



YEDITEPE UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

PARAMETRIC FOOT DESIGN AND MODEL BASED OPTIMIZATION OF
YU-BIBOT PLANAR BIPED ROBOT

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ABSTRACT

PARAMETRIC FOOT DESIGN AND MODEL BASED OPTIMIZATION OF YU-BIBOT PLANAR BIPED ROBOT

In this thesis, the planar bipedal robot previously developed (YU-Bibot) is simulated, and an improved parametric foot design is proposed and studied.

The anatomy of the human foot is investigated to better understand the operating mechanism. The experiments which include experiments to find important parameters of the human foot are researched. Also, other robot feet are studied in the literature to examine how the problems are solved.

A common tendency to reduce impact forces while walking the robots is using elastic materials under the feet. So, elastic materials are designed and printed on a 3D printer. The materials are tested to find properties such as stiffness and damping coefficients. Elastic parts are studied to implement under the foot designs. For different situations, variables of the pads are optimized for both walking and dropping (free-fall) of YU-Bibot.

A new generation simulation model is designed for YU-Bibot. Real human walking cycles are studied and simulated. The simulation is used to optimize parameters. The simulation will include different gait parameters concerning different ground angles.

Based on the natural characteristics of the human foot, a mechanical design that can accommodate small bumps and irregularities of the ground is proposed. Two different methods are studied. One of them is implementing elastic pads under the existing feet of YU-Bibot. And the other method is designing parametric feet. For both methods, pad specifications are optimized via a simulation model. And for the second design, dimensions are optimized via the simulation model.

Optimization criteria for the designs are found and developed from previous studies of YU-Bibot. One of the past studies found the maximum torque for the capacity of the motors on the joints of the current YU-Bibot. Considering these maximum torque values, an objective function is defined. The designs are optimized by this objective function using a genetic algorithm.

ÖZET

YU-BIBOT DÜZLEMSEL İKİ AYAKLI ROBOTUN PARAMETRİK AYAK TASARIMI VE MODEL TABANLI OPTİMİZASYONU

Bu tezde mevcut YU-Bibot kısaca açıklanmış ve iyileştirme yöntemleri incelenmiştir.

Çalışma mekanizmasını daha iyi anlamak için insan ayağının anatomisi araştırılmıştır. İnsan ayağının önemli parametrelerini bulmak için yapılmış deneyler taranmıştır. Ayrıca literatürdeki diğer robot ayaklar araştırılarak problemlerin nasıl çözüldüğü irdelenmiştir.

Robotları yürütürken darbe kuvvetlerini azaltmak için yaygın bir eğilim olarak ayakların altında elastik malzemeler kullanılmaktadır. Bu yüzden, tasarlanan elastik malzemeler bir 3d yazıcıdan yazdırılmıştır. Malzemeler, sertlik ve sönümlenme katsayıları gibi özellikleri bulmak için test edilmiştir. Ayak tasarımları altında uygulamak için elastik kısımlar çalışılmıştır. Farklı durumlar için, ped değişkenleri YU-Bibot'un hem yürümesi hem de düşmesi (serbest düşüş) için optimize edilmiştir.

YU-Bibot için yeni nesil simülasyon modeli tasarlanmıştır. Gerçek insan yürüme döngüleri incelenmiş ve simüle edilmiştir. Simülasyon, parametreleri optimize etmek için kullanılmıştır. Simülasyon, farklı zemin açılarıyla ilgili farklı yürüyüş parametreleri içermektedir.

İnsan ayağının doğal özelliklerine bağlı olarak, zemindeki küçük tümsekleri ve düzensizlikleri barındırabilecek mekanik bir tasarım önerilmiştir. İki farklı yöntem incelenmektedir. Bunlardan biri YU-Bibot'un mevcut ayaklarının altına elastik pedler uygulanmasıdır. Diğer yöntem ise parametrik ayaklar tasarlamaktır. Her iki yöntem için de ped özellikleri bir simülasyon modeli aracılığıyla optimize edilmektedir. İkinci tasarım için boyutlar simülasyon modeli aracılığıyla optimize edilmiştir.

Tasarımların optimizasyon kriterleri YU-Bibot'un önceki çalışmalarından bulunarak geliştirilmiştir. Geçmiş çalışmalardan biri, mevcut YU-Bibot'un eklemlerindeki motorların kapasitesi için maksimum tork değerlerine sahiptir. Bu maksimum tork değerleri dikkate alınarak bir amaç fonksiyonu tanımlanır. Ve tasarımlar, bir genetik algoritma kullanılarak bu amaç fonksiyonu tarafından optimize edilmektedir.

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LIST OF ABBREVIATIONS

YU-Bibot	Yeditepe University biomimetic robot
TUBİTAK	Scientific and Technological Research Institution of Turkey
DOF	Degree of freedom
TMT	Tarsometatarsal
MLA	Medial longitudinal arch
FL	Foot length
L_0	Projection length between the endpoint of big toe and contact point under toe joint
H_0	Height of the contact point
P_1	Middle of the contact height
P_2	Middle of the ankle
P_3	The most anterior point of plane parallel to XY plane of P_2
H_i	1.2*i mm in X direction after H_0
FW	Foot width
ZMP	Zero moment point
PVSU	Pneumatic variable stiffness unit
Ga	Genetic algorithm
F	Force
ΔW	Area between lines and the energy lost
k	Spring constant / stiffness
β	Dimensionless measure of damping
ζ_{eq}	Equivalent viscous damping ratio
τ	Torque
c	Damping coefficient
COP	Center of pressure
TBS	Three beam structure
m	Mass
g	Gravitational acceleration
E	Elastic modulus
A	Area

L	Length
RMS	Root mean square
F/T	Force - Torque



1. INTRODUCTION

1.1. CURRENT ROBOT PLATFORM

Yeditepe Biomimetic Robot (YU-Bibot) is a humanoid planar biped robot project of the Mechanical Engineering Department of Yeditepe University, which has been developed with the support of TÜBİTAK (Scientific and Technological Research Institution of Turkey). The robot resembles the human lower extremities and has been designed and manufactured at anthropomorphic dimensions. The robot legs have six actuated joints, each one is controlled by a motor. The motor controllers are connected to a computer, and the motors are controlled via a mobile computer. It weighs 22 kilograms and has a height of 1.1 meters. With a support frame and a crane, YU-Bibot can be moved easily when it does not operate. Also, the frame eliminates 3 DOFs that YU-Bibot cannot operate. The structural material of the robot is mostly aluminum. YU-Bibot and the frame which are used in this graduation project are shown in Figure 1.1.



Figure 1.1. YU-Bibot planar robot platform [1]

The robot has six joints: right ankle, right knee, right hip, left ankle, left knee, and left hip. The hip joint is driven directly by the motion transmitted by the motor-gearhead assembly

as shown in Figure 1.2. Ankle and knee joints are driven by bevel gears; one is connected to the shaft and the other one is connected to the motor as shown in Figure 1.3. [2]

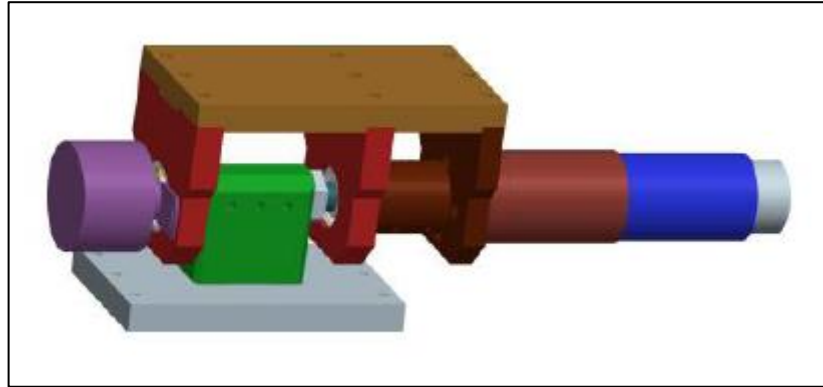


Figure 1.2. 3D model of hip joint [1]

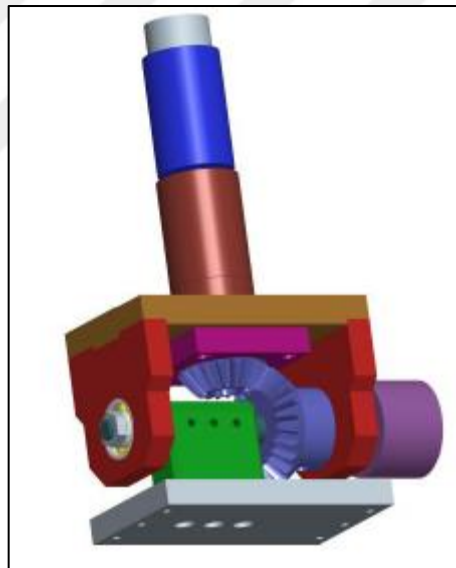


Figure 1.3. 3D model of knee joint [1]

The planar designed feet of the robot are produced from a light and high strength material cast polymide. Current flat feet has no elasticity and not any movable parts. This design restricts stability and balance of the robot. Also, inelastic material results energy loss due to impact in each step. Despite these disadvantages, existing design was easy to manufacture. The light material was important to keep the robot weight less. Each foot has two plated sandwich design and sensors between plates which can be seen in Figure 1.4.

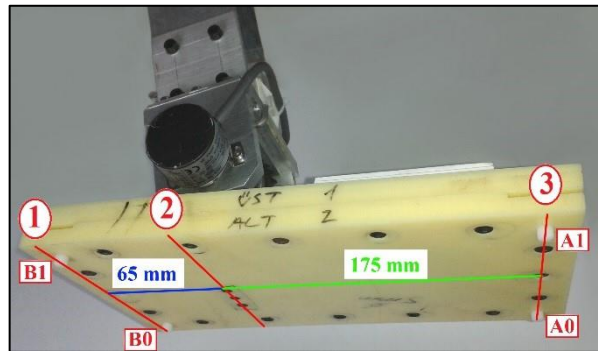


Figure 1.4. Existing foot structure and sensors (Measurements are made from A0, A1, B0, B1 points.)

1.2. ANATOMY OF THE HUMAN FOOT

The human foot consists of three parts: the hindfoot, the midfoot, and the forefoot which are shown in Figure 1.5. The hindfoot is the part between the ankle joint and the transverse tarsal joint. Talus and calcaneus bones are in the hindfoot part. These bones are shown in Figure 1.6.

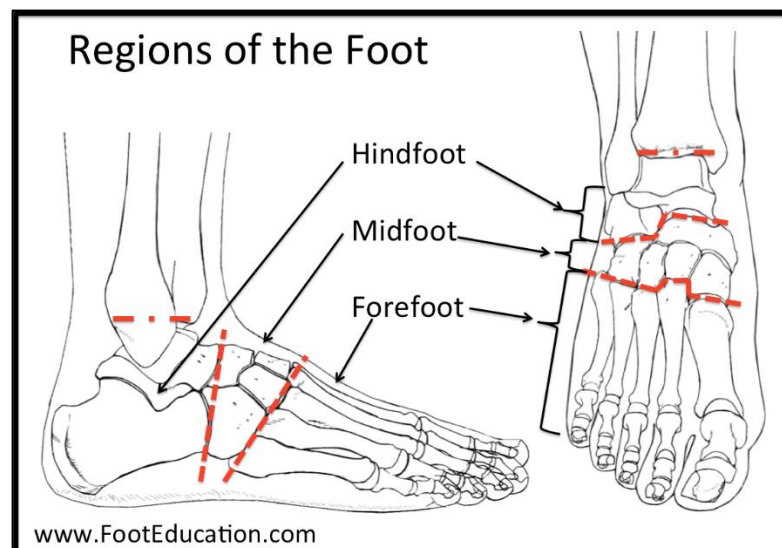


Figure 1.5. Regions of the foot [3]

The calcaneus carries large loads during weight lifting and enabling rotation of the foot at the ankle. The midfoot is the part between transverse tarsal joint and tarsometatarsal (TMT) joints. Although, the midfoot has more joints than the hindfoot, mobility of these joints are

limited. The navicular, cuboid, and the three cuneiforms are the bones in the midfoot. These bones are shown in Figure 1.6. The midfoot transmits and absorbs forces. The midfoot helps the foot adapt to different floor surfaces. It has an arched structure and with compression the arch changes shapes (both angle and contact surface). Also, with elasticity midfoot work as a shock-absorber. The forefoot has the most bones in these three parts. The forefoot bones are five metatarsals, fourteen phalanges, and two sesamoids. The great toe has only two phalanges (proximal, distal), but the other four toes have three phalanges (proximal, middle, distal). These bones are shown in Figure 1.6. And there are two sesamoid bones located directly underneath the first metatarsal head. The pitch movement of the toe is due to the sesamoid bones. The foot adapts to the change of the gravitational axes with the metatarsals for the stability. Also, lower leg is important part to transmit movement to the foot. In the lower leg, there are two bones called the tibia (shin bone) and the fibula. They are coupled to ankle motion by the tibial rotation, which is coupled to hindfoot, connected to fibular translation and rotation in all cardinal planes. [4]

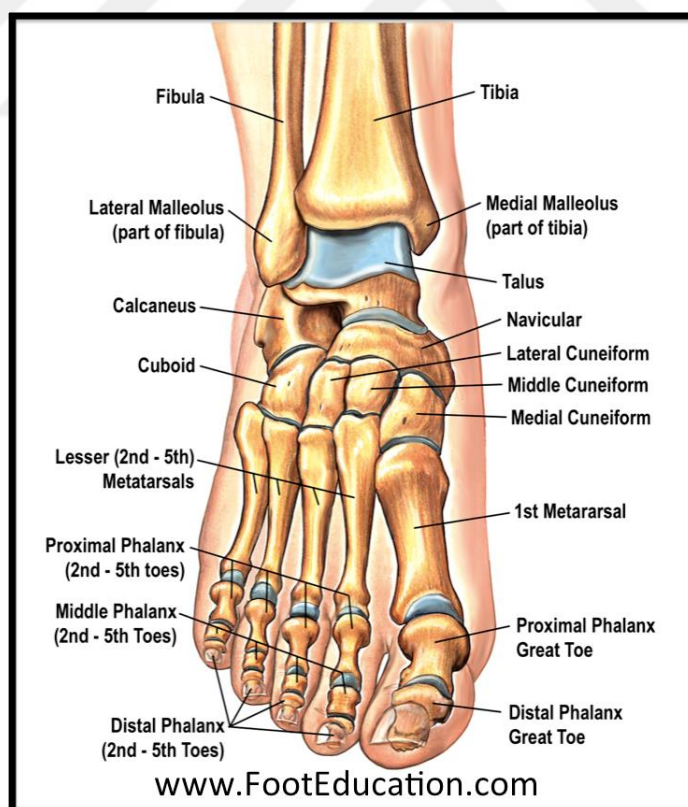


Figure 1.6. Bones of the foot and ankle [3]

All the bones mentioned before are covered with veins, nerves, muscles, and skin tissue. These covered materials give elasticity for the foot, especially for the bottom of the foot. To simplify all the complex mechanics of a foot, it can be described as a combined spring system.

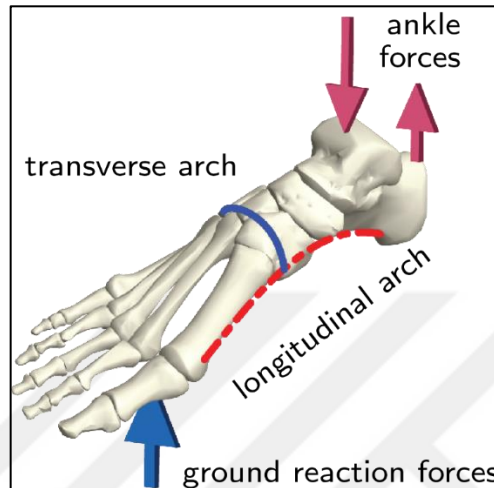


Figure 1.7. The two arches of the human foot help to stiffen the foot against the forces acting on it during locomotion [5]

A foot has two basic archs which are transverse and longitudinal archs shown in Figure 1.7. The plantar fascia, running from heel to toe, contributes around 25% to the foot's stiffness through the Medial Longitudinal Arch (MLA) [5]. When DOFs of YU-Bibot are considered, transverse arch can be eliminated and an equivalent spring and beam system can be created like in the Figure 1.9. Also in the article, as a result of their literature survey, stiffnesses are estimated from published load versus displacement data for humans. For intact foot condition, estimated value is 481 N/mm for human foot. It is calculated from experimental data from load and displacement graphic which is shown in Figure 1.8 from article [6]. So it represents equivalent stiffness for the whole human foot.

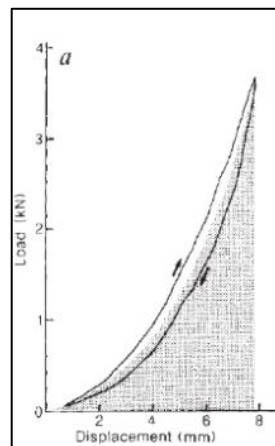


Figure 1.8. Load & displacement graph from [6]

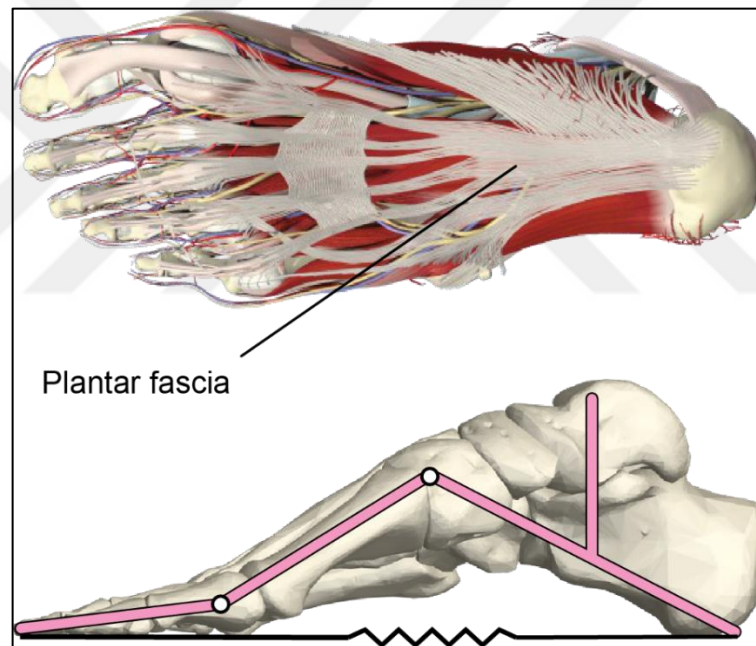


Figure 1.9. Anatomical image showing the plantar fascia [5]

In another study [7], stiffness and damping coefficients of the foot and ankle parts of a foot are obtained experimentally. 24 points of the foot are determined to measure, then over all foot and ankle are modeled as a planar lumped-parameter model.

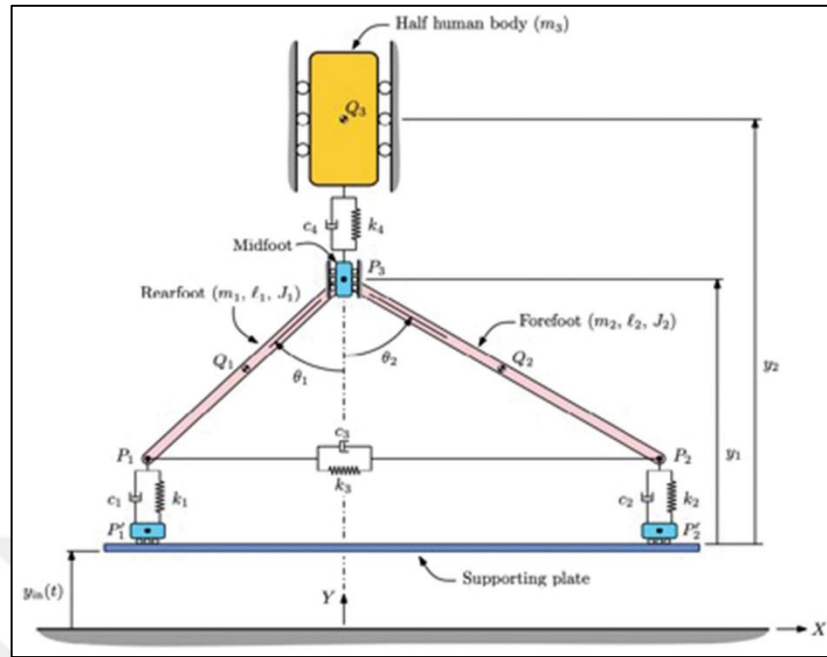


Figure 1.10. Schematic representation of the proposed planar lumped-parameter model of the foot-ankle system [7]

The vibration experiments of the study are done with three different center of pressure situations (forward, natural, backward). The results are shown in Table 1.1.

Table 1.1. Estimated model parameters, including the stiffness and damping coefficients of each model segment in the natural standing position and under two changes in centre of pressure location (towards the forefoot and rearfoot) [7]

Parameter	Forward COP	Natural COP	Backward COP	Description
k_1 (N/m)	1.33×10^6	2.86×10^6	4.11×10^6	Stiffness of the plantar aponeurosis
k_2 (N/m)	2.76×10^5	9.00×10^5	1.72×10^5	Stiffness of the calcaneus fat pad
k_3 (N/m)	100	1.21×10^4	100	Stiffness of the mass of the body
k_4 (N/m)	5.57×10^5	6.46×10^4	102	Stiffness of the tarsals fat pad
c_1 (Ns/m)	0.10	0.10	0.10	Damping of the plantar aponeurosis
c_2 (Ns/m)	1.26×10^4	0.10	0.10	Damping of the calcaneus fat pad
c_3 (Ns/m)	2.24×10^3	5.09×10^3	621	Damping of the mass of the body
c_4 (Ns/m)	0.10	7.89×10^3	2.52×10^5	Damping of the tarsals fat pad

In the article, the descriptions in Table 1.1 and the numbering of springs and dampers in Figure 1.10 are not consistent. But the important regions to compare the overall stiffness and

damping coefficients under the foot are tarsals fat pad and calcaneus fat pad. So equivalent stiffness and damping coefficient for the foot are calculated below.

$$k_{eq} = k_2 + k_4 = 9.00 * 10^5 + 6.46 * 10^4 = 964600 \text{ N/m} \quad (1.1)$$

$$c_{eq} = c_2 + c_4 = 0.10 + 7.89 * 10^3 = 7890.1 \text{ N/m} \quad (1.2)$$

There are studies focusing on relations between foot heights and shapes. One of the articles examines the foot heights of a group of people to find some relationships [8]. In the article, laser foot scanners were used to measure the right feet of an adult group of 50 people consisting of men and women without any visible foot abnormality.

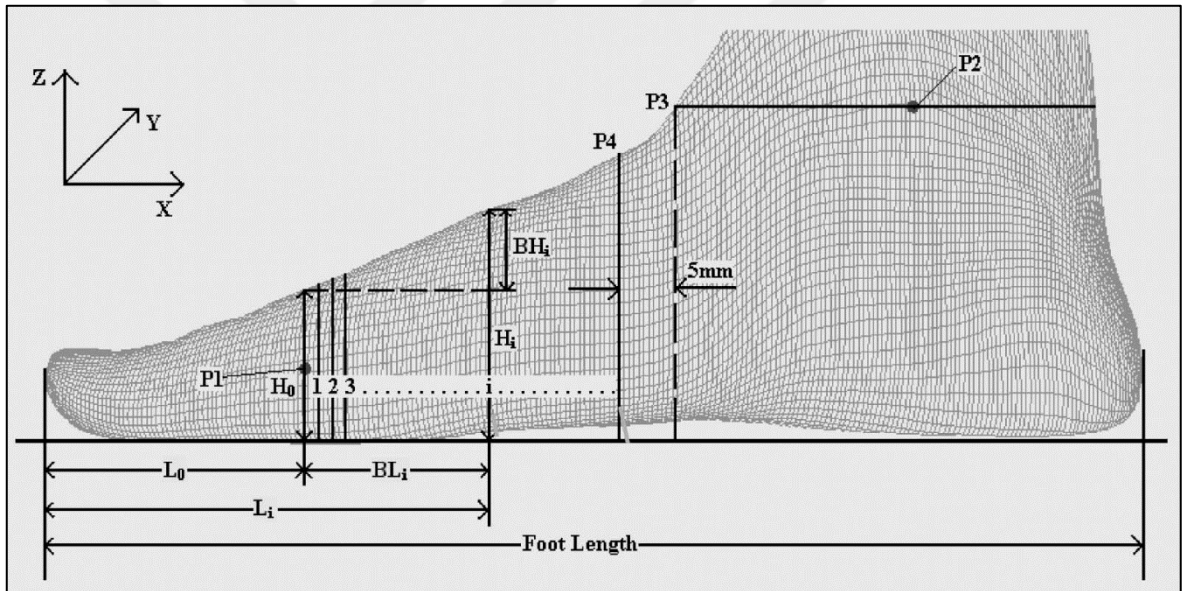


Figure 1.11. Foot heights in the midfoot region [8]

They determine some points and lengths, the important ones are also shown in Figure 1.11. Foot length (FL) is basically length of all foot while standing. L_0 is the projection length between the endpoint of big toe and contact point under toe joint. H_0 is the height of this contact point. P_1 is the middle of this contact height. P_2 is the middle of the ankle. P_3 is the most anterior point of plane parallel to XY plane of P_2 . After H_0 , they mark some heights which are H_i , and they are the height at each 1.2 mm in X direction. And foot width (FW) is also important.

After scanning of the feet, they find these correlations for male cases;

$$FW = 1,045 * FL^{0,817} \quad (1.3)$$

$$H_{35} = 12,206 * FL^{0,243} \quad (1.4)$$

$$H_{40} = 11,280 * FL^{0,280} \quad (1.5)$$

$$H_{45} = 9,483 * FL^{0,330} \quad (1.6)$$

$$H_{50} = 5,596 * FL^{0,443} \quad (1.7)$$

And these correlations for female cases;

$$FW = 0,524 * FL^{0,941} \quad (1.8)$$

$$H_{35} = 55,208 * FL^{0,043} \quad (1.9)$$

$$H_{40} = 50,407 * FL^{-0,0045} \quad (1.10)$$

$$H_{45} = 49,122 * FL^{0,018} \quad (1.11)$$

$$H_{50} = 47,120 * FL^{0,044} \quad (1.12)$$

These equations are used to compare the optimization results of YU-Bibot with human foot data.

1.3. BIPED ROBOT FEET

There are different designs in literature for the bipedal robot feet. Some of the general designs and some unique designs are observed in this survey. The goals and capabilities of the researched designs and structures are given in Table 1.2.

Table 1.2. Classification of types of robotic feet in literature survey

Robot or foot name	Goals and/or Capabilities*	Foot structure	Foot DoF**
Current Yu-Bibot	-	Flat foot	0
[9] BHR-2	• Impact absorption	Flat foot with pads	0
[10]	• Impact absorption • Adaptability on uneven terrains	Flat foot with pads (adjustable stiffness)	0
[11] 2(s)	• Extension capabilities with toe joint	2 part-flat foot with passive joint	1 P
[12]	• Impact absorption	Flat foot with pads (2 material, sandwich type)	0
[13]	• Impact absorption • Extension capabilities with toe joint	2 part-flat foot with active joint	1A
Asimo	• Operate freely in the human living space	Unique segment	2A
Atlas	• Adaptability on uneven terrains	Flat foot with pads	0
* Goals and/or Capabilities mean that current YU-Bibot doesn't have. ** A: Active, P: Passive			

Flat-foot is one of the most basic methods for robot foot. Most of the project starts with flat-foot than some of the research are focused on developing the basic design of the feet. In the article [9], flexible rubber pads are added under the foot shown in Figure 1.12. The purpose is to increase the capability to deal with rough terrain and obstacle environments. Also, the inclined shape of the bottom of the foot is provided to stabilize the posture. Robot uplifts the heel of the back foot with the toe touching at the ground when stepping forward shown in Figure 1.13. This extends the double-supported state period as long as possible to stabilize its body.

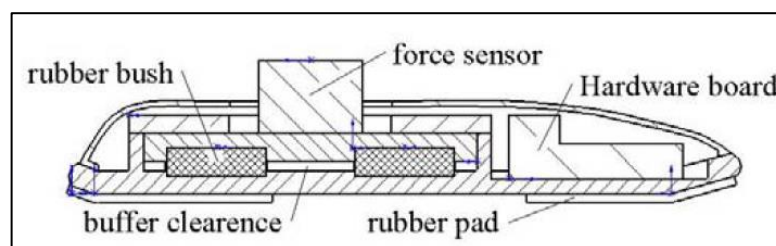


Figure 1.12. Structure of the foot with rubber pad [9]

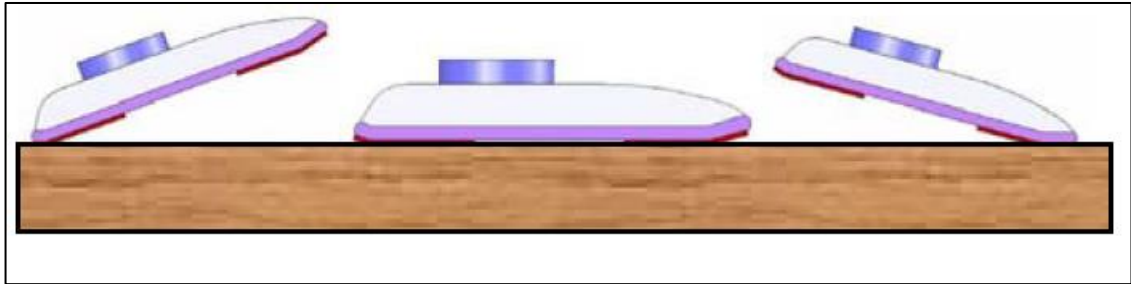


Figure 1.13. Foot laying down and uplifting Mode [9]

Another advantage of the foot in the article [9] is using a force/torque sensor in the ankle part. Instead of using force or pressure sensors under the foot, one force/torque sensor is quite enough to monitor the contact state of the robot. Calculating ZMP (zero moment point) is easier with this sensor, also additional calculations are not necessary to calculate the torques for the ankle.

Elasticity addition to flat-foot is a method for improving flat-foot designs. One of them is in the article [10], Stiffness-Adjustable Foot System was examined by adding pneumatic variable stiffness units (PVSUs) under a flat foot shown in Figure 1.14.

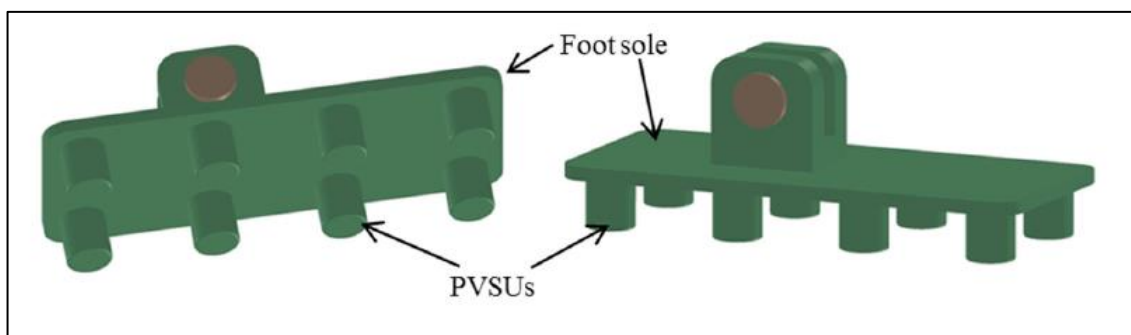


Figure 1.14. Schematic diagram of the stiffness adjustable foot system [10]

In this design, one of the goals is reducing impact and the other is providing walking on a road with small obstacles. Pneumatic bladders are made of silica gel shown in Figure 1.15. Piston and valve control system were implemented on bladders. The benefit of the system is that the system has adjustable stiffness.

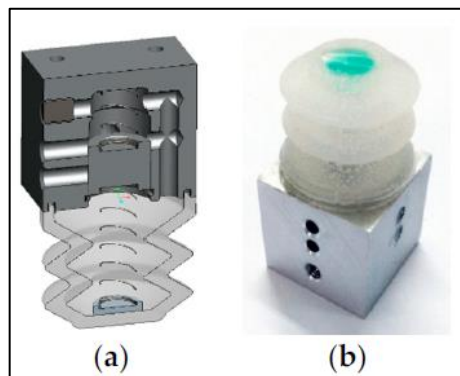


Figure 1.15. The PVSU (a) The sectional view of the PVSU; (b) the prototype of the PVSU [10]

In another design in [11], a passive toe joint used for the robot foot. The foot is designed by 2 parts, (fore and hind) and non-actuated movable part is created by adding torsional spring. The advantage of the design is mostly observed in toe-off phase of walking gait.

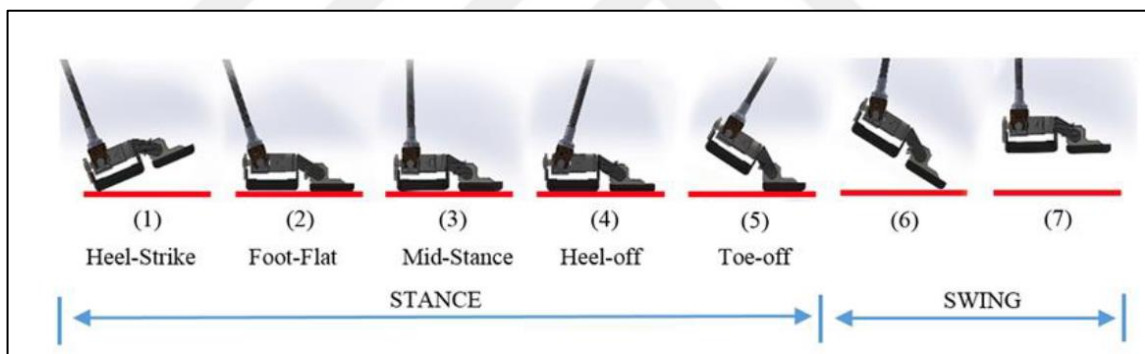


Figure 1.16. A Simulation of one biomechanical leg during the stance and swing phases of a normal gait [11]

In the article, the limits of the human foot are examined. The limits are used to arrange the boundaries of the torsional spring by using a stopper. The result of the simulations show that due to the presence of the passive toe joint, the reduction in energy consumption by the actuated joints. Stages for one step are shown in Figure 1.16.

Using elastic material is a common way to improve robotic feet. In the article [12], a sandwich-type foot is designed which is hard material covered with rubber material shown in Figure 1.17.

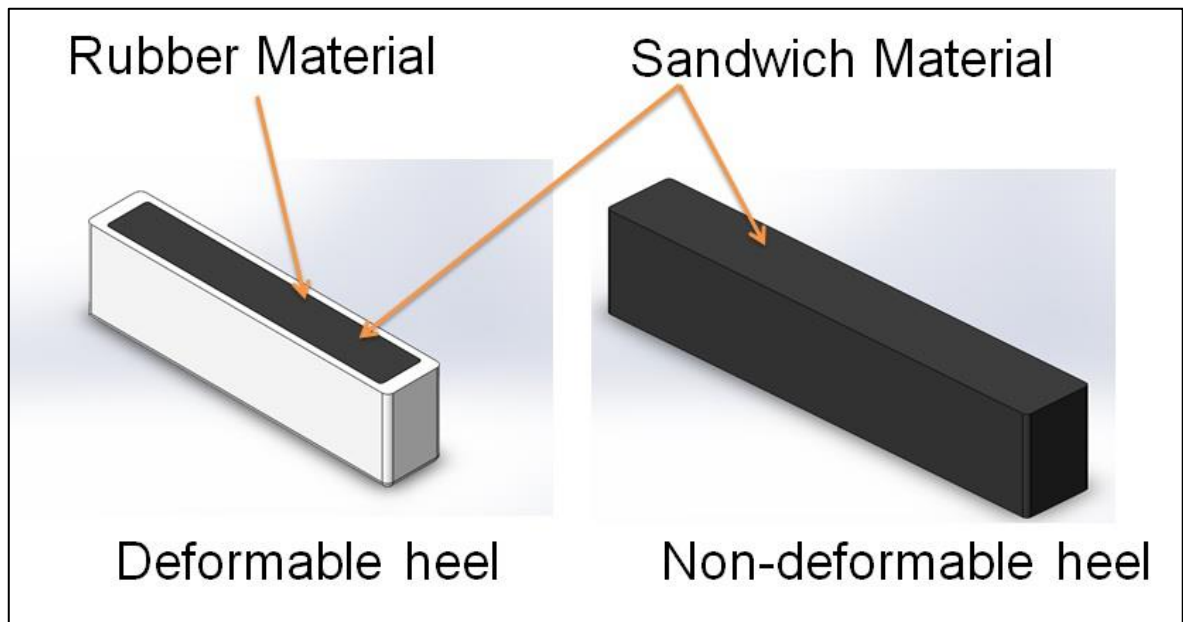


Figure 1.17. Deformable and non-deformable heels 3D-Model [12]

The foot height and aspect ratio of the rubber material is determined by using genetic algorithm. Genetic algorithms (ga) are basically a category of optimization algorithms. Ga used to optimize for the minimum or the maximum, of an objective function. It is considered as one branch of evolutionary computations. The benefits of genetic algorithms is their efficiency with respect to random and exhaustive search algorithms. In the article, the maximum bending stress is estimated to be lower than than the acceptable bending strength of the sandwich skin. And the maximum shear stress is estimated to be lower than the acceptable shear strength of the core. These conditions are put in an equations as ratios. Then the equation is minimized by using genetic algorithm optimization tool in MATLAB.

In another article [13], a bipedal robot is optimized to find the most energy efficient version. Optimization variables are both gait parameters and design paramaters shown in Figure 1.18.

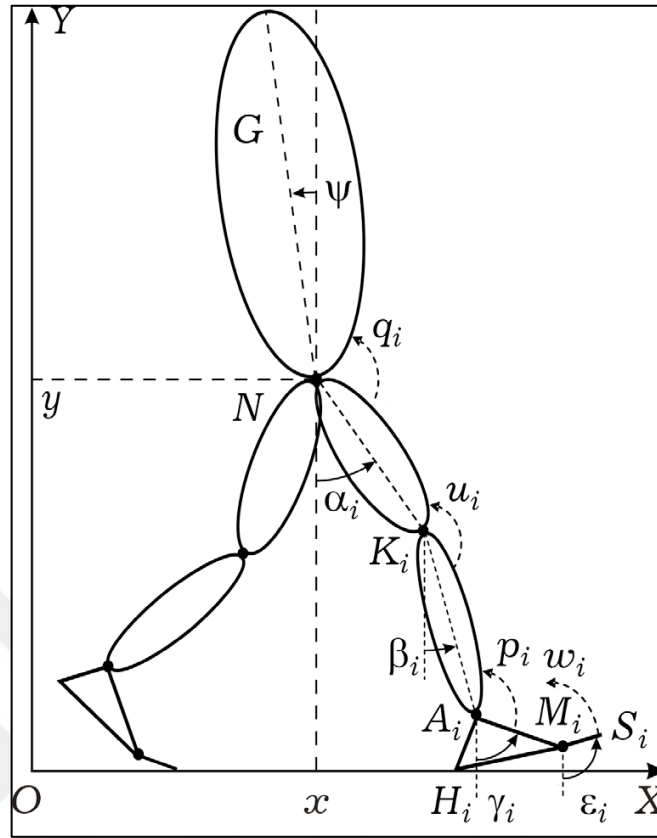


Figure 1.18. The gait and design parameters of the bipedal robot [13]

A series of boundary conditions and an equation are used to describe the problem. The objective equation in the study is used to find the optimal control for the robotic systems. The joints are driven by electric motors. And they release energy in the form of heat. So, the equation below represents the energy loss during motor actuation. There are other parameters related to motors and electrical connections, but as soon as the same motors are used, these constants don't affect the optimization results. On the other hand, loads on the joints are different. Even with the same angle change, different joints consume different energies.

$$\Phi = \frac{1}{L} \int_0^T \sum_{i=1}^2 [q_i^2(t) + u_i^2(t) + p_i^2(t) + w_i^2(t)] dt \quad (1.13)$$

T is a period of one step. L is the length of one step. Also, foot parameters are used for the optimization. Dimensions of the feet are shown in Figure 1.19.

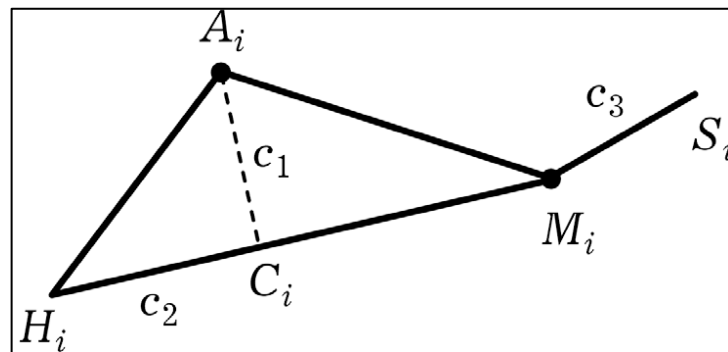


Figure 1.19. Variable dimensions of the feet [13]

In the article, for optimization, a combination of genetic algorithms and `fmincon` is used to find the best values. `Fmincon` is a function to find minimum of constrained nonlinear multivariable function.

Also, there are prosthetic foot types. For example from the article [14], the flex-foot cheetah is used for intended as a part of a prosthetic system that replaces the foot and ankle function of a missing lower limb. The design is shown in Figure 1.20. The design can be used as a robot leg too. This type of flex-foot stores energy for the contact stage and releases the energy for the take-off stage. Additionally, the geometry of the foot allows it to roll. Usually carbon-fiber-reinforced polymer is used to produce this kind of foot.

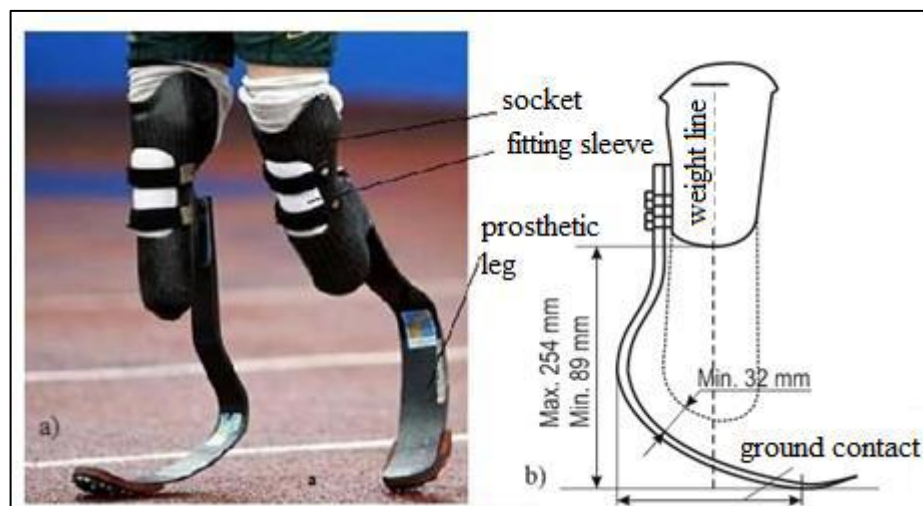


Figure 1.20. (a) An athlete using prosthetic flex-foot cheetah (b) Side view and dimensions of prosthetic flex-foot cheetah [14]

In this thesis, after all this robotic foot and human foot mechanics researchs, the feet of YU-Bibot will be improved. Similarly to some of the works, elastic materials will be implemented under the robot feet. Firstly, an elastic pad will be designed. Then, the specimens with different materials and different densities will be printed on a 3-D printer. The characteristics of the specimens will be tested to determine the specifications, such as stiffness and damping coefficients.

For the second part, a simulation model is designed for YU-Bibot. Walking cycles will be studied and simulated. New walking gaits will be generated for the new designs of the feet. Also, the simulation will be used to optimize the parameters of the new designs. Then the results of the optimization are compared with the current YU-Bibot and other information from the literature survey.

2. ELASTIC MATERIALS FOR SOLE OF THE FEET

Literature surveys for this thesis shows that the elasticity of the robot foot has different advantages which can be seen in [9], [10]. Known advantages are impact absorpsion, reduced energy consumption, and dealing with rough terrain and obstacle environments. For the enlightening information of the surveys, adding elastic parts under the feet is decided.

Elastic materials should be light and capable of carrying the weight of a robot. To obtain these elastic parts, a sandwich structure with a grid inside is built with a 3D printer. The shape of the structure is inspired by the big toe. And some connection holes are added. Two different pads are printed with different materials and different grid densities. The materials of the pads are thermoplastic polyurethane (TPU), and the thickness of the filaments is 1.75 mm. The stiffness of the orange specimen is Shore-A 90, and the stiffness of the white specimen is Shore-A 80. The orange specimen has fewer dense grids than the white one. The characteristics of these designs are examined to form an opinion for optimizations, and after that, new designs can be implemented on YU-Bibot.

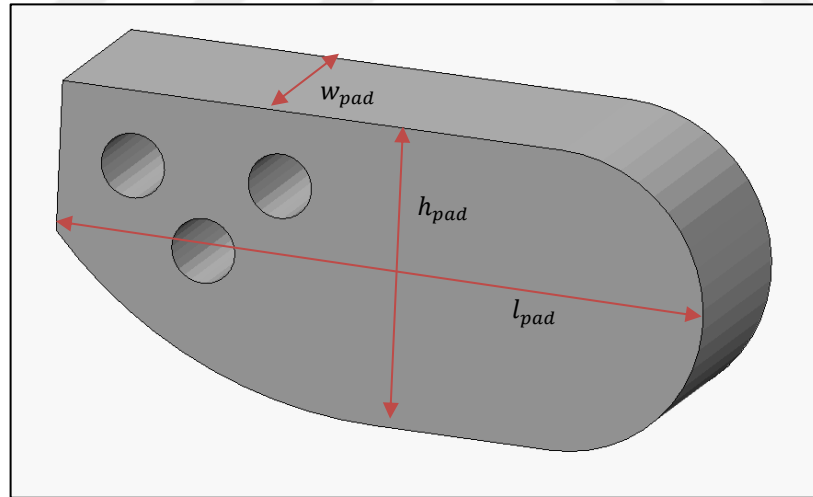


Figure 2.1. Dimensions of the pads

Dimensions of the pads are shown in Figure 2.1. The height, length, and width of the pads are: h_{pad} is 40 mm, l_{pad} is 88 mm, and w_{pad} is 26 mm. It weighs 36.5 grams.

2.1. COMPRESSION TESTS AND OUTPUTS OF SPECIMEN-1 (ORANGE)

In order to determine the characteristic of the pad, a series of tests applied on it. The first specimen is orange one. By using a universal testing machine (Instron), the specimen is put to compression tests with different velocities (0.5mm/s; 1 mm/s; 1.5 mm/s; 2 mm/s; 2.5 mm/s; 3 mm/s). Photo of the experimental setup is shown in Figure 2.2.

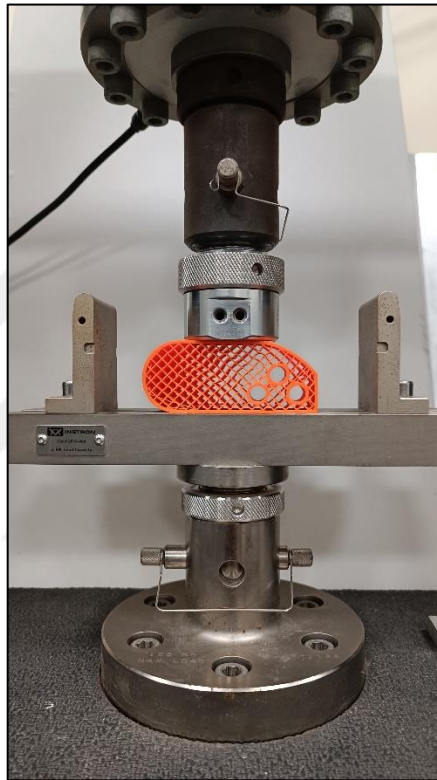


Figure 2.2. Orange pad test setup in Instron

The scale of the tests is beginning from 0 mm (barely touching point) to 10 mm compression. Triangle cycles are created for each velocity value. 5 cycles were used. Extension vs. time graph is shown in Figure 2.3.

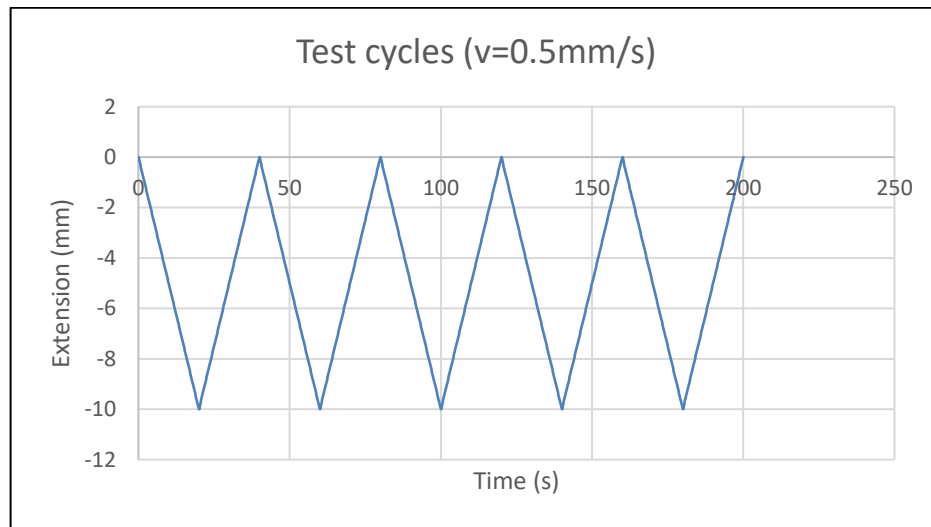


Figure 2.3. Test cycles ($V=0.5$ mm/s)

Test outputs are time (s), extension (mm), and force (N). Obviously, for this test extension is minus which means compression. The first cycle and some data (close to zero extension) are cleaned. Then the data are centralized due to calculate the slope of the trendline. Centralized data is seen as the movement between -5mm and +5 mm instead of 0 mm to 10 mm. Also, the force is centralized with the same method. Load vs. extension graph is shown in Figure 2.4.

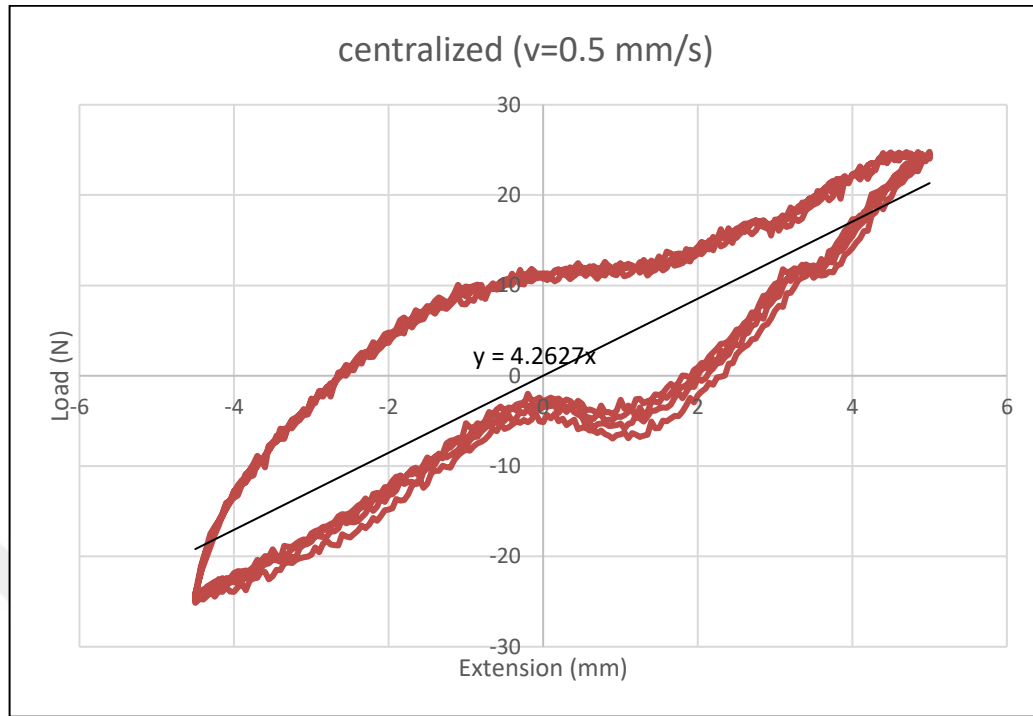


Figure 2.4. Load and extension data for V=0.5 mm/s

The lines in the lower part of the graph show the compression parts of the test and the upper lines show the releasing parts. The area between these compression and release lines is the energy lost during the test. (Lost energy means the energy which is transformed to heat) This energy is calculated with the data. First, each small area is found by the equation:

$$W_{2-1} = (\Delta x_1 - \Delta x_2) * (F_2 + F_1)/2 \quad (2.1)$$

After calculating sum of all pressure and all compression areas separately. The differentiation of these areas gives the area between the lines which means the energy converted to heat. Following equations are found in the book [15].

$$\Delta W = \beta * \pi * k * X^2 \quad (2.2)$$

ΔW is the area between lines and the energy lost

k is the spring constant and it is found by the slope of the trendline

X is the maximum extension which is 5 mm for the tests

β is the dimensionless measure of damping and is found by this equation because it is the only unknown value in the equation;

$$\zeta_{eq} = \frac{\beta}{2} \quad (2.3)$$

ζ_{eq} is the equivalent viscous damping ratio

c_c is critical damping constant

m is mass of the pad (0.0325 kilograms)

$$\left(\frac{c_c}{2m}\right)^2 - \frac{k}{m} = 0 \quad (2.4)$$

$$c_c = 2m \sqrt{\frac{k}{m}} \quad (2.5)$$

$$\zeta_{eq} = \frac{c}{c_c} \quad (2.6)$$

Using the equations above, values are calculated for each velocity. For each velocity more than one test made so the averages of the values are used in the Table 2.1.

Table 2.1. Spring constants and damping coefficients for different speeds

v (mm/s)	k (N/m)	β	ζ_{eq}	c_c (Ns/m)	c (Ns/m)
0.5	4158	0.345	0.173	23.3	4.0
1	4533	0.354	0.177	24.3	4.3
1.5	4852	0.328	0.164	25.1	4.1
2	5020	0.331	0.166	25.5	4.2
2.5	5193	0.329	0.165	26.0	4.3
3	5258	0.334	0.167	26.1	4.4

2.2. COMPRESSION TESTS AND OUTPUTS OF SPECIMEN-2 (WHITE)

Similarly with other specimen, in order to determine the characteristic of the pad, a series of tests applied on it. The second specimen is white one. By using Instron, the specimen is put to compression tests with different velocities (0.5mm/s; 1 mm/s; 2 mm/s; 3 mm/s; 4 mm/s; 5 mm/s). Photo of the experimental setup is shown in Figure 2.5.

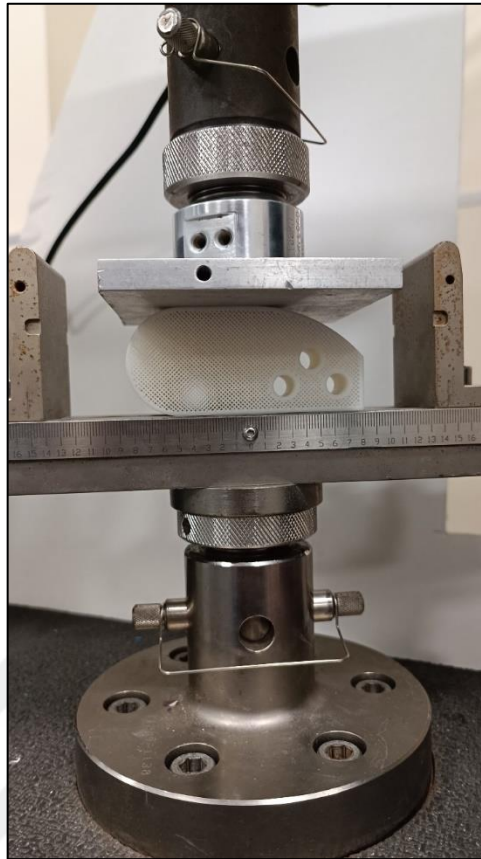


Figure 2.5. White pad test setup in Instron

The scale of the tests is beginning from 0 mm (barely touching point) to 5 mm compression because specimen-2 is stiffer than specimen-1. Triangle cycles are created for each velocity value. 5 cycles were used. However, before the triangles, the specimen is compressed as a pretest. The first, specimen is compressed to 2.5 mm then waited. The cycles are applied after the pretest. Extension and time graph is shown in Figure 2.6.

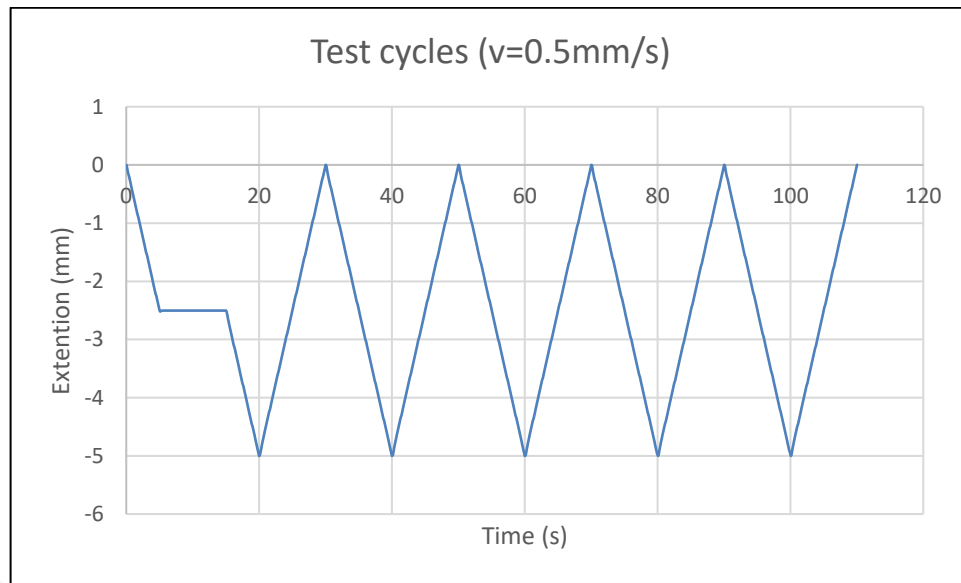


Figure 2.6. Test cycles ($V=0.5$ mm/s)

Test outputs are the same with specimen-1; time (s), extension (mm), force (N). The first cycle and some data (close to zero extension) are cleaned, again. Then the data are centralized due to calculate the slope of the trendline. But this time, centralized data is seen as the movement between -2.5 mm and +2.5 mm instead of -5 mm to 5 mm. Also, the force is centralized with the same method. Load vs. extension graph is shown in Figure 2.7.

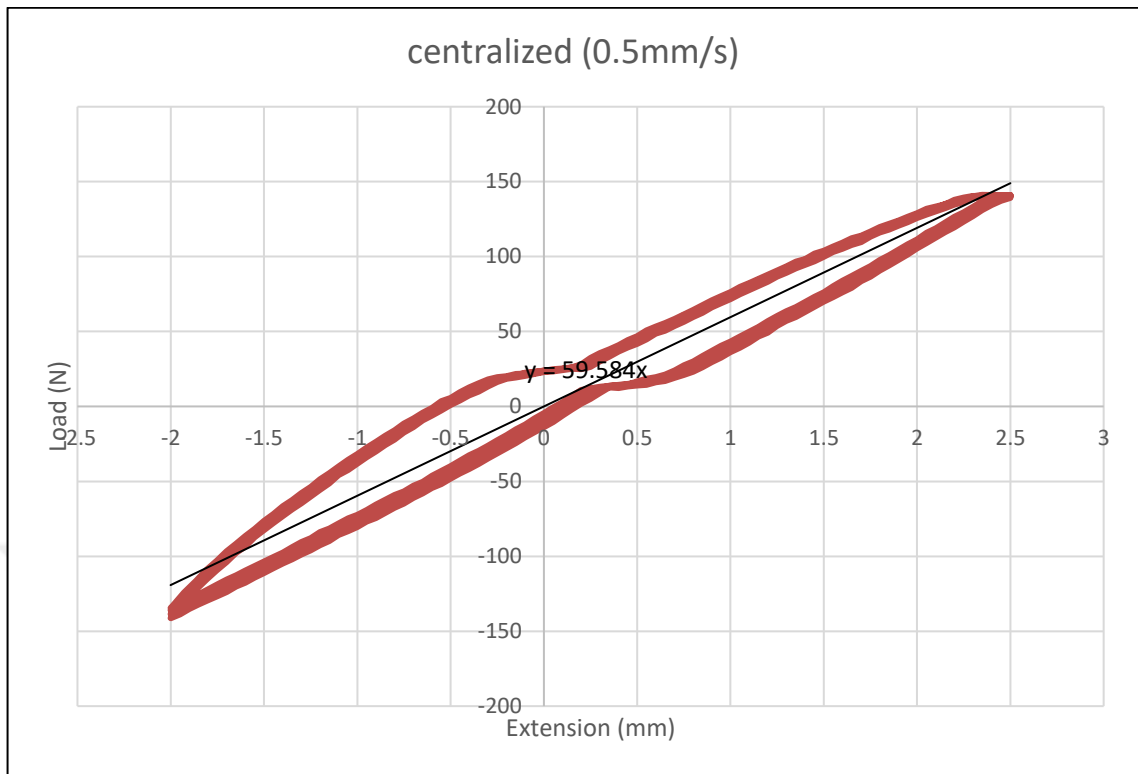


Figure 2.7. Load and extension data for $V=0.5$ mm/s

Using the same equations for specimen-1; values of Table 2.2 are calculated. The only difference is X ; the maximum extension which is 2.5 mm for the tests and the white pad has a mass of 35 grams.

Table 2.2. Spring constants and damping coefficients for different speeds

v (mm/s)	k (N/m)	β	ζ_{eq}	c_c (Ns/m)	c (Ns/m)
0.5	59584	0.112	0.056	91.3	5.1
1	61923	0.114	0.057	93.1	5.3
2	64667	0.068	0.034	95.1	3.2
3	66460	0.087	0.044	96.5	4.2
4	67907	0.081	0.040	97.5	3.9
5	69148	0.058	0.029	98.4	2.8

2.3. DISCUSSION OF COMPRESSION TEST RESULTS

For both specimens and for all different velocities of experiments, damping constants are less than 1, this means systems are underdamped. Light damping is observed. The characteristics can also be understood when the experiments are observed. After the universal testing machine pressed the specimens to the maximum point, it released the specimen for the second phase. The pressing part (head) of the machine goes with the specimen. This can be only underdamped or critically damped cases. If the system was heavily damped, the specimen would fix itself slower than the moving of the head while the head of the machine releases. Also, if the system were heavily damped, the damping ratio would be more than 1. For the white specimen damping is lighter than the orange specimen experiments. Because the damping ratio of the white specimen is less than the orange one. The obtained values are used in the simulations in the following sections.

3. SIMULINK ROBOT MODEL (VIA SIMMECHANICS 2ND GEN)

In this section, YU-Bibot is simulated with Matlab Simulink. On the contrary of the earlier report [2] SimMechanics Second Generation is used for the simulation. By this simulation, the robot actuated in virtual world and the motions are observed. The torques and forces are computed via calculation method of the new generation. Before real experiments on YU-Bibot, all the results of the modifications are simulated.

Also like in the earlier report [2], a 3D simulation of YU-Bibot is obtained by this Simulink model and the 3D characteristics of motions are visualized. The simulink model can be easily changed if a modification is done. Adding new parts such as pads or changing the design can be easily adopted on the model.

Various types of new gaits for walk or standing on one foot to observe and comparison or even a revolutionary gait like sloping road can be obtained without any damage on YU-Bibot. When all new motions are firstly tried in simulation, it would be safer to actuate the robot.

3.1. SIMULATION OF YU-BIBOT WITH FLAT FEET

One of the main differences between 1st Generation and 2nd Generation SimScape is Spatial Contact Force block in 2nd Generation. In the earlier report [2] , each contact point was defined as a hypotethic spring & damper system. In 2nd generation SimScape Spatial Contact Force block makes the simulation easier and defines the contact for two bodies. The floor and the Spatial Contact Force block are shown in Figure 3.1.

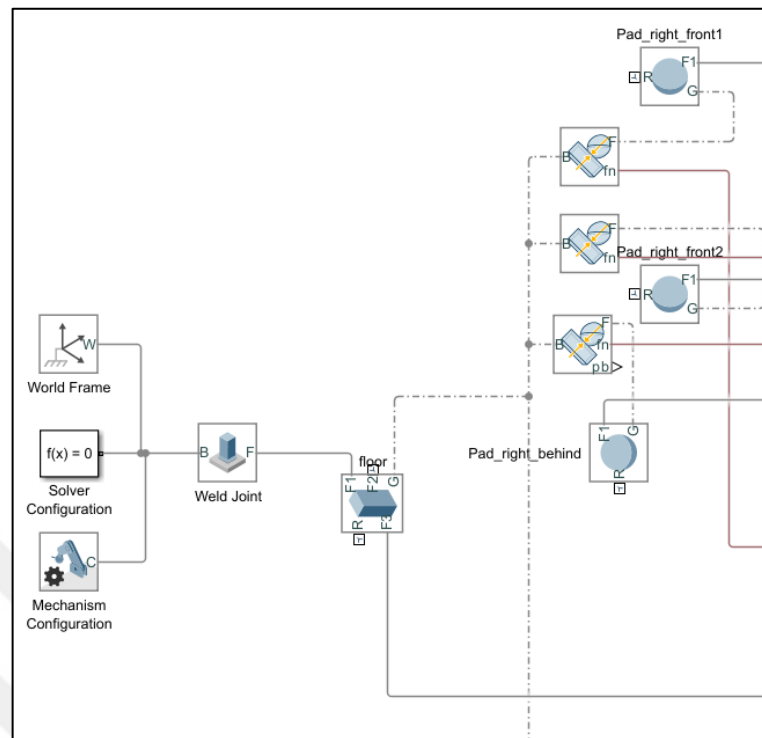


Figure 3.1. Ground contact in Simulink

In the simulation, the contact is expected between floor and pads, so spatial contact force blocks were put between each pad and floor. The mechanism of the block is shown in Figure 3.2.

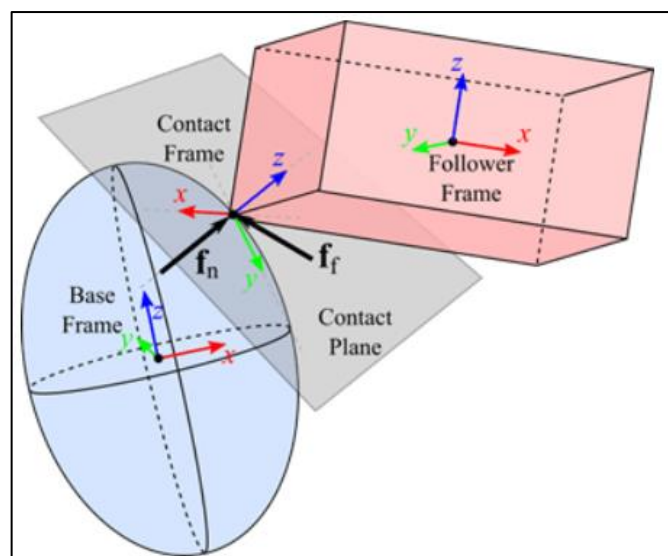


Figure 3.2. Mechanism of spatial contact force block [16]

Assuming that the white pads are used for feet, stiffness and damping coefficients are taken as the average of the tests and Table 2.2.

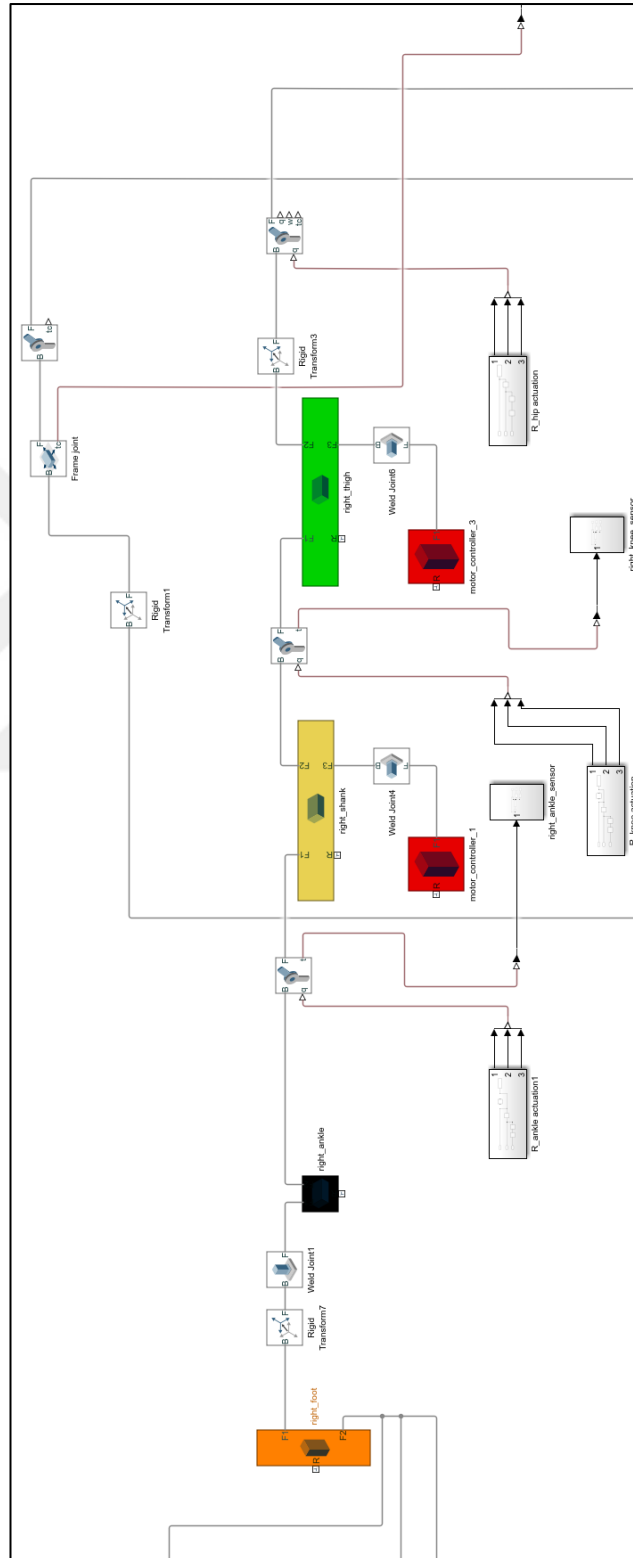


Figure 3.3. Bodies of the right part of YU-Bibot

After defining contact force, pads under the right foot were connected to right foot, right foot connected to right ankle shown in Figure 3.3. Then right ankle is connected to right shank and right shank is connected to right thigh. Finally, right thigh is connected to the torso and dock. Each actuating motor is defined as revolute joint block shown in Figure 3.4. Then actuation is given by another block.

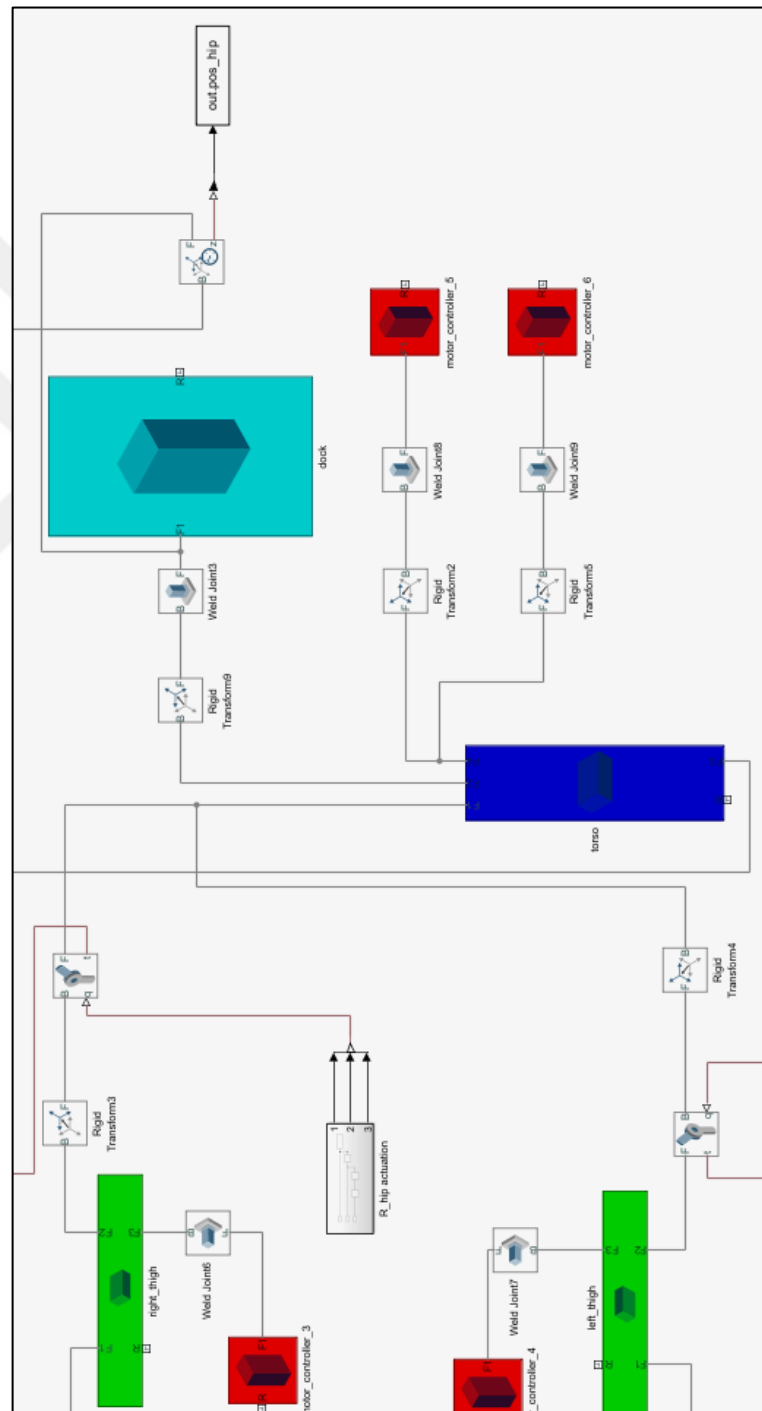


Figure 3.4. Bodies of the top part of YU-Bibot

During the simulation the position of the hip is the key if the robot falls or not. The position is known while YU-Bibot stands up-right and while it walks. If the position of the hip is less than expected it means the robot falls during the simulation. To obtain the position a transformation block is connected between the hip and the world frame.

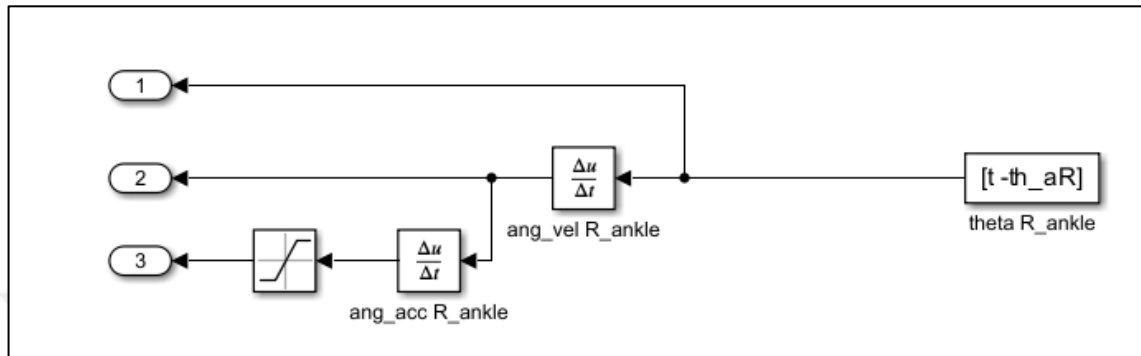


Figure 3.5. Actuation of right ankle

Each actuation block is using the angle of the joint which is created by gait generation algorithms. The angle, first derivative, and second derivative of the angles are inputs for the motion profile of the joints. Actuation blocks of other joints are like the actuation blocks of the right ankle in Figure 3.5.

Backlash, sometimes called lash or play or slop, is a clearance between mating components, sometimes described as the amount of lost motion due to clearance or slackness when movement is reversed and contact is reestablished. It can be defined as "the maximum distance or angle through which any part of a mechanical system may be moved in one direction without applying appreciable force or motion to the next part in mechanical sequence." [17] Also, backlash on the gears is shown in Figure 3.6.

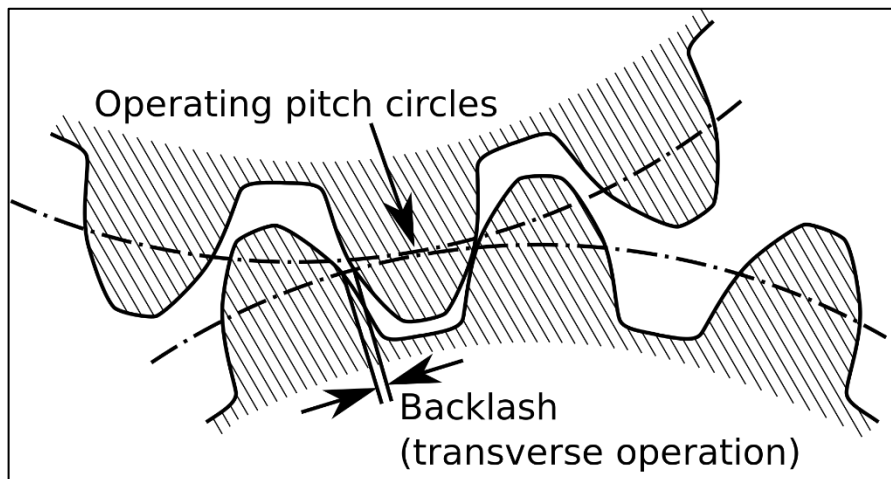


Figure 3.6. Backlash on gears

Some attempts have been made to improve since YU-Bibot was built for the first time. During some projects, reducing backlash methods were studied and feasible ones are tried. One of the projects [2] used the pre-load method to eliminating backlash. By using torsional springs on ankle and knee joints, energy loss was reduced. Within time backlash in the joints was increased by the deformation of gears. In this thesis, other backlash-reducing methods were not tried. On the other hand, the backlash phenomenon has to be explained due to its used in the simulation of the model and the blocks are shown in Figure 3.7.

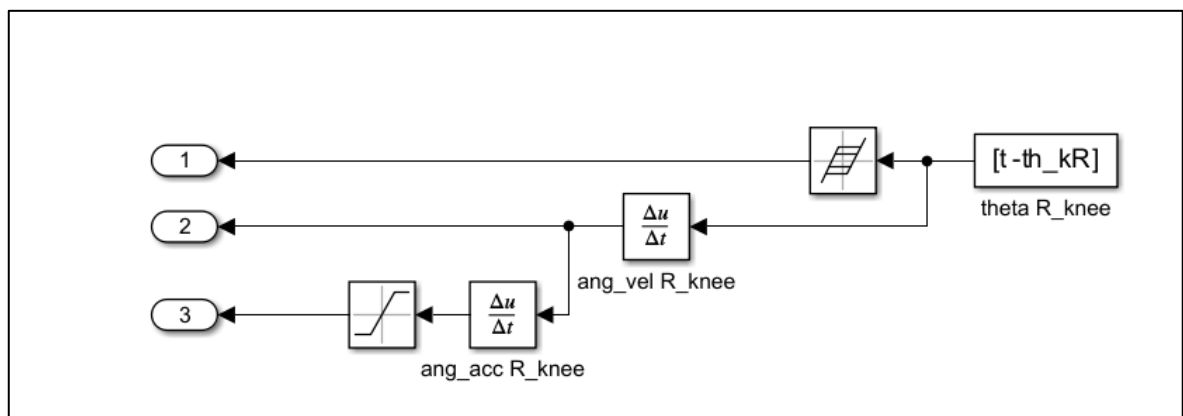


Figure 3.7. Actuation of right knee with backlash

Current YU-Bibot has backlash at joints for several reasons. To obtain this effect in the model a backlash block is used. On the other hand, these actuation blocks with backlash are not used for optimizations in order not to affect the result of the optimizations.

YU-Bibot was improved several times. One of them contains additional joint springs for the ankle and knee joints. The spring coefficient of the joints was taken from [2] and added to the joints. These spring coefficients are: k_{knee} is 7.82 Nm/rad, and k_{ankle} is 5.25 Nm/rad.

The left part blocks are built with the same procedure with only one difference. The difference is the frame connection joint for the left part of the robot. The frame is defined as the rectangular and revolute joint between the floor and the left part of the torso.

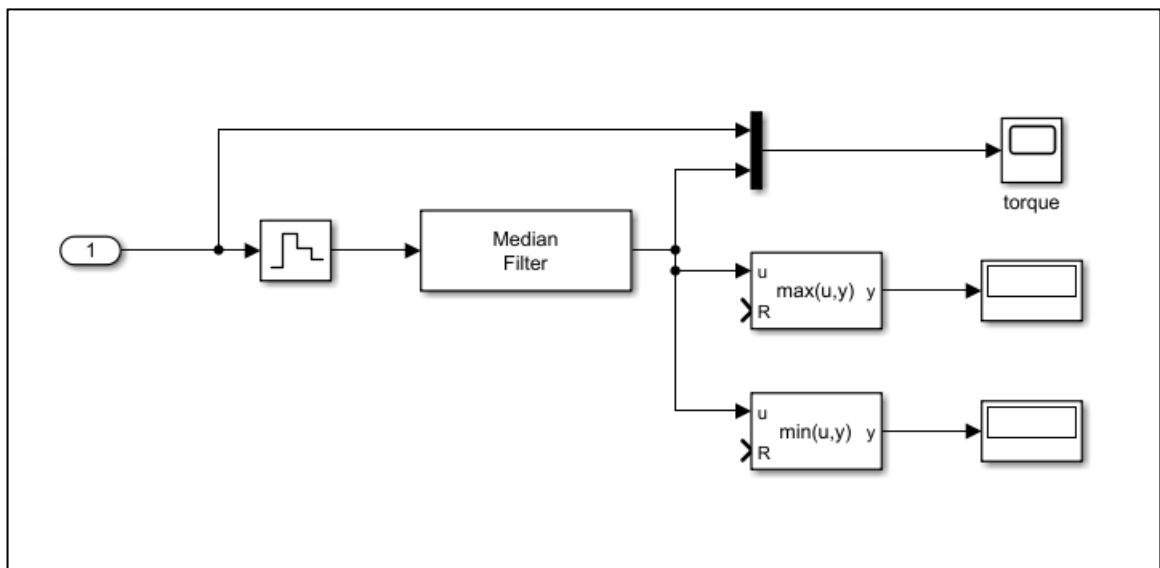


Figure 3.8. Torque calculation block

Sensor of the joints measures torque, but the measured torque has undesired jumps, as a result of discrete measurement. Although in real life, expected jumps are not so high, measurements are more continuous. To create more realistic values a zero-order-hold and a median filter block used to obtain the torque of each joint. Zero-order-hold block converts an input signal with a continuous sample time to an output signal with a discrete sample time. The Median Filter block computes the moving median of the input signal along each channel independently over time. The torque calculation block is shown in Figure 3.8.

The visualization of the simulation is complete by the defining of all of the bodies and contacts. The visual simulation of the robot is shown in Figure 3.9.

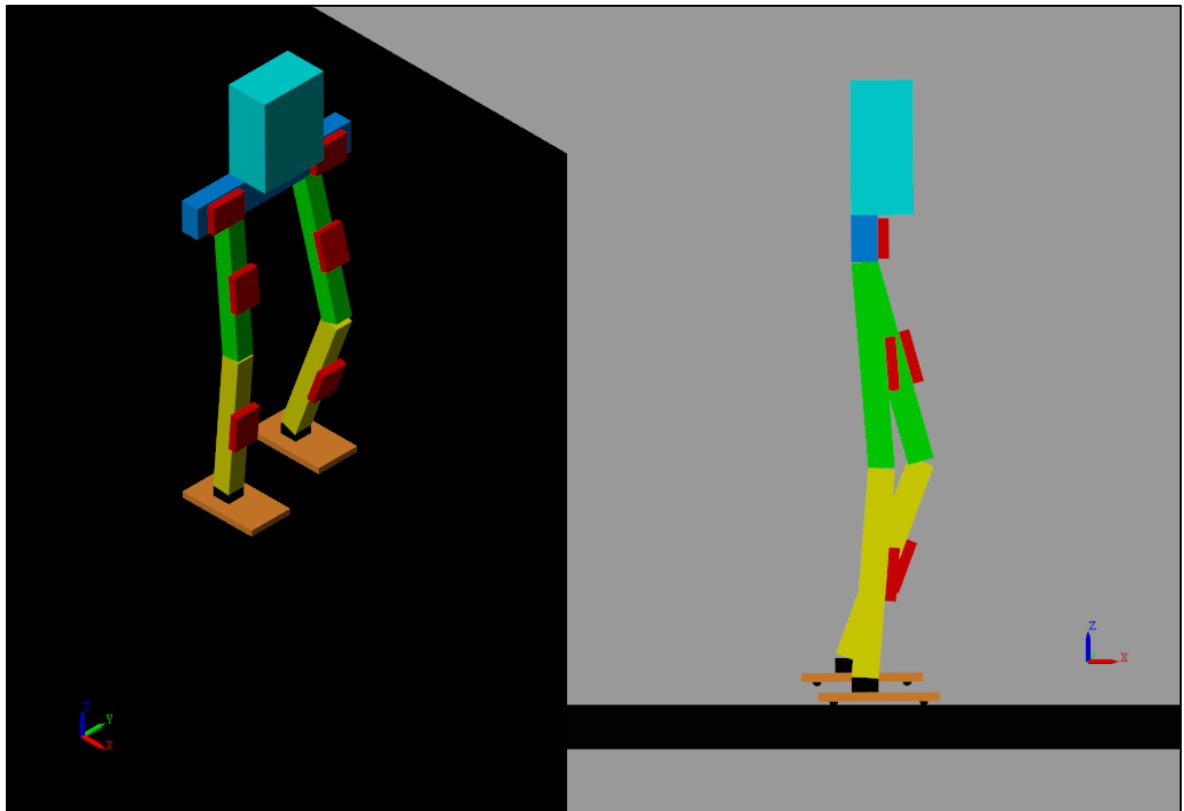


Figure 3.9. (a) Isometric and (b) Side view of simulation

3.1.1. Implementing Pads On The Model

Pad drawing was in the format of Standard Triangle Language (.stl file) which is used for 3D printing. After using an available convertor, it is converted into STEP-file. STEP-file format is suitable with simulink.

Pads are defined as bodies and connected to ground blocks after Spatial Contact Force blocks. Two pads are put for the forefoot and one pad is for the hindfoot under each foot. The visual simulation of the robot with pads is shown in Figure 3.10.

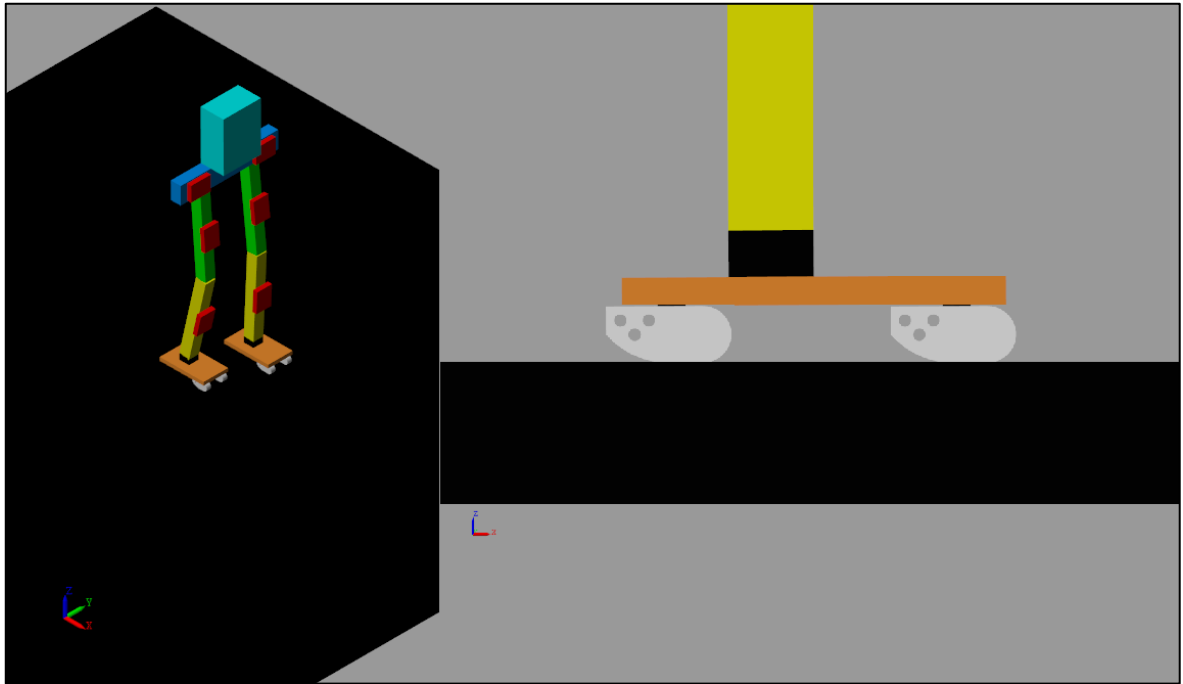


Figure 3.10. (a) Isometric view of the robot and (b) Side view of the foot design for simulation with pad implemented foot

3.2. SIMULATION OF YU-BIBOT WITH TREE BEAM STRUCTURE (TBS) FOOT DESIGN

When the real-human foot is considered, adding pads for the flat-foot model can be improved more. First, the real-human foot has three contact points when it moves perpendicular to the ground. These are the the big toe mound, the base of the little toe mound, and the center of the heel shown in Figure 3.11. As can be seen in the same figure, the big toe mound and the base of the little toe are not at the same level. The degree of freedom of real-human ankle compensate these differences. On the other hand, the structure of the ankle of YU-Bibot allows these two contact points at the same level due to stability problems.

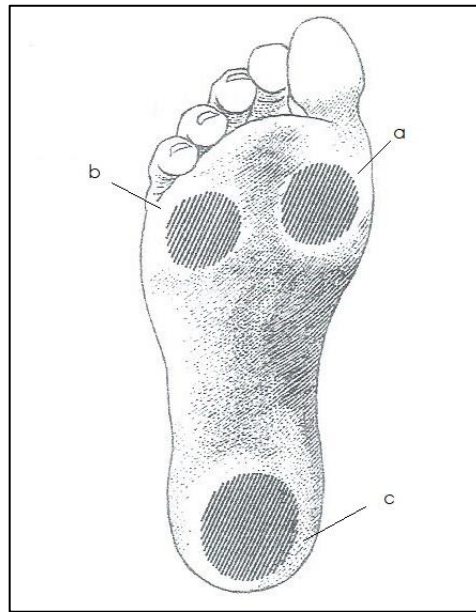


Figure 3.11. Foot contact points. (a) Big toe mound, (b) Base of little toe, (c) Center of the heel

The internal mechanics of the real human foot can be modeled as an arched structure with bending ability, like in Figure 1.9. On the other hand, for simulink simulations, designing a foot structure with beams and a spring for the bottom of the foot is not easy. Instead of this another spring-beam structure is used for simulations which is shown in Figure 3.12.

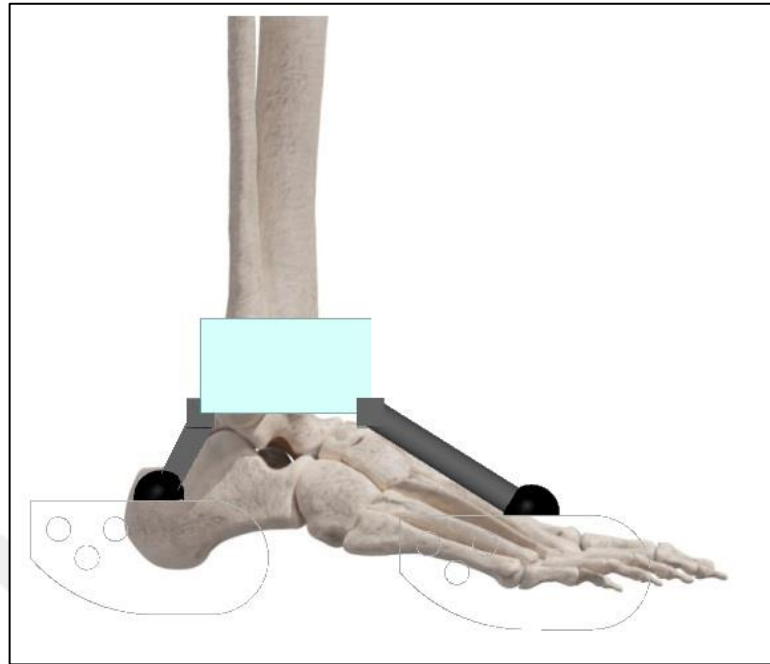


Figure 3.12. Three beam structure foot design showing on real foot bones

To characterize this foot design for simulations, the foot is designed as Three Bem Structure (TBS) Foot which has two beams for the forefoot and one beam for the hindfoot. And pads are implemented bottom of the beams. These beams are connected to the ankle with joints. The elasticity is given by these passive joints.

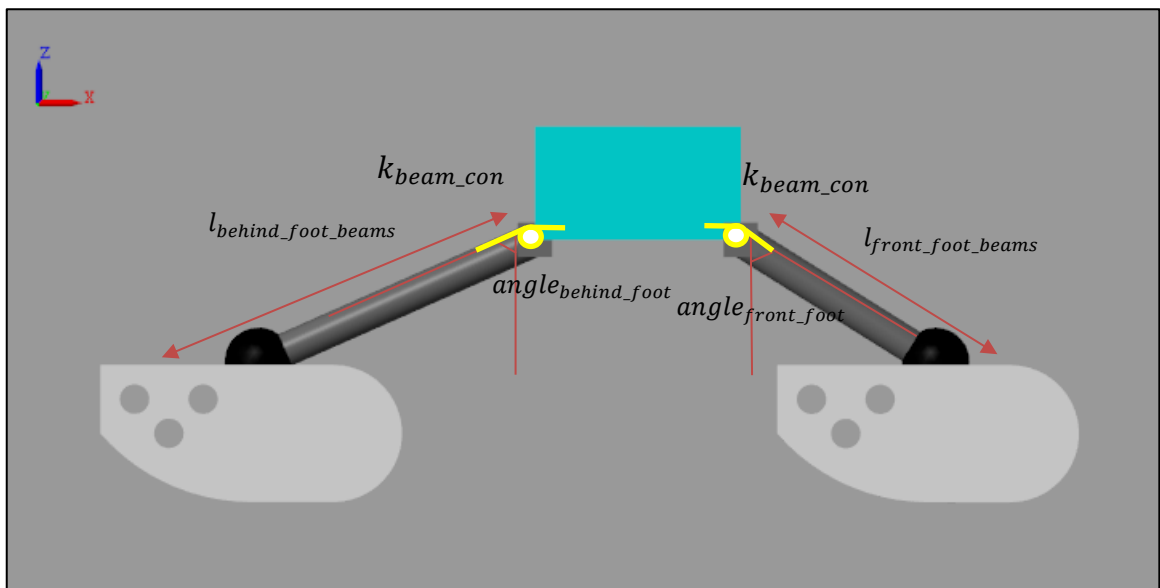


Figure 3.13. Variables of the TBS foot design

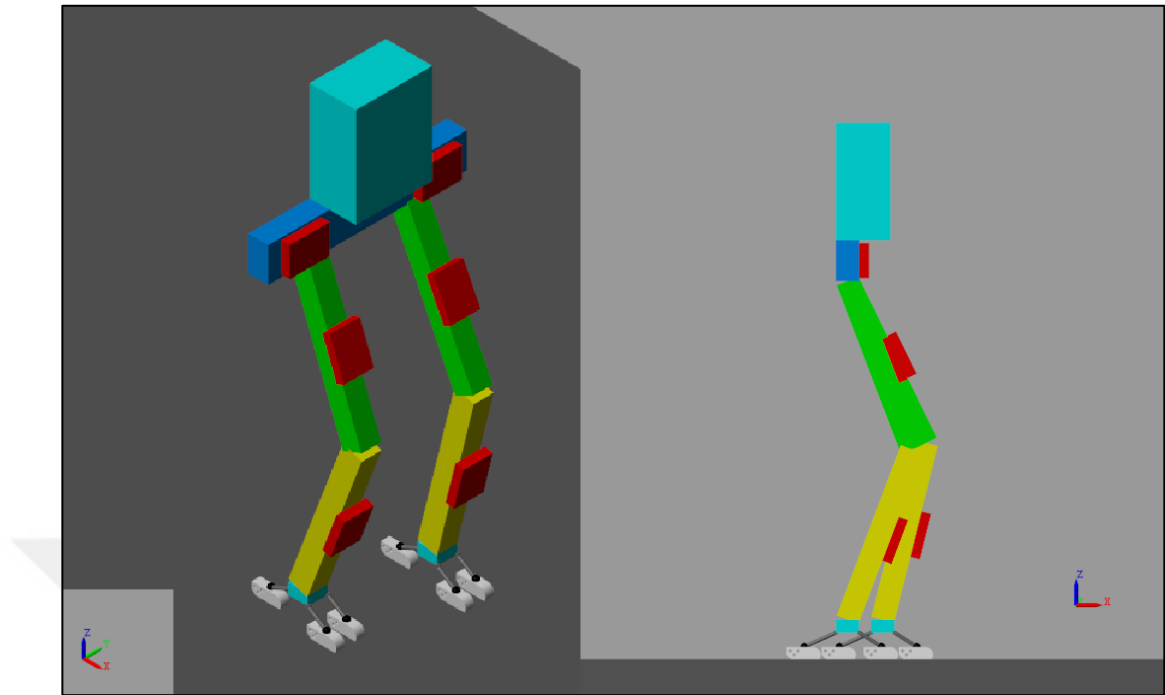


Figure 3.14. (a) Isometric and (b) Side view of TBS foot design simulation

For this design, some new variables are added. The most important of these are; spring constants for beams attached to the ankle joints, beam lengths, and angles of the beams. These lengths and angles are shown in Figure 3.13.

3.3. GAIT GENERATION

In this thesis, different types of gaits are used. Some of them are walking gaits and one of them is basically free-fall to eliminate effects of other variables. Matlab codes of the gaits can be seen in APPENDIX A. Some of the gaits are developed within time, so they have different names and number. Just the best versions of the gaits are mentioned and used in this thesis.

Stepdata: is obtained from earlier report [2]. It is a walking data for 15.9 seconds. It is suitable for flat foot models with or without pads. Angles of joints are given in Figure 3.15. The rest of the gaits are written for this thesis.

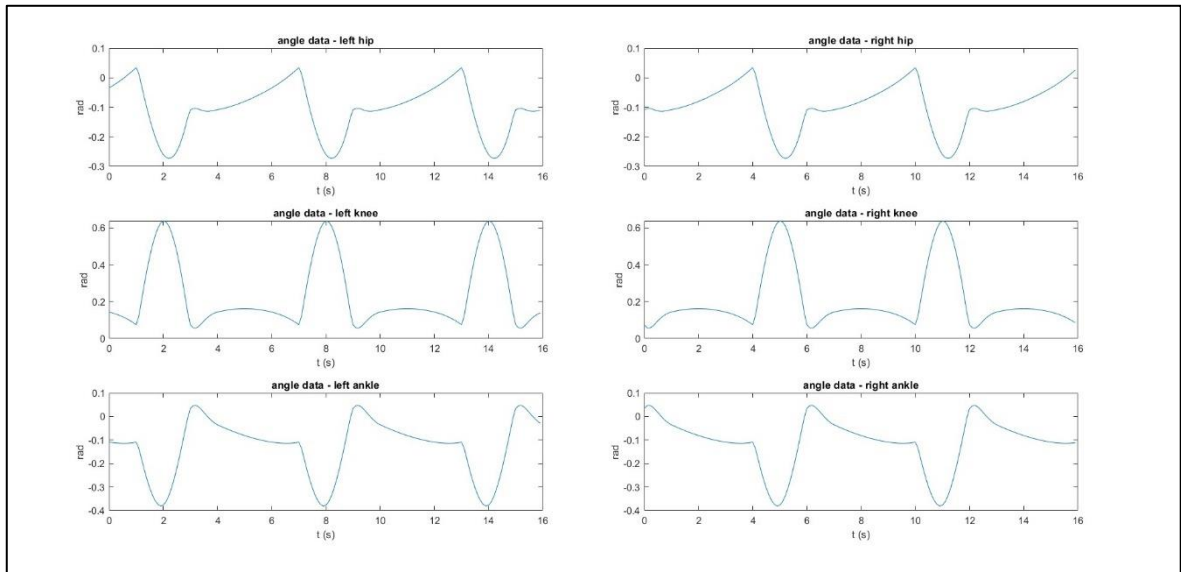


Figure 3.15. Angle data of stepdata.mat

Simulation of dropping at a slight elevation: In this simulation, YU-Bibot is located 10 cm above the ground while it is standing up-right and time is started like this. It is basically free fall and hitting the ground with locked joints (constant angles). This simulation is used for all type of feet. This simulation allows to observe characteristics of designs, because of its simplicity.

TBS Foot walking gait (gait8): Stepdata can not be used for TBS Foot designs. The beams and beam angles are not constant. These variables are changing with optimization results. So, a new gait must be designed for TBS Foot model. Although the gait can be set for more steps, it is set for 5 steps and each step is one second long. For different beam lengths and beam angles, joint angles are also changing. An example set of joint angles is given in Figure 3.16.

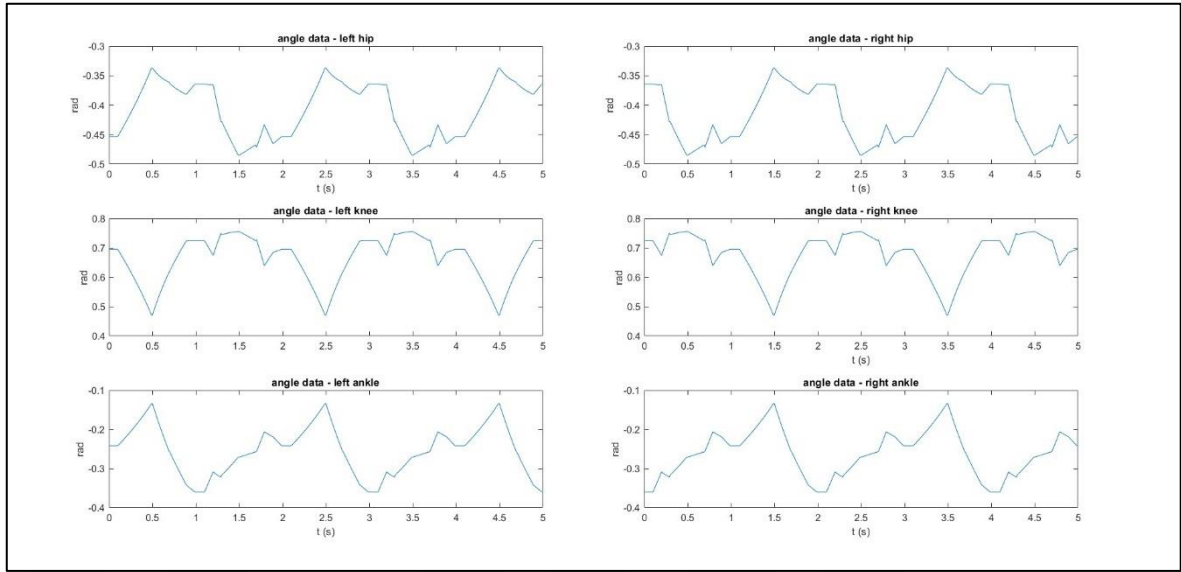


Figure 3.16. An example of angle data of gait8

After the optimization results, an example of gait8 with the optimized variables is given in APPENDIX A. This gait is a step based gait. And each step is divided by 10 stages. Step time (ts), step high (sh) and step length (xs) can be arranged. The first step is special, but second step is basically symmetric with the third step (for different foot), and the others are same with 2nd and 3rd steps.

For the first step; in the first 5 stages hip doesn't move in the x direction, moves $\frac{1}{4}$ of step length for 2 stages and moves $\frac{1}{4}$ of step length more for the rest 3 stages. Also in the first stage hip doesn't move in the z direction, and moves up for 4 stages for the amount of the difference between starting position (zf0) and hip fall at top (zf), then moves down for the 4 stages and stops for the last stage. Right foot stops for the first stage. Then it moves $\frac{1}{2}$ of step length in the x direction for 4 stages. Then moves another $\frac{1}{2}$ step length more for the next 4 stages. It stops for the last stage. In the z direction, right foot stops for the first 2 stages, then it moves up until foot fall length (ffl:zone determined for slow impact) for one stage. Then it moves up until step high (sh) for 2 stages. Then it moves down until ffl for 2 stages. Then moves down until ground contact for one stage. Then, stops for 2 stages. During the first step left foot doesn't move. The stages of the first step can be seen in Figure 3.17. Also, displacements of the hip and the feet of the first step are shown in Table 3.1.

Table 3.1: Displacements of the hip and the feet of YU-Bibot during the stages for the first step of gait8

Stage Body	1	2	3	4	5	6	7	8	9	10
Hip-x	0					$\frac{1}{4}$ of xs		$\frac{1}{4}$ of xs		
Hip-z	0	zf0-zf				zf-zf0				0
Left foot-x	0	$\frac{1}{2}$ of xs				$\frac{1}{2}$ of xs				0
Left foot-z	0		ffl	sh-ffl		ffl-sh		-ffl		0
Right foot-x	0									
Right foot-z	0									

For the second step; in the first 5 stages hip doesn't move in the x direction, moves $\frac{1}{4}$ of step length (xs) for 2 stages and moves $\frac{1}{4}$ of step length more for the rest 3 stages. Also in the first stage hip doesn't move in the z direction, and moves up for 4 stages, then moves down for the 4 stages and stops for the last stage. Left foot stops for the first stage. Then it moves $\frac{1}{2}$ of step length in the x direction for 4 stages. Then moves another $\frac{1}{2}$ step length more for the next 4 stages. It stops for the last stage. In the z direction, left foot stops for the first 2 stages, then it moves up until foot fall length (ffl:zone determined for slow impact) for one stage. Then it moves up until step high (sh) for 2 stages. Then it moves down until ffl for 2 stages. Then moves down until ground contact for one stage. Then, stops for 2 stages. During the second step right foot doesn't move. Displacements of the hip and the feet of the second step are shown in Table 3.2.

Table 3.2: Displacements of the hip and the feet of YU-Bibot during the stages for the second step of gait8

Stage Body	1	2	3	4	5	6	7	8	9	10
Hip-x	0					$\frac{1}{4}$ of xs		$\frac{1}{4}$ of xs		
Hip-z	0	zf0-zf				zf-zf0				0
Left foot-x	0									
Left foot-z	0									
Right foot-x	0	$\frac{1}{2}$ of xs				$\frac{1}{2}$ of xs				0
Right foot-z	0		ffl	sh-ffl		ffl-sh		-ffl		0

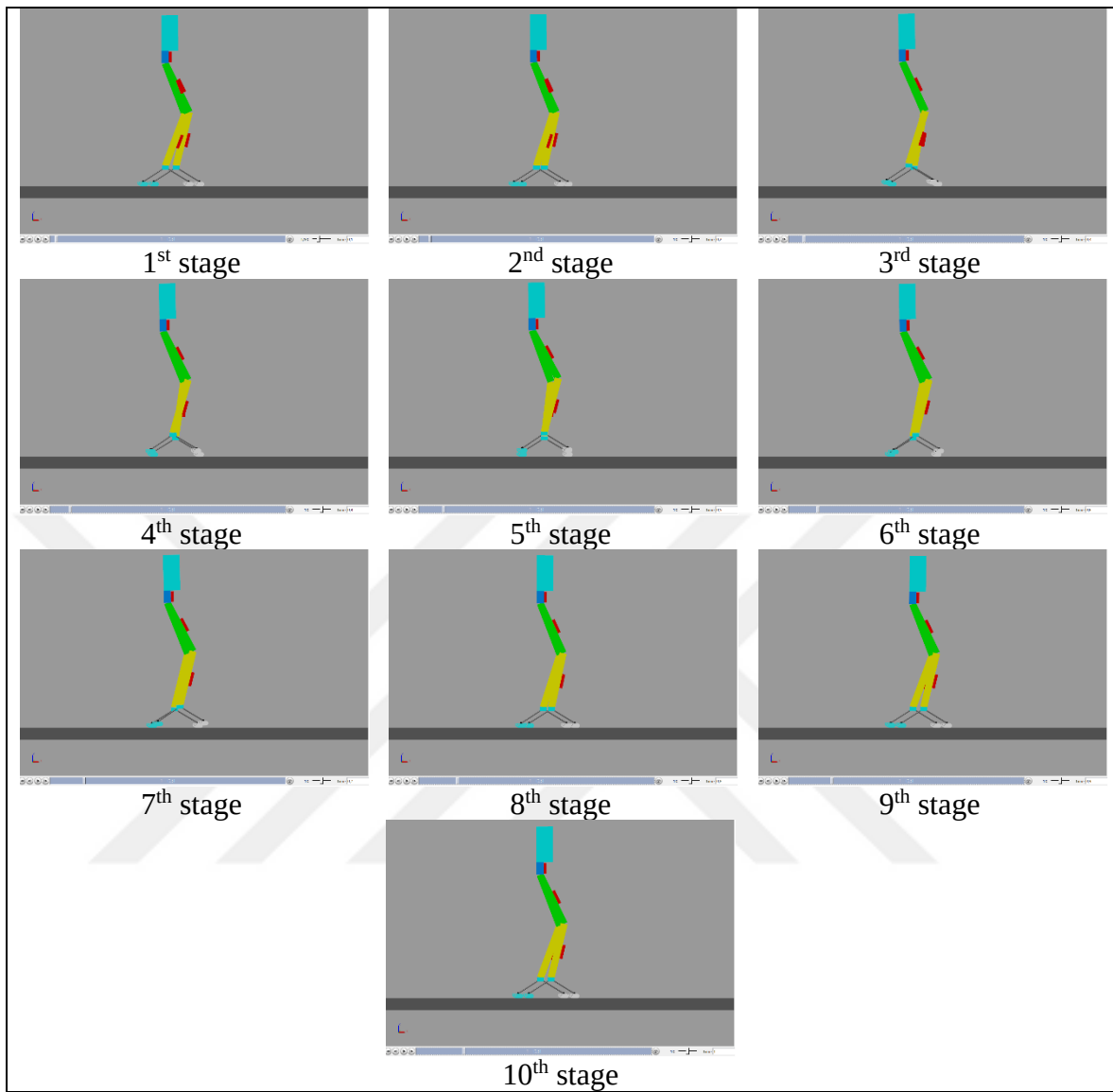


Figure 3.17. Stages of the first step of gait8

Gait with slope (gait9): This gait is basically same with TBS Foot walking gait just with one difference which ground is not flat. Ground has slope and robot is climbing. To obtain a healthy walking (without fall) slope can be maximum 10° . This gait is not used for optimizations. But the resultant optimum values are used to examine this gait. And the gait can be used for future works or observe other phenomena. Also, a visual simulation moment is shown in Figure 3.18.

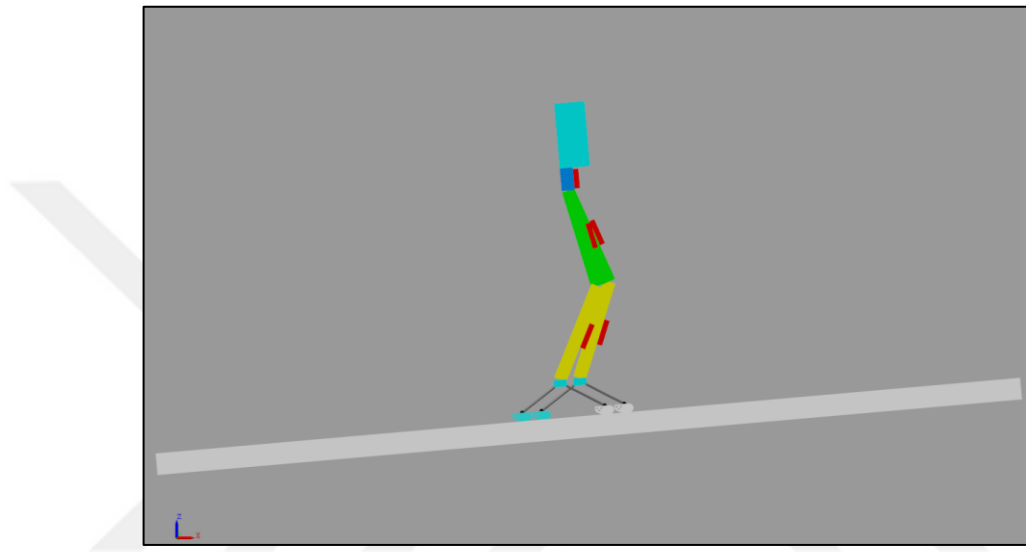


Figure 3.18. Gait with slope

4. OPTIMIZATION OF THE DESIGNS

Optimization of designs is important to the model of the new foot. In this thesis, the torques of the joints are used as the main criteria for optimizations. The possible maximum torques were calculated. The maximum currents of the motors are restricted to 5 amps, because of safety issues. All calculated torques and maximum expected torques are shown in Table 4.1 for comparison. [2] Also, it is known that these values can be more in reality, the current of the motors can be up to 10 A for a short time. But it is not suggested.

Table 4.1. Maximum torque values of the joints for motor currents 5A [2]

Case	τ_{ankle} (Nm)	τ_{knee} (Nm)	τ_{hip} (Nm)
max at available torque (5A)	24.2	-17.7	11.8

The minus value of the torque represent the opposite direction. Reducing the max torque for each joint is one of the aims of the optimization. To measure the max torque from simulation, a subsystem is created as shown in Figure 4.1.

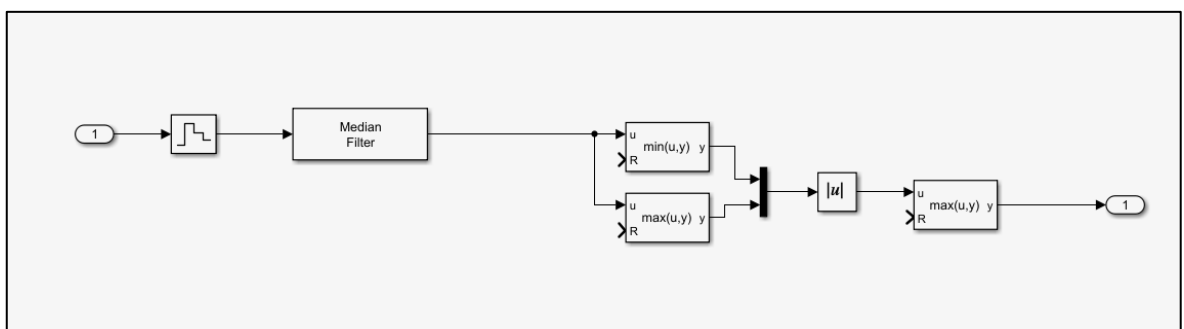


Figure 4.1. Subsystem for maximum torque in one joint

Input of the subsystem is coming from joint sensor part. The signal goes Zero-Order-Hold and Median Filter blocks to obtain more realistic values which is explained in page 32. Then

minimum and maximum values of the signal taken. In most cases minimum is minus because of the direction of the torque. Then absolute value of these two maximum and minimum (maximum in different direction) is taken. Then another maximum block takes the absolute maximum of the torque. If absolute block was put after median filter, block tries to find absolute of each torque value for each calculation step, the calculation will be very slow. Not only for calculation of absolute values of each input but also it is difficult to calculate absolute values of inputs which are close to zero.

4.1. GENETIC ALGORITHM

The genetic algorithm follows these steps. First, ga creates an initial population randomly within boundary conditions. After, ga checks the results for the first population, a new sequence of new populations is created. Creating criteria for new populations is like this. Raw fitness scores are calculated for each member of the first population by computing its fitness value. Then expectation values are calculated by converting raw fitness scores into a more usable range of values. Concerning expectation values, ga selects some members from the first population and they are called parents. Some individuals have better fitness values. They are called elite members and they are passed to the next population directly. For the new population, some children values are created from parents. There are two options to create children values. One of them is making random changes to a single parent. It is called mutation. The second option is using two parents and combining them, and that is called crossover. These elites and children are used for the next population and ga goes on like this. In Matlab, crossover fraction of 1 means that all children other than elite individuals are crossover children, while a crossover fraction of 0 means that all children are mutation children.

Ga doesn't calculate results for each population forever. It should stop at some point. There are several stopping criteria for ga and they depend on the program that is used. In this thesis, Matlab is used in this thesis, so it will be better to explain the stopping criteria of ga in Matlab. One of them is maximum generation. Ga stops when the number of generations are reached. The other one is the maximum time which is the amount of time in seconds. When ga reaches the maximum time, it stops. The maximum time depends on the speed of the computer. So, it is not one of the suggested ways to stop ga unless a supercomputer is used

or optimization is held for a very simple model. The third criterion is determining the fitness limit. When the best point of the current population is equal to or less than the determined fitness limit, ga stops. It can be used to find desired models. If there is a desired fitness limit before, this option can be used. The last three stopping criteria are related to the concept of the stall. Stall means no change or a little change (tolerance) between the fitness function value of the best points of the previous and next populations. Ga can be stopped by maximum generations with a stall or maximum time with a stall. Again using the criteria of maximum stall time depends on the speed of the computer, so it is not suggested either. On the other hand, maximum stall generations criteria can be used for the models in this thesis. Another criterion that is also related to a stall is function tolerance which is used to set the changes between the fitness function value of the best points of previous and next populations for defining stall.

In this thesis, genetic algorithm is used to find best values. The advantage of genetic algorithm is its efficiency. The aim of the optimization is to find solutions which have less maximum torque for the given gait than maximum available torques in Table 4.1 or if they are more, at least they should be close to Table 4.1 as much as possible. So, an objective function is created and try to find minimum value for this objective with the help of genetic algorithm.

Matlab Optimization Tool is used to find the minimum of the objective function. If one of the objective is less than the maximum value from Table 5.1, the fraction will be less than 1. It means that value is in the safe region. The effect of the values in the safe region should be decreased because the fractions more than 1 are more important to reduce. To obtain this effect, square of the fractions are tried to be minimized. The genetic algorithms are used to find the best possible solution for optimization variable which is pad stiffness.

obj1 ($\tau_{\max\text{-ankle}}$) is the maximum of the maximum torque of the left and right ankles joints

obj2 ($\tau_{\max\text{-knee}}$) is the maximum of the maximum torque of the left and right knee joints

obj3 ($\tau_{\max\text{-hip}}$) is the maximum of the maximum torque of the left and right hip joints

And the objective function is:

$$objective = \left(\frac{obj1}{24.2}\right)^2 + \left(\frac{obj2}{17.7}\right)^2 + \left(\frac{obj3}{11.8}\right)^2 \quad (4.1)$$

The minimization of equation (4.1) is carried out for different sets by using genetic algorithm with the following parameters: the size of population is 50 individuals; the value of the constraint tolerance is 10^{-3} ; the crossing probability is 0.8. The numerical calculations were performed with the help of a computer with an Intel Core I7–11800H processor (with a frequency of 2.3 GHz) and a random-access memory of 16 Gb.

4.2. FLAT-FOOT MODEL WITH PADS

The stepdata is obtained from the earlier report [2]. The most important variable to design the pads is stiffness of them. The known stiffness values are 4836 N/m for orange pad and 64948 N/m for white pad. So optimization boundaries are determined between 20000 N/m and 300000 N/m.

After some iterations, Ga finds an optimum value for pad stiffness which is 213911 N/m and the objective value is 25.7416. Figure 4.2 shows the settings of the Matlab optimization tool.

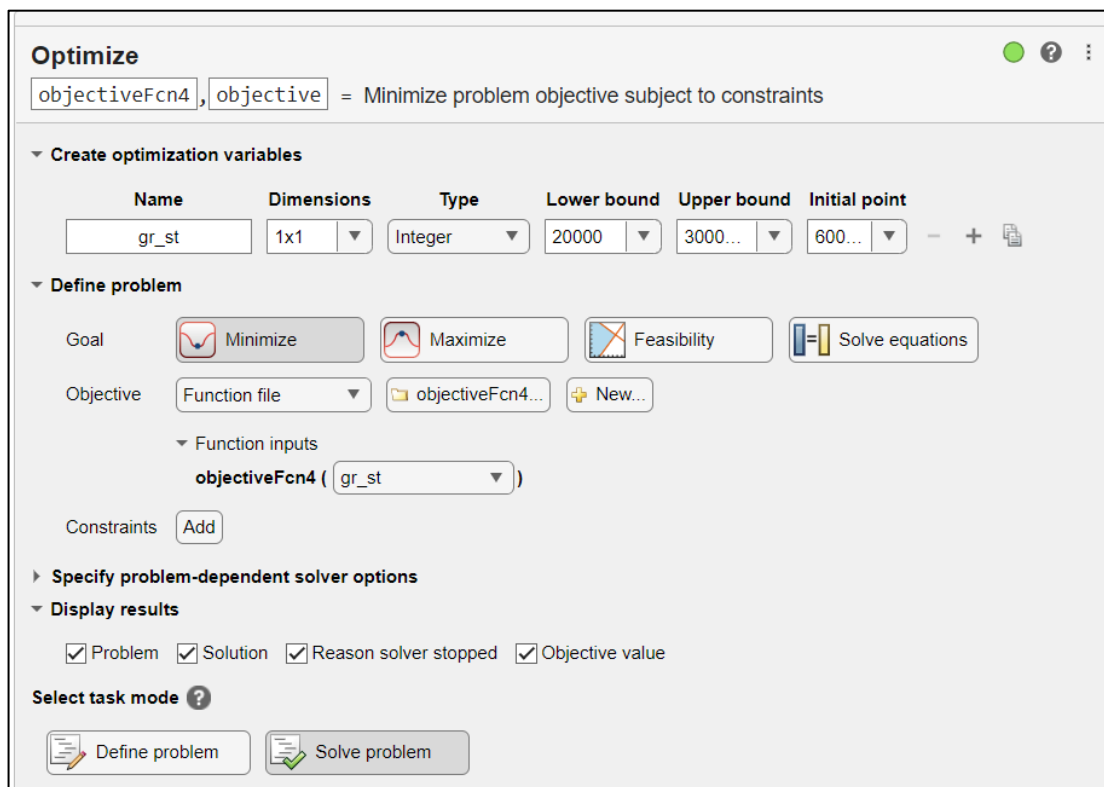


Figure 4.2. Matlab optimization tool set-1

If the robot falls like defined in the section 3.1, objective will be a bigger value. So genetic algorithm tries to avoid iterations that falling is happened. The solution graphics of ga is given in Figure 4.3.

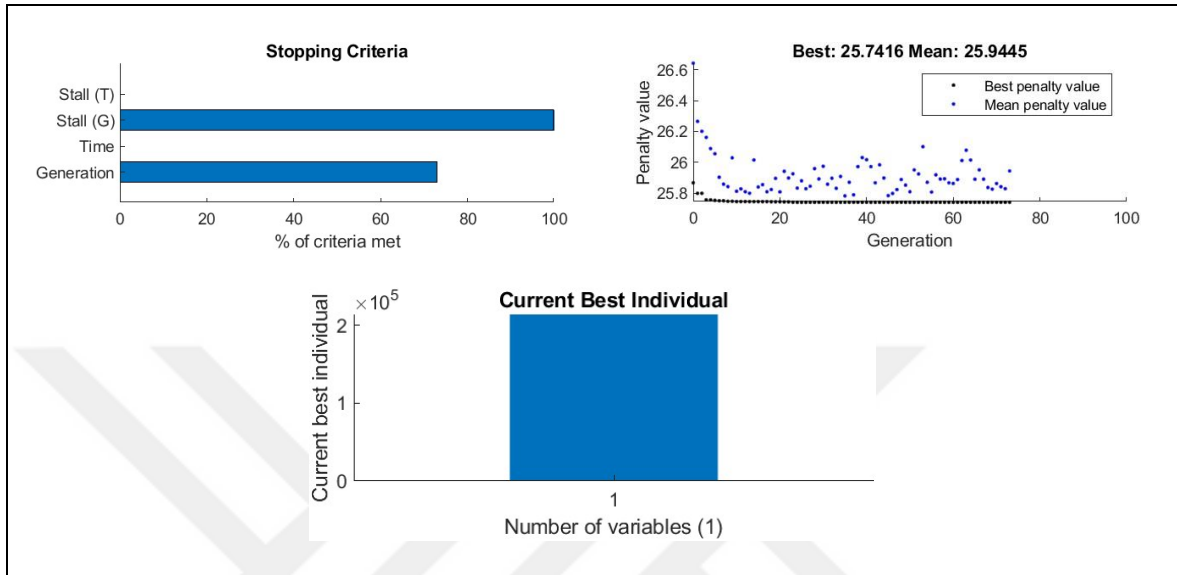


Figure 4.3. Optimization results for the flat-foot model with pads

While generation is continuing (73%) Ga stopped at maximum generation of stall (%100). The stiffness is not at the edge of the boundary conditions. So, these result shows local minimum for the objective function. The experimental impact stiffness of overall human foot is 481000 N/m [5] which is mentioned before in 1.2. Optimized stiffness for pads are half of stiffness of human foot.

To find a better solution, more comprehensive optimization is arranged. For the same objective function, damping coefficient is also defined as another optimization variable. Also, damping coefficients and stiffness of fore and hind pads are separated from each other. So, four variables which are stiffnesses of fore (k_{ff}) and hind (k_{hf}) pads, damping coefficients of fore (c_{ff}) and hind (c_{hf}) pads are tried to be optimized. Figure 4.4 shows the settings of Matlab optimization tool.

objectiveFcn5, objective = Minimize problem objective subject to constraints

▼ Create optimization variables

Name	Dimensions	Type	Lower bound	Upper bound	Initial point
gr_st_fr	1x1	Integer	20000	3000...	600...
gr_st_bh	1x1	Integer	20000	3000...	600...
gr_dc_fr	1x1	Integer	20000	3000...	600...
gr_dc_bh	1x1	Integer	20000	3000...	600...

▼ Define problem

Goal ☒ Minimize ☐ Maximize ☐ Feasibility ☐ Solve equations

Objective

▼ Function inputs
 objectiveFcn5 (, , , ...
)

Constraints

► Specify problem-dependent solver options

▼ Display results

☒ Problem ☒ Solution ☒ Reason solver stopped ☒ Objective value

Select task mode ?

Figure 4.4. Matlab optimization tool set-2

The optimization results are; k_{ff_pads} is 2154830 N/m, k_{hf_pads} is 642654 N/m, c_{ff_pads} is 78350 N/(m/s), c_{hf_pads} is 136671 N/(m/s), and $objective_{w/pad(set2)}$ is 8.38098.

There are significant differences for the values of fore and hind pads. It means different pads should be used for fore and hind. The solution graphics of ga is given in Figure 4.5.

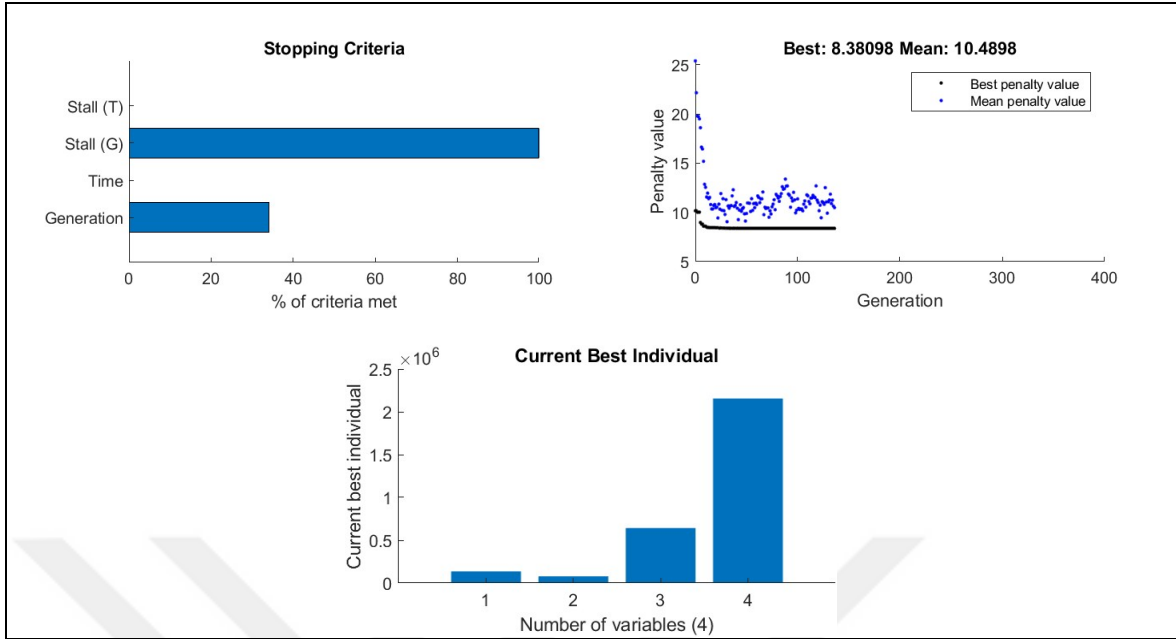


Figure 4.5. Optimization results for the flat-foot model with pads for 4 variables

While generation is continuing (34%) Ga stopped at maximum generation of stall (%100). When the local minimum values are observed, stiffnesses for fore pads are more than triple of stiffnesses for hind pads. These results show fore pads should be more stiff and the hind pads should be more soft. This structure is also the same in the human feet. The heels are softer and the below of the forefoot are stiffer. This can be the result of natural selection and it can be considered as optimization by natural selection. Although the relationship between fore and hind pads looks like biological solutions.

In this foot model, there are 3 pads. To compare with the article [5] and article [7], equivalent overall stiffness and damping coefficients are calculated for pads.

$$k_{eq_pads} = 2 * k_{ff_pads} + k_{hf_pads} = 4952314 \text{ N/m} \quad (4.2)$$

$$c_{eq_pads} = 2 * c_{ff_pads} + c_{hf_pads} = 293371 \text{ N/(m/s)} \quad (4.3)$$

The experimental impact stiffness of the overall human foot is 481000 N/m [5] which is mentioned before in 1.2. Optimized equivalent stiffness for pads is approximately 10 times of stiffness of the human foot.

The experimental stiffness of the human foot for natural COP is 964600 N/m [7] which is mentioned before in 1.2. Optimized equivalent stiffness of the pads is approximately 5 times of stiffness of the human foot. The experimental damping coefficient of the human foot for natural COP is 7890,1 Ns/m [7]. The optimized equivalent damping coefficient of the pads is approximately 33 times of the damping coefficient of the human foot.

4.3. TBS FOOT MODEL

TBS Foot model was explained in section 3.2 and shown in Figure 3.14. As mentioned before, main parameters for TBS Foot model are beam lengths, beam angles and spring constant for attachment points. These new variables are tried to be optimized via same method. Although optimization method is the same with flat-foot optimizations, the gait is different. Thus makes impossible to compare the results, but it is necessary because of the design. Note that the inertias of the foot beams are automatically calculated by Simulink and it is assumed that the variations of sizes of the feet do not affect their mass. Figure 4.6 shows the settings of Matlab optimization tool.

The screenshot shows the Matlab optimization tool interface with the following settings:

- Objective:** objectiveFcn2, objective = Minimize problem objective subject to constraints
- Create optimization variables:**

Name	Dimensions	Type	Lower bound	Upper bound	Initial point
k_f	1x1	Continuous	1	60	1
l_ffl	1x1	Integer	10	200	120
a_ff	1x1	Integer	15	75	45
l_bfl	1x1	Integer	10	200	90
- Define problem:**
 - Goal:** Minimize (selected), Maximize, Feasibility, Solve equations
 - Objective:** Function file (selected), objectiveFcn2..., New...
 - Function inputs:** objectiveFcn2 (k_f, l_ffl, a_ff, ... l_bfl)
 - Constraints:** Add
- Specify problem-dependent solver options**
- Display results**

Figure 4.6. Matlab optimization tool set-3

So, the results are; $k_{\text{beam_connections}}$ is 8.95786 Nm/deg, $\text{angle}_{\text{front_foot}}$ is 58° , $l_{\text{front_foot_beams}}$ is 188 mm, $l_{\text{behind_foot_beams}}$ is 194 mm, and $\text{objective}_{\text{TBS}(\text{set3})}$ is 23.3978.

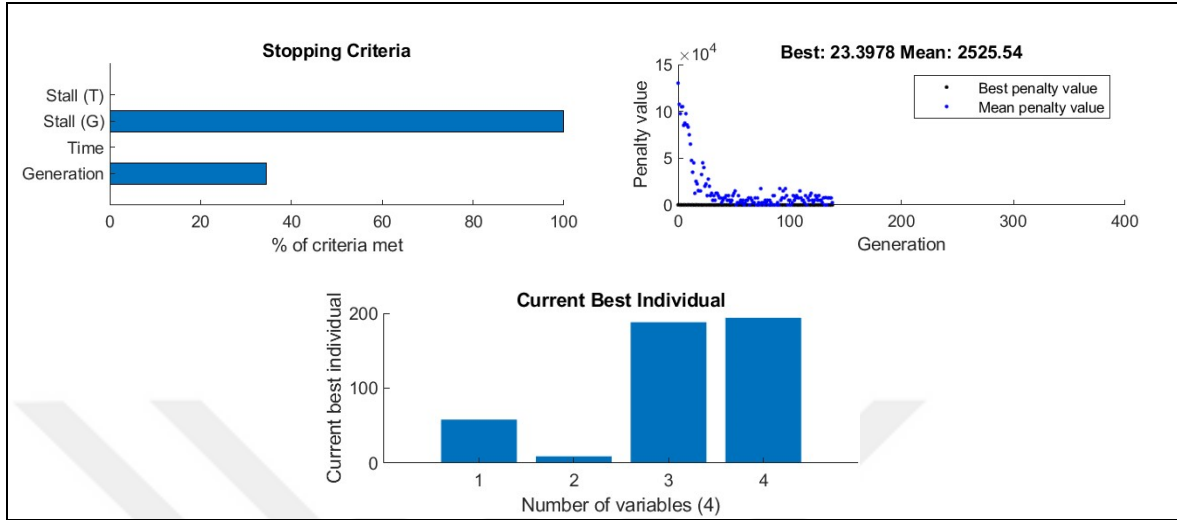


Figure 4.7. Optimization results for the TBS foot model

The solution graphics of ga is given in Figure 4.7. While generation is continuing (34.5%) Ga stopped at maximum generation of stall (%100). The spring constant of the beam connection point are 70 or 100 times of the springs implemented on knees and ankles in the previous study [2]. This means it can be used more stiff torsion springs or this spring effect can be modeled by structure. Instead of designing three beam structure, the body of the foot can be designed as one part and the torsion spring effect can be given by the material. Screenshots of the some different iterations are shown in Figure 4.8.

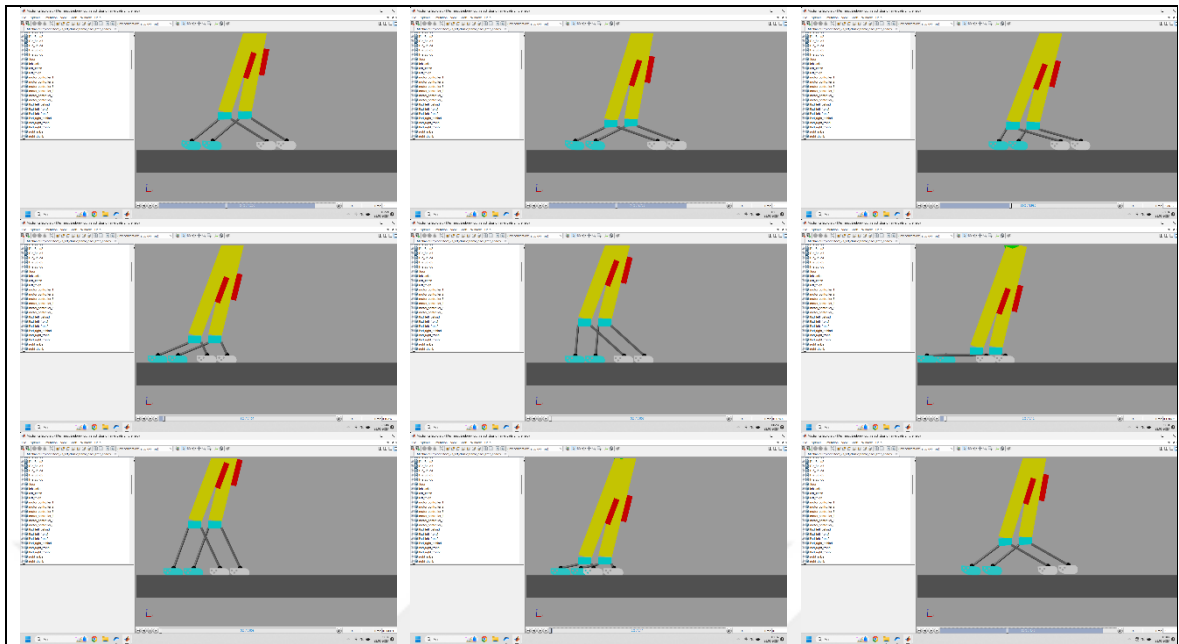


Figure 4.8. Some examples of different iterations for genetic algorithm

5. COMPARISON OF THE RESULTS

5.1. RESULTS FOR WALKING GAITS

5.1.1. Optimization for the Flat-Foot Model

Maximum torque values are obtained with the objective function used in the genetic algorithm. For the best values, the stiffness of the pads is found. For optimized stiffness, the simulation is run again and the results are given in Table 5.1.

Table 5.1. Maximum and RMS torques from tool set-1

τ (N.m)	$\tau_{\max}$ Left	$\tau_{\max}$ Right	τ_{rms} Left	τ_{rms} Right
Ankle joint	26.6832	26.6853	4.6598	5.0600
Knee joint	30.5751	30.0192	11.0581	11.0965
Hip joint	54.7674	50.6067	19.5681	19.6069

Maximum torque values for the simulation without pad implementation are given in Table 5.2. To obtain Table 5.1 and Table 5.2, the same walking gaits are used. The stiffness of the buttons is calculated by the formula below and the elastic modulus of polycarbonate is 2.38 GPa [18].

$$k = E * \frac{A}{L} \quad (5.1)$$

$$k_{\text{buttons}} = 2.38 * 10^9 * \frac{\pi * (2 * 10^{-3})^2}{10 * 10^{-3}} = 29907962 \text{ N/m} \quad (5.2)$$

Table 5.2. Maximum and RMS torques for the model (without pads)

τ (N.m)	$\tau_{\max}$ Left	$\tau_{\max}$ Right	τ_{rms} Left	τ_{rms} Right
Ankle joint	13.7331	13.7665	4.1752	5.0712
Knee joint	31.2120	31.2703	12.0436	12.2279
Hip joint	57.2384	57.1159	22.0616	22.1509

Maximum torques for ankle and knee joints are better for the model with pads but maximum torque for hip joints is less for the model with pads. For overall comparison, the defined objective for optimization is applied for the simulation without pads:

$$objective_{wo/pad} = \left(\frac{13.7665}{24.2}\right)^2 + \left(\frac{31.2703}{17.7}\right)^2 + \left(\frac{57.2384}{11.8}\right)^2 = 26.9742 \quad (5.3)$$

$$objective_{wo/pad} > objective_{w/pad (set1)} \quad (5.4)$$

It seems that the flat-foot model with pads is better for maximum torques. It means torque jumps are less if the pads are implemented to YU-Bibot.

Table 5.3. Maximum and RMS torques from tool set-2

τ (N.m)	$\tau_{\max}$ Left	$\tau_{\max}$ Right	τ_{rms} Left	τ_{rms} Right
Ankle joint	11.6411	11.6440	4.4262	4.9946
Knee joint	20.4093	17.8072	8.6176	8.4930
Hip joint	30.8159	30.8056	14.1408	14.1965

$$objective_{wo/pad} > objective_{w/pad (set1)} > objective_{w/pad (set2)} \quad (5.5)$$

On the other hand, when the pads with different specifications (stiffness and damping coefficient) for hind and fore are implemented under the flat foot, the objective value is quite smaller than other versions. It means torque jumps are less if these pads are implemented to YU-Bibot.

When root mean square of torque values are compared with the model without pads and the model Tool Set-1, knee and hip rms torques of Tool Set-1 are slightly lower than rms torques of the model without pads. But rms torques of ankle joints are bigger than rms torques of the model without pads. One reason can be the weight of the pads make a negative effect on ankle joints. Also, the differences are not so significant for both rms torques and objective values. It means adding pads is not so effective if we just change the stiffness of the pads and the rest of the variables remain the same as the current YU-Bibot.

When rms of torque values are compared with the model without pads and the model Tool Set-2, all rms torque values and objectives are less than the model without pads. It is noticed that rms and maximum torques of Tool Set-2 don't have significant differences from the model without pads. But other values have important differences. So, we can accept that

creating a new model with different fore and hind pad stiffness and damping coefficient like the optimization solutions in Figure 4.4 is better than the current YU-Bibot.

For many variable sets, generally, the resultant maximum torques are so close for the right and the left of the same joints. Only if there is a jump at the start of the simulation one of the joints can have a different maximum torque for the other side (left or right) of the same joint (ankle, knee, hip). In this situation, the maximum torque of the left knee joint is slightly more than the right one for other joint couples. Also, this jump can be seen in Figure 5.1.

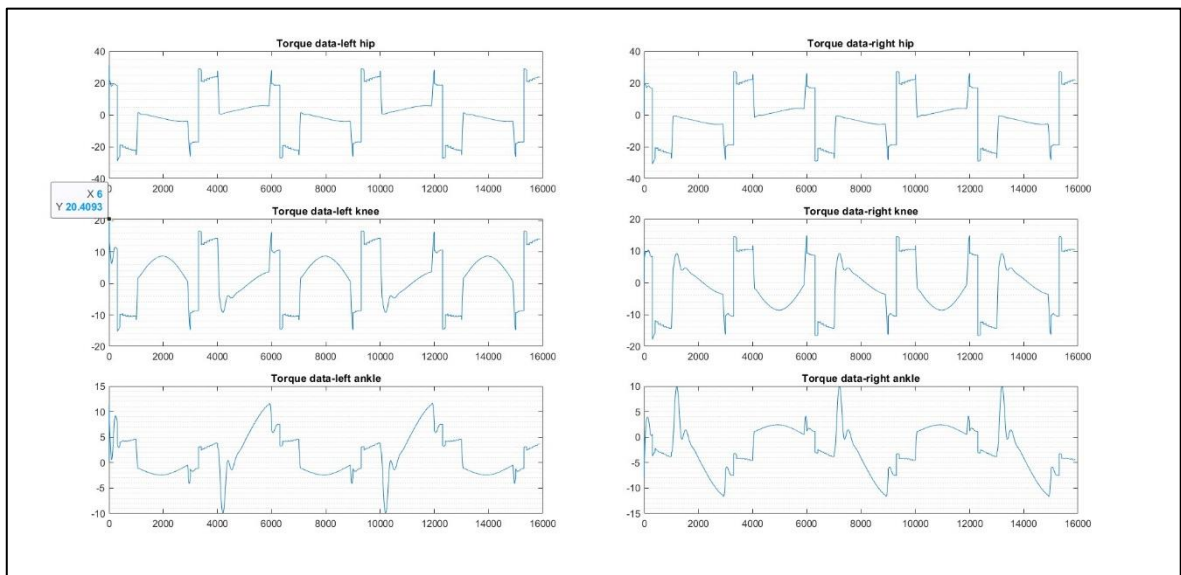


Figure 5.1. Torque data of joints for tool set-2

With this information, Table 5.3 can be fixated. The maximum torque of the left knee joint can be changed by another value which is found that the average percentage difference from the other two joints calculated.

To obtain fixated value of maximum torque of left knee joint from Table 5.3. Fixated values are shown in Table 5.4.

$$\frac{error_{ankle} + error_{hip}}{2} = \frac{\frac{|11,6411 - 11,6440|}{11,6411 + 11,6440} + \frac{|30,8159 - 30,8056|}{30,8159 + 30,8056}}{2} = 0,00029 \quad (5.6)$$

$$17,8072 + (17,8072 * 0,00029) = 17,8124 \quad (5.7)$$

Table 5.4. Maximum torques from tool set-2 (fixated begining-jump)

$\tau_{\max}$ (N.m)	Left	Right
Ankle joint	11.6411	11.6440
Knee joint	17.8124	17.8072
Hip joint	30.8159	30.8056

$$objective_{w/pad (set2)} = \left(\frac{11.6440}{24.2}\right)^2 + \left(\frac{17.8124}{17.7}\right)^2 + \left(\frac{30.8159}{11.8}\right)^2 = 8.0643 \quad (5.8)$$

5.1.2. Optimization for the TBS Foot Model

Maximum torque values are obtained with the objective function used in the genetic algorithm. For the best values of beam lengths, beam angles and spring constant for attachment points are found in section 4.3. For optimized values, the simulation is run again and the results are given in Table 5.5.

Table 5.5. Maximum torques from tool set-3

τ (N.m)	$\tau_{\max}$ Left	$\tau_{\max}$ Right	τ_{rms} Left	τ_{rms} Right
Ankle joint	29.9570	30.1153	12.2106	11.1943
Knee joint	37.8174	37.0305	16.3411	15.3589
Hip joint	49.0852	49.0932	19.2708	18.9830

$$objective_{tf (set3)} > objective_{w/pad (set2)} \quad (5.9)$$

These objectives are calculated with same equations. On the other hand, walking gaits are not same for both sets. So this comparison is not valid. Local minimum of optimization solution for TBS Foot is only valid for its own design.

Also, the resultant beam lengths are so close to upper boundary. It should be recheck if minimum objective can be obtained by using boundary lengths. If it is possible, boundary values must be extended for less objective values.

When other three values are same for results of optimization tool set-3 and only length of fore beam is 200 mm (boundary). Maximum Torques are shown in Table 5.6.

Table 5.6. Maximum torques from tool set-3 (except for $l_{\text{forefoot_beams}}=200$ mm)

τ (N.m)	τ_{max} Left	τ_{max} Right
Ankle joint	30.2875	30.9514
Knee joint	40.8251	41.8848
Hip joint	49.2648	49.2503

So the $\text{objective}_{\text{tf}(\text{set3})}'$ is 24.6660.

When the other three values are the same for the results of optimization tool set-3 and only the length of the fore beam is 200 mm (boundary). Maximum Torques are shown in Table 5.7.

Table 5.7. Maximum torques from tool set-3 (except for $l_{\text{hindfoot_beams}}=200$ mm)

τ (N.m)	τ_{max} Left	τ_{max} Right
Ankle joint	28.8974	30.1915
Knee joint	42.1619	44.7398
Hip joint	48.5794	48.6077

So the $\text{objective}_{\text{tf}(\text{set3})}''$ is 24.9142.

$$\text{objective}_{\text{tf}(\text{set3})} > \text{objective}_{\text{tf}(\text{set3})}' > \text{objective}_{\text{tf}(\text{set3})}'' \quad (5.10)$$

Objectives for boundary conditions of beam lengths are both bigger than the original objective. So, the close boundary condition was not an optimization set error.

TBS Foot model beam lengths and angles create a reference shape for the foot design. It is mentioned that these design parameters can be used as equivalent designs for other designs. Also, the shape can be compared with real foot shapes like in the article [8].

For optimized values, FW, H₃₅, H₄₀, H₄₅, H₅₀, and FL can be found.

$$FW = w_{\text{ankle}} + w_{\text{pad}} \quad (5.11)$$

$$FL = L_{\text{pad}} + L_{\text{ankle}} + [l_{\text{front_foot_beams}} * \sin(\text{angle}_{\text{front_foot}})] \quad (5.12)$$

$$H_i = [1,2 * i * \cos((\text{angle}_{\text{front_foot}}))] + h_{\text{pad}} \quad (5.13)$$

TBS Foot model with the parameters above is shown in Figure 5.2.

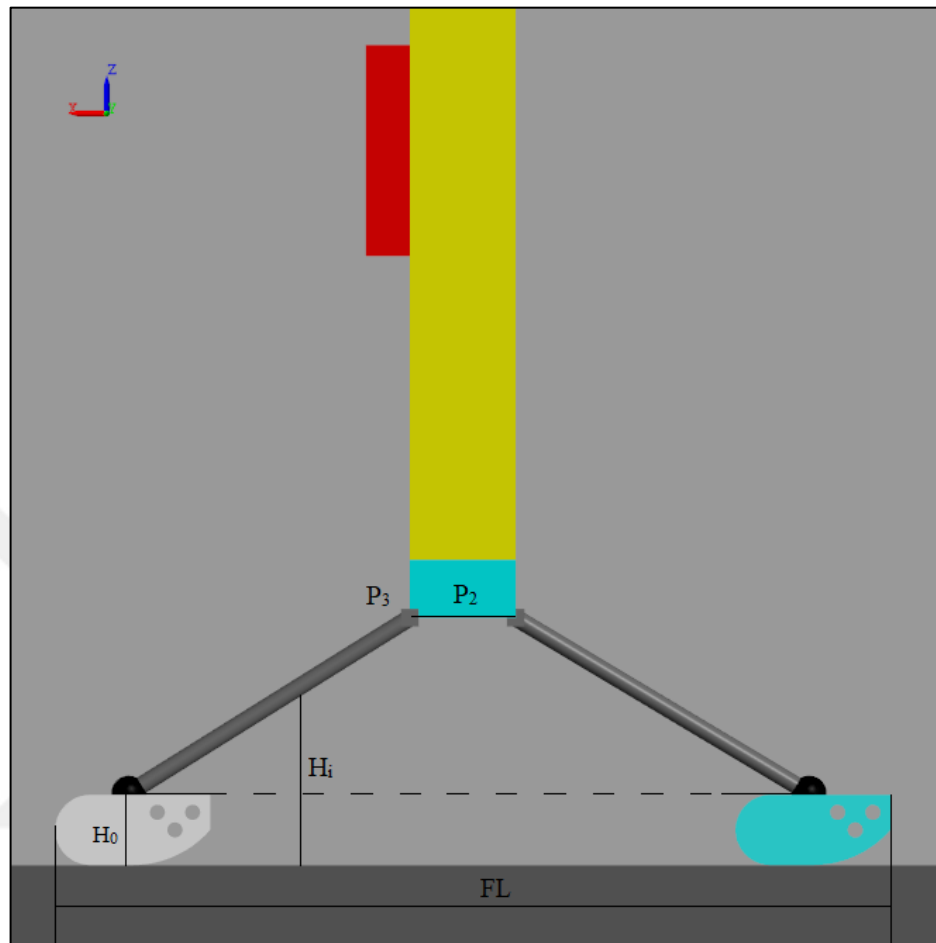


Figure 5.2. YU-Bibot TBS foot design heights

For the results of the optimizations the dimensions of the TBS foot model are; FW is 86 mm, FL is 307.4330 mm, H_{35} is 62.2566 mm, H_{40} is 65.4361 mm, H_{45} is 68.6156 mm, H_{50} is 71.7952 mm.

Using the equations in the article [8], FL can be used to calculate other values for males and females. Calculated and found values are shown in Table 5.8.

Table 5.8. Calculated and found variables of the foot

Gender	Variable	Equation	Calculated variable (mm)	Found variable (mm)	Error %
Male	FW	$FW = 1.045 * FL^{0.817}$	151.4148	86	43.2024
	H ₃₅	$H_{35} = 12.206 * FL^{0.243}$	279.5263	62.2566	77.7278
	H ₄₀	$H_{40} = 11.280 * FL^{0.280}$	49.1017	65.4361	33.2665
	H ₄₅	$H_{45} = 9.483 * FL^{0.330}$	62.7919	68.6156	9.27460
	H ₅₀	$H_{50} = 5.596 * FL^{0.443}$	70.7866	71.7952	1.42485
Female	FW	$FW = 0.524 * FL^{0.941}$	114.8959	86	25.1496
	H ₃₅	$H_{35} = 55.208 * FL^{0.043}$	70.6277	62.2566	11.8524
	H ₄₀	$H_{40} = 50.407 * FL^{-0.0045}$	49.1243	65.4361	33.2052
	H ₄₅	$H_{45} = 49.122 * FL^{0.018}$	54.4572	68.6156	25.9991
	H ₅₀	$H_{50} = 47.120 * FL^{0.044}$	60.6270	71.7952	18.4212

When the root-mean-square vales are calculated; $RMS_{\text{error_for_male}}$ is 42.6679 and the $RMS_{\text{error_for_female}}$ is 24.0452.

Also, required shoe size for the resultant FL is 48 in the EU system [19]. Thus, the feet of the final design look like 48 shoe-sized feminine robot feet.

5.2. RESULTS FOR DROPPING SIMULATION

All joints are locked while robot stands full upright. Flat foot without pad is dropped from 10 cm height in Matlab model. The resultant maximum and rms torques re shown in Table 5.9. The objective is calculated with the same equations as before.

Table 5.9. Max and RMS torques of flat-foot without pad

τ (N.m)	τ_{max} Left	τ_{max} Right	τ_{rms} Left-Right
Ankle joint	7.9345	7.9345	0.6990
Knee joint	3.6215	3.6215	0.7249
Hip joint	2.0736	2.0736	0.4700

The drop objective_{wo/pad} is 0.1802.

The flat-foot model with pads is dropped from 10 cm height in the Matlab model. The resultant maximum and rms torque are shown in Table 5.10. The objective is calculated with the same equations as before.

Table 5.10. Max and RMS torques of flat-foot with pads

τ (N.m)	$\tau_{\max}$ Left	$\tau_{\max}$ Right	τ_{rms} Left-Right
Ankle joint	54.2629	54.2629	1.3569
Knee joint	30.7535	30.7535	1.0437
Hip joint	11.4871	11.4871	0.8940

The drop objective_{w/pad} is 8.9943. Objective value of the model with flat-foot design with pads is quite bigger than the model without flat-foot design with pads. Maybe, the constants of pads are optimal for walking gaits but not optimal for dropping simulations. In order to understand the relation, several different values given to the model and objective values are observed. Then finally, Matlab optimization tool is used to find best values to obtain the lowest objective value. They are all shown in Table 5.11.

Table 5.11. Max and RMS torques of flat-foot with pads with different variables

Difference	Joint	$\tau_{\max}$ L-R	τ_{rms} L-R	Drop Objective
$k_{ff_pads'} = \frac{1}{2}k_{ff_pads}$	Ankle	29.2351	1.0617	2.9949
	Knee	17.8200	0.9566	
	Hip	8.5242	0.8911	
$k_{hf_pads'} = \frac{1}{2}k_{hf_pads}$	Ankle	58.6285	1.3008	10.3681
	Knee	32.9831	0.9961	
	Hip	11.9545	0.8814	
$c_{ff_pads'} = \frac{1}{2}c_{ff_pads}$	Ankle	60.3852	1.3606	15.6858
	Knee	47.2277	1.1456	
	Hip	18.0507	0.9164	
$c_{hf_pads'} = \frac{1}{2}c_{hf_pads}$	Ankle	79.0713	1.7493	21.6773
	Knee	50.7686	1.2393	
	Hip	19.6544	0.9217	
	Ankle	16.3311	1.0052	1.2244

$k_{ff_pads'} = \frac{1}{4} k_{ff_pads}$	Knee	11.3233	0.9550	
	Hip	7.0775	0.8957	
$k_{ff_pads'} = \frac{1}{10} k_{ff_pads}$	Ankle	10.0192	1.1259	0.7190
	Knee	8.6084	1.0092	
	Hip	6.5810	0.9057	
$k_{bh_pads'} = 2 * k_{bh_pads}$	Ankle	45.8654	1.3632	6.7478
	Knee	26.9544	1.0666	
	Hip	10.7933	0.9026	
$c_{hf_pads''} = 538925 \text{ N/(m/s)}$ $c_{ff_pads''} = 305498 \text{ N/(m/s)}$ $k_{hf_pads''} = 25001 \text{ N/m}$ $k_{ff_pads''} = 1591880 \text{ N/m}$	Ankle	0.6846	0.2756	0.0083041
	Knee	0.8095	0.4812	
	Hip	0.8681	0.7987	

For dropping simulation, stiffness of pads should be reduced. The fore pads should be reduced about 1.35 times and the hind pad should be reduced about 25.7 times. Damping coefficients should be increased about 4 times for dropping simulations.

$$k_{ff_pads(set2)} \approx 1.35 * k_{ff_pads''} \quad (5.14)$$

$$k_{hf_pads(set2)} \approx 25.7 * k_{hf_pads''} \quad (5.15)$$

$$c_{ff_pads(set2)} \approx 0.26 * c_{ff_pads''} \quad (5.16)$$

$$c_{hf_pads(set2)} \approx 0.25 * c_{hf_pads''} \quad (5.17)$$

These results give opinion about dropping and walking gaits. Dropping simulation shouldn't be considered only dropping, it is the gait to observe high impact. For different walking gaits including more impact forces such as running or jumping, specifications of the pads should be changed like this way.

In this foot model, there are 3 pads. To compare with the article [5] and article [7], equivalent overall stiffness and damping coefficients are calculated for pads.

$$k_{eq_pads''} = 2 * k_{ff_pads''} + k_{hf_pads''} = 3208761 \text{ N/m} \quad (5.18)$$

$$c_{eq_pads''} = 2 * c_{ff_pads''} + c_{hf_pads''} = 844423 \text{ N/(m/s)} \quad (5.19)$$

The experimental impact stiffness of the overall human foot is 481000 N/m [5] which is mentioned before in Section 1.2. Optimized equivalent stiffness for pads (for dropping simulation) is approximately 6.5 times of stiffness of the human foot.

The experimental stiffness of the human foot for natural COP is 964600 N/m [7] which is mentioned before in Section 1.2. Optimized equivalent stiffness of the pads is approximately 3.3 times of stiffness of the human foot. The experimental damping coefficient of the human foot for natural COP is 7890.1 Ns/m [7]. The optimized equivalent damping coefficient of the pads is approximately 100 times of the damping coefficient of the human foot.

All joints are locked while the robot stands with its knees bent. Bending angles are 0.52 radians (approx. 30°) for ankles and hips and 1.4 radians (approx. 60°) for knees. The model with flat foot without pad is dropped from 10 cm height in the Matlab model. The resultant maximum torques are shown in Table 5.12. The objective is calculated with the same equations as before.

Table 5.12. Max torques of flat-foot without pads for bent position

τ (N.m)	$\tau_{\max}$ Left	$\tau_{\max}$ Right
Ankle joint	8.7988	8.7988
Knee joint	13.3984	13.3984
Hip joint	1.4338	1.4338

The drop objective_{wo/pad-b} is 0.72. The position of the robot at the beginning of the simulation is shown in Figure 5.3.

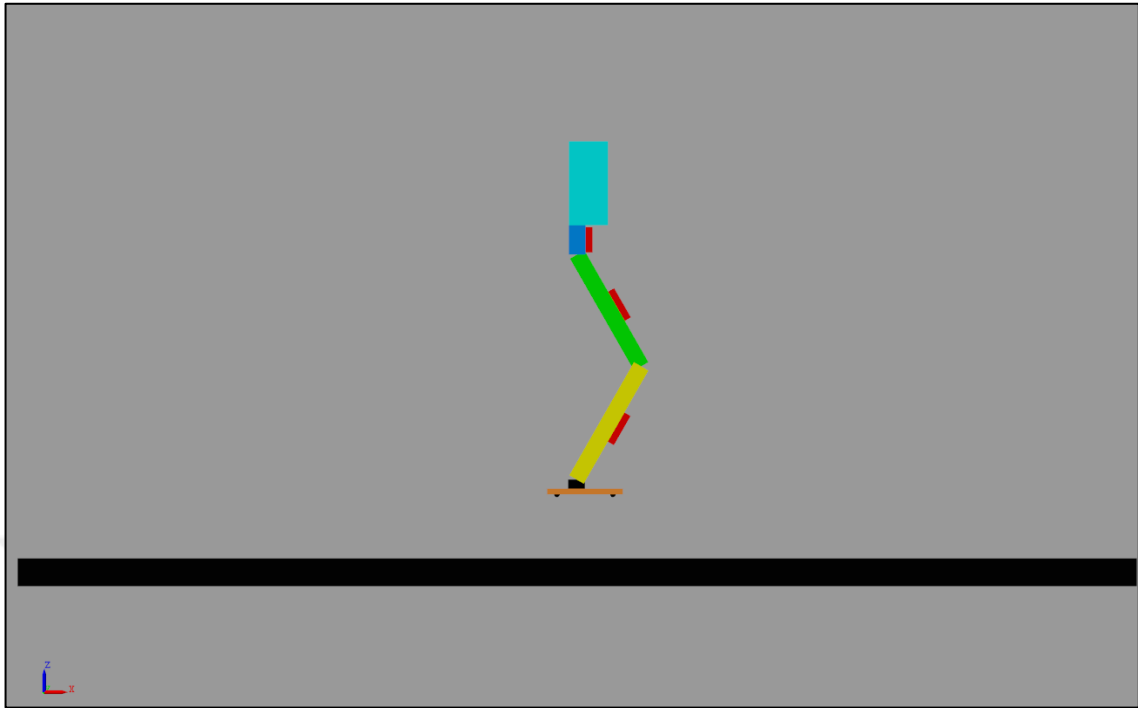


Figure 5.3. The starting position of the robot at the beginning of the simulation (design with the foot without pads)

All joints are locked while the robot stands with its knees bent. The model with flat foot without pad is dropped from 10 cm height in the Matlab model. The resultant maximum torques are shown in Table 5.13. The objective is calculated with the same equations as before.

Table 5.13. Max torques of flat-foot with pads for bent position

τ (N.m)	$\tau_{\max}$ Left	$\tau_{\max}$ Right
Ankle joint	92.3925	92.3925
Knee joint	41.8249	41.8249
Hip joint	12.1935	12.1935

The drop objective_{w/pad-b} is 21.2277. These dropping simulations are types of the most extreme situations. High impact forces are created and the effects are observed. The impact forces are transmitted to all joints from above to the top. So, transmitted forces increase the loads and torques on the joints.

The TBS Foot model with pads is dropped from 10 cm height in the Matlab model and the genetic algorithm is used to optimize the best objective while variables are beam lengths,

beam angles, and spring constant for attachment points. The resultant maximum torques are shown in Table 5.14. The objective is calculated with the same equations as before.

Table 5.14. Max torques of TBS foot model

$\tau_{\max}$ (N.m)	Left	Right
Ankle joint	3.3867	3.3867
Knee joint	2.5791	2.5791
Hip joint	3.5762	3.5762

The drop objective_{TBS} is 0.1327. Objective value is better than the other designs, on the other hand, all the variables are on their boundary conditions. And the variables are; $k_{\text{beam_connections}}$ is 1 Nm/deg, $\text{angle}_{\text{front_foot}}$ is 15° , $l_{\text{front_foot_beams}}$ is 200 mm, and $l_{\text{behind_foot_beams}}$ is 200 mm.

This means for dropping simulation, TBS foot design gives better solutions if the lengths of the beams are the longest possible, angle of the beams are the smallest possible and spring constant for attachment points the smallest possible.

When the beam angles are small (close to zero), it means the pads are closing to projection of ankles. If the projection gets closer, torques are reducing. Torques are effected by distance and force. The impact force are always the same for each iteration of the optimization, so the best method is getting pads close to the projection. Also, as it is mentioned before it is assumed that the variations of sizes of the feet do not affect their mass. As a result of this longer foot beams don't have negative effect for optimization.

5.3. RESULTS FOR THE GAIT WITH SLOPE

TBS Foot design with optimized values from section 4.3 is run for gait with the slope of 5° ground. Maximum and RMS torques of the joints are given in Table 5.15.

Table 5.15. Maximum torques for 5° ground with TBS foot

τ (N.m)	$\tau_{\max}$ Left	$\tau_{\max}$ Right	τ_{rms} Left	τ_{rms} Right
Ankle joint	44.8820	36.5637	14.6114	14.5861
Knee joint	46.0200	47.8175	18.9097	18.2778
Hip joint	65.2622	71.7443	21.2391	21.1965

The $\text{objective}_{\text{TBS_with slope}}$ is 47.7048.

$$\text{objective}_{\text{TBS}(5^\circ)} \approx 2 * \text{objective}_{\text{TBS}} \quad (5.20)$$

The objective value of the gait when walking on a 5° incline ground is nearly double of flat ground. It is expected that the torques of joints are higher.

5.4. DISCUSSION OF OPTIMIZED YU-BIBOT FOOT VARIANTS

The goals and capabilities of the present YU-Bibot and preliminary designs which are obtained in this thesis are shown in Table 5.16.

Table 5.16. Classification of types of robotic feet for YU-Bibot

Robot or foot name	Goals and/or Capabilities	Foot structure	Foot DoF
Current YU-Bibot		Flat foot	0
YU-Bibot with pads	• Impact absorption	Flat foot with pads	0
YU-Bibot with TBS Foot	• Impact absorption • Adaptability on uneven terrains	Three beam foot with pads	2P

Two preliminary designs of this thesis have more goals or capabilities than the current YU-Bibot. Impact absorption capability is obtained by adding elastic pads. With TBS Foot, YU-Bibot can have adaptability on uneven terrains. Also, TBS Foot design has 3 passive joints for 2 degrees of freedom. The passive joints also increase the capacity of impact absorption.

The specifications of the elastic materials are found with optimization. The stiffness and damping coefficients of the pads are different from elastic pad specimens. There are some possible ways to produce elastic pads that has the desired specifications. One of them is increasing the width of the pads to increase the stiffness. Also, different filaments can be used to change the specifications. Grid density is another factor which affects the stiffness and damping coefficients. The beams of TBS foot design has the diameter of 5 mm and a mass of 400 grams. To produce these beams, high-speed steel can be used. Also, beams must be tested and analyzed for the forces. Torsional springs of the design can be produced as spring or the effect of torsion can be given by designing of the upper part of the TBS foot design.

6. CONCLUSION

Improvements on YU-Bibot have been studied; new concepts are preliminary designed. The effects are compared with current design and new designs.

New generation simulation is modeled for all parts of YU-Bibot. This simulation is capable of changing parts and trials for new possible designs. 3D modeled elastic materials are tested and a range of properties are found.

Two new preliminary designs are simulated and optimized to minimize the maximum torques generated by joints. For the ratio of expected maximum torques an objective function is created and optimization is done for minimizing the objective function by using genetic algorithm.

The first one is flat-foot with pads. For the same walking gait data this preliminary design with optimized parameters, has lower objective function than the current YU-Bibot. On the other hand, with these optimized parameters objective function is more than the current YU-Bibot for dropping simulation. It is fixed by re-optimizing parameters. This means there are different local best values for different gaits. Also parameters of pads are compared with the human foot. Overall stiffness of pads and damping coefficients are more than the human foot.

The second design is TBS foot model. It has a lower objective function than the current YU-Bibot. But the objective function is more than flat-foot with pads. The reason is TBS foot model has different walking gait than flat foot models. For dropping simulation, TBS foot model is optimized for dimensions and it has lower objective function than the current YU-Bibot and flat-foot with pads. But for the optimization results, foot dimensions reaches to the upper boundaries.

Also dimensions of TBS foot model is compared with the human foot from literature. For the foot length, the final design has 48 shoe number. And when the errors are considered, the dimensions are closer to a female foot.

7. FUTURE WORK

TBS Foot design can be improved by considering the equations in [8]. If the beams of the TBS design is modeled as in the mentioned article, it can have a more realistic view for a human foot.

The passive joints of TBS Foot design can be activated with motors. For the known uneven terrains, gaits can be created. The locations of the foot contact points (pads) can be adjusted with active joints which are located between beams and ankle.

The backlash is caused by the bevel gears used in the motion transmission elements on the existing YU-Bibot system. Therefore, in the control of the joints, the transmission of the movement is delayed and the performance degrades. By replacing the bevel gear transmission elements in the knee and wrist joints of the existing robot with spiral bevel gears, the gaps can be reduced, and thus the movement will be transferred more smoothly.

New force sensors can be integrated, and multi-axis force/torque measurement will be possible with a unique sensor with high measurement precision and repeatability. Multi-axis force/moment sensors can be used for balanced walking of YU-Bibot. Instead of button force sensors under the feet, one F/T sensor can be used for each foot.

Minimizing the weight in robot design can also reduce the forces and moments affecting the joints. By consuming less power, it can be achieved the desired movements and provide efficiency in terms of energy. By lightening the robot fittings, the total weight can be reduced. The central control computer on YU-Bibot stands on the top of the robot and reflects its weight on all attachments. Changing the computer to a lighter one will significantly reduce the power consumption of the YU-Bibot. These stages are aimed at executing a smaller/lightweight and high-end computer system.

After these improvements or with different developments the implementation of the proposed improvements can also be included. The designed foot and sensor system can be implemented on the robot.

Walking gait can be improved via studying human gaits. Also, phases of the gaits can be optimized for less energy consumption.

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APPENDIX A

Algorithm A.1. dropofrobot4var

```
mdlWks =
get_param('foot_v2_act_classic_frame_pads_zmp_pad4','ModelWorkspace');

gr_st_fr=2154830;
gr_st_bh=642654;
gr_dc_fr=78350;
gr_dc_bh=136671;

th_aL=zeros(160,1);
th_kL=zeros(160,1);
th_hL=zeros(160,1);
th_aR=zeros(160,1);
th_kR=zeros(160,1);
th_hR=zeros(160,1);
t=linspace(0,15.9,160)';

assignin(mdlWks,'gr_st_fr',gr_st_fr);
assignin(mdlWks,'gr_st_bh',gr_st_bh);
assignin(mdlWks,'gr_dc_fr',gr_dc_fr);
assignin(mdlWks,'gr_dc_bh',gr_dc_bh);

assignin(mdlWks,'t',t);
assignin(mdlWks,'th_aL',th_aL);
assignin(mdlWks,'th_kL',th_kL);
assignin(mdlWks,'th_hL',th_hL);
assignin(mdlWks,'th_aR',th_aR);
assignin(mdlWks,'th_kR',th_kR);
assignin(mdlWks,'th_hR',th_hR);
mdlWks.DataSource = 'MAT-File';
mdlWks.FileName = 'stepdata.mat';
saveToSource(mdlWks)
```

Algorithm A.2. gait8

```
mdlWks =
get_param('foot_v3_act_classic_frame_pads_zmp_energy','ModelWorkspace');

gr_st_fr=2154830; % spatial contact force stiffness of forefoot (N/m)
gr_st_bh=642654; % spatial contact force stiffness of hindfoot (N/m)
gr_dc_fr=78350; % spatial contact force damping coefficient of forefoot
(N/(m/s))
gr_dc_bh=136671; % spatial contact force damping coefficient of hindfoot
(N/(m/s))

l_ffl=194; % length of forefoot cylinders
r_ffl=5; % radius of forefoot cylinders
```

```

a_ff=58; % degree of forefoot cylinders
h_f=l_ffl*cosd(a_ff); % height of foot cylinders (mm)
p_ffl=l_ffl*sind(a_ff); % projection of forefoot length
w_fb=0.4; % weight of each beam (kg)

l_bfl=188; % length of hindfoot cylinders
r_bfl=5; % radius of hindfoot cylinders
a_bf=acosd(h_f/l_bfl); % degree of hindfoot cylinders
p_bfl=l_bfl*sind(a_bf); % projection of forefoot length

k_f=8.95786; % spring coefficient of foot sensors

R=100; % resolution
st=5; % step
ts=1; % step time

T=ts*st; % simulation time
Ts=ts/10; % one stage time

t=linspace(0,T-(1/R),T*R)';

lsh=465; %shank-incik
lth=460; %thigh-uyluk
sl=540; %step length 540
fla=30+p_bfl; %foot length a
flb=30+p_ffl; %foot length b
fh=h_f; %foot high
ah=33; %ankle high
sh=40; %step high
zf0=60; %starting hip fall
zf=30; %hip fall at top
xs=180; % step length
ffl=20; %foot fall length

q_aL=zeros(T*R,1);
q_aR=zeros(T*R,1);
q_h=zeros(T*R,1);

x_aL=0.5*xs*ones(Ts*R*10,1);
z_aL=zeros(Ts*R*10,1);

x_h=[zeros(Ts*R*5,1);linspace(0,xs/4,Ts*R*2)';linspace(xs/4,xs/2,Ts*R*3)'];
z_h=[ones(Ts*R,1)*(lsh+lth-zf0);linspace(lsh+lth-zf0,lsh+lth-
zf0+zf,4*Ts*R)';linspace(lsh+lth-zf0+zf,lsh+lth-
zf0,4*Ts*R)';ones(Ts*R,1)*(lsh+lth-zf0)];

x_aR=[0*ones(Ts*R,1);linspace(0,0.5*xs,4*Ts*R)';linspace(0.5*xs,xs,4*Ts*R)';o
nes(Ts*R,1)*xs];
z_aR=[zeros(Ts*R*2,1);linspace(0,ffl,Ts*R)';linspace(ffl,sh,Ts*R*2)';linspace
(sh,ffl,Ts*R*2)';linspace(ffl,0,Ts*R)';zeros(Ts*R*2,1)];

i=2;

while st-i+1~=0
if (mod(i,2)==0) %çift adımlar, sol

```

```

x_aR=[x_aR;x_aR(end)*ones(Ts*R*10,1)];
z_aR=[z_aR;z_aR(end)*ones(Ts*R*10,1)];

x_h=[x_h;linspace(0.5*xs,0.5*xs,5*Ts*R)'+xs*(i-
2)/2;linspace(0.5*xs,0.75*xs,Ts*R*2)'+xs*(i-
2)/2;linspace(0.75*xs,xs,Ts*R*3)'+xs*(i-2)/2];
z_h=[z_h;ones(Ts*R,1)*(lsh+lth-zf0);linspace(lsh+lth-zf0,lsh+lth-
zf0+zf,4*Ts*R)';linspace(lsh+lth-zf0+zf,lsh+lth-
zf0,4*Ts*R)';ones(Ts*R,1)*(lsh+lth-zf0)];

x_aL=[x_aL;0.5*xs*ones(Ts*R,1)+xs*(i-2)/2;linspace(0.5*xs,xs,4*Ts*R)'+xs*(i-
2)/2;linspace(xs,1.5*xs,4*Ts*R)'+xs*(i-2)/2;ones(Ts*R,1)*1.5*xs+xs*(i-2)/2];
z_aL=[z_aL;zeros(Ts*R*2,1);linspace(0,ffl,Ts*R)';linspace(ffl,sh,Ts*R*2)';lin
space(sh,ffl,Ts*R*2)';linspace(ffl,0,Ts*R)';zeros(Ts*R*2,1)];

end
if (mod(i,2)==1) %tek adımlar, sağ

x_aL=[x_aL;x_aL(end)*ones(Ts*R*10,1)];
z_aL=[z_aL;z_aL(end)*ones(Ts*R*10,1)];

x_h=[x_h;linspace(0,0,5*Ts*R)'+xs*(i-1)/2;linspace(0,0.25*xs,Ts*R*2)'+xs*(i-
1)/2;linspace(0.25*xs,0.5*xs,Ts*R*3)'+xs*(i-1)/2];
z_h=[z_h;ones(Ts*R,1)*(lsh+lth-zf0);linspace(lsh+lth-zf0,lsh+lth-
zf0+zf,4*Ts*R)';linspace(lsh+lth-zf0+zf,lsh+lth-
zf0,4*Ts*R)';ones(Ts*R,1)*(lsh+lth-zf0)];

x_aR=[x_aR;ones(Ts*R,1)*xs*(i-1)/2;linspace(0,0.5*xs,4*Ts*R)'+xs*(i-
1)/2;linspace(0.5*xs,xs,4*Ts*R)'+xs*(i-1)/2;ones(Ts*R,1)*xs+xs*(i-1)/2];
z_aR=[z_aR;zeros(Ts*R*2,1);linspace(0,ffl,Ts*R)';linspace(ffl,sh,Ts*R*2)';lin
space(sh,ffl,Ts*R*2)';linspace(ffl,0,Ts*R)';zeros(Ts*R*2,1)];

end
i=i+1;
end

[x_kL,z_kL,flag]=kneesolver2(x_aL,z_aL,x_h,z_h,lsh,lth);
[x_kR,z_kR,flag]=kneesolver2(x_aR,z_aR,x_h,z_h,lsh,lth);

% calculate absolute joint angles (from horizontal, ccw positive.)
% LEFT
q1 = atan((x_aL-x_kL)./(z_kL-z_aL));
q2 = atan((x_kL-x_h)./(z_h-z_kL));
% RIGHT
q3 = atan((x_aR-x_kR)./(z_kR-z_aR));
q4 = atan((x_kR-x_h)./(z_h-z_kR));

% calculate relative joint angles:
% LEFT
th_aL = q_aL + q1;
th_kL = q2 - q1;
th_hL = q_h - q2;

% RIGHT
th_aR = q_aR + q3;
th_kR = q4 - q3;
th_hR = q_h - q4;

```

```

assignin mdlWks, 'gr_st_fr', gr_st_fr);
assignin mdlWks, 'gr_st_bh', gr_st_bh);
assignin mdlWks, 'gr_dc_fr', gr_dc_fr);
assignin mdlWks, 'gr_dc_bh', gr_dc_bh);
assignin mdlWks, 'l_ffl', l_ffl);
assignin mdlWks, 'r_ffl', r_ffl);
assignin mdlWks, 'a_ff', a_ff);
assignin mdlWks, 'h_f', h_f);
assignin mdlWks, 'p_ffl', p_ffl);
assignin mdlWks, 'w_fb', w_fb);
assignin mdlWks, 'l_bfl', l_bfl);
assignin mdlWks, 'r_bfl', r_bfl);
assignin mdlWks, 'p_bfl', p_bfl);
assignin mdlWks, 'a_bf', a_bf);
assignin mdlWks, 't', t);
assignin mdlWks, 'zf0', zf0);
assignin mdlWks, 'th_aL', th_aL);
assignin mdlWks, 'th_kL', th_kL);
assignin mdlWks, 'th_hL', th_hL);
assignin mdlWks, 'th_aR', th_aR);
assignin mdlWks, 'th_kR', th_kR);
assignin mdlWks, 'th_hR', th_hR);
assignin mdlWks, 'k_f', k_f);

mdlWks.DataSource = 'MAT-File';
mdlWks.FileName = 'myVars.mat';
saveToSource(mdlWks)

```

Algorithm A.3. gait9

```

mdlWks =
get_param('foot_v3_act_classic_frame_pads_zmp_angleground', 'ModelWorkspace');

R=100; % resolution
st=5; % step
ts=1; % step time
gr_ang=5 % ground angle in degree (max 10)

T=ts*st; % simulation time
Ts=ts/10; % one stage time

t=linspace(0,T-(1/R),T*R)';

gr_st_fr=2154830; % spatial contact force stiffness of forefoot (N/m)
gr_st_bh=642654; % spatial contact force stiffness of hindfoot (N/m)
gr_dc_fr=78350; % spatial contact force damping coefficient of forefoot
(N/(m/s))
gr_dc_bh=136671; % spatial contact force damping coefficient of hindfoot
(N/(m/s))

lsh=465; %shank-incik
lth=460; %thigh-uyluk

```

```

sl=540; %step length 540
fla=30+p_bfl; %foot length a
flb=30+p_ffl; %foot length b
fh=h_f; %foot high
ah=33; %ankle high
sh=40; %step high
zf0=60; %starting hip fall
zf=30; %hip fall at top
xs=180; % step length
ffl=20; %foot fall length

q_aL=zeros(T*R,1);
q_aR=zeros(T*R,1);
q_h=zeros(T*R,1);

x_aL=0.5*xs*ones(Ts*R*10,1);
z_aL=zeros(Ts*R*10,1);

z_h=[ones(Ts*R,1)*(lsh+lth-zf0);linspace(lsh+lth-zf0,lsh+lth-
zf0+zf,4*Ts*R)';linspace(lsh+lth-zf0+zf,lsh+lth-
zf0,4*Ts*R)';ones(Ts*R,1)*(lsh+lth-zf0)];
x_h1=[zeros(Ts*R*5,1);linspace(0,xs/4,Ts*R*2)';linspace(xs/4,xs/2,Ts*R*3)'];
x_h=x_h1+[z_h*1.5*sind(gr_ang)];

x_aR=[0*ones(Ts*R,1);linspace(0,0.5*xs,4*Ts*R)';linspace(0.5*xs,xs,4*Ts*R)';o
nes(Ts*R,1)*xs];
z_aR=[zeros(Ts*R*2,1);linspace(0,ffl,Ts*R)';linspace(ffl,sh,Ts*R*2)';linspace
(sh,ffl,Ts*R*2)';linspace(ffl,0,Ts*R)';zeros(Ts*R*2,1)];

i=2;

while st-i+1~=0
    if (mod(i,2)==0) %çift adımlar, sol

x_aR=[x_aR;x_aR(end)*ones(Ts*R*10,1)];
z_aR=[z_aR;z_aR(end)*ones(Ts*R*10,1)];

z_h1=[ones(Ts*R,1)*(lsh+lth-zf0);linspace(lsh+lth-zf0,lsh+lth-
zf0+zf,4*Ts*R)';linspace(lsh+lth-zf0+zf,lsh+lth-
zf0,4*Ts*R)';ones(Ts*R,1)*(lsh+lth-zf0)];
z_h=[z_h;z_h1];
x_h1=[linspace(0.5*xs,0.5*xs,5*Ts*R)'+xs*(i-
2)/2;linspace(0.5*xs,0.75*xs,Ts*R*2)'+xs*(i-
2)/2;linspace(0.75*xs,xs,Ts*R*3)'+xs*(i-2)/2+[z_h1*1.5*sind(gr_ang)];
x_h=[x_h;x_h1];

x_aL=[x_aL;0.5*xs*ones(Ts*R,1)+xs*(i-2)/2;linspace(0.5*xs,xs,4*Ts*R)'+xs*(i-
2)/2;linspace(xs,1.5*xs,4*Ts*R)'+xs*(i-2)/2;ones(Ts*R,1)*1.5*xs+xs*(i-2)/2];
z_aL=[z_aL;zeros(Ts*R*2,1);linspace(0,ffl,Ts*R)';linspace(ffl,sh,Ts*R*2)';lin
space(sh,ffl,Ts*R*2)';linspace(ffl,0,Ts*R)';zeros(Ts*R*2,1)];

    end
    if (mod(i,2)==1) %tek adımlar, sağ

x_aL=[x_aL;x_aL(end)*ones(Ts*R*10,1)];
z_aL=[z_aL;z_aL(end)*ones(Ts*R*10,1)];

```

```

z_h1=[ones(Ts*R,1)*(lsh+lth-zf0);linspace(lsh+lth-zf0,lsh+lth-
zf0+zf,4*Ts*R)';linspace(lsh+lth-zf0+zf,lsh+lth-
zf0,4*Ts*R)';ones(Ts*R,1)*(lsh+lth-zf0)];
z_h=[z_h;z_h1];
x_h1=[linspace(0,0.5*Ts*R)'+xs*(i-1)/2;linspace(0,0.25*xs,Ts*R*2)'+xs*(i-
1)/2;linspace(0.25*xs,0.5*xs,Ts*R*3)'+xs*(i-1)/2+[z_h1*1.5*sind(gr_ang)];
x_h=[x_h;x_h1];

x_aR=[x_aR;ones(Ts*R,1)*xs*(i-1)/2;linspace(0,0.5*xs,4*Ts*R)'+xs*(i-
1)/2;linspace(0.5*xs,xs,4*Ts*R)'+xs*(i-1)/2;ones(Ts*R,1)*xs+xs*(i-1)/2];
z_aR=[z_aR;zeros(Ts*R*2,1);linspace(0,ffl,Ts*R)';linspace(ffl,sh,Ts*R*2)';lin
space(sh,ffl,Ts*R*2)';linspace(ffl,0,Ts*R)';zeros(Ts*R*2,1)];

    end
    i=i+1;
end

[x_kL,z_kL,flag]=kneesolver2(x_aL,z_aL,x_h,z_h,lsh,lth);
[x_kR,z_kR,flag]=kneesolver2(x_aR,z_aR,x_h,z_h,lsh,lth);

% calculate absolute joint angles (from horizontal, ccw positive.
% LEFT
q1 = atan((x_aL-x_kL)./(z_kL-z_aL));
q2 = atan((x_kL-x_h)./(z_h-z_kL));
% RIGHT
q3 = atan((x_aR-x_kR)./(z_kR-z_aR));
q4 = atan((x_kR-x_h)./(z_h-z_kR));

% calculate relative joint angles:
% LEFT
th_aL = q_aL + q1;
th_kL = q2 - q1;
th_hL = q_h - q2;

% RIGHT
th_aR = q_aR + q3;
th_kR = q4 - q3;
th_hR = q_h - q4;

assignin(mdlwks,'gr_ang',gr_ang);
assignin(mdlwks,'gr_st_fr',gr_st_fr);
assignin(mdlwks,'gr_st_bh',gr_st_bh);
assignin(mdlwks,'gr_dc_fr',gr_dc_fr);
assignin(mdlwks,'gr_dc_bh',gr_dc_bh);
assignin(mdlwks,'l_ffl',l_ffl);
assignin(mdlwks,'r_ffl',r_ffl);
assignin(mdlwks,'a_ff',a_ff);
assignin(mdlwks,'h_f',h_f);
assignin(mdlwks,'p_ffl',p_ffl);
assignin(mdlwks,'w_fb',w_fb);
assignin(mdlwks,'l_bfl',l_bfl);
assignin(mdlwks,'r_bfl',r_bfl);
assignin(mdlwks,'p_bfl',p_bfl);
assignin(mdlwks,'a_bf',a_bf);
assignin(mdlwks,'t',t);
assignin(mdlwks,'zf0',zf0);

```

```

assignin mdlWks, 'th_aL', th_aL);
assignin mdlWks, 'th_kL', th_kL);
assignin mdlWks, 'th_hL', th_hL);
assignin mdlWks, 'th_aR', th_aR);
assignin mdlWks, 'th_kR', th_kR);
assignin mdlWks, 'th_hR', th_hR);
assignin mdlWks, 'k_f', k_f);

mdlWks.DataSource = 'MAT-File';
mdlWks.FileName = 'myVars.mat';
saveToSource(mdlWks)

```

Algorithm A.4. objectiveFcn4

```

function [objective] = objectiveFcn4(gr_st)

gr_dc=400000; % spatial contact force damping coefficient (N/(m/s))

mdlWks =
get_param('foot_v2_act_classic_frame_pads_zmp_pad', 'ModelWorkspace');
assignin(mdlWks, 'gr_dc', gr_dc);
assignin(mdlWks, 'gr_st', gr_st);
mdlWks.DataSource = 'MAT-File';
mdlWks.FileName = 'stepdata.mat';
saveToSource(mdlWks)

sim('foot_v2_act_classic_frame_pads_zmp_pad', 15.9)

z_hip=reshape(ans.pos_hip.data, [], 1);
z_hipe=z_hip(end);
assignin('base', 'z_hipe', z_hipe);

t_max=max([ans.tmax_l_knee.data(end), ans.tmax_r_knee.data(end),
ans.tmax_l_ankle.data(end), ans.tmax_r_ankle.data(end),
ans.tmax_l_hip.data(end), ans.tmax_r_hip.data(end)]);
obj1=max([ans.tmax_l_ankle.data(end), ans.tmax_r_ankle.data(end)])/24.2;
obj2=max([ans.tmax_l_knee.data(end), ans.tmax_r_knee.data(end)])/17.7;
obj3=max([ans.tmax_l_hip.data(end), ans.tmax_r_hip.data(end)])/11.8;
objective=obj1^2+obj2^2+obj3^2;

if z_hipe<=0.9
    objective=500;
end
end

```

Algorithm A.5. objectiveFcn5

```

function [objective] = objectiveFcn5(gr_st_fr, gr_st_bh, gr_dc_fr, gr_dc_bh)

mdlWks =
get_param('foot_v2_act_classic_frame_pads_zmp_pad4', 'ModelWorkspace');

```

```

assignin mdlWks, 'gr_st_fr', gr_st_fr;
assignin mdlWks, 'gr_st_bh', gr_st_bh;
assignin mdlWks, 'gr_dc_fr', gr_dc_fr;
assignin mdlWks, 'gr_dc_bh', gr_dc_bh;
mdlWks.DataSource = 'MAT-File';
mdlWks.FileName = 'stepdata.mat';
saveToSource(mdlWks)

sim('foot_v2_act_classic_frame_pads_zmp_pad4', 15.9)

z_hip = reshape(ans.pos_hip.data, [], 1);
z_hipe = z_hip(end);
assignin('base', 'z_hipe', z_hipe);

t_max = max([ans.tmax_l_knee.data(end), ans.tmax_r_knee.data(end),
ans.tmax_l_ankle.data(end), ans.tmax_r_ankle.data(end),
ans.tmax_l_hip.data(end), ans.tmax_r_hip.data(end)]);
obj1 = max([ans.tmax_l_ankle.data(end), ans.tmax_r_ankle.data(end)])/24.2;
obj2 = max([ans.tmax_l_knee.data(end), ans.tmax_r_knee.data(end)])/17.7;
obj3 = max([ans.tmax_l_hip.data(end), ans.tmax_r_hip.data(end)])/11.8;
objective = obj1^2 + obj2^2 + obj3^2;

if z_hipe <= 0.9
    objective = 500;
end
end

```

Algorithm A.6. objectiveFcn2

```

function [objective] = objectiveFcn2(k_f, l_ffl, a_ff, l_bfl)

mdlWks =
get_param('foot_v3_act_classic_frame_pads_zmp_energy', 'ModelWorkspace');

gr_st_fr = 2154830; % spatial contact force stiffness of forefoot (N/m)
gr_st_bh = 642654; % spatial contact force stiffness of hindfoot (N/m)
gr_dc_fr = 78350; % spatial contact force damping coefficient of forefoot
(N/(m/s))
gr_dc_bh = 136671; % spatial contact force damping coefficient of hindfoot
(N/(m/s))

% l_ffl = 194; % length of forefoot cylinders
r_ffl = 5; % radius of forefoot cylinders
% a_ff = 58; % degree of forefoot cylinders
h_f = l_ffl * cosd(a_ff); % height of foot cylinders (mm)
p_ffl = l_ffl * sind(a_ff); % projection of forefoot length
w_fb = 0.4; % weight of each beam (kg)

% l_bfl = 188; % length of hindfoot cylinders
r_bfl = 5; % radius of hindfoot cylinders
a_bf = acosd(h_f / l_bfl); % degree of hindfoot cylinders
p_bfl = l_bfl * sind(a_bf); % projection of forefoot length

% k_f = 8.95786; % spring coefficient of foot sensors

```

```

R=100; % resolution
st=5; % step
ts=1; % step time

T=ts*st; % simulation time
Ts=ts/10; % one stage time

t=linspace(0,T-(1/R),T*R)';

lsh=465; %shank-incik
lth=460; %thigh-uyluk
sl=540; %step length
fla=30+p_bfl; %foot length a
flb=30+p_ffl; %foot length b
fh=h_f; %foot high
ah=33; %ankle high
sh=40; %step high
zf0=60; %starting hip fall
zf=30; %hip fall at top
xs=180; % step length
ffl=20; %foot fall length

q_aL=zeros(T*R,1);
q_aR=zeros(T*R,1);
q_h=zeros(T*R,1);

x_aL=0.5*xs*ones(Ts*R*10,1);
z_aL=zeros(Ts*R*10,1);

x_h=[zeros(Ts*R*5,1);linspace(0,xs/4,Ts*R*2)';linspace(xs/4,xs/2,Ts*R*3)'];
z_h=[ones(Ts*R,1)*(lsh+lth-zf0);linspace(lsh+lth-zf0,lsh+lth-
zf0+zf,4*Ts*R)';linspace(lsh+lth-zf0+zf,lsh+lth-
zf0,4*Ts*R)';ones(Ts*R,1)*(lsh+lth-zf0)];

x_aR=[0*ones(Ts*R,1);linspace(0,0.5*xs,4*Ts*R)';linspace(0.5*xs,xs,4*Ts*R)';o
nes(Ts*R,1)*xs];
z_aR=[zeros(Ts*R*2,1);linspace(0,ffl,Ts*R)';linspace(ffl,sh,Ts*R*2)';linspace
(sh,ffl,Ts*R*2)';linspace(ffl,0,Ts*R)';zeros(Ts*R*2,1)];

i=2;

while st-i+1~=0
    if (mod(i,2)==0) %çift adımlar, sol

x_aR=[x_aR;x_aR(end)*ones(Ts*R*10,1)];
z_aR=[z_aR;z_aR(end)*ones(Ts*R*10,1)];

x_h=[x_h;linspace(0.5*xs,0.5*xs,5*Ts*R)'+xs*(i-
2)/2;linspace(0.5*xs,0.75*xs,Ts*R*2)'+xs*(i-
2)/2;linspace(0.75*xs,xs,Ts*R*3)'+xs*(i-2)/2];
z_h=[z_h;ones(Ts*R,1)*(lsh+lth-zf0);linspace(lsh+lth-zf0,lsh+lth-
zf0+zf,4*Ts*R)';linspace(lsh+lth-zf0+zf,lsh+lth-
zf0,4*Ts*R)';ones(Ts*R,1)*(lsh+lth-zf0)];

x_aL=[x_aL;0.5*xs*ones(Ts*R,1)+xs*(i-2)/2;linspace(0.5*xs,xs,4*Ts*R)'+xs*(i-
2)/2;linspace(xs,1.5*xs,4*Ts*R)'+xs*(i-2)/2;ones(Ts*R,1)*1.5*xs+xs*(i-2)/2];

```

```

z_aL=[z_aL;zeros(Ts*R*2,1);linspace(0,ffl,Ts*R)';linspace(ffl,sh,Ts*R*2)';lin
space(sh,ffl,Ts*R*2)';linspace(ffl,0,Ts*R)';zeros(Ts*R*2,1)];

    end
    if (mod(i,2)==1) %tek adımlar, sağ

x_aL=[x_aL;x_aL(end)*ones(Ts*R*10,1)];
z_aL=[z_aL;z_aL(end)*ones(Ts*R*10,1)];

x_h=[x_h;linspace(0,0.5*Ts*R)'+xs*(i-1)/2;linspace(0,0.25*xs,Ts*R*2)'+xs*(i-
1)/2;linspace(0.25*xs,0.5*xs,Ts*R*3)'+xs*(i-1)/2];
z_h=[z_h;ones(Ts*R,1)*(lsh+lth-zf0);linspace(lsh+lth-zf0,lsh+lth-
zf0+zf,4*Ts*R)';linspace(lsh+lth-zf0+zf,lsh+lth-
zf0,4*Ts*R)';ones(Ts*R,1)*(lsh+lth-zf0)];

x_aR=[x_aR;ones(Ts*R,1)*xs*(i-1)/2;linspace(0,0.5*xs,4*Ts*R)'+xs*(i-
1)/2;linspace(0.5*xs,xs,4*Ts*R)'+xs*(i-1)/2;ones(Ts*R,1)*xs+xs*(i-1)/2];
z_aR=[z_aR;zeros(Ts*R*2,1);linspace(0,ffl,Ts*R)';linspace(ffl,sh,Ts*R*2)';lin
space(sh,ffl,Ts*R*2)';linspace(ffl,0,Ts*R)';zeros(Ts*R*2,1)];

    end
    i=i+1;
end

[x_kL,z_kL,flag]=kneesolver2(x_aL,z_aL,x_h,z_h,lsh,lth);
[x_kR,z_kR,flag]=kneesolver2(x_aR,z_aR,x_h,z_h,lsh,lth);

% calculate absolute joint angles (from horizontal, ccw positive.)
% LEFT
q1 = atan((x_aL-x_kL)./(z_kL-z_aL));
q2 = atan((x_kL-x_h)./(z_h-z_kL));
% RIGHT
q3 = atan((x_aR-x_kR)./(z_kR-z_aR));
q4 = atan((x_kR-x_h)./(z_h-z_kR));

% calculate relative joint angles:
% LEFT
th_aL = q_aL + q1;
th_kL = q2 - q1;
th_hL = q_h - q2;

% RIGHT
th_aR = q_aR + q3;
th_kR = q4 - q3;
th_hR = q_h - q4;

assignin mdlwks,'gr_st_fr',gr_st_fr);
assignin mdlwks,'gr_st_bh',gr_st_bh);
assignin mdlwks,'gr_dc_fr',gr_dc_fr);
assignin mdlwks,'gr_dc_bh',gr_dc_bh);
assignin mdlwks,'l_ffl',l_ffl);
assignin mdlwks,'r_ffl',r_ffl);
assignin mdlwks,'a_ff',a_ff);
assignin mdlwks,'h_f',h_f);
assignin mdlwks,'p_ffl',p_ffl);
assignin mdlwks,'w_fb',w_fb);
assignin mdlwks,'l_bfl',l_bfl);

```

```

assignin(mdlWks,'r_bfl',r_bfl);
assignin(mdlWks,'p_bfl',p_bfl);
assignin(mdlWks,'a_bf',a_bf);
assignin(mdlWks,'t',t);
assignin(mdlWks,'zf0',zf0);
assignin(mdlWks,'th_aL',th_aL);
assignin(mdlWks,'th_kL',th_kL);
assignin(mdlWks,'th_hL',th_hL);
assignin(mdlWks,'th_aR',th_aR);
assignin(mdlWks,'th_kR',th_kR);
assignin(mdlWks,'th_hR',th_hR);
assignin(mdlWks,'k_f',k_f);

mdlWks.DataSource = 'MAT-File';
mdlWks.FileName = 'myVars.mat';
saveToSource(mdlWks)
fall=100000;
obj=100000;
if h_f<l_bfl
    myTimer = timer('StartDelay',60,
    'TimerFcn','set_param(''foot_v3_act_classic_frame_pads_zmp_energy'', 'SimulationCommand','stop')');
    start(myTimer);
    sim('foot_v3_act_classic_frame_pads_zmp_energy');
    stop(myTimer);
    delete(myTimer);
    stop_time=ans.SimulationMetadata.ModelInfo.StopTime;
    z_hip=reshape(ans.pos_hip.data,[],1);
    z_hipe=z_hip(end);
    fall=0;
    if z_hipe<=0.9
        fall=100000;
    end
    if stop_time==5

        t_max=max([ans.tmax_l_knee.data(end), ans.tmax_r_knee.data(end),
ans.tmax_l_ankle.data(end), ans.tmax_r_ankle.data(end),
ans.tmax_l_hip.data(end), ans.tmax_r_hip.data(end)]);
        obj1=max([ans.tmax_l_ankle.data(end), ans.tmax_r_ankle.data(end)])/24.2;
        obj2=max([ans.tmax_l_knee.data(end), ans.tmax_r_knee.data(end)])/17.7;
        obj3=max([ans.tmax_l_hip.data(end), ans.tmax_r_hip.data(end)])/11.8;
        obj=obj1^2+obj2^2+obj3^2;
    end
end
delete myVars.mat
objective = obj+fall;
end

```