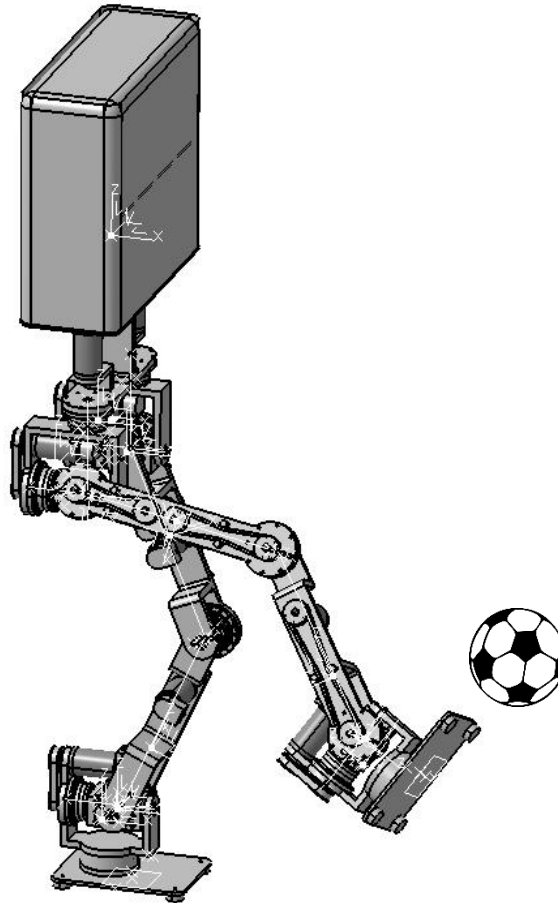


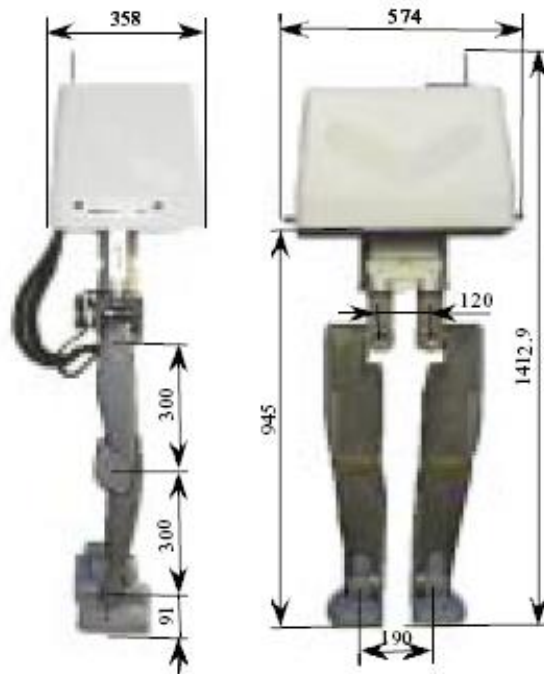
BIPED DESIGN & DEVELOPMENT

Oytun Yapıcı / Research Engineer



WORK PLAN

İş Paketleri		Mart				Nisan				Mayıs				Haziran				Temmuz			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
İP 1	Yapılmış Prototiplerin Mekanik Tasarım Detaylarının Araştırılması																				
İP 2	Ekipmanların Firma ve Tür Bazında Belirlenmesi																				
İP 3	Mekanik Tasarım Konseptinin Oluşturulması ve Konsepte Uygun Başlangıç Tasarımının Yapılması																				
İP 4	Tasarım Sürecinin Benzetimler Yoluyla Doğrulanması ve Ekipmanların Boyutlandırılması																				
İP 5	Yatakların Boyutlandırılması																				
İP 6	Tasarımın Montaja ve İmalata Uygunluk Açısından Değerlendirilmesi Gerekli Değişikliklerin Yapılması																				
İP 7	Malzeme Seçimi, Sonlu Elemanlar Analizi ile Parçaların Boyutlandırılması																				



HRP-2L

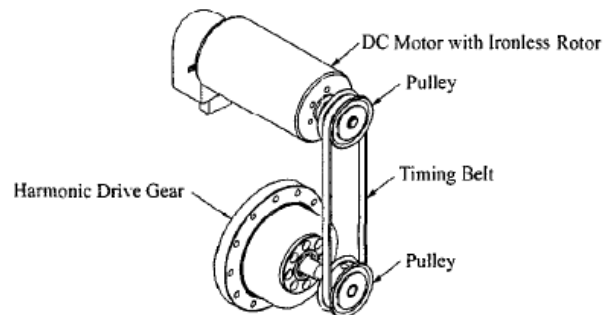


Figure 7. Mechanism of Drive System employed for HRP-2L

Dimensions

Upper leg: 300 mm

Lower leg: 300 mm

Ankle to ground : 91 mm

Height : 1.4 m

Weight

Single Leg: 8.6 kgf (Mg Alloy)

Total : 56 kgf

Joint		Actuator	Harmonic Drive Ratio
Hip	Yaw	DC 20W	1/160
	Roll	DC 90W	1/160
	Pitch	DC 90W	1/120
Knee	Pitch	DC 150W	1/160
Ankle	Pitch	DC 90W	1/160
	Roll	DC 70W	1/160



Height : 1.4 m

Weight : 51 kgf

Joint		Actuator
Hip	Yaw	DC 20W
	Roll	DC 90W
	Pitch	DC 90W
Knee	Pitch	DC 150W
Ankle	Pitch	DC 90W
	Roll	DC 90W

H7

WABIAN



Figure 7: Drive system of WABIAN-2

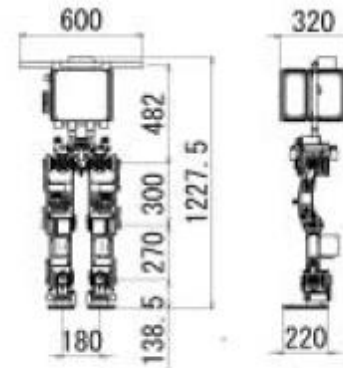


Figure 8: Link size of WABIAN-2



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HUBO



Joint		Harmonic drive reduction ratio	Input gear ratio	Motor power
Hip	Roll	120:1	Gear (2.5:1)	150 W
	Pitch	160:1	Pulley belt (1.78:1)	150 W
	Yaw	120:1	Pulley belt (2:1)	90 W
Knee	Pitch	120:1	Pulley belt (1:1)	150 W*2
Ankle	Roll	100:1	Pulley belt (2:1)	90 W
	Pitch	100:1	Pulley belt (1.93:1)	

- MOTORS

Brand: Maxon (Johnnie, HUBO)

Type: Graphite Brushed DC (Easy Control, Low Cost, Less Heat)

Motor: RE (max. 150 W, 480gr)

- ENCODERS

Company: Maxon Modular System

Type: Optical

Series: HEDL

- 6 AXIS FORCE-TORQUE SENSOR

Company: ATI

Type: Mini85 (special product for bipeds)

- GEARS

Company: Harmonic Drive (No backlash, Compact, High Ratio)

Type: Unit (Integrated ball bearing, Time and cost effective, Heavy)

Series: CSG (%30 more torque and life, Resistant to instantaneous torque)

- POWERTRAIN

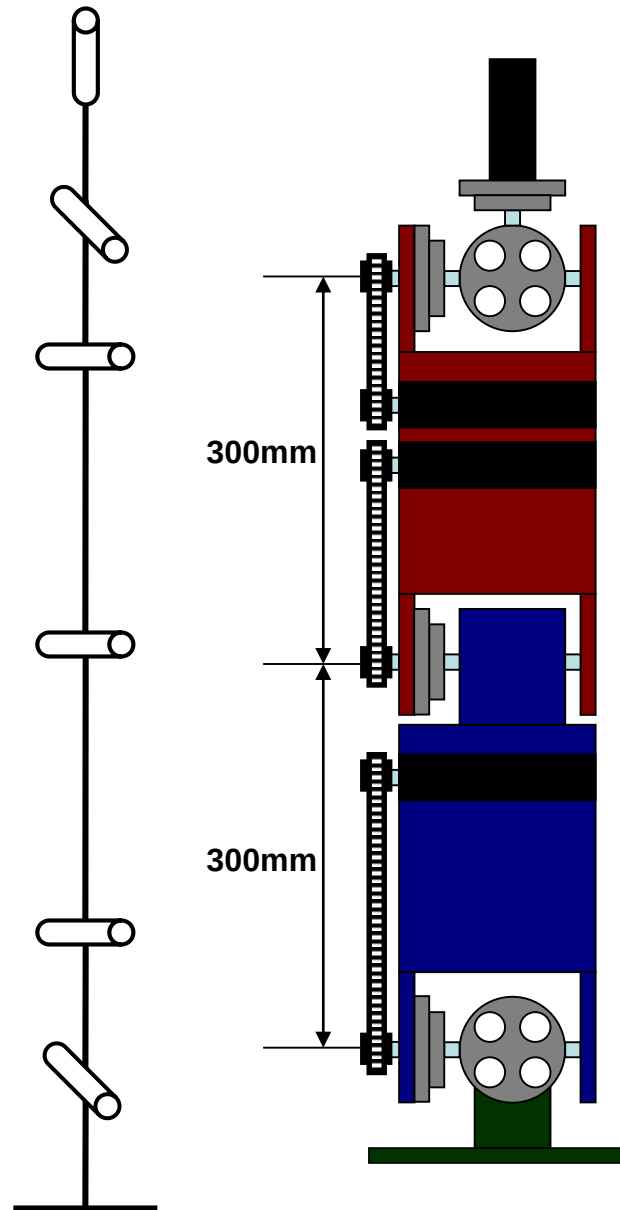
Company: SKF

XL series timing belts and pulleys.

- RUBBER BUSHING

Company: Las-Par

Will be used to soften ground contact forces.



- 3 axis on the hip and 2 axis on the ankle to be aligned
- Centre of mass to be as close as possible to the hip joint
- Material to be Magnesium or Aluminum Alloy (Mg alloy %35 less denser)

Highly stressed parts : Al7075

Others : Al6061

Dimensions:

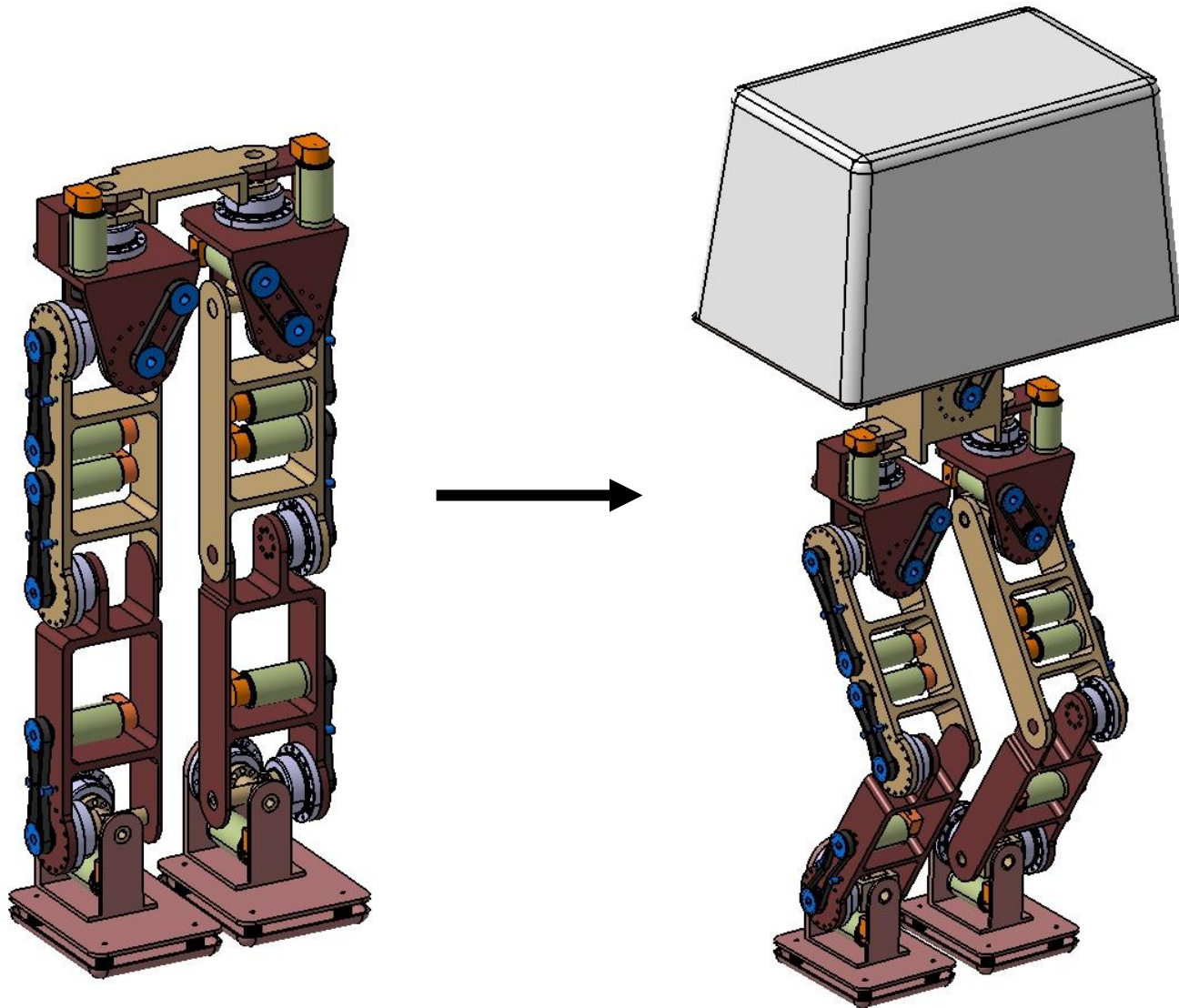
Upper leg and lower leg: 300 mm

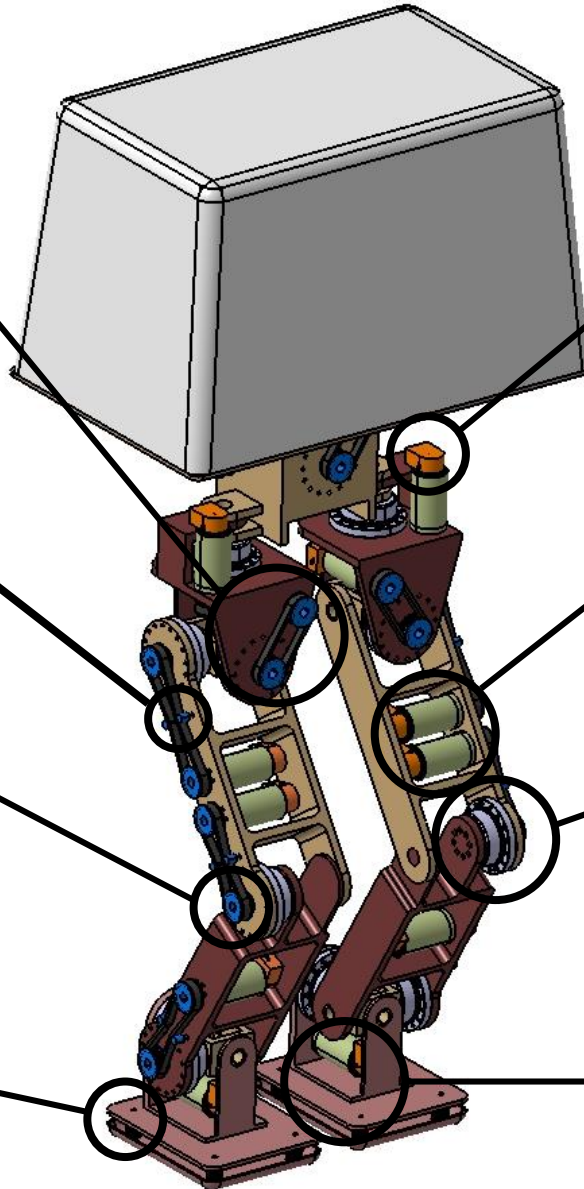
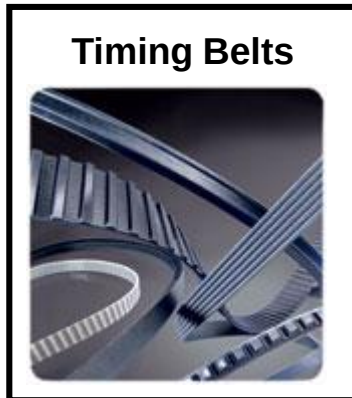
Distance between hip joints: 200 mm

Weight:

Single leg: 10 kgf

Total: 25-35 kgf





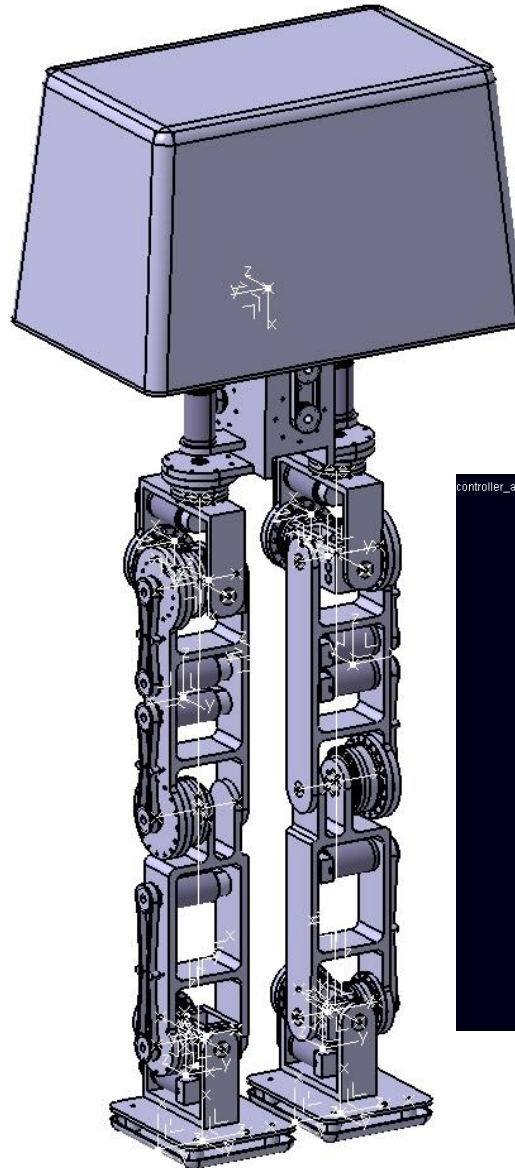
WORKSTREAM 3. INITIAL DESIGN AND SIMULATION

Harmonic Drives

Ankle	X – CSG 17
	Y – CSG 17
Knee	Y – CSG 25
	Z – CSG 20
	Y – CSG 25
Hip	X – CSG 20
	X – CSG 17
	Y – CSG 17

Motors

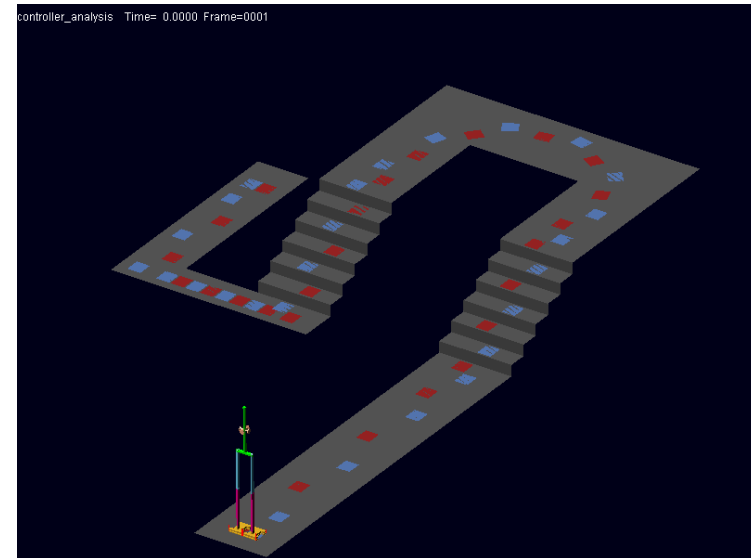
All 150W.



Height : 1.4 m

Total Weight: 50 kgf

Single Leg: 14 kgf



Harmonic Drives

Ankle X – CSG 14

Y – CSG 14

Knee Y – CSG 20

Hip Z – CSG 17

Y – CSG 20

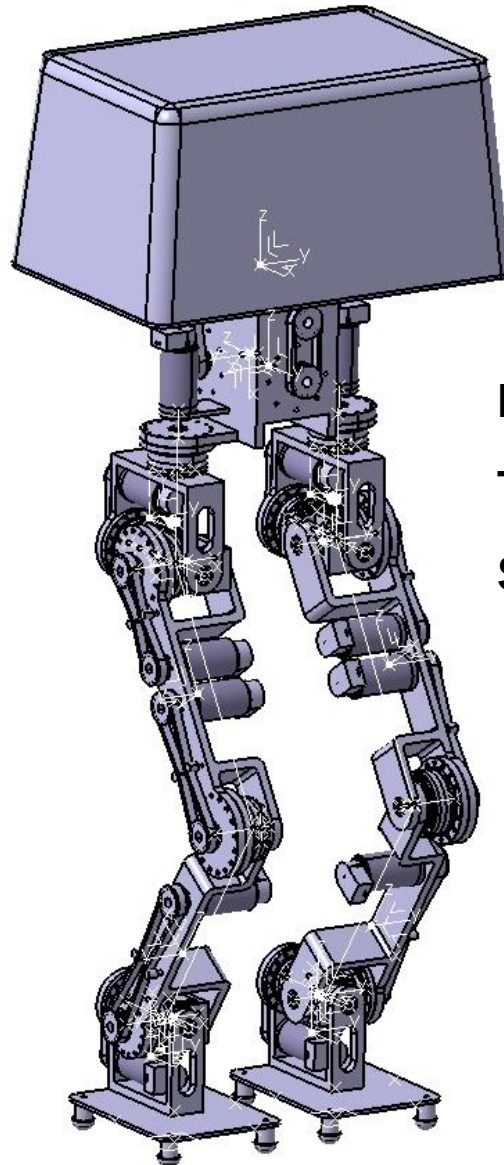
X – CSG 17

Body X – CSG 17

Y – CSG 17

Motors

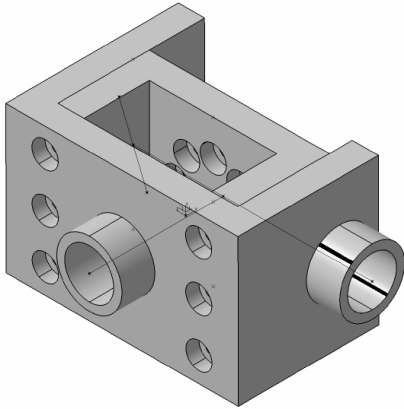
All 150W.



Height : 1.3 m

Total Weight: 35 kgf

Single Leg : 10 kgf



Ankle Link

$$m = 0.225$$

$$I_{xx} = 8.157e-005$$

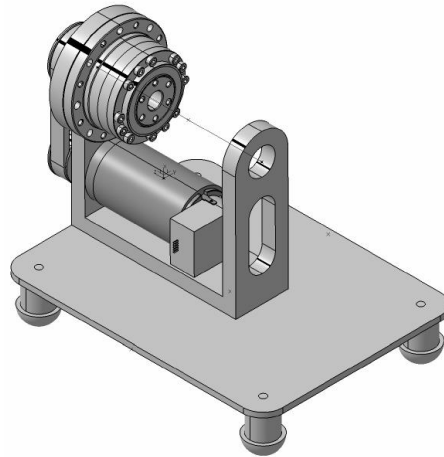
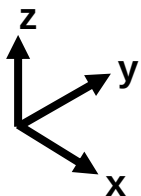
$$I_{yy} = 1.759e-004$$

$$I_{zz} = 1.795e-004$$

$$I_{xy} = I_{yx} = 6.444e-006$$

$$I_{xz} = I_{zx} = 4.525e-022$$

$$I_{yz} = I_{zy} = 5.177e-021$$



Foot

$$m = 1.817$$

$$I_{xx} = 0.004$$

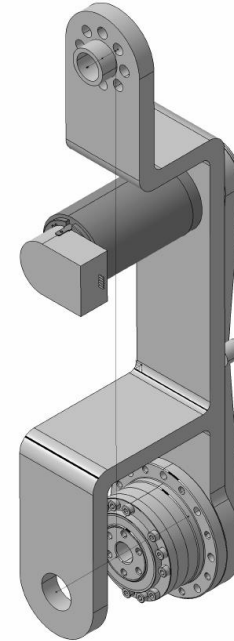
$$I_{yy} = 0.007$$

$$I_{zz} = 0.005$$

$$I_{xy} = I_{yx} = 5.516e-006$$

$$I_{xz} = I_{zx} = 0.002$$

$$I_{yz} = I_{zy} = -1.472e-006$$



Lower Leg

$$m = 1.852$$

$$I_{xx} = 0.019$$

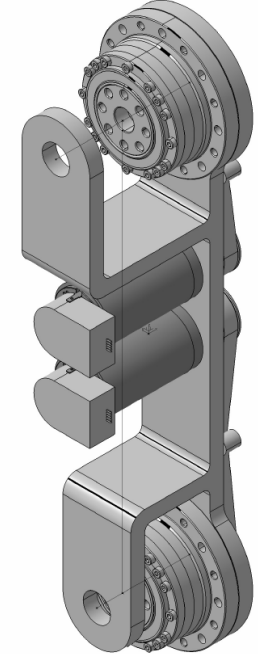
$$I_{yy} = 0.018$$

$$I_{zz} = 0.002$$

$$I_{xy} = I_{yx} = 8.563e-006$$

$$I_{xz} = I_{zx} = -1.327e-005$$

$$I_{yz} = I_{zy} = 0.001$$



Upper Leg

$$m = 4.108$$

$$I_{xx} = 0.063$$

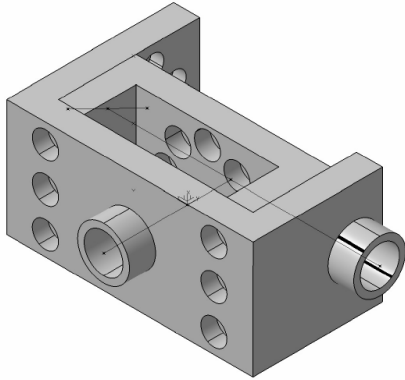
$$I_{yy} = 0.062$$

$$I_{zz} = 0.004$$

$$I_{xy} = I_{yx} = 1.769e-005$$

$$I_{xz} = I_{zx} = -3.651e-006$$

$$I_{yz} = I_{zy} = 8.613e-004$$



Hip Joint 1

$$m = 0.339$$

$$I_{xx} = 1.449e-004$$

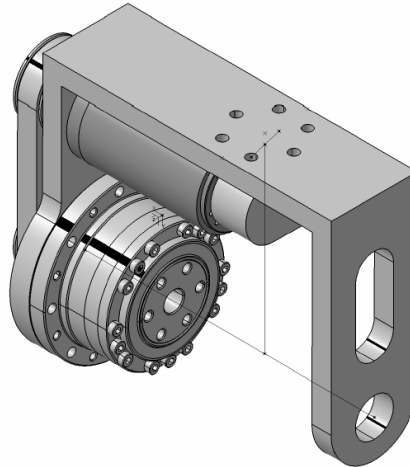
$$I_{yy} = 4.251e-004$$

$$I_{zz} = 4.524e-004$$

$$I_{xy} = I_{yx} = 2.036e-005$$

$$I_{xz} = I_{zx} = 1.95e-008$$

$$I_{yz} = I_{zy} = 1.078e-007$$



Hip Joint 2

$$m = 1.69$$

$$I_{xx} = 0.003$$

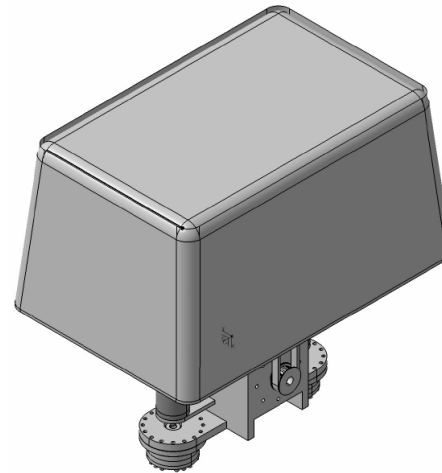
$$I_{yy} = 0.005$$

$$I_{zz} = 0.003$$

$$I_{xy} = I_{yx} = -7.389e-006$$

$$I_{xz} = I_{zx} = -9.462e-004$$

$$I_{yz} = I_{zy} = -4.895e-006$$



Body

$$m = 14.258$$

$$I_{xx} = 0.432$$

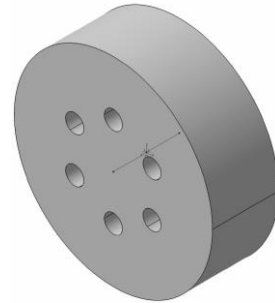
$$I_{yy} = 0.323$$

$$I_{zz} = 0.305$$

$$I_{xy} = I_{yx} = -7.576e-004$$

$$I_{xz} = I_{zx} = 0.003$$

$$I_{yz} = I_{zy} = -0.004$$



Flywheel

$$m = 0.423$$

$$I_{xx} = 1.121e-004$$

$$I_{yy} = 1.961e-004$$

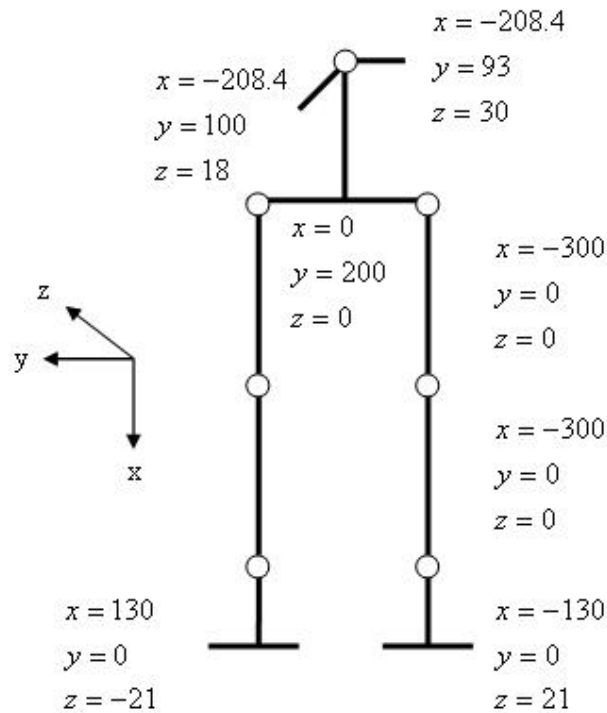
$$I_{zz} = 1.121e-004$$

$$I_{xy} = I_{yx} = 0$$

$$I_{xz} = I_{zx} = 0$$

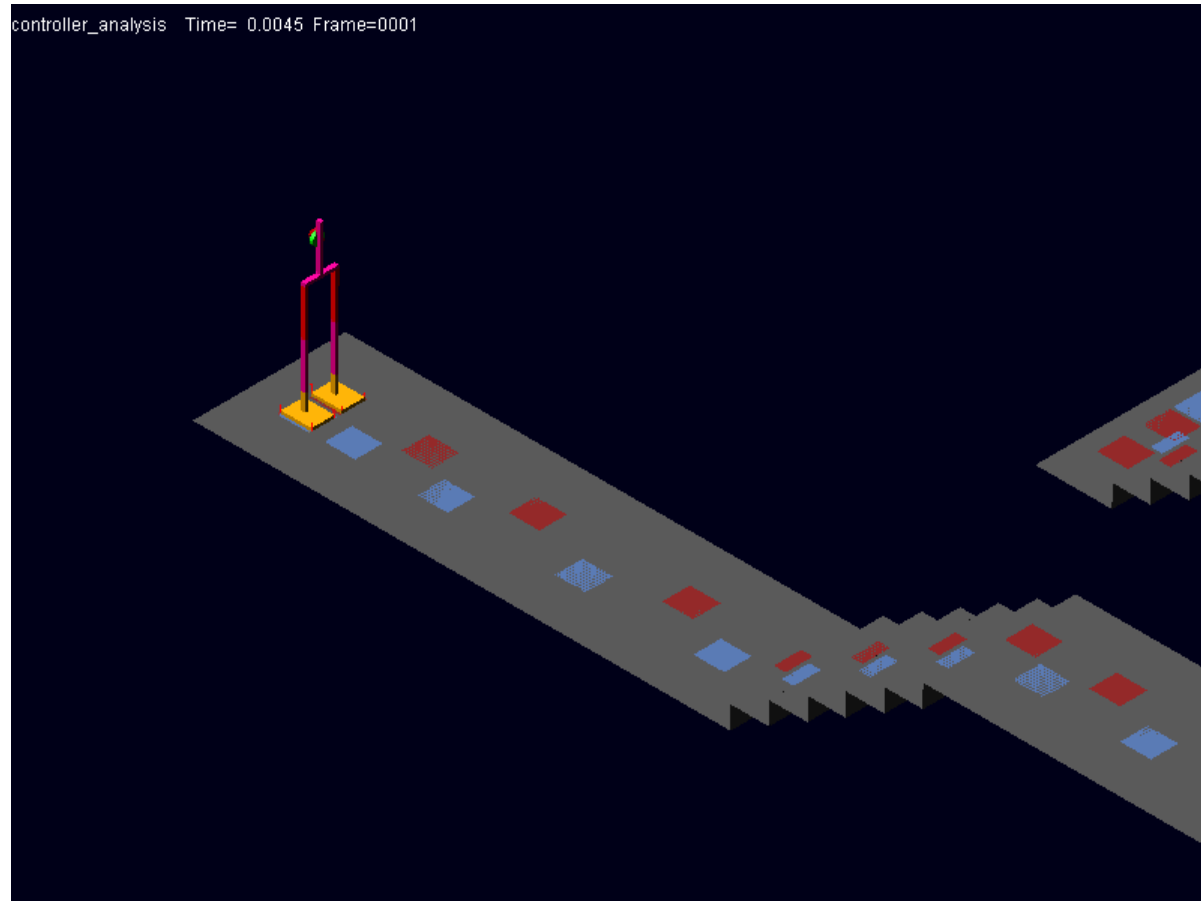
$$I_{yz} = I_{zy} = 0$$

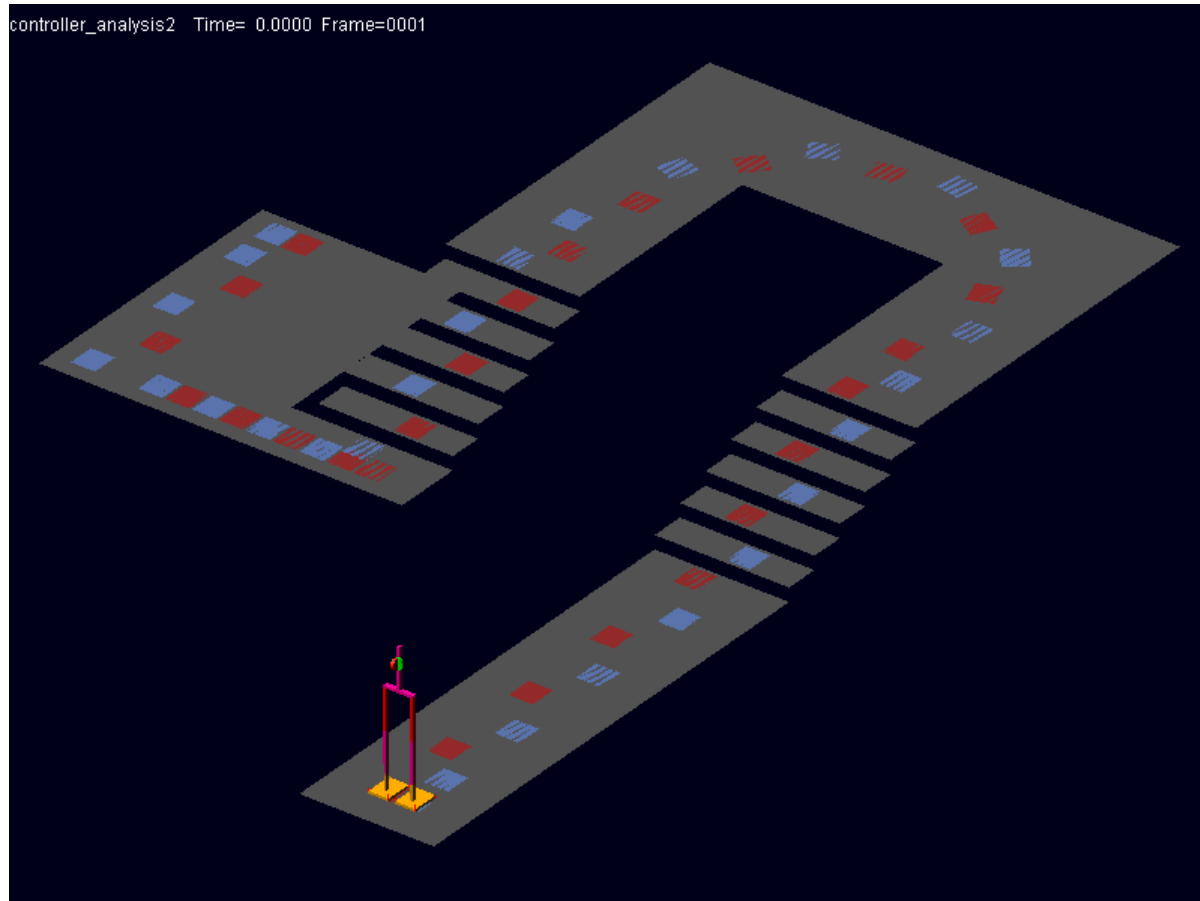
Joint Coordinates



CoM Position Vectors

$$\begin{aligned}
 P_{C1} &= [-0.498 \quad -10.889 \quad 0]^T \\
 P_{C2} &= [0.08 \quad 17.049 \quad 105.628]^T \\
 P_{C3} &= [0.072 \quad 18.848 \quad 155.292]^T \\
 P_{C4} &= [-1.179 \quad -15.621 \quad -1.077]^T \\
 P_{C5} &= [-53.932 \quad 0.085 \quad 36.077]^T \\
 P_{C6} &= [3.102 \quad -105.117 \quad 229.85]^T \\
 P_{C7} &= [-53.932 \quad 0.085 \quad 36.077]^T \\
 P_{C8} &= [-1.179 \quad 15.621 \quad 1.077]^T \\
 P_{C9} &= [-0.072 \quad -18.848 \quad -144.708]^T \\
 P_{C10} &= [-0.08 \quad -17.049 \quad -194.372]^T \\
 P_{C11} &= [-0.498 \quad 10.889 \quad 0]^T \\
 P_{C12} &= [-28.773 \quad -0.082 \quad -47.821]^T \\
 P_{C13} &= [0 \quad 0 \quad 0]^T \\
 P_{C14} &= [0 \quad 0 \quad 0]^T
 \end{aligned}$$





- Stair height reduced.
- Step length shortened.

WORKSTREAM 4. SELECTION OF MOTORS AND GEARS ACC. TO SIMULATION OUTPUT

Average Torque (Nm)

Ankle X :	8
Ankle Y :	12
Knee :	34
Hip X :	23
Hip Y :	16
Hip Z :	10

Max Torque (Nm) (peak)

Ankle X :	20 (60)
Ankle Y :	40 (100)
Knee :	60 (120)
Hip X :	45 (70)
Hip Y :	40 (200)
Hip Z :	25 (50)

Max Speed (d/dk)

Ankle X :	15
Ankle Y :	70
Knee :	60
Hip X :	15
Hip Y :	70
Hip Z :	15

Average Speed (d/dk)

Ankle X :	4
Ankle Y :	12
Knee :	13
Hip X :	4
Hip Y :	11
Hip Z :	2

Power (W)

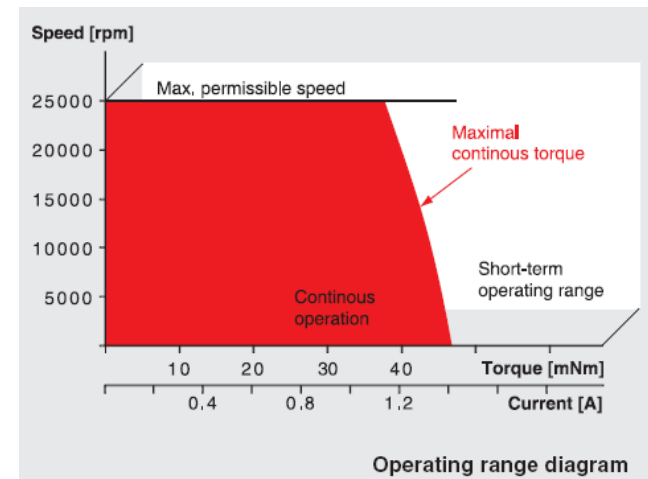
Ankle X :	70
Ankle Y :	150
Knee :	150
Hip X :	90
Hip Y :	150
Hip Z :	40

MOTOR			
GİRİŞLER			
X	RMS Torque(joint) (Nm) (Mrms)	25	
X	Maximum Torque (Joint) (Nm)	90	
X	Mechanical Peak Power (W)	60	
X	Motor Speed (rpm)	7000	
X	Motor eta	0.92	
X	Reducer eta	0.75	
X	Speed torque gradient (rpm/mNm)	3.04	
X	Voltage (V) dropped	68	
X	Speed constant (rpm/V)	158	
X	Torque constant (mNm/A)	60.3	
X	No load current (A)	0.0686	
HESAPLANANLAR			
	Total eta	0.69	
	M motor RMS (mNm)	233.7540907	
	M motor Max (mNm)	841.5147265	
	No load speed (rpm)	9533.204769	
	Speed Constant (rpm/V)	140.1941878	< 158
	I max (A)	14.0240681	< 10
REDÜKTÖR			
		rad/s	rpm
		2	19.098593
GİRİŞLER			
X	Average Torque HD (Nm) (T av)	22	
X	Average Output Speed (rpm) (no av)	12.5	
X	max output speed(joint speed) (rpm) (no max)	45	
X	Rated torque (Nm) (nr)	50	
X	Impact torque speed (rpm) (ns)	60	
X	Impact torque interval (sec) (ts)	0.01	
HESAPLANANLAR			
	Gear Ratio (R)	155.5555556	
X	Gear Ratio Selected (smaller)	155	
	Average Input Speed (ni av)	1937.5	
	Max. Input Speed (ni max)	6975	
	Number of allowable turns	3214.285714	< 10000
	Lifetime (Lh10)	121179.8066	> 10000
	Lifetime (Lh50)	605899.033	> 50000
SABİTLER			
	Rated speed (rpm)	2000	
	L10	10000	
	L50	50000	

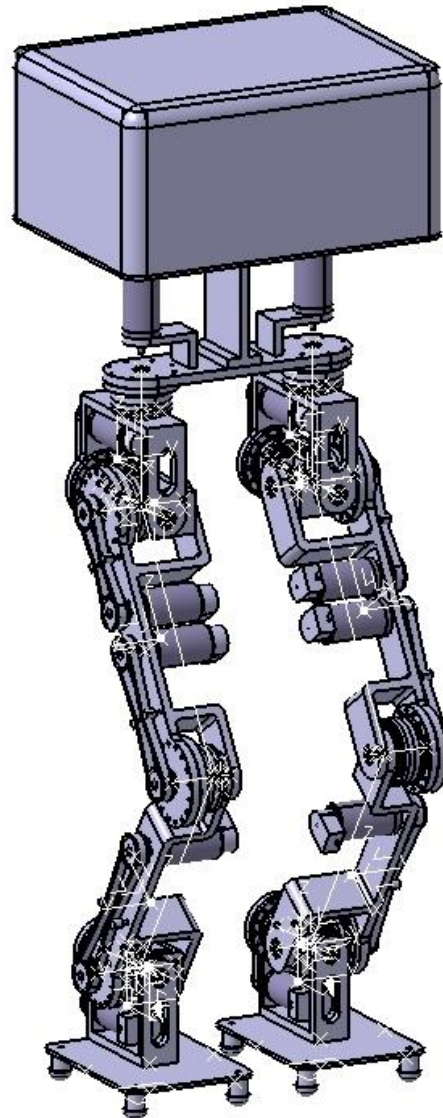
WORKSTREAM 4. SELECTION OF MOTORS AND GEARS ACC. TO SIMULATION OUTPUT

<u>EKLEM</u>	<u>MOTOR</u>	<u>REDÜKTÖR</u>	<u>Hesaplanan ÇevrimOranı</u>	<u>Kasnak Çevrim Oranı</u>
Ayak Bileği X	90W	CSG-14-100	466	1.5:1
Ayak Bileği Y	150W	CSG-17-100	100	1:1
Diz	150Wx2	CSG-17-120	120	1:1
Kalça X	150W	CSG-17-100	466	2:1
Kalça Y	150W	CSG-20-100	100	1:1
Kalça Z	90W	CSG-14-100	536	1:1

<u>EKLEM</u>	<u>MOTOR</u>	<u>REDÜKTÖR</u>
Ayak Bileği X	150W	CSG-14
Ayak Bileği Y	150W	CSG-14
Diz	150W	CSG-20
Kalça X	150W	CSG-17
Kalça Y	150W	CSG-20
Kalça Z	150W	CSG-17



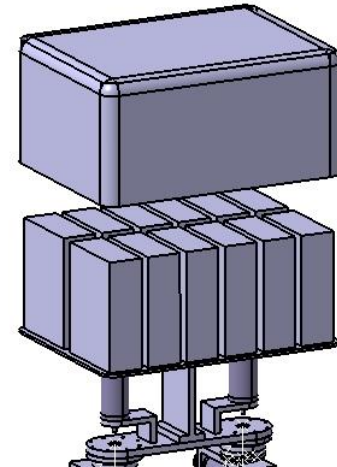
- Closed loop control of dynamic walking with flywheels is impractical. Removed from design.
- Electronics weight added.

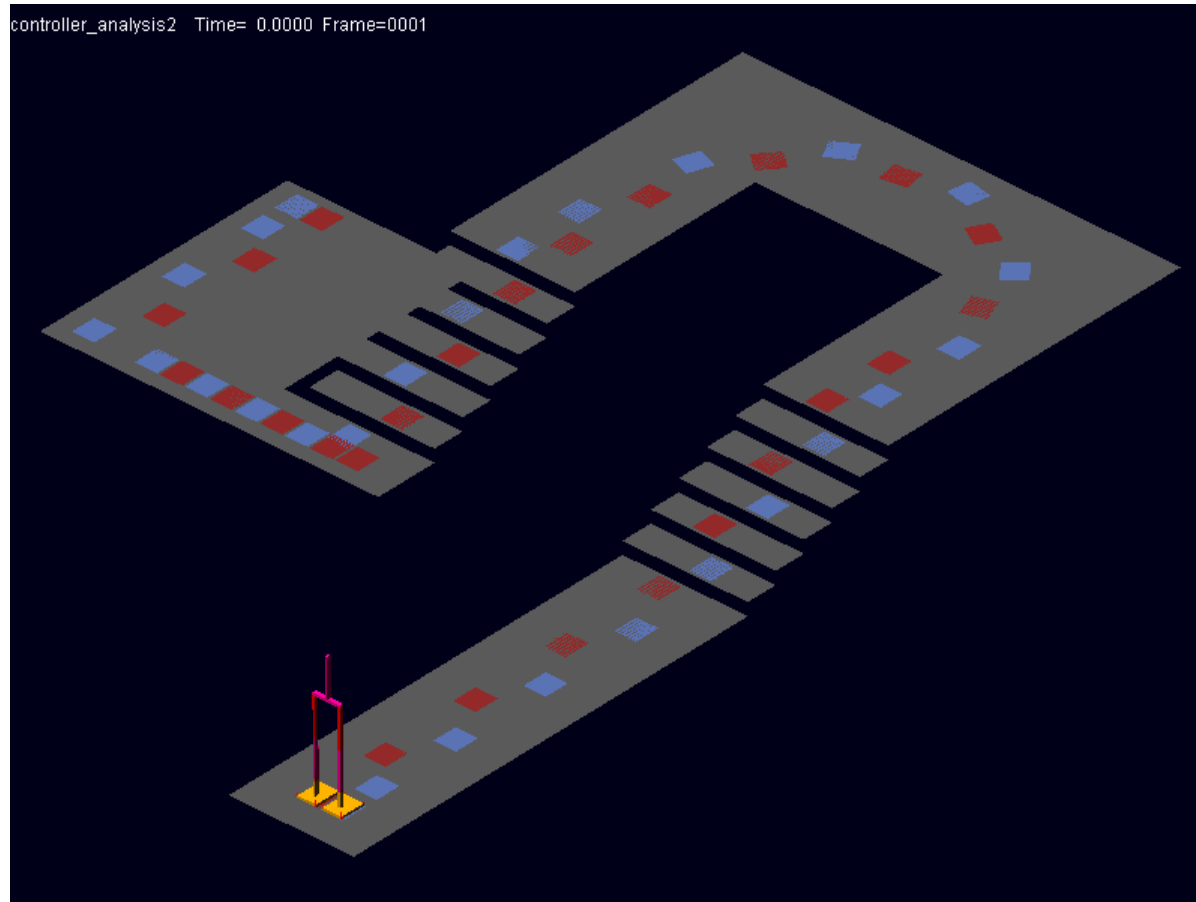


Height : 1.4 m

Weight : 35 kgf

Electronics Weight : 7 kg





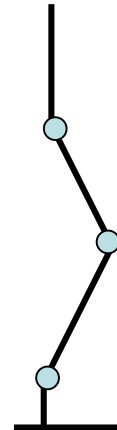
<u>EKLEM</u>	<u>MOTOR</u>	<u>REDÜKTÖR</u>	<u>Hesaplanan Çevrim Oranı</u>	<u>Kasnak Çevrim Oranı</u>
Ayak Bileği X	60W	CSG-14-100	466	1.5:1
Ayak Bileği Y	150W	CSG-17-100	100	1:1
Diz	2 x 150W	CSG-17-120	120	1:1
Kalça X	150W	CSG-17-120	466	1.5:1
Kalça Y	150W	CSG-17-100	100	1:1
Kalça Z	60W	CSG-14-100	536	1:1

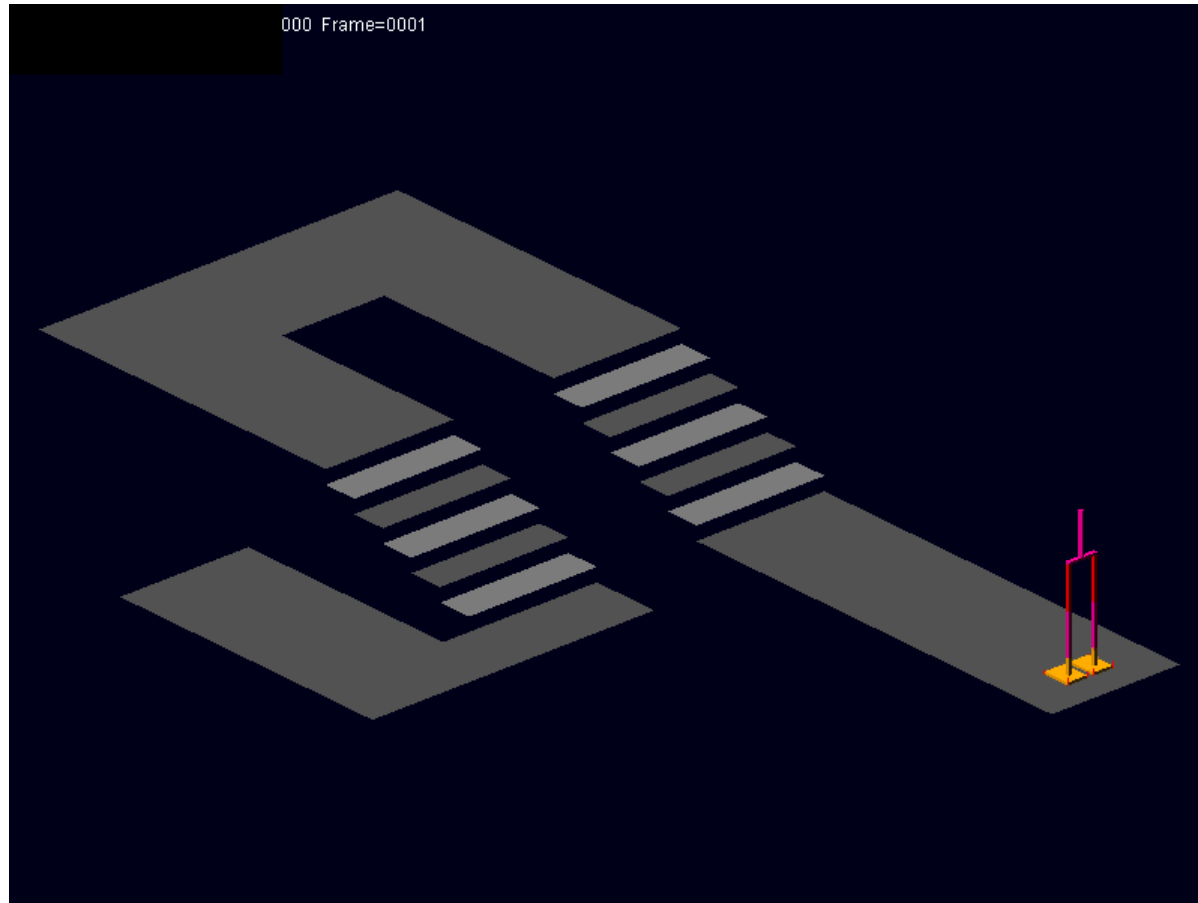
Knee joint torque and speed is too high. To be able to reduce these:

- Step lengths during cornering reduced.
- Knee bending height reduced from 10 cm to 7 cm.
- Step length during straight walking reduced.
- Walking speed reduced.

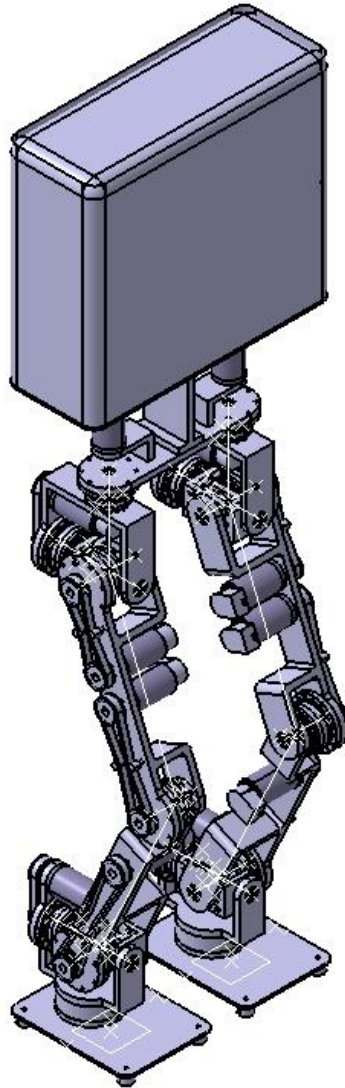
In addition to this;

- Weights will be reduced.
- Joint friction will be added to simulations.





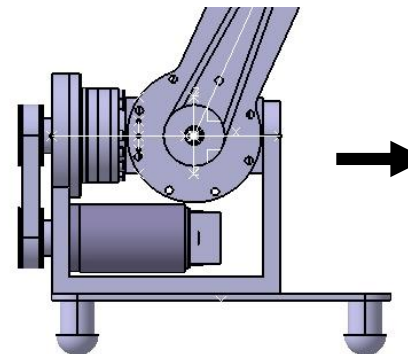
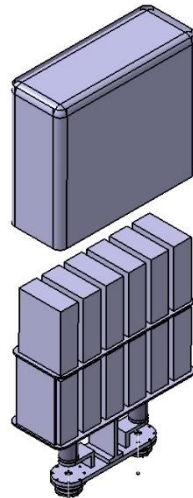
<u>EKLEM</u>	<u>MOTOR</u>	<u>REDÜKTÖR</u>	<u>Hesaplanan Çevrim Oranı</u>	<u>Kasnak Çevrim Oranı</u>
Ayak Bileği X	60W	CSG-14-100	466	1.5:1
Ayak Bileği Y	150W	CSG-17-100	116	1:1
Diz	150W	CSG-17-100	100	1:1
Kalça X	150W	CSG-17-100	466	2:1
Kalça Y	150W	CSG-17-100	100	1.1:1
Kalça Z	60W	CSG-14-100	536	1:1



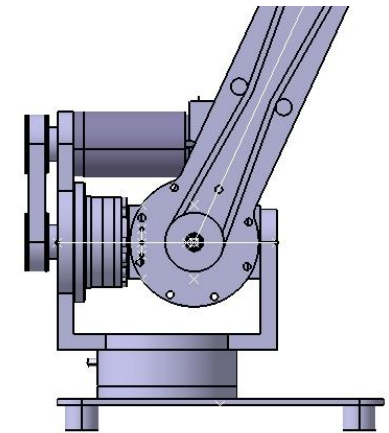
Height : 1.35 m

Weight : 30.5 kgf

- Motor drivers positioned in two rows alignment. 400gr is considered for the weight of each driver.
- Design updated acc. to selected harmonic drives.
- Force-torque sensor added. Ankle joint design modified accordingly.

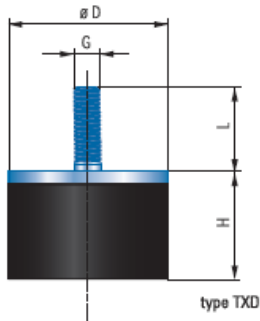


Ankle joint to
ground distance:
130 mm



Ankle joint to
ground distance:
110 mm

- Friction effects are included. (Viscous friction, $\mu = 0.1$)
- Rubber bushings are added to the model. (Peak torques decreased.)
- Design change on the ankle knee is implemented to simulation model.



Kinematic Limits

Determined

Ankle X : -22.5° +22.5°

Ankle Y : -10° +76°

Knee : -114° 0

Hip X : -22° +22°

Hip Y : -17° +74°

Hip Z : -20° +20°

Met with Design

Ankle X : -25° +25°

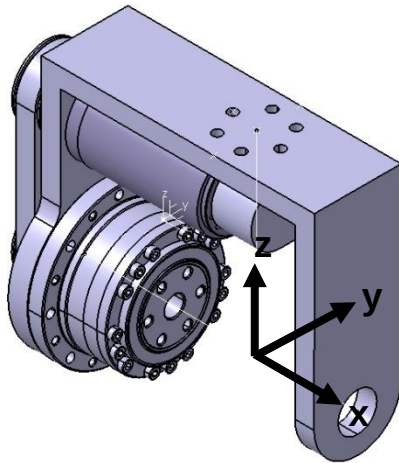
Ankle Y : -20° +120°

Knee : -130° 0

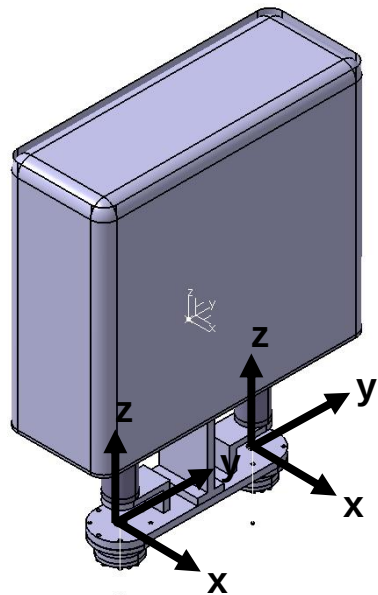
Hip X : -25° +25°

Hip Y : -40° +90°

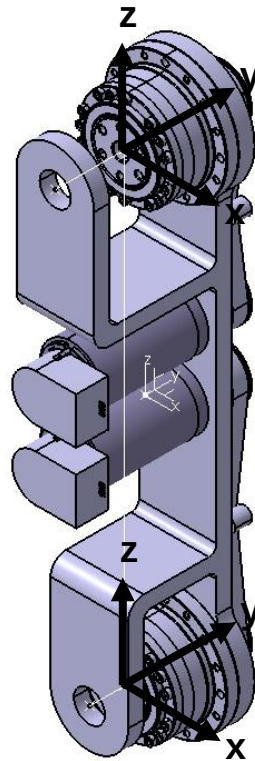
Hip Z : -180° +180°



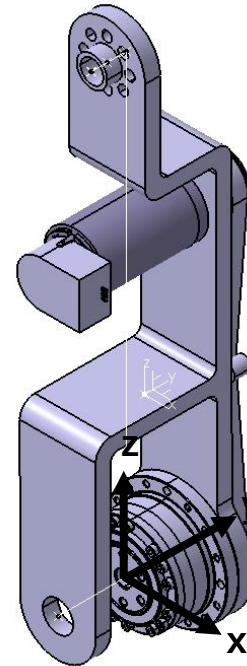
Hip X



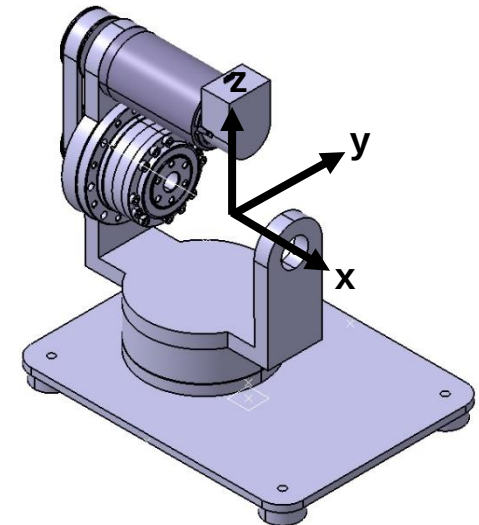
Hip Z



Hip Y
and Ankle



Ankle Y



Ankle X

- Forces on the roller bearings will be determined.
- Forces on the links will be determined.

NEXT STEPS

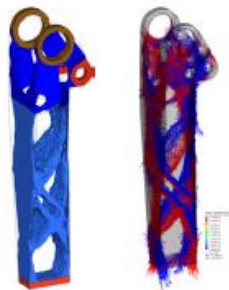
1. Forces acting on the joints and links will be determined.
2. Forces on the DC motors' shaft will be determined.
3. Motor shaft, pulleys and timing belts and harmonic drive shaft inertias will be considered for torque calculations and gear ratio will be determined accordingly.
4. Assembly and manufacturing feasibility checks and addition of bolts to the design for the assembly.
5. Material selection, geometry optimization with CAE analysis and dimensioning (Altair Hyperworks - Optistruct).



(a) Mockup



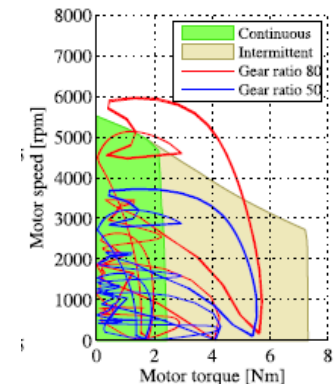
(b) Optimization model



(c) Optimization result



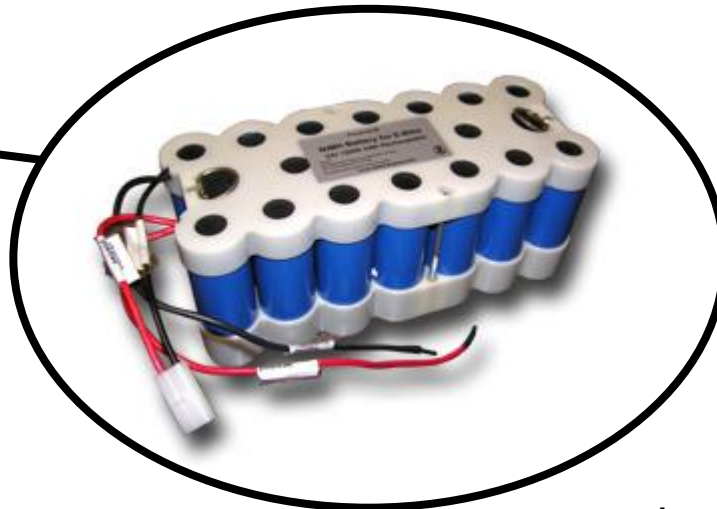
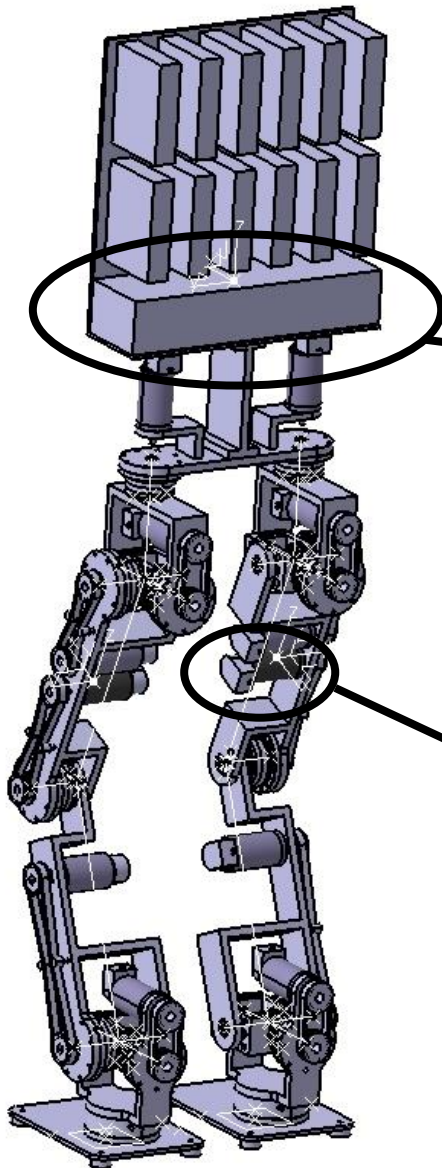
(d) Part design



LATEST DESIGN

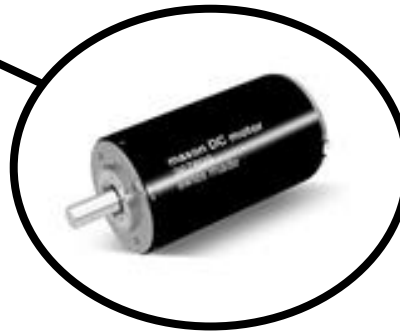
Total Weight: 38 kgf

Structural Weight: 11 kgf



24V 13Ah

Weight : 5 kgf

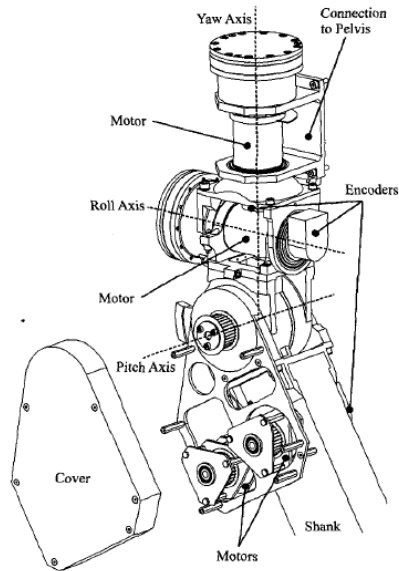


RE 65 : 250W 2480 gr

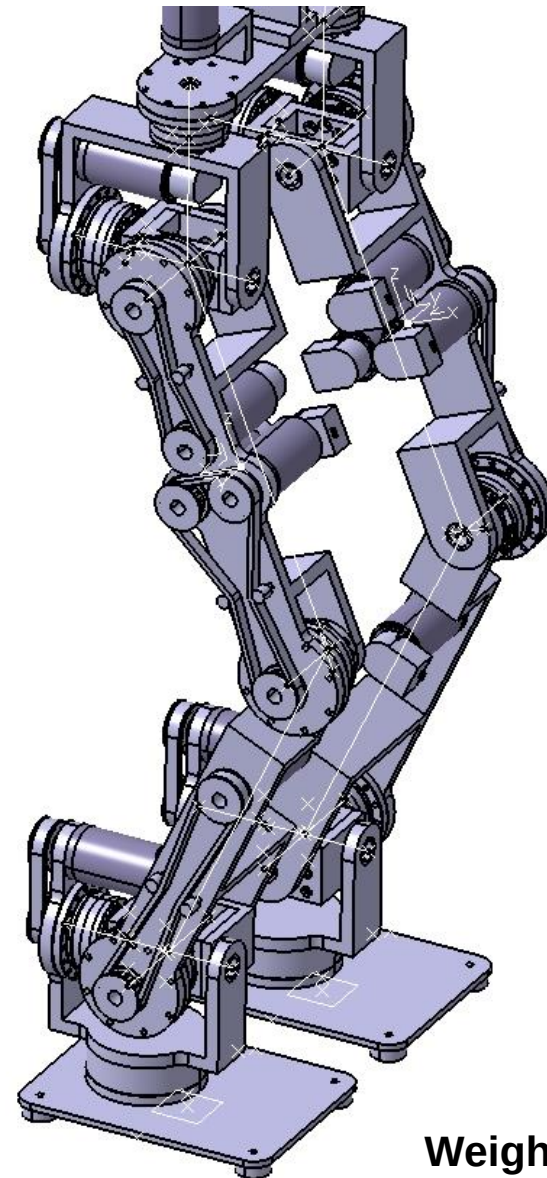
Disadvantages of 250W DC Motor

- 48V requirement
- Increases the weight of the leg
- Total CoM is moved down

LATEST DESIGN



	Pitch
Motor	2 x Maxon RE40
Gear	HFUC26-80 modified
Transmission ratio	80
Max. static joint torque	220Nm
Average static joint torque	22,3Nm
Max. joint velocity	9,4rad/s



Weight : 35.5 kgf

LATEST DESIGN

<u>EKLEM</u>	<u>MOTOR</u>	<u>REDÜKTÖR</u>	<u>Hesaplanan ÇevrimOran</u>	<u>Kasnak Çevrim Oran</u>
Ayak Bileği X	60W	CSG-14-100	670	2:1
Ayak Bileği Y	150W	CSG-17-120	138	1:1
Diz	2x150W	CSG-17-120	154	1:1
Kalça X	150W	CSG-17-120	577	2:1
Kalça Y	150W	CSG-17-120	138	1:1
Kalça Z	60W	CSG-14-100	670	1:1

Kinematic Limits

Determined

Ankle X : -22.5° +22.5°

Ankle Y : -10° +76°

Knee : -114° 0

Hip X : -22° +22°

Hip Y : -17° +74°

Hip Z : -20° +20°

Met with Design

Ankle X : -25° +25°

Ankle Y : -20° +120°

Knee : -130° 0

Hip X : -25° +25°

Hip Y : -40° +90°

Hip Z : -180° +180°

RADIAL FORCES ACTING ON THE MOTOR SHAFT

Max Tork (Nm)

Redüksiyon Oranı

Ayak Bileği X :	20	Peak: 30	200
Ayak Bileği Y :	30	40	120
Diz :	50	70	120
Kalça X :	45	80	240
~~Kalça Z :~~	~~20~~	~~30~~	~~100~~
Kalça Y :	30	80	120

Acc. to 40mm diameter pulley:

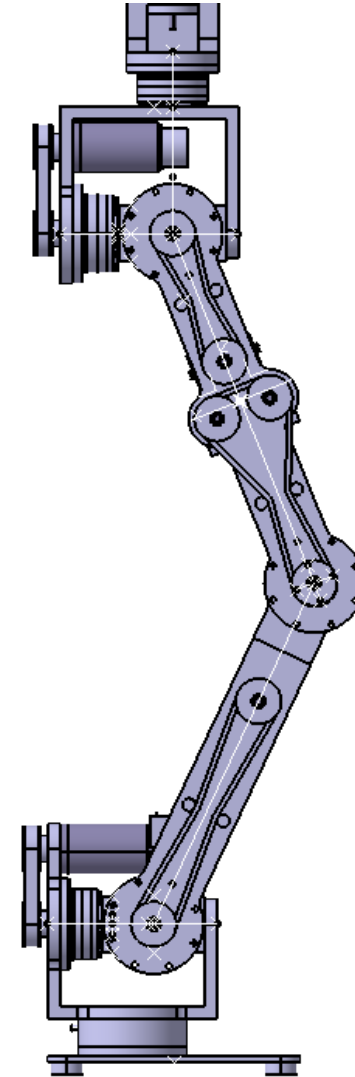
Ankle X : 7.5N

Ankle Y : 16 N

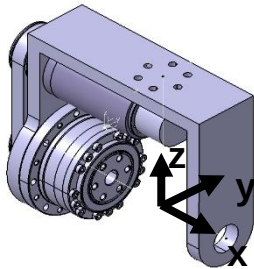
Knee : 30 N / 2 < 28N

Hip X : 16 N

Hip Y : 25 N

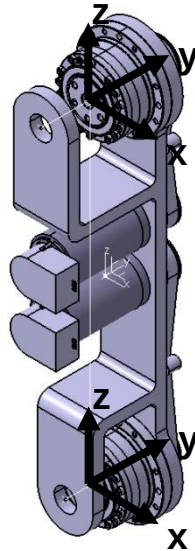


FORCES AND TORQUES ACTING ON THE JOINTS



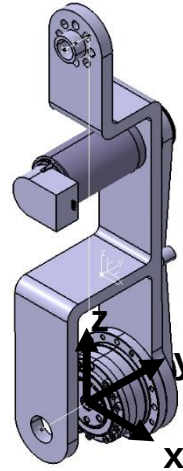
Hip X

$$\begin{aligned} F_x &= 70 \text{ N} \\ F_y &= 80 \text{ N} \\ F_z &= 300 \text{ N} \\ N_x &= 50 \text{ Nm} \\ N_y &= 42 \text{ Nm} \\ N_z &= 10 \text{ Nm} \end{aligned}$$



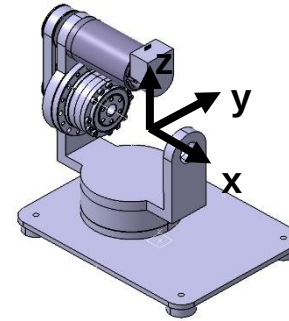
Hip Y and Knee

$F_x = 200 \text{ N}$	$F_x = 230 \text{ N}$
$F_y = 80 \text{ N}$	$F_y = 80 \text{ N}$
$F_z = 270 \text{ N}$	$F_z = 310 \text{ N}$
$N_x = 46 \text{ Nm}$	$N_x = 40 \text{ Nm}$
$N_y = 40 \text{ Nm}$	$N_y = 72 \text{ Nm}$
$N_z = 30 \text{ Nm}$	$N_z = 30 \text{ Nm}$



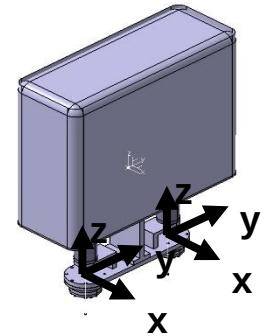
Ankle Y

$$\begin{aligned} F_x &= 250 \text{ N} \\ F_y &= 80 \text{ N} \\ F_z &= 325 \text{ N} \\ N_x &= 42 \text{ Nm} \\ N_y &= 44 \text{ Nm} \\ N_z &= 23 \text{ Nm} \end{aligned}$$



Ankle X

$$\begin{aligned} F_x &= 70 \text{ N} \\ F_y &= 60 \text{ N} \\ F_z &= 365 \text{ N} \\ N_x &= 50 \text{ Nm} \\ N_y &= 44 \text{ Nm} \\ N_z &= 2 \text{ Nm} \end{aligned}$$



Hip Z

$$\begin{aligned} F_x &= 70 \text{ N} \\ F_y &= 60 \text{ N} \\ F_z &= 285 \text{ N} \\ N_x &= 50 \text{ Nm} \\ N_y &= 40 \text{ Nm} \\ N_z &= 9 \text{ Nm} \end{aligned}$$

FORCES AND TORQUES ACTING ON THE JOINTS

Tabelle / Table 173.1

CSG- 2UH Baugröße	Lagertyp ¹⁾	Teilkreis Ø ²⁾	Abstand ³⁾	Dynamische Tragzahl	Statische Tragzahl	Zulässiges dynamisches Kippmoment ¹⁾	Zulässiges statisches Kippmoment ²⁾	Kippsteifigkeit	Zulässige Axiallast ³⁾	Zulässige Radiallast ³⁾
CSG- 2UH Size	Bearing type ¹⁾	Pitch Circle Ø ²⁾	Offset ³⁾	Dynamic load rating	Static load rating	Permissible dynamic Tilting Moment ¹⁾	Permissible static Tilting Moment ²⁾	Moment Stiffness	Permissible Axial Load ³⁾	Permissible Radial Load ³⁾
		d _p [m]	R [mm]	C [N]	C ₀ [N]	M [Nm]	M ₀ [Nm]	K _θ [Nm/arcmin]	F _a [N]	F _r [N]
14	C	0,035	9,5	4740	6070	41	53	13	3374	2256
17	C	0,043	9,5	5290	7550	64	80	22,5	3207	2148

17 Hip X

$$M = 43Nm$$

$$F_a = 70N$$

$$F_r = 310N$$

17 Hip Y

$$M = 55Nm$$

$$F_a = 80N$$

$$F_r = 336N$$

14 Hip Z

$$M = 64Nm$$

$$F_a = 285N$$

$$F_r = 92N$$

17 Knee

$$M = 50Nm$$

$$F_a = 80N$$

$$F_r = 386N$$

14 Ankle X

$$M = 44Nm$$

$$F_a = 70N$$

$$F_r = 370N$$

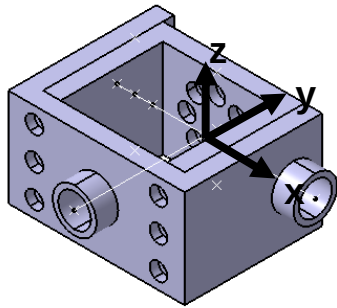
17 Ankle Y

$$M = 47Nm$$

$$F_a = 80N$$

$$F_r = 410N$$

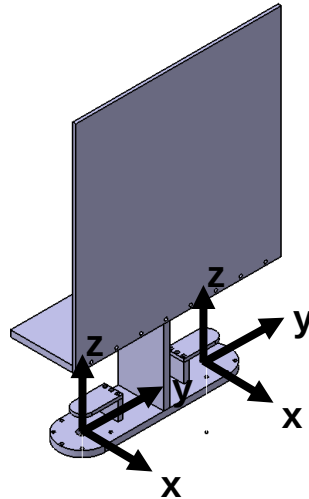
FORCES AND TORQUES ACTING ON THE LINKS



Ankle Joint Part

$$\begin{aligned} F_x &= -60 \text{ N} & F_x &= 70 \text{ N} \\ F_y &= -80 \text{ N} & F_y &= 80 \text{ N} \\ F_z &= -165 \text{ N} & F_z &= 375 \text{ N} \\ N_x &= -50 \text{ Nm} & N_x &= 50 \text{ Nm} \\ N_y &= -44 \text{ Nm} & N_y &= 36 \text{ Nm} \\ N_z &= -7 \text{ Nm} & N_z &= 7 \text{ Nm} \end{aligned}$$

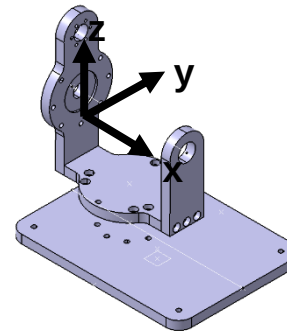
$$\begin{aligned} F_x &= 70 \text{ N} \\ F_y &= 80 \text{ N} \\ F_z &= 375 \text{ N} \\ N_x &= 50 \text{ Nm} \\ N_y &= 44 \text{ Nm} \\ N_z &= 7 \text{ Nm} \end{aligned}$$



Body

$$\begin{aligned} F_x &= -60 \text{ N} & F_x &= 70 \text{ N} \\ F_y &= -60 \text{ N} & F_y &= 60 \text{ N} \\ F_z &= -85 \text{ N} & F_z &= 285 \text{ N} \\ N_x &= -50 \text{ Nm} & N_x &= 50 \text{ Nm} \\ N_y &= -35 \text{ Nm} & N_y &= 40 \text{ Nm} \\ N_z &= -9 \text{ Nm} & N_z &= 9 \text{ Nm} \end{aligned}$$

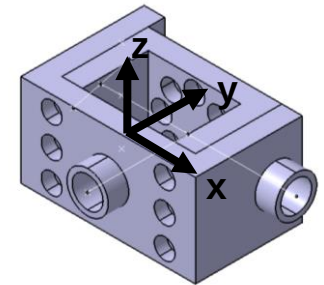
$$\begin{aligned} F_x &= 70 \text{ N} \\ F_y &= 60 \text{ N} \\ F_z &= 285 \text{ N} \\ N_x &= 50 \text{ Nm} \\ N_y &= 40 \text{ Nm} \\ N_z &= 9 \text{ Nm} \end{aligned}$$



Foot

$$\begin{aligned} F_x &= -60 \text{ N} & F_x &= 70 \text{ N} \\ F_y &= -60 \text{ N} & F_y &= 60 \text{ N} \\ F_z &= -165 \text{ N} & F_z &= 365 \text{ N} \\ N_x &= -50 \text{ Nm} & N_x &= 50 \text{ Nm} \\ N_y &= -44 \text{ Nm} & N_y &= 36 \text{ Nm} \\ N_z &= -2 \text{ Nm} & N_z &= 2 \text{ Nm} \end{aligned}$$

$$\begin{aligned} F_x &= 70 \text{ N} \\ F_y &= 60 \text{ N} \\ F_z &= 365 \text{ N} \\ N_x &= 50 \text{ Nm} \\ N_y &= 44 \text{ Nm} \\ N_z &= 2 \text{ Nm} \end{aligned}$$

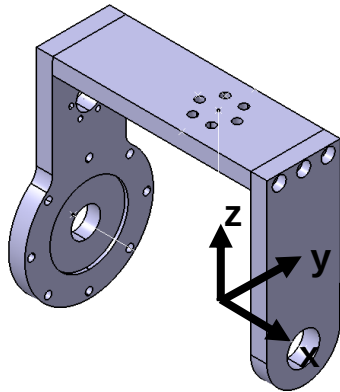


Hip Joint Part 1

$$\begin{aligned} F_x &= -60 \text{ N} & F_x &= 70 \text{ N} \\ F_y &= -80 \text{ N} & F_y &= 80 \text{ N} \\ F_z &= -100 \text{ N} & F_z &= 300 \text{ N} \\ N_x &= -50 \text{ Nm} & N_x &= 50 \text{ Nm} \\ N_y &= -35 \text{ Nm} & N_y &= 42 \text{ Nm} \\ N_z &= -10 \text{ Nm} & N_z &= 10 \text{ Nm} \end{aligned}$$

$$\begin{aligned} F_x &= 70 \text{ N} \\ F_y &= 80 \text{ N} \\ F_z &= 300 \text{ N} \\ N_x &= 50 \text{ Nm} \\ N_y &= 42 \text{ Nm} \\ N_z &= 10 \text{ Nm} \end{aligned}$$

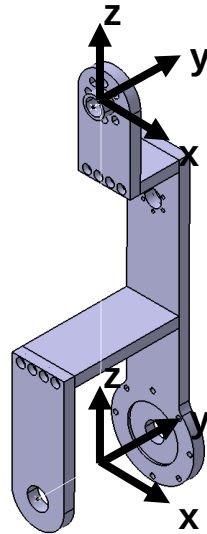
FORCES AND TORQUES ACTING ON THE LINKS



Hip Joint 2

$$\begin{aligned} F_x &= -60 \text{ N} & F_x &= 70 \text{ N} \\ F_y &= -60 \text{ N} & F_y &= 60 \text{ N} \\ F_z &= -100 \text{ N} & F_z &= 300 \text{ N} \\ N_x &= -50 \text{ Nm} & N_x &= 50 \text{ Nm} \\ N_y &= -35 \text{ Nm} & N_y &= 41 \text{ Nm} \\ N_z &= -10 \text{ Nm} & N_z &= 10 \text{ Nm} \end{aligned}$$

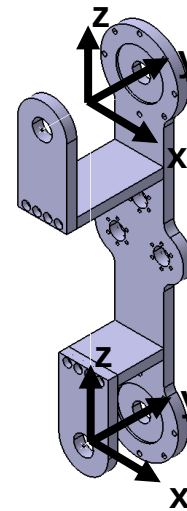
$$\begin{aligned} F_x &= 70 \text{ N} \\ F_y &= 60 \text{ N} \\ F_z &= 300 \text{ N} \\ N_x &= 50 \text{ Nm} \\ N_y &= 41 \text{ Nm} \\ N_z &= 10 \text{ Nm} \end{aligned}$$



Lower Leg

$$\begin{aligned} F_x &= -250 \text{ N} & F_x &= 80 \text{ N} \\ F_y &= -80 \text{ N} & F_y &= 80 \text{ N} \\ F_z &= -150 \text{ N} & F_z &= 325 \text{ N} \\ N_x &= -40 \text{ Nm} & N_x &= 42 \text{ Nm} \\ N_y &= -44 \text{ Nm} & N_y &= 73 \text{ Nm} \\ N_z &= -25 \text{ Nm} & N_z &= 25 \text{ Nm} \end{aligned}$$

$$\begin{aligned} F_x &= 250 \text{ N} \\ F_y &= 80 \text{ N} \\ F_z &= 325 \text{ N} \\ N_x &= 42 \text{ Nm} \\ N_y &= 73 \text{ Nm} \\ N_z &= 25 \text{ Nm} \end{aligned}$$



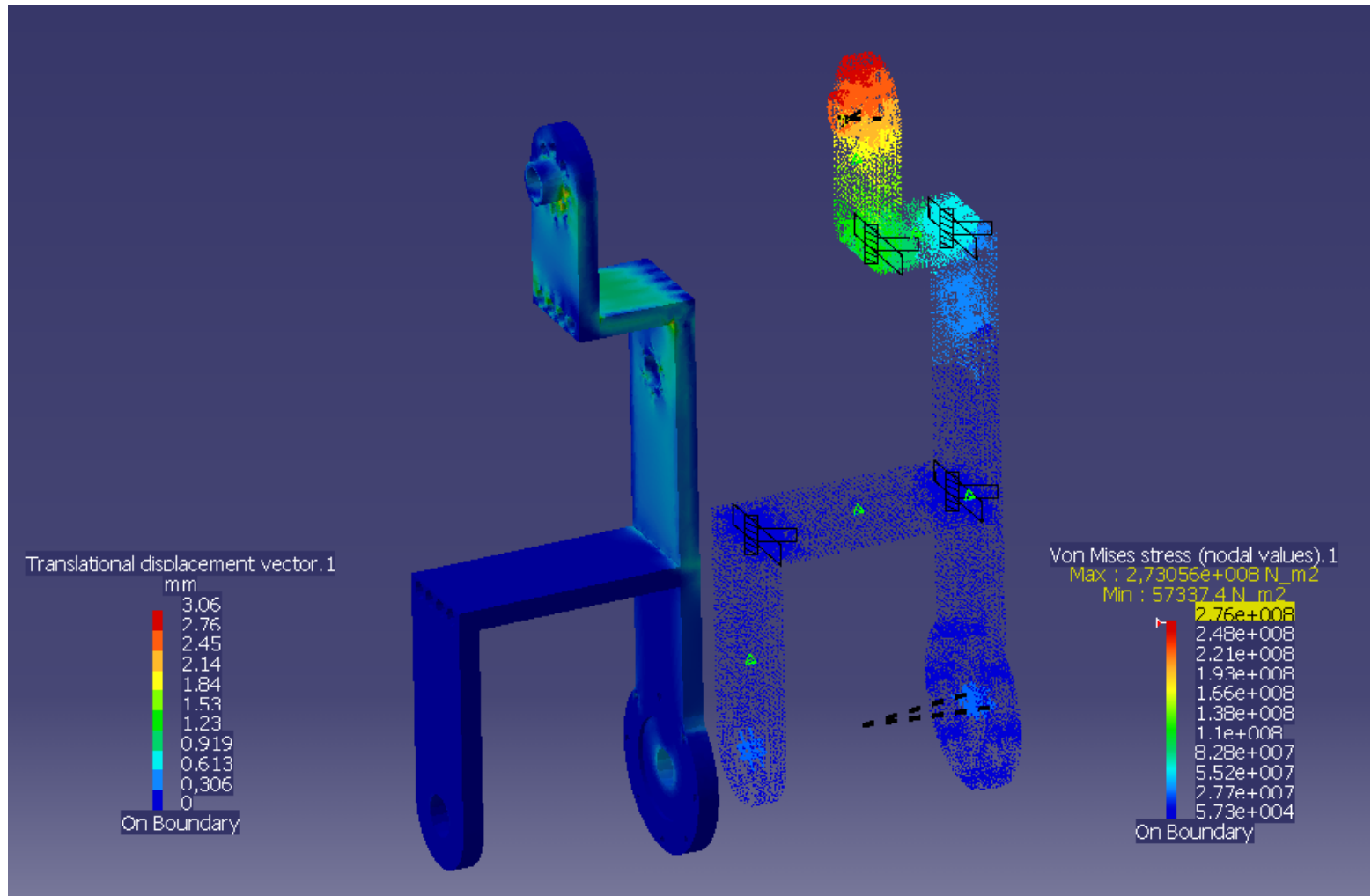
Upper Leg

$$\begin{aligned} F_x &= -80 \text{ N} & F_x &= 230 \text{ N} \\ F_y &= -80 \text{ N} & F_y &= 80 \text{ N} \\ F_z &= -130 \text{ N} & F_z &= 310 \text{ N} \\ N_x &= -44 \text{ Nm} & N_x &= 46 \text{ Nm} \\ N_y &= -35 \text{ Nm} & N_y &= 72 \text{ Nm} \\ N_z &= -30 \text{ Nm} & N_z &= 30 \text{ Nm} \end{aligned}$$

$$\begin{aligned} F_x &= 230 \text{ N} \\ F_y &= 80 \text{ N} \\ F_z &= 310 \text{ N} \\ N_x &= 46 \text{ Nm} \\ N_y &= 72 \text{ Nm} \\ N_z &= 30 \text{ Nm} \end{aligned}$$

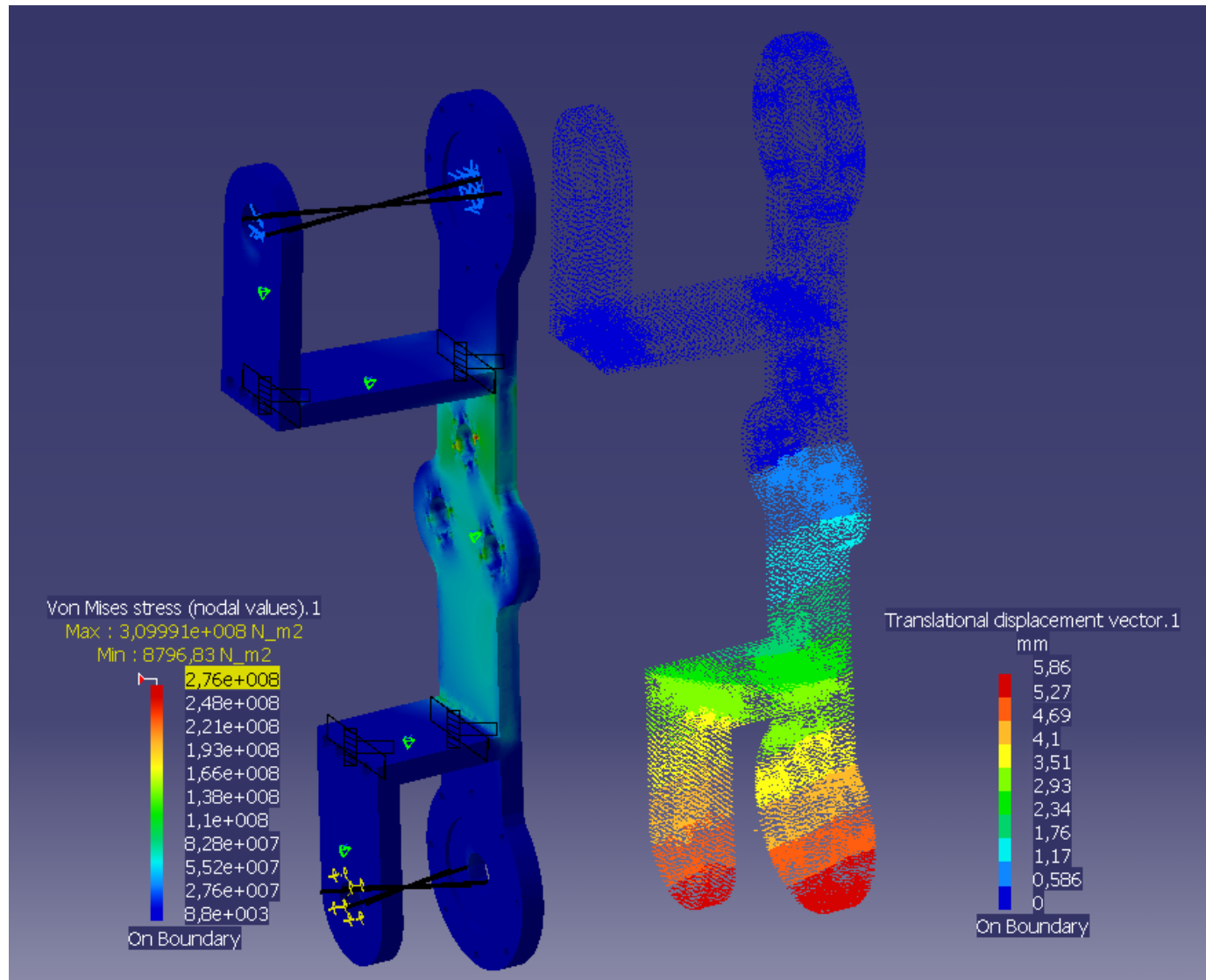
CAE ANALYSIS

Lower Leg

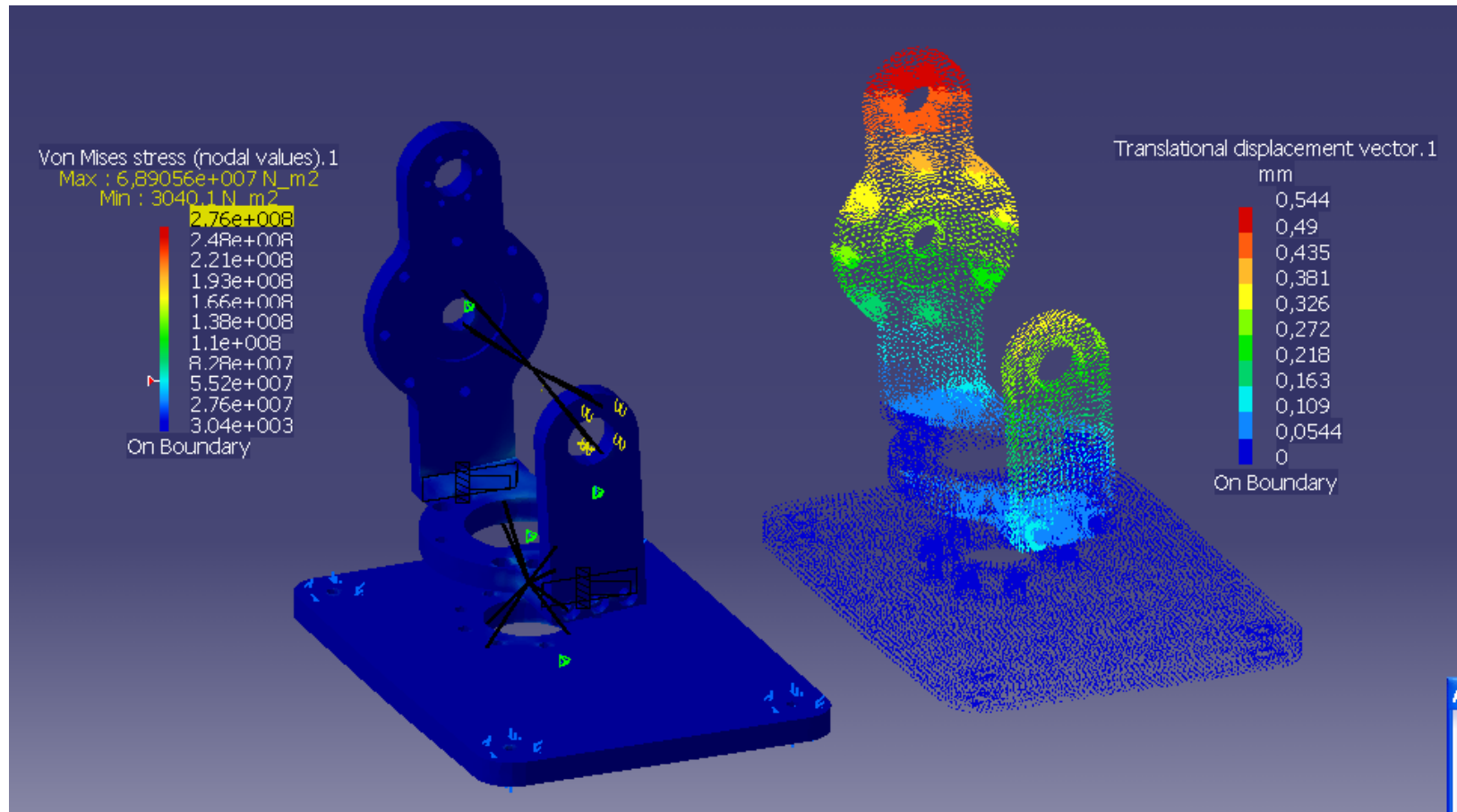


CAE ANALYSIS

Upper Leg

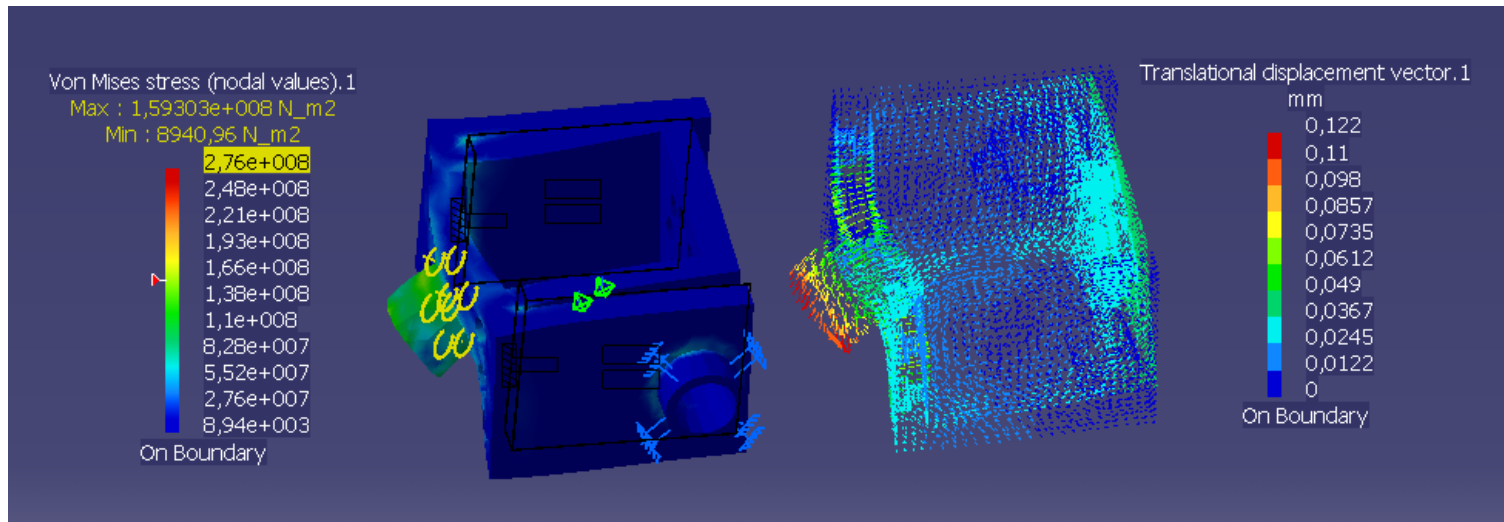


Foot

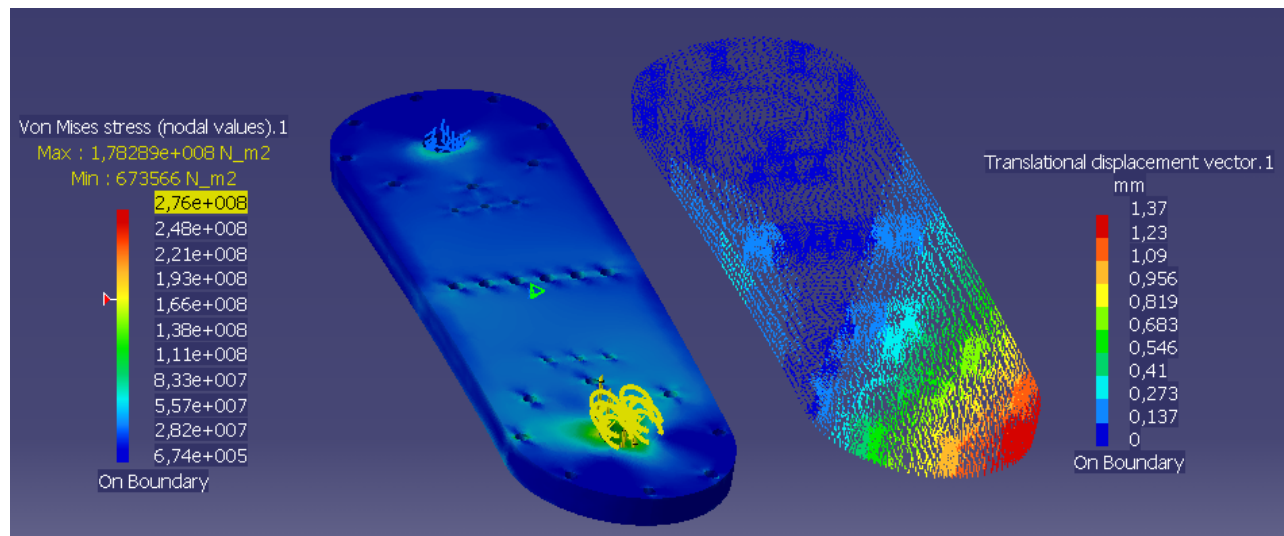


CAE ANALYSIS

Ankle Part

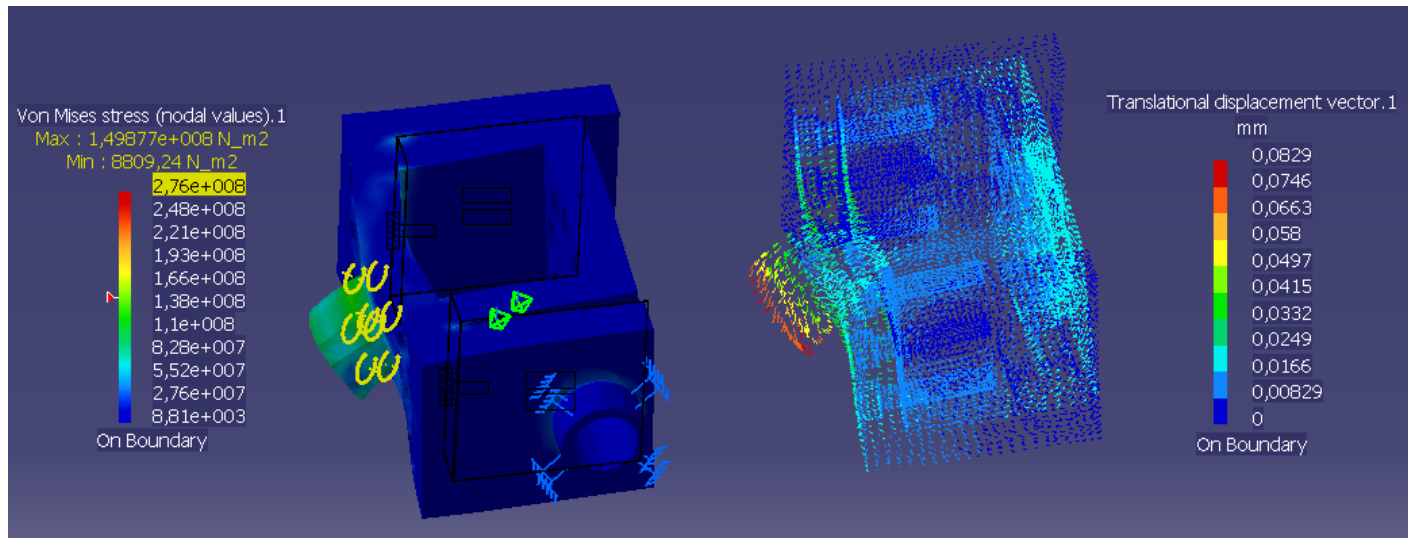


Body

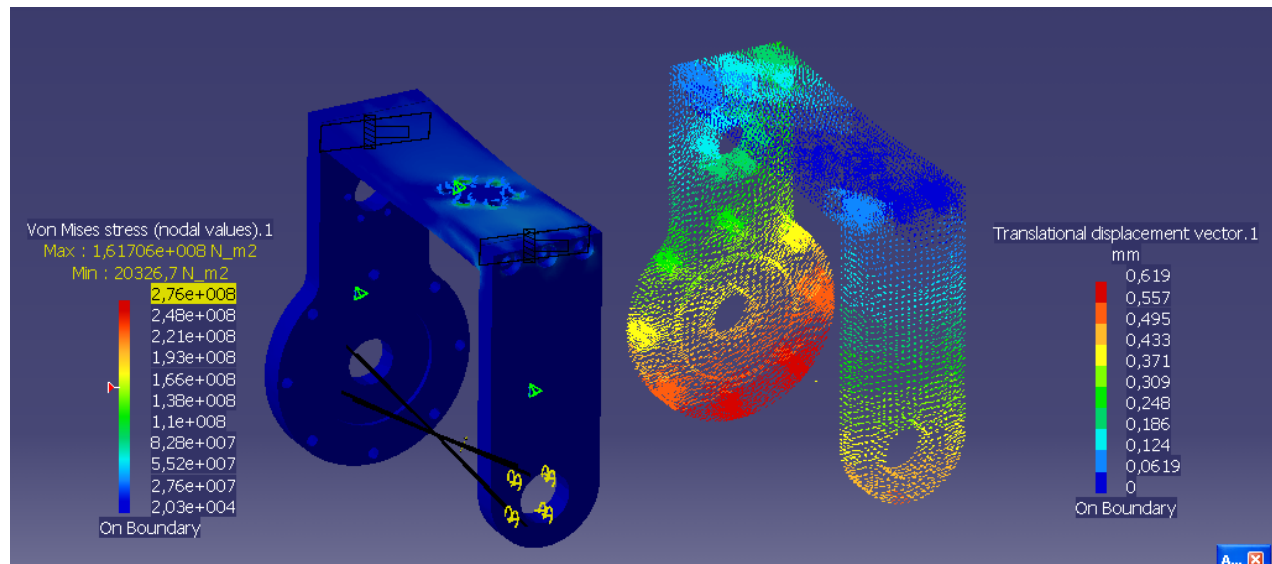


CAE ANALYSIS

Hip Part 1



Hip Part 2



MODIFIED DESIGN

