Design and development of knee rehabilitation robot

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ABSTRACT

This research presents a comprehensive design and analysis of a knee rehabilitation platform aimed at aiding individuals with knee dysfunction. Dysfunction in the knee joint can lead to an imbalance in gait and posture during activities of daily living (ADLs) such as standing, walking, and running. This study focuses on developing a 2-degree-of-freedom (2-DoF) knee rehabilitation device capable of mimicking linear and angular movements. A slider mechanism-based knee rehabilitation device is developed and simulated alongside various other mechanisms. The proposed mechanism achieves 32.5° of flexion for a linear movement of 0.45 m within 6 seconds, outperforming other mechanisms. To validate simulation results, a 3D-printed model is fabricated, and experimental studies are conducted under no-load conditions, showing close alignment with simulation outcomes with a deviation of ±5%. The device's key features include portability, compliance, compactness, and enhanced stiffness. Future research will involve conducting pilot studies to further evaluate the practical efficacy and potential enhancements of the proposed knee rehabilitation platform.

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1. INTRODUCTION

Knee rehabilitation is essential for assisting individuals who have knee injuries or have undergone knee surgery to regain strength, function, and mobility in the knee joint. The need for knee rehabilitation arises due to ligament tears, fractures, osteoarthritis, knee surgeries, and knee replacements. Rehabilitation helps increase muscular strength and joint stability, reduces pain and swelling, and aids in tissue repair, thereby achieving the natural range of motion [1], [2]. The knee symmetry model emphasizes achieving a symmetrical range of motion and strength post-surgery, designed to optimize outcomes and promote joint health [3]. Traditional rehabilitation procedures performed by physiotherapists can be time-consuming and sometimes less efficient [4]. Robotic technologies optimize the rehabilitation process by providing physicians with constant feedback, allowing them to evaluate and modify therapy regimens as needed [5]–[7]. Robotic knee rehabilitation devices have become essential tools in rehabilitation, offering significant benefits over traditional approaches. These devices can adjust to the unique characteristics of each patient, enabling personalized therapy and real-time progress tracking [8]. Recent research advancements in knee rehabilitation robotics demonstrated significant potential in improving rehabilitation outcomes. These developments emphasize innovations in structural design, drive units, and control strategies aimed at advancing personalized rehabilitation approaches and optimizing patient care [9].

Currently, several knee rehabilitation tools are available, each with its own set of features, design principles, and mechanisms. These include wearable technology, continuous passive motion (CPM) machines, and robotic exoskeletons. Robotic exoskeletons, which are external devices placed around the lower limb, aid in knee movement by providing mechanical support and can be programmed to control specific joint trajectories [10]. Wearable technology models, on the other hand, are portable and small, making them easy to incorporate into regular activities. CPM machines consist of a motorized device that moves a joint passively through a predetermined range of motion. These devices can alleviate joint stiffness and enhance the range of motion following surgery by preventing scar tissue formation, promoting circulation, and allowing adjustable knee flexions. However, CPM machines primarily provide passive motion and do not address muscle weakness, offering limited functional training [11], [12].

To overcome the limitations found in existing models, this research aims to develop a 2-degree-of-freedom (DoF) knee rehabilitation device that provides both linear and angular actuation movements simultaneously. This device provides the necessary actuation for flexion and extension motions. The proposed knee robotic system is designed to be compact, cost-effective, and adaptable for use by multiple patients, ensuring an effective and efficient rehabilitation process.

2. RELATED WORK

A critical review was conducted to examine the use of different types of robotic devices in knee rehabilitation and stated the significance of rehabilitation and the role of different robotic device types in knee rehabilitation [10], [13]. A lower-limb rehabilitation robot, human adaptive mechatronics (HAM) was developed with the framework for patients with paralysis, which is aimed to enhance human-machine interaction and skill improvement. This robot's mechanism includes three rotary joints with crank rocker mechanisms, offering flexibility to cater to diverse user needs [14]. CPM machine-based knee rehabilitation is considered to promote joint mobility, reduce stiffness, and naturally achieve the knee's range of motion [11]. Similarly, a separate study focused on developing a 1-DoF robot that offers passive, active, and resistive exercise capabilities using position and force control techniques [15]. The selection of appropriate mechanisms for linear and angular actuation is crucial in the design of rehabilitation robots [16]. A comprehensive design and analysis of six different linear mechanisms was conducted to evaluate their suitability for knee rehabilitation applications. The mechanisms studied included lead screw, hydraulic, 4-bar, roller-based belt, grasshopper, and rack and pinion slider mechanisms. Each mechanism offers unique characteristics and advantages that can contribute to the effectiveness and functionality of knee rehabilitation robots. Moreover, other models are expensive, complex, and challenging to set up for personal usage, often requiring the assistance of a physiotherapist [12]. Minimizing motor slippage is a critical factor for achieving ideal rehabilitation outcomes, as it directly affects energy losses and accuracy. Therefore, addressing these issues is crucial for the development of an optimal knee rehabilitation robot.

Based on the literature survey, it was inferred that achieving optimal range of motion of the knee requires careful consideration of the angle at which the actuation is performed, while also taking into account the comfort of the patient. Furthermore, the study highlights the utilization of the lead screw mechanism for angular actuation purposes, specifically in lifting the top frame that incorporates the linear actuation mechanism [17]. The lead screw mechanism offers a straightforward and efficient solution for generating linear motion with high resolution achievable making it suitable to initiate angular actuation with some design addition so we incorporated this design approach. Existing literature reveals a gap in the development of a CPM robot specifically designed with 2-DoF (linear and elevation) to facilitate a curved range of motion in knee rehabilitation, highlighting the targeted focus of our current research [18].

The literature review also highlights the potential of knee rehabilitation robots in improving mobility and strength for individuals with knee injuries or disabilities. The study of various variables and actions that are included in the motion of the patella (knee) in the human body is determined by surveying and collecting data based on parameters such as gender, age, body mass index (BMI), and knee-to-foot length. It helped in the selection of appropriate mechanisms for linear and angular actuation which is crucial, with the rack and pinion-based slider mechanism identified as the most suitable choice for linear actuation. The lead screw mechanism proves effective for angular actuation by lifting the top frame [17]. Furthermore, the literature review highlights the significance of conducting a comprehensive structural analysis for fabricating rehabilitation devices using thermoplastics [19]. The selection of thermoplastics for fabrication, known for their advantageous properties such as high strength-to-weight ratio and excellent impact resistance [20], has contributed to achieving a durable and efficient design suitable for the intended application of knee rehabilitation. Integrating control strategies such as bio-signals, position, force, and adaptive control will enhance patient engagement, tailor assistance levels, promote active participation, and provide personalized assistance based on individual needs and progress [21], integration of electromyography (EMG), and motion sensors to monitor patient recovery. Additionally, the incorporation of skin conductivity sensors for more precise pain monitoring and the optimization of control algorithms will aid the rehabilitation process [22]. Using a pneumatic artificial muscle (PAM) actuator, and a neural network control approach is also explored in knee rehabilitation, to overcome challenges like air compressibility and lack of damping [23], [24].

3. METHODOLOGY

The objective was to design and evaluate these mechanisms to achieve the required flexion motions for an effective rehabilitation procedure. Figure 1 illustrates the detailed process flow of the design. The need to determine the extension length of the foot and inclination is crucial to execute the actuation and flexion movement. The average foot length was found to be 0.185 m and the average leg weight i.e., lower limb weight 11.5 kg. Also, the range of motion (RoM) for the knee extension angle to be achieved by the patient post-surgery is 65° for ease of movement of the knee, which reduces and limits the pain to the patient during the extension and retraction process during the rehabilitation procedure [11].

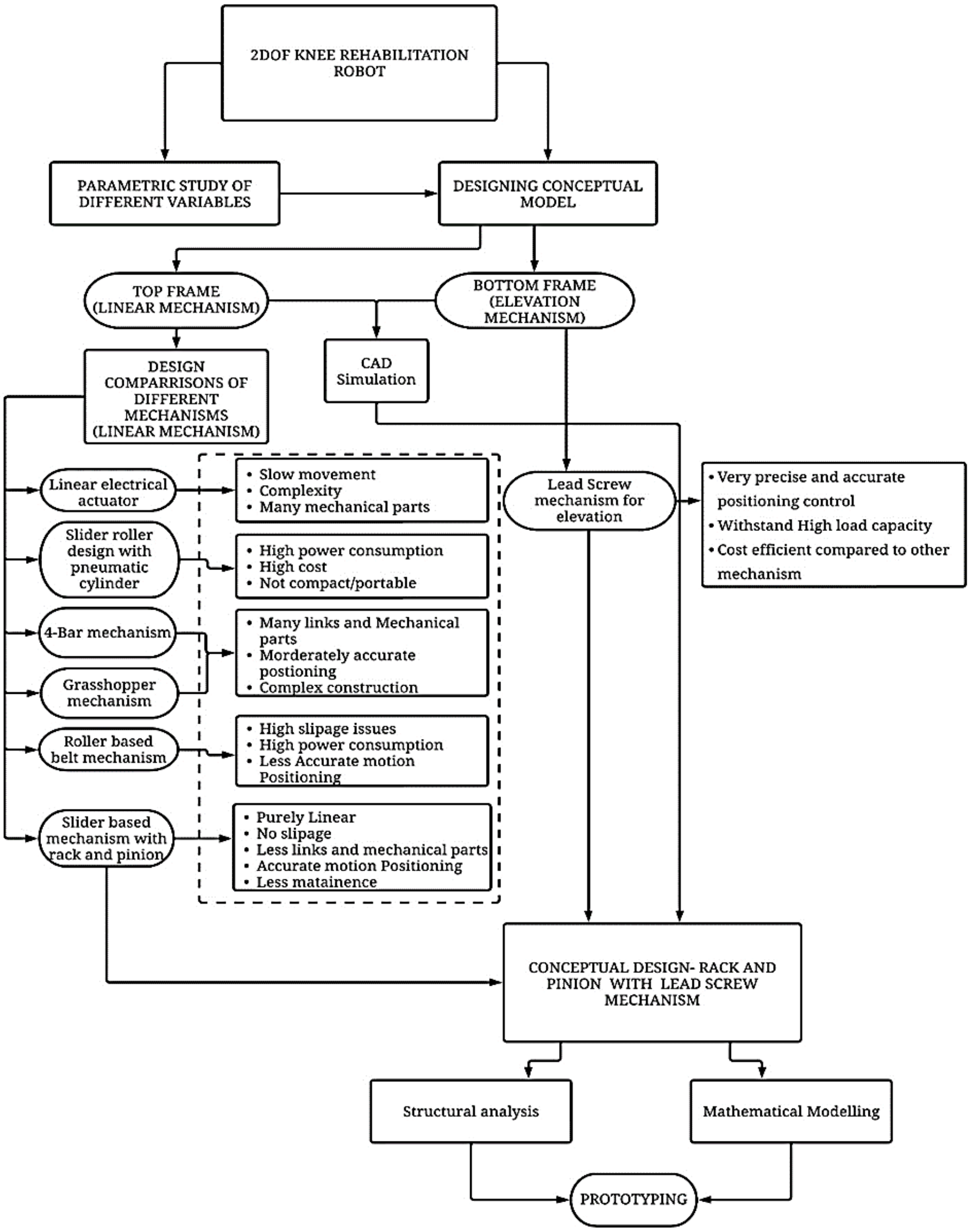


Figure 1. Workflow chart

Figure 2 shows the lower part of the leg which includes the knee and heel region, her dashed red lines indicate a strictly linear path without any angular actuation and the green curved line shows the path achieved by the foot when both linear and angular actuations take place. The data found and collected is used for designing the framework of the system that is created including the inclination and range of motion [11]. The actuation methods are classified into two categories, i.e., linear and rotary actuation resulting in 2-DoF motion to obtain the curvature projectile for the knee joint to move [25].

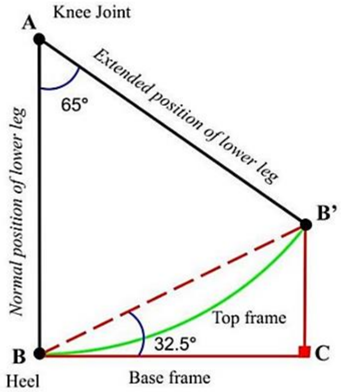


Figure 2. Frame diagram of the mechanism and position of the human lower limb

3.1. Linear actuation mechanism

A study was conducted on possible mechanisms that could allow the top frame to mimic 1-DoF of knee motion which is the linear motion. Figure 3 shows the mechanisms that were designed and studied, which were slider based mechanism, grasshopper mechanism, lead screw-based mechanism, roller belt, and 4-bar mechanism, and rack and pinion mechanism was used to achieve the flexion and extension motion [26].

Based on the study, it is found that the linear actuation should be done at a certain angle as shown in Figure 4, to achieve optimum and better results, while considering the comforts of the patient to achieve the same type of actuation devices such as hydraulic cylinders, pneumatic cylinders, tandem cylinder, gear-based mechanism and a manual slot bar mechanism to adjust the linkages according to patients comfortability. This can be used to lift the top frame which contains a mechanism for linear actuation that was proposed [10].

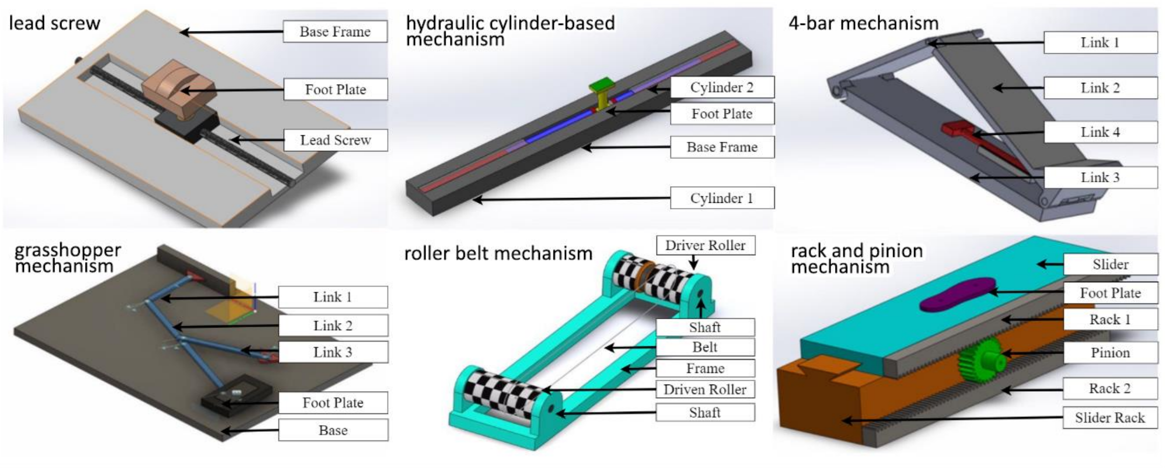


Figure 3. Different linear actuation

3.2. Structural analysis

To verify the model the structure analysis is needed to analyze the load and the material loading capacity of the integrated model. The material polyimide (PI) thermoplastic and aluminium alloy for the joints and connection respectively were considered based on their properties at specific locations for testing, making them durable, lightweight, and feasible [20].

The static structural analysis is carried out on 3 different positions: home position, mid position, and fully extended position to determine the structural integrity of the model. Figure 5 explicitly depicts the structural analysis in 2 positions i.e. home and fully extended position. The force applied on the footplate placed on the slider is 150 N, with fixed support applied on the base. The net force 150 N is the force acting on the lower limb weight on the machine, safety factor (1.33), and gravitation force i.e. F = $ma \times 1.33$.

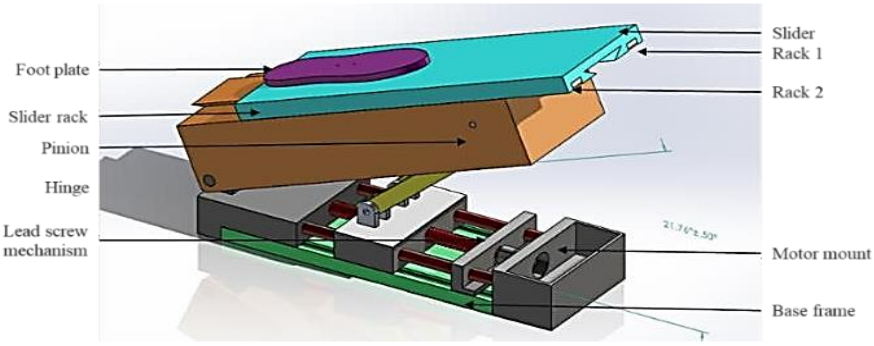
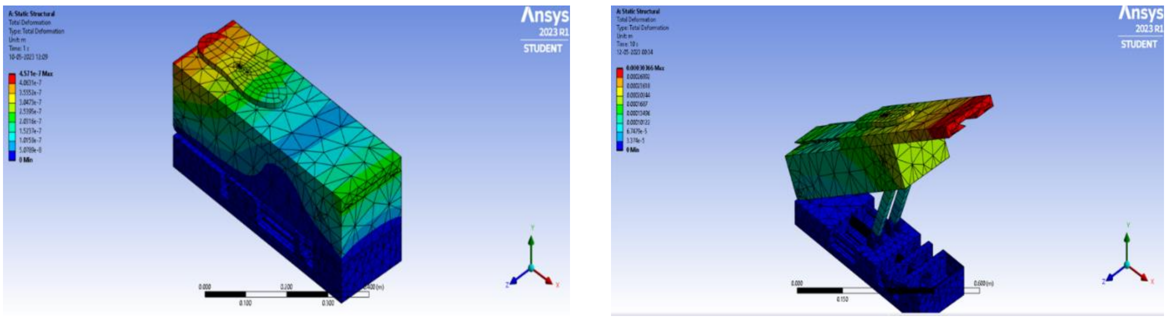
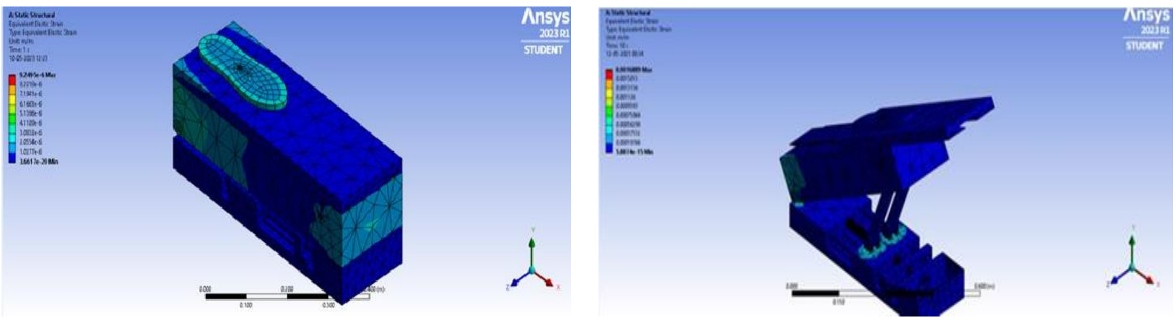


Figure 4. Finalized design to achieve curved path using two mechanisms



Home position Extended position

Figure 5. Total deformation at the (a) home and (b) extended position



Home position Extended position

Figure 6. Equivalent stress

Deformation is typically measured using displacement, which is defined as the change in position of a point in a structure. A stress analysis was performed as shown in Figure 6 and observed that the stress distribution within a structure is calculated using Ansys under varied loading circumstances. The stress distribution can be applied to determine the structure's maximum stress sites and likely failure modes. Ansys strain analysis is used to calculate the distribution of strain within a structure [19].

4. RESULTS AND DISCUSSION

A comprehensive comparison of six linear mechanisms is provided in Table 1. The lead screw mechanism is a simple and less complex design with fewer mechanical parts which is easy to implement but exhibits relatively high-power consumption and the movement of its components could potentially cause damage to joints if reflex actions occurred. The roller belt mechanism, while offering linear motion and flexibility in routing, suffered from slippage issues that could adversely affect the knee due to sudden movements. The 4-bar mechanism, although capable of implementation in a sleeping posture, was found unsuitable for the intended purpose [19]. The grasshopper mechanism, despite its unique motion, deviated from purely linear motion and required a large setup, making it impractical. The hydraulic-based mechanism displayed a huge setup, high cost, and significant power consumption, which were deemed undesirable.

Table 1. Comparison of linear actuation mechanisms

Factors	Roller-based linear actuation	Slider-based linear actuation	Four-bar mechanism based	Grasshopper mechanism	Lead screw mechanism based	Hydraulic cylinder based
Motion	Non-linear	Purely linear	Purely linear	Linear	Purely linear	Purely linear
Power consumption	High	Low	Low	Low	Low	Very high
Slippage	Yes	No	Yes	Yes	No	No
Complexity	High	Low	High	High	Low	Moderate
Links	Too many	Less	Too many	Too many	Too many	Less
Cost	High	Low	Moderate	Moderate	Moderate	Very high
Maintenance	High	Moderate	Low	Low	Moderate	Very high
Motion precision	Less accurate	Highly accurate	Moderately accurate	Moderately accurate	Highly accurate	Moderately accurate
Mechanism	Roller and belt	Rack and pinion	4-bar mechanism	Modified Scott Russel's	Lead screw	Hydraulic actuation

Figure 7 presents the final design to achieve a curved path using two mechanisms. From Table 1, it is observed that the slider-based linear mechanism with rack and pinion offers linear motion with no slippage, enabling better control and reduced energy consumption. Similarly, for the elevation motion, lead screw-based actuation was selected considering the slippage, tolerance, weight-to-force ratio, and other constraints. The slider mechanism provides the final motion to the system in terms of linearity. The main mechanisms to transmit energy from stepper motors are bevel and then rack and pinion. The motor shaft will be connected to the bevel gear and the motion will be transmitted to the pinion via a cantered shaft. The rack is connected to the slider and pinions move the slider via racks. The slider mechanism can also compensate for any reflex actions by the user. To elevate the top frame simultaneously when the slider actuates, the lead screw mechanism is considered to perform the motion according to requirements and the comparative study provided above. The lead screw elevation mechanism is designed to achieve up to 32.5° of elevation.

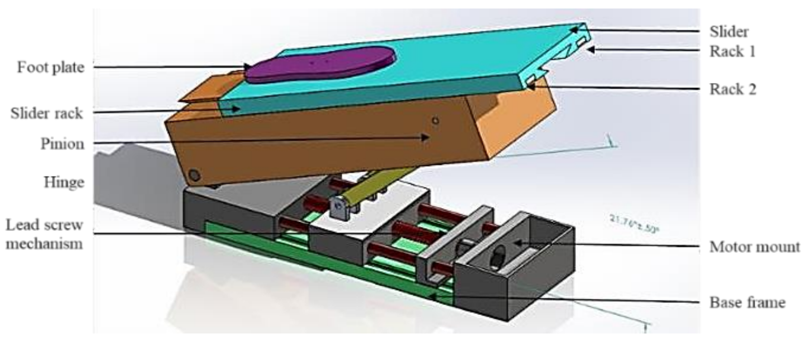


Figure 7. Final design to achieve curved path using two mechanisms

The lead screw length is 0.3 m and its pitch is 0.004 m. This mechanism is single lead as one revolution moves the carriage 0.004 m. In the analysis study, the total deformation levels from the different positions obtained are 4×10^{-6} m to 3.03×10^{-4} m when the model is analyzed from the base position to a fully extended condition. The deformation was checked for the load conditions in the home and an extended position in the simulation studies. It found that during the loaded conditions, the deformation was 0.14% from home to a fully extended position, which is minimal for the given material. This ensures that range has no negative impacts on the knee joint's movement in the machine's practical operation. It can be stated that the model is safe to operate under normal conditions.

5. PROTOTYPE

This system consists of a 2-DoF actuation mechanism and linear and angular actuation. A lead screw-based mechanism is used to elevate the top frame from the base position with the desired inclination, and a rack and pinion-based mechanism is used with a bevel gear transmission mechanism for the linear actuation of the slider mechanism. A prototype at a 1:3 scale is developed with fused deposition modeling (FDM) printing as it is one of the popular and well-known manufacturing techniques for manufacturing custom-made parts; therefore, for prototyping, the same technique is used.

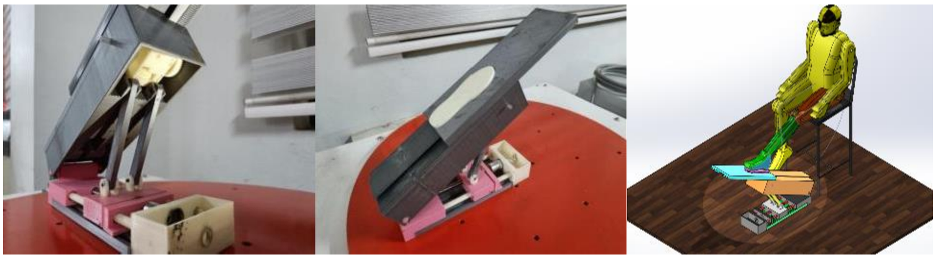


Figure 8. The 3D printed prototype at a scale of 1:3 and the rendering design with a CAD model of mannequin

Figure 8 showcases the small-scaled prototype (scale 1:3) with the internal gear system, manufactured using one of the additive manufacturing techniques called 3D printing with polylactic acid (PLA) material, which is a thermoplastic monomer derived from renewable, organic sources such as corn starch or sugar cane. It is easily available, low cost, and reliable as well hence best suited for small-scale prototyping.

All the parts are 3D printed individually with the infill density ranging from 20% to 100%, then assembled, as per the computer-aided design (CAD) model shown in Figure 4. A 0.120 m trapezoidal 4 start lead screw 0.008 m thread 0.002 m pitch lead screw with copper nut is used in elevation mechanism and for sliding motion. The rotary actuator is connected to bevel gears and these bevel gears are further connected to the spur gear which drives the slider back and forth, transmission ratio is 1 in all cases.

6. CONCLUSION

This study identified optimal design parameters for the top platform and the angular rotation of the lead screw necessary to mimic linear motion effectively. The design and parametric study facilitated the development of a portable rehabilitation knee platform. The simulation studies of the proposed lead screw-based slider mechanism demonstrated promising results, including a maximum slider displacement of 0.450 m, a maximum inclination angle of 32.5° from the base position, and a pinion speed of 2.89 rad/s. Additionally, the system exhibited minimal deformation (0.14%) and equivalent strain (0.05%) from the base to the fully extended position, with deformation ranging from 4 μm to 0.3 mm and strain from 9 μm to 1.7 mm, respectively. To validate these findings, a 3D-printed model was fabricated, and experimental studies were conducted under no-load conditions, yielding similar results with a deviation of ±5%.

The future scope of this research includes conducting pilot studies to experimentally validate the knee rehabilitation robotic system's performance in clinical settings. These studies will assess the system's effectiveness, safety, and usability, ensuring its feasibility for therapeutic use. This validation will bridge the gap between theoretical design and real-world application, enhancing rehabilitation outcomes for patients with knee impairments.

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