mises) Stress Solution at 1 s. for Static Analysis in ANSYS

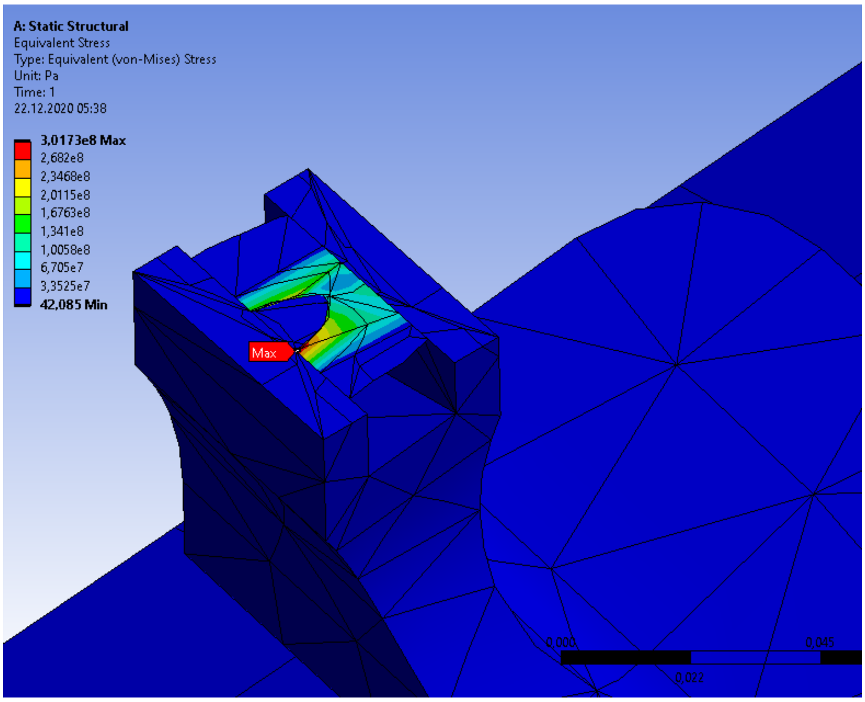


Figure 80 : Maximum Equivalent (von-Mises) Stress at 1 s. for Right Ankle Section view in ANSYS

At the 1.5 s., both feet are in contact with the ground. The angles in right leg joints are 32° on the hip, 35.41° on the knee and 3.42° on the ankle; the angles in left leg joints are 0° on the hip, 0° on the knee and 0° on the ankle. Static analysis results in this case were examined. As can be seen in the Figure, maximum equivalent von-Mises stress is 15.40 MPa in the right knee.

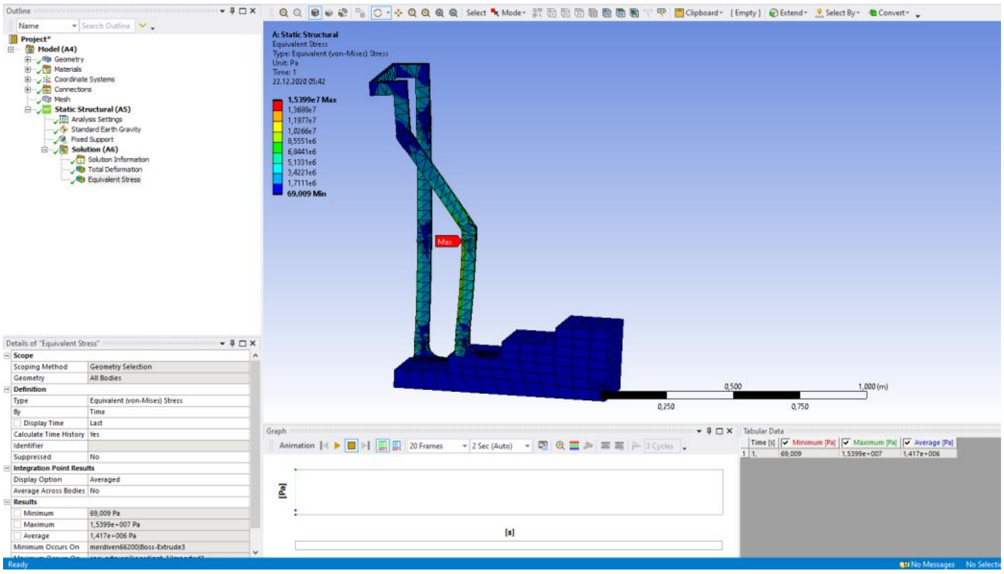


Figure 81 : Equivalent (von-Mises) Stress Solution at 1.5 s. for Static Analysis in ANSYS

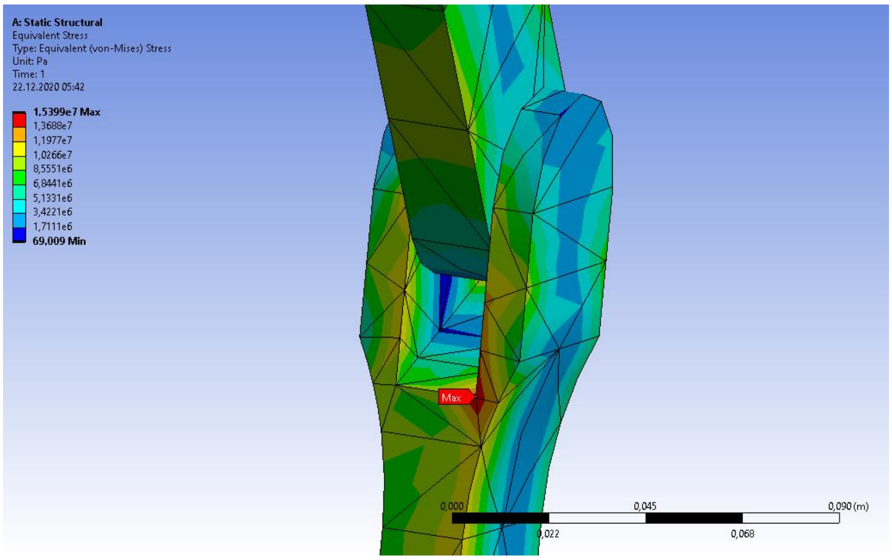


Figure 82 : Maximum Equivalent (von-Mises) Stress at 1.5 s. for Right Knee in ANSYS

At the 2 s., the angles in right leg joints are 16.73° on the hip, 17.45° on the knee and 0.72° on the ankle; the angles in left leg joints are 10.84° on the hip, 29.94° on the knee and 9.46° on the ankle. Static analysis results in this case were examined. As can be seen in the Figure, maximum equivalent von-Mises stress is 389.55 MPa in the left ankle.

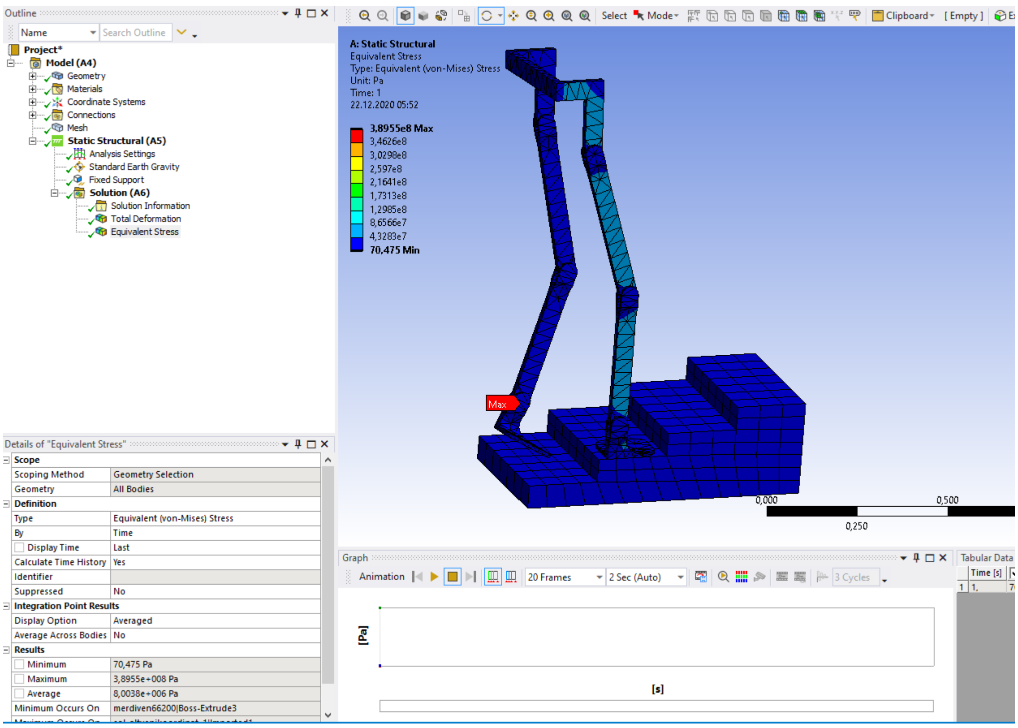


Figure 83 : Equivalent (von-Mises) Stress Solution at 2 s. for Static Analysis in ANSYS

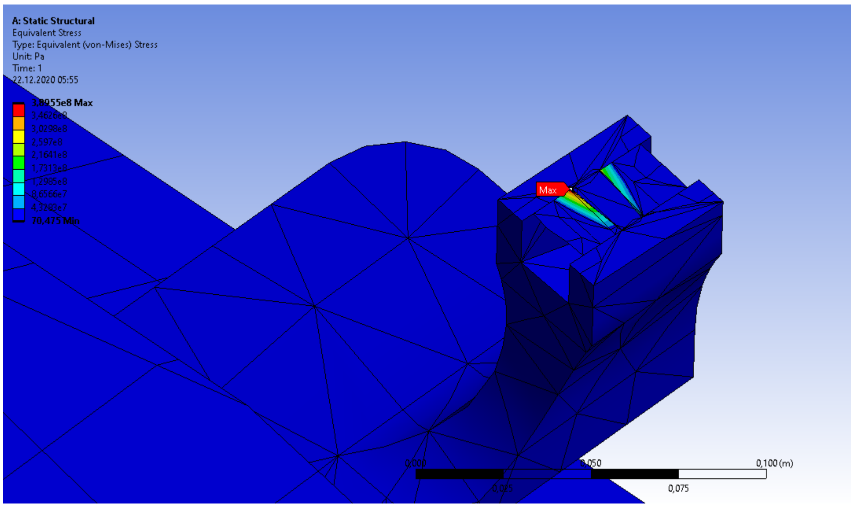


Figure 84 : Maximum Equivalent (von-Mises) Stress at 2 s. for Left Ankle Section View in ANSYS

At the 2.5 s., the angles in right leg joints are 16.73° on the hip, 17.45° on the knee and 0.72° on the ankle; the angles in left leg joints are 32.05° on the hip, 61.17° on the knee and 16.11° on the ankle. Static analysis results in this case were examined. As can be seen in the Figure, maximum equivalent von-Mises stress is 270.78 MPa in the left ankle.

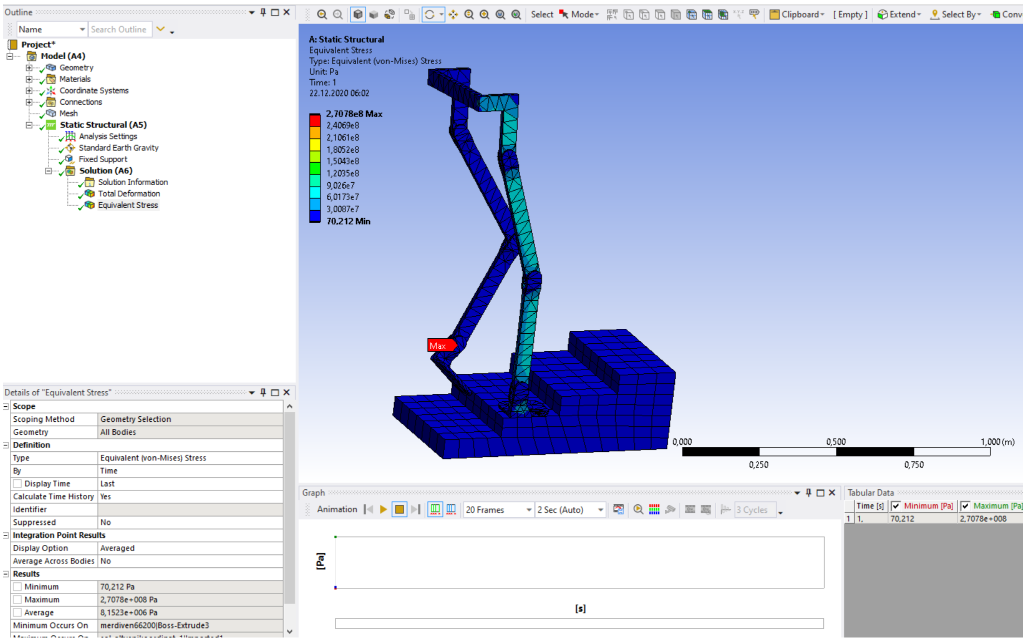


Figure 85 : Equivalent (von-Mises) Stress Solution at 2.5 s. for Static Analysis in ANSYS

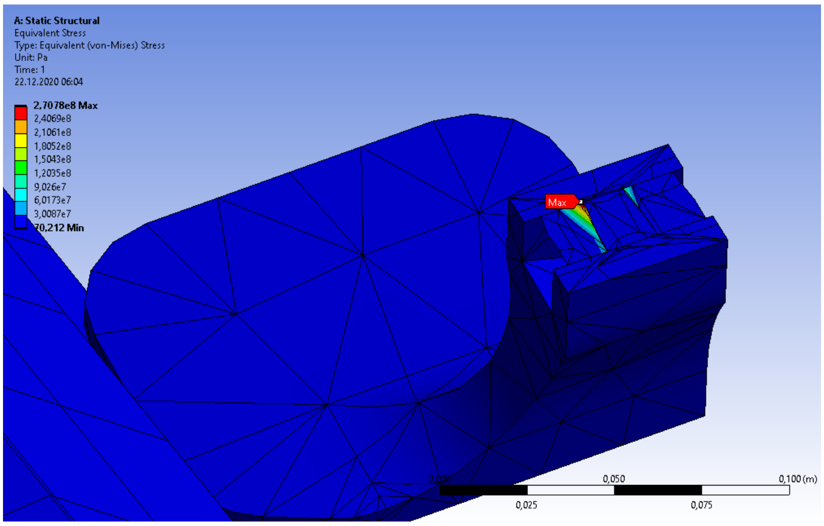


Figure 86 : Maximum Equivalent (von-Mises) Stress at 2.5 s. For Left Ankle Section View in ANSYS

At the 3 s., the angles in right leg joints are 16.73° on the hip, 17.45° on the knee and 0.72° on the ankle; the angles in left leg joints are 47.82° on the hip, 59.78° on the knee and 7.97° on the ankle. Static analysis results in this case were examined. As can be seen in the Figure, maximum equivalent von-Mises stress is 431.27 MPa in the left ankle.

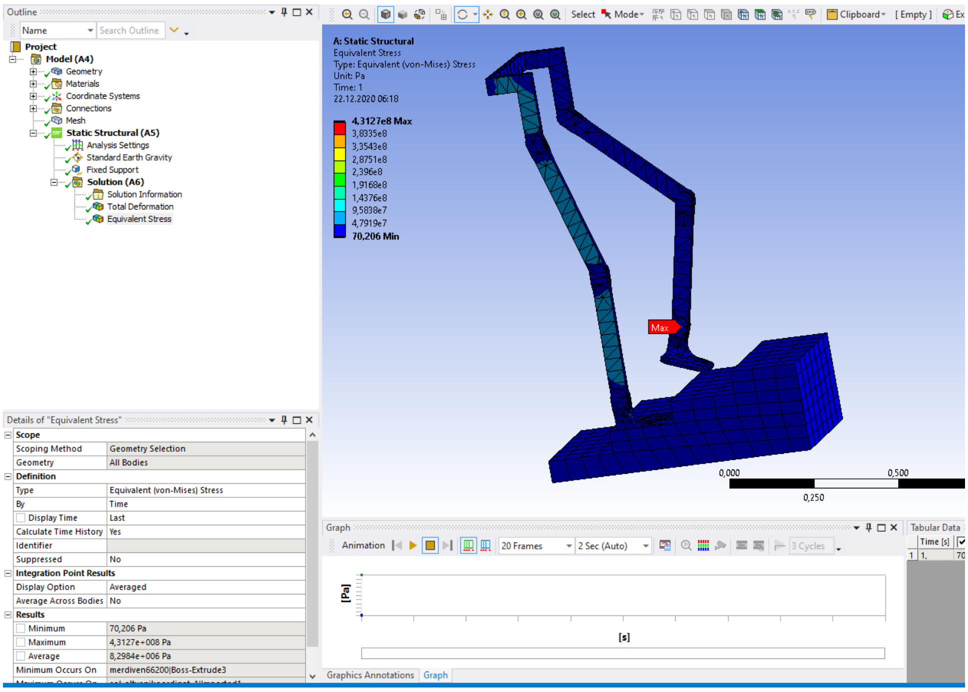


Figure 87 : Equivalent (von-Mises) Stress Solution at 3 s. for Static Analysis in ANSYS

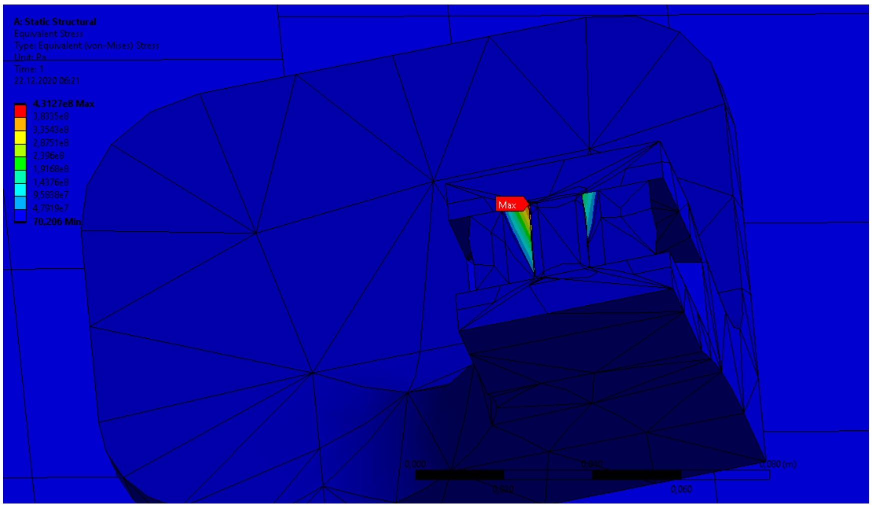


Figure 88 : Maximum Equivalent (von-Mises) Stress at 3 s. For Left Ankle Section View in ANSYS

At the 3.5 s., the angles in right leg joints are 1.21° on the hip, 1.97° on the knee and 0.72° on the ankle; the angles in left leg joints are 32.51° on the hip, 46.3° on the knee and 1° on the ankle. Static analysis results in this case were examined. As can be seen in the Figure, maximum equivalent von-Mises stress is 401.23 MPa in the left ankle.

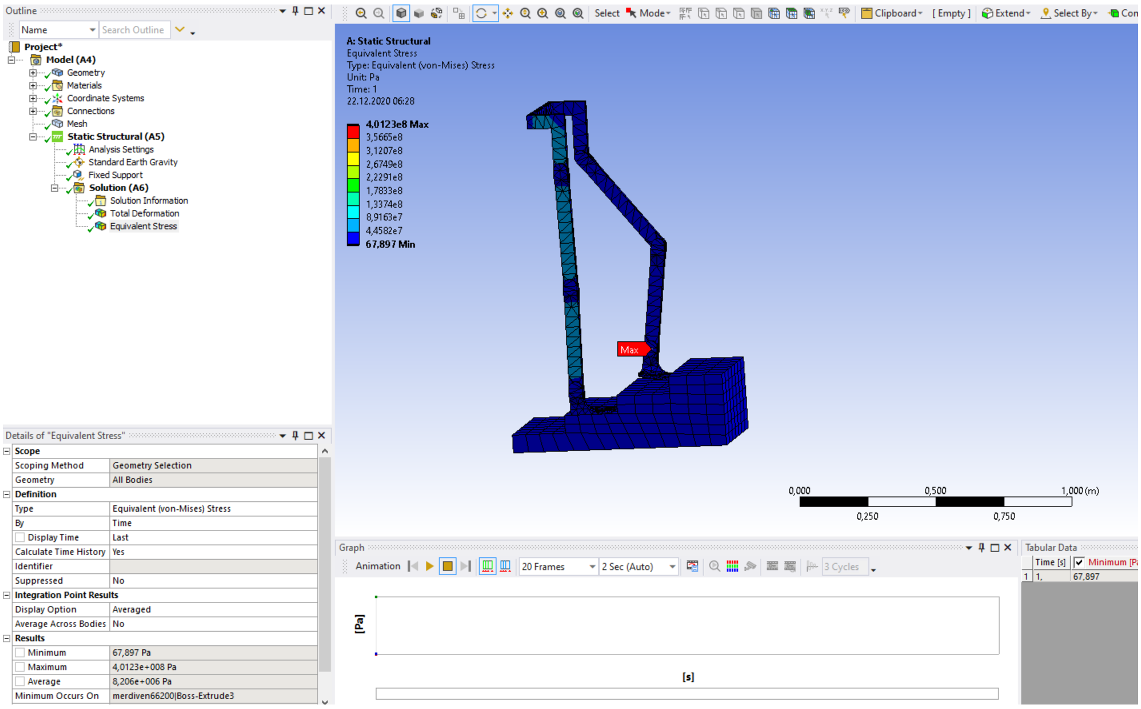


Figure 89 : Equivalent (von-Mises) Stress Solution at 3.5 s. for Static Analysis in ANSYS

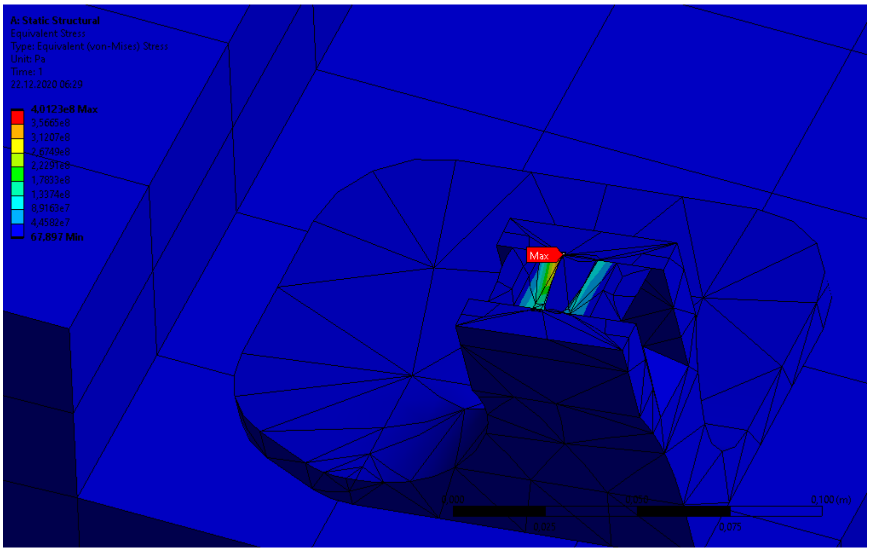


Figure 90 : Maximum Equivalent (von-Mises) Stress at 3.5 s. For Left Ankle Section View in ANSYS

At the 4 s., the angles in right leg joints are 0° on the hip, 0° on the knee and 0° on the ankle; the angles in left leg joints are 32.51° on the hip, 36.99° on the knee and 5.2° on the ankle. Static analysis results in this case were examined. As can be seen in the Figure, maximum equivalent von-Mises stress is 13.03 MPa in the left knee.

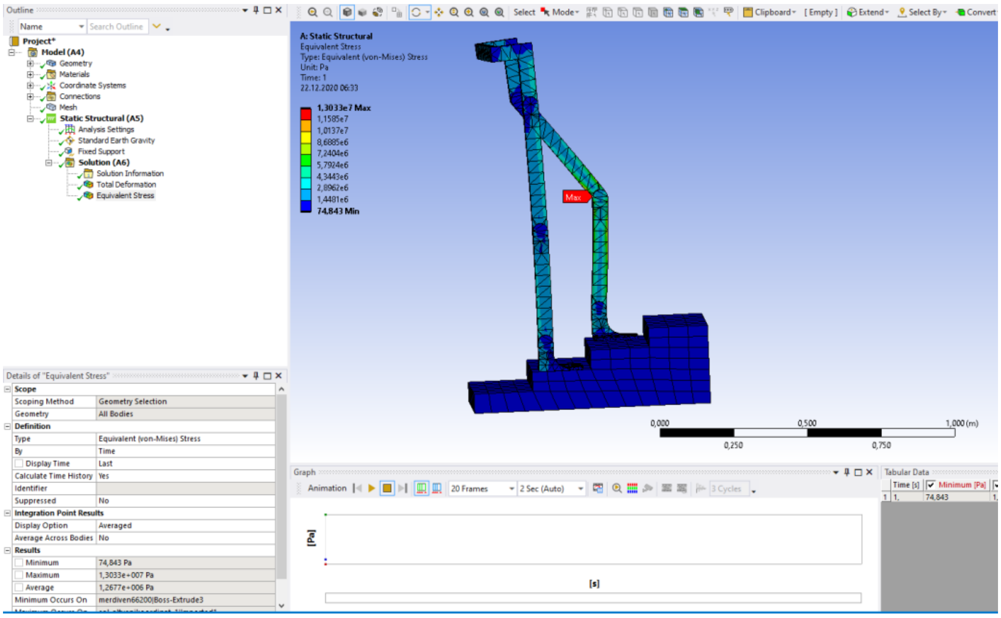


Figure 91 : Equivalent (von-Mises) Stress Solution at 4 s. for Static Analysis in ANSYS

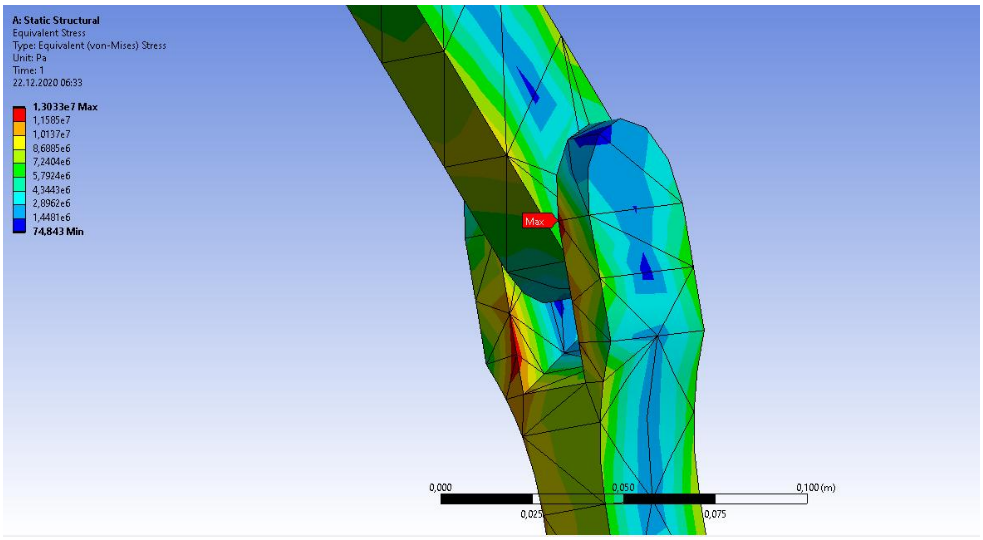


Figure 92 : Maximum Equivalent (von-Mises) Stress at 4 s. For Left Knee Section View in ANSYS

7. OPTIMIZATION OF MATERIAL AND ACTUATOR SELECTION

7.1 Actuator Selection

After analyzing the kinematic analysis of the exoskeleton and joint torque equation, simulation values that made with MATLAB/Simmechanics were taken into consideration for the actuator selection since the required torque values in the simulation were higher. These values can be seen in the Exoskeleton Walking Simulation section, for the hip, the maximum peak torque is 231.1 N.m, the maximum continuous torque is 22.9 N.m; for the knee, the maximum peak torque is 54.4 N.m, the maximum continuous torque is 15 N.m; for the ankle, the maximum peak torque is 185 N.m and the maximum continuous torque is 36 N.m. The following actuators are comparde for the actuator selection to be made according to these values.

	Hip	Knee	Ankle
Maximum Peak Torque(N.m)	231.1	54.4	185
Maximum Continuous Torque(N.m)	22.9	15	36

Table 8 : Maximum Required Torque Values for Joint Actuators for Simulation

Item / Model		FHA-17C					FHA-25C					FHA-32C					FHA-40C				
Gear Ratio		50	80	100	120	160	50	80	100	120	160	50	80	100	120	160	50	80	100	120	160
Max torque	Nm	39	51	57	60	64	150	213	230	247	260	281	364	398	432	453	500	659	690	756	820
Max Speed of Rotation	rpm	96	60	48	40	30	90	56	45	37	28	80	50	40	33	25	70	43	35	29	22
Torque Constant 200VAC	Nm/Arms	21	33	42	50	67	22	36	45	54	72	27	43	54	64	86	31	51	64	76	102
Torque Constant 100VAC	Nm/Arms	11	17	21	25	33	11	17	22	26	36	16	26	33	39	52	-	-	-	-	-
Moment of Inertia($GD^2/4$)	$kg.m^2$	0.17	0.43	0.67	0.97	1.7	0.81	2.1	3.2	4.7	8.3	1.8	4.5	7.1	10.2	18.1	4.9	12.5	19.5	28.1	50

Table 9 : Harmonic Drive FHA-C Specs Rotary Actuators with Reducers[18]

Figure 93 : Harmonic Drive Rotary Actuator FHA-C[18]

	Hip	Knee	Ankle
Model	FHA-25C	FHA-17C	FHA-25C
Maximum Peak Torque(N.m)	247	57	213
Maximum Continuous Torque(N.m)	26	21	36

Reduction Ratio	120	100	80
Weight(kg)	4	2.5	4

Table 10 : Selected Actuators with Reducers Specs for Hip, Knee and Ankle Joints

As can be seen in the Exoskeleton Walking Simulation section, the leaps in Figure 38 and Figure 39 are lower in real human walking analysis. For that reason, lighter actuators that produce lower maximum peak torque than the actuators selected above can be selected.

7.2 Material Selection

Dynamic and static analysis was first performed with Structural Steel material. Afterwards, the materials whose properties are compared in the table 8 below are examined for the selection of suitable materials for the exoskeleton.

Material\Specifications	Density(kg/m^3)	Tensile Yield Strength(MPa)	Tensile Ultimate Strength(MPa)
Structural Steel	7850	250	460
Stainless Steel	7750	207	586
Aluminum Alloy(2024, T6)	2770	363	449
Aluminum Alloy(6061, T6)	2710	259	313
Low Alloy Steel(4340,heat treated)	7850	1070	1170
Martensitic Stainless Steel	7750	762	840
Low Alloy Steel(4140,normalized)	7850	652	1015
Stainless Steel(316, annealed)	7969	252	565

Table 11 : Material Properties for Material Selection with Different Materials

Dynamic analysis and 9 phases of static analysis were examined separately with these materials.

	Maximum von-Mises Stress(MPa)					
Analysis\Material	Structural Steel	Stainless Steel	Aluminum Alloy(2024,T6)	Aluminum Alloy(6061,T6)	Low Alloy Steel(4340)	Martensitic Stainless Steel
Dynamic Analysis	175.46	167.11	100.96	282.5	245.38	71.74
Static Analysis – Standing Straight	2.52	2.52	2.33	2.32	2.52	2.51
Static Analysis 2nd Phase	156.05	155.2	133.15	133.12	156.74	157.15
Static Analysis 3rd Phase	334.17	331.42	281.53	282.05	336.03	336.97
Static Analysis 4th Phase	10.06	10.06	9.11	9.09	10.05	10
Static Analysis 5th Phase	264.01	262.14	225.01	225.27	265.22	265.75
Static Analysis 6th Phase	248.36	246.45	211.41	211.77	249.64	250.29
Static Analysis 7th Phase	276.21	274.33	235.03	235.23	277.38	277.84
Static Analysis 8th Phase	10.45	10.45	9.63	9.61	10.43	10.39

Table 12 : Dynamic and Static Analysis for Gait Cycle Maximum von-Mises Stress Values for Different Material

	Maximum von-Mises Stress(MPa)					
Analysis\Material	Structural Steel	Stainless Steel	Aluminum Alloy(2024,T6)	Aluminum Alloy(6061,T6)	Low Alloy Steel(4140)	Stainless Steel(316,annealed)
Dynamic Analysis	88.93	136.91	34.95	31.92	-	-
Static Analysis – Standing Straight	2.52	2.52	2.33	2.33	2.52	2.53
Static Analysis - 0.5s	306.26	303.92	260.87	260.42	307.80	311.90
Static Analysis - 1s	301.73	299.50	257.16	256.71	303.19	307.19
Static Analysis - 1.5s	15.40	15.39	14.15	14.13	15.38	15.38
Static Analysis - 2s	389.55	386.33	330.35	329.76	391.74	397.48
Static Analysis - 2.5s	270.78	268.70	229.95	229.54	272.15	275.84
Static Analysis - 3s	431.27	427.67	364.33	363.67	433.71	440.11
Static Analysis - 3.5s	401.23	398.01	339.03	338.40	403.36	409.00
Static Analysis - 4s	13.03	13.04	12.02	12.00	13.00	12.97

Table 13 : Dynamic and Static Analysis for Stair Gait Cycle Maximum von-Mises Stress Values for Different Materials

As can be seen in the table 9, dynamic and static analysis with different materials are examined. As a result of this examination, the values seen in dynamic and static analyzes with Structural Steel, Stainless Steel and Aluminum Alloy (6061,T6) exceeded the Tensile Yield Strength values of that material. For Aluminum Alloy (2024,T6), Low Alloy Steel (4340), Martensitic Stainless Steel, Low Alloy Steel (4140) and Stainless Steel(316), the maximum von-Mises Stress values are suitable and these materials are compared by looking at the lightness and safety factor criteria.

Compared to the lightness, the weights of Martensitic Stainless Steel and Low Alloy Steel (4340) are close together, but Aluminum Alloy (2024,T6) is 2.8 times lighter than them. Safety Factor is calculated with the formula;

$$Safety\ Factor = \frac{Tensile\ Yield\ Strength}{Maximum\ von - Mises\ Stress}$$

and it is 0.99 for Aluminum Alloy (2024,T6), 1.94 for Low Alloy Steel (4140), 1.50 for Low Alloy Steel(4140,normalized),

Although Aluminum Alloy (2024,T6) is lightweight, due to the low Safety Factor, it has been decided that the appropriate material is Low Alloy Steel (4140).

8. RESULTS and CONCLUSION

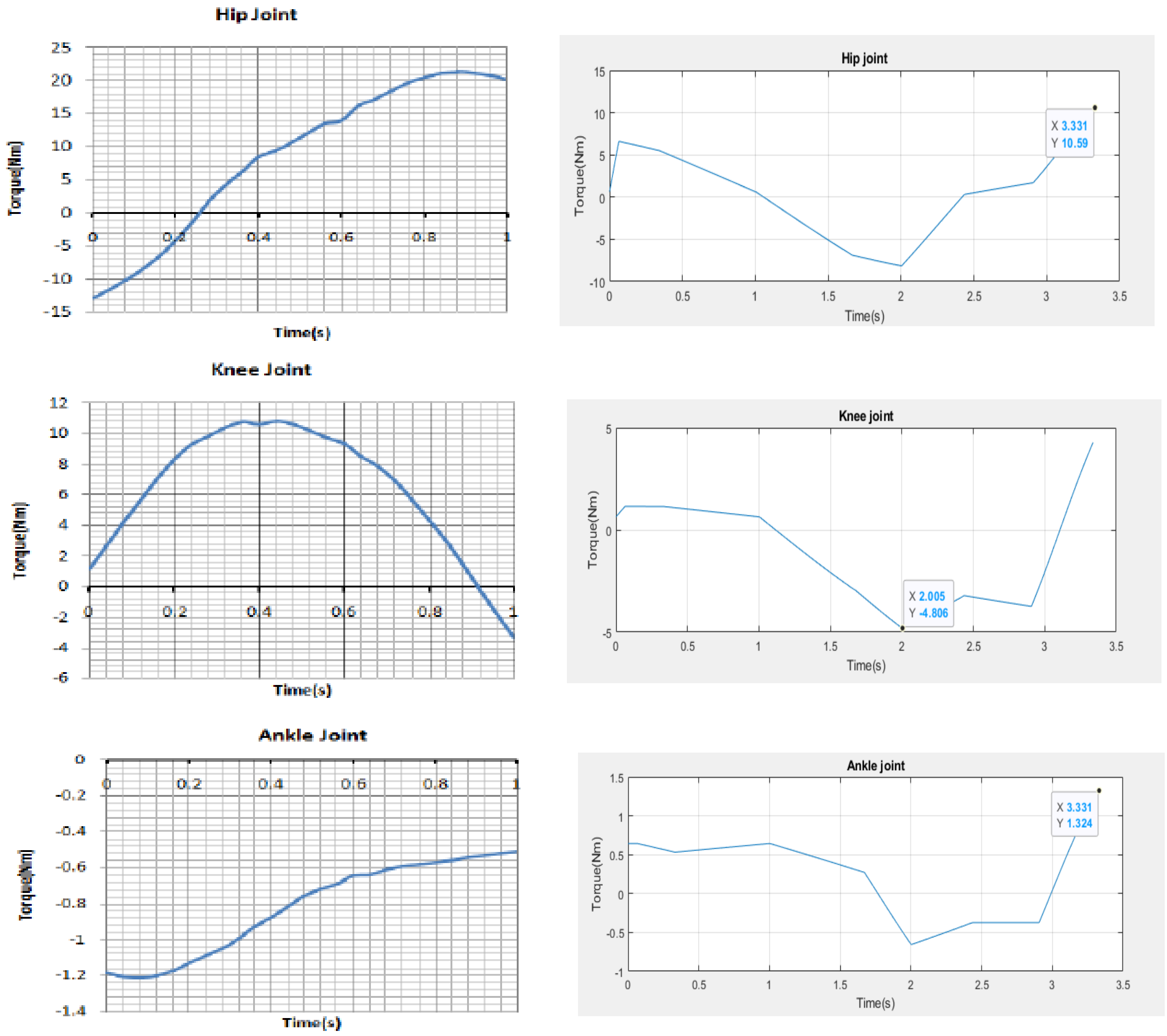
Firstly, the main article "TORQUE ANALYSIS OF THE LOWER LIMB EXOSKELETON ROBOT DESIGN"[1], which is helpful in preparing the project, is examined. Subsequently, exoskeletons developed for military purposes were examined and reported.

In section 2, for Kinematic Analysis, the relationship between joint angles and positions using Denavit-Hartenberg Representation is defined by creating Joint-Torque equations using forward kinematic and inverse kinematic.

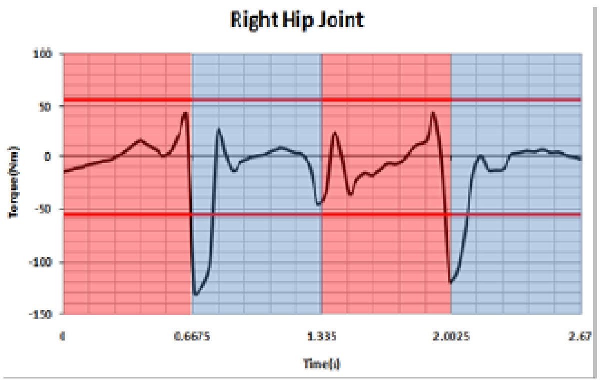
Using MATLAB Software, the maximum required torque value for Hip Joint is 10.59 N.m, the maximum required torque value for Knee Joint is 4.81 N.m and the maximum required torque value for Ankle Joint is 1.32 N.m. In the Mechanical Design section, the features used for each component of the designed exoskeleton are explained.

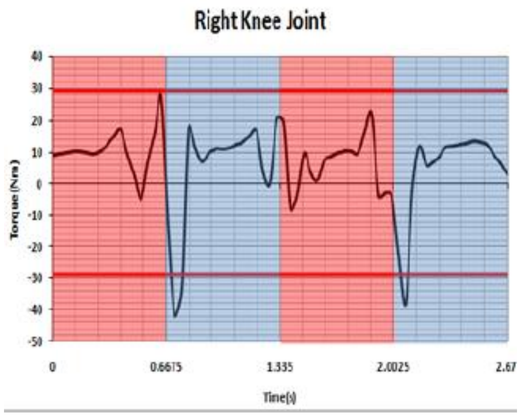
Based on the information obtained as a result of the Gait Cycle research, walking was simulated with the MATLAB / Simulink software. Thus, for the hip, the maximum peak torque is 231.1 N.m, the maximum continuous torque is 14 N.m. For the knee, the maximum peak torque is 54.4 N.m, the maximum continuous torque is 6.9 N.m. For the ankle, the maximum peak torque is 7.74 N.m, the maximum continuous torque is 0.35 N.m. For the right leg(contact with the ground), for the hip, the maximum peak torque is 156 N.m, the maximum continuous torque is 22.9 N.m. For the knee, the maximum peak torque is 19.1 N.m, the maximum continuous torque is 15 N.m. For the ankle, the maximum peak torque is 185 N.m, the maximum continuous torque is 36 N.m.

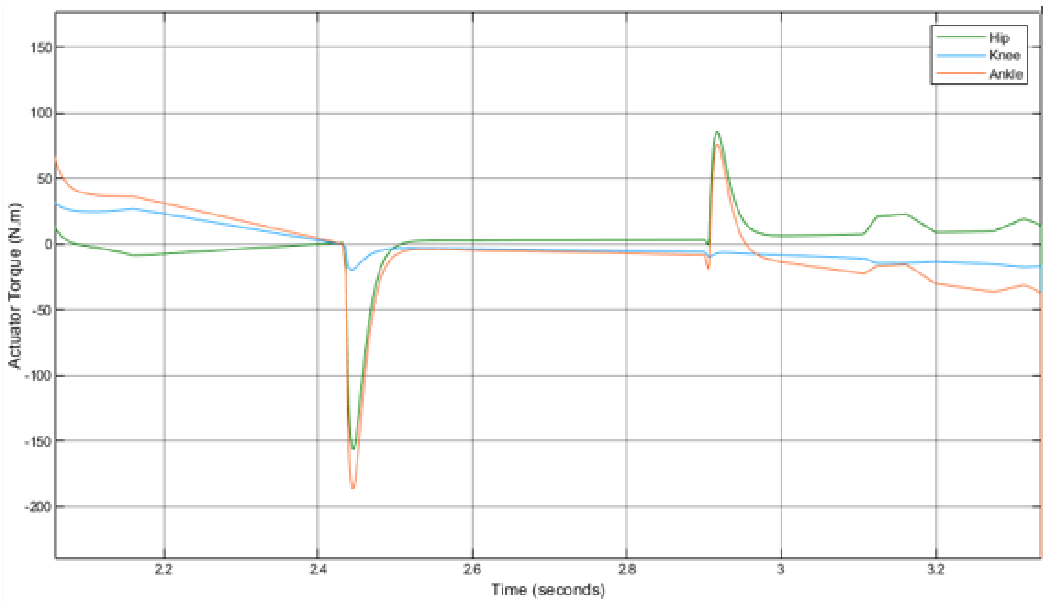
Afterwards, dynamic and static analysis for Gait Cycle and Stair Gait Cycles are examined. Based on the results obtained here, the material to be selected was decided as Low Alloy Steel, based on the tables in section 7.



In the figure above, Graph of torque against time for joints in the main article and Graph of torque against time for joints resulting from our kinematic analysis are compared. The required torque values are close to each other, although they do not exactly match each other.







When we compare the simulation of the main article with our simulation, it is seen that the required maximum torque values are very close for hip joints and knee joints, but our maximum torque value for ankle is too high. In the main article, the maximum value of torque in terms of magnitude for hip joint is 130 N.m, for knee joint is 42 N.m and for ankle joint is 4 N.m. But in our simulation, for the hip, the maximum peak torque is 231.1 N.m, for the knee, the maximum peak torque is 54.4 N.m and for the ankle, the maximum peak torque is 185 N.m. Therefore, the actuator chosen for an ankle joint was chosen from the same actuator that used for hip joint, unlike the main article.

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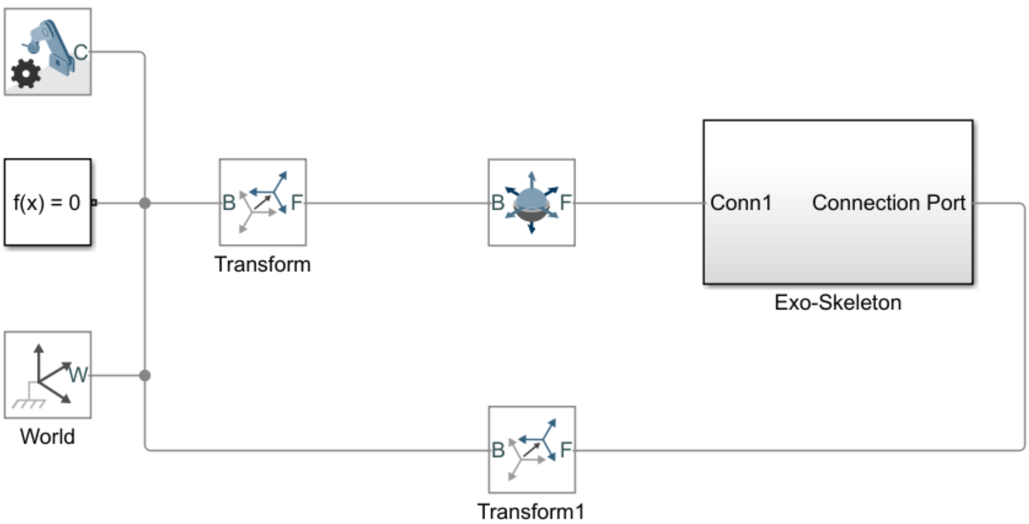
APPENDICES

Appendix A

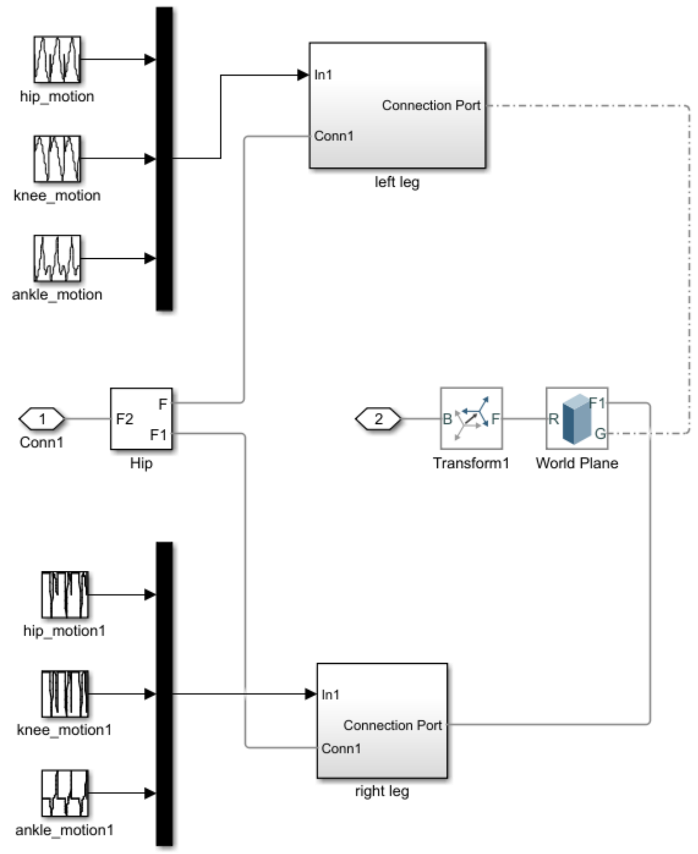
```
theta1=hip_motionleft;        %%  hip angle - degree
theta2=knee_motionleft;       %%  knee angle - degree
theta3=ankle_motionleft;      %%  ankle angle - degree
l1=0.43;                      %%  thigh(femur) length - meter
l2=0.38;                      %%  shank(fibula) length - meter
l3=0.1;                       %%  ankle length - meter
l4=0.123;                     %%  foot length - meter
m_a1=0;                       %%  firstly neglected
m_a2=0;                       %%  firstly neglected
m_a3=0;                       %%  firstly neglected
m_l1=1.3;                     %%  thigh(femur) link mass - kilogram
m_l2=1.2;                     %%  shank(fibula) link mass - kilogram
m_l3=0.9;                     %%  foot link mass - kilogram
m_s1=4.8;                     %%  thigh(femur) mass - kilogram
m_s2=1.95;                    %%  shank(fibula) mass - kilogram
m_s3=0.7;                     %%  foot mass - kilogram
g=9.81;                       %%  m/s^2

T1=(m_l1+m_s1)*sind(theta1)*g*(l1/2)+m_a2*sind(theta1)*g*l1 ...
    +(m_l2+m_s2)*sind(theta1-theta2)*g*(l2/2)+m_a3*sind(theta1-
theta2)*g*l1 ...
    +(m_l3+m_s3)*sind(theta1-theta2-theta3)*g*l3 ...
    +(m_l3+m_s3)*cosd(theta1-theta2-theta3)*g*(l4/3);

T2=(m_l2+m_s2)*sind(theta1-theta2)*g*(l2/2)+m_a3*sind(theta1-
theta2)*g*l1 ...
    +(m_l3+m_s3)*sind(theta1-theta2-theta3)*g*l3 ...
    +(m_l3+m_s3)*cosd(theta1-theta2-theta3)*g*(l4/3);

T3=(m_l3+m_s3)*sind(theta1-theta2-theta3)*g*l3 ...
    +(m_l3+m_s3)*cosd(theta1-theta2-theta3)*g*(l4/3);

subplot(3,2,2)
plot(timeleft,hip_motionleft)
xlabel('Time(s)')
ylabel('Joint Angle(°)')
title('Hip joint')
grid on
subplot(3,2,4)
plot(timeleft,knee_motionleft)
xlabel('Time(s)')
ylabel('Joint Angle(°)')
title('Knee joint')
grid on
subplot(3,2,6)
plot(timeleft,ankle_motionleft)
```

```
xlabel('Time(s)')
ylabel('Joint Angle(°)')
title('Ankle joint')
grid on
subplot(3,2,1)
[m,idx] = max(T1)
plot(timeleft,T1,timeleft(idx),max(T1))
xlabel('Time(s)')
ylabel('Torque(Nm)')
title('Hip joint')
grid on
subplot(3,2,3)
[m,idx2] = max(T2)
plot(timeleft,T2,timeleft(idx2),max(T2))
xlabel('Time(s)')
ylabel('Torque(Nm)')
title('Knee joint')
grid on
subplot(3,2,5)
[m,idx3] = max(T3)
plot(timeleft,T3,timeleft(idx3),max(T3))
xlabel('Time(s)')
ylabel('Torque(Nm)')
title('Ankle joint')
grid on
```

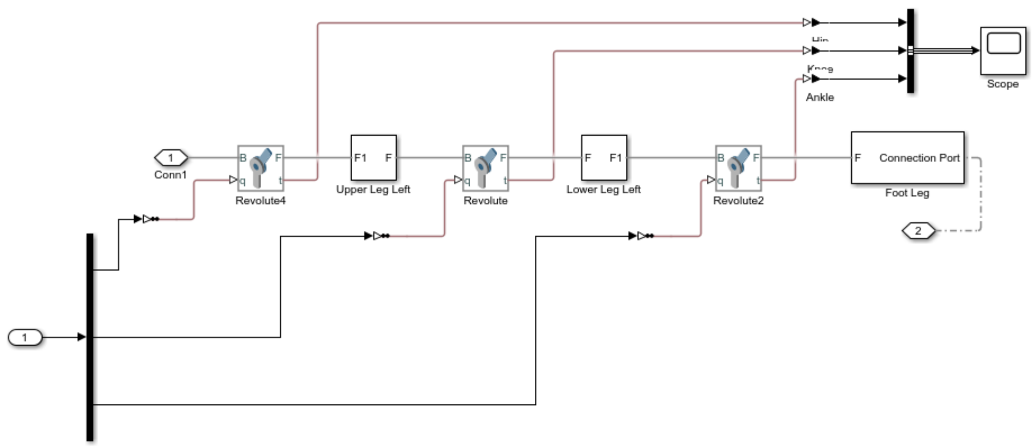
Appendix B



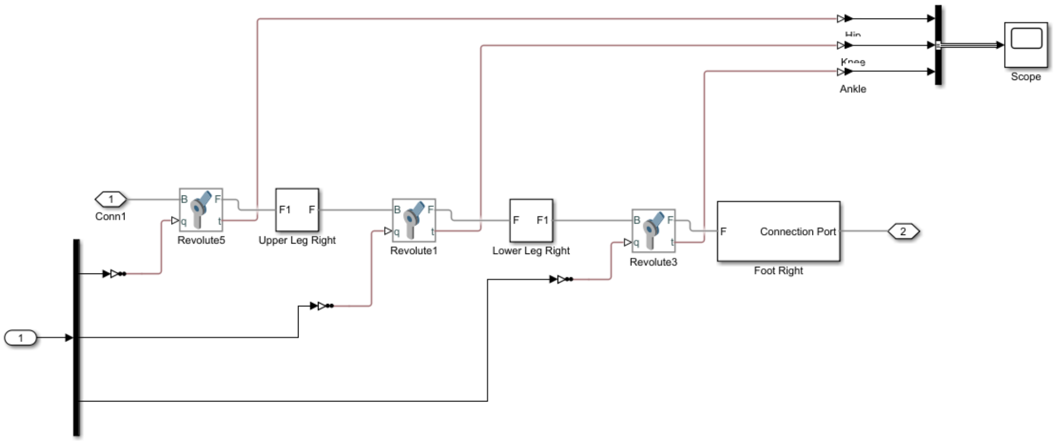
General Simulink Block Diagram of Walking Analysis



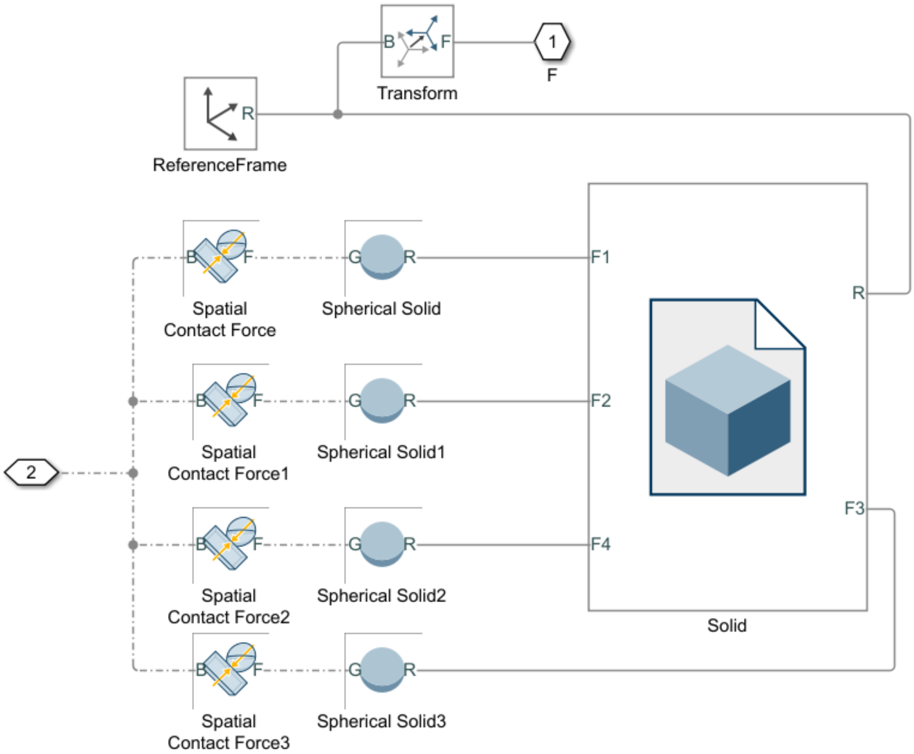
Subsystem of Exoskeleton



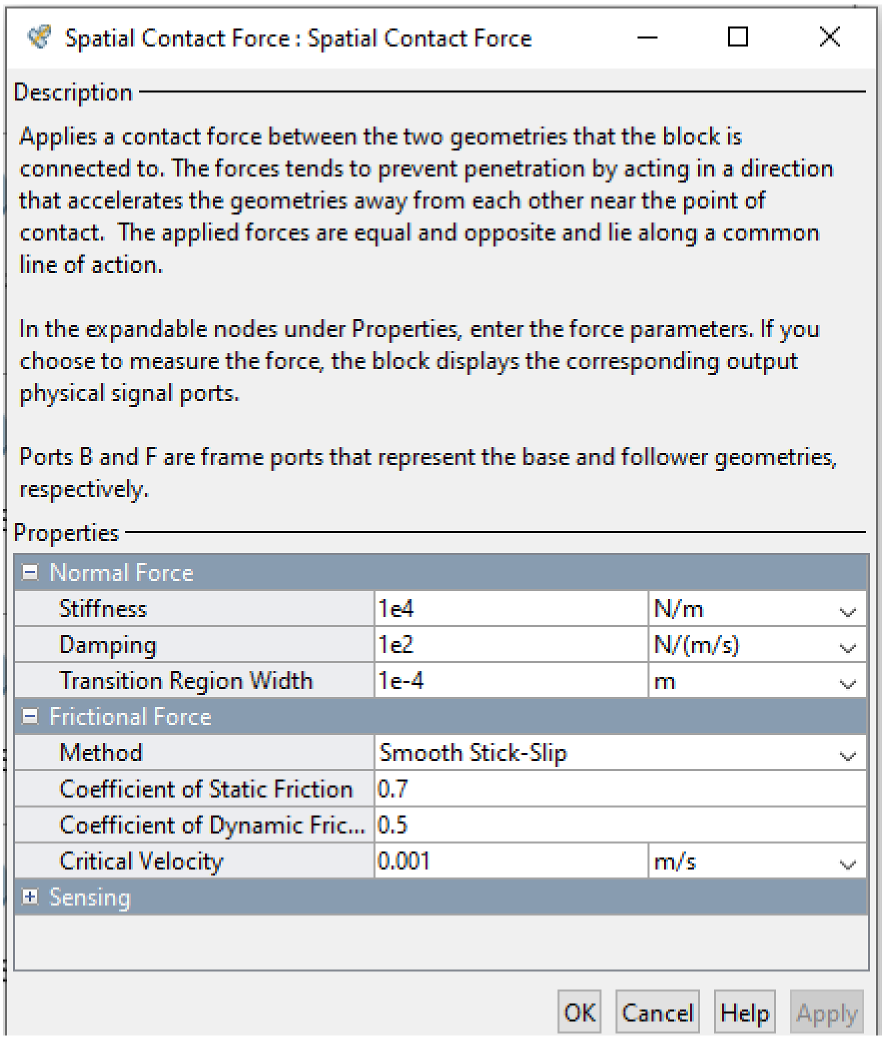
Subsystem of Left Leg



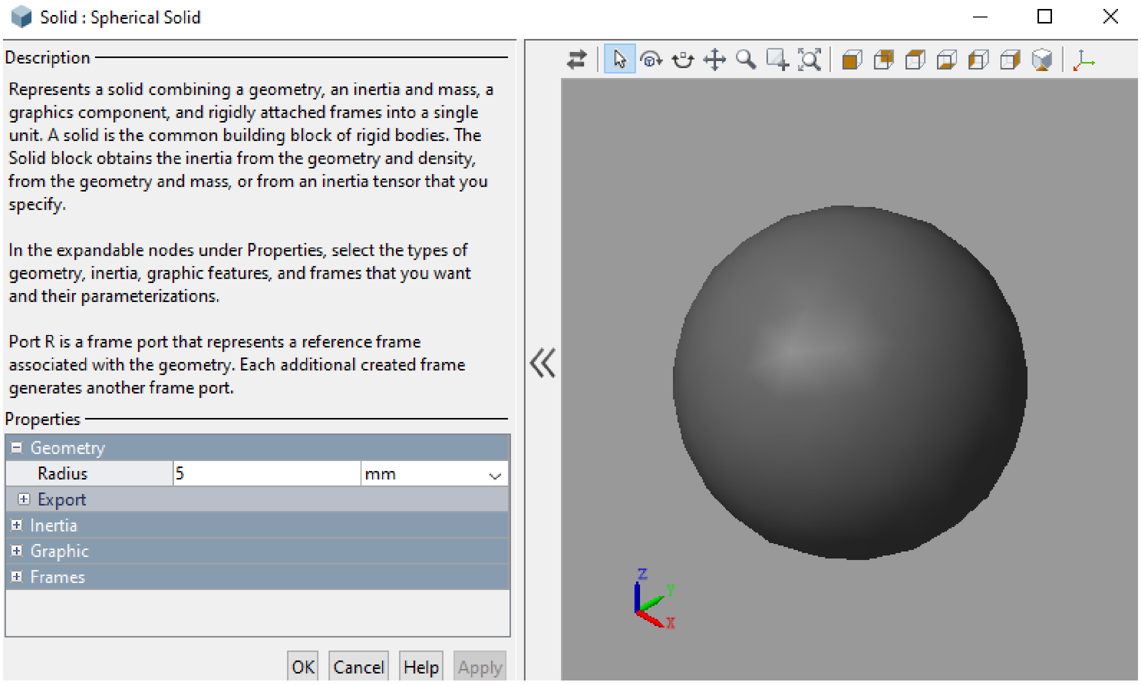
Subsystem of Right Leg



Subsystem of Foot



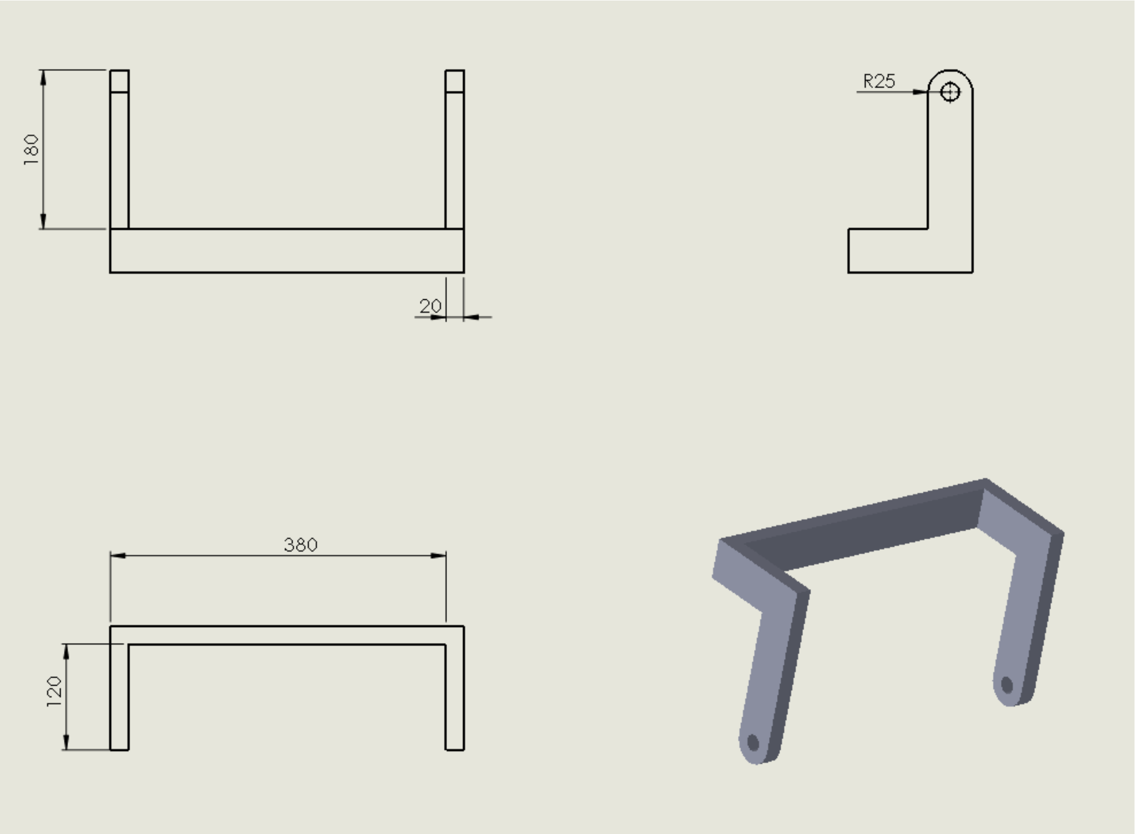
Spatial Contact Force Properties



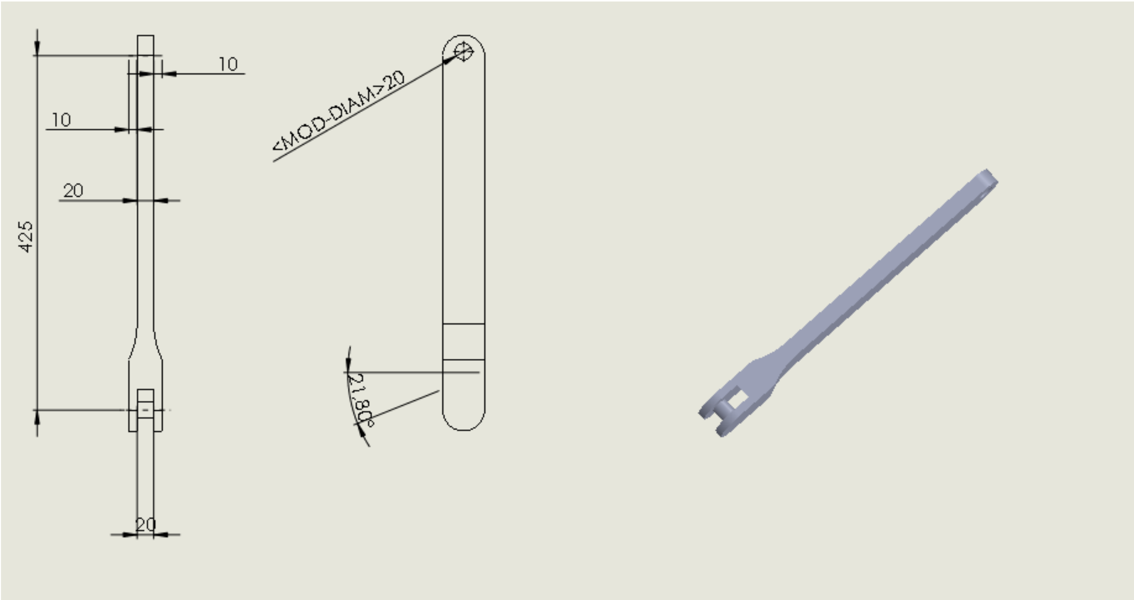
Spherical Solid Properties

Appendix C

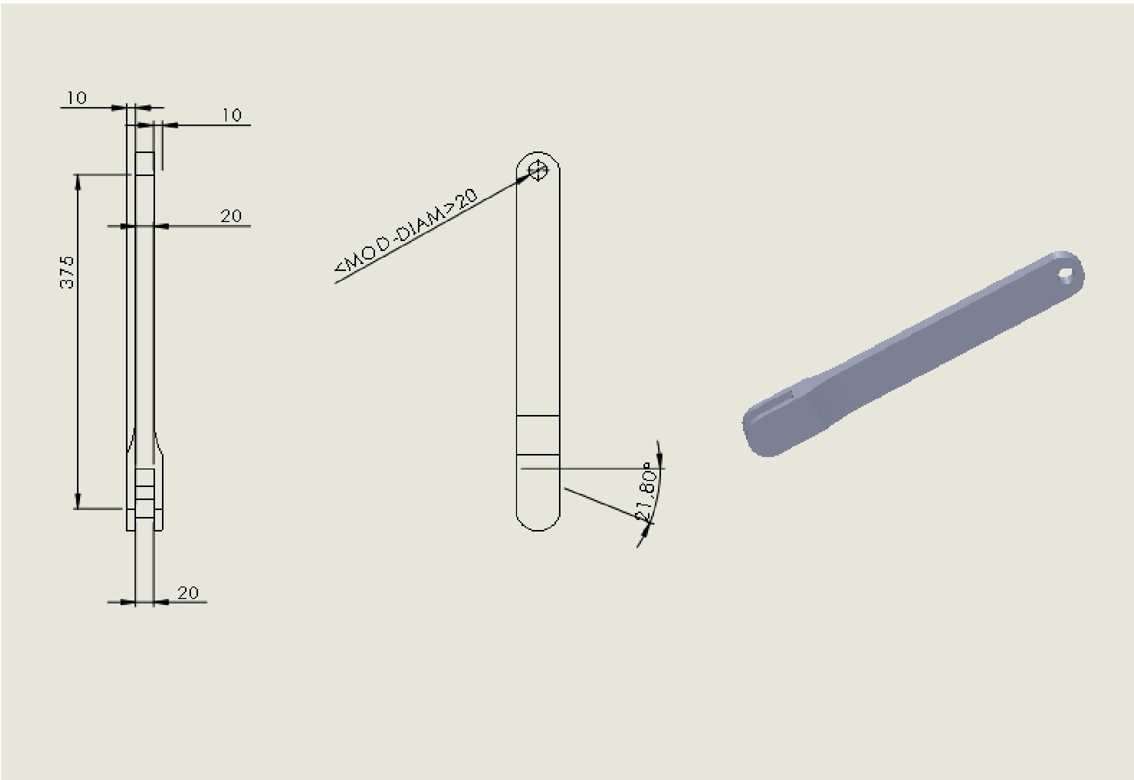
Technical Drawings of Design



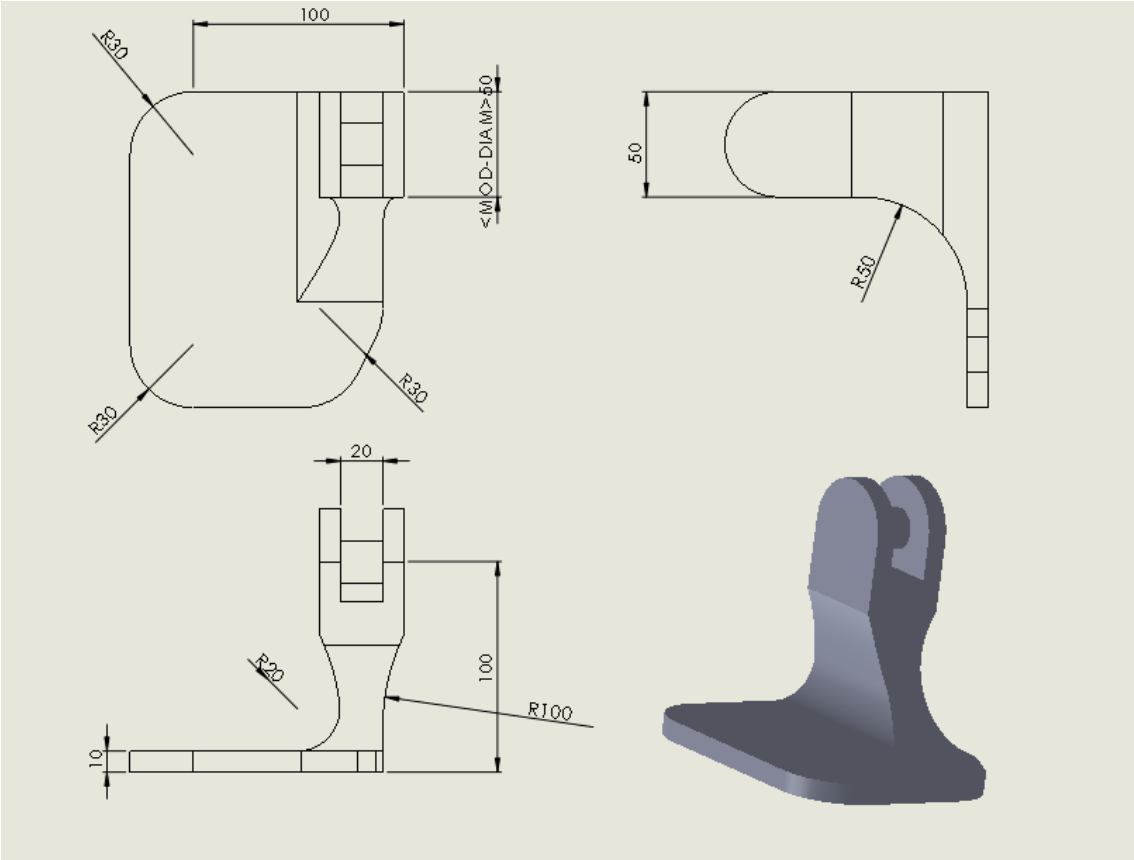
Waist Design



Upper Leg Design

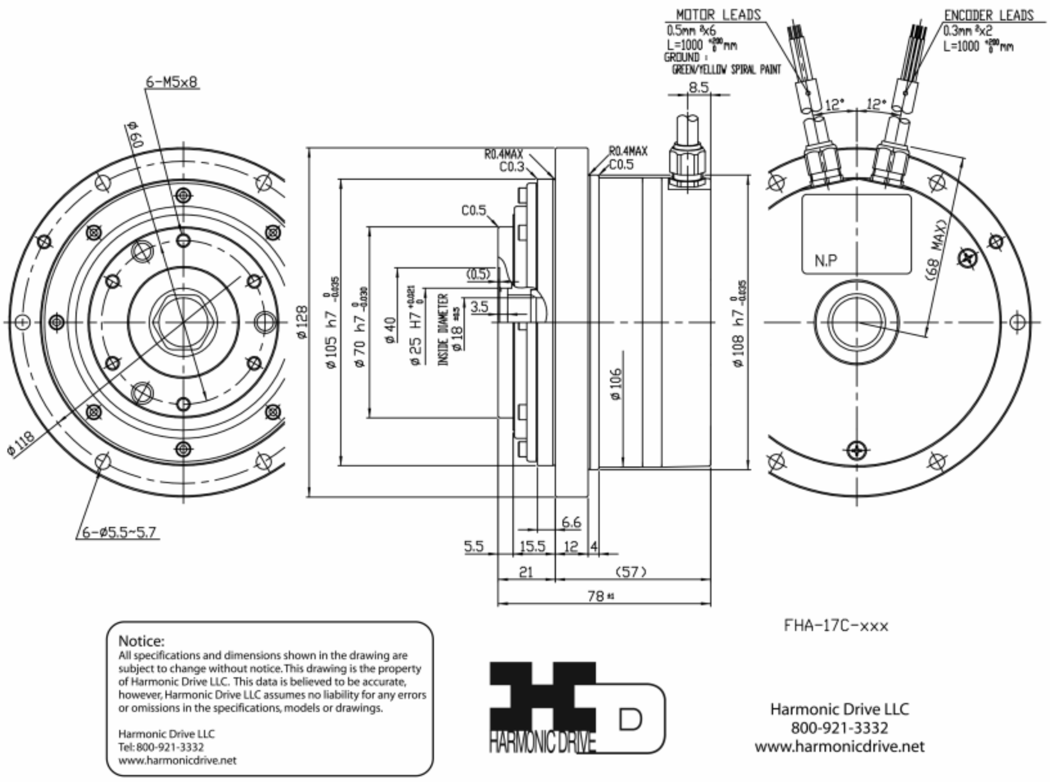


Lower Leg Design



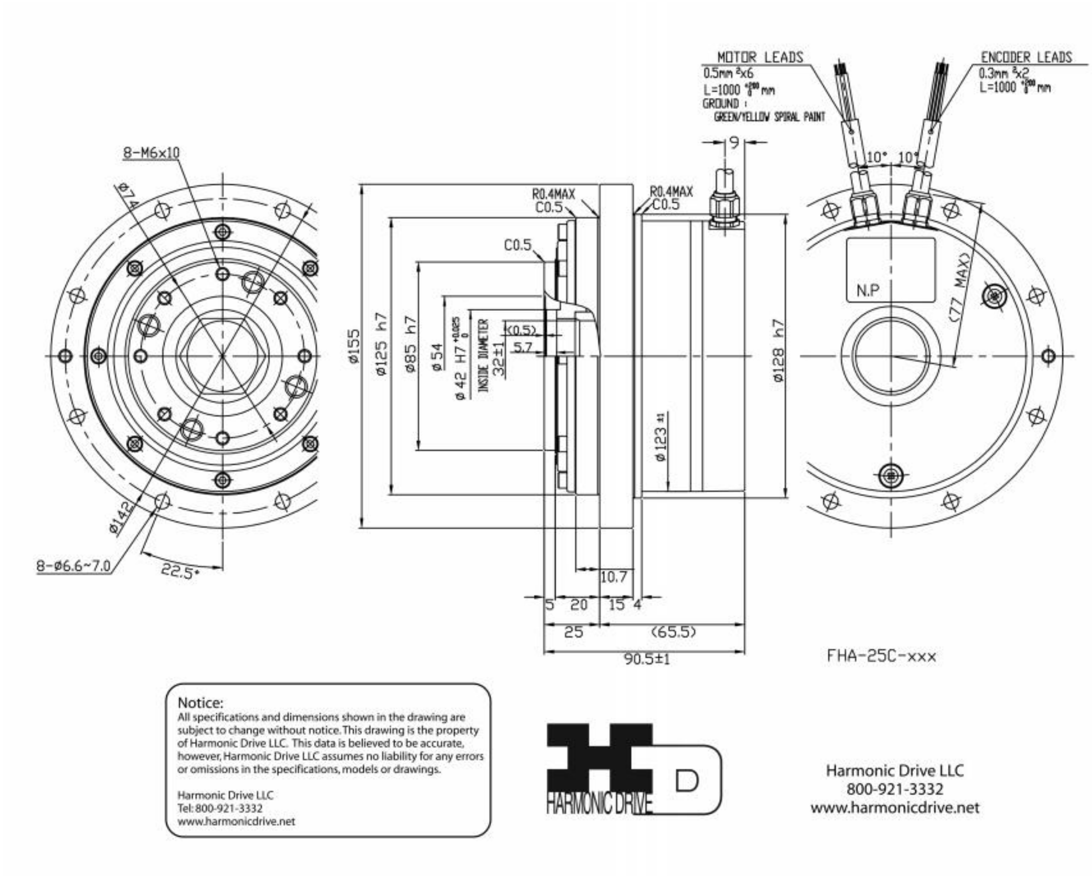
Foot Design

Appendix D



Harmonic Drive Rotary Actuator FHA-17C Drawing (www.harmonicdrive.net)

Figure 7 : The HULC Developed by Lockheed Martin – 2Harmonic Drive Rotary Actuator FHA-17C Drawing (www.harmonicdrive.net)



Harmonic Drive Rotary Actuator FHA-25C Drawing (www.harmonicdrive.net)