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An Underactuated Hand-Exoskeleton with Adaptive Kinematics for Bilateral Rehabilitation

Tommaso Bagneschi*, Cristian Camardella*, Massimiliano Gabardi*, Daniele Leonardis* and Antonio Frisoli*
*Institute of Mechanical Intelligence, Sant'Anna School of Advanced Studies, Pisa, Italy
Email: name.surname@santannapisa.it

***Abstract*—The study introduces a hand exoskeleton designed to assist hand closing and opening. It uses a unique under-actuated kinematics approach adaptable to different hand sizes. This peculiar design applies only linear forces to the finger segments, which helps to overcome problems caused by the flexible connection between the exoskeleton and finger tissues. The system is improved from previous versions for clinical use, with enhanced kinematics layout, more compact flexure hinges, and built-in electronics supporting strain-gauge force sensors for durability and comfort.**

A control method is also developed for adjusting the grasping assistance based on the patient's evolving motor abilities. This method features symmetric tasks with both the affected and unaffected hand to provide just the necessary support for completing task. This work outlines the hand exoskeleton's design and its initial testing on five healthy participants.

***Index Terms*—Hand exoskeleton, underactuated, adaptive, rehabilitation, bilateral, haptics**

I. INTRODUCTION

The hand's role in our interaction with the environment is crucial, especially for Activities of Daily Living (ADL) involving fine manipulation, grasping, and usage of tools. Restoring hand motor functions is vital for patients who've lost motor abilities, enhancing their quality of life. Robotic hand devices are valuable for both assistance [1] and neurorehabilitation, where haptic feedback aids brain plasticity and motor function restoration [2].

However, providing motor assistance at the hand level is challenging due to hand complexity, size variability, limited workspace, and high forces. Different approaches exist: rigid exoskeletons offer precise forces but struggle with size adaptation [3]. Soft exoskeletons adapt better but struggle with force transmission [4], [5]. Adaptive rigid solutions have been proposed [6], but stability becomes crucial. An adaptive-kinematic design [7] transmits linear forces only, limiting issues.

We introduced a bilateral approach using a healthy limb's signals to modulate assistance for an impaired limb [8]. The bilateral EMG-driven exoskeleton approach has been extended [9], [10]. We proposed an alternative approach using pressure-sensitive objects [11].

We developed an under-actuated hand exoskeleton from [7], [12]. It applies only linear forces to the finger segments (pushing and pulling hand phalanxes without propagating torques), improving comfort and stability of the interface. The second version of the device features flexure hinges and redesigned kinematic links for a compact finger mechanism. The fully embedded electronics drives 6-DOF linear actuators with force sensing (for transparency and clinical evaluation). In the following paragraphs, we detail the device's design, kinematics, and an initial evaluation with healthy participants. The evaluation implements a clinical-focused control paradigm, adjusting grasp assistance based on patients' motor abilities.

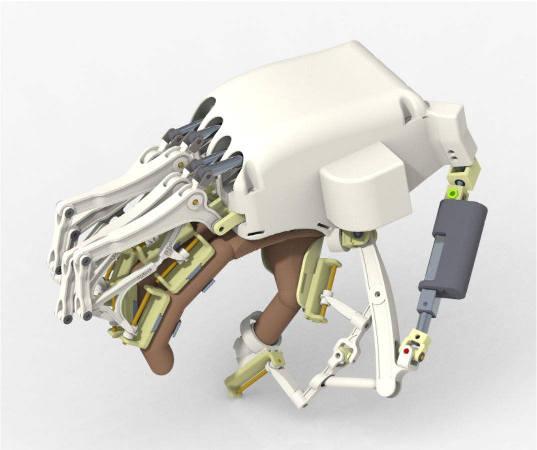

Fig. 1. Design of the proposed Hand-Exoskeleton

II. METHODS

A. Device Characteristics

The hand exoskeleton proposed assists metacarpophalangeal and proximal interphalangeal joints, with specific assistance for the thumb's trapeziometacarpal and interphalangeal joints. The device features several key properties:

1) **Self-Adaptability to Hand Size**: The finger stages are part of the kinematic chain, providing adaptability without mechanical adjustments for different hand sizes.
2) **Allowed Misalignment of Joints**: No need to align device joints with finger joints.
3) **Effective Force Transmission**: Normal forces are applied to the finger, improving design and functionality of fasteners, without the need to over-tighten fingers for torque transmission.

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4) **Under-Actuation**: Sub-actuation based on contact forces simplifies actuators, allowing stable forces for grasping tasks with various objects, maintaining lightweight design.
5) **Back Structure**: Positioned over fingers, allowing free palm and side movement for grasping tasks without interference.

The finger exoskeleton design is based on a previous work [7], while the thumb's mechanism is a redesign of an under-actuated thumb exoskeleton [13].

To make the device suitable for medical use, the base was ergonomically designed. Shapes were modeled after a 3D hand model, and electronics were embedded inside the base for compactness and safety.

B. Fingers and Thumb Modules

The finger modules implement a planar kinematic design with under-actuation. One linear actuator for each finger (Firgelli PA12) is coupled with a parallel kinematic mechanism, closed on the finger kinematic to ensure adaptability to different finger sizes. Similarly, the thumb module caters to the thumb's three-dimensional mobility, using parallel kinematics and underactuation for self-adaptation and effective force transmission. It maintains 4 DoFs (degree of freedom) while conveying forces to thumb segments.

In the second version, the device has been re-designed targeting the final clinical application. The finger parallel mechanism has been re-designed including flexure hinges in a more slim and compact shape, to avoid inter-finger interference. Parts were printed in Carbon fiber reinforced Nylon. Covers were added to the actuators, and embedded electronics were designed and enclosed under the actuators, at the hand dorsum. Electronics supports control and communication, actuators driving, and sensor readings. Each finger is equipped with a position sensor,(linear potentiometer) embedded in each actuator, and with an additional precision, micro-sized strain gauge located between the actuator and the frame of the exoskeleton.

C. Experiments

The experimental assessment began with a characterization of grasping performance, followed by a bimanual task involving both healthy and impaired hands, in line with the proposed rehabilitation paradigm.

	S1	S2	S3	S4	S5
Hand Length $[mm]$	188	176	194	180	177
Middle Finger Length $[mm]$	85	81	84	80	75
Hand Width $[mm]$	87	86	86	83	76

TABLE I
HAND SIZE DATA OF EACH SUBJECT

Five healthy participants (aged 24-35) were involved, with hand dimensions detailed in Table I. Hand length, middle finger length, and hand width were measured. Grasping effectiveness was evaluated by measuring the internal pressure of sensorized water bottles using an internal pressure sensor (Bosch BMP280), similar to [8].

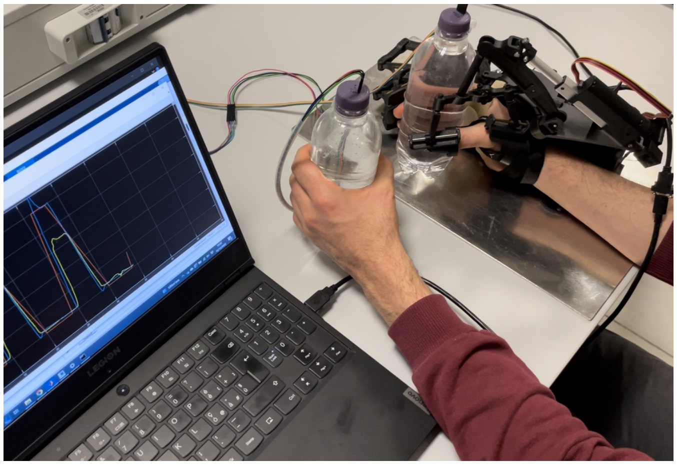

Fig. 2. Experimental setup for bilateral tasks.

Five sessions were conducted with both hands, where subjects grasped two sensorized water bottles. The control paradigm relies the pressure difference between the bottles to regulate the exoskeleton's assistance in a closed-loop control.

Sessions included two subject conditions (Active and Passive grasping) and two exoskeleton conditions (100% and 50% robotic assistance), resulting in four experimental combinations, plus a baseline measurement without the exoskeleton (Bare Hands condition).

During Passive sessions, participants relaxed the assisted hand while using the other hand to follow a pressure reference displayed on a screen. The control loop prompted the exoskeleton to mimic the free hand's grasping action around the bottle.

For Active sessions, participants actively grasped bottles with both hands, following visual pressure references and adjusting assistance levels. These sessions also involved EMG signal measurements using a Myo Armband.

Finally, the Bare Hands condition involved grasping bottles with both hands without the exoskeleton, while utilizing the Myo Armband for data collection.

III. RESULTS AND DISCUSSION

In the passive hand condition, the exoskeleton supported a symmetric grasp guided by the left hand, avoiding the need for complex tuning and calibration procedures. The exoskeleton's control, based on pressure error between objects, demonstrated its adaptability across different hand sizes.

Notably, the approach also accommodates active support for hand opening. If pressure on the healthy hand is less than the assisted hand, the exoskeleton actively opens the assisted hand to match values. This feature is valuable in cases of rehabilitation for patients with hand spasticity, providing stability and comfort due to the exoskeleton's application of pure pulling forces to the phalanxes.

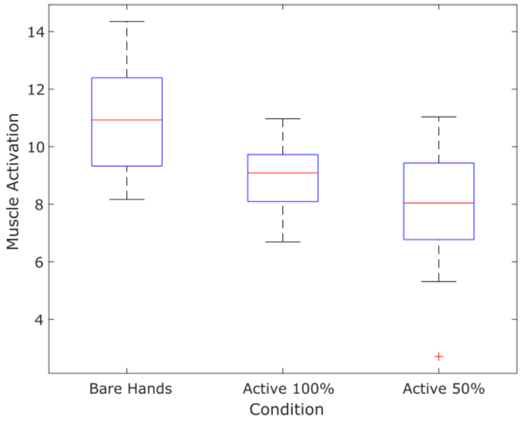

Fig. 3. Muscle activation under three different conditions: without the exoskeleton (Bare Hands), with the exoskeleton with 100% assistance (Active 100%), with the exoskeleton with 50% assistance (Active 50%).

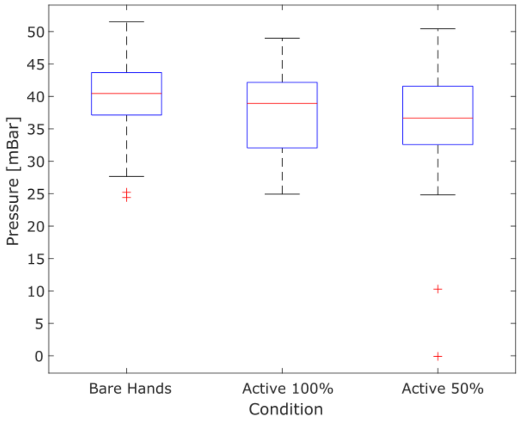

Fig. 4. Grasping pressure under three different conditions: without the exoskeleton (Bare Hands), with the exoskeleton with 100% assistance (Active 100%), with the exoskeleton with 50% assistance (Active 50%).

Active condition experiments yielded two key outcomes. The first pertains to differences in muscular activations between experimental conditions. EMG signals were measured during Active and Bare Hands conditions. Figure 3 illustrates the distribution of mean values of the Myo Armband's 8 channels for different conditions, highlighting the effect of exoskeleton assistance.

Comparing bottle pressures in the same conditions (Figure 4) confirmed that lower muscular activations were not due to different pressure references.

The Active 50% condition was explored, although differences from the 100% condition were limited. Healthy participants primarily provided the necessary grasping action, leaving minimal assistance for the exoskeleton.

IV. CONCLUSIONS

This study presents improved design and tests of an underactuated hand exoskeleton for rehabilitation-assisted grasping. The device boasts adaptable kinematics, forming a parallel chain with the fingers. Its design transmits only linear forces between links and finger phalanxes (no torques), noticeably reducing issues introduced by non-rigid connections between the robot and the finger. The device optimizes kinematics for compactness, especially in the thumb module, and introduces flexure hinges for slimmer mechanisms and reduced interference between fingers.

Preliminary evaluation involved a clinically relevant bimanual task paradigm with healthy subjects. Results indicate the exoskeleton's efficacy in accommodating different hand sizes and its compliance with passive and active hand conditions. This study supports further testing with impaired patients, particularly in challenging scenarios like hand spasticity and active hand opening. Though theoretically capable, empirical validation is needed.

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