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EXOSKELETON FOR KNEE ARTHRITIS PATIENTS

Mahatwa Kumar[1] and Kimberly Bowal[#]

[1]Delhi Public School International, New Delhi, Delhi, India
[#]Advisor

ABSTRACT

Nearly 23 percent of the US adult population suffers from arthritis and patients of knee arthritis find it extremely painful to sit down or stand from a sitting position. In this research paper I have endeavoured to design a total knee support exoskeleton to assist people suffering from knee arthritis. High torque DC and servo motors were used in the model which can be controlled using a Bluetooth remote control or app. The choice of motors was based on the torque that is borne by the knee when the leg or thigh move. The model lends support to both the thigh and the lower leg and helps in motion of sitting, standing and lying down. The present model has been developed keeping in mind considerations of portability, affordability and commercial viability. The model has been conceptualized after making calculations on torque about the knee, and successfully reduces the metabolic cost of moving the leg or thigh. This exoskeleton will assist a wide population being lightweight, portable, and affordable and uses electrical parts to maximize the reduction in torque.

Additional materials

- 3D Design file of the exoskeleton in: .stl format
- Projected view drawings
- Parts list
- Working of the exoskeleton
- Upper leg servo animation
- Lower leg DC motor animation
- Video showing process of designing the exoskeleton

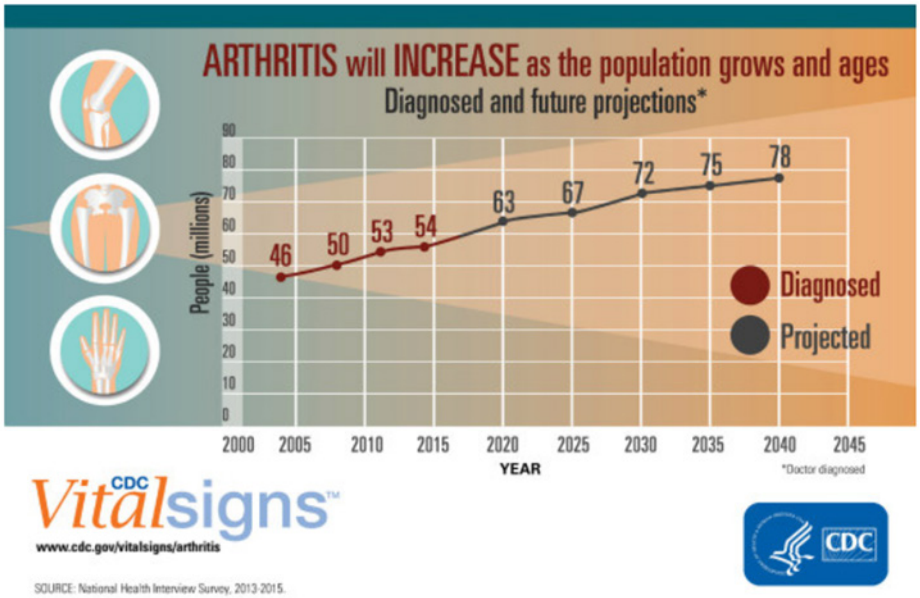


Figure 1: Chart showing us adult population diagnosed with and pro-jected to suffer from arthritis [1]

Motivation and problem statement

The idea of developing an exoskeleton device for assisting knee arthritis patients occurred to me during my visit to my grandmother, who underwent knee replacement surgeries in both her knees. I witnessed the discomfort she experiences while carrying out simple everyday tasks of sitting and standing to the extent of even going on outings seem too much of a hassle for her. She would take support of crutches or a walker frame or in absence of these a simple shopping trolley.

From 2013–2015, an estimated 54.4 million US adults (22.7 percent) (See figure 1) annually have been told by a doctor that they had some form of arthritis, rheumatoid arthritis, gout, lupus, or fibromyalgia. By 2040, an estimated 78 million (26 percent) US adults aged 18 years or older are projected to have doctor-diagnosed arthritis. Arthritis is a common joint disease involving pain in joints. Common symptoms of arthritis include swelling, pain, stiffness and decreased range of motion. People who suffer from arthritis have limited bending or functionality of their joints and face difficulties and a lot of pain in doing so. Therefore, my project is targeting a specific category of arthritis, i.e., knee arthritis. I hope to design an exoskeleton which will assist patients in performing their day-to-day tasks and help them in walking and bending (sitting down and standing up) without any pain or suffering.

Background

Figure 2: Replaced knee joint diagram [2]

Total knee replacement surgery (total knee arthroplasty) – Patients who suffer from a very severe case of knee arthritis cannot be treated with non-surgical methods. In this case, the patients might consider to undergo a complete knee joint replacement surgery. (See figure 2) The surgery involves cutting the arthritically damaged ends of the tibia (shin bone) and femur (thighbone) and capping both with prostheses (like capping teeth). These two pieces are either made of a very durable plastic (polyethylene) or metal. This provides the patients with relief in their pain, but again limit some of the functionality of the human knee which may put too much strain on it. Such activities include jogging which is not an option for such patients.

Partial knee replacement surgery (unicompartmental knee arthroplasty) – Partial knee replacement, often called unicompartmental knee replacement, involves replacing only one of the knee's three parts which include -

- The medial compartment refers to the inner knee (where a person's knees touch when the legs are together).
- The lateral compartment refers to the outer knee.
- The patellofemoral compartment is at the front of the knee, where the patella (kneecap) meets the femur (thighbone).

However, this is not an option for all patients, but it is only for those who have some healthy parts in the knee which don't need to be replaced with surgery. It involves operating and removing a unhealthy compartment and then replace it with a prosthetic one. People who suffer from a more serious form or don't have perfectly aligned knees are also not eligible for this type of surgery. Compared to total knee replacement, partial knee replacement is less invasive, so it is usually less painful and requires less recovery time. However, partial knee replacement is not as reliable as total knee replacement for alleviating pain.

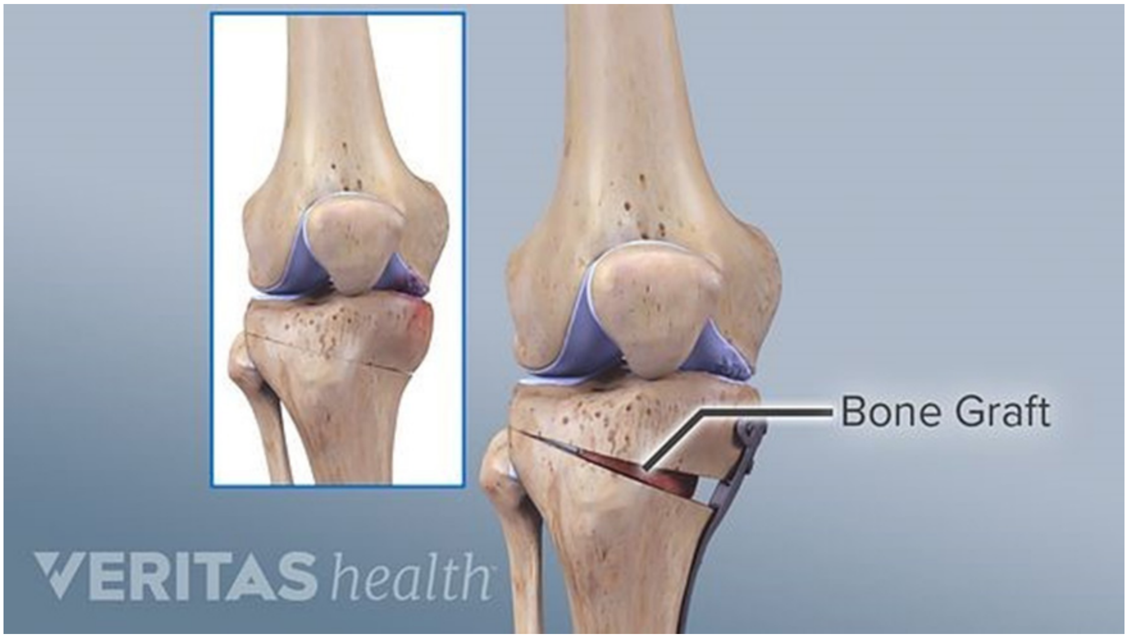


Figure 3: Knee joint after it has gone through knee osteotomy surgery [2]

Knee osteotomy (tibial osteotomy or femoral osteotomy) – This type of surgery (See figure 3) is fit for those who are very physically active as post this surgery, the patients can engage in high impact sports. This kind of surgery however, is not available to all age groups and is only for those who are 60 years or younger.

Knee osteotomy re-aligns the joint to shift more pressure onto the "good" side of the knee joint and reduce wear and tear on the bad side. The goal is to reduce pain and perhaps slow down the progression of knee osteoarthritis. A successful knee osteotomy surgery can postpone the need for total knee replacement surgery up to 10 years. This is a major surgery with potential risks and complications, and patients must be committed to extensive post-surgical physical therapy. A full recovery may take months or even an entire year.

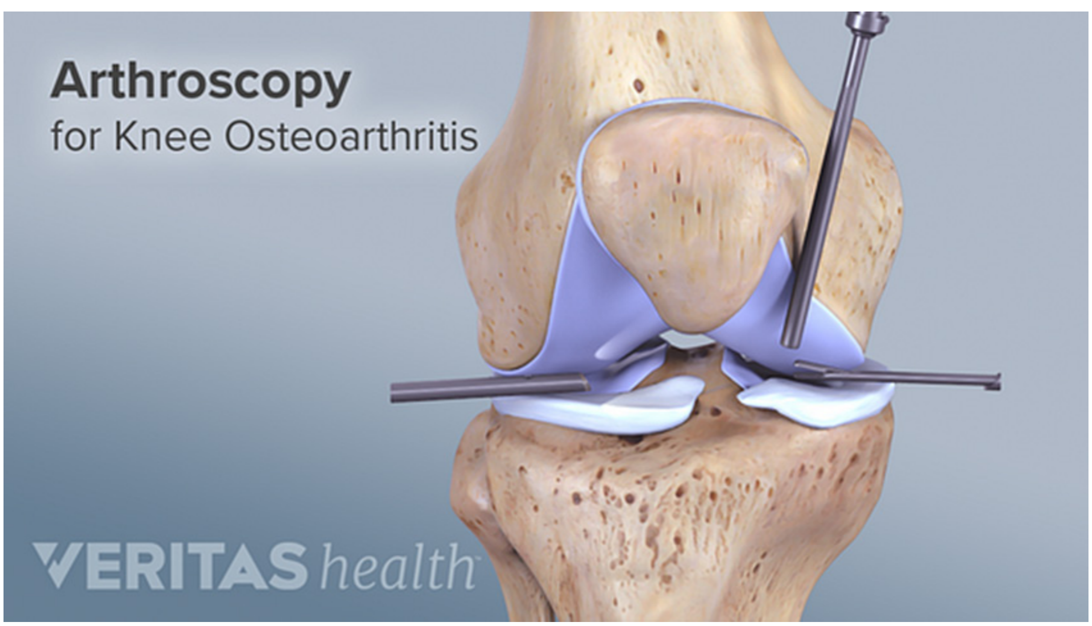


Figure 4: Knee joint after going through knee arthroscopy surgery [2]

Knee arthroscopy – Arthroscopic surgery requires only small incisions through a small video camera and some tools are inserted. During knee arthroscopy, a surgeon can make an assessment of joint degeneration due to arthritis. The surgeon can also perform knee debridement and lavage, which includes the following process:

- Remove loose pieces of cartilage or bone (loose osteophytes) suspected of causing irritation
- Trim or smooth out cartilage that has grown irregular and bumpy
- Remove inflamed synovial tissue
- Flush the joint with a saline solution, a process called lavage, to clean out materials known to cause irritation and swelling'

Knee joint after going through knee arthroscopy surgery

These surgeries pose as a cure for knee arthritis and aim to cure different types of the disease. They provide a long-term treatment for patients and help relieve them of their pain. However, being a surgery, i.e., performing incisions in the patient's knee has one obvious caveat, which is the extreme pain that they have to bear after the surgery for a brief period of time. There is also a chance of infection or inflammation post-surgery. Also, in either case a medication is prescribed. The different surgeries also have different drawbacks.

Total knee replacement surgery (total knee arthroplasty): limits some of the functionality of the human knee which may put too much strain on it. Such activities include jogging which is not an option for such patients.

Partial knee replacement surgery (unicompartmental knee arthroplasty): Not an option for all patients and only for those who have healthy parts. Also, it is not as reliable as total knee replacement in relieving pain.

Knee osteotomy (tibial osteotomy or femoral osteotomy): This is not an option for all patients and is only for those who a 60 or younger. Also, this is a major surgery with potential risks and complications, and patients must be committed to extensive post-surgical physical therapy. A full recovery may take months or even an entire year.

Knee arthroscopy: Experts' opinions differ on whether knee arthroscopy is a worthwhile treatment option for knee osteoarthritis. Some experts point to clinical studies that suggest knee arthroscopy does not provide benefit to knee osteoarthritis patients.

From this data, we can conclude that there are many different available surgeries but there is yet to be a solution which does not require incisions and does not cause any other pain to the patient and is available to all. There are many exoskeletons of different types which have been developed, but what we need is an exoskeleton which is not overly expensive and not only available to the 1% of the global economy. We need something not too expensive which is commercially available. It is also to be noted that this solution is not a replacement or a substitute to the surgery and is only something that would aid the patients in relieving their pain by making their movement less strenuous and reducing the metabolic-cost.

Existing exoskeletons

Jung Hoon Kim et al. studied the development of a modular knee exoskeleton system (See figure 5) that supports the knee joints of hemiplegic patients. The device was designed to realize the polycentric motion of real human knees using a four-bar linkage and to minimize its total weight. In order to determine the user's intention, force-sensitive resistors in the user's insole, a torque sensor on the robot knee joint, and an encoder in the motor were used.

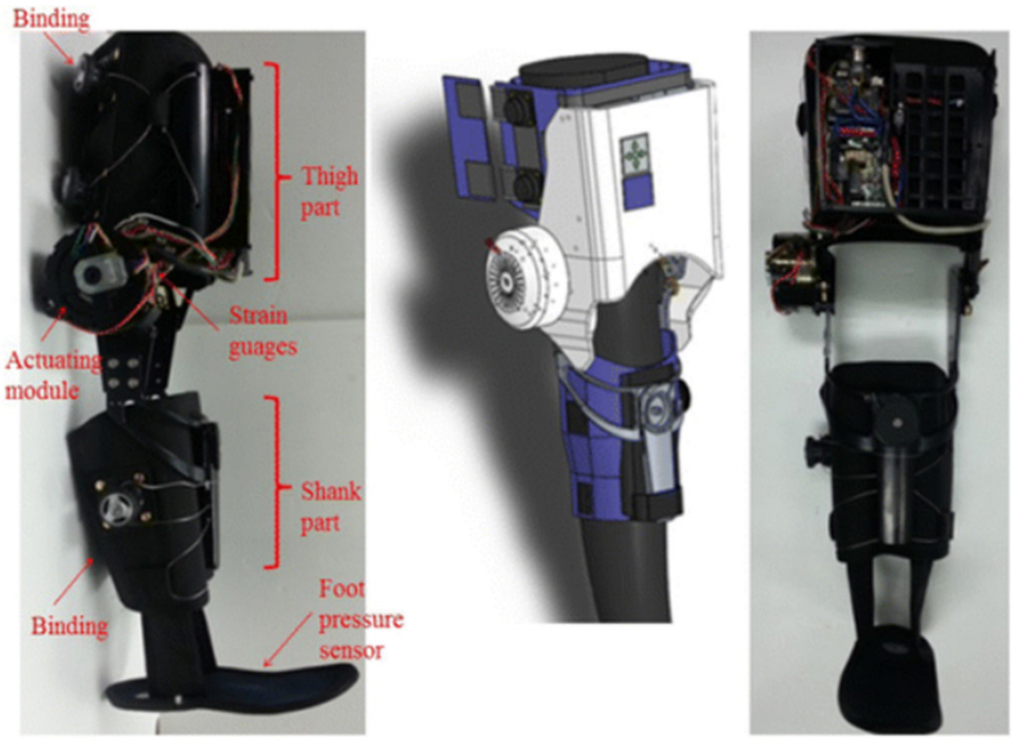


Figure 5. Modular Knee Exoskeleton [3]

In a paper titled 'Design and Control of a Polycentric Knee Exoskeleton Using an Electro-Hydraulic Actuator' (See figure 6), Taesik Lee et al. designed a simple 1 degree of freedom (DoF) structure, which was mainly used in the knees of exoskeleton robots with a polycentric (multi-axial) structure to minimize the misalignment between wearer and robot, so that torque transfer could be carried out efficiently. In addition, the overall robot system was constructed by using an electro-hydraulic actuator (EHA) to solve the problems of the energy inefficiency of conventional hydraulic actuators and the low load capacity of conventional electric actuators. After the configuration of the hardware system, the sliding mode controller was designed to address the EHA nonlinear models and the uncertainty of the plant design.

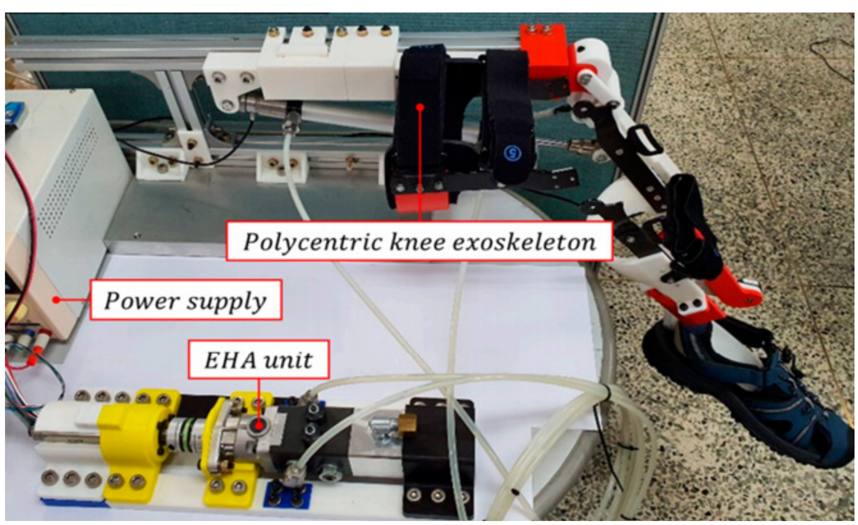


Figure 6. Polycentric knee exoskeleton [4]

Clutch spring knee exoskeleton: - This exoskeleton employs a spring-clutch mechanism. The spring clutch mechanism works in parallel with the calf muscle. The design also includes a control system to enable clutch locking and unlocking throughout a running gait cycle (See figure 7). This is an exoskeletal architecture for augmenting running leveraging a spring–clutch exoskeleton consisting of a custom interference clutch with an integrated planetary gearbox.

Figure 7 Clutch spring exoskeleton [5]

ABLE Exoskeleton: - The ABLE Exoskeleton is a knee powered exoskeleton (See figure 8) which is run by high power-density lithium-ion batteries. It has a modular design and weight up to a total of 8 kg. It incorporates a remote controller to select operation modes (stand, walk, sit), show the battery status and warning alerts. It comes with a companion app to control the device, configure it, monitor variables and progress, upgrade its firmware and allow remote monitoring by clinicians.

Figure 8 ABLE Exoskeleton [6]

EXO – H3 This is a powered hip-knee-ankle exoskeleton. It employs six motors and 16 positional, torque and pressure sensors. It also has WIFI and Bluetooth compatibility for wireless communication.

Figure 9 EXO-H3 Exoskeleton [7]

When we take a look individually at these exoskeletons closely, we see certain limitations. The first three models were developed to carry out particular studies for example the first one listed is only for hemiplegic patients who have paralysis in one side of the body. It is a form of a prosthetic limb which acts as an exoskeleton as well. The second one listed is a concept which does not seem portable and wearable. The parts such as the power supply and the EHA unit are too bulky to fit on to a leg without providing discomfort to the user. The third one is designed for assisting in running and walking without any motorized components and thus the purpose of such an exoskeleton is at variance with the goal of present design. The ABLE exoskeleton is aimed at persons suffering from lower limb paralysis and does not target a wider range of users. Lastly, as per the manufacturers comments the EXO – H3 is designed as a research platform and thus does not appear to be targeted for everyday usage. There is also a drawback that is common to all. This being that they are not available to the public and the ones that are, are hard to find. There is a complicated chain of websites and links that need to be opened in order for a consumer to reach the web page. There is also no link present on the web pages to place an order for them and only the details of how they are manufactured and how they work are available. After considering the above limitations of each model, I intend to develop an exoskeleton for persons suffering from arthritis which is a common medical condition suffered by roughly 23% of the US adult population. Besides that, its use would be limited to arthritis patients, but can be used by everyone as its main purpose is to reduce the metabolic cost of knee rotation when sitting down or getting up. It should portable and convenient to wear and not too heavy. The design should use material that serve the purpose but don't drive up the cost a lot and should be commercially available. I would use components which would help support the leg and reduce the torque about the knee.

Brainstorming

Design Criteria/Requirements
Supports bending of knee joint
Reduce metabolic cost
Not too complicated
Durability
For adults of different sizes
Does not require training or expertise to use
Safe and does not hurt user

Design Criteria and Requirements

People suffering from arthritis experience severe discomfort when they need to stand or sit.This is because of joint pains and joint swelling which can make such simple movements of standing up and sitting down extremely painful. Exoskeletons are gaining popularity as a useful device for helping those suffering from paralysis or partial loss of strength in limbs. They reduce the metabolic cost of metabolic cost of motion. I thought of expanding the scope of usage of exoskeletons as means of reducing metabolic cost of motion for arthritis patients. The metabolic cost of motion is the energy expended by the human body to move. At the same time such exoskeletons cannot be cumbersome to wear, should be light weight and affordable. I therefore had the meet these three requirements and a bunch of others to be able to put exoskeletons to such use.

Mathematical calculations

Mathematical calculations of torque about the knee for selecting appropriate electronic components were carried out. The diagrams show the calculations made for the moment about the knee joint due to the weight of the leg and the thigh. This helps us understand the constraints such as the minimum and the maximum torques that the motors should deliver.

The torque,τ_1 about the knee due to weight distribution about it when the leg is straight is as follows

$$\tau_1 = 0.48 * \phi + 0.81 * \alpha = 23.025Nm$$

Where $\phi = 35.35N$ is the weight of the leg and $\alpha = 9.66N$ is the weight of an average human foot. See Figure(10)

Volume 10 Issue 4 (2021)

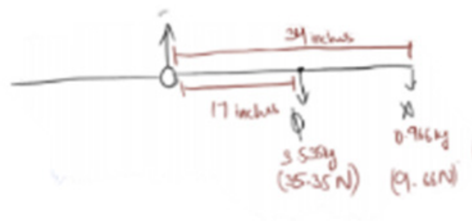
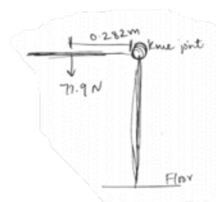


Figure 10 Torque about knee when the leg is straight

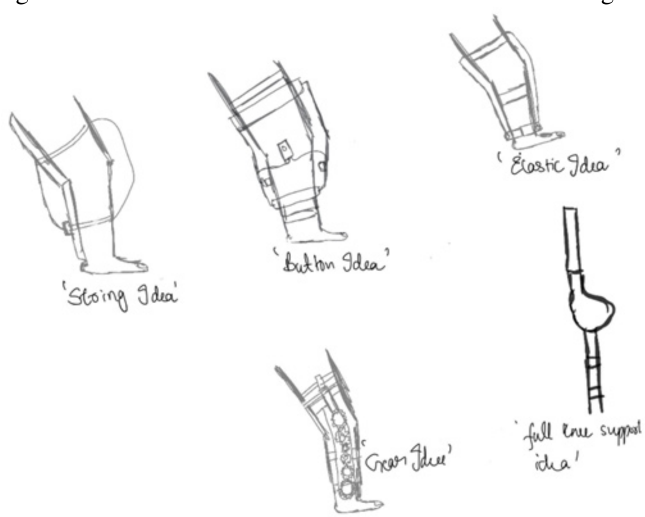
The torque, τ_2 about the knee due to weight distribution about it when the leg is bent at angle of 90° is as follows

$$\tau_2 = 77.9N * 0.282m = 21.97Nm$$



Development of ideas and selection of the best one

I thought of five different design ideas and then sketched them out so that I had a rough idea about their workings.



After this I used a design matrix/rubric to help me choose the best idea. I rated the ideas out of 2 to see how well they fulfilled the requirements. In the first attempt, i.e., the string idea, I used a string between two components attached to the thigh and the lower leg. However, this did not provide motion in both directions and the thigh cannot be supported with this design. The button idea involves the user's leg hitting a button on either side which tells the exoskeleton in which direction to move. However, this idea was not particularly comfortable. In the third idea, elastics were used in place of a string, but such an arrangement cannot be held in place and will slip. The gear idea was over complicated and would not be lightweight.

2 – totally meets requirement,
1 - somewhat meets requirement,
0 – does not meet requirement.

Design Criteria	Design #1: String Idea	Design #2: Button Idea	Design #3: Elastic Idea	Design #4: Gear Idea	Design #5: Full Knee Support Idea
Requirement #1: Supports bending of knee joint	1	1	1	2	2
Requirement #2: Reduces metabolic cost	2	1	1	2	2
Requirement #3: Not too complicated	1	2	2	0	2
Requirement #4: Safe to use/does not require training	2	2	2	2	2
Other Requirements: One size fit all	2	1	2	1	1
Total:	8	7	8	7	9

Decision Matrix

Development of the CAD design

I then finalized the last design idea, i.e., Full knee support idea which had the best score according to the matrix. I developed the 3D models using the CAD Software, Fusion 360.

I first developed a model of the full knee support which uses a series of bevel gears and spur gears in order to make the supports rotate and thus reduce the torque on the knee. It uses a high torque DC Motor in order to rotate a bevel gear so that the rest of the gears rotate along with it. The two spur gears are attached to the side of the bevel gears and thus rotate in the same direction.

As shown in the figures above, the gears are placed in such a way that the two bevel gears would rotate in opposite directions, thus causing the spud gears to rotate in the same direction. The leg and thigh supports are attached to these spud gears and thus rotate along with them, helping in reducing the torque that is required to rotate the leg or thigh

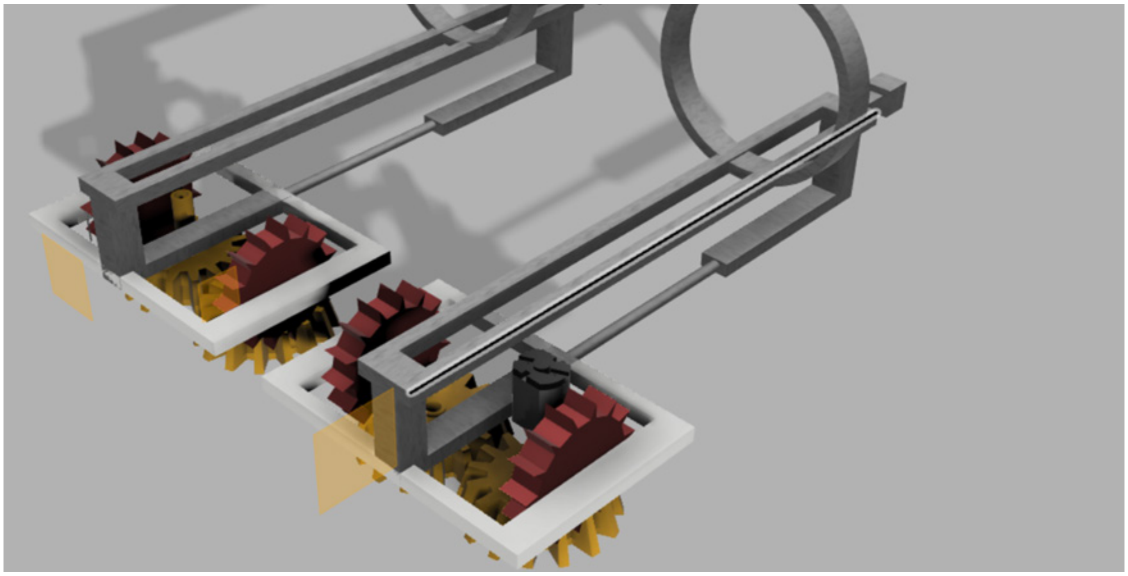


Figure 13 Closeup of the working of the gears

However, there are certain drawbacks attached with this model. The first one being that it is extremely hard to build a case for this kind of model because covering four gears with a box would have two major problems. The first one being that it would seriously limit the functionality of the gears and the rotation might be difficult. Also, it would be very difficult to get used to the boxes on the back of the leg as it would be very uncomfortable to wear anything underneath the leg. therefor my next chain of thought was to somehow design a full knee support on the side of the leg as that would be less uncomfortable and also not too bulky.

Therefore, I came up with this design. It uses a completely different design from the first one, but it does solve the main purpose that I wanted to achieve, i.e., it reduces the torque that is needed to move the leg and the thigh. It is a also very lightweight and does not add up to more that 6 kg. This is because the steel supports are hollow which reduces their weight. There is also no other heavy component in the model as the rest of it is mostly polyethylene and 3D printed ABS plastic. The whole design mechanism is not on the sides and there is only a strap to fasten the exo-skeleton that goes all the way around to the back. This increases the comfort of the exoskeleton. The exoskeleton uses a screw-based system instead of a gear-based system.

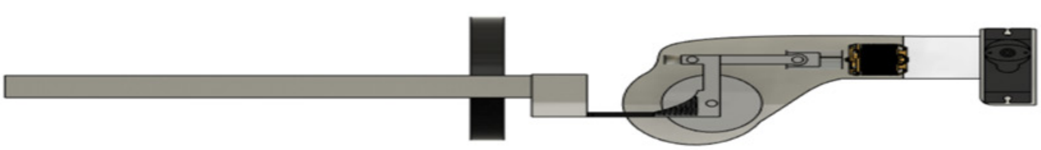


Figure 14 Closeup of the working of the Screw system

Item	Part Name	Description	Material
2	Screw	Connected to Motor- Facilitates motion of cylinder	Iron
3	Moving cylinder	Connected to axles – Moves due to rotation of screw	ABS (Plastic)
4	Axle1	Gradually rotate through 90 degrees due to forward & backward movement of moving cylinder	ABS (Plastic)
5	Axle2	Gradually rotate through 90 degrees due to forward & backward movement of moving cylinder	ABS (Plastic)
6	Connector1	Attached to the wheel, when the axle rotates 90 degrees, it also rotates through 90 degrees in the same direction as the axle	ABS (Plastic)
7	Connector2	Attached to the wheel, when the axle rotates 90 degrees, it also rotates through 90 degrees in the same direction as the axle	ABS (Plastic)
8	Connector3	Attached to the wheel, when the axle rotates 90 degrees, it also rotates through 90 degrees in the same direction as the axle	ABS (Plastic)
9	Case	Provides protection and housing ot the inner components	Polethylene
10	Wheel	Connectors are connected to the wheel and it helps them to rotate without itself rotating. Can be round or any other shape	Aluminium
11	High Torque DC Motor	Provides upto 12 Nm when combined and it is responsible of motion of screw	
23	Lower Leg Support	To help leg rotate Reduces torque on the knee due to light weight of leg and foot	Steel
30	High Torque Servo Motor	Provides high torque and presise rotations. The rotations are degree based not time based making it more accurate	
31	Upper Thigh Suport	Provides support to thigh Helps in rotation of thigh, thus reducing torque on knee due to upper body weight and weight of thigh	Steel

Parts Used

I have used ABS Plastic for manufacturing the axles, connectors and the moving cylinder because it is a fairly durable material and is readily available therefore making it not too expensive. It is also extremely lightweight and can be easily used to develop bespoke parts using a 3d printer. I have used a form of plastic, polyethylene for the case because it is one of the lightest materials available and is not too expensive as well (about 30 cents per pound). It is also very flexible and not rigid, which is a very important quality for my design as if it is rigid, a slight movement of the leg or thigh may break the case if it is not flexible.

I have used Aluminum for the wheel as it is extremely durable and also is a very lightweight metal. After careful consideration, I have decided not to use aluminum and steel for the supports (both thigh and lower leg) although it is much lighter than steel. The reason for this is that steel is steel is much more flexible and flexibility is a extremely important factor as the supports should be able to withstand high weight on them so that they don’t snap when a person rests their leg or thigh on it.

Conclusion

Knee arthritis patients find it uncomfortable and painful to sit or stand and keeping this aspect in mind, I have conceptualized a total knee support exoskeleton, which consists of a high torque servo and DC motor which provide 6 Nm or more of torque and double when used together thus reducing the torque by more than 12 Nm. This model to my best knowledge is one-of-a-kind exoskeleton which can cater to a wide population and not only to those suffering from paralysis. The components used are affordable and lightweight making the final product portable and wearable and not too expensive. This study is based on preliminary research visualized through 3D animation, but even though the model has not been put to test practically, however the design has been zeroed upon after considering various ideas which should stand the test of practicality which can be ascertained through a supplementary project. The model can be further improved by adding a rechargeable battery and also through development of the companion mobile application.

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References

1. “Arthritis-Related Statistics.” Centers for Disease Control and Prevention, Centers for Disease Controland Prevention, 18 July 2018, www.cdc.gov/arthritis/data_statistics/arthritis-related-stats.htm.

2. Vivek Sood, MD. “Types of Knee Surgery for Arthritis Treatment.” Arthritis, Arthritis-Health, www.arthritis-health.com/surgery/knee-surgery/types-knee-surgery-arthritis-treatment.

3. Jung-Hoon Kim, Myounghoon Shim. “Design of a Knee Exoskeleton Using Foot Pressure andKnee Torque Sensors - Jung-Hoon Kim, Myounghoon Shim, Dong Hyun Ahn, Byoung Jong Son,Suk-Young Kim, Deog Young Kim, Yoon Su Baek, Baek-Kyu Cho, 2015.” SAGE Journals, jour-nals.sagepub.com/doi/full/10.5772/60782.

4. Lee, Taesik, et al. “Design and Control of a Polycentric Knee Exoskeleton Using an Electro-HydraulicActuator.” MDPI, Multidisciplinary Digital Publishing Institute, 30 Dec. 2019, www.mdpi.com/1424-8220/20/1/211.

5. Wevolver.com, www.wevolver.com/wevolver.staff/clutch.spring.knee.exoskeleton.

6. “ABLE Exoskeleton.” Exoskeleton Report, 12 May 2020, exoskeletonreport.com/product/able-exoskeleton/.[7]"EXO-H3.” Exoskeleton Report, 7 May 2021, exoskeletonreport.com/product/exo-h3/.

7. "EXO-H3.” Exoskeleton Report, 7 May 2021, exoskeletonreport.com/product/exo-h3/.