Improving Grip Strength Using a Non-invasive Underhand Exoskeleton

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***Abstract*— Reduced grip strength due to arthritis presents a major barrier to independence for millions of people worldwide. In response, biomechatronic systems have emerged as a promising avenue for providing at-home grip assistance. This paper describes a non-invasive underhand exoskeleton that assists users by improving their grip strength during daily tasks. Unlike conventional hand exoskeletons that apply force through the fingers, the proposed design employs a cable-driven actuation system that amplifies finger movements without stressing hand joints. The compliant interface leverages soft thermoplastic polyurethane fingers with a silicone skin layer, actuated by a single continuous servo guided through Bowden cables. As a preliminary feasibility study, the device was evaluated by a single able-bodied operator, providing an initial proof of concept. Experimental evaluation demonstrates a statistically significant mean increase in grip strength from 135.3N to 234.4N ($p < 0.001, d = 5.7$), and a 96.9% success rate across 162 trials involving basic activities of daily living, such as opening doors, filling a mug, and manipulating jars. The results indicate that the non-invasive underhand exoskeleton can provide significant assistance for daily activities, highlighting its potential as an assistive device for individuals with arthritis. While current performance is affected by material deformation, single-motor dexterity constraints, and control-signal artefacts, future research aims to overcome these limitations through robust fabrication, independent multi-finger actuation, and advanced control, towards the development of clinically testable devices.**

I. INTRODUCTION

Grip strength is fundamental to a wide range of everyday tasks, from workplace manual handling to basic Activities of Daily Living (ADLs). Its decline, whether due to ageing, injury, or musculoskeletal conditions, significantly reduces quality of life and the ability to live independently. Edemekong et al. [1] provide a categorisation of ADLs which help assess an individual's ability to live independently. Basic ADLs include ambulating (moving from one place to another) and feeding oneself; tasks such as grasping a cup, opening a jar, or opening a door all require adequate grip strength, and difficulty with these tasks often necessitates external assistance.

In the workplace, people encounter numerous manual handling operations that have been found to affect their overall health [2] [3]. Extensive research has highlighted concerns regarding hand health [4]. Mueller et al. [5] argue that musculoskeletal disorders of the hand are linked to work-related tasks involving manual handling and that semi-automation and assistive solutions are essential when policy-level interventions alone are insufficient to reduce risk. In the UK and in many other countries, the pension age is increasing; in the UK, it is set to rise to 67 between May 2026 and 2028 [6], increasing the likelihood of workplace grip-related conditions. Hawker et al. [7] found that among people aged 65 and older, one in three had osteoarthritis, indicating a growing need for assistive technologies in the workplace.

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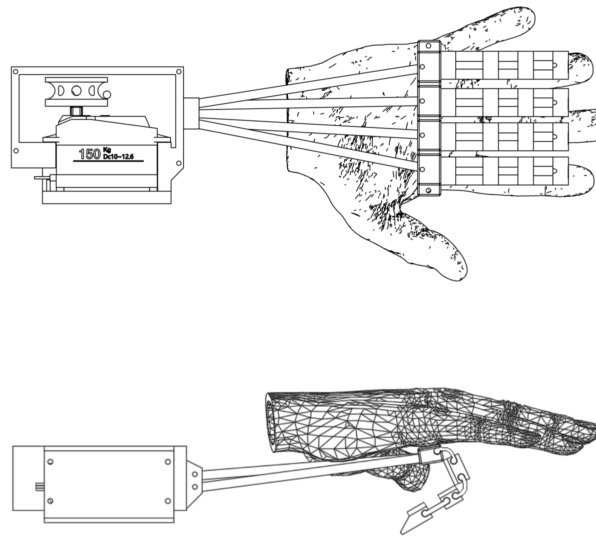

Fig. 1. Non-invasive Underhand Exoskeleton

Decline in grip strength due to arthritis and old age is well studied [8], [9], [10], [11]. Arthritis is a condition affecting millions worldwide [12] that causes joint pain, stiffness, and reduced mobility, and represents one of the most significant drivers of grip strength loss. Haugen et al. [13] used a Jamar dynamometer alongside data from the Nor-hand study [14] to compare grip strength between individuals with and without osteoarthritis, finding that elderly participants with symptomatic hand osteoarthritis experienced a 10% loss of grip strength attributable to disease-related effects at the base of the thumb.

Exoskeletons have the potential to help many people with daily tasks [15] [16]. However, there is often significant pushback against adopting this technology [17]. One particular reason is that many systems are invasive and can feel like they constrain the user's movement [18], [19], [20].

Current products for people with arthritis tend to be single-purpose and stand out as accessibility aids [21]. People prefer general-purpose tools that feel more natural; rather than a tool clearly identifiable as an accessibility aid, an exoskeleton that amplifies a person's natural movements could be well integrated into an individual's life.

A further challenge is detecting the user's intention when actuating an exoskeleton. Pre-existing solutions, such as force sensors, can exhibit unintended actuation [22]. Cheon et al. used a single EMG sensor placed on the musculo-tendinous junction (MTJ) of the flexor digitorum superficialis (FDS) to detect the user's intention to perform a power grasp. While they successfully determined whether the user intended to perform a power grasp, they were unable to detect individual finger-actuation intentions, limiting the richness of the data available for dexterous control.

Most hand exoskeletons are designed for rehabilitation [23], [24], [25] and are not optimised for broader populations experiencing grip weakness; most studies focus on conditions such as stroke [26], Parkinson's disease, and hand numbness. Current robotics research concerning arthritis focuses on detection and treatment, with a considerable lack of research into assistive solutions [27]. A notable exception is Watanabe et al. [28], which focuses on amplifying finger movement using a linkage-based system. However, their prototype is designed for single-finger wear and was tested only for grasping simple objects, leaving multi-finger grip augmentation largely unexplored.

Given these limitations, this project aims to develop a prototype robotic underhand exoskeleton (Fig. 1) designed to enhance grip strength and assist with everyday tasks in a non-invasive manner. Unlike conventional hand exoskeletons that rely on full finger flexion, the proposed system sits beneath the user's hand. It enhances grip via a cable-driven actuation system, amplifying the user's natural finger movements without applying force at the joints, following an amplification principle similar to that of Watanabe et al. [28]. The system is evaluated on an able-bodied participant as a proof of concept for grip augmentation across key ADL tasks, including feeding-category activities (filling a mug, holding it, and drinking; opening a jar) and ambulating-category activities (opening a door). Arthritis represents a compelling and underserved application domain for future clinical investigation, in which grip strength deficits and joint sensitivity introduce additional design constraints beyond those captured by testing with an able-bodied participant.

II. SYSTEM DESIGN

The exoskeleton (Fig. 1) has four soft TPU fingers, with Bowden cables guiding the tendons from the fingers to a single servo that actuates all four fingers via a pulley. Only one motor was used as the main focus was on grasping objects rather than performing dexterity-based tasks.

The Bowden cables allow for the motor that controls the fingers to be placed remotely, for example, on the belt of the user; however, to reduce cost in the experiment, it was placed on the wrist, reducing the length of the Bowden cables. Placing the actuator remotely has specific benefits for people with disabilities, where extra weight placed on the arm would be undesirable. The TPU fingers are mounted on the palm, parallel to the hand's knuckles, and are not directly connected to the user's fingers.

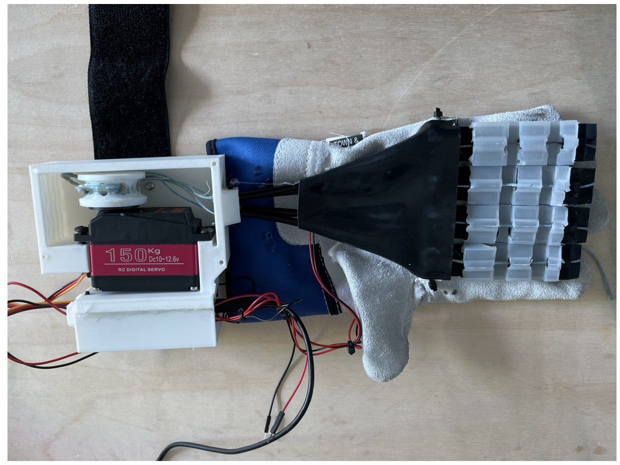

Fig. 2. Exoskeleton with silicone skin integrated

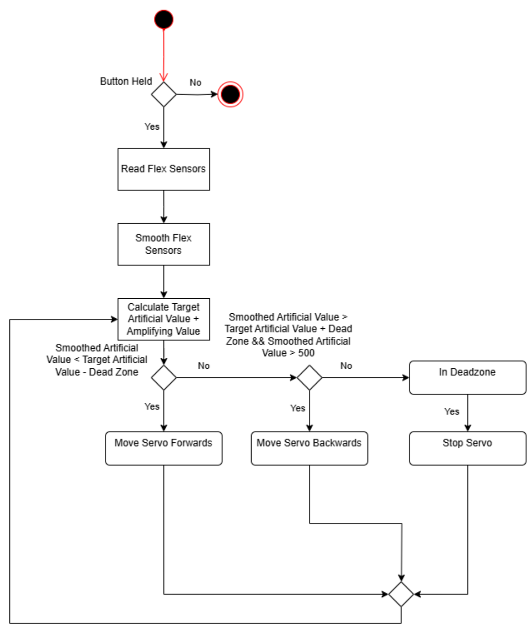

Fig. 3. System Design of the Exoskeleton

To increase grip strength for the exoskeleton, silicone skin was created using a three-part moulding process, producing a layer of silicone that could be placed over the finger. Because silicone's coefficient of friction is much higher than TPU's, it substantially reduces slippage during operation.

A. Control Architecture

The exoskeleton is driven by a DS51150 servo, providing an output torque of approximately 14.7 Nm at 52 RPM when operated at 12.6 V. The servo was operated in position-control mode, using a single pulley to actuate all four fingers simultaneously. An Arduino Nano was used as the controller, providing a straightforward interface for position-based motor control and implemented within the Arduino IDE. The control architecture is illustrated in Fig. 3.

Flex resistors were mounted on the operator's fingers to monitor finger position during flexion, with the index finger used as the reference input. Flex sensors were also embedded within the TPU fingers to measure their actuated position. The resistance measured from the operator's finger during flexion was amplified by a fixed value, so that the TPU fingers would flex further than the operator's fingers for a given input movement. This allowed the operator to achieve much greater flexion in the TPU fingers with only a small amount of finger movement.

The servo continues to actuate until the resistance measured at the TPU finger reaches this amplified target value, at which point movement stops. A dead zone was introduced around the target value to stabilise finger movement and prevent oscillation, allowing the operator to maintain a stable grasp while flexing their fingers only slightly. For safety, a dead man's switch was implemented throughout testing.

This switch had to be held down continuously for the exoskeleton to operate; releasing it at any point cut all power to the motor, allowing the operator to immediately stop actuation if any issues occurred during a trial. Furthermore, the exoskeleton is designed to be non-invasive, positioned under the hand so that it does not apply force through the user's fingers, making it unlikely that any harm would occur during operation.

B. *Modelling the finger*

As this is an underactuated system, robust grasping was achieved by varying the mechanical properties rather than by incorporating additional actuation. Each joint in the TPU finger increases in thickness as it moves up to the distal phalanx of the finger. This creates a relationship between the distance the tendon is pulled (x) and the fact that the joints can perform full flexion only after the last joint has reached its maximum position.

It was found that full flexion of the finger occurred when the tendon was displaced by more than 24mm. Further displacement of the tendon beyond 24mm applied additional force through the finger but did not alter the joint angles.

Fig. 4 shows the desired grasping process of the TPU finger. There is slight flex in the second two joints when $x < 10$; however, this can be ignored, as the angles of the PIP and DIP, $\theta_2 \approx 0$ and $\theta_3 \approx 0$, have a negligible impact on the grasping dynamics.

III. METHODS

All testing was conducted with a single operator rather than multiple participants. A single-operator approach was adopted at this stage to allow rapid, iterative testing of the prototype across a wide range of tasks, given that the primary aim of this study was to establish initial feasibility before progressing to broader participant testing.

Ethical approval for the study was obtained through Falmouth University's internal ethics review process, in accordance with the university's procedures for undergraduate research.

For each test, the operator was provided with simple tasks, each with the steps to be completed and the checkpoints to be assessed. The operator then attempted the task while wearing the exoskeleton. An external marker, independent of the operator, observed each trial and recorded whether each checkpoint was completed successfully, using a binary yes (1) or no (0) outcome, without input from the operator during scoring. This separation between task execution and outcome recording was intended to reduce bias in the completion data.

The operator's gripping strength while wearing the underhand exoskeleton was measured using a dynamometer, with the arm held at a 90-degree angle and the other hand placed beneath it to secure the dynamometer. This meant that the actuation force could be accurately measured without the equipment falling from the palm. The next test stage had the operator again hold the arm at a 90-degree angle, with the underhand exoskeleton actuated to measure grip strength.

Tests were clearly defined in a working area, and were conducted with checkpoints marked as completed, yes (1) or no (0). The external data collector was provided with a spreadsheet listing the checkpoints for each test. These were marked as completed or failed during the test. Binary data was collected on completion success.

1) Filling a Mug: Pick up the mug - this tested the functional grip of the hand in a small space (a U-shaped handle) - then hold the mug for one minute - this tested how the gripper dealt with stress for some time. Then fill up the mug with water - this determined how the gripper coped with the load it was gripping, with a steady increase in weight. Finally, move it to the mouth and take a sip; this final process demonstrated how it handled the motion of an unstable object as the water moved, changing the centre of gravity.

2) Opening a Door: The test was conducted at the entrance of the robotics lab. The test began by forming a grip around the handle and confirming it was securely grasped. The second part assessed whether the door handle moved with the door as it was pulled down. The final part tested whether the exoskeleton could pull the door after successfully grasping the handle.

3) Manipulating a Jar: To control variables and ensure repeatability, a 3D-printed jar holder was bolted to a wooden plank and clamped to a desk to prevent rotation while twisting the jar lid. This eliminated the possibility that the operator's other hand could aid in turning the jar. First, the operator opened the jar to test whether the exoskeleton aided grip during turning. Secondly, the user picked up the lid and screwed it back onto the jar to verify that a tightening force could be applied.

IV. RESULTS

A. *Grip Strength*

Without actuation, the average grip strength was 135.3 N; with actuation, the average grip strength was 234.4 N. This means that a robotic hand exoskeleton that sits beneath the fingers and does not transmit force through the finger joints

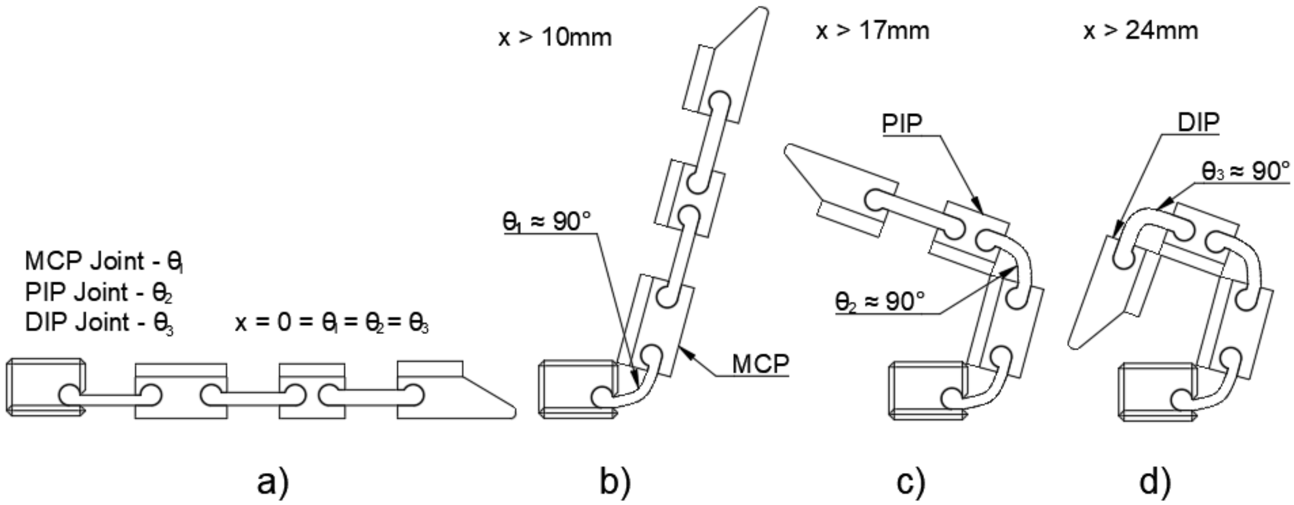

Fig. 4. Grasping process of the finger due to tendon displacement

Fig. 5. Filling a mug

Fig. 6. Opening a door

provides an additional gripping force, thereby enhancing the user's grip.

B. Task Completion

The exoskeleton achieved an overall success rate of 92.5% when lifting a mug and filling it with water. It successfully opened a door in 100% of trials and achieved a 98.1% success rate when manipulating a jar. This shows that a robotic hand exoskeleton that sits beneath the fingers and does not transmit force through the finger joints can assist with everyday tasks.

Fig. 7. Manipulating a jar

TABLE I
COMPARING GRIP STRENGTH (N) WITH AND WITHOUT ACTUATION USING AN INDEPENDENT SAMPLES T-TEST

Condition	$\bar{x}$	SD	t	p	d
No Actuation	135.3	16.1	38.01	3.38E-86	5.7
With Actuation	234.4	20.7			

V. DISCUSSION

The research findings show that a non-invasive underhand exoskeleton can provide an additional gripping force and be used for daily tasks. It opens a new avenue for exploring an exoskeleton that does not transmit force through the joints, benefiting people with many disabilities and those who are uncomfortable with the safety concerns surrounding exoskeletons that drive force through the user's body.

Furthermore, the artefact performs tasks such as manipulating jars and opening doors with a success rate above 90%, demonstrating its suitability for various daily activities compared with specifically designed tools. When it failed a task, this typically occurred during longer operations, where a control glitch was at fault rather than an issue with the overall mechanical design.

In theory, an underhand exoskeleton is a better approach

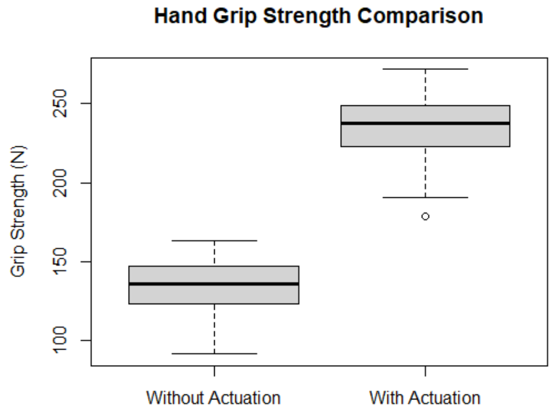

Fig. 8. Comparison between no actuation and actuation of the exoskeleton

TABLE II
ADL TASK COMPLETION RATES WITH ACTUATION USING ONE-TAILED BINOMIAL TEST AGAINST A 90% SUCCESS BENCHMARK

Task	*Success*	*Failure*	*Total*	*p*
Filling a Mug	50	4	54	.360
Opening a Door	54	0	54	.003
Manipulating a Jar	53	1	54	.020

for people with arthritis pain than a full exoskeleton that drives force through the joints. Design refinement is warranted, as this concept is underdeveloped and has not been clinically tested. Future research should focus on medical development and on investigating the specific needs of people with disabilities, such as those with arthritis.

VI. LIMITATIONS

The main limitations of the artefact's development lie in the materials, dexterity, sensors, the control architecture, and the lack of testing across a broad demographic.

During development, numerous rapid prototyping techniques have been employed to produce multiple iterations of the artefact. Several iterations exhibited material deformation due to the high forces applied. Many of these issues were addressed by using larger, stronger, and thicker components, such as bike brake cables used as Bowden tubes, which have an inner metal tube that resists deformation, instead of standard PTFE tubing.

Full TPU fingers make printing easier; however, cable-related filament tearing suggests that placing metal inserts in the guide along the finger where the cable threads through would help prevent this.

These issues clearly indicate that further research is needed into alternative fabrication techniques for the design, including the use of cut metal parts, which would enable a far more robust artefact than PLA parts.

The literature indicates that exoskeletons should be lightweight, which informed the artefact's design, including the use of a single servo to drive all fingers. However, additional motors for independent control of each finger joint are required for more dexterous tasks. More research is needed to determine the motor's specific strength requirements and the necessary degree of dexterity, rather than focusing primarily on a firm grip and general grasping.

While suitable for testing, the control architecture was prone to glitches during continuous use. This was mainly due to the sensing. The flex sensors are noisy and do not provide robust data. The control architecture should be able to discern glitches from genuine intention to actuate; by monitoring muscle activity on the MTJ of the FDS, building on the work of Cheon et al. [22], unintended or slight finger flexion can be ignored.

A significant limitation of this study is that testing was conducted by a single operator, an able-bodied adult without any hand or grip impairment. While this single-operator approach was appropriate for a preliminary feasibility evaluation (see Section III), it substantially limits the generalisability of the results presented in this paper. Grip strength, hand size, finger length, and joint flexibility vary considerably across the population, particularly with age and sex, and the device's fit, comfort, and performance may differ for users with different hand morphologies. Furthermore, the results may be influenced by learning effects, such as the operator becoming more familiar with the device's control dynamics over repeated trials, which would not be captured through single-subject testing alone.

VII. FUTURE WORK

Future work should look into augmenting thumb actuation. This is highly beneficial for individuals with arthritis, as the thumb joint can be affected, leading to soreness. This augmentation should follow the same principles as the current artefact and not drive force through the joints. It should aim to determine whether augmentation is needed for both the thumb's pressing force and rotation. Furthermore, research should explore a multisensor approach in which an EMG sensor is placed on the wrist to detect grasping intention, with flex sensors then used for individual finger actuation, building on the work of Cheon et al. [22]. In terms of design, various orientations and types of gripping mechanisms can be applied to the hand. This paper focuses on a cable-driven gripper; however, future research into this type of system should not dismiss other forms of actuation and mechanisms. For example, an investigation into the use of softer robotics with McKibben muscles and fluid elastomers should be evaluated, even though actuation with pumps and solenoids typically adds more parts and weight. Systems that use linkages should also be considered; although this can reduce finger flexibility, it increases the robustness and lifespan of the parts by preventing wear from flexion.

The next steps would be to redesign the exoskeleton with the following considerations in mind, then trial it on a broader demographic of able-bodied participants, testing the proposed system alongside more classical exoskeleton designs. This would allow research to be conducted on how people feel about a non-invasive exoskeleton and would clearly build on this preliminary investigation to inform the principal design. After research in able-bodied participants is conducted on a much broader scale, clinical testing can be carried out in people with arthritis to account for the more specific needs of this condition.

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