Design optimization of a knee joint for the gait rehabilitation exoskeleton

by

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Submitted to the Department of Robotics and Mechatronics
in partial fulfillment of the requirements for the degree of

Master of Science in Robotics

at the

NAZARBAYEV UNIVERSITY

Apr 2023

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Abstract

This work is done towards the enhancement of the knee joint mechanism to achieve best alignment possible between exoskeleton and human knee joint motion. Various studies have concluded that the misalignment at the knee joints causes inconveniences and unnecessary stress to the points where the exoskeleton is attached to the human limbs. The literature review done for this work, confirmed that improper exoskeleton's knee joint design negatively affects rehabilitation process, this also can be confirmed by the results of clinical trials conducted by the research team in one of the national polyclinics. Therefore, the complex structure of biological human joints has to be considered during the design process of the exoskeleton. In this thesis work, several design concepts were compared, then the most promising concept among those was revealed as the result of the computational and practical experiments.

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Acknowledgments

I would like to thank my thesis supervisors Prof. Aibek Niyetkaliyev and Prof. Prashant Jamwal for their support. Also I am thankful to Daulet Sagidoldin, Darkhan Keykibayev and Aibek Ishangaliyev, for their help and guidance during the development of the prototypes. They are members of a research team that developed the gait rehabilitation exoskeleton discussed in this paper.

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Chapter 1

Introduction

There are a number of cases where people are experiencing lower limb dysfunction. Some of them are caused by a stroke, physical trauma or other types of injuries. Certain percentage of those people have a chance to rehabilitate and at least partially regain their lower limb functionality. Gait rehabilitation exoskeletons are built to increase the efficiency of a physical therapy for semi-paralyzed patients with lower limb disability, by performing repeated tasks with gradual reduction of robot assistance during the recovery. According to the survey papers [1] [2] regarding robotic exoskeleton role on rehabilitation efficiency, it is proven that such exoskeletons have a sufficient potential, and may greatly facilitate the therapists' work.

In order to develop proper lower limb exoskeleton, human lower limb anatomy has to be studied in detail. Especially when it comes to complex bio-mechanics of human joints. Some of these joints create complicated kinematics even when performing simple motion. Thus, exoskeleton design has to take into account such joint actions in order to properly align with human limbs. While to align with the hip joint it is enough to design a simple revolute joint, the design for the exoskeleton's knee joint requires consideration of certain factors. A number of studies concluded that the kinematics of a human knee joint consists of more than one degree of freedom (DOF) as illustrated in figure 1-1, which shows total of 5 DOF-s [3]. In order to simplify overall design of the orthoses, prostheses or exoskeletons engineers use only one DOF revolute joint. This approach has a few but essential trade-offs. Although, for not actuated orthoses it might be enough, however actuated wearable robots create inconveniences and unnecessary orthogonal forces at the touching points between exoskeleton and human limbs at belts and braces. It was also confirmed by the clinical experiments conducted in one of the polyclinics under the supervision of local specialists, where an exoskeleton developed by Prof. Prashant Jamwal's research team was tested on test subjects (Figure B-3). Author of this thesis paper helped to conduct these experiments by monitoring an exoskeleton operation throughout the entire duration of clinical trials. During those experiments several flaws in the design of the exoskeleton were revealed by rehabilitation specialists, including the problem with one DOF knee joint mechanism. This simple design caused stability loss problems at the lower leg that lead to the frequent untying of the belts. It was almost impossible to accomplish the whole 10 minute physiotherapy session, since after two-three minutes from the start, the belts at lower leg began to loosen. Author of this thesis paper also participated in those experiments as a test subject and witnessed these challenges by himself.

The result of this thesis work should provide an answer for the following research question:

Is there any alternative for motor actuated knee joint that will have proper alignment with human knee joint and will be compatible with rehabilitation exoskeleton?

In order to find an answer for mentioned question, in this paper, several conceptual designs of the knee joints were selected as the result of a literature review. The models were preliminary compared according to their compatibility with the AK80-64 motor and alignment with the knee joint. Then, several design solutions were modeled in computer aided design (CAD) software SolidWorks and virtually simulated. Afterwards, for final tests, the prototypes, with the most suitable parameters, were printed out via 3D printers. Overall assembly of the knee joint mechanism is designed to be compatible with the exoskeleton developed in Nazarbayev University by Professor Prashant Kumar Jamwal's research team (Figure B-1). Joints of this robot are actuated by brushless direct current (BLDC) motors at each of the hip and knee joints (Figure B-2). Also, there are two controllers that drive two motors each and

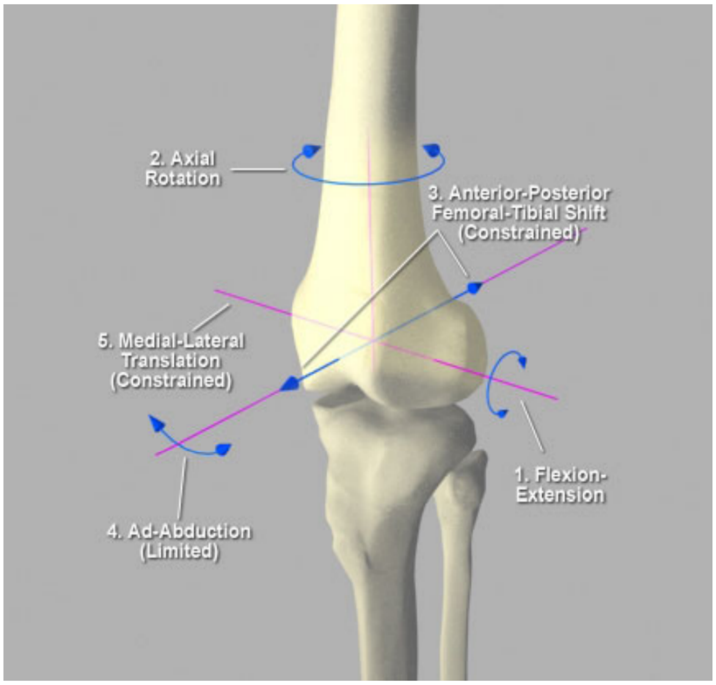


Figure 1-1: Natural human knee DOF-s [3]

synchronize by a special software developed by the research team. This gait rehabilitation system is stationary and combined with a special treadmill that comes with a mounted gravity compensation system, which can provide variable assistance to the patient on a vertical axis with compensation of up to 45 kg of weight. Pneumatic valve regulates the pressure inside the system to maintain constant gravity compensation, in other words, the valve releases the air when tension decreases, and inflates by the compressor if the weight increases.

Design validation of the assembled prototypes was performed in two stages. First, the software simulation to evaluate the model kinematics was made before assembling the prototype model. This helped to add necessary modifications without testing everything in practice, thereby saving a decent amount of consumable materials. Second stage is practical validation where tests were done by wearing the knee joint mechanism on a human leg. This was done to check the ergonomics of the prototype and detect flaws, if there are some. Additionally motion capture system was used to fully evaluate prototype designs.

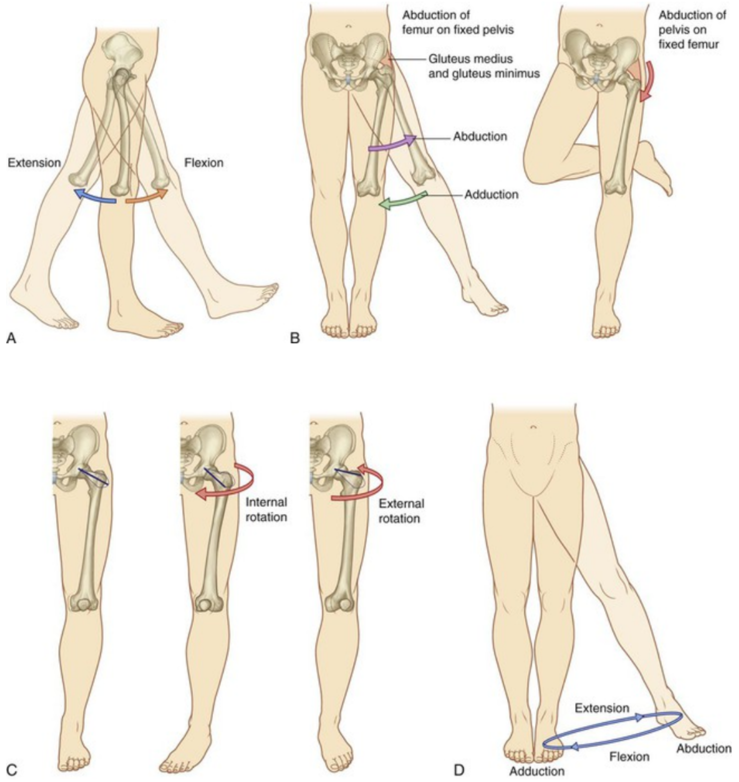
Chapter 2

Related works

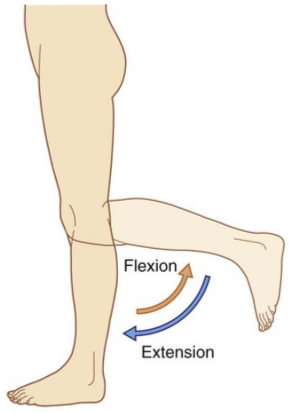
Preliminarily it can be concluded that there are a number of approaches to design a lower limb exoskeleton. Mainly, proposed models differ by mechanical concept of actuation and the joint design. For instance, Shamaei et al. suggest to use stiffness adjustable springs to actuate the gait assisting mechanism [4], whereas, Luo, Yuan and Li propose electromechanical actuation [5]. Both methods have pros and cons, however by applying electric motors it is possible to perform exoskeleton operation in partially assistive, assistive or motor driven modes. This advantage allows to rehabilitate the gait of patients at all phases of recovery.

To make the rehabilitation process as efficient as possible it is also essential to develop joint mechanisms that will mimic the motion of the biological movement of the limbs. The phases of the gait motion are similar for all people with normal physical body [6]. According to the clinical gait analysis (CGA) database, for basic walk at 1 m/s constant speed, human hip joint rotates between -5 and 33 degrees, knee joint from 0 to 60 degrees and ankle joint from -5 to 25 degrees for extension and flexion respectively [7]. In addition, motions of lower limb joints are also common for all. It can be seen from illustrations in figure 2-1 taken from [8], that hip joint undertakes three kinds of motion, and knee joint mainly operates in only one motion pattern.

In order to simplify the model, some researchers [6], [7], [9], [10], consider the hip joint as a spherical joint with 3 degrees of freedom (DOF), knee joint as 1 DOF



(a) Hip joint



(b) Knee joint

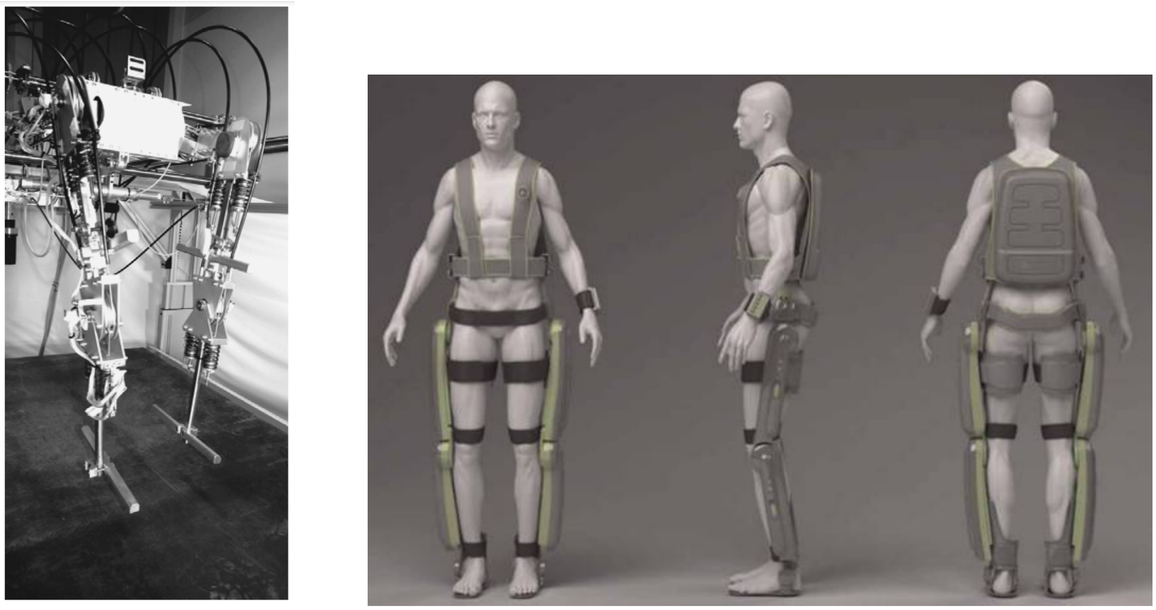
Figure 2-1: Main movements at lower limbs [8]

revolute joint and ankle as 3 DOF spherical joint. Also, some studies [11], [12] took the hip and ankle joints only as 1 DOF revolute joints that rotate only around the frontal axis. In other words, all three joints will perform only flexion and extension. On the other hand, some suggest designing a joint mechanism that will operate in the same way as a human knee joint does, with some axis displacement during the rotation [13], [14]. On the one hand to make more practical design most of the mechanical engineers suggest to place revolute joint on an exoskeleton. Because developing the models described in [13], [14] will significantly increase the complexity of the knee joint mechanism. While on the other hand, these complicated designs allow to definitely diminish the effect of misalignment that leads to the decreased lateral force where the belts and braces of the exoskeleton are attached to the lower limbs.

In order to understand the exoskeleton design and development processes in more detail, it is necessary to overview and assess practical exoskeleton models and prototypes developed in recent years.

One of the earliest developed interactive gait rehabilitation exoskeleton LOPES was presented in 2007 [15]. from Institute of Biomedical technology (BMTI) located in Enschede, Netherlands. Comparing with other solutions of that time, e.g., pneumatically actuated POGO and PAM [16], Haptic Walker [17] and others, this solution is adaptable to the patient's movement. This exoskeleton has bidirectional control method, i.e., it can operate as an assistive and as a guiding exoskeleton. In the paper author clearly clarify the design criteria that they have followed in order to develop the exoskeleton. Authors also stated the characteristics of the robot touching the mechanical features, control method and practical performance evaluation. This device has two revolute joints at a hip, for abduction-deduction and flexion-extension, also one revolute joint at the knee for flexion-extension as well. And the robot has electromyography (EMG) sensors for monitoring the muscle tension during walk. The prototype of the LOPES can be seen in figure 2-2(a). Although, the exoskeleton is not wearable, it allows to train patients on a treadmill thereby increasing the efficiency of a rehabilitation.

Another lower limb exoskeleton, ReWalk [18], but now with wearable structure was presented by ReWalk Robotics in 2011. From figure 2-2(b) it can be observed that the robotic device has a backpack with batteries and battery management system (BMS), along with control system that monitors and controls four motors, mounted one at each hip joint and one at each of the knee joints. Exoskeleton has a variety of



(a) LOPES [15] (b) ReWalk [18]

Figure 2-2: Lower limb exoskeletons

sensors that monitor the tilt angle of the torso, position of rotors, and also center of mass, to prevent the user from falling down. As it was in LOPES, this exoskeleton does not actuate the ankle joint, however it provides passive assistance to the feet. ReWalk has remote control device from which user can change the modes of operation, like sitting down, standing up, and walking. In order to make a step, user should lean forward or back and tilt his or her torso [19]. According to papers [18], [19], patients rehabilitated by ReWalk were able to restore their ability to walk normally.

Professor Yoshikuyi Sankai from University of Tsukuba in cooperation with Japanese company Cyberfyne developed the Hybrid Assistive Limb (HAL) [20] exoskeleton that is controlled mostly by EMG sensors that cover the surface of a user's skin, which provides more accurate human-robot interaction [21]. Nowadays, the team is working on a full body exoskeleton for assistance of each limb, and can be used not only for rehabilitation purposes, but also for enhancement of physical ability of a human. The lower limb part of an exoskeleton actuates hip and knee joints via DC motors that help to perform flexion-extension motion. Similar to LOPES and ReWalk, this option provides passive assistance of an ankle joint. The development of HAL over time can be observed in figure 2-3, where all three generations of HAL exoskeletons are demonstrated.


(a) HAL-1 (1996) (b) HAL-3 (1999) (c) HAL-5 (2005)

Figure 2-3: HAL exoskeleton generations

Robotics engineers from automation department of university of science and technology of China, developed another wearable lower limb exoskeleton [5]. Their model is based on the BLEEX, XoR, ALEX and Rex. Developers analyzed and concluded that even though those exoskeletons were successful in realization, they still had certain cons. Therefore, researchers tried to design a model which will not have such issues. Proposed model has a backpack which carries a battery, sensors and motor drivers. In order to decrease the weight of the robot as much as possible, aluminum alloy was chosen. There are two active hip joints for abduction-adduction and flexion-extension, and one active knee joint for flexion-extension as well. At the bottom part, there is also passive ankle joint.

In 2020 authors of [22] presented the low-cost wearable exoskeleton, which can be operated autonomously for 36 minutes. Even though, this model is not commercialized yet, it is possible to develop commercial exoskeletons which will not have high price as previously presented ones, but still be as effective as expensive variants. This robot overall has four motors mounted on each hip and knee joints. In addition, special gearboxes were designed to reduce the angular speed of actuation, but increase the output torque. Mass of the exoskeleton is 15 kg, which is relatively low comparing to others. The robot can be programmed to operate on a certain cycle of motion; therefore, it may assist the patient only on limited range of movements.

Researchers from University of Salford, proposed a 10 DOF soft-actuated lower limb exoskeleton [23], that uses artificial muscles to actuate the limbs. These muscles are installed to imitate the real muscles of the legs by performing similar tasks. Authors compared the ranges of human and exoskeleton joint motion, and it can be concluded that artificial muscles are more than enough to imitate the motion of the legs during walk. Figure 2-4, illustrates the picture of an exoskeleton worn by its author, also indicating the parts of a robot.

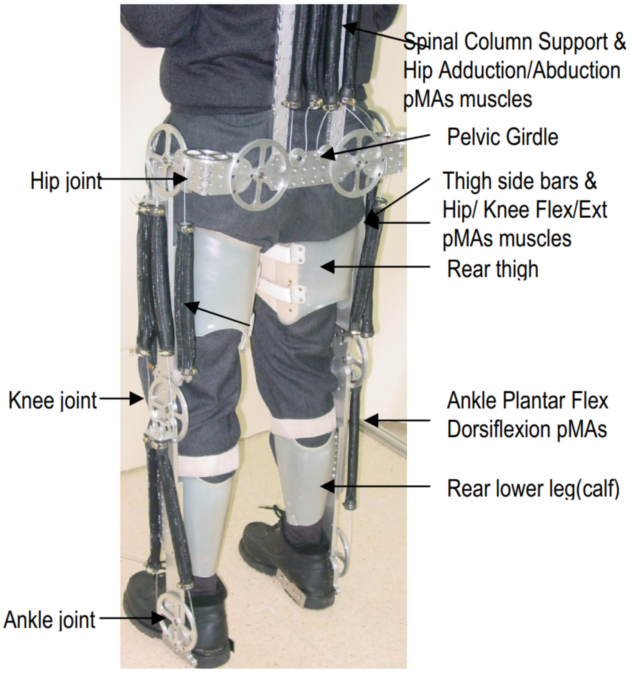
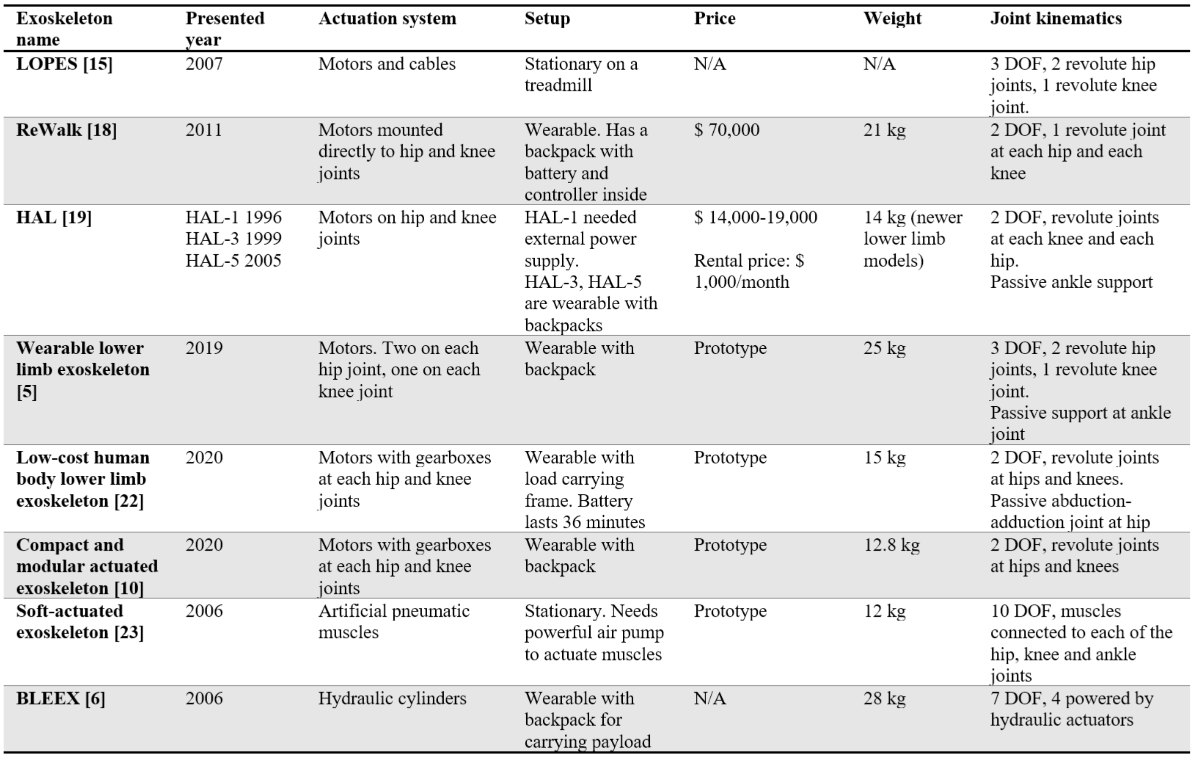


Figure 2-4: Soft-actuated 10 DOF exoskeleton [23]

Berkley lower extremity exoskeleton or BLEEX [6], was designed by Zoss, Kazerooni and Chu in 2006. Authors proposed the exoskeleton that will assist the user by removing the weight of a payload from him. The motion of BLEEX joints is comparable to a human hip, knee and ankle joint movement. Zoss et al. clearly stated the mechanical design aspects, mathematical model and the results of experiments [6]. This work shows that it is possible to design wearable pneumatic actuated exoskeleton without losing the human-robot interaction accuracy. However, the exoskeleton was initially designed to assist healthy human while carrying the heavy payload. More studies are needed, in order to understand whether such kind of exoskeletons are applicable for rehabilitation purposes.



Exoskeleton name	Presented year	Actuation system	Setup	Price	Weight	Joint kinematics
LOPES [15]	2007	Motors and cables	Stationary on a treadmill	N/A	N/A	3 DOF, 2 revolute hip joints, 1 revolute knee joint.
ReWalk [18]	2011	Motors mounted directly to hip and knee joints	Wearable. Has a backpack with battery and controller inside	$ 70,000	21 kg	2 DOF, 1 revolute joint at each hip and each knee
HAL [19]	HAL-1 1996 HAL-3 1999 HAL-5 2005	Motors on hip and knee joints	HAL-1 needed external power supply. HAL-3, HAL-5 are wearable with backpacks	$ 14,000-19,000 Rental price: $ 1,000/month	14 kg (newer lower limb models)	2 DOF, revolute joints at each knee and each hip. Passive ankle support
Wearable lower limb exoskeleton [5]	2019	Motors. Two on each hip joint, one on each knee joint	Wearable with backpack	Prototype	25 kg	3 DOF, 2 revolute hip joints, 1 revolute knee joint. Passive support at ankle joint
Low-cost human body lower limb exoskeleton [22]	2020	Motors with gearboxes at each hip and knee joints	Wearable with load carrying frame. Battery lasts 36 minutes	Prototype	15 kg	2 DOF, revolute joints at hips and knees. Passive abduction-adduction joint at hip
Compact and modular actuated exoskeleton [10]	2020	Motors with gearboxes at each hip and knee joints	Wearable with backpack	Prototype	12.8 kg	2 DOF, revolute joints at hips and knees
Soft-actuated exoskeleton [23]	2006	Artificial pneumatic muscles	Stationary. Needs powerful air pump to actuate muscles	Prototype	12 kg	10 DOF, muscles connected to each of the hip, knee and ankle joints
BLEEX [6]	2006	Hydraulic cylinders	Wearable with backpack for carrying payload	N/A	28 kg	7 DOF, 4 powered by hydraulic actuators

Figure 2-5: Comparison table of exoskeletons

Overall, the short conclusion of comparison of the exoskeletons, discussed above, is indicated in the comparison table (Figure 2-5). Also it is clearly seen that the most of these proposed exoskeleton models do not consider the complex kinematics of the knee joint. While recent researches confirm that in order to design proper exoskeleton for rehabilitation purposes, it is crucial to take into account this specialty of human knee biomechanics. Otherwise, there will be misalignment between exoskeleton and human lower limbs.

The misalignment issue can be clearly seen in the illustration figure 2-6 from Gao M. et al. [24]. Authors of this work implemented a four bar linkage mechanism at the knee joint of the exoskeleton that is actuated by a motor located at the upper part of the thigh. Since, authors did not include comparative analysis of their design with other possible solutions, it might be needed to recreate their design and compare with mechanisms that could serve as an alternative or maybe better solution.

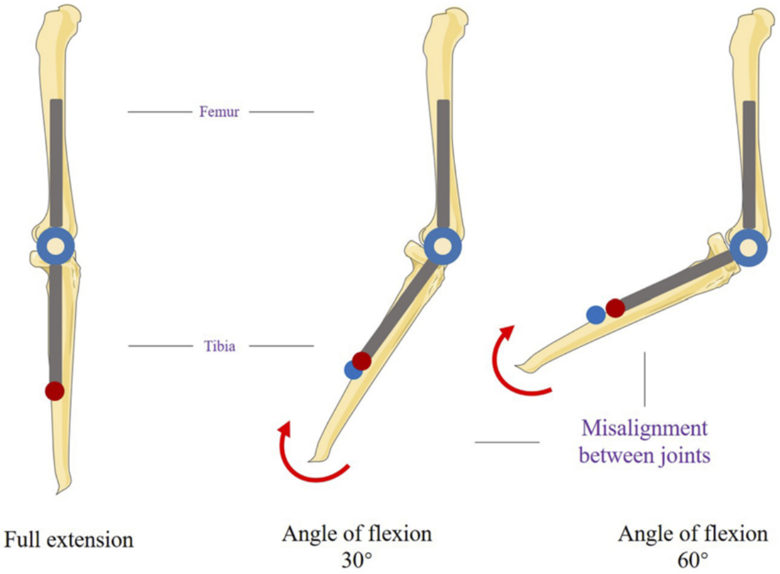


Figure 2-6: Misalignment at the knee joint

The closest approach of designing the knee joint, similar to the one that is being proposed, for a motorized exoskeleton is described in [14], where authors were inspired by the biomechanics of the human knee joint. They achieved position misalignment of almost 0.75 mm, which is an excellent result compared to the revolute joint, where an error varied around 3 mm. Such misalignment of the revolute mechanism on a knee joint of a robotized exoskeleton creates perceptible inconvenience to the user.

While in [14] authors proposed optimized design of a knee joint for wearable lower limb exoskeleton, in this thesis knee joint mechanism is designed for a stationary system. Although this model uses a similar approach to properly align with the human knee, the implementation is completely different, due to the fact that the gait rehabilitation system discussed in this thesis also actuates the hip joint and there is a need to consider two motors per leg.

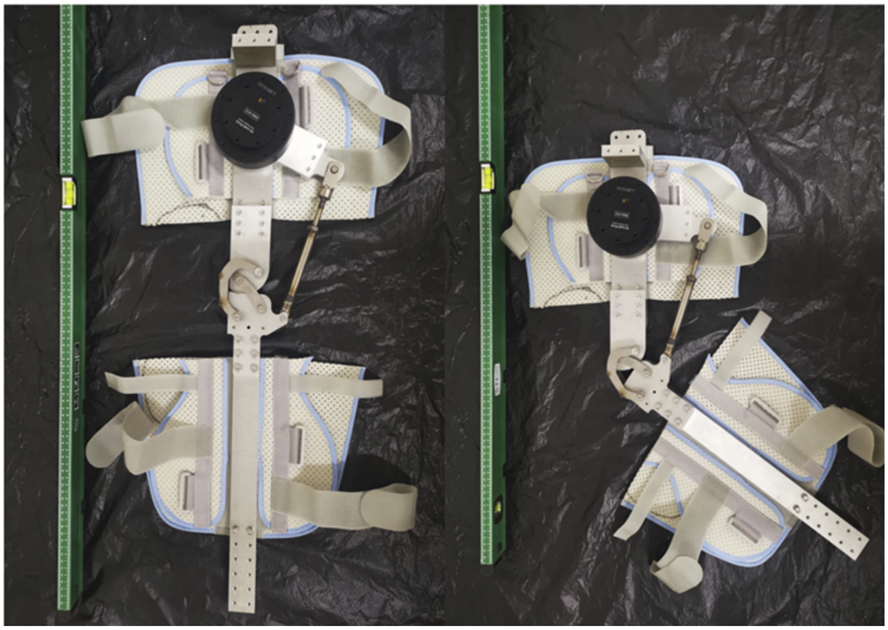
Chapter 3

Design concept selection

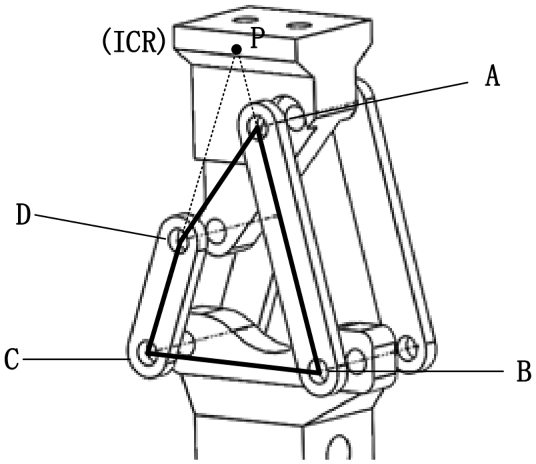
There are a number of suggested designs for a motorized knee joint that achieved very close alignment between human knee joint and exoskeleton. Only a few of them are compatible with the stationary gait rehabilitation robotic system.

The knee joint of an exoskeleton developed by Gao M. et al. (Figure 3-1) [24], which is built to assist knee joint rehabilitation, and based on a cross four-bar linkage mechanism. An exoskeleton is actuated by a BLDC servo motor which provides 50 N*m of torque at 700 W of power. Motor lifts the lower part of the leg with a cylindrical telescopic rod that allows prismatic movement along its axis. Another approach of designing a knee joint with four-bar linkage method is to connect the bars without the crossing. Similar design was proposed by Xiao Y. et al., and illustrated in Fig. B-3b [25]. Four-bar linkage mechanism allows to create an elliptical trajectory of the ICR, which will cause misalignment at certain stages of knee flexion motion. In addition, placement of the knee joint actuator has a high risk of overlapping with the hip joint motor platform.

Wearable knee exoskeleton designed by Xiaolu Tang and Chen Lumin (Figure 3-2(a)) [26], and a self aligning knee joint for walking assistance devices (Figure 3-2(b)) [27]. Both of these robots are based on a combination of 3 revolute joints that have planar motion parallel to the sagittal plane. An effective workspace of these three DOF-s is sufficient to achieve the desired trajectory for instantaneous center of rotation (ICR) of the lower leg. Even though the concept is very novel, adapting



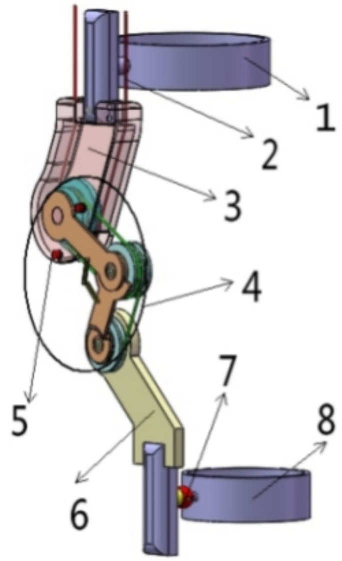
(a) Gao M. et al. design



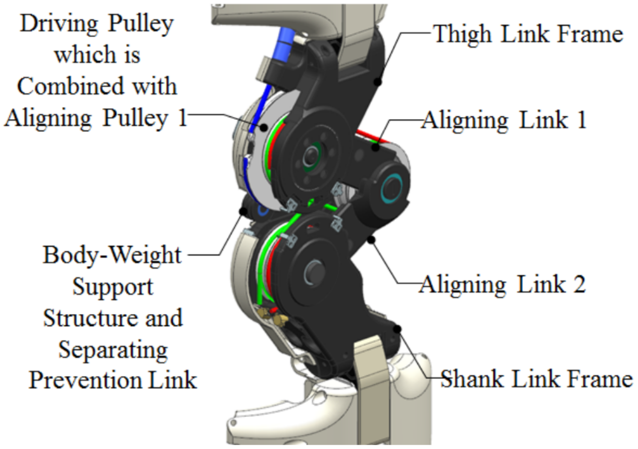
(b) Xiao Y. et al. design

Figure 3-1: Cross four-bar linkage knee joint prototypes [24], [25]

it to the motor actuated exoskeleton might be challenging. Since, every joint of this mechanism needs separate actuators that actuate them by ropes connected to corresponding pulleys. It is still possible to design these joints as passive and attach the lower leg to the motor with a spring or a prismatic rod as it was implemented in the previously mentioned concepts. However, this approach will result in a high number of redundant constraints. Which should be avoided in order to develop an effective design.



(a) Tang and Lumin design: 1.Thigh bandage; 2.Driving cable; 3.Shell; 4.Selfaligning device; 5.Stopper; 6.Connection frame of leg; 7.Sphere-pin pair; 8.Leg bandage;



(b) Choi et al. design

Figure 3-2: Self aligning knee joint concepts [26], [27]

A bioinspired knee joint (Figure 3-3) designed to minimize the misalignment provides the most precise results so far [14]. These kinds of joints are modeled with the consideration of the femur bone curvature at the knee joint. This curvature can be drawn from the side view picture of the magnetic resonance imaging (MRI) or computer tomography (CT) scan. This is very useful for designs that require personal adjustment, to create joints that are aligned as much as possible.

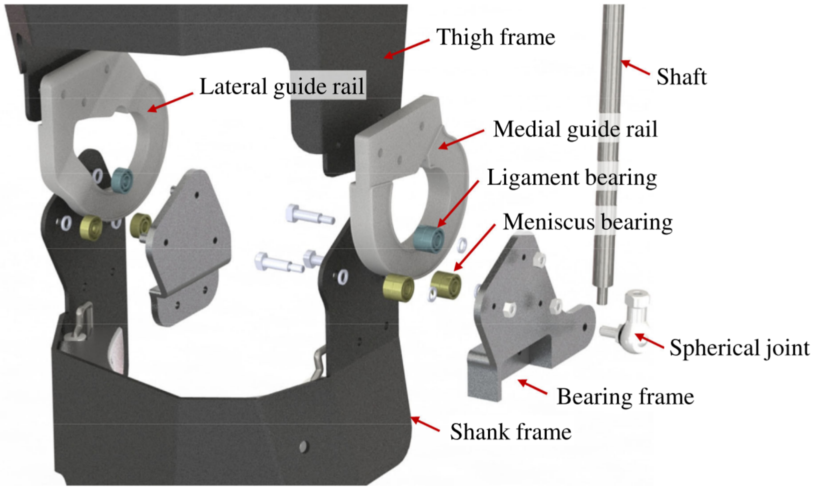


Figure 3-3: Bio inspired knee joint [14]

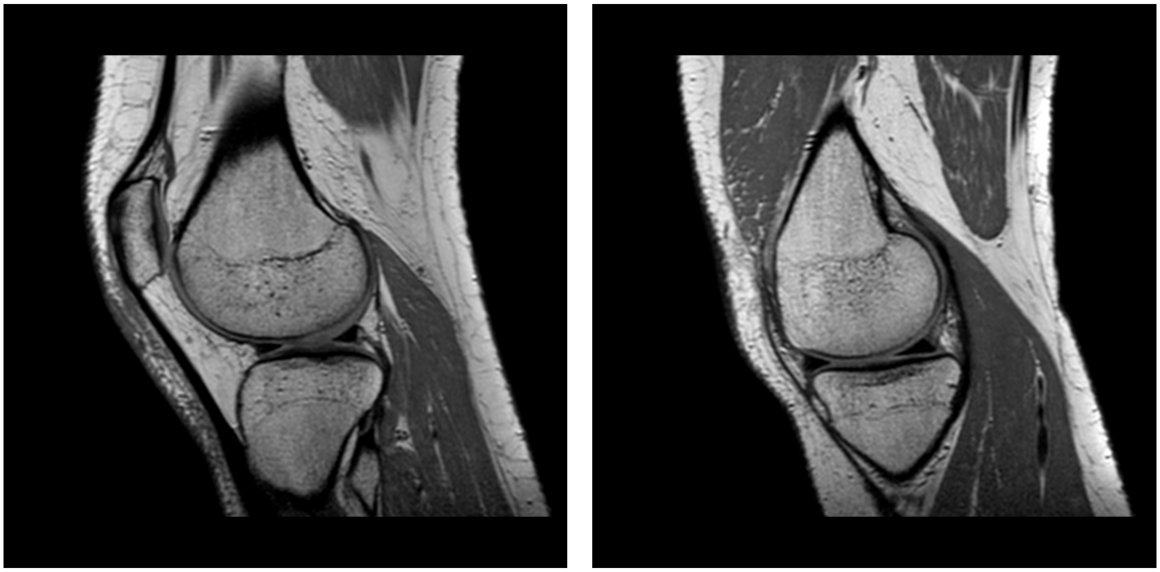
Out of these three approaches of a knee joint design, the most promising is the last one. In the next section, two concepts are going to be evaluated. Both of them are based on the bioinspired knee joint design approach to achieve better alignment.

Chapter 4

Methodology

As it was decided in the previous chapter, two design approaches are going to be considered in this work. Both of them are based on the bioinspired knee joint developed by Kim, Jeong and Kong from KAIST university [14].

In order to adapt the proposed design for developing gait rehabilitation exoskeleton, it is necessary to reconsider knee joint mechanism in the way that it will not overcomplicate or weaken the exoskeleton's structure. Since this approach has an essential advantage over other concepts in terms of the trajectory alignment precision, it is important to keep bioinspired design of a knee joint. While engineers from KAIST university designed the guide rail's curvature by drawing the trajectory of the virtual markers on a lower leg from a captured video clip and then processed a graph to achieve a smoother curve, the approaches in this work are designed according to the MRI pictures (Figure 4-1) of the knee joint from a sagittal plane view. These MRI pictures were taken from a 25 year old female subject, as a part of Tim Luijkx's studies that are available online [28]. Designing a knee joint with this method allows to imitate natural knee joint flexion and extension as it is described in [3]. The first method is to design spur gear mechanism at the knee joint with one gear having non-circular edge, which will replicate the curvature of femur bone's condyle. Although using gear teeth increases reliability and improves stability of the mechanism, in order to achieve the smoothest motion, there is a better way to design the knee joint. The second model will use ball bearings at the lower part of the knee joint that will roll on the curved surface of the upper part. In both designs the upper part and lower part of the knee joint will be connected via springs and metal bars. Metal bar itself will be mounted to the rotor, and move the lower part according to the predefined trajectory.



(a) Lateral condyle

(b) Medial condyle

Figure 4-1: Knee joint MRI pictures (saggital plane) [28]

Since the femur bone at the knee joint has two condyles that have different surface curvature, it is necessary to decide which condyle should be considered in the design of a trajectory curve. In the human knee joint there is soft tissue, cartilage, in between the femur and tibia bones that can deform under the stress during flexion or extension. Since the exoskeleton is built only from hard materials such as metal and plastic, there is a need for a mechanism that could replace cartilage without sacrificing its functionality. Therefore, it is necessary to come up with a universal solution to this problem. From the MRI pictures of the knee joint (Figure 4-1) it can be seen that at the lowest points of the both condyles, the lateral condyle has a larger curvature profile. Thus, for drawing of non-circular upper gear's curve profile the lateral condyle's curvature was selected. Then, the slice of MRI scan at the widest part of the femur bone's lateral condyle was projected on a sketch in SolidWorks to draw a trajectory curve (Figure 4-2). The MRI picture was scaled in a way to match the real knee dimensions of an average 23-25 age male. For drawing of the curvature profile, uniform radius arcs with following radii values were used: R1 - 27.8mm, R2 - 79.21mm, R3 - 47.13mm, R4 - 18.61mm and R5 - 24.48mm. Uniform radius arcs allow to create a more accurate and compatible curvature profile for geared concept. This is crucial for software design validation of the geared knee joint concept.

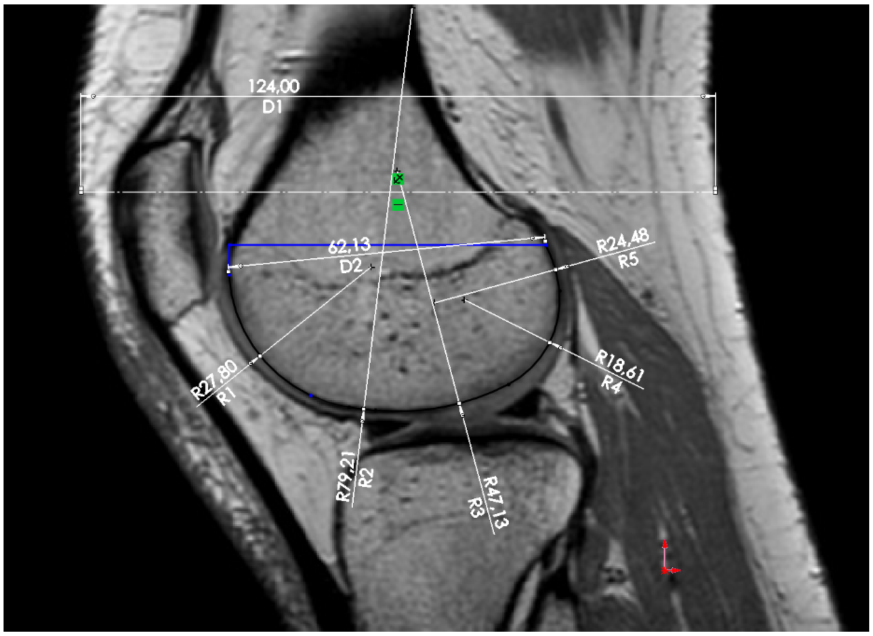


Figure 4-2: Curvature profile drawing on a lateral condyle MRI picture's projection

Both of the design concepts, based on a bioinspired knee joint mechanism, are modeled around the sketch illustrated in the figure 4-2. In order to be able to place a motor's shaft at the initial center of rotation of a knee joint, the sketch was scaled twice. This magnification is sufficient to place the AK80-64 BLDC motor (Figure B-2) inside of the curvature contour and to keep the kinematics of the knee joint motion.

4.1 Knee joint concept kinematics

After obtaining the curvature profile and dimensional parameters of the centers of rotation for both parts, it is possible to evaluate the kinematics of the concepts. Although the knee joint has only one actuated joint, the curvature profile of the upper parts caused unwilled translation motion along the metal bars. Therefore, it can be assumed that the concept uses two actuated joints, the revolute and prismatic. Parameters of the exoskeleton knee joint concepts can be seen in (Figure 4-3). According to those characteristics Denavit-Hartenberg (DH) parameters were obtained and indicated in Craig convention (Table 4.1).

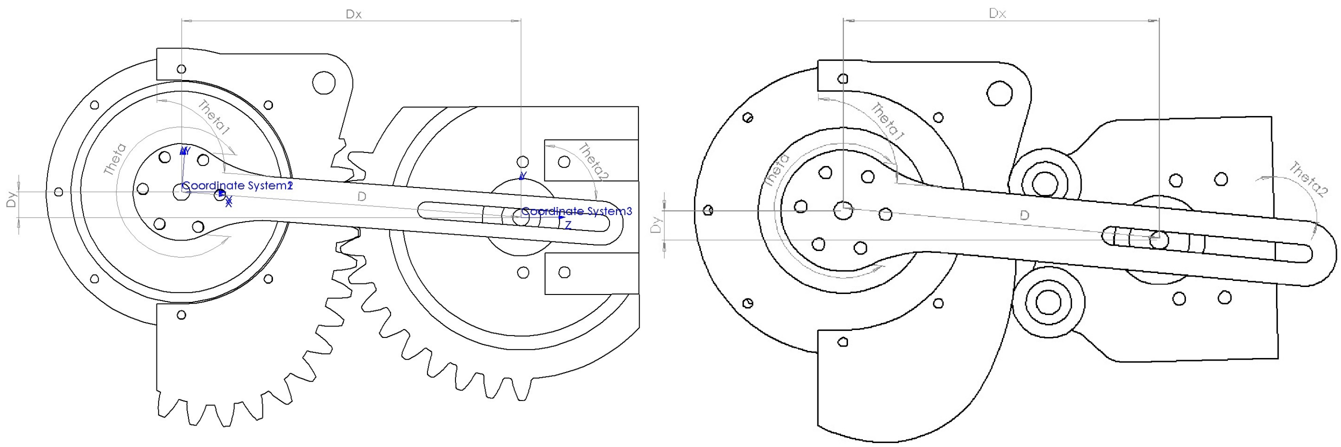


Figure 4-3: Parameters of the concepts. Left: Design with gear teeth. Right: Design with ball bearings

i	α_{i-1}	a_{i-1}	d_{i-1}	θ_i
1	0	0	0	θ_1
2	90°	D_x	0	0

Table 4.1: Denavit-Hartenberg parameters

According to the DH parameters from table 4.1, the transformation matrix ${}^0_2T$ was obtained.

$$
{}^0_2T = \begin{bmatrix} \cos(\theta_1) & -\sin(\theta_1) & 0 & D_x * \cos(\theta_1) \\ \sin(\theta_1) & \cos(\theta_1) & 0 & D_x * \sin(\theta_1) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Due to the non-circular curvature profile of the upper part, there will be another rotation (θ_2) between the centers of rotation of these parts. This angle is dependent on θ_1 by the factor of the gear ratio which can be calculated by equation 4.1.

$$Gear\,ratio = \frac{N_2}{N_1} \tag{4.1}$$

Where $N_1 = 11$ and $N_2 = 14$ are the number of gear teeth on corresponding parts of the knee joint. Substitution of those values provides following result: $Gear\,ratio = 1.28$. Taking into account the limits for the rotation of a knee joint, there will be certain constraints for the angles of rotation (4.2) (4.3).

$$0 < \theta_1 < 47.2^\circ \tag{4.2}$$

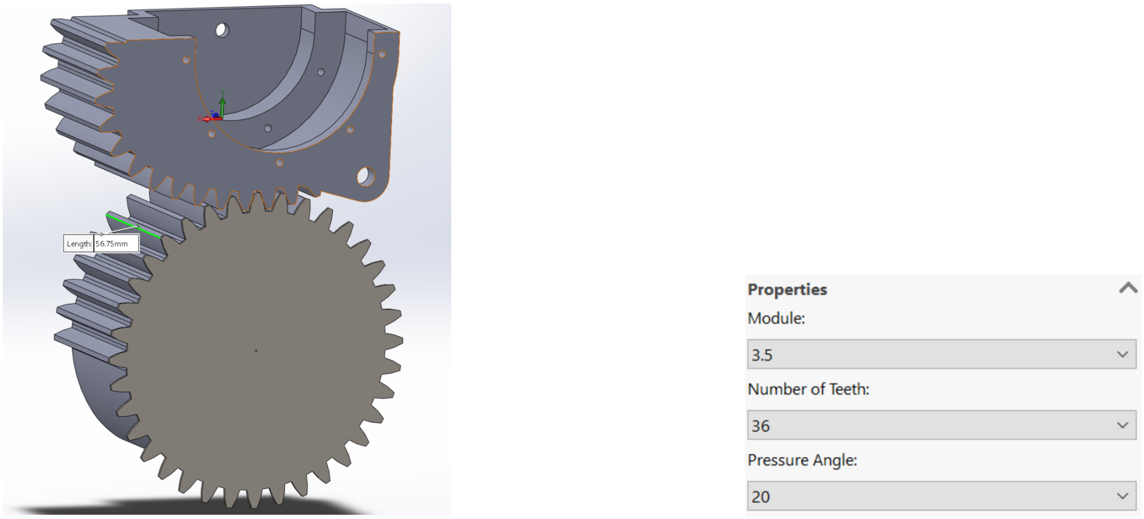
$$0 < \theta_2 < 60^\circ \tag{4.3}$$

In addition, there is one more non-constant parameter in this setup, D which is the distance between the centers of rotation. This parameter is dependent on the angle of rotation of the rotor θ_1, and can be calculated by the equation 4.4. Where distances between centers of rotation along axis X (D_x) and axis Y (D_y) are also dependent on the value of θ_1.

$$r(\theta_1) = \sqrt{(D_x(\theta_1))^2 + (D_y(\theta_1))^2} \tag{4.4}$$

4.2 Knee joint design with gear teeth

Spur gears are commonly used for power transmission systems in various machines. Their main advantage is reliability due to their high durability. Although the strength of such gears mostly depends on the material they were made from, for the purpose of this project the robustness of the plastic spur gears is enough. Moreover, all plastic details that were modeled within the scope of this thesis work are printed by 3D printers at Nazarbayev University. When the compressive stress is applied to the plastic component, the triangular infill at 35% amount was configured. According to [29], where authors tested various infill patterns and their influence on the strength and material consumption rates, it was found that triangular infill patterns are able to provide the highest strength with the lowest amount of a material used for printing.



Properties

Module:

3.5

Number of Teeth:

36

Pressure Angle:

20

(a) Standard spur gear template highlighted in brown

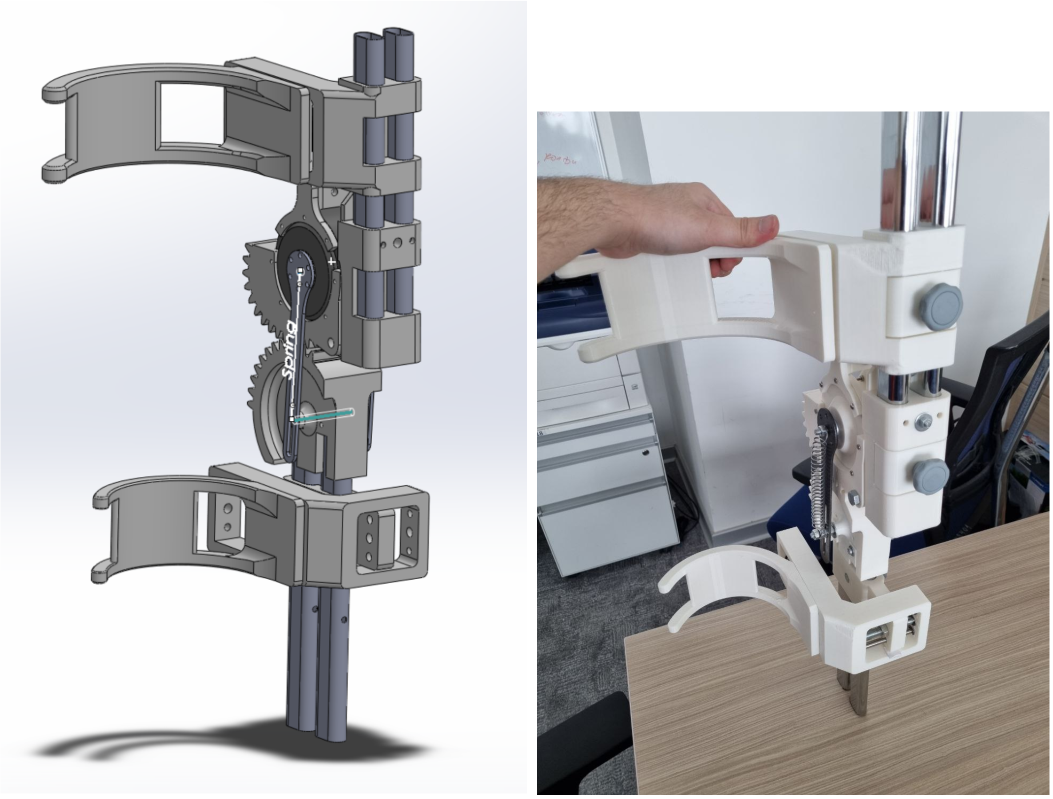
(b) Properties of the spur gear

Figure 4-4: Spur gear tooth profile selection process

Standardized spur gear tooth profile was used to design both upper and lower parts of this concept (Figure 4-4). This standard model is based on a spur gear design template that is available in the power transmission toolbox included in SolidWorks add-in library. Module coefficient 3.5 with 36 teeth was sufficient to withstand the forces that will act on each individual tooth during motion. Also pressure angle of 20 degrees and face width of 56.75mm significantly decrease the amount of stress applied per unit area.

Final model of the prototype assembly can be seen in figure 4-5(a). In order to design a prototype that will be compatible with existing exoskeleton, some plastic models were reused from the actual gait rehabilitation exoskeleton assembly model. To keep upper and lower parts connected, stiff springs were placed on both sides at the centers of rotation, and to keep parts aligned in the sagittal plane, steel bars were hard mounted to both parts.

After every plastic part was printed out and steel bars were laser cut, the prototype was assembled using mainly M6 bolts, nuts and corresponding washers (Figure 4-



(a) in SolidWorks

(b) in live

Figure 4-5: Assembled model

5(b)). Later when the real prototype was assembled, it turned out that manually turning the rotor shaft of the AK80-64 motor required a significant amount of torque. Since, for validation of the knee joint's kinematic in practice, the use of a real motor is not required, it was decided to model a plastic alternative that would have all the threaded holes and axis of rotation to match the AK80-64 motor.

4.3 Knee joint design with ball bearings

All steps of drawing the curvature profile are the same with the previous design concept. Since this concept uses ball bearings to imitate roll back motion between femur and tibia bones, there is no need to use spur gear teeth profiles. Thus the curved surface of the upper part totally corresponds to the lateral condyle curvature of femur bone. This feature allows to accurately mimic flexion and extension motions of the human knee joint.

Regarding the design of a lower part, it was necessary to model a new plastic part with 4 slots for ball bearings (Figure 4-6). It was decided to use four ball bearings as rollers, since it will stabilize the lower part during the motion and significantly decrease the stress per unit area at the touching points between upper and lower parts.

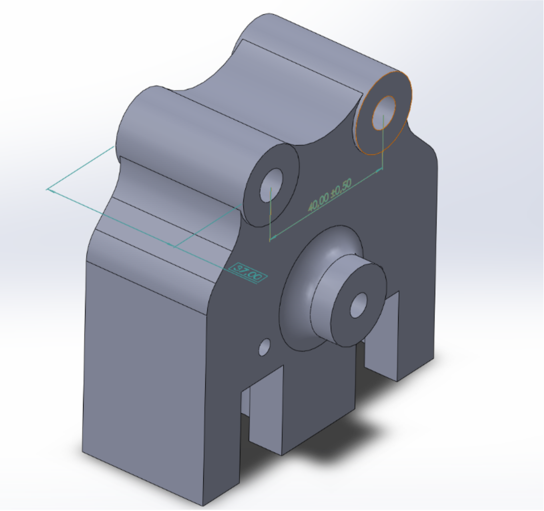


Figure 4-6: Lower part of the ball bearing concept prototype

For this concept four steel ball bearings with following dimensions were used: Outer diameter - 24mm; Inner diameter - 15mm; Thickness - 5mm. To attach these bearings onto the lower part 3D printed plastic bushings were used. These bushings are used to not overtighten the bolts that hold the bearings. Prototype and SolidWorks model have exactly the same size and kinematics (Figure B-4).

Chapter 5

Results

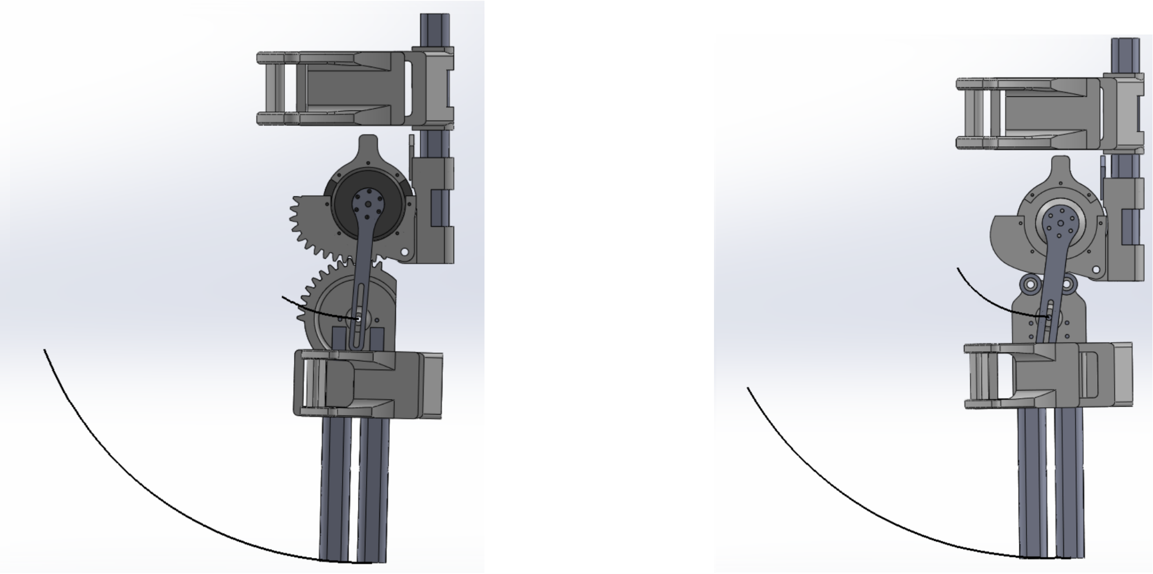
For an assessment of the designed prototypes, firstly the motion analysis tool in SolidWorks was used. This tool allows simulating the assembly model by adding physical interaction between solid bodies. Motion analysis also helps to identify the trajectory of certain points (Figure 5-1). Secondly, practical experiments were conducted to evaluate the ergonomics of the knee joint and identify flaws in the design. In addition, motion capture system from Noraxon company was used to track the trajectories of inertial measurement unit (IMU) sensors attached to human leg and prototypes of a knee joint.

5.1 Design validation in CAD software

Design evaluation in SolidWorks is very useful at the first stages of the design process, since it provides important information about kinematics of the assembly and allows to compare this data with previously recorded data taken from human knee joints. Studies that investigate the trajectory of human knee joints were already conducted and the comparison of the data can be done accordingly [14].

Certain tools were used to extract the data from the graphs that were obtained from the experiments conducted by other researchers. Also the data from assembly models were taken in a similar way to make the results comparable.

Authors of [14] have recorded a video clip of a swing phase with attaching special



(a) Geared concept (b) Ball bearing concept

Figure 5-1: Trajectory graphs

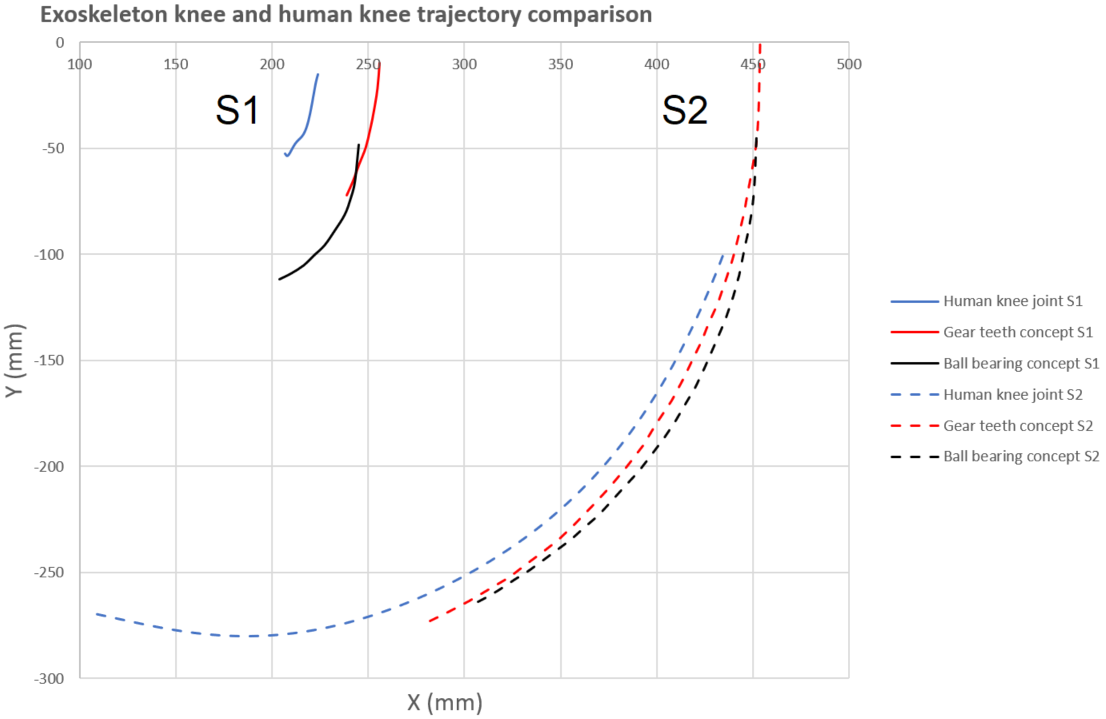


Figure 5-2: Diagram with trajectories of markers on a human leg and knee joint concept

markers on the leg of a person. Then, they traced the displacement of these markers on a virtual coordinate system. The markers on a thigh were named T1 and T2, while on a lower leg were named S1 and S2, referring to the shank. Since the thigh is fixed and the only moving part is the lower leg, it is suggested to compare the data from lower leg markers and use thigh markers as a reference. After these procedures, the following diagram was obtained (Figure 5-2). Distance between markers on a human leg was 250mm, while on the assembly models it was 230mm, therefore it created a visible offset between the trajectories of markers.

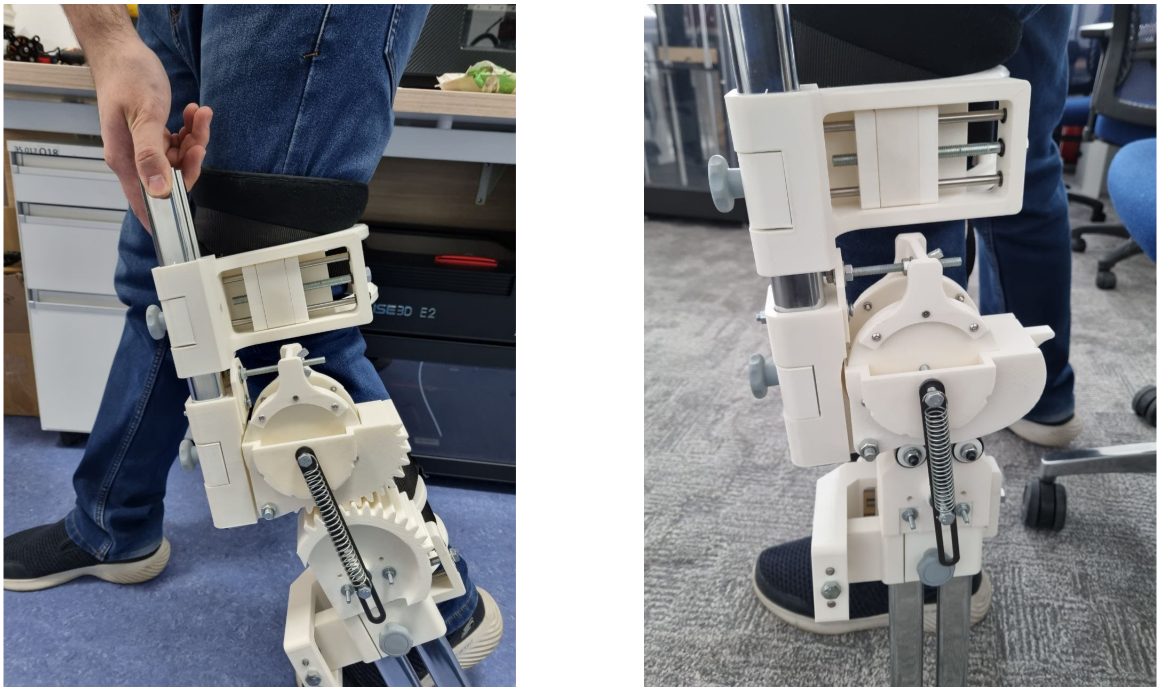
5.2 Practical design validation

After software validation of the concepts, it was possible to develop a real prototype. Hence, practical experiments were carried out for final validation of the design. Both braces of the prototype are made from solid plastic, therefore for the comfort of the user, soft pads were placed between the braces and the belts. Also these belts were fastened by plastic fastexes that could create undesired inconveniences.

Both models were tested one by one in order to identify which one is better (Figure 5-3). During the practical tests some plastic parts were damaged, thus it was decided to slightly redesign the CAD models to improve the durability of those parts without changing the kinematics of the models (Figure B-5). Also the practical model of a concept with ball bearings had issues caused by misalignment of the upper and lower parts. Therefore guiding tracks were added to the model (Figure B-6).

In the middle of practical design validation it was revealed that the concept with gear teeth caused overbending at the lower brace after a certain flexion angle (Figure B-7). Nonetheless, for the slow gait motion with low flexion angle, the level of alignment is sufficient to not cause inconveniences. Regarding ball bearing design, the lack of support of an ankle caused slight twisting of the exoskeleton during the gait cycle.

In order to thoroughly assess the practical models it is needed to use certain measurement tools. Fortunately school of medicine of Nazarbayev University has


(a) Geared concept

(b) Ball bearing concept

Figure 5-3: Practical test pictures

portable Noraxon Ultium lab, which is able to record motion capture data with IMU-s and muscle activity data with EMG sensors (Figure B-8). For evaluation of the developed prototypes, the measurement of its kinematics in practice with motion capture system would be enough.

Firstly the data from the human leg with flexion and extension motion was recorded with the IMU sensors (Figure B-9). Then IMU sensors were attached to knee joint prototypes, to record the same motion (Figure B-10). After capturing motion data, every recorded session was compared with others. From figure 5-4 it can be noted that recorded trajectory of knee flexion-extension movement of human leg has certain degree of fluctuation due to the unintended movement of the hip joint. Therefore multiple flexion-extension movement processes were captured. These pictures also depict the comparison between various sessions. On the comparison of the conceptual prototypes between each other, it is clearly seen that trajectories do not match (Figure 5-4(c). It is caused by the aforementioned overbending caused by the design with gear teeth. However, at the early stages of the swing motion the trajectories tend to overlap. Thus for low amplitude gait cycles the geared design is still valid.

(a) Human leg vs. design with gear teeth

(b) Human leg vs. design with ball bearings

(c) Gear teeth vs. ball bearing design

Figure 5-4: Trajectory comparison of human leg and prototypes

Chapter 6

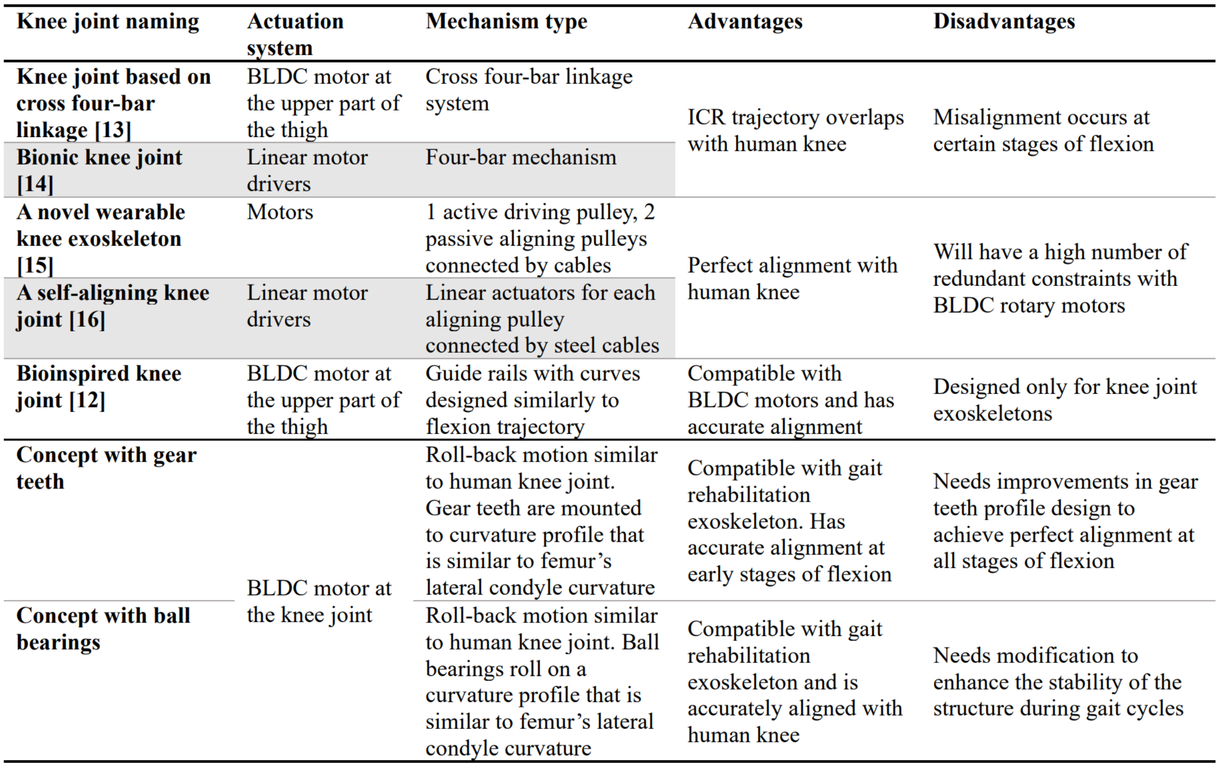
Discussion

After obtaining the results of a software assessment of the design, it became clear that designing the curvature profile according to the femur bone's lateral condyle leads to the proper alignment of human and exoskeleton knee joints. Although additional experiments with actual exoskeleton have to be conducted in order to finally verify the validity of the concepts. However at this stage, kinematic constraints of the real exoskeleton were taken into account.

Practical tests allowed to identify design flaws in the structure of the exoskeleton. Most of them were rectified by redesigning the CAD models. However the overbending problem of a geared design needs more thorough investigation. It was assumed that this is caused because of the unequal amount of gear teeth at upper and lower parts. Attempts were made in order to solve this problem, however increasing the number of teeth at the lower part leads to the significant increase in the diameter of the whole lower part, which is not desired at all.

Comparison of different joint designs can be seen in the table below (Figure 6-1). This table concludes the features of various knee joint concepts in detail, and compares their design strength and weaknesses.

Even though the concepts proposed in this paper achieved a proper alignment in terms of kinematics, these designs still need improvements. Some parameters can be adjusted to create more rigid and at the same time more ergonomic design solutions.



Knee joint naming	Actuation system	Mechanism type	Advantages	Disadvantages
Knee joint based on cross four-bar linkage [13]	BLDC motor at the upper part of the thigh	Cross four-bar linkage system	ICR trajectory overlaps with human knee	Misalignment occurs at certain stages of flexion
Bionic knee joint [14]	Linear motor drivers	Four-bar mechanism		
A novel wearable knee exoskeleton [15]	Motors	1 active driving pulley, 2 passive aligning pulleys connected by cables	Perfect alignment with human knee	Will have a high number of redundant constraints with BLDC rotary motors
A self-aligning knee joint [16]	Linear motor drivers	Linear actuators for each aligning pulley connected by steel cables		
Bioinspired knee joint [12]	BLDC motor at the upper part of the thigh	Guide rails with curves designed similarly to flexion trajectory	Compatible with BLDC motors and has accurate alignment	Designed only for knee joint exoskeletons
Concept with gear teeth	BLDC motor at the knee joint	Roll-back motion similar to human knee joint. Gear teeth are mounted to curvature profile that is similar to femur's lateral condyle curvature	Compatible with gait rehabilitation exoskeleton. Has accurate alignment at early stages of flexion	Needs improvements in gear teeth profile design to achieve perfect alignment at all stages of flexion
Concept with ball bearings		Roll-back motion similar to human knee joint. Ball bearings roll on a curvature profile that is similar to femur's lateral condyle curvature	Compatible with gait rehabilitation exoskeleton and is accurately aligned with human knee	Needs modification to enhance the stability of the structure during gait cycles

Figure 6-1: Comparison of knee joint concepts

Chapter 7

Conclusion

Problem of a knee joint misalignment between human and exoskeleton knees, cause perceptible inconveniences. Although most of the exoskeleton manufacturers try to implement simple knee joint mechanisms with a single revolute joint, for exoskeletons that will be used for medical purposes the perfect alignment is required. In this paper, several attempts were made to achieve a properly aligned knee joint mechanism for gait rehabilitation exoskeleton. In addition this mechanism had to be compatible with existing gait robot. Considering all of the constraints of human biomechanics and rehabilitation exoskeleton, two concepts were developed. Both of them were prototyped and tested in simulation software and in practice. After the validation of the concepts, it was defined that the concept with ball bearings provided more accurate alignment at all flexion angles. However, the geared model has also shown promising results, although it might need improvements regarding the gear teeth design. The concept with ball bearings also needs some modifications in order to obtain perfect alignment, but at this stage after assessment of the mechanism kinematics and investigation of the concept validity it can be concluded that this knee joint model is properly aligned with a human knee.

Appendix A

Tables

Appendix B

Figures

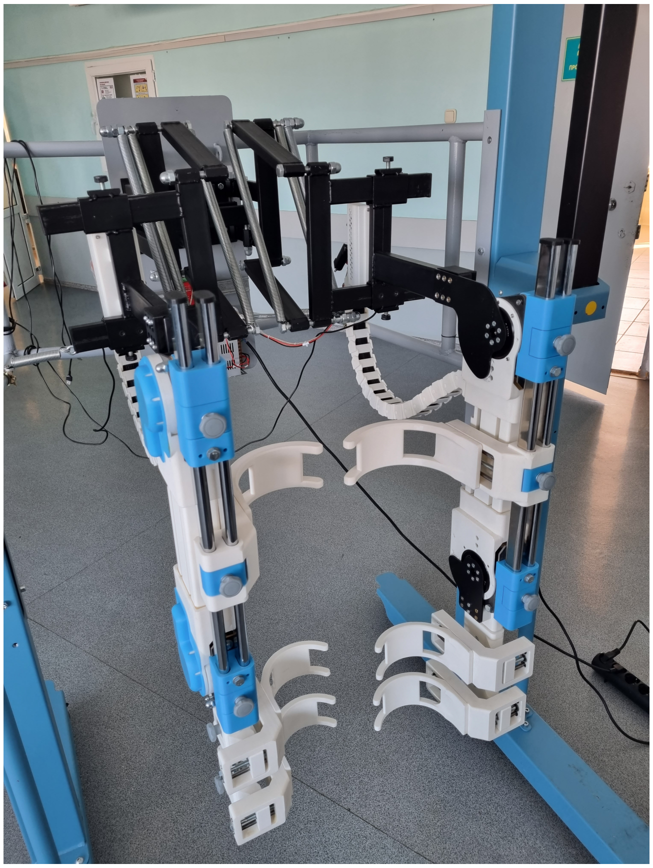
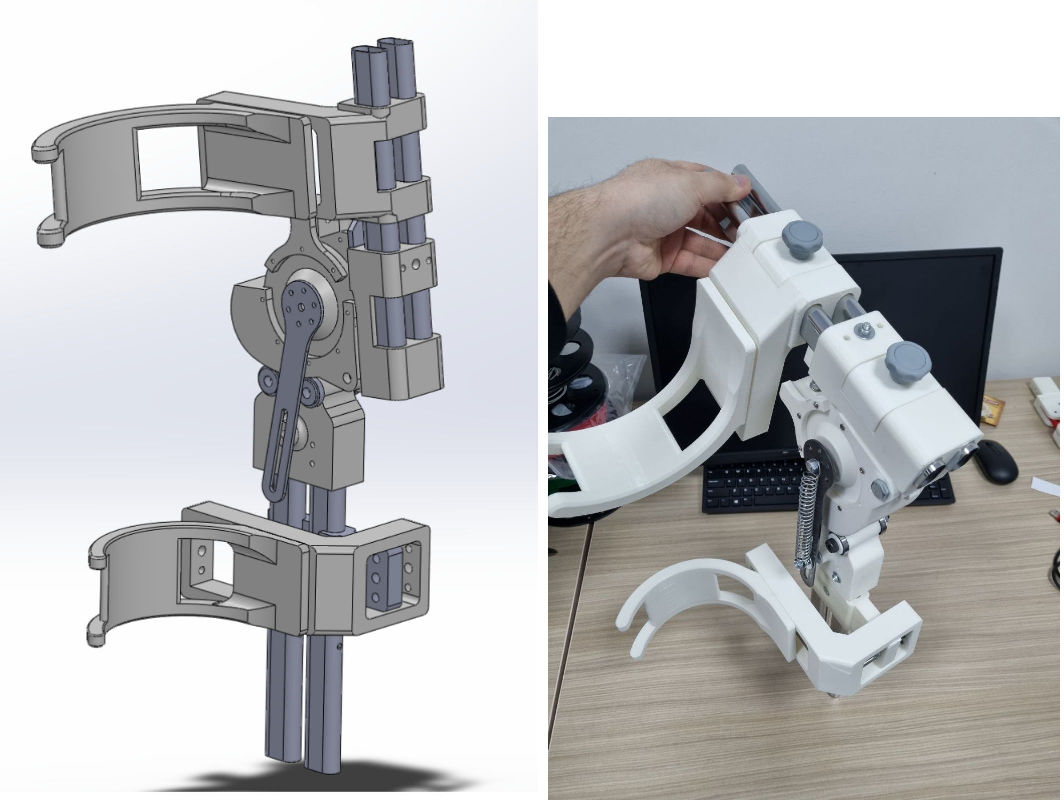


Figure B-1: Exoskeleton

Figure B-2: AK80-64 BLDC motor

Figure B-3: Clinical trials of an exoskeleton on human test subjects



(a) in SolidWorks (b) in live

Figure B-4: Assembled model

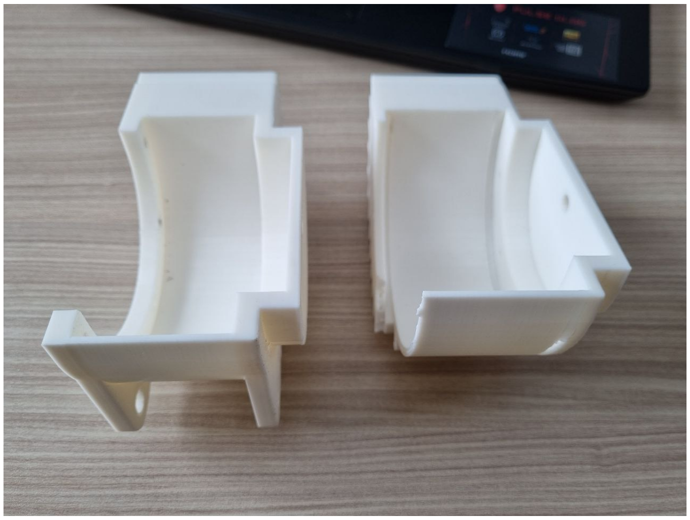


Figure B-5: Redesigned part and broken part

(a) Without tracks

(b) With tracks

Figure B-6: Solution to misalignment problem of the concept with ball bearings

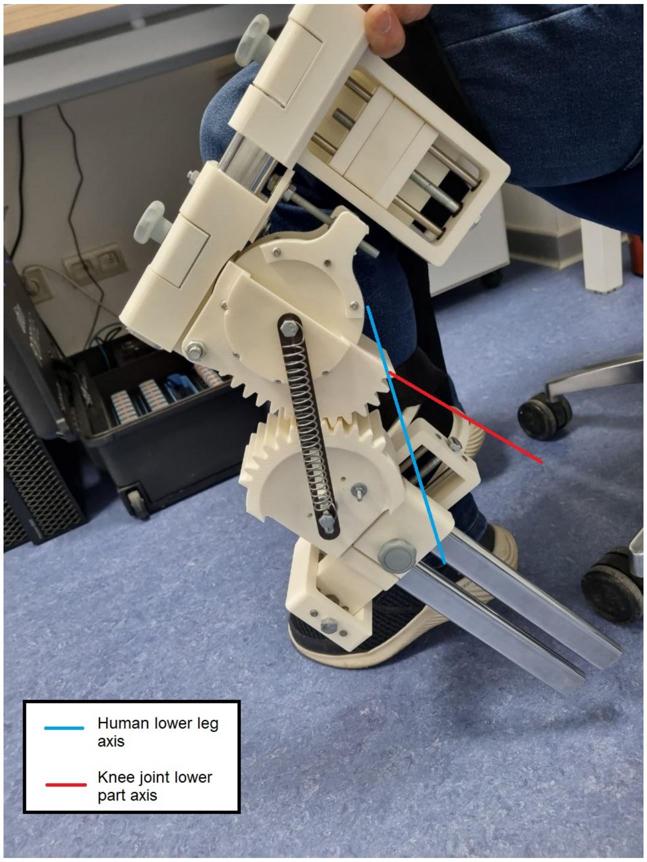


Figure B-7: Overbend at the brace

Figure B-8: Noraxon Ultium portable lab

Figure B-9: IMU sensors attached to human leg

Figure B-10: IMU sensors attached to knee joint prototype

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