KnExo, Design, Development, and Functional Evaluation of a Bio-joint Shaped Knee Exoskeleton Assisting in Sit to Stand

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Abstract—In addressing age-related muscle strength decline among elderly individuals, the development of assistive devices for daily living becomes imperative. This paper introduces a passive knee exoskeleton designed to aid older adults during sit-to-stand movements. Inspired by knee joint biomechanics encompassing rotational and translational motions, this exoskeleton employs a cam mechanism. This mechanism facilitates thigh rotation within a linear slot, adjusting the exoskeleton’s rotational center and effectively minimizing misalignment with the body’s knee joint. As the upper part attached to thigh rotates within the cam mechanism, a spring in the lower part attached to the shank compresses via a crank, storing energy during the sitting phase and releasing it during standing. The evaluation involves using an instrumented chair and footplate to collect force data during sit-to-stand motions. Force sensor resistors are positioned to measure force and pressure distribution across various regions. Notably, the developed knee exoskeleton (KnExo) provides 25% and 31% assistance of body weight under no-loaded and loaded (with a 20kg load) conditions, respectively, according to initial functional evaluation. Furthermore, compared to a revolute joint, the proposed knee-exoskeleton exhibits a substantial 51% reduction in misalignment with the user’s knee joint. This underscores its potential as an effective assistive device for elderly individuals coping with diminished muscle strength.

Index Terms—Assistive device, Biomechanics, Knee Exoskeleton, Sit-to-Stand

I. INTRODUCTION

The elderly population has increased in the U.S. recently [1]. It is stated that in 2008, there are 38.8 million people over 65 years of age, and it was 52.4 million in 2018 (35% increase in 10 years), and this population is expected to increase to more than 94.7 million by 2060 [1]. Aging causes the loss of muscle fibers; therefore, it decreases muscle strength capacities and metabolism [2]. Consequently, reduced muscle power may increase the risk of falling by decreasing the postural stability in older adults [3]-[5]. In these individuals, the strength of the muscles reduces by 12-15% every decade [6]. Among the human activities of daily living (ADL), the sit-to-stand (STS) movement is one of the repetitive ones. For instance, standing up from a chair is an activity that is repeated daily for several times. Lower limb muscles such as the quadriceps, tibialis anterior, hamstrings, and glutes contribute to this ADL [7]. Aged people exhibit more muscle activities of the lower limb muscles during the STS movement [8]. Several research studies are conducted to design assistive devices to help older people with ADL [9]-[11]. These devices, such as Indego Exoskeletons [9], can aid individuals with muscle weakness and influence the postural controls and upper body postures [9]. These assistive devices are classified as passive and active devices. Passive elements such as mechanisms with elastic elements are employed in passive devices for assistance. whereas, in the active devices, external power is injected via actuators, i.e., D.C. motors. For instance, Beyl et al. introduced KNEXO, utilizing pleated pneumatic artificial muscles (PAMs) to offer adjustable knee joint support [12]. Kong et al. employed a rotary series elastic actuator (SEA) for precise torque generation during gait rehabilitation [13], while FUM-KneeExo and other models incorporated linear SEAs for knee joint assistance [14], [15].

While active exoskeletons fulfill the varying requirements of different ADL, there is higher mass and complexity within these systems. Moreover, their reliance on batteries often limits the operational duration. Consequently, some researchers advocate for passive exoskeletons to address these constraints, aiming for lighter, more compact designs with reduced complexity. Libo Zhu et al. [10] propose a passive lower-limb exoskeleton to compensate for gravity, including springs, gears, and a lead screw nut mechanism to convert the axial forces to the torques on the hip and knee joints. Kong et al. present a tendon-driven exoskeleton to assist patients and older people in carrying heavy objects [11]. Diego Felipe et al. propose a passive exoskeleton to assist the STS transition with a torso lifting mechanism [16]. This exoskeleton can reduce more than 30% of the muscle activities engaging in this transition.

Although passive exoskeletons assist elderly individuals with their ADL, addressing the misalignment between these exoskeletons and the body’s joints remains a significant challenge in designing lower-body exoskeletons. The biomechanics of the knee joint encompass rotational and sliding motions [17], maintaining a specific ratio between these movements [18]. Previous studies emphasize the significance of a cam mechanism, crucial in providing both rotational and sliding motions to replicate human activities like walking or sit-to-stand motions [19], [20].

Addressing these limitations, this paper presents a passive mechanism tailored to aid older individuals and those with weakened muscles by providing support of up to 25% of their body weight, alleviating the strain on their muscles. To replicate the natural behavior of the knee joint during sit-to-stand movements, this study minimizes misalignment between the knee exoskeleton and the user’s knee joint by integrating a cam mechanism based on the concept we proposed in our previous study [21]. The KnExo and the braces to fix it to the body are manufactured using Aluminum and ABS materials. Additionally, an instrumented chair equipped with 16 force-sensitive resistors (FSRs), meticulously designed to capture the nuanced distribution of forces during STS cycle, is introduced in this paper. This innovation aims to enhance our understanding and approach to developing assistive technologies for individuals with specific mobility challenges.

II. DESIGN AND DEVELOPMENT OF KNExO

A. Mechanical and conceptual design

A biomechanical analysis of human sit-to-stand (STS) behavior reveals that the required knee torque for a 75kg body amounts to approximately 45 N.m during the stance phase. Analyzing the kinetics of the sitting phase suggests an opportunity to harness potential energy that can be stored and subsequently released during the standing phase. Thus, employing elastic elements becomes instrumental in storing energy during the sitting phase.

As part of the conceptual design (Fig. [1]), the rotation center of the exoskeleton at the upper link is positioned within a linear slot at the lower link to prevent the misalignment of the bio-joint rotation center.
and increase the shank’s length with respect to the fixed rotation center at the femur. As the lateral compartment of the femur rotates and slides on the tibia, the cam slot path is designed according to its sagittal shape. While the crank mechanism moved horizontally and vertically in the upper link, a compression spring is deflected in the lower link. The exoskeleton’s functionality is closely connected to the dynamics of the femoral lateral compartment, which undergoes both rotational and translational movements along the tibia. The design of the cam slot path is specifically tailored to accommodate the sagittal profile of these motions, as shown in Fig. 1 (left).

The mechanical aspects of this system come into play when the crank mechanism operates horizontally and vertically within the cam slot. Simultaneously, in the lower link, a compression spring experiences deflection. The length of the linear slot is determined based on the variation in distance between the exoskeleton’s rotational center and the cam rollers. This distance varies, extending to 15 mm during full flexion and contracting to 10 mm at a 90-degree angle. These values correspond to the posterior translation of the femur relative to the tibia, as elucidated in [22].

The proposed exoskeleton in this paper comprises three primary components: the thigh link, the bio-joint shaped mechanism, and the shank link, meticulously designed based on both the conceptual framework and design parameters derived from biomechanical data obtained from OpenSim gait2392 [23]. The CAD model of the proposed KnExo is depicted in Fig. 1 (right), includes a shank, femur, compression springs, connection braces to the body, and a crank responsible for energy transfer. The knee exoskeleton is linked to the body through two position adjustable metallic elements and supporting braces.

### B. Kinematic and kinetic analyses

Referring to Fig. 2 the arm \( r_m \) momentously transmits the generated force within the elastic element encased within the shank, exerting torque around the knee joint. The magnitude of the moment arm vector dynamically alters with the knee joint’s flexion/extension, governed by the relationship:

\[
 r_m = r \cos q_k
 \]  \hspace{1cm} (1)

Here, \( r \) denotes the radius of the cam slot, while \( q_k \) represents the knee joint angle. The schematic diagram illustrating the human leg joints alongside the corresponding cam slot mechanism is depicted in Fig. 2 (left). Notably, the maximum value of the moment arm occurs when the subject is in a seated position, whereas it diminishes to zero when the body is in a stance position.

The configuration of the crank mechanism and the cam slot during the STS task is shown in Fig. 2 (right). Based on this figure, the deflection of the spring inside the shank can be calculated as follows,

\[
 s = r \left( 1 - \cos q_k \right) \]  \hspace{1cm} (2)

Where \( s \) is the spring deflection during the stance phase of the STS task. Based on the generated force and moment arm vectors, the generated torque around the knee joint is determined as follows,

\[
 \vec{T} = \vec{r}_m \times \vec{F} \]  \hspace{1cm} (3)

Where \( \vec{r}_m \) and \( \vec{F} \) are the moment arm and force vectors. Since the angle between the force vector and the moment arm is \( q_k \), the generated torque is determined as follows,

\[
 T = F r \cos q_k \]  \hspace{1cm} (4)

As indicated in Fig. 2 (right), the spring deflection depends only on the knee joint angle. A force-deflection graph depicted in Fig. 3 is generated using the biological torque profile and equations of torque and deflection (2) and (4) to determine the necessary stiffness of the elastic element for the knee exoskeleton for the fully assistive condition as follows.

![Fig. 2. Schematics of human leg joints (left) and spring deflection (right)](image)

![Fig. 3. Force-deflection graph for fully support mode](image)
the design parameters while ensuring functionality within specified limits: a maximum outer diameter of 12 mm and an initial length of 140 mm. This selected stiffness achieves the desired assistance level and functionality within the exoskeleton’s constraints, as depicted in Fig. 4 in the simulation of generated torque with the selected springs.

Fig. 4. Performance evaluation of the knee exoskeleton for 25% assistance

According to this simulation, the KnExo can provide 25% assistance of the knee joint torque during the STS task with 0.2 s shift in the time.

C. Prototyping

For the realization of the KnExo CAD model, components like the thigh link, shank link, crank mechanism, and brace holders are made from standard Al 7075. Rotational pins, linked via ball bearings, facilitate movement in the thigh and shank. 3D-printed ABS braces attach to each leg, forming part of the KnExo. Fig. 5 (a) illustrates these pins enabling exoskeleton rotation during STS. The KnExo prototype (Fig. 5 (b)) is worn by the user (Fig. 5 (c)), attached to the lower limbs with braces and straps, and aligned with the user’s knee.

Fig. 5. a: The rotational pins of the knee exoskeleton, b: KnExo prototype, c: KnExo worn by the healthy subject

The total mass of the exoskeleton is 2.25 kg for each goal, and the dimensions for each leg are $20 \times 24 \times 60$ cm.

III. EVALUATION OF THE KNEEEXO

This KnExo evaluation study is approved by the Clinical Research Ethics Committee of Istanbul Medipol University with document number of E-10840098-772.02-6696. One of the author of this manuscript has been participated to this experimental study.

A. Functional Evaluation

A well-designed experimental setup is crucial for a comprehensive evaluation of a KnExo’s performance during STS tasks. To find the best configuration of the sensors, the previous studies, which indicate the pressure distribution for each body segment and involve various sensors, such as sensor sheets [24], a pressure plate [25], and graphene textile-based sensors [25] are considered. These sensors facilitate the placement of 5 Force-Sensing Resistors (FSRs) per foot, strategically focusing on critical areas like the ball and heel regions (Fig. 6 right). Additionally, insights from pressure distribution findings [25] guide the strategic placement of 2 A502 (Tekscan, USA) FSRs in each thigh’s sitting region. For assessing hand forces during STS, 2 A402 FSRs (Tekscan, USA) per hand are meticulously positioned on the chair’s arm (Fig. 6 left), providing a total of 16 FSRs to measure forces from feet, hands, and thighs during the tasks. The sensor outputs are interconnected to an Arduino Mega 2560 board for analog output reading, forming a circuit arrangement comprising two 0.22µF capacitors, a 100kΩ resistor in parallel for each FSR sensor, and a TLC 272 Op-Amp amplifier. Each sensor is connected to a -0.75V source derived from an ICL 7660 voltage regulator, ensuring a standardized voltage for accurate measurements.

The instrumented chair, positioned 50cm above ground level, is integral to the setup. This chair integrates hand and thigh plates (Fig. 6 left), while a footplate hosts the feet FSRs, and the electronic equipment is centrally positioned (Fig. 6 right). This arrangement enables simultaneous contact of all FSRs with feet and hand plates, ensuring synchronized data recording.

Fig. 6. Instrumented chair to measure the forces during STS movement (Left), footplate and the electronic equipment of the knee exoskeleton (Right)

For the experiments, a healthy individual, 175cm tall and weighing 80kg, has been participated in assessing KnExo’s functional capabilities. The STS cycle is performed in 6 cases: unloaded and subsequently with a 20-kg load evenly distributed across a backpack without wearing KnExo to collect the baseline data. Loaded scenario has been adopted to resemble the case of 25% assist to elderly people wearing the KnExo. Additionally, the subject repeats the cycles with and without exoskeleton assistance condition, encompassing both loaded and unloaded STS cycles. This evaluation allows for a comprehensive comparison of force data between various conditions, shedding light on the exoskeleton’s efficacy under different loads and assistance modes. Each STS cycle, lasting four seconds, captures ground reaction forces, hand, and sitting region forces. Wearing the exoskeleton takes about 40 seconds. Thus, the whole experiment takes about only 13 minutes with 2 minutes breaks in between each case.

Data collection encompasses applied total forces on feet, hands, sitting region, and overall feet/heads forces, resulting in 23 data sets. The testing duration averages 4 seconds per STS cycle, repeated five times for result repeatability. Graphical representations illustrate load-bearing modes (with/without backpack load) assisted by the exoskele-
ton (A.E.) and without exoskeleton assistance (NoAE), facilitating comprehensive analysis of the results.

The total forces from the hands, while the subject has no load and has a load in both (A.E.) and (NoAE) cases, are shown in Fig. 7.

![Fig. 7. Hands FSRs total forces (a), Hands FSRs average forces in five cycles (b) without any load, and Hands FSRs total forces (c), Hands FSRs average forces in five cycles (d) with 20kg load in the backpack in NoAE and A.E. modes](image)

As it is depicted in Fig. 7 (a and c), the maximum force from hands is 180 N and 200 N for no-load and loaded cases, respectively. The moving average filter is implemented in these figures. Since the sample rate is 50 Hz, the average duration of each STS cycle is 4.5 and 5.75 seconds for the no-load and loaded cases, respectively. Hence, the average of the five cycles in both no-load and loaded cases are plotted. Fig. 7 (b and d) show the average forces from the hand FSRs during the five cycles of STS movement. As it is shown in this figure, the maximum average forces from the hands FSRs in the loaded case are 124N and 91N for the NoAE and A.E. modes, respectively.

Five sensors in each foot also measure the total force on the feet for the loaded and unloaded cases in both NoAE and A.E. modes depicted in Fig. 9.

![Fig. 9. Feet total forces for unloaded (a) and loaded (b) cases in both NoAE and A.E. modes](image)

From the observations in Fig. 9, the average total forces in five cycles on both right and left in no-load and loaded cases for the AE mode are 815N and 1027N, respectively.

**B. Misalignment Evaluation**

Two markers are placed on both the subject and the knee joint of the exoskeleton to measure the alignment discrepancies between them. These markers are positioned in a manner ensuring their axes align when both the subject and exoskeleton are in a standing position. The three-dimensional positional data of these markers are recorded using five motion capture cameras (NaturalPoint, Inc. DBA OptiTrack, U.S.), operating at a sample rate of 50 measurements per second. Misalignment between the subject’s knee and the exoskeleton’s knee joint is quantified by examining the difference in the longitudinal data of these two markers. These tests are conducted five times, with each STS cycle lasting 5 seconds. In this study, the average of these cycles is being reported. The knee exoskeleton is considered a 3DOF linkage system, with the foot assumed to be fixed on the ground during the STS, to facilitate a comparison between the misalignment results of the bio-joint shaped knee exoskeleton and those with a revolute joint. Consequently, the longitudinal position of the knee joint can be calculated as referenced in Equation 5.

\[
P_x = l_f \sin q_a + l_k \sin (q_a + q_k)
\]

Where \(l_f\) and \(l_k\) are the foot and shank links lengths, and \(q_a\) and \(q_k\) are the ankle and knee angles during the STC cycle. The results of these two methods are shown in Fig. 10.

![Fig. 10. Knee exoskeleton longitudinal position for unloaded (a) and loaded (b) cases in both NoAE and A.E. modes](image)
The misalignment results of the bio-joint shaped knee mechanism when compared with the revolute joint mechanism, highlight that taking into account both rotational and translational movements in the knee joint, akin to the biomechanics of the human knee joint, provides a more accurate emulation of the actual knee biomechanics compared to the use of a standard revolute joint in the knee exoskeleton. Any existing misalignment in the knee exoskeleton may stem from the mechanical constraints of the prototype and the disparities between the implemented data and the specific biomechanical characteristics of the subject, such as foot and knee angles during STS. While collecting subject-specific biomechanical data is theoretically feasible, it may not be practical in many situations. In this study, only STS activity is investigated, whereby adding an additional mechanism in the foot to engage and disengage the spring mechanism can make this device to be employed during walking, as well. Additionally, this study present the initial prototype of the KnExo for functional evaluation purpose by using the 3D manufactured part, such as plastic reinforced by carbon fiber or tough PLA, significant mass and volume reduction would be achieved.

V. Conclusion

Design, development, and functional evaluation of a bio-joint shaped knee exoskeleton capable of storing energy during sitting and releasing it to assist during standing are presented in this study. Initially assessed for functionality, the KnExo offers assistance equivalent to 25% of body weight without a load and 31% when carrying a 20kg load. Additionally, the misalignment of the device from the knee joint of the subject is evaluated. Compared to a revolute joint, the suggested knee exoskeleton showcases a significant decrease of 51% in misalignment with the user’s knee joint. As a future work, implementing dis/engaging mechanism to enable this knee exoskeleton for walking assistance would be very beneficial for elderly people and industrial workers during their daily activities. We would also like to evaluate this exoskeleton with more subjects and possibly with EMG measurements to show the efficacy of the device in a more generic way. After these evaluations and improvements on the design of the KnExo, it would of course be necessary to evaluate the efficacy of the device with its end-users for putting it into service of elderly people to improve the quality of their life.

VI. Supplementary video

The experimental evaluations of the KnExo are illustrated in a [video](https://youtu.be/6bJUe16uAmQ) with the link address of https://youtu.be/6bJUe16uAmQ.
REFERENCES