TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 69, Issue Special III, July, 2026

DESIGN OF A NOVEL ROBOTIC HAND REHABILITATION DEVICE

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Abstract: *This paper presents a wearable glove-based hand rehabilitation device driven by Bowden cables and manufactured via multi-material 3D printing. A middle-finger sleeve module is used to study cable routing, cutout geometry, and local stiffness governing compliant bending. The CAD design combines flexible finger interfaces with rigid routing and sheath anchors to reduce distal mass and improve comfort. Linear static FEA (Nastran SOL 101) under 10 – 40 N cable loads quantifies deformation, revealing excessive proximal bending and axial elongation with limited distal flexion. The routing is then redesigned and prototyped. Preliminary tests on printed parts show improved flexion and enable fingertip force estimation using an FSR-based setup, supporting feasibility for full-glove integration.*
Keywords: *wearable robotics; hand rehabilitation; soft glove; Multi-material 3D printing; flexible sleeve; tendon-driven actuation.*

1. INTRODUCTION

Loss of hand motor function is a common consequence of neurological injury, including stroke or traumatic events, [1,2]. The main motor impairments are represented by spasticity and weakness with spasticity manifesting as muscle stiffness and increased resistance to passive movements, while weakness affects the motor function of the fingers [3].

Soft wearable robotic devices have gained significant traction due to their safety, compactness, and ability to conform to the human hand geometry. Unlike rigid exoskeletons, soft systems use flexible structures and tendon-driven mechanisms that reduce inertia and increase user comfort [4].

Tendon-driven mechanisms, especially Bowden cables, enable remote placement of actuators while transmitting motion to the fingers through lightweight structures. Despite advantages, Bowden cable systems exhibit nonlinear friction, bending-dependent tension loss, and difficulty in precise control, [5].

Soft wearable hand robots leverage flexible structures and tendon/Bowden transmissions to keep heavy actuators off the hand while still delivering finger flexion–extension, [6]. Dorsal placement of mechanisms is most common, followed by glove-based, lateral, and palmar configurations, due to reduced inter-digit collisions and preserved palmar sensation, [7,8].

In tendon-driven gloves, the actuator can be placed away from the hand, while power is transmitted through routed cables; however, precise joint-level control is affected by nonlinear friction (Capstan effect), changing routing geometry during motion, and limited sensing at the distal end, [8].

To improve force transmission and anchor stability, similar works explores rigid – soft hybrid structures embedded into soft wearable bodies. Adjustable rigid–soft rings and multi-mode actuation architectures aim to stabilize cable anchors, enhance adaptability to different finger sizes, and balance functional versatility with control simplicity, [9-12].

This work aims to develop a robotic rehabilitation device with a glove–like architecture, focusing on a multi-material 3D-printed design. The paper presents a flexible middle-finger sleeve used to investigate cable routing, cutout geometry, and local stiffness, which will later be integrated into a full rehabilitation glove. The rest of the paper is structured as follows: section 2 presents the glove conceptual design and the finger sleeve design details, section 3 the results following a

Finite Element Method (FEM) analysis and an improved design, while section 4 focuses on initial experimental tests with the proposed finger sleeve. Section 5 presents the conclusions and future work.

2. THE ROBOTIC ASSISTED REHABILITATION DEVICE DESIGN

The conceptual design of the proposed robotic rehabilitation device is shown in Fig.1. The 3D-printed hand rehabilitation glove is mounted on the patient's hand in a dorsal configuration (back-of-hand mounting), leaving the palmar side largely unobstructed for comfort and grasping. The device consists of a dorsal support frame that conforms to the hand and wrist, and modular finger sleeves aligned with each digit. Along the fingers, segmented guide elements are distributed over the phalangeal regions to define the Bowden-cable path and maintain a controlled moment arm during actuation. The routing guides constrain the cable trajectory, reduce lateral drift, and provide discrete attachment points for tuning local stiffness and bending behavior. Cable-driven actuation transmits tensile forces through the Bowden sheaths to assist or resist finger flexion/extension, enabling rehabilitation exercises with compliant, lightweight distal components. The architecture is intended for multi-material additive manufacturing, allowing rigid structural sections (frame and guides) to be combined with more compliant finger interfaces to improve fit, safety, and comfort.

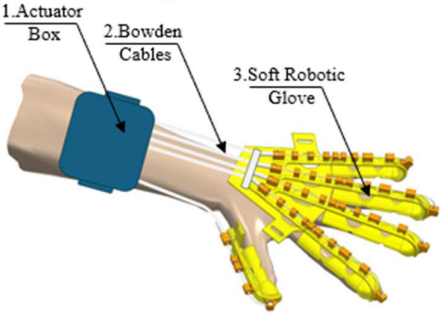


Fig. 1. Concept design of the soft rehabilitation glove

2.1 Human Finger Motion Anatomy Analysis

A thorough analysis of the human finger anatomy is required for the detailed design of a finger sleeve (Fig. 2).

Finger motion arises from the coordinated action of osteo-articular elements, the flexor – extensor apparatus, and the fibro-osseous structures that guide and constrain the tendons along the phalanges. Structurally, each finger (except the thumb) comprises three phalanges—proximal, middle, and distal—connected by the metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints. The PIP and DIP joints are hinge-type articulations (single degree of freedom, flexion–extension), whereas the MCP joint permits flexion–extension and abduction–adduction, enabling the finger to adapt to grasping tasks and varying hand postures, [13].

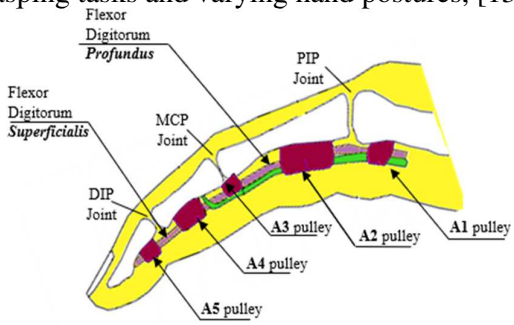


Fig. 2. Anatomy of a human finger

The flexor apparatus of the fingers consists primarily of the flexor digitorum superficialis (FDS) and flexor digitorum Profundus (FDP) muscles. Their tendons, originating in the forearm, enter the hand within synovial sheaths and are held closely against the phalanges by a series of fibrous pulleys (annular pulleys) arranged from palm to fingertip (A1–A5).

The FDS tendon splits at the proximal phalanx and inserts on the base of the middle phalanx, acting chiefly on PIP flexion; the FDP tendon passes deep through the FDS split (chiasma) and inserts on the base of the distal phalanx, producing DIP flexion, [14,15].

2.2 Finger Sleeve Design

The glove sleeve enables controlled flexion and extension via a Bowden cable routed through dedicated tunnels integrated into the flexible structure. Cable tension produces bending of the elastomeric sleeve, mimicking natural joint rotation. The cable is tensioned by a servomotor with a guiding wheel (Fig.3).

When tension T is applied, the tendon generates distributed bending moments along the sleeve, with compliant cut-outs concentrating deformation in regions corresponding to the PIP and DIP "virtual joints". The effective moment arm depends on the instantaneous geometry of the tendon path and the local tangential direction of each phalange segment; consequently, both the joint torque and the cable stroke vary with the finger posture.

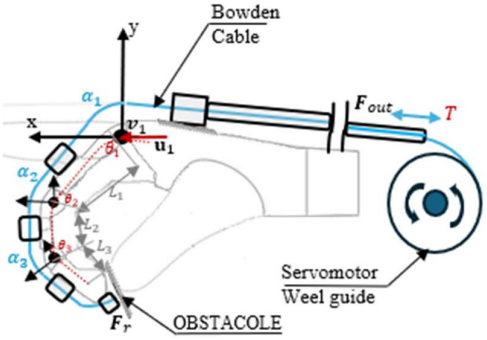


Fig. 3. Schematic view of the tendon routing method and actuation

For the kinematic modelling, a planar 3-R serial chain (MCP–PIP–DIP) with link lengths (L_1, L_2, L_3) can be considered. Let the cumulative angles be:

$$\phi_1 = \theta_1, \phi_2 = \theta_1 + \theta_2, \phi_3 = \theta_1 + \theta_2 + \theta_3. \quad (1)$$

The fingertip position in the base frame is:

$$x(\boldsymbol{\theta}) = L_1 \cos\phi_1 + L_2 \cos\phi_2 + L_3 \cos\phi_3$$
$$y(\boldsymbol{\theta}) = L_1 \sin\phi_1 + L_2 \sin\phi_2 + L_3 \sin\phi_3 \quad (2)$$

where $\theta = f(\theta_1, \theta_2, \theta_3)$.

2.3 Finger Sleeve CAD Modeling

The CAD model of the flexible finger sleeve is presented in Fig.4. The model integrates soft and rigid components into a single multi-material structure: the compliant sleeve printed using 3d printed materials featuring elastic properties to provides the necessary flexibility for joint-level bending, while rigid plastic materials are used for the tendon clamps, cable guides, and sheath-anchoring features required for reliable force transmission.The tendon path, local moment arms, and the interaction between cable routing and the sleeve cutouts (Fig.5) were defined directly in the CAD environment to replicate the anatomical bending pattern of the human finger (MCP, PIP, DIP).

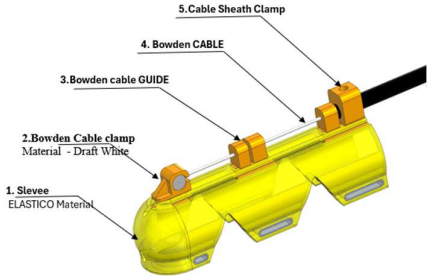


Fig. 4. Flexible finger sleeve design description

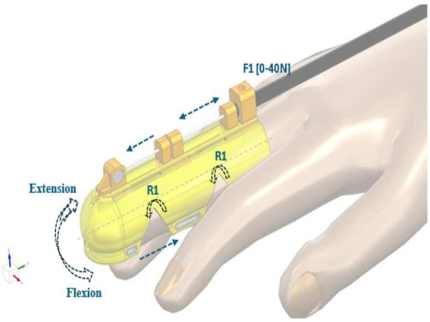


Fig. 5. Sleeve position on human hand

This approach offers advantages, such as that the tendon-driven soft mechanisms are highly sensitive to local geometry, such as guide placement, cutout shape, and regional stiffness.

The flexible materials are printed using Elastico™, which is a rubber-like PolyJet photopolymer engineered to replicate the mechanical behavior of soft elastomers. With a Shore A hardness of 65, it provides a balance between flexibility, durability, and structural integrity, making it suitable for repetitive bending applications such as rehabilitation devices. The material exhibits high elongation at break and stable elastic recovery, allowing the sleeve to undergo multiple deformation cycles without permanent set or tearing.

The rigid material is DraftWhite™ is a stiff PolyJet photopolymer optimized for printing structural or load-bearing components within multi-material assemblies. Compared to Elastico™, DraftWhite™ offers significantly higher modulus and dimensional stability, making it suitable for embedding rigid features directly into the flexible sleeve. These rigid regions form the tendon guides, anchor points for the Bowden cable sheath, and mechanical

attachment features needed for interfacing with straps or external actuation systems.

2.4 Finite Element Analysis for the Finger Sleeve

A linear-static finite element analysis (FEA) was performed using Nastran SOL 101 to evaluate the structural response of the flexible finger sleeve under tendon-generated loads, [16,17].

The objective of the analysis was to quantify deformation, stress distribution, and potential failure modes for forces between 10 N and 40 N, corresponding to typical Bowden-cable actuation levels required in hand-rehabilitation devices.

The CAD geometry of the middle-finger sleeve was discretized using second-order tetrahedral solid elements, providing increased accuracy for curved, multi-material regions. The mesh was generated with a global element size of 0.5 mm, with adaptive refinement allowing element lengths between 0.25 mm and 0.75 mm.

A standard Nastran quality control file was used to ensure mesh consistency and prevent distorted elements (Fig.6).

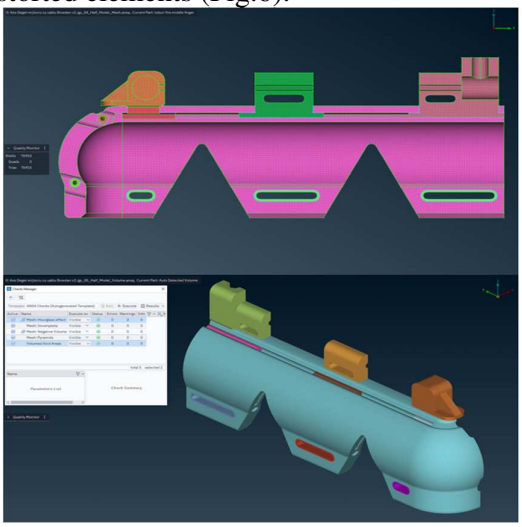


Fig. 6. Nastran Mesh configuration for FEA analysis of finger sleeve

The Bowden cable was represented as a CBAR element, with its end-point serving as the location where the actuation load was applied. Additional boundary constraints **were defined to stabilize the model, prevent rigid-body** motion, and guide the cable path inside the sleeve.

Linear-static load cases were evaluated as shown in Fig. 7 on Z direction of displacements.

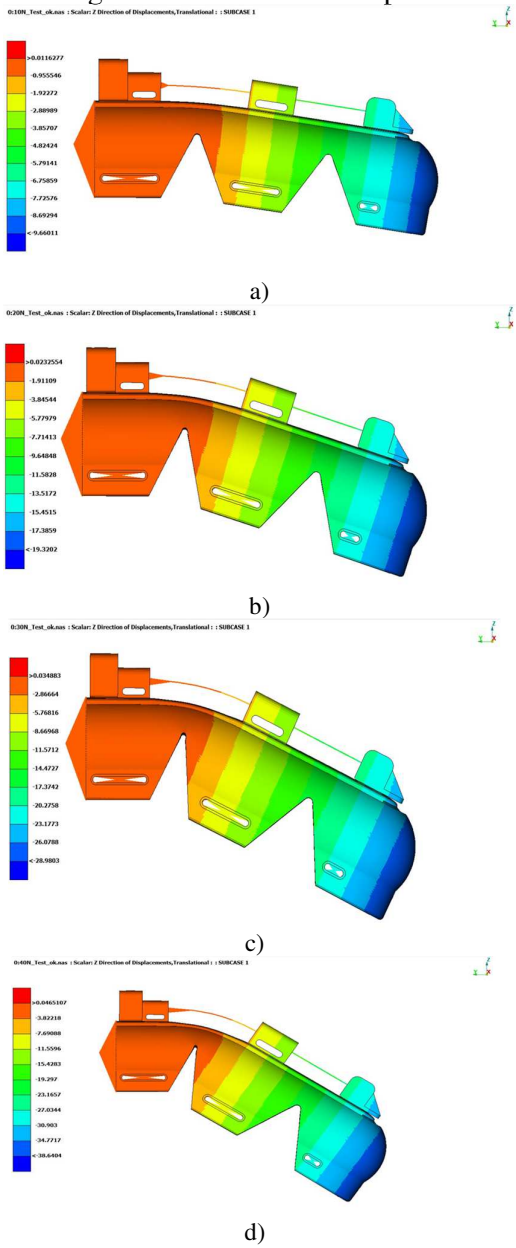


Fig. 7. FEA stress results at different force load: a) at 10N; b) at 20N; c) at 30N; d) at 40N.

These were applied sequentially to the same geometric configuration, allowing direct comparison of deformation trends and identifying nonlinear geometric effects even within a linear-static framework. Results for each load level were summarized through contour plots of displacement and stress fields.

Across all load cases (10–40 N), the simulation revealed a consistent deformation pattern:

i) Excessive bending at the first cutout (proximal region) (Fig.8). This region acted as an unintended hinge, absorbing most of the deformation instead of transmitting bending toward the fingertip.

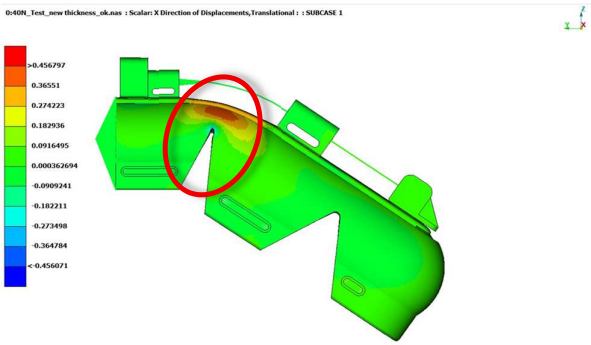


Fig. 8. FEA result showing excessive bending at the first cutout

ii) Minimal deformation at the distal cutout (Fig.9). The fingertip region exhibited almost no flexion, indicating that the tendon's force was not effectively translated into distal bending.

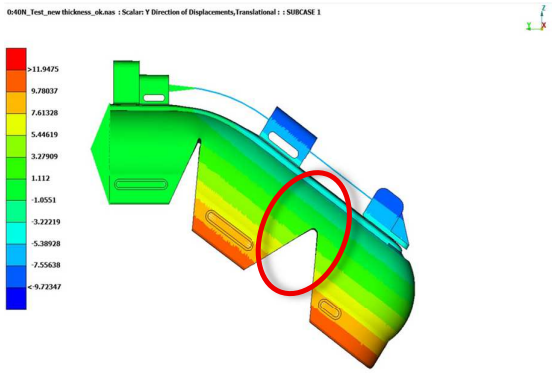


Fig. 9. FEA result showing minimal deformation at the distal cutout

iii) Axial elongation instead of rotational bending (Fig.10). The Bowden cable generated a dominant longitudinal force component, stretching the sleeve rather than causing joint-like flexion.

This was particularly evident at 30–40 N load levels. Despite these mechanical inefficiencies, stresses remained below the allowable limits of the Elastico™ material, confirming that material strength was not a limiting factor for loads up to 40 N. Despite these mechanical inefficiencies, stresses remained below the allowable limits of the Elastico™ material, confirming that material strength was not a limiting factor for loads up to 40 N. The conducted FEA demonstrates that the current geometric routing of the Bowden cable is the main limiting factor, not the material choice. Elastico™ withstands loads up to 40 N without overstress, but the tendon path produces inadequate bending moments in distal regions and excessive deformation proximally.

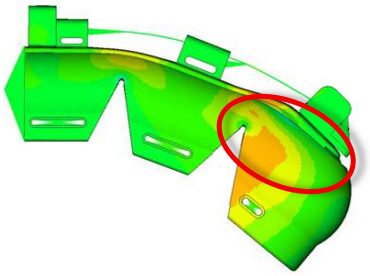
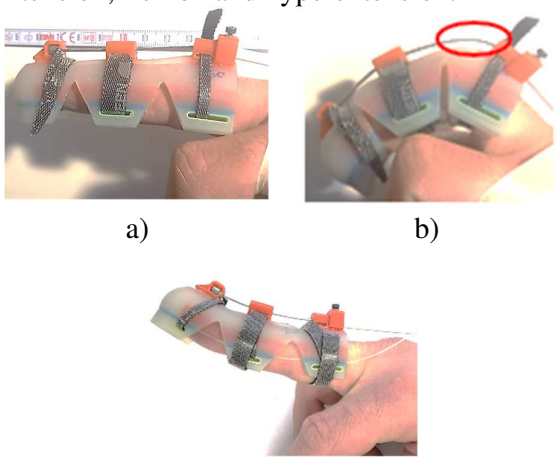


Fig. 10. FEA result showing axial elongation instead of rotational bending

3. EXPERIMENTAL TESTS

For testing, a prototype for the middle finger was printed as shown in Fig.11 and we tested for extension, flexion and hyperextension.



a) b)

c)

Fig. 11. Sleeve Test on human finger
a) extension b) flexion c) hyperextension

When applying a tension in cable, extension and hyperextension were guiding the finger mimicking the realistic movement (Fig.11 a. and c.). When reversing the force on the cable, the extension of the finger was performed just around 70% of the total realistic flexion of human finger. The experimental flexion observed at the proximal region is consistent with our FEA findings: the tendon load concentrates bending at the first cutout while

providing insufficient distal leverage, so the sleeve stretches longitudinally instead of rotating at the PIP/DIP zones (fig.9 a.). This behavior confirms that the current routing and cutout geometry—not the material strength—are the primary limitations. Bowden guides are therefore required to restore distal bending.

The FEA simulation results underline the need for geometric optimization of tendon guides, cutout shapes, and stiffness distribution to ensure that the sleeve bends in a finger-like manner rather than elongating under tension (Fig.12). The immediate results are better for the flexion, yielding around 90% of the total flexion (Fig. 13 c).

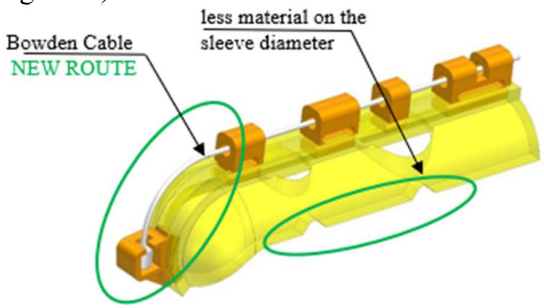


Fig. 12. Improvement of the Bowden cable route

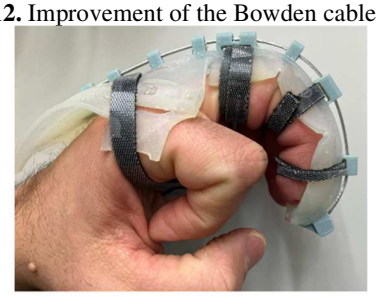


Fig. 13. Finger flexion using the improved design

3.1 Experimental determination of the actuating force

The force was measured at the tip of finger on a flat surface with Force Sensing Resistor (FSR), a type of analog, polymer thick-film (PTF) pressure/force sensor. It is designed for human-touch force measurement and general force/pressure-sensing applications. The analog signal was acquired with DAQ device model NI-USB6008. Analog signal was converted from Volt to Force using LabVIEW software (Fig. 14)

The force result test yielded a maximum value of 4N as shown in the graphic below (Fig.15). Using the initial design, the tests confirm that FEA analysis, where the force dissipates longitudinally and stretching the sleeve.

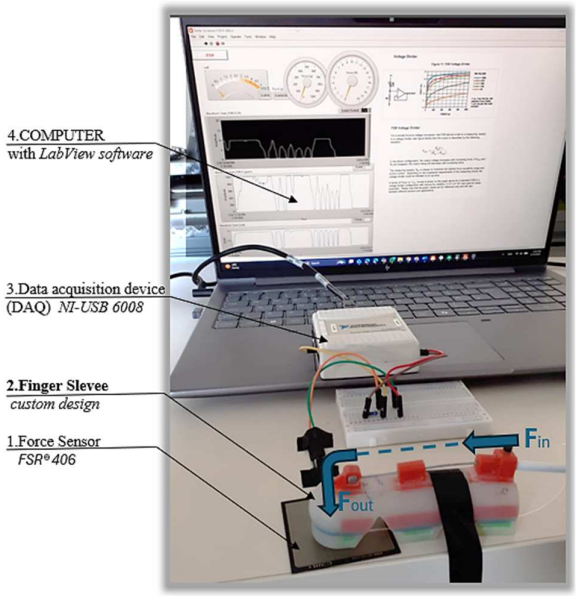


Fig. 14. Sleeve touch Force measurement Stand

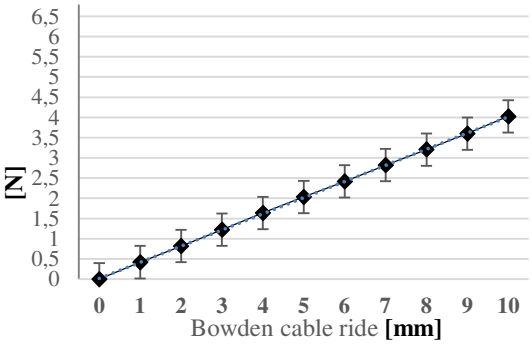
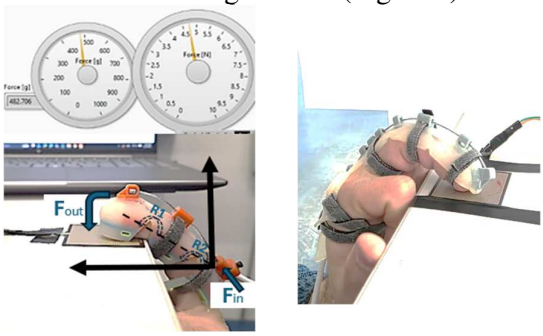


Fig. 15. Force at sleeve tip without Human finger

When performing the test with human finger position perpendicular with the sensor at 90°, a higher force of around 5 Newton was obtained, as shown in the image below (Fig.16 a).



a) **b)**

Fig. 16. Force measurement Stand with human finger and sleeve: a) Initial design; b) Improved design

The force is higher due to more bending of material because human fingers can act like a natural hinge. The sleeve bent and started touching the sensor at around 40mm of the cable stroke.

The same stand was used to test the improved design of the finger sleeve and replicated the same position of human hand to obtain similar results (fig.16a). The force tests results using the two deigns comparison is shown on Fig.17.

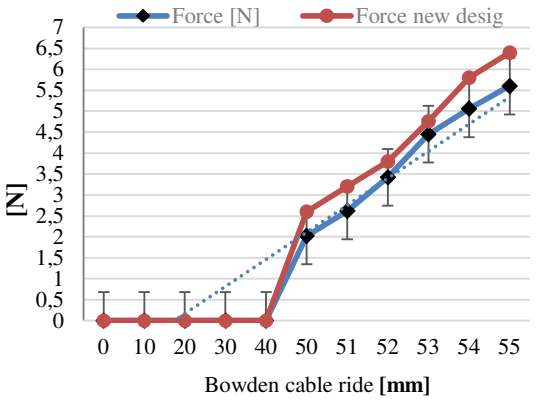


Fig. 17. Graphic with force comparison: force at sleeve tip initial vs. improved design, with human finger

4. CONCLUSION

This work introduced a glove-based, Bowden-cable–actuated hand rehabilitation concept enabled by multi-material 3D printing. Using a middle-finger sleeve as a representative module, the routing features, cutout geometry, and local stiffness shape the achievable bending profile were analyzed. Linear static FEA highlighted that the initial configuration produced excessive proximal bending and axial elongation with limited distal flexion, motivating a revised routing strategy. Prototypes of the improved design demonstrated more effective flexion and supported preliminary fingertip force estimation using an FSR-based setup. Future work will extend the design to a full glove, refine material and geometric parameters, and validate performance in broader bench and user-centered trials.

5. ACKNOWLEDGEMENT

This research was supported by the project New Frontiers in Adaptive Modular Robotics for Patient-centered Medical Rehabilitation—ASKLEPIOS, funded by the European Union—NextGenerationEU, and the Romanian Government under the National Recovery and Resilience Plan for Romania, contract no. 760071/23 May 2023, code CF 121/15 November 2022, with the Romanian Ministry of Research, Innovation and Digitalization within Component 9, investment I8.

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Proiectarea unui nou dispozitiv robotic pentru reabilitarea mâinii

Rezumat: Această lucrare prezintă un dispozitiv purtabil de reabilitare a mâinii, de tip mănușă, acționat prin cabluri Bowden și realizat prin imprimare 3D multi-material. Un modul tip manșon pentru degetul mijlociu este utilizat pentru a studia rutarea cablului, geometria decupajelor și rigiditatea locală care guvernează îndoirea compliantă. Proiectul CAD combină interfețe flexibile pentru degete cu elemente rigide de ghidare și ancorare a tecii, pentru a reduce masa distală și a îmbunătăți confortul. O analiză cu elemente finite liniară statică (Nastran SOL 101), pentru sarcini în cablu de 10–40 N, cuantifică deformațiile, evidențiind o îndoire proximală excesivă și alungire axială, cu flexie distală limitată. Rutarea este apoi reproiectată și prototipată. Testele preliminare pe piese imprimate indică o flexie îmbunătățită și permit estimarea forței la vârful degetului folosind un sistem bazat pe FSR, susținând fezabilitatea integrării într-o mănușă completă.

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