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DEVELOPMENT OF A LOW-COST LINKAGE-DRIVEN TWO-FINGER EXOSKELETON FOR HAND REHABILITATION

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Abstract

Hand rehabilitation plays a crucial role in restoring motor function in individuals with neurological impairments such as stroke, and robotic-assisted therapy has demonstrated significant therapeutic benefits. However, the practical application of existing hand exoskeletons is limited by high costs and complex designs, particularly in healthcare systems with constrained financial and technical resources. Current research lacks a verified system that provides essential finger mobility through a low-cost, simple, and easily fabricable structure.

This study focuses on the mechanical design and preliminary evaluation of a hand exoskeleton that employs a planar linkage system to guide the index and middle fingers. A detailed CAD model was developed to ensure accurate component dimensions and proper assembly alignment. The prototype was fabricated using laser-cut acrylic linkages, actuated with standard servo motors, and transmitted motion via a bevel gear pair. Control was implemented through an Arduino microcontroller, programmed to drive finger trajectories according to predefined flexion-extension angles.

The design demonstrates mechanical simplicity, with a six-bar linkage system constructed from readily available components forming a precise therapeutic motion unit. The complete prototype weighs approximately 100 grams, with material costs under $50 USD, and requires no specialized parts for assembly. Performance testing confirmed controlled finger flexion and extension, verifying mechanical integrity, actuation reliability, and electronic responsiveness.

These results highlight the potential for a mechanically feasible and economically accessible hand exoskeleton, offering a framework for expanding rehabilitation access in resource-limited settings. The study indicates that affordable robotic mechanisms can reliably facilitate finger mobilization, supporting improved recovery outcomes for patients with hand paralysis or post-stroke motor deficits.

INTRODUCTION

Human hands support both forceful grips and fine object control. These functions are needed in basic tasks involving domestic care, self-maintenance, and workplace duties [1]. Neural injury caused by stroke often causes long-term motion loss in the arms. This remains a top factor linked to limited upper limb function in affected adults worldwide [2], [3]. Impaired hand use leads to lower physical independence. Tasks such as feeding, grooming, and buttoning become harder to perform without outside help [4]. Treatment is often cantered on exercises repeated at high volume. These actions retrain the brain using plastic responses to recover voluntary joint motion [5], [6]. Conventional therapy relies on constant support from trained staff. Regular patient attendance and individualized care raise direct costs and limit long-term availability [7], [8]. Automated tools are now used in place of direct therapist-led sessions. These platforms supply timed, repeatable help with accurate joint paths over long periods [9], [10]. Wearable robotic hand frames help restore hand motion. These devices guide finger movement using force from electric or mechanical sources [11]. Passive or active movement can be given depending on the joint type. Predefined patterns allow controlled motion under fixed speed and range [12], [13]. These systems often support higher therapy doses with reduced physical fatigue in staff. Many also work under remote control systems [14], [15]. Several actuation methods have been adopted. Pneumatic forms, smart metals, tendon wires, and joint-link motors each offer different motion and force results [16], [17], [18], [19], [20]. Despite these efforts, weight and cost remain major design hurdles. These issues reduce use among people needing portable or long-use devices [21], [22].

Early robotic hands copied the full joint layout of the human finger. This included over 20 axes and required complex motor controls [23]. Most early tools were too heavy and slow for regular use. High cost and poor fit made them hard to use outside clinical labs [24]. Later work showed that fewer motions could still assist therapy. Closing and opening the hand gave key gains in early recovery [25], [26]. A reduced motion count cuts weight and makes the controls easier to manage. Simpler builds use fewer joints and require less complex circuits. This shift also helps lower part costs [27]. Material use affects the tool's final price. Older models used metals that needed careful shaping. Newer designs have replaced these with printed parts made from low-cost plastic [28], [29]. This project used cut sheets made from acrylic. These were shaped by low-cost laser tools. This cut costs and shortened the time needed to prepare new builds [30].

Recent projects have tested many hand device designs. Tendon-driven tools match finger shape and often weigh less than fixed-link styles [31], [32]. Cable slack and routing limits have been noted as problems. Soft gloves that fill with air or liquid help user comfort but lose control over finger position [33], [34], [35]. Rigid joint tools give stronger force paths and hold joint shape across repeated uses [36], [37]. One glove by Polygerinos included a soft shape that helped users regain grip strength. Other builds used printed fixed joints to match user finger sizes for improved comfort and motion repeatability [38], [39], [40]. Cost has blocked wide access to most of these designs. Strong tools that gave high recovery scores still needed many expensive parts. High price remains a key issue in reaching more users needing home-based or low-income care [41].

Most published studies on hand exoskeletons have emphasized accurate finger motion tracking, multi-joint actuation, and complex sensory features. These developments often result in units priced in the thousands or tens of thousands of dollars [42], [43], [44]. This technical progress, while noteworthy, has limited practical impact in settings where patients cannot afford such systems or lack access through insurance or public health services [45]. A visible research gap remains in designing systems based on 'frugal innovation', where simplicity and cost take precedence over extensive functionality [46]. A major question emerges regarding whether a working therapy solution can be created using basic tools and widely available electronic parts such as acrylic sheet, generic motors, and accessible microcontrollers [47]. This study directly addresses the feasibility of creating a safe, light, and resilient wearable system with an expense below 100 dollars, intended to deliver grasping-related rehabilitation using basic flexion and extension movements for the most essential fingers [48], [49].

This study aims to validate the feasibility of a linkage-driven wearable hand device intended for physiotherapy at ultra-low cost. Three specific objectives are outlined for this purpose. A complete virtual mechanical design of a two-finger unit focusing on index and middle fingers will be prepared using a six-bar linkage model that approximates anatomical motion. A physical version of the system will be built using laser-cut acrylic components and economical drive units, including basic servo motors and mechanical gears. A simple controller will then be created using an Arduino board to deliver repeatable bending and straightening actions across a therapeutic range. Together, these stages are intended to form a validated low-cost solution for robotic therapy and mechanical motion assistance.

This work carries practical value in making rehabilitative technology more accessible to underserved communities. Demonstration of a reliable assistive solution under 100 dollars could address long-standing financial barriers to technology-based therapy [50]. An open-design prototype would enable hospitals, hobbyists, and caregivers in low-resource settings to replicate and improve the solution without expensive tools or components [51]. The outcomes contribute to engineering work cantered on reducing cost while retaining core functionality. This study is positioned within the domain of low-cost medical robotics and frugal engineering and supports applications where price constraints often prevent technical adoption [52]. The intent is to support patient rehabilitation and reduce long-term treatment cost by offering scalable access to functional robotic support systems [53].

I. METHODOLOGY

The process was divided into four structured stages. These included the mechanical design, selection of materials and components, fabrication and assembly steps, and integration of the control system.

A. Mechanical Design and Kinematic Analysis

This design followed principles emphasizing low cost, simplicity in structure, and practical function for hand therapy. The device was intended to actuate the index and middle fingers, which are essential for gripping. Anatomical measurements informed the finger link geometry. The three finger joints, namely the Metacarpophalangeal, Proximal Interphalangeal, and Distal Interphalangeal, were used as reference points. A subject's anthropometric data was applied. Phalanx measurements of the fingers are given in table 1.

Table 1. Phalanx measurement of the fingers

Phalanges	Index	Middle
Proximal(mm)	35	40
Middle(mm)	28	33
Distal(mm)	24	25

The motion was modelled using a six-bar linkage for each finger. This model converted a single rotating movement into a coordinated finger bend and release. The design forced the Proximal Interphalangeal joint to move simultaneously with the Metacarpophalangeal joint. This reduced the system's degrees of freedom to one per finger and did not include sideways finger motion to simplify operation. Three-dimensional modelling of the device was performed using CAD software. This included separate models for the triangle-shaped base, shaft units, and individual links as shown in figure 1. Assembly simulations were used to check part fit and to study motion before physical construction, shown in figure 2.

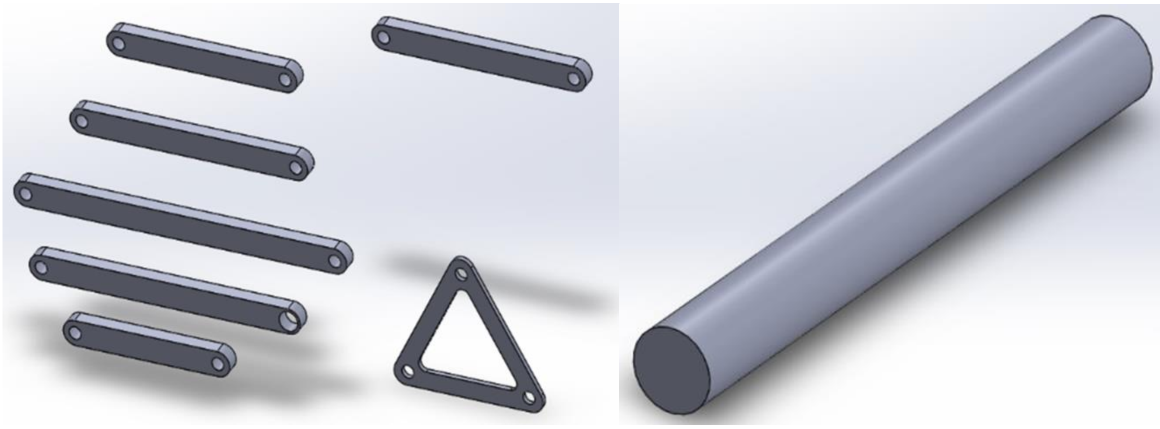

Figure 1. CAD Models of triangle-shaped link, straight links and shaft unit

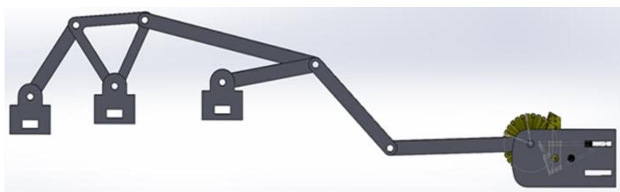

Figure. 2. Assembly of single finger exoskeleton device

B. **Material and Component Selection**

C. Component choices followed a strict requirement for affordability, local sourcing, and ease of production. The mechanical structure was made using 3 mm thick polymethyl methacrylate

D. sheet. Acrylic was selected for being lightweight and strong enough for assisted hand motion. Its mechanical properties are shown in table 2.

Table 2. Acrylic Plastic Properties

PROPERTY	METRIC	UNITS
General		
Density	1390 - 1430	kg/m^3
Mechanical		
Yield Strength	28.6 - 72.4	MPa
Tensile Strength	60 - 89.6	MPa
Elongation	0.1 - 0.75	% strain
Hardness (Vickers)	143 - 243	MPa
Fracture Toughness	1.71 - 4.2	MJ/m^3
Young's Modulus	2.5 - 5	GPa
Thermal		
Max Service Temperature	76.9 - 96.9	°C
Melting Temperature	160 - 184	°C
Specific Heat Capability	1.36 - 1.43	kJ/kg °C
Thermal Expansion Coefficient	$7.57e^{-5}$- $2.02e^{-4}$	strain/°C

The acrylic sheet was suitable for laser cutting, which was widely available. The servo motors were chosen for actuation. These motors delivered 4.1 kilogram-centimetre torque at 6 volts and were driven using a simple Pulse Width Modulation signal. The Characteristics of servo motor is given in table 3.

Table 3. Characteristics of servo motor

Description	Values
weight	37g
Dimensions	39.9 mm x 20.1 mm x 36.1 mm
wire size	200mm
Torque	4.1kg.cm
Voltage	4.8/6V
Speed	0.23sec/60 degree

Their availability and cost made them suitable for this purpose. Plastic bevel gears with 15 teeth were used in pairs to redirect the motor torque at ninety degrees, shown in figure 3.

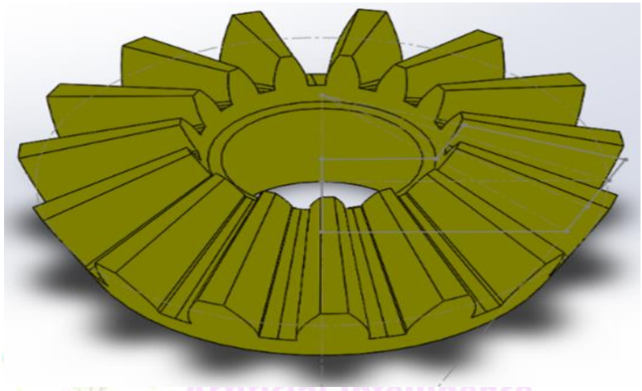

Figure 3. Bevel gear for 90° rotation

The complete CAD assembly for two fingers is shown in figure 4. This enabled a more compact fit behind the glove, where the servos were mounted. A cloth glove was used as the wearable base. It supported the entire structure while allowing comfort. Assembly was done using bolts and nuts. These fasteners allowed quick mounting and made future adjustments simple.

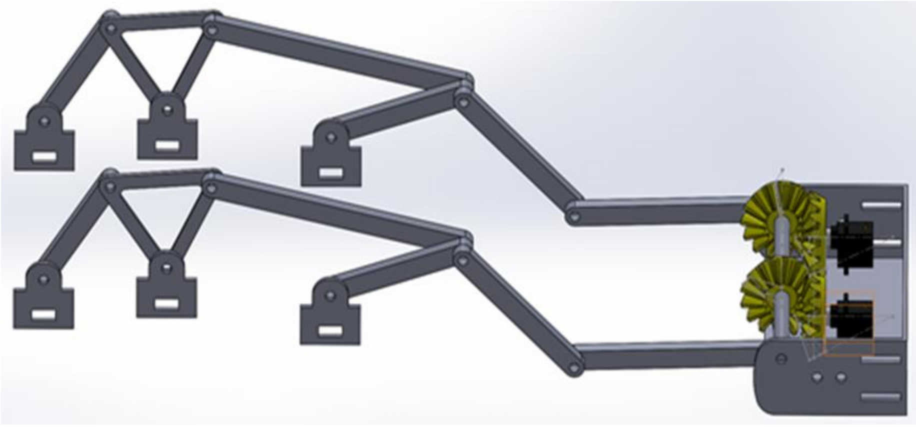

Figure. 4. Assembly of two fingers exoskeleton device

E. **Fabrication and Assembly**

The physical model was built as per the virtual design. The acrylic sheet was selected of 28 by 28 centimetre size and the length of each joint link is given in table 4. CAD software was used to generate two-dimensional DXF files for laser cutting. A local cutting service processed the file and shaped the parts from the acrylic sheet as shown in figure 5.

Table 4. Length of Links

Link Number	Length (cm) [Index-finger]	Length (cm) [Middle finger]
1	3.0	3.5
2 (equilateral triangle)	3.0	3.5
3	3.5	4.5
4	4.0	4.5
5	5.2	6.5
6	4.0	4.5

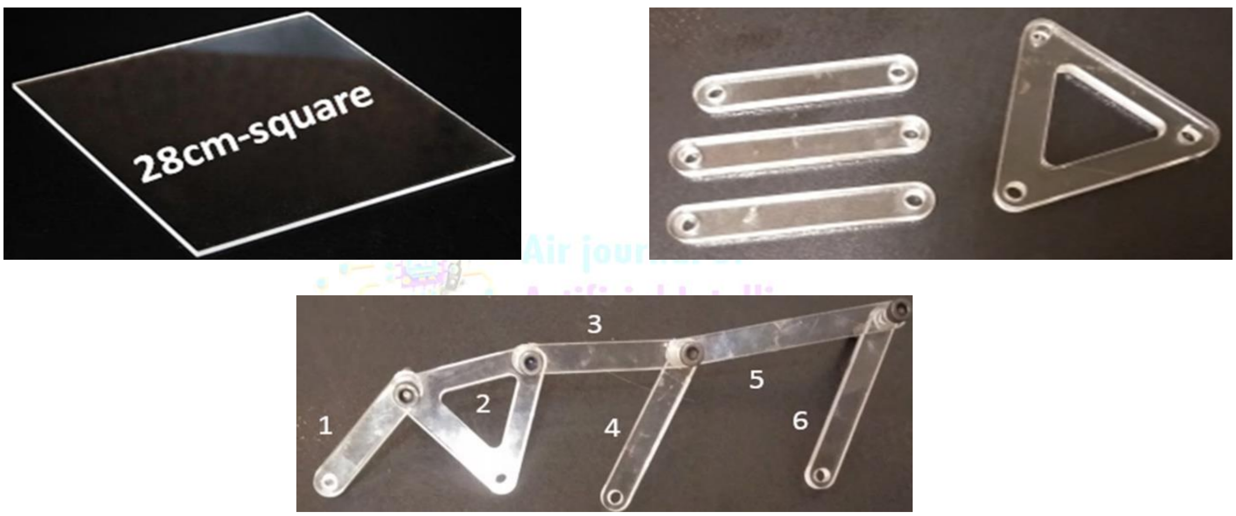

Figure 5. Physical links setup

Two identical six-bar mechanisms were then assembled using bolts and nuts. Motors and bevel gears were fixed onto a shared acrylic plate. The plate was then mounted on the glove. The finger mechanisms were aligned and joined to complete the mechanical structure of the prototype. The assembled bevel gears are shown in figure 6.

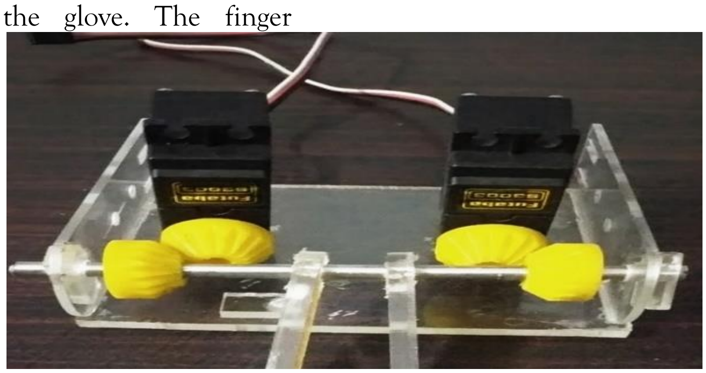
Figure 6. Bevel gear assembly with servo motors

F. Control System and Integration

The electronic system was centred around an Arduino UNO microcontroller board. This unit was selected for its low cost, wide support network, and ease of programming. Wiring involved connecting each servo to a 5-volt line, a shared ground, and a digital pin capable of Pulse Width Modulation. Pins 9 and 10 were used for the motor signal control. Servos were powered by an external 5-volt supply. This supply shared its ground with the Arduino to maintain a common reference. A serial Bluetooth module of type HC-05 was added. Its transmit and receive pins were wired to the Arduino serial ports. The device was powered using the 3.3-volt output of the board to prepare the system for future wireless upgrades. The complete control is shown in figure 7. Software was written using the Arduino IDE. The script cycled the motors between two fixed positions. These positions simulated full extension at 0° and near full flexion around 90° at the Metacarpophalangeal joint. Delay commands adjusted the motion pace to suit therapeutic exercises. The code was uploaded onto the board for autonomous control.

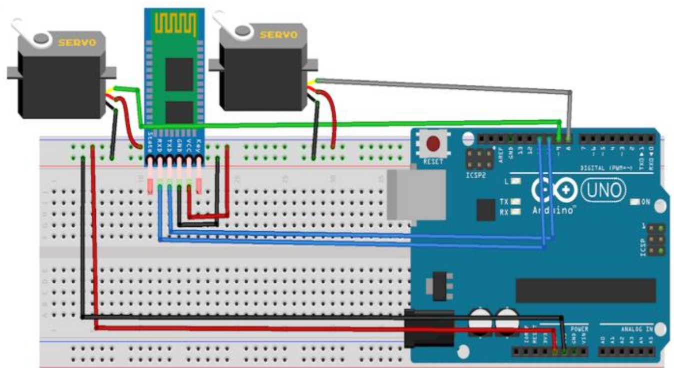

Figure 7. Control systems arrangements

II. Results and Discussion

This section presents the outcomes obtained during the design and fabrication phases and aligns them with the original objectives and current usage in robotic rehabilitation devices.

A. Prototype Realization and Characteristics

A two-finger hand exoskeleton was fabricated with accuracy and matched the initial design expectations. Functional testing confirmed that the prototype performed as intended without deviation from its modelled specifications. The overall system mass was approximately 100 grams and allowing extended use during therapy without user fatigue. This reduced weight resulted from using acrylic in the structural framework instead of heavier alternatives. The final construction cost was PKR 14000, which is approximately 50 US dollars and significantly below most commercial rehabilitation tools. All parts were manufactured directly from the CAD software digital model. The fabricated assembly reflected the intended geometry from the digital design. This confirmed the modelling strategy allowed cost-efficient prototyping with good dimensional accuracy.

B. Performance Assessment

A qualitative assessment validated prototype functionality. Power was applied and the autonomous control program initiated. Motion execution was verified for the exoskeleton device. Servo motors drove bevel gears and linkage systems. This action cycled the index and middle finger mechanisms smoothly. Full extension flexion and full flexion extension positions were achieved. Motion coupling occurred effectively through the six-bar linkage mechanism. Finger joint movement exhibited a naturalistic bending pattern. Sufficient torque from the selected servo motors was confirmed. Passive resistance from the mechanism was overcome. Resistance from a healthy user's finger was also overcome. Control system reliability was demonstrated using Arduino. Desired start and end positions were accurately reached by servo motors. This precise control utilized PWM signals. Exercise timing management proved straightforward. Adjustments to code delay parameters controlled the timing. This simple control architecture suitability was confirmed for the application.

Figure 8. Exoskeleton device in flexion state

Figure 8 presents the fabricated hand exoskeleton in a flexed position, where the mechanical linkages have retracted to induce finger curling. figure 9 displays the same prototype during extension, with the linkages fully elongated to straighten the fingers. These sequential photographs document the prototype's mechanical function and physical integration. They depict the transition from computer-generated geometry to an operational system applied to the human hand. The design intention captured in the CAD model has been translated into a functioning assistive device. The figures offer direct visual evidence of actuation capability and physical conformity to anatomical motion requirements.

Figure 9. Exoskeleton device in extended state

C. **Discussions**

The findings from this study provide relevance when measured against the original research aims and current published reports. Three main aims were completed during the work. Full digital models were made. A working model was built using cost-saving materials. An automatic control system allowed the device to move when needed during therapy. The design philosophy was proven with a full demonstration. When comparing with published studies, cost-saving remains the main advancement reported here. Other teams in the field have built advanced exoskeleton devices. Those systems often include expensive parts or complex production, such as using different types of 3D-printed plastics. This study gave results from using materials like acrylic sheets and laser cutting. A more basic device was obtained, but the results show that cost can be lowered where price limits options in earlier designs from other teams. No tests with patient groups were performed for this first version. Only mechanical performance was reviewed. Patient safety, daily use, and treatment outcomes must be checked in later trials. Such work must be done in connection with doctors and therapists, so real use in clinics can be addressed. Clinics with low resources may use these results to make their own treatment devices. Home programs could become more common, and more people recovering from stroke could receive help than is now possible.

III. CONCLUSION

The aim of this was to solve the access problem in robotic hand therapy through a design approach rooted in minimal-cost engineering. A mechanical exoskeleton was developed and built, providing finger movement assistance using a simple two-link system. The final unit weighed approximately 100 grams and required around $50 USD in total cost. Its construction relied on commonly available components. Acrylic sheets and standard electronics were selected to reduce production and sourcing difficulty. The applied mechanical design followed the six-bar linkage method to enable motion transmission. The complete design process moved from CAD modelling to physical fabrication. This process confirmed that the virtual model could be accurately built as a functional prototype. An Arduino microcontroller board was used to manage actuation. The low-complexity electrical system was tested and found suitable for driving basic rehabilitation movements.

The key outcome was the working validation of a concept demonstrating that physical therapy tools can be low-cost without being nonfunctional. The current version was limited to two fingers with one degree of movement per finger and had no sensing features. However, its performance confirmed that passive motion therapy is possible using a simplified build. The following stages of research need to cover key gaps in mechanical function and feedback. Additional finger movement must be supported, including thumb articulation. Motion sensing and force feedback are also necessary for responsive control modes. This prototype served as a practical base to support more accessible and affordable recovery tools for individuals with motor disabilities due to stroke or injury.

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