Robotics Exoskeleton for Load Transportation

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Abstract

Exploiting mechanical advantages from carefully designed machines to help us accomplish otherwise impossible tasks is the heart and soul of mechanical engineering. With the help of modern-day technology, machines can lift millions of times more weight than humans ever could. However, in many situations, human labor input is still needed due to different constraints. Since lifting heavy objects constantly will lead to fatigue in short term and lumbar spine injury in long term, there are many exoskeleton robots in the manufacturing logistics industry aimed to tackle this problem and improve the efficiency of lifting and transporting task.

This project aims to develop a mechanical exoskeleton to assist any lifting motion, increase productivity and avoid injury.

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Background and Literature Review

Background on Exoskeleton Robot

The wearable exoskeleton robot is designed to adapt to human natural lifting and walking movement, to provide assistant for the wearer.

There are two main types of assistant method for wearable exoskeleton robot to provide energy for the wearer to perform lifting and transiting task: Passive and Active. While passive exoskeleton does not provide energy directly using actuator such as motor, and active type does.

Passive exoskeletons generally rely on spring-like mechanism to provide energy to lift the wearer, this kind of exoskeleton usually store energy form the bending phase of the lifting cycle and release this energy during the lifting phase. [1] [2] These kinds of machine are usually relatively cheap and light, more adaptive due to its softness, more degree of freedom for the user, and provide higher assistive force the lower the user bend their back. However, the force generated is quite low compared to the active one, and the user needs to actively provide energy to bend the spring in the bending phase of the lifting cycle.

Active exoskeletons have component that will actively provide energy to assist the wearer during the lifting cycle, usually motors in the hip joint to assist the body in lifting tasks. [3] [4] This kind of exoskeletons can provide higher force of assistance but will usually be more heavy and more expensive to manufacture. Comparing commercially available exoskeletons with those in research, the prior generally uses a rigid structure, therefore, the control of these kind of machine is simpler.

Figure 2 BackX Exoskeleton, Passive

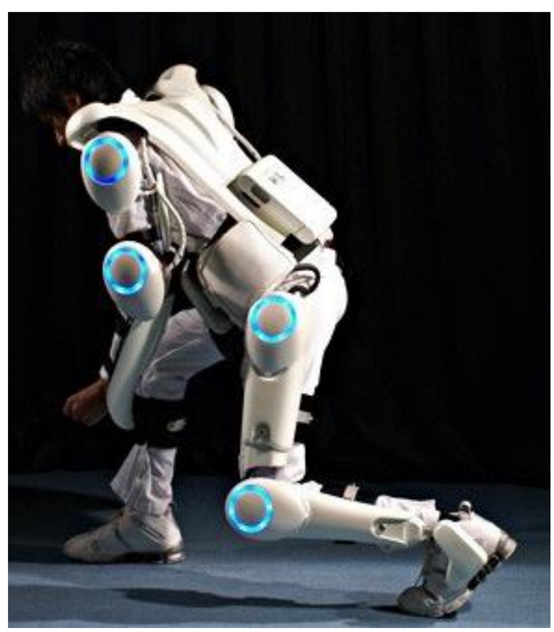

Figure 1 HAL Exoskeleton, Active

Literature Review

This project is a hybrid of both passive and active exoskeleton, where an active novel cable-driven series parallel elastic actuation (SPEA) is used in parallel with a passive flexible elastic beam to try and capture the advantage of both passive and active exoskeleton.

Mechanical Design

The project's mechanical design considers three main factors: comfort of the wearer, lifting effectiveness and weight [5]. The design also tried to put asymmetric lifting into the consideration, where the dynamic of the lateral bending is different than normal bending.

Experimental data shows that in the lifting cycle, maximum torque occurs during the maximum bending angle, and the maximum power occurs before and after the maximum bending.

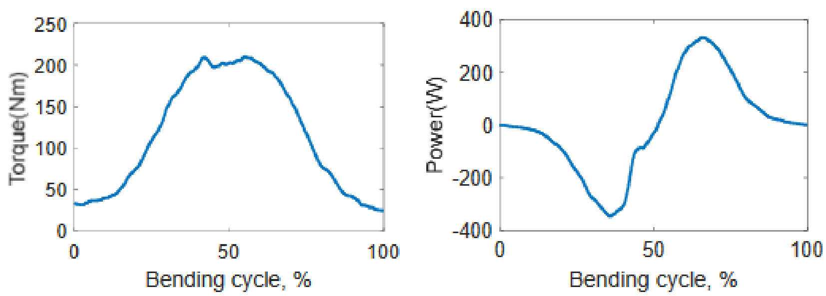

Figure 3 Torque and Power of bending cycle [5]

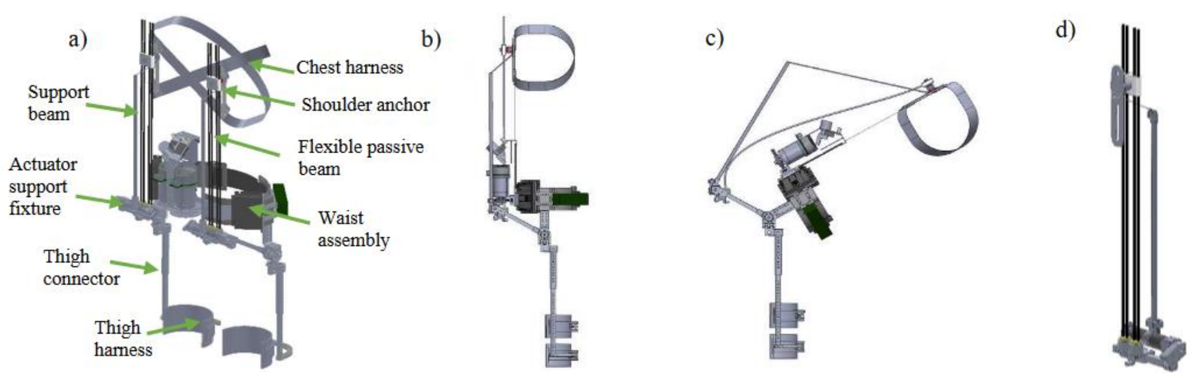

Figure 4 The layout of the design of the exoskeleton [5]

The design composes of 2 parts (passive and active) of assistance system on each side of the hip. A group of flexible passive beam is attached to the back and the lower part of the hip vertically, such that when the wearer bend forward, the beam will spring back and provide resistance torque.

In addition, a motor-driven cable is attached to the back of the wearer and the tip of the support beam and provide torque for the user to lift when the motor is activated.

Such design provides a feedback correction to asymmetric bending and joint misalignment to prevent back and lumbar injury.

The flexible beam and cable attachment also ensure that the wearer can experience relatively higher degree of freedom compared to other rigid active exoskeleton in the market.

Motion Control

To provide adaptive assistance to the lifting motion the control of the motor must closely follow the motion of natural human lifting cycle and walking cycle. Therefore, the main control goal of the system is to minimize hindrance to human motion to maximize comfortability and provide sufficient energy for the task [6].

The exoskeleton has two control mode: transparent mode and assistive mode. The transparent mode provides almost zero torque so that the wearer will experience no hindrance during the walking cycle. While the assistive mode transmits torque for assistance during the lifting motion.

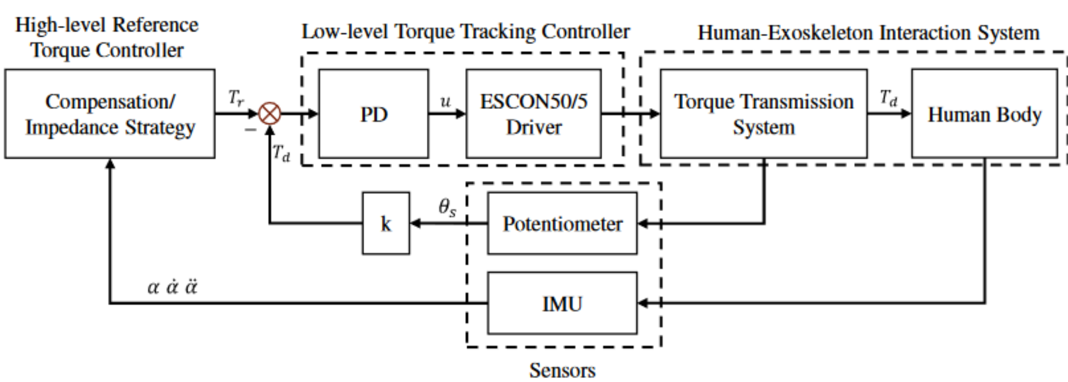

Figure 5 Control Diagram of the exoskeleton

The system will have a high-level controller to decide what mode should the system be undertaking, and the signal will pass to the low-level controller to actualize the torque. An IMU and two angle sensors on the hip is used to sense the human motion and decide the mode of the system.

Problem Definition

Design Problem

The design of the exoskeleton robot provides more degree of freedom by adding a supporting beam and attaching the cable to the tip of said beam and wearer back. However, this decision introduced complexity in the hip joint of the robot and the different mode of the usage also add a layer of mechanical design difficulty.

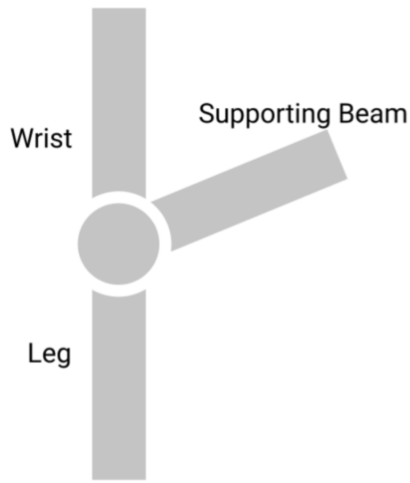

Figure 6 Simplify design, side view

Since the joint required different behavior in different mode, some mechanical part is needed to control or switch the behavior. In Transparent mode, the wrist and supporting beam needs to lock/couple together for the user to freely walk; while in assistive mode, the leg and support beam needed to lock/couple together so that the cable driven system can provide torque to the wearer's back.

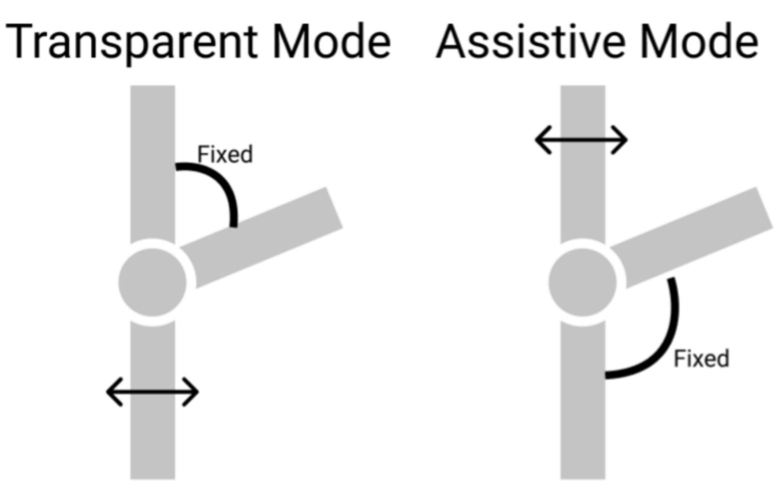

Figure 7 Transparent and Assistive Mode behavior

Past Solution

Last year's student, Andy Wong, of this project proposed 2 solutions.

Spring-based Lock

First is a spring-based joint lock mechanism, where it will lock itself once a certain joint position is reached by the leg and the wrist, and the lock will lock accordingly to produce desired behavior for the hip joint.

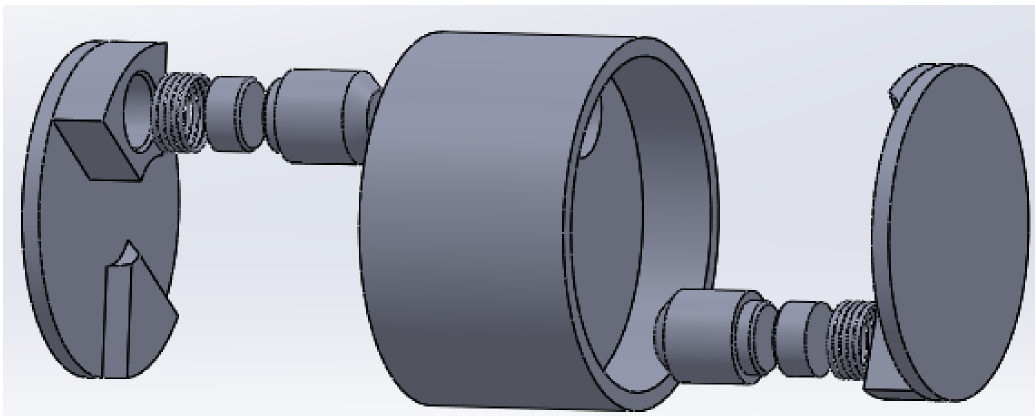

Figure 8 joint lock mechanism [7]

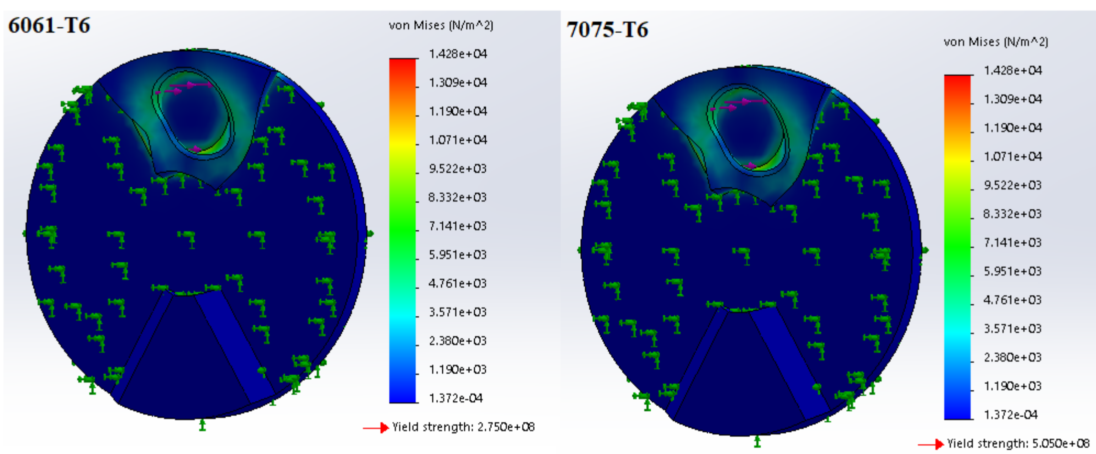

Figure 9 FEM for the joint [7]

However, this design is pure mechanical and cannot be adjusted, the wearer must reach certain joint position for the joint to lock, which is not practical for most of the lifting task. Also, the concentration of the stress also easily causes fatigue and creep and lead to failure.

Sleeve and hub-based Synchronizer

The second design of the student is a sleeve and hub-based synchronizer, inspired by the manual transmission system in automobile.

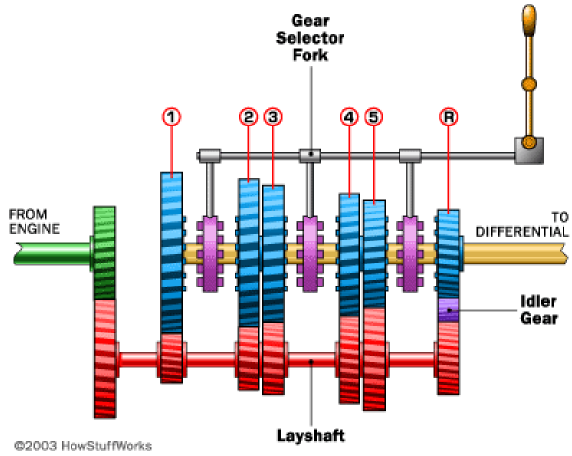

Figure 11 Automobile manual transmission system

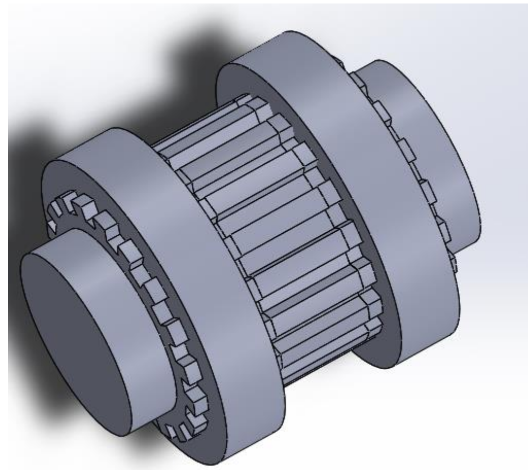

Figure 10 Student's design [7]

For the joint to achieve different behavior, a sleeve will slide between the 3 gears of the three beams, and when the sleeve slide between the leg and the support beam's gear, they will be lock together, same goes for the wrist and the support beam.

This design needed addition control for the sliding motion, but it grant the ability for the joint to be locked in more joint position, more applicable in logistic and manufacturing task.

However, it will be very difficult for the sleeve to slide in during the motion, since the edge of the gear is strictly defined, the sliding motion might cause impact, and lead to material failure. The design is also complex to assemble. If more safety mechanism for smoother transition and fail-safe ability were employed, the joint will become too heavy and large to carry around.

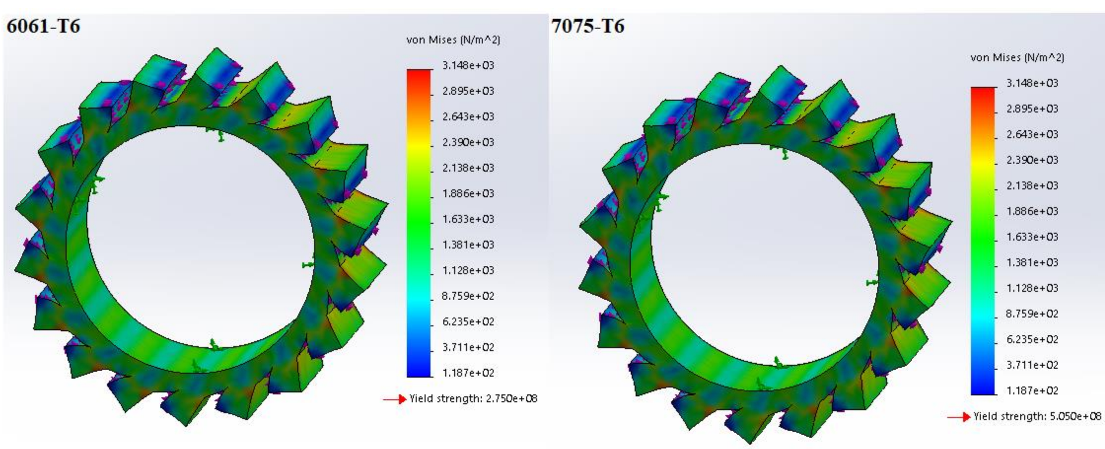

Figure 12 FEM for the gear [7]

Problem Requirement

Basic Requirement

- Design a mechanism to couple the movement of the support beam to the movement of the wrist.
- Light, ideally less than 1kg each side.
- Do not constrain the movement of the wearer
- Able to endure the torque will applied by the cable torque: 50Nm, tension: 250N
- Simple to assemble
- Long Lifetime

Bonus Feature

- Channel some energy to assist leg in lifting motion
- Resistant to sudden movement

Proposed Solution

Linkage-based Lock

The first proposed design is a linkage-based lock, where two linkage is added to the system, the one attached to the support beam will have an extra hole on it, and the support beam will have a switch which when the hole and the switch align and turn on, the linkage will lock in place and coupled with the leg's beam, and ready for the bending and lifting motion. Since the support beam and the back would be close and touch against each other in the walking mode, no lock is needed for it.

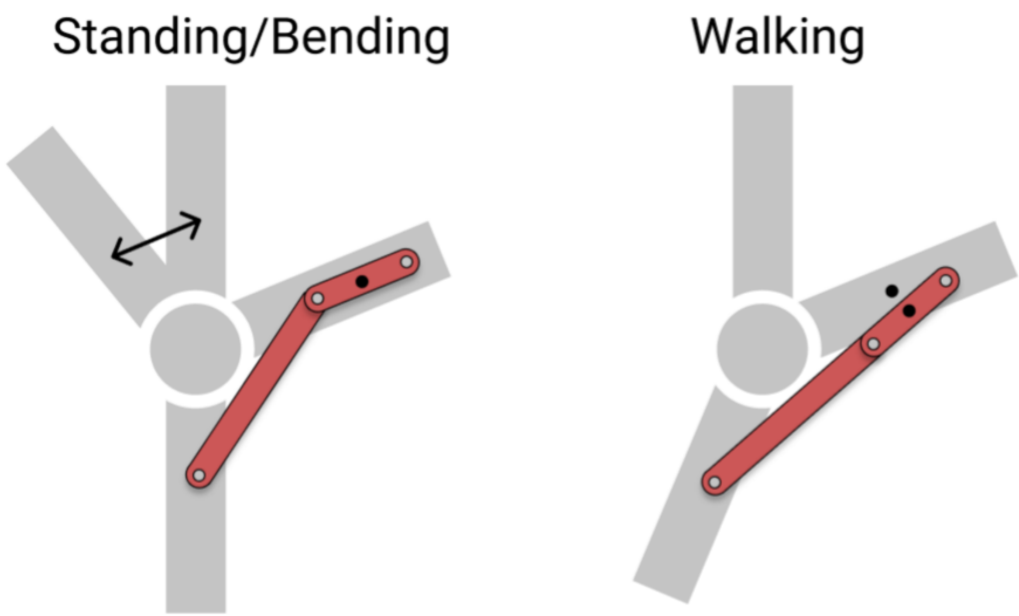

Figure 13 Linkage-based Lock

This Design is rejected due to many of the disadvantage and violation of the requirement.

The extra linkage will constrain the movement of the wearer, the geometry of the linkage will make the leg of the user loose one degree of freedom, only one switch is responsible to hold all the force to hold the support beam in place which easily lead to failure, the wearer can leverage the energy of the cable in only one position.

Some of those problem can be solved with more design part, but they might make part too heavy and large.

Improve Sleeve and hub

Extending the idea of sleeve and hub design, some incremental improvement can be employed to make the design more appropriate.

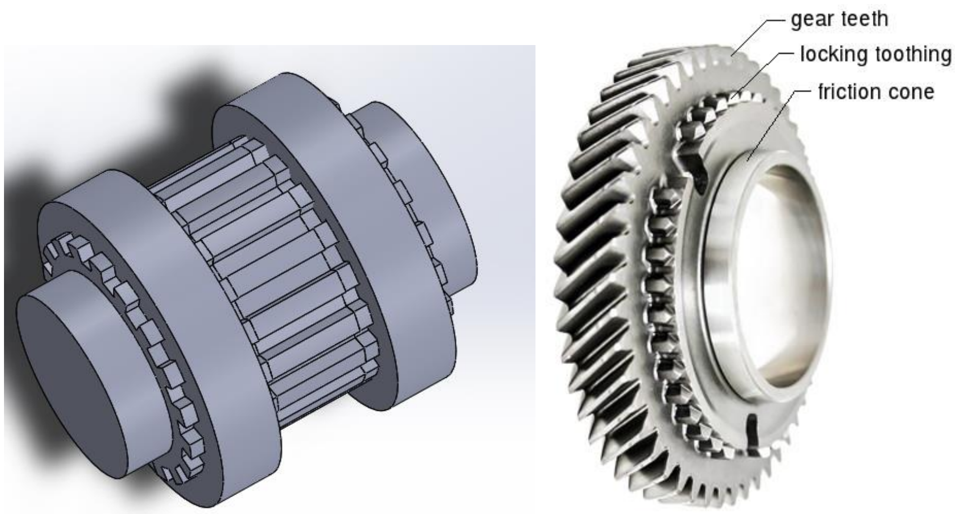

Figure 14 Sleeve and Hub design [7], locking toothing

Also inspired by the design of automobile, the gear inside the joint should have a synchronizing teeth/ locking toothing, where the teeth decrease in width at the edge to provide a smoother transition.

Plus, instead of 2 sleeves, only one sleeve is possible for the design to work, which can decrease the complexity of the design, since the exoskeleton is either in transparent mode or assistive mode.

However, many problems and disadvantage are persisted in the improvement, such as extra actuator is need, heavy and large.

Planetary Gear based Design

Using automobile transmission design as an inspiration again, a planetary gear is added to the design to couple the joint position of the wrist and the support beam. The stock gear box in the market is either too weak or too heavy for our application, therefore, it's beneficial to craft our own gear box to tailor to the application needed.

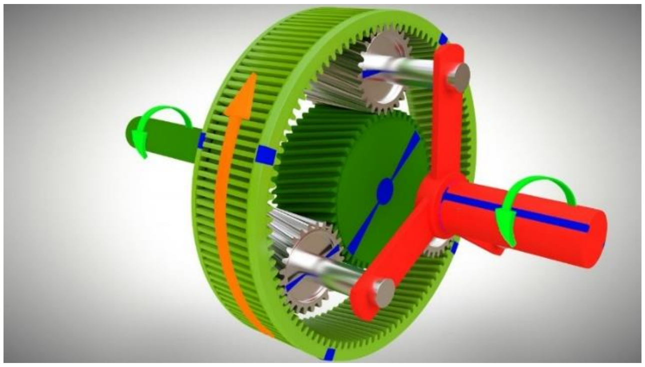

Figure 15 Planetary Gear

Gear Input/Output Choice

In the analysis, we examine only the standing and bending motion of the leg and wrist and the behavior of the supporting beam since we can view walking as small bending. Therefore, we consider the leg as fixed and hence we need to find the desired combination of sun, carrier, ring and leg, wrist, supporting beam.

Fixing the Ring		Fixing the Carrier		Fixing the Sun	
Carrier/Sun	$\boldsymbol{\frac{1}{1+\frac{R}{S}}}$	Ring/Sun	$-\frac{S}{R}$	**Carrier/Ring**	$\boldsymbol{\frac{1}{1+\frac{S}{R}}}$
Sun/Carrier	$1+\frac{R}{S}$	Sun/Ring	$-\frac{R}{S}$	Ring/Carrier	$1+\frac{S}{R}$

Consider the leg is the fixing gear, and the input of the gear is the wrist, and the output of the gear is the supporting beam. We want the supporting beam to go to the same direction as the wrist but slower to avoid collisions. Therefore, the bold one can be our choice.

To further filter combination, we aim the gear ratio to get as close to 1 as possible, since if the output joint is slowed, the torque will also decrease, and we want the transmission of torque not to scale down. Therefore, final choice (blue accented cells):

- Sun: Leg (fixed)
- Ring: Wrist (input)
- Carrier: Supporting Beam (output)

Gear Ratio Selection

Using the KHK stock gear catalog, we can find some pair of planetary that is possible to employ in out design in figure on the right.

To eliminate some possibility of choice, we exclude any gear combination that exceed 10cm in ring radius, to make sure the size of the joint will not be too large, which will constrain the user movement and comfortability resulting with the gear combination in figure at the middle.

Next, we calculate the maximum allowable bending stress of the gear set. We discover that all the gear with 0.5 module can endure very little bending torque, which is not applicable for our needs, therefore, we reject all the gear set with 0.5 module.

Since All the gear ratio is similar, we just choose the two strongest one in each ring size, see figure at the bottom.

Since the gear with 10 gear is too heavy for our needs, we will go for the MSG, sun:24, ring 60 one for our gear box.

Noted that we choose all gear in steel and MSG, which is a higher strong material compared to gear with other material, such as plastic and polymer.

The detail table is in the appendix

Planetary Gear Calculation													MSG	MSG										
module	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
sun teeth	20	24	30	30	40	50	20	30	40	50	60	44	24	20	20	30	30	40	50	20	30	40	50	60
ring teeth	60	60	60	80	80	80	100	100	100	100	100	80	60	60	60	60	80	80	80	100	100	100	100	100
n	5	6	6	5	8	10	4	5	5	6	10	4	6	5	4	6	5	2	2	3	2	5	6	10
planet teeth	20	18	15	25	20	15	40	35	30	25	20	18	18	20	20	15	25	20	15	40	35	30	25	20
Size	OK	OK	OK	OK	OK	OK	Too big	Too big	Too big	Too big	Too big	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK

Figure 17 Gear Ratio table

Planetary Gear Calculation								MSG	MSG											
module	1	1	1	1	1	1	1	1	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
sun teeth	20	24	30	30	40	50	44	24	20	20	30	30	40	50	20	30	40	50	60
ring teeth	60	60	60	80	80	80	80	60	60	60	60	80	80	80	100	100	100	100	100
n	5	6	6	5	8	10	4	6	5	4	6	5	2	2	3	2	5	6	10
Fixing sun																			
ωc/ωr	0.7500	0.7143	0.6667	0.7273	0.6667	0.6154	0.6452	0.7143	0.7500	0.7500	0.6667	0.7273	0.6667	0.6154	0.8333	0.7692	0.7143	0.6667	0.6250
Torque (experience by leg and back)																			
τs/τr	-0.3333	-0.4000	-0.5000	-0.3750	-0.5000	-0.6250	-0.5500	-0.4000	-0.3333	-0.3333	-0.5000	-0.3750	-0.5000	-0.6250	-0.2000	-0.3000	-0.4000	-0.5000	-0.6000
τr/τc	1.3333	1.4000	1.5000	1.3750	1.5000	1.6250	1.5500	1.4000	1.3333	1.3333	1.5000	1.3750	1.5000	1.6250	1.2000	1.3000	1.4000	1.5000	1.6000
Planet																			
	16	14	15	22	15	13	31	14	16	20	15	22	60	65	40	65	28	25	16
Evenly?	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly
	22	20	17	27	22	17	20	20	22	12	9.5	14.5	12	9.5	22	19.5	17	14.5	12
	23.5114101	21	22.5	32.3281889	22.9610059	20.0861046	43.8406204	21	23.5114101	14.1421356	11.25	16.1640944	30	32.5	25.9807621	32.5	20.5724838	18.75	12.3606798
Possible?	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible
Bending Strength																			
Ring	30	30	30	38.8	38.8	38.8	38.8	30	30	3.75	3.75	4.85	4.85	4.85	5.97	5.97	5.97	5.97	5.97
Sun	5.75	7.47	10.1	10.1	14.7	19.5	16.6	18.5	14.2	0.72	1.27	1.27	2.38	2.43	0.72	1.27	2.38	2.43	3.03
Planet	5.75	4.91	3.69	7.91	5.75	3.69	4.91	12.1	14.2	0.72	0.46	0.99	0.72	0.46	2.38	No Such Gear	1.27	0.99	0.72
Bending torque (Nm)																			
ring	150	180	180	194	310.4	388	155.2	180	150	15	22.5	24.25	9.7	9.7	17.91	11.94	29.85	35.82	59.7
sun	86.25	112.05	121.2	134.666667	235.2	312	120.727273	277.5	213	8.64	15.24	16.9333333	9.52	7.776	10.8	8.466666667	29.75	29.16	50.5
planet	86.25	98.2	88.56	126.56	184	196.8	87.2888889	242	213	8.64	11.04	15.84	5.76	4.90666667	17.85	0	21.1666667	23.76	36
allowable torque	**86.25**	**98.2**	**88.56**	**126.56**	**184**	**196.8**	**87.2888889**	**180**	**150**	**8.64**	**11.04**	**15.84**	**5.76**	**4.90666667**	**10.8**	**0**	**21.1666667**	**23.76**	**36**
	115	**137.48**	**132.84**	**174.02**	**276**	**319.8**	**135.297778**	**252**	**200**	**11.52**	**16.56**	**21.78**	**8.64**	**7.97333333**	**12.96**	**0**	**29.6333333**	**35.64**	**57.6**

Figure 16 List of possible gear ratio

Planetary Gear Calculation		MSG
module	1	1
sun teeth	50	24
ring teeth	80	60
n	10	6
Fixing sun		
ωc/ωr	0.6154	0.7143
Torque (experience by leg and back)		
τs/τr	-0.6250	-0.4000
τr/τc	1.6250	1.4000
Planet		
	13	14
Evenly?	Evenly	Evenly
	17	20
	20.0861046	21
Possible?	Possible	Possible
Bending Strength		
Ring	38.8	30
Sun	19.5	18.5
Planet	3.69	12.1
Bending torque (Nm)		
ring	388	180
sun	312	277.5
planet	196.8	242
allowable torque	**196.8**	**180**
	319.8	**252**
Weight		
ring	0.35	0.28
sun	0.22	0.038
planet	0.044	0.02
Total	**1.01**	**0.438**

Figure 18 Last 2 candidate

Visualization

Before the static analysis, one more proposal is added in the design.

We add one more arm at the leg beam, which is parallel to the supporting beam direction. When the wearer is standing, the two beams are parallel and when the user bend, there will be some angular difference. We can then pass the cable to the extra arm of the leg beam, which can provide some counter torque to decrease the load of the gear set.

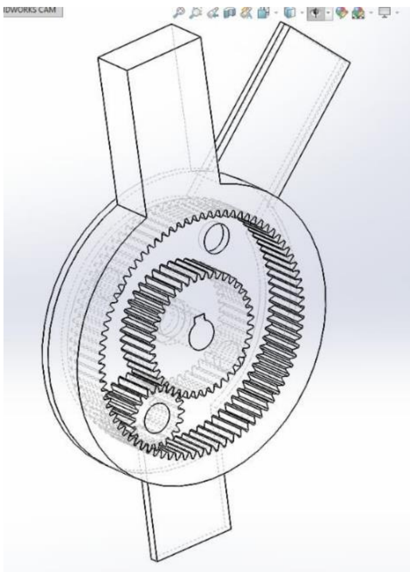

Figure 19 Design concept Wireframe

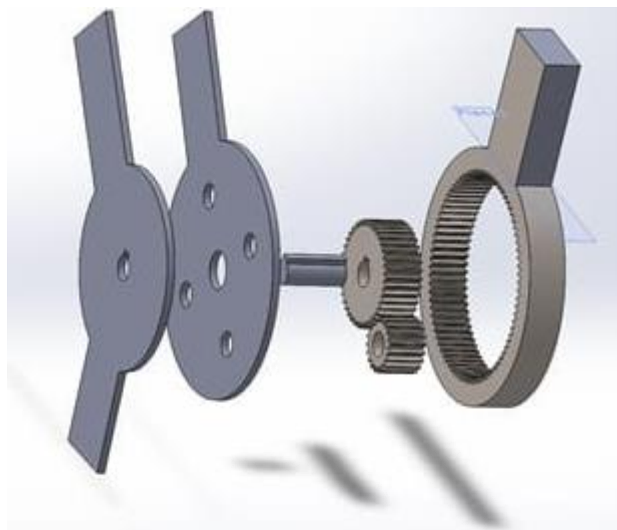

Figure 20 Design Concept Model

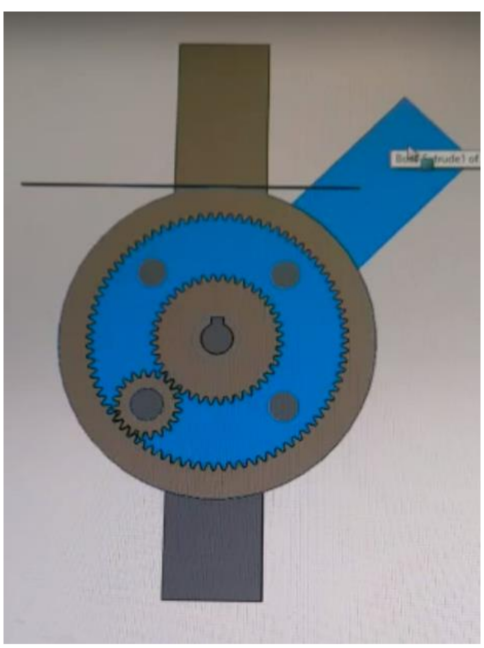

Figure 21 Wearer standing

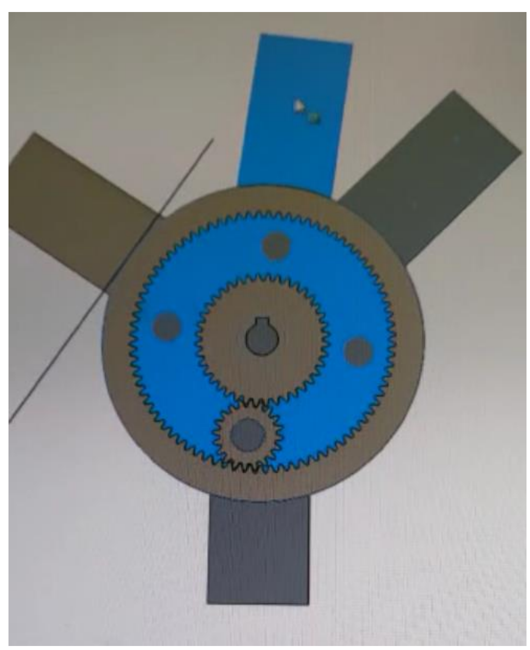

Figure 22 Wearer Bending

Using this design, we can have the gear box experience torque in both direction that will cancel each a part of each other. This can help to reduce the torque that the gear box endure, and hopefully allow the system have longer life span.

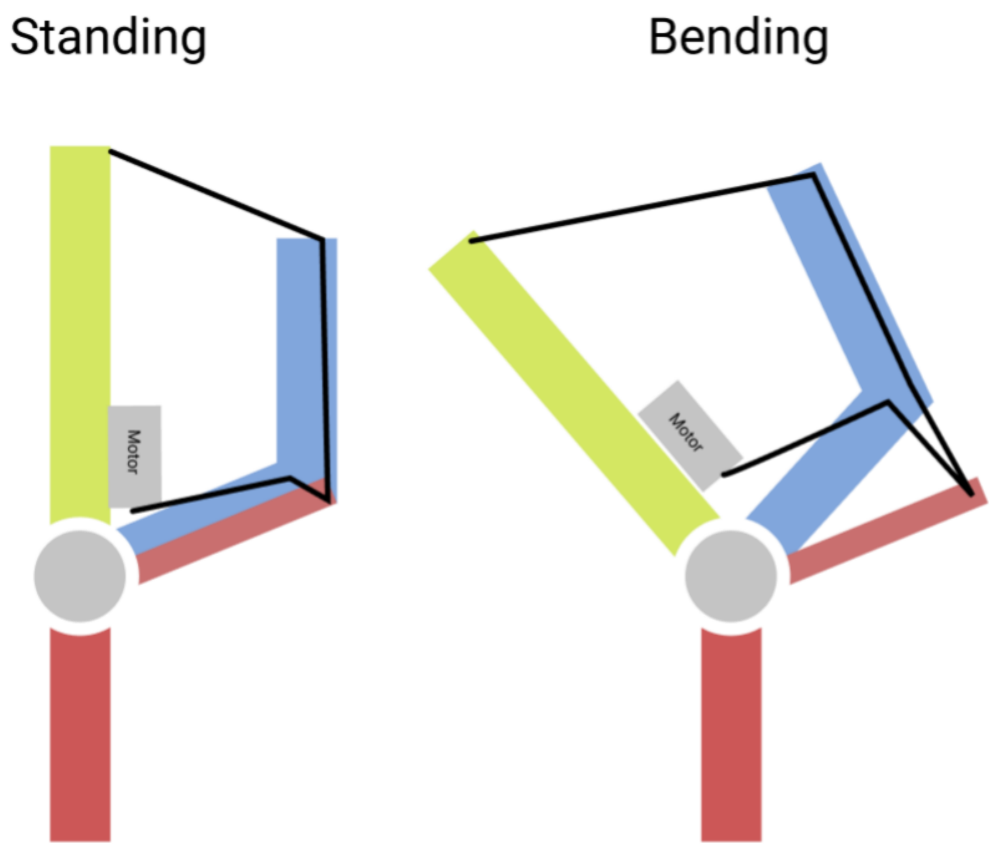

Figure 23 Bi-directional Design

Static Analysis

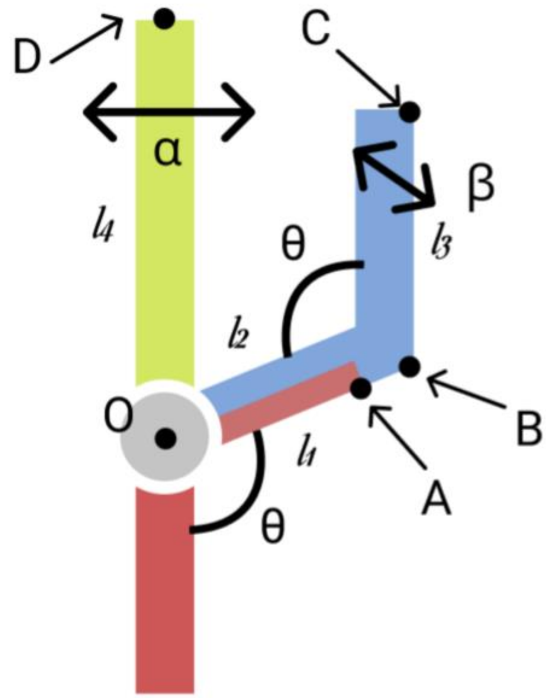

Figure 24 Analytic Drawing

Using the Planetary gear analysis:

$$\beta = \frac{1}{1+\frac{S}{R}} \cdot \alpha$$

Using Vector Method to find all the point:

$$\begin{aligned}
\vec{OA} &= r\theta z(l_1, \theta - \frac{\pi}{2} \qquad\quad , 0) \\
\vec{OB} &= r\theta z(l_2, \theta - \frac{\pi}{2} + \beta \quad , 0) \\
\vec{OC} &= r\theta z(l_3, \beta + \frac{\pi}{2} \qquad\quad , 0) + \vec{OB} \\
\vec{OD} &= r\theta z(l_4, \alpha + \frac{\pi}{2} \qquad\quad , 0)
\end{aligned}$$

And:

$\vec{AB} = \vec{OB} - \vec{OA}$, $\vec{DC} = \vec{OC} - \vec{OD}$

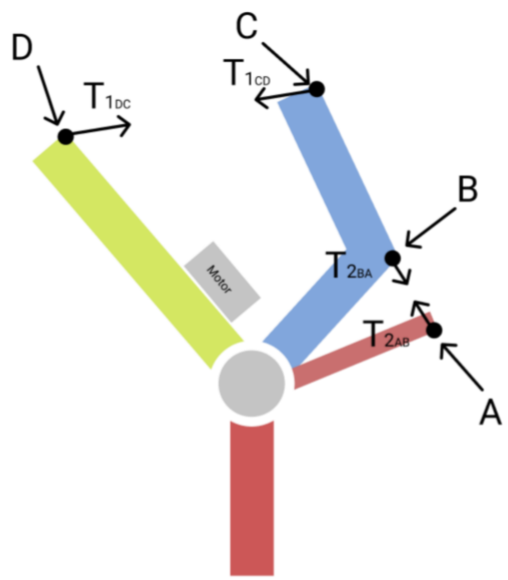

Figure 25 Force and Torque Analysis

Using force and torque analysis, we can find the torque experience by the wrist and leg:

$$\vec{T_{1_{DC}}} = T\frac{\vec{DC}}{|\vec{DC}|}$$
$$\tau_{wrist} = \vec{OD} \times \vec{T_{1_{DC}}}$$
$$\vec{T_{2_{AB}}} = 2T\frac{\vec{AB}}{|\vec{AB}|}$$
$$\tau_{leg} = \vec{OA} \times \vec{T_{2_{AB}}}$$

And the torque experience by the beam:

$$\tau_{Beam_1} = \vec{OC} \times -\vec{T_{1_{DC}}}$$
$$\tau_{Beam_2} = \vec{OB} \times -\vec{T_{2_{AB}}}$$
$$\tau_{Beam} = \tau_{Beam_1} + \tau_{Beam_2}$$

Plus, the force experience by the joint:

$$F_{T_1} = \frac{-\vec{T_{1_{DC}}} \cdot -\vec{OC}}{|-\vec{OC}|} \cdot \frac{-\vec{O}C}{|-\vec{OC}|}$$
$$F_{T_2} = \frac{-\vec{T_{2_{AB}}} \cdot -\vec{OB}}{|-\vec{OB}|} \cdot \frac{-\vec{O}B}{|-\vec{OB}|}$$
$$F_T = F_{T_1} + F_{T_2}$$

Simulation

Using MATLAB for simulation[1]:

Dimension	
l1	0.1m
l2	0.2m
l3	0.3m
l4	0.8m
theta	120 degree
sun teeth	24
ring teeth	60
Tension	250N

Figure 26 Simulation Dimension and data

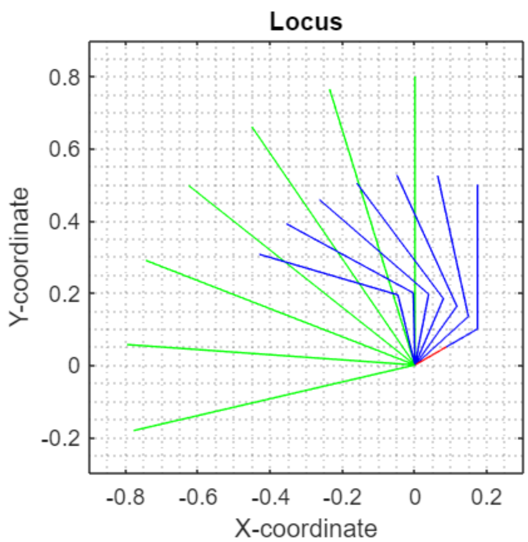

Figure 27 Locus of different linkage of the robot

We can see that the torque the gear set (beam) experienced is decreasing due to the bi-directional torque.

The torque peek at 100Nm at 0 degree, however, this will not be the case in real application, since there shall be little to no force form the cable during standing phase, this simulation overestimates the force for safety purposes.

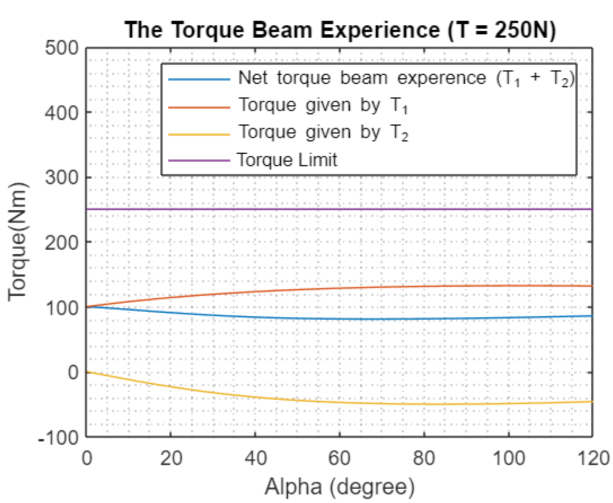

Figure 29 Torque the Beam (the gear set) experience

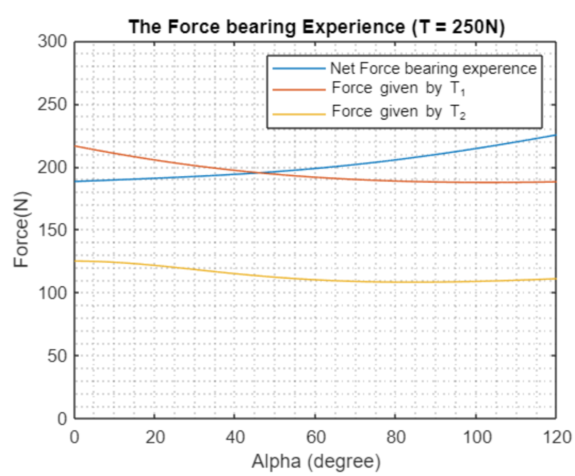

Figure 28 Force the joint experience

[1] The back height is taken as 80cm, rounded from average man 82cm http://macoshdesign.com/en/theory/articles/anthropometrical

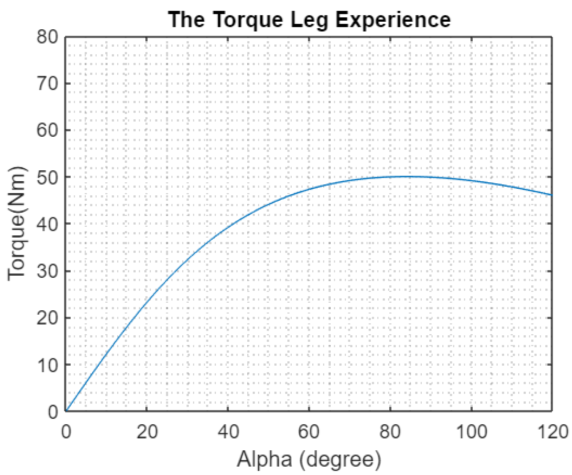

Figure 30 Torque Leg Experience against bending angle

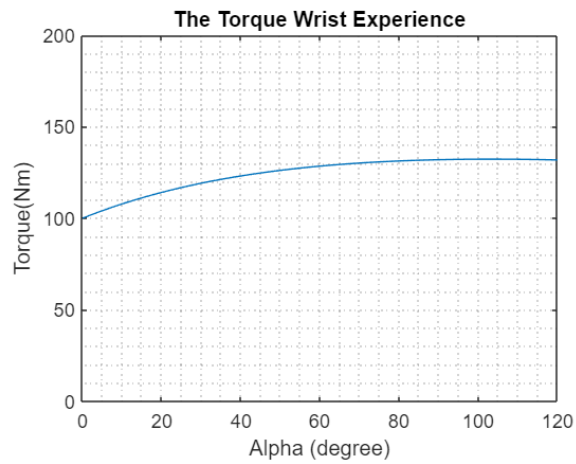

Figure 31 Torque Wrist Experience against bending angle

We can change the length ratio of linkage 1 and linkage 2 to produce different torque-alpha curve. From Figure 32, we discover that the closer the ratio, the faster it rises to peak torque, therefore, if we want the system to be sensitivity, we can adjust the length to be close; on the other hand, if we want the system to be less sensitive to small change, we can increase the length of linkage 2.

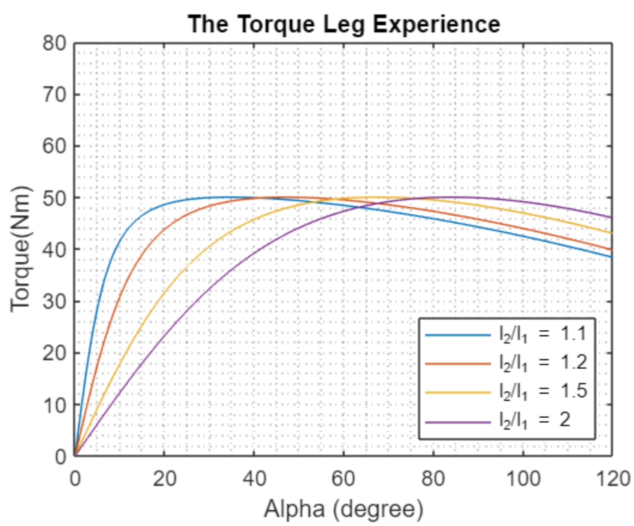

Figure 32 Different ratio that the leg experience

Result

If we use this design:

- planetary gear set,
- sun MSG spur gear 24 teeth
- planet MSG spur gear 18teeth
- ring steel internal gear 60 teeth
- the leg beam extends an extra arm for bi-directional torque

We can achieve:

- Coupled movement of the supporting beam and the bending angle
- 250Nm maximum allowable torque
    - 100Nm maximum torque in operation
    - ~2.5 factor of safety
- Weight around 0.6-0.8 kg each side
- Around 5kg in total
- Does not significantly constrain wearer's movement
- Simple to assemble
- Long lifetime due to low torque utilization of metal gear

Compare with all the exoskeleton on the market:

Manufacturer	Name	Weight	Assistive force
Ours	Ours	~5kg	100Nm
HAL	HAL Lumber type for Labour Support[2]	3.1kg	unstated
Innophys	Muscle Suit[3]	6.6kg	140Nm
ATOUN	Model Y[4]	4.5kg	78Nm

[2] https://www.cyberdyne.jp/english/products/Lumbar_LaborSupport.html
[3] https://innophys.jp/en/product/power/
[4] https://atoun.co.jp/en/products/atoun-model-y/

Mechanical Design

Gear Box Design

As discussed at previous section, the gear ratio we will be using is as following:

Gear	Ring	Sun	Planet
No. of Teeth	60	24	18
Bore Diameter (mm)	\	10	8
Width w/ hub (mm)	\	15	15

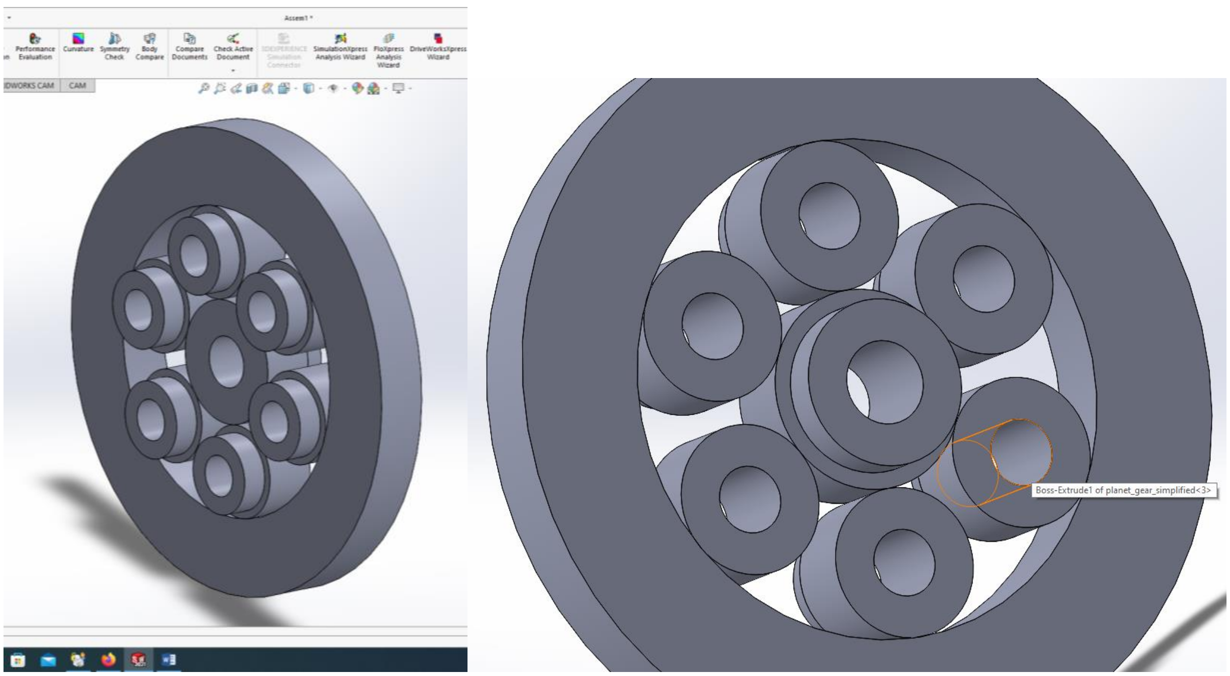

Figure 33 Simplified 3D model for the planetary gear set

The Bearing Placing

Since the gear box required high payload and constant movement, therefore we need to use bearing to lighten the contact damage on the gear and the shaft.

The first idea is to stack the bearings and directly put them into the bore of the gear, however, since the bore size of the gear small, that mean the shaft inside will be even thinner, which might not be able to withstand the load of the gear box.

Therefore, we need to employ a rod inside the bore hole of the gear.

Yellow: rod;

Green: bearing, 8mm bore, 16 outer diameter, 5mm thickness;

Orange: Carrier

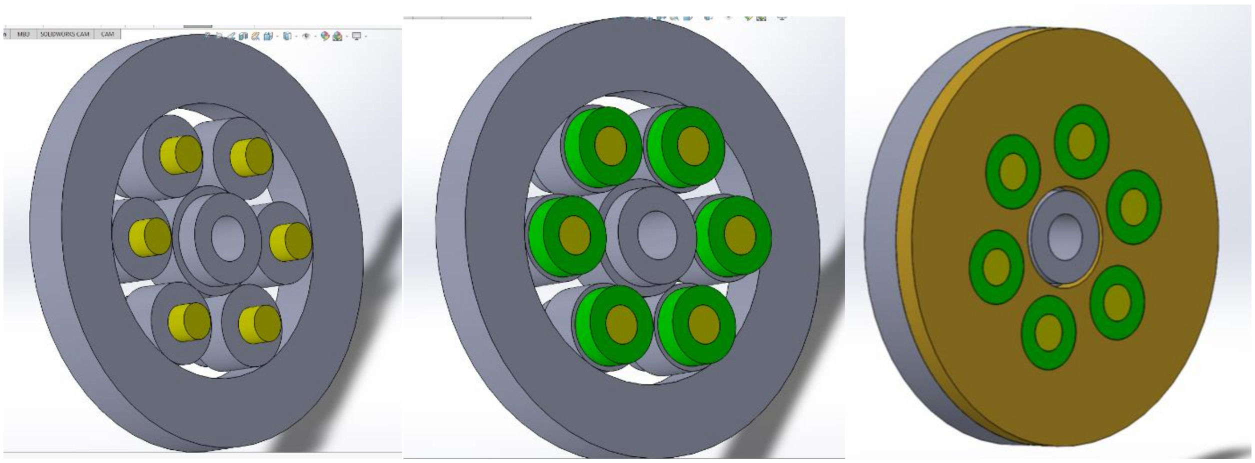

Figure 34 Simplify 3D model for the gear box assemble

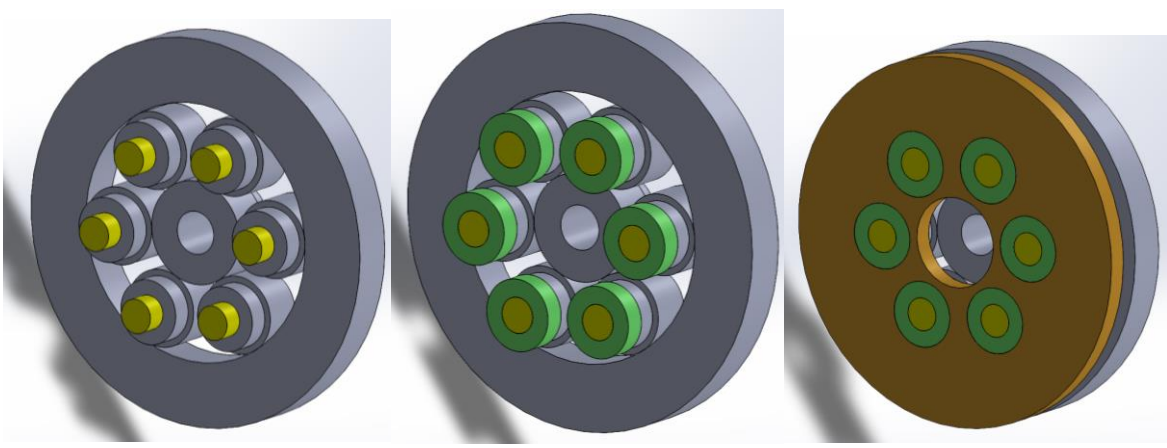

Figure 35 Simplify 3D model for the gear box assemble 2

The first assemble is chosen since, the second one leaves some gap in between, which is a waste of space and it allow for unexpected object to fall in and cause malfunction of the gear box.

The detail Assemble of the Gear Box

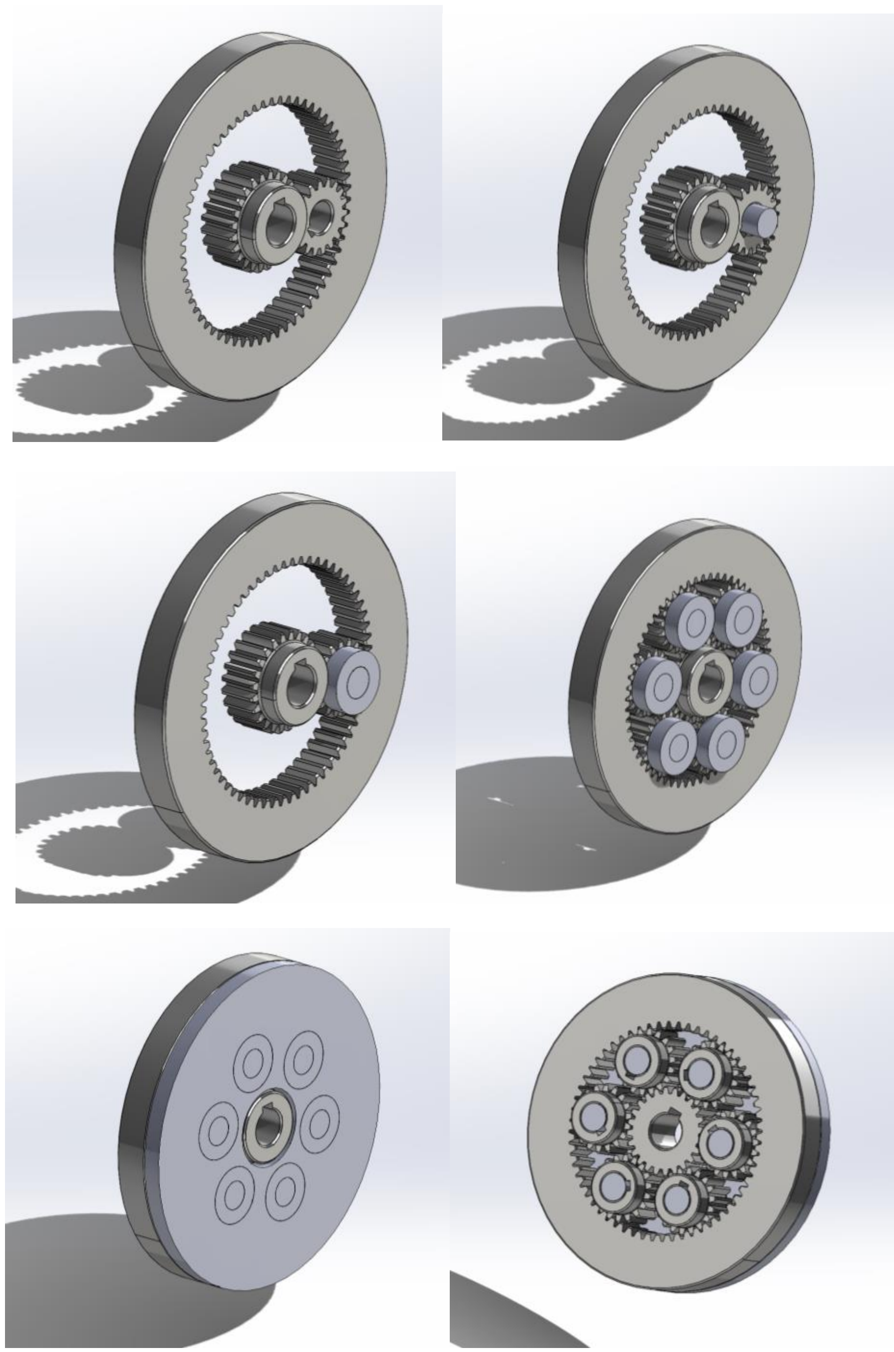

Figure 36 The detail assembles of the gear box

The Input Output Design

Design Challenge

Unlike other gear set, planetary have 3 input/output gear which we utilize to produce different position for our three beams.

In usual use case of the planetary gear, like the automatic transmission gear set, there are only 2 shaft that connected to the outside of the gear box, the input shaft, and the output shaft.

Figure 37 Automatic Transmission Gear

However, in our design all, three of the components: sun, ring and the carrier needed to connect to outside. Also, we need to fix the gear box in place horizontally.

Design Draft

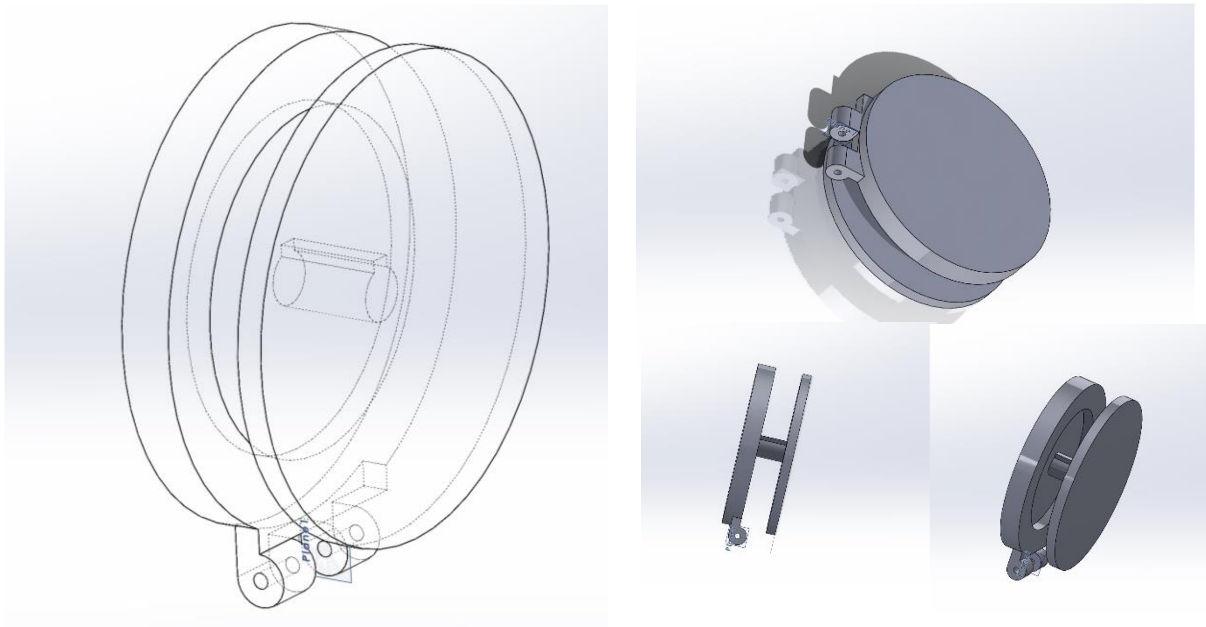

Figure 38 Sun's Rod design

The design of the sun's shaft consist of a rod connecting the two shell, which will sandwich the gear set and keep them in place while not interfere with the motion freedom of the three beam. This provide a compact design for the whole joint.

However, it is impossible to assemble, thus we needed to divide this part into 2 separate part and create some locking mechanism for ease of assembling.

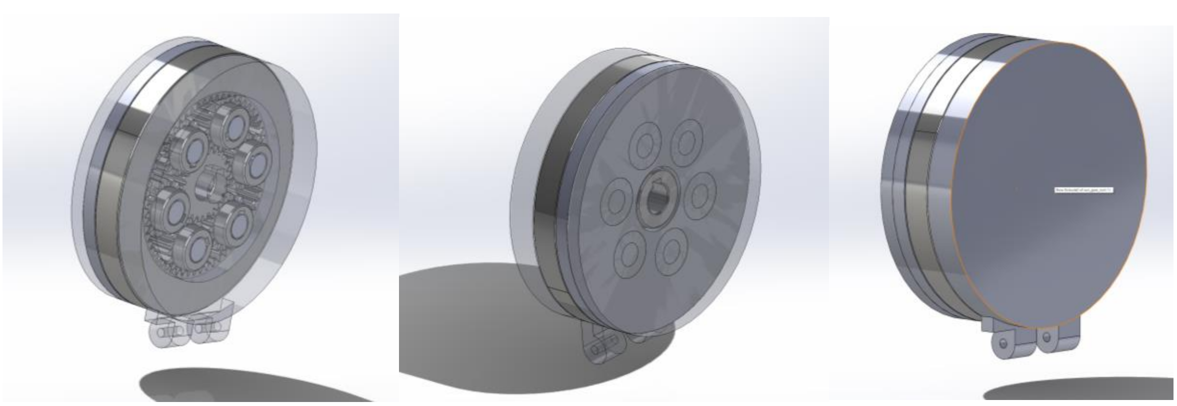

Figure 39 Assemble

Detail Design

The design of the shell will be two part: the base and the cap, which will be held together by a M3 screw. This locking mechanism is simple and easy to manufacture. And since there are little to no force load act on it, a single M3 screw should be able to keep the shell together.

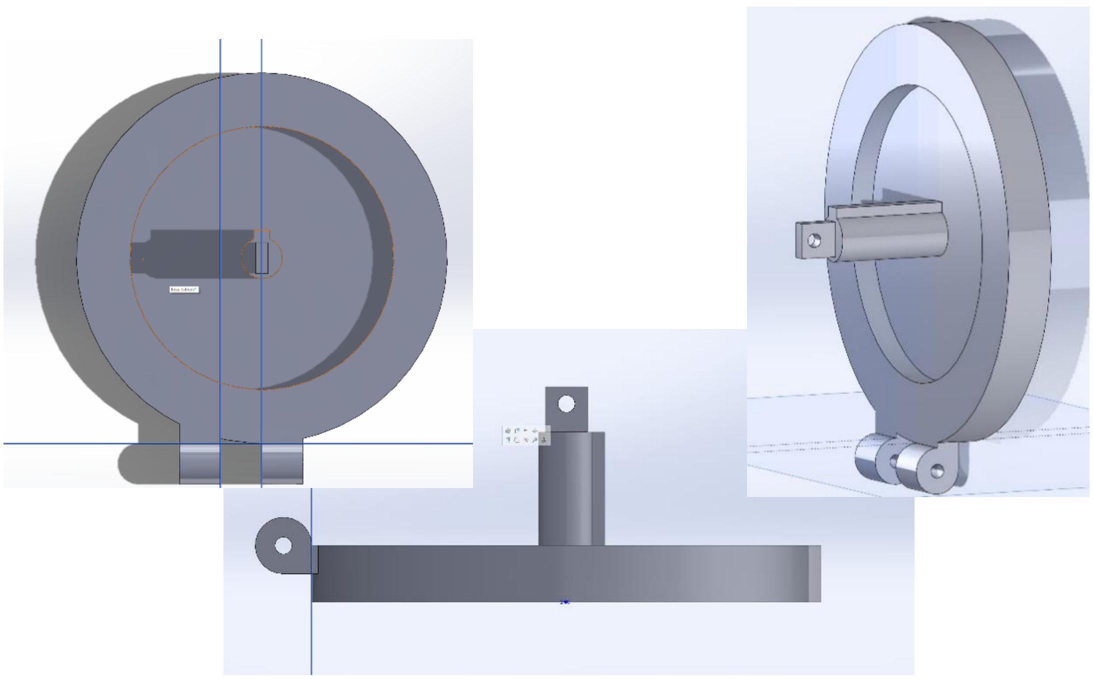

Figure 40 The Base's 3D model

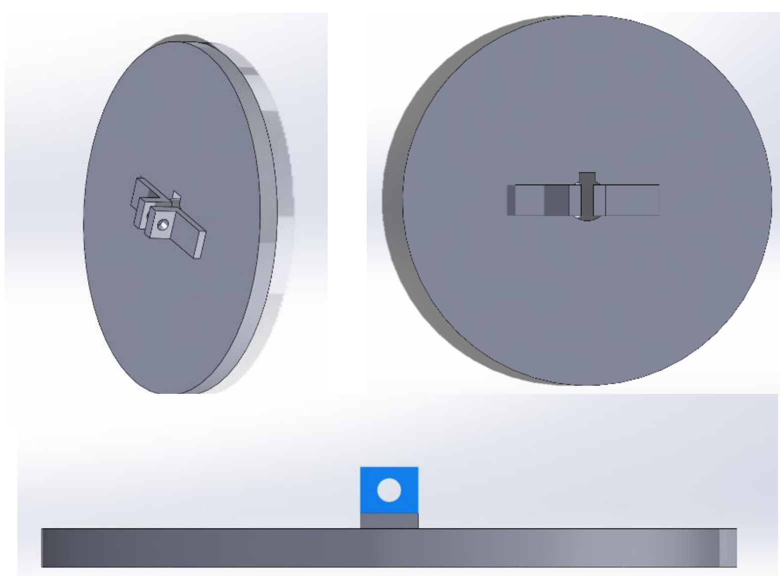

Figure 41 The Cap's 3D model

The Assemble

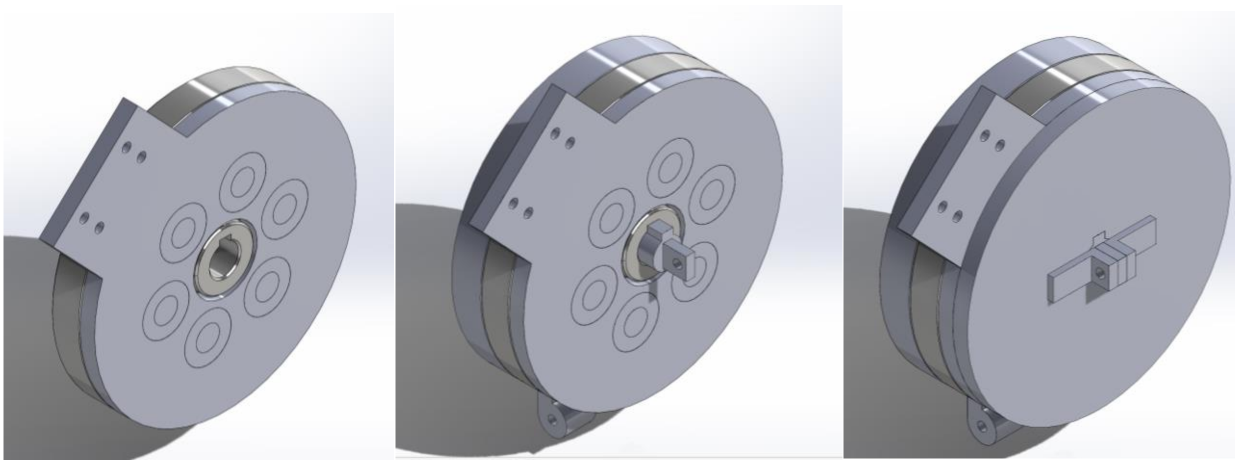

Figure 42 The Full Assemble of the joint

Improvement

Size

The current design is 90mm in diameter which is the size of the factory premade ring gear's size. We can decrease the size and the weight of the design if we can decrease the thickness of the ring gear (form the teeth to the outside diameter), this will allow the whole system to shrink down. However, this might cost some structural change of the ring gear, which might decrease the workload of the gear set.

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[1] S. Emily Chang, et al, "Design and preliminary evaluation of a flexible exoskeleton to assist with lifting," *Wearable Technologies,* vol. 1 , 2020.

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[3] H. Hara and Y. Sankai, "Development of HAL for lumbar support," *SCIS & ISIS 2010: Japan Society for Fuzzy Theory and Intelligent Informatics,* pp. 416-421, 2010.

[4] "ATOUN MODEL Y," ATOUN, [Online]. Available: https://atoun.co.jp/en/products/atoun-. [Accessed 30 11 2021].

[5] H. L. F. G. X. Z. a. W.-H. L. Hugo Hung-tin Chan, "A Back-Support Exoskeleton with a Cable-Driven," in *International Conference on Mechatronics and Automation*, Takamatsu, Japan, August 8 - 11, 2021.

[6] H. H.-t. C. F. G. X. Z. a. W.-H. L. Hongpeng Liao, "Design and Characterization of a Cable-Driven Series Elastic Actuator Based Torque Transmission for Back-Support Exoskeleton," in *International Conference on Mechatronics and Automation*, Takamatsu, Japan, August 8 - 11, 2021.

[7] A. Wong, "Robotics Exoskeleton for Load Transportation," 2020-2021.

Appendix

Spur Gear							
Series	module	no. of teeth	Pitch Diameter (mm)	Bending Strength (Nm)	Surface Durability (Nm)	Weight (kg)	Remark
SS	0.5	15	7.5	0.460	0.022	0.006	
SS	0.5	20	10	0.720	0.040	0.010	
SS	0.5	25	12.5	0.990	0.064	0.014	
SS	0.5	30	15	1.270	0.093	0.012	
SS	0.5	50	25	2.430	0.270	0.037	
SS	0.5	60	30	3.030	0.390	0.058	
SS	1	15	15	3.690	0.170	0.044	
SS	1	18	18	4.910	0.260	0.057	
SS	1	20	20	5.750	0.330	0.037	
SS	1	24	24	7.470	0.490	0.055	
SS	1	25	25	7.910	0.540	0.055	
SS	1	30	30	10.100	0.790	0.089	
SS	1	35	35	12.400	1.090	0.120	
SS	1	40	40	14.700	1.450	0.160	
SS	1	44	44	16.600	1.770	0.180	
SS	1	50	50	19.500	2.320	0.220	
SS	1	60	60	24.200	3.400	0.290	
SSG	0.5	30	15	1.630	0.290	0.012	
SSG	0.5	40	20	2.380	0.550	0.230	
SSG	0.5	50	25	3.140	0.890	0.037	
SSG	0.5	60	30	3.910	1.320	0.058	
SSG	1	15	15	2.960	1.030	0.016	
SSG	1	20	20	4.600	1.940	0.034	
SSG	1	25	25	6.330	3.070	0.048	
SSG	1	30	30	8.110	4.480	0.072	
SSG	1	40	40	9.830	6.790	0.120	
SSG	1	50	50	13.000	10.800	0.180	
SSY	1	15	15	2.220	0.110	0.012	
SSY	1	20	20	3.450	0.200	0.024	
SSY	1	25	25	4.740	0.320	0.033	
SSY	1	30	30	6.080	0.470	0.061	
SSY	1	40	40	8.840	0.870	0.092	
SSY	1	50	50	11.70	1.39	0.130	
MSG	1	18	18	12.10	6.37	0.020	
MSG	1	20	20	14.200	6.370	0.027	
MSG	1	24	24	18.500	12.000	0.038	
MSG	1	25	25	19.600	13.100	0.038	
MSG	1	30	30	25.100	19.000	0.065	
MSG	1	40	40	36.500	34.600	0.110	
MSG	1	50	50	48.100	55.100	0.180	

Figure 43 KHK stock gear spec

Internal Gear (Steel S45C)							
module	no. of teeth	Pitch Diameter (mm)	Outside Diameter (mm)	Bending Strenght (Nm)	Surface Durability (Nm)	Preesure Angle	Weight(kg)
0.5	60	30	50	3.75	0.67	20	0.05
0.5	80	40	60	4.85	0.75	20	0.06
0.5	100	50	70	5.97	0.87	20	0.07
1	60	60	90	30.00	5.95	20	0.28
1	80	80	110	38.80	6.59	20	0.35
1	100	100	130	47.80	7.64	20	0.43

Figure 44 KHK Internal Gear Spec

Specifications	
Precision grade	JIS grade N8 (JIS B1702-1: 1998)*
Gear teeth	Standard full depth
Pressure angle	20°
Material	S45C
Heat treatment	—
Tooth hardness	(less than 194HB)
Surface treatment	Black oxide coating

Figure 45 SS (steel spur gear) material Spec

Specifications	
Precision grade	JIS grade N5 (JIS B1702-1: 1998)
Gear teeth	Standard full depth
Pressure angle	20°
Material	SCM415
Heat treatment	Carburized
Tooth hardness	55 to 60HRC

Figure 46 MSG material Spec

Planetary Gear Calculation													MSG	MSG										
module	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
sun teeth	20	24	30	30	40	50	20	30	40	50	60	44	24	20	20	30	30	40	50	20	30	40	50	60
ring teeth	60	60	60	80	80	80	100	100	100	100	100	80	60	60	60	60	80	80	80	100	100	100	100	100
n	5	6	6	5	8	10	4	5	5	6	10	4	6	5	4	6	5	2	2	3	2	5	6	10
planet teeth	20	18	15	25	20	15	40	35	30	25	20	18	18	20	20	15	25	20	15	40	35	30	25	20
Size	OK	OK	OK	OK	OK	OK	Too big	Too big	Too big	Too big	Too big	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Dimension (mm)																								
sun diameter	20	24	30	30	40	50	20	30	40	50	60	44	24	20	10	15	15	20	25	10	15	20	25	30
planet diameter	20	18	15	25	20	15	40	35	30	25	20	18	18	20	10	7.5	12.5	10	7.5	20	17.5	15	12.5	10
ring Diameter	60	60	60	80	80	80	100	100	100	100	100	80	60	60	30	30	40	40	40	50	50	50	50	50
Fixing sun																								
ωc/ωr	0.7500	0.7143	0.6667	0.7273	0.6667	0.6154	0.8333	0.7692	0.7143	0.6667	0.6250	0.6452	0.7143	0.7500	0.7500	0.6667	0.7273	0.6667	0.6154	0.8333	0.7692	0.7143	0.6667	0.6250
ωr/ωc	1.3333	1.4000	1.5000	1.3750	1.5000	1.6250	1.2000	1.3000	1.4000	1.5000	1.6000	1.5500	1.4000	1.3333	1.3333	1.5000	1.3750	1.5000	1.6250	1.2000	1.3000	1.4000	1.5000	1.6000
Fixing Ring																								
ωc/ωs	0.2500	0.2857	0.3333	0.2727	0.3333	0.3846	0.1667	0.2308	0.2857	0.3333	0.3750	0.3548	0.2857	0.2500	0.2500	0.3333	0.2727	0.3333	0.3846	0.1667	0.2308	0.2857	0.3333	0.3750
ωs/ωc	4.0000	3.5000	3.0000	3.6667	3.0000	2.6000	6.0000	4.3333	3.5000	3.0000	2.6667	2.8182	3.5000	4.0000	4.0000	3.0000	3.6667	3.0000	2.6000	6.0000	4.3333	3.5000	3.0000	2.6667
Fixing Carrier																								
ωr/ωs	-0.3333	-0.4000	-0.5000	-0.3750	-0.5000	-0.6250	-0.2000	-0.3000	-0.4000	-0.5000	-0.6000	-0.5500	-0.4000	-0.3333	-0.3333	-0.5000	-0.3750	-0.5000	-0.6250	-0.2000	-0.3000	-0.4000	-0.5000	-0.6000
ωs/ωr	-3.0000	-2.5000	-2.0000	-2.6667	-2.0000	-1.6000	-5.0000	-3.3333	-2.5000	-2.0000	-1.6667	-1.8182	-2.5000	-3.0000	-3.0000	-2.0000	-2.6667	-2.0000	-1.6000	-5.0000	-3.3333	-2.5000	-2.0000	-1.6667
Torque (experience by leg and back)																								
τs/τr	-0.3333	-0.4000	-0.5000	-0.3750	-0.5000	-0.6250	-0.2000	-0.3000	-0.4000	-0.5000	-0.6000	-0.5500	-0.4000	-0.3333	-0.3333	-0.5000	-0.3750	-0.5000	-0.6250	-0.2000	-0.3000	-0.4000	-0.5000	-0.6000
τs/τc	0.2500	0.2857	0.3333	0.2727	0.3333	0.3846	0.1667	0.2308	0.2857	0.3333	0.3750	0.3548	0.2857	0.2500	0.2500	0.3333	0.2727	0.3333	0.3846	0.1667	0.2308	0.2857	0.3333	0.3750
τr/τc	1.3333	1.4000	1.5000	1.3750	1.5000	1.6250	1.2000	1.3000	1.4000	1.5000	1.6000	1.5500	1.4000	1.3333	1.3333	1.5000	1.3750	1.5000	1.6250	1.2000	1.3000	1.4000	1.5000	1.6000
Planet																								
	16	14	15	22	15	13	30	26	28	25	16	31	14	16	20	15	22	60	65	40	65	28	25	16
Evenly?	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly	Evenly
	22	20	17	27	22	17	42	37	32	27	22	20	20	22	12	9.5	14.5	12	9.5	22	19.5	17	14.5	12
	23.5114101	21	22.5	32.3281889	22.9610059	20.0861046	42.4264069	38.2060414	41.1449677	37.5	24.7213595	43.8406204	21	23.5114101	14.1421356	11.25	16.1640944	30	32.5	25.9807621	32.5	20.5724838	18.75	12.3606798
Possible?	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible
Bending Strength																								
Ring	30	30	30	38.8	38.8	38.8	47.8	47.8	47.8	47.8	47.8	38.8	30	30	3.75	3.75	4.85	4.85	4.85	5.97	5.97	5.97	5.97	5.97
Sun	5.75	7.47	10.1	10.1	14.7	19.5	5.75	10.1	14.7	19.5	24.2	16.6	18.5	14.2	0.72	1.27	1.27	2.38	2.43	0.72	1.27	2.38	2.43	3.03
Planet	5.75	4.91	3.69	7.91	5.75	3.69	14.7	12.4	10.1	7.91	5.75	4.91	12.1	14.2	0.72	0.46	0.99	0.72	0.46	2.38	No Such Gear	1.27	0.99	0.72
Bending torque (Nm)																								
ring	150	180	180	194	310.4	388	191.2	239	239	286.8	478	155.2	180	150	15	22.5	24.25	9.7	9.7	17.91	11.94	29.85	35.82	59.7
sun	86.25	112.05	121.2	134.666667	235.2	312	115	168.333333	183.75	234	403.333333	120.727273	277.5	213	8.64	15.24	16.9333333	9.52	7.776	10.8	8.466666667	29.75	29.16	50.5
planet	86.25	98.2	88.56	126.56	184	196.8	147	177.142857	168.333333	189.84	287.5	87.2888889	242	213	8.64	11.04	15.84	5.76	4.90666667	17.85	0	21.1666667	23.76	36
allowable torque	**86.25**	**98.2**	**88.56**	**126.56**	**184**	**196.8**	**115**	**168.333333**	**168.333333**	**189.84**	**287.5**	**87.2888889**	**180**	**150**	**8.64**	**11.04**	**15.84**	**5.76**	**4.90666667**	**10.8**	**0**	**21.1666667**	**23.76**	**36**
	115	**137.48**	**132.84**	**174.02**	**276**	**319.8**	**138**	**218.833333**	**235.666667**	**284.76**	**460**	**135.297778**	**252**	**200**	**11.52**	**16.56**	**21.78**	**8.64**	**7.97333333**	**12.96**	**0**	**29.6333333**	**35.64**	**57.6**
Weight																								
ring	0.28	0.28	0.28	0.35	0.35	0.35	0.43	0.43	0.43	0.43	0.43	0.35	0.28	0.28	0.05	0.05	0.06	0.06	0.06	0.07	0.07	0.07	0.07	0.07
sun	0.037	0.055	0.089	0.089	0.16	0.22	0.037	0.089	0.16	0.22	0.29	0.18	0.038	0.027	0.01	0.012	0.012	0.23	0.037	0.01	0.012	0.23	0.037	0.058
planet	0.037	0.057	0.044	0.055	0.037	0.044	0.16	0.12	0.089	0.055	0.037	0.057	0.02	0.027	0.01	0.0056	0.014	0.01	0.0056	0.23	No Such gear	0.012	0.014	0.01
Total	**0.502**	**0.677**	**0.633**	**0.714**	**0.806**	**1.01**	**1.107**	**1.119**	**1.035**	**0.98**	**1.09**	**0.758**	**0.438**	**0.442**	**0.1**	**0.0956**	**0.142**	**0.31**	**0.1082**	**0.77**	**No such Gear**	**0.36**	**0.191**	**0.228**

Figure 47 Planetary Gear Calculation

All the Internal Gear are Steel

All the Spur Gear are Steel, expect if “MSG” is stated in the first row, then it will be using MSGA/MSGB material.

Table of Figure