

Article

Pneumatic Robot for Finger Rehabilitation After Stroke: A Pilot Validation on Short-Term Effectiveness Depending on FMA Score

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Featured Application

The pneumatic soft robotic system developed in this study can be applied to home-based rehabilitation and spasticity management for post-stroke survivors with hand motor impairments.

Abstract

Pneumatic soft robotic devices are emerging as promising tools for assisting hand rehabilitation in individuals with post-stroke motor impairment. However, evidence regarding their immediate functional impact remains limited, particularly across different impairment levels. This study presents a pilot validation of the YAD_V2 pneumatic finger rehabilitation robot and evaluates acute changes in finger range of motion (ROM) and task performance during a single intervention session. Twenty stroke participants were categorized into two groups based on the Fugl-Mayer Hand sub score: severe impairment (FMA-Hand < 10) and mild-to-moderate impairment (FMA-Hand ≥ 10). ROM was measured using integrated bending sensors during voluntary flexion–extension before, during, and after a 10-min pneumatic actuation session. A mixed 2×3 repeated-measure ANOVA revealed a significant Group $\times$ Time interaction ($F(2, 36) = 4.628$, $p = 0.016$, partial $\eta^2 = 0.205$). In the severe group, ROM increased from 8.53° to 28.46° during actuation ($p = 0.002$), and partially returned to baseline afterward. In the mild–moderate group, no significant ROM changes were observed; however, cube-transfer time improved significantly (mean improvement: 0.88 s, $p = 0.039$). These findings indicate that pneumatic assistance induces distinct acute effects depending on impairment severity. This study provides preliminary evidence supporting the feasibility of the YAD_V2 robotic system and highlights the need for multi-session clinical trials to determine therapeutic efficacy.



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1. Introduction

Stroke is a leading cause of long-term motor disability, and impaired hand function represents one of the most persistent barriers to independence in daily life [1,2]. Recovery of finger mobility typically requires high-intensity, high-repetition, and task-oriented training [3]; however, continuous one-to-one therapy imposes a considerable burden on clinicians and limits the achievable training volume [4,5]. Wearable robotic devices have

been proposed as a scalable solution to increase repetition and provide consistent movement assistance, bridging the gap between clinical demand and available resources [6–8]. In particular, recent advancements in 2024 and 2025 have increasingly focused on integrating flexible sensors and lightweight actuation strategies to enhance the portability and efficacy of these systems for home-based rehabilitation [9,10].

Among various robotic technologies, pneumatic soft robotics offer intrinsic compliance, lightweight design, and improved safety during interaction with fragile joints compared to traditional rigid exoskeletons [11–15]. Previous studies have demonstrated the feasibility of pneumatic gloves for post-stroke rehabilitation and reported short-term improvements in hand opening, movement effort, and task performance [16–21]. However, most studies have focused on mechanical design optimization, actuator characterization, or user acceptance questionnaires rather than quantified joint-level mobility changes [22,23]. Moreover, the acute mobility response may differ depending on impairment severity, as patients with low residual voluntary motion may benefit through passive stretching and altered muscle tone [24], while patients with mild deficits may exhibit ceiling effects or kinematic interference [25].

To address these gaps, this study conducts a pilot validation of the YAD_V2 pneumatic finger rehabilitation robot and quantitatively evaluates acute changes in finger range of motion during a single intervention session. This work does not attempt to establish clinical efficacy but instead focuses on technical validation and immediate mobility response as a feasibility indicator. We hypothesize that pneumatic assistance will induce distinct acute effects depending on impairment severity. Validating this distinction is crucial for optimizing rehabilitation protocols. Consequently, this study aims to clarify the immediate biomechanical and functional impacts of the YAD_V2 system, thereby establishing a rationale for impairment-specific application of soft robotic technology.

This paper is organized as follows: Section 2 describes the design and control mechanism of the YAD system and the experimental protocol. Section 3 presents the results of the biomechanical and functional assessments. Section 4 discusses the implications of the findings in relation to patient severity, and Section 5 concludes the paper with limitations and future directions.

2. Materials and Methods

2.1. Participants and Study Environment

Twenty individuals with post-stroke hemiparesis were recruited through the Korea Association for Human Rights of Persons with Brain Lesions (Gyeongbuk Branch). All experiments were conducted in a dedicated rehabilitation space within this community-based facility, which provides specialized physical training for individuals with chronic brain injuries.

Participants were classified into two groups based on their Fugl–Meyer Assessment Hand score (FMA-Hand) [26]: a severe impairment group (FMA-Hand < 10) and a mild-to-moderate impairment group (FMA-Hand $\geq$ 10). Selection criteria included a diagnosis of stroke and the ability to understand experimental instructions. Individuals with rigid joint contractures or severe hand deformities preventing the donning of the wearable device were excluded.

Prior to recruitment, the required sample size was computed using G*Power (version 3.1.9.7, Heinrich-Heine-Universität, Düsseldorf, Germany). Based on the study design with two subject groups and repeated measurements, the power analysis for a within-between interaction ANOVA indicated a minimum sample size of 22, assuming a conventional statistical power ($1 - \beta = 0.80$) and a large effect size ($f = 0.40$). Although the recruited

sample ($n = 20$) fell slightly short of this target, it was deemed sufficient for this pilot feasibility study.

The study protocol was reviewed and approved by the Institutional Review Board of Handong Global University, Pohang, Korea (Approval No. 2025-HGUA030). All participants provided written informed consent prior to the experiment. Detailed demographic and clinical characteristics of the participants are presented in Table 1.

Table 1. Demographic and clinical characteristics of the participants ($N = 20$).

No.	Sex	FMA-UE	FMA-Hand	Affected Side
1	M	6	0	R
2	M	12	0	R
3	M	12	2	R
4	M	12	0	R
5	F	16	4	R
6	M	12	0	R
7	M	20	2	R
8	M	7	0	R
9	M	53	5	R
10	F	36	0	L
11	F	9	0	L
12	F	57	13	R
13	M	62	14	R
14	M	53	10	R
15	F	66	14	R
16	M	66	14	R
17	M	66	14	L
18	F	53	10	L
19	M	57	14	L
20	F	53	12	L

2.2. System Overview

The YAD_V2 is a research prototype pneumatic finger rehabilitation robot designed to provide repetitive flexion–extension assistance and quantitative motion assessment for individuals with post-stroke hemiparesis. The device integrates sensing, actuation, and control into a lightweight wearable glove and an external control unit, enabling therapist-independent mobilization training. The overall architecture consists of a sensing module, a pneumatic actuation module, and a main control unit that operate in coordination to generate rhythmic inflation–deflation cycles while capturing real-time kinematic data.

Real-time finger kinematics are obtained through integrated bending sensors and pressure sensors embedded in the wearable glove. Each glove connects to a dedicated Glove Sensor Board, where raw signals are amplified, filtered, and digitized before transmission to the Main Control Board, as shown in Figure 1a. This sensor-to-controller pathway enables continuous monitoring of voluntary flexion–extension during pre- and post-intervention assessments. The pneumatic subsystem comprises two miniature pumps (vacuum and exhaust) and two solenoid valves. Based on control signals from the Main Control Board, airflow is routed to induce either inflation or deflation of the glove’s internal air chambers. Power is supplied externally, placing heavy components in the control unit rather than on the glove to minimize distal mass.

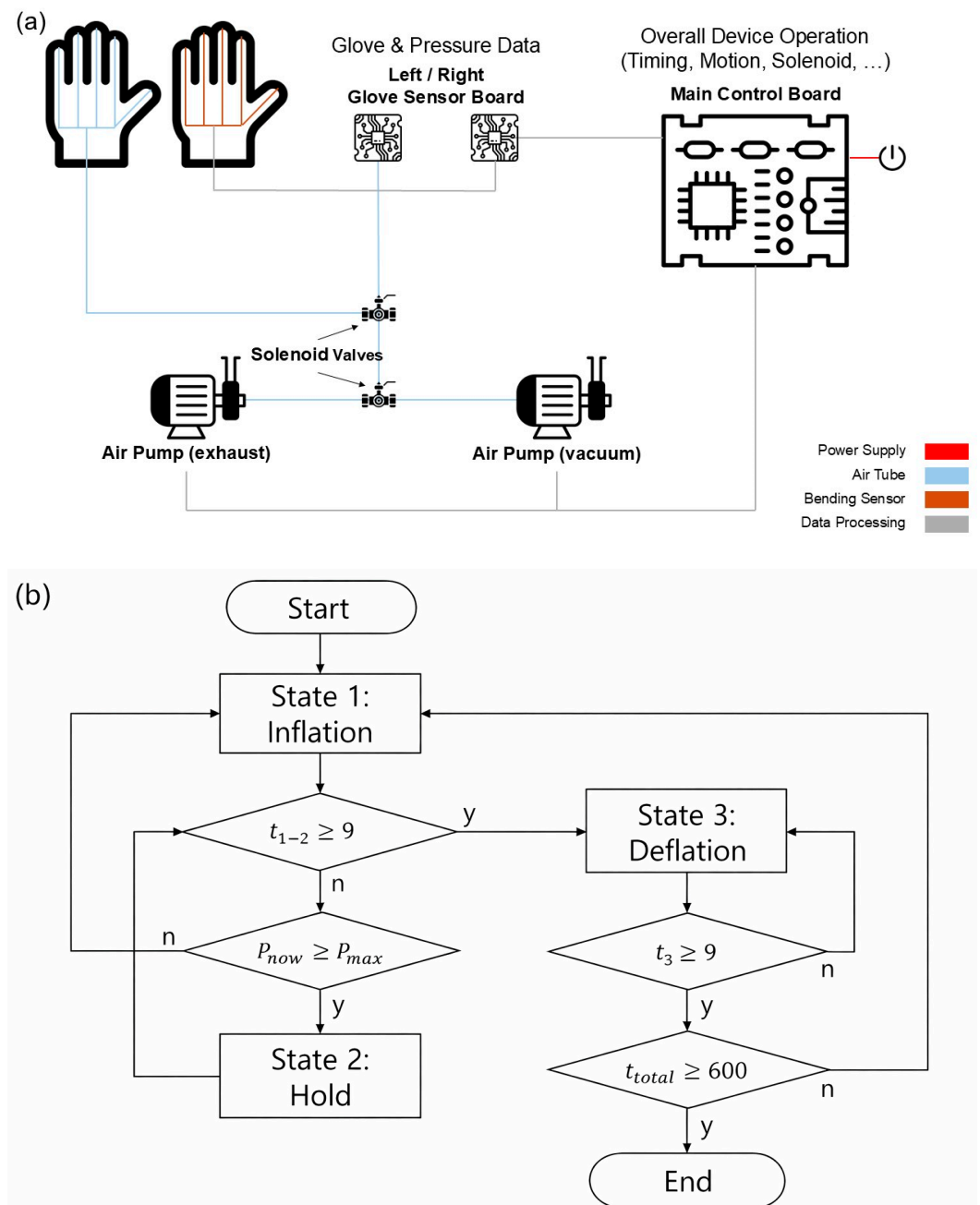


Figure 1. Overview of the YAD_V2 system. **(a)** Schematic diagram of the system architecture illustrating the data communication pathway between the wearable glove sensors, sensor boards, and the main control unit regulating the pneumatic airflow circuit. **(b)** Control logic diagram of the Auto Mode algorithm, illustrating the state transitions (Inflation–Hold–Deflation) governed by the preset pressure threshold (P_{max}) and the session duration limit ($t_{total} \geq 600$ s). Abbreviations: y, yes; n, no.

To provide repetitive passive stretching therapy, the device operates in ‘Auto Mode’, mimicking manual extension techniques used to reduce flexor spasticity. As illustrated in Figure 1b, the control algorithm follows a predefined inflation–hold–deflation sequence without reliance on real-time feedback. At the start of each cycle, the vacuum-side pump delivers pressurized air into the glove until the pressure reaches a preset maximum threshold (P_{max}). Once P_{max} is reached, a sustained stretch phase (approx. 3 s) maintains the extension to lengthen flexor musculature. Subsequently, the exhaust-side pump evacuates

air, allowing the hand to naturally re-flex due to residual muscle tone before the next cycle begins.

2.3. Experimental Protocol

The experiment followed a three-stage protocol: (1) Pre-intervention, where participants performed five voluntary flexion–extension cycles of the affected hand while wearing the inactive device (5 s interval between cycles). (2) Intervention, during which the YAD_V2 provided 10 min of rhythmic assistance using 9 s inflation and 9 s deflation cycles at Level 3 intensity. This slow cycle duration was selected to induce quasi-static movement, minimizing the risk of triggering stretch reflexes. Consequently, approximately 33 repetition cycles were administered during the 10-min session, as illustrated in Figure 2. The system was powered by a source pressure of 0.65 MPa, which was determined in preliminary tests as the effective pressure required to overcome finger spasticity. Although personalized settings are ideal, fixed parameters were used in this pilot study to ensure consistency. (3) Post-intervention, where participants repeated the five-cycle voluntary movement protocol under identical conditions. Only the five-cycle datasets were included in the analysis to ensure consistency.

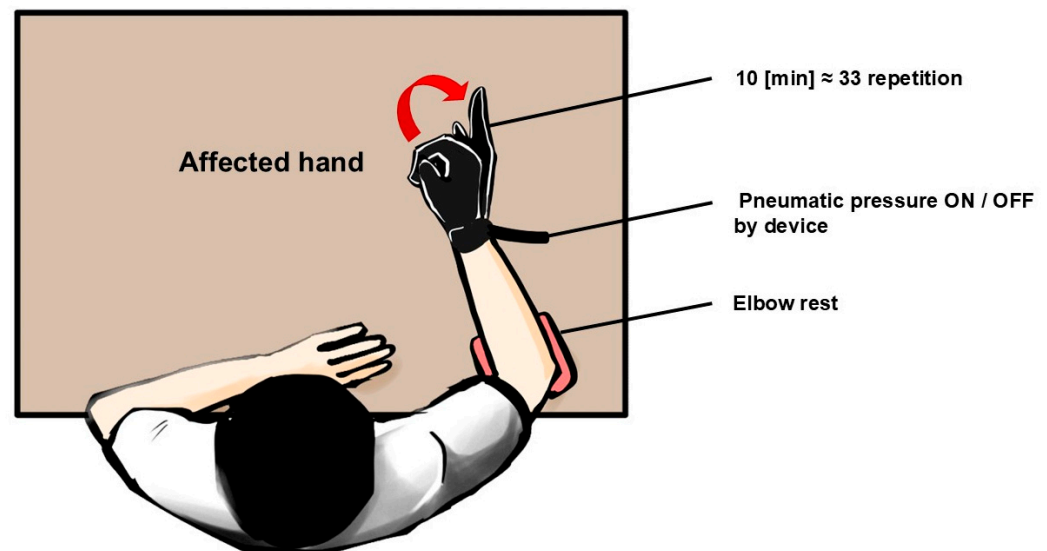


Figure 2. Schematic representation of the experimental setup during the intervention phase. The participant sits with the affected arm supported by an elbow rest to isolate hand movements. The YAD_V2 system provides rhythmic pneumatic actuation (approximately 33 cycles) for 10 min. The red arrow indicates the repetitive flexion and extension motion.

2.4. Outcome Measures

2.4.1. Range of Motion

ROM was computed as the peak-to-peak angular difference for each cycle using the glove's bending sensors (Spectra Symbol, Salt Lake City, UT, USA). To ensure measurement reliability, a calibration process was performed prior to the experiment by correlating the sensor outputs with reference angles measured by a standard goniometer (at 0°, 45°, and 90°). Figure 3 illustrates the measurement conditions: voluntary movement utilized for baseline and retention assessments (left), and pneumatically assisted motion during the intervention (right). For each participant, the mean ROM was calculated across the five cycles for the pre-, during-, and post-intervention stages.

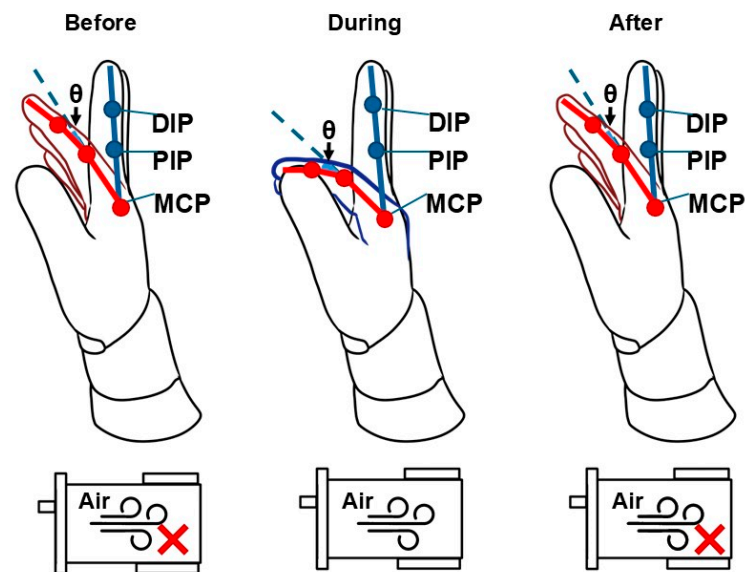


Figure 3. Experimental setup for Range of Motion (ROM) assessment illustrated across the procedural timeline. The ‘Before’ and ‘After’ panels depict the unassisted state used for voluntary motion assessment, while the ‘During’ panel demonstrates the maximum passive extension induced by pneumatic actuation. Bottom icons indicate the corresponding pneumatic supply status (Off/On). The blue and red lines represent the skeletal segments of the index finger and thumb used to define the angle θ . The red cross mark indicates that the pneumatic supply is turned off.

2.4.2. Functional Task

Participants in the mild-to-moderate impairment group additionally performed a cube-transfer task, modified from the standard Box and Block Test [27], which involved moving ten wooden blocks (edge length: 1 cm) placed 25 cm apart across a flat surface, as depicted in Figure 4. The total completion time was recorded.

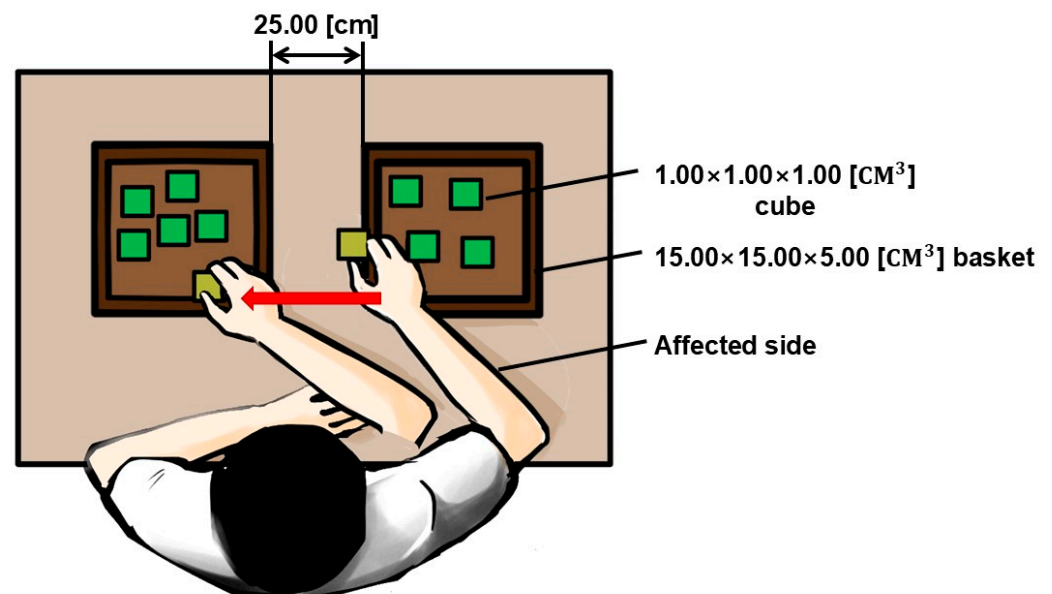


Figure 4. Experimental setup for the functional cube-transfer task. The left panel shows a participant performing the task using the affected hand. The right panel schematically illustrates the spatial arrangement, where cubes are transferred to a target container placed 25 cm away. The distinct color of the cube being manipulated is solely for visual contrast; all cubes possess identical physical properties.

2.5. Statistical Analysis

A 2×3 mixed repeated-measures ANOVA was used to analyze the effect of impairment severity (between-subject factor: severe vs. mild) and time (within-subject factor: pre, during, post) on ROM. Post hoc pairwise comparisons were conducted using Bonferroni correction. For the cube-transfer task, a paired t -test compared pre- vs. post-intervention movement time. Statistical significance was set at $p < 0.05$. All statistical analyses were performed using IBM SPSS Statistics (version 26.0, IBM Corp., Armonk, NY, USA).

3. Results

A total of twenty participants completed the full experimental protocol. No adverse events or device-related discomfort were reported during or after the intervention.

3.1. Range of Motion (ROM)

A 2×3 mixed repeated-measures ANOVA revealed a significant Group $\times$ Time interaction ($F(2, 36) = 4.628$, $p = 0.016$, partial $\eta^2 = 0.205$), under the assumption of sphericity, indicating that the acute mobility response differed between the severe and mild impairment groups. To decompose this interaction, simple main effects of Time were analyzed for each group using Bonferroni adjustment.

Figure 5 illustrates the changes in finger ROM across the three experimental stages. To visualize individual response trajectories, data points from the same participant are connected by lines, while the error bars represent the group means and standard deviation. Participants with severe impairment exhibited a substantial acute increase in ROM during pneumatic assistance. Mean ROM increased significantly from 8.53° (SD 4.29) at baseline to 28.46° (SD 13.99) during the intervention ($p = 0.002$). After device removal, ROM decreased to 9.09° (SD 7.25), which was significantly lower than the during-intervention value ($p = 0.001$) and not different from baseline ($p = 0.134$).

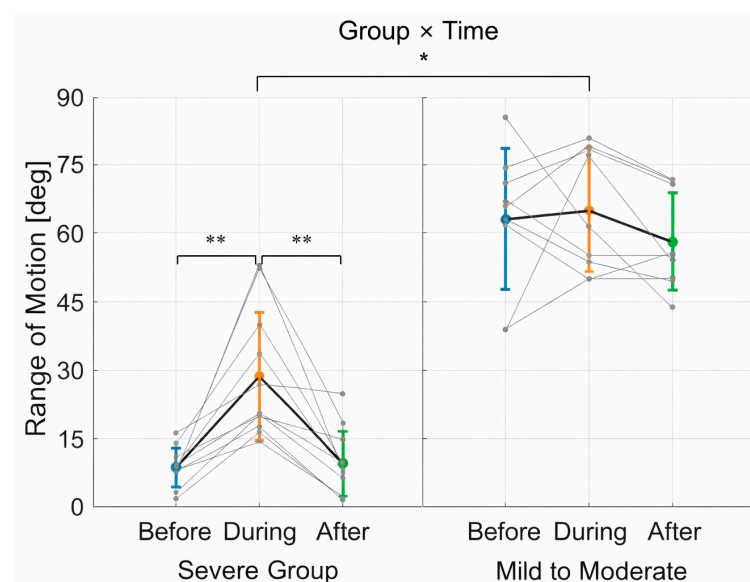


Figure 5. Comparison of finger Range of Motion (ROM) between severe ($n = 11$) and mild-to-moderate ($n = 9$) impairment groups across experimental stages (Pre, During, Post). Bars represent the mean ROM, and error bars indicate the standard deviation. Individual participant data points are connected by lines to visualize response trajectories across the discrete experimental stages. The error bars are color-coded by stage: blue (Before), orange (During), and green (After). The black line indicates the group mean, while gray lines represent individual participant trajectories. Asterisks denote statistically significant differences (* $p < 0.05$, ** $p < 0.01$).

In contrast, for participants with mild-to-moderate impairment, mean ROM remained stable across the three time points. Baseline ROM was 63.02° (SD 15.60), increasing slightly to 64.99° (SD 13.76) during the intervention, and decreasing to 57.82° (SD 10.70) post-intervention. None of the pairwise comparisons reached statistical significance (all $p > 0.05$). These results indicate that pneumatic assistance induced a marked acute ROM expansion only in the severe impairment group, whereas individuals with mild-to-moderate impairment showed minimal change, potentially reflecting ceiling effects associated with higher residual voluntary motion.

3.2. Functional Task Performance

Participants in the mild impairment group additionally performed a cube-transfer task to assess functional movement speed. Figure 6 illustrates the individual and mean change in task completion time before and after the intervention. Individual pre-post data points are linked to depict subject-specific performance shifts. A paired t -test revealed a significant reduction in task completion time after the intervention (mean improvement = 0.88 s, $t(9) = 2.471$, $p = 0.039$).

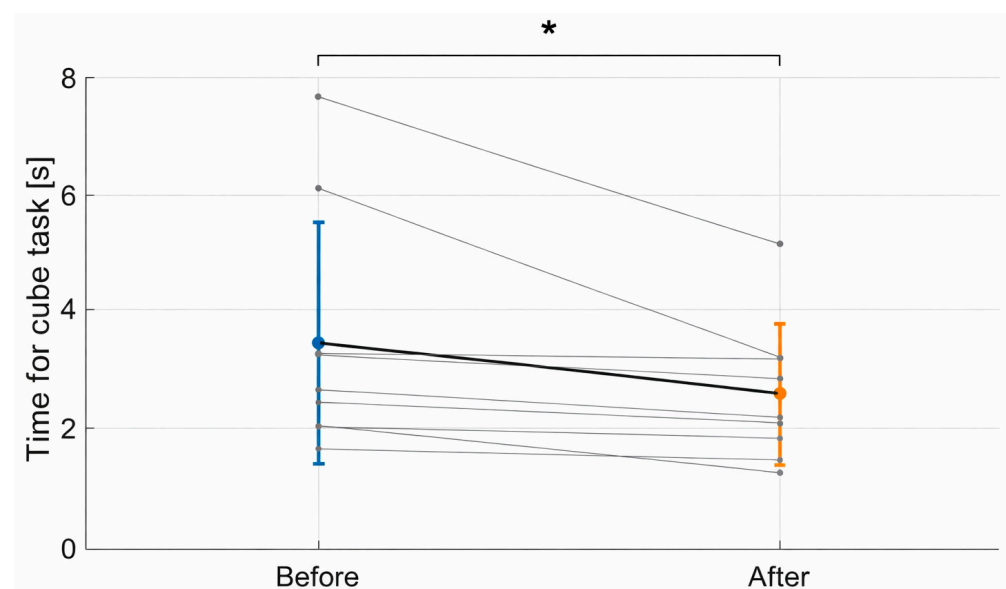


Figure 6. Changes in cube-transfer task completion time for the mild-to-moderate impairment group ($n = 9$). Gray lines connect individual participant data points between discrete time points to visualize subject-specific performance shifts, showing a consistent trend of reduced time post-intervention. The bold black line indicates the group mean, with error bars representing the standard deviation. Asterisk denotes a statistically significant difference (* $p < 0.05$).

The severe impairment group did not perform the task due to insufficient functional ability to manipulate the blocks.

3.3. Summary of Findings

Acute mobility responses to pneumatic assistance varied according to impairment severity. For individuals with severe motor deficits, robotic actuation yielded a pronounced expansion in ROM, though this gain diminished partially following the cessation of assistance. In comparison, the mild-to-moderate cohort maintained consistent ROM levels throughout the session but demonstrated a statistically significant enhancement in the velocity of functional task execution.

4. Discussion

The primary objective of this study was to evaluate the immediate therapeutic effects of the YAD_V2 pneumatic finger-rehabilitation system in stroke survivors with varying levels of hand motor impairment. Our findings confirmed a significant interaction between impairment severity and rehabilitation outcomes. Specifically, participants with severe impairment (FMA-Hand < 10) demonstrated a marked increase in passive range of motion (ROM) of approximately 20° during the robotic intervention, whereas those with mild-to-moderate impairment (FMA-Hand ≥ 10) exhibited significant improvements in functional task speed (mean reduction of 0.88 s) despite negligible ROM changes. These results suggest that the therapeutic mechanism of pneumatic soft robotics is not uniform but is modulated by the patient's baseline motor capacity.

The pronounced increase in ROM observed in the severe impairment group is consistent with the known physiological effects of cyclic pneumatic actuation. Previous studies have reported that repetitive passive stretching can temporarily reduce hypertonicity and viscoelastic stiffness in spastic muscles [24]. The YAD_V2 likely facilitated these effects through mechanical elongation of the flexor digitorum muscles and enhanced proprioceptive stimulation during the inflation–deflation cycles [18]. However, the rapid decline in ROM immediately after device removal suggests that a single 10-min intervention is insufficient to induce durable plastic changes in neuromuscular properties. This aligns with prior reports indicating that high-frequency, multi-session training is required to achieve persistent improvements in spasticity or joint excursion [7].

In contrast, participants with mild-to-moderate impairment showed minimal ROM changes, likely due to a ceiling effect as they already possessed near-functional joint mobility [25]. Instead, this group demonstrated a significant reduction in cube-transfer time 233 post-intervention. This functional gain supports the premise that pneumatic robotic intervention can serve as a “motor priming” mechanism [28,29]. Even in the absence of kinematic changes, the rhythmic passive mobilization provided by the glove may have enhanced sensorimotor integration and neuromuscular readiness, thereby improving the efficiency of subsequent voluntary movements [30,31]. This finding highlights the potential 238 of soft robotic devices not only for passive stretching but also as a preparatory tool for 239 task-oriented training in patients with residual voluntary control.

From a clinical perspective, these findings advocate for an impairment-specific application of soft robotic technology. For severely impaired patients, the device serves effectively as a continuous passive motion (CPM) tool to prevent contractures and maintain soft-tissue compliance. Conversely, for mild-to-moderate patients, the device may be better utilized to facilitate movement efficiency prior to functional tasks. The portability and safety of the pneumatic design further support its potential for high-frequency home-based rehabilitation, addressing the gap between recommended and actual training doses [18,32].

This study has several limitations that warrant consideration. First, neuromuscular analysis via electromyography (EMG) was excluded from this study due to inherent challenges in interpreting surface signals from the forearm musculature. Although electrodes were targeted at the extrinsic flexor and extensor muscle bellies, accurately resolving specific finger grasp-and-release patterns proved difficult. This limitation arises from the complex anatomical layering of the forearm muscles, where significant signal crosstalk between deep and superficial muscles often obscures the distinction between individual digit actuations [33,34]. Furthermore, in stroke survivors, abnormal co-contraction patterns can further confound signal clarity [35]. Combined with electromagnetic interference originating from the metallic components of the pneumatic control hardware, these factors compromised signal reliability. Consequently, EMG data were excluded to ensure analytical rigor. Future iterations will prioritize sensor optimization and shielding to enable

reliable neuromuscular analysis. Second, the intervention consisted of a single 10-min session, which limits conclusions regarding long-term therapeutic retention. Future work should incorporate repeated sessions and longitudinal follow-ups. Third, an a priori power analysis targeting a large effect size ($f = 0.40$) indicated a required sample size of 22. Although the sample size ($n = 20$) was slightly below this target, the effect sizes observed in the primary outcomes were substantial, supporting the validity of the pilot findings. However, we acknowledge that the small sample size, particularly in the mild-to-moderate subgroup, limits the generalizability of the results. Fourth, this pilot study employed a self-controlled design without a separate control group to evaluate acute feasibility. Future research should include a randomized control group to rule out placebo effects and spontaneous recovery. Fifth, although the assessors were not explicitly informed of the participants' specific FMA scores, complete blinding was challenging because the groups were distinguished by observable motor severity. To minimize potential observational bias, this study relied on quantitative sensor data and timed tasks rather than subjective clinical judgment. Finally, kinematic analysis relied on integrated bending sensors; future studies should incorporate external motion capture systems for more comprehensive multi-joint motion characterization.

5. Conclusions

This study presented a pilot validation of the YAD_V2 pneumatic finger rehabilitation robot and evaluated its acute therapeutic effects on stroke survivors with varying levels of hand motor impairment. Unlike previous studies that often relied on qualitative observations, this research utilized integrated bending sensors to provide quantitative kinematic evidence of rehabilitation outcomes. Our findings demonstrate that the impact of pneumatic assistance is highly dependent on baseline motor capacity. Participants with severe impairment exhibited significant immediate gains in passive range of motion (approximately 20° increase), highlighting the device's utility for spasticity management and joint mobilization. Conversely, participants with mild-to-moderate impairment showed improvements in functional task speed (0.88 s reduction in completion time), suggesting a motor priming effect that enhances movement efficiency. These results underscore the necessity of tailoring soft robotic interventions to the specific needs of the user—focusing on mechanical stretching for severe cases and functional facilitation for moderate cases. However, as this was a single-session pilot study without a control group, these findings should be interpreted as preliminary feasibility data. Future work will focus on integrating active-assisted control strategies, optimizing sensor hardware for neuromuscular analysis, and conducting longitudinal Randomized Controlled Trials (RCTs) to verify long-term therapeutic efficacy and rule out confounding factors.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board of Handong Global University (protocol code 2025-HGUA030 and date of approval).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Written informed consent has been obtained from the patients to publish this paper.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy and ethical restrictions involving human participants.

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Abbreviations

The following abbreviations are used in this manuscript:

ROM	Range of Motion
FMA	Fugl-Meyer Assessment
EMG	Electromyography
sEMG	Surface Electromyography
ANOVA	Analysis of Variance SD
IRB	Institutional Review Board

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