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Efficacy of robotic training gloves in improving hand function and movement in stroke patients

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ABSTRACT

Robotic training gloves are designed to assist with hand movements by providing resistance, support, or guidance. The efficacy of robotic training gloves on hand function in stroke patients, particularly when using the mirror mode, is an intriguing topic in rehabilitation therapy. This study aimed to investigate the effect of assistive robotic rehabilitation devices on hand function in stroke patients. A controlled randomized study was conducted with thirty (9 males and 21 female) stroke patients, who were selected from the outpatient clinic of Al-Delingat Central Hospital - Al-Buhaira Governorate. These patients were randomly assigned to two groups: the study group (A), which received the selected physical therapy program and mirror therapy assisted by a robotic rehabilitation glove, and the control group (B), which received only the conventional physical therapy program. When comparing between both groups, the results indicate that the patients in group A that underwent the combined therapy had a statistically significant improvement in grip strength when tested by the Jamar dynamometer (MD= 1.87 [0.39, 3.35], P=0.015) and in motor function when evaluated by the Fugl-Meyer scale than the group who had only conventional physical therapy (Group B) (MD= 16.67 [3.9, 29.4], p=0.012). This controlled randomized study provides evidence that combining robotic rehabilitation with a standard physical therapy program yields superior improvements in grip strength and motor function compared to standard physical therapy alone.

KEYWORDS

Stroke; Rehabilitation; Robotic; Conventional Physical Therapy; Motor Training

1. INTRODUCTION

Stroke is a neurological condition characterized by the obstruction of blood vessels (Lu et al., 2023). Clots grow in the brain, disrupting blood flow, blocking arteries, and forcing blood vessels to rupture, resulting in hemorrhage (Campbell et al., 2023). Stroke is the main cause of developed physical disability in individuals worldwide, as well as the second-highest cause of death in high and middle-income countries (Carr et al., 2022). Additionally, 87% of stroke-related life years are adjusted for disability and 85% of all stroke-related fatalities occur in countries with low incomes (Alayat et al., 2022).

Every minute that an acute stroke goes untreated decreases the likelihood of full neurological recovery (Lo et al., 2023). Impairments following a stroke can be both transient and long-lasting. Daily activities such as walking and utilizing the toilets are typically affected by visual and sensorimotor impairments (Grevet et al., 2023; Shankaranarayana et al., 2023). After a stroke, rehabilitation may involve speech, physical, occupational, and/or cognitive therapy (Fujii et al., 2022; Igarashi et al., 2022). Its goals are to assist patients become more independent, improve their range of motion, acquire access to social and psychological support, and restore their ability to solve problems (Kawada & Goto, 2017). Rehabilitation can also involve neurobiological exercises aimed at reducing the effect of cognitive impairment and inducing synaptic plasticity, in addition to long-term potentiation (Zheng et al., 2016).

Recently, robotic-aided therapies have been incorporated into rehabilitation projects, where the rehabilitation team customized interventions based on patient typologies and intensity (Saragih et al., 2023). These therapies offer a fresh and exciting method for the rehabilitation of the paretic upper limb following a stroke (Chan, 2022). Many robotic devices have been created to offer individuals with mild to severe motor deficits following neurologic damage intensive and safe rehabilitation (Leerskov et al., 2024).

These devices can help individuals perform repetitive movements and engage in task-specific training, which are essential for motor recovery (Li et al., 2020). Among the various modalities employed, mirror mode—where the movements of the unaffected hand are mirrored to stimulate the affected hand—has gained attention for its potential benefits. Mirror mode leverages the concept of visual feedback to promote motor recovery (Kottink et al., 2022). This method is based on the premise that visual and sensory feedback can influence motor learning and recovery processes (Nasrallah et al., 2021). Our study is designed to investigate the effect of assistive robotic rehabilitation devices on hand function in stroke patients. We hypothesized that robotic training gloves will significantly improve hand function in stroke patients compared to conventional physical therapy. Specifically, the use of robotic training gloves will enhance motor recovery, dexterity, and strength in the affected hand, leading to better functional outcomes in daily activities.

2. METHODS

2.1. Study design

In this controlled randomized study, we included patients with subacute stroke who were diagnosed and referred to our department by neurologists. Thirty male and female stroke patients were selected from the outpatient clinic of AL-Delingat Central Hospital - Al-Buhaira Governorate. These patients were randomly assigned into two groups: Study group (A) received the selected physical therapy program and mirror therapy by the assistive robotic rehabilitation glove. Control group (B) only received the selected physical therapy program. The patients were diagnosed by a neurologist and the diagnosis was confirmed by magnetic resonance imaging (Figure 1).

The patients were selected according to the following criteria: Thirty hemiplegic male and female patients; patients' ages ranged from 50 -65 years old; upper limb spasticity ranged from 1 to 1+ according to the Modified Ashworth scale; Brunstrom's stage of hand recovery ranged from 2nd to 3rd stage; patient with sub-acute cerebrovascular accident due to ischemic stroke in the domain of the carotid system; duration of illness ranged from 6 weeks to 6 months; mini-mental state score > 24 enables comprehension of basic spoken instructions; according to the manual muscle testing scale, the paretic upper limb's degree of weakness was at least grade 2; complete passive range of motion in the fingers and wrist.

The patients were excluded if they had one of the following: The wrist joints' range of motion was limited in patients with contractures, including the metacarpophalangeal and interphalangeal joints; excessive spasticity in the upper limb as measured by the Modified Ashworth scale; comorbidities have a substantial impact on pre-existing musculoskeletal disease and upper limb function (e.g., osteoarthritis, prior hand surgeries); the sickness lasted for less than half a year; patients had diabetic polyneuropathy; patients had dominant affection.

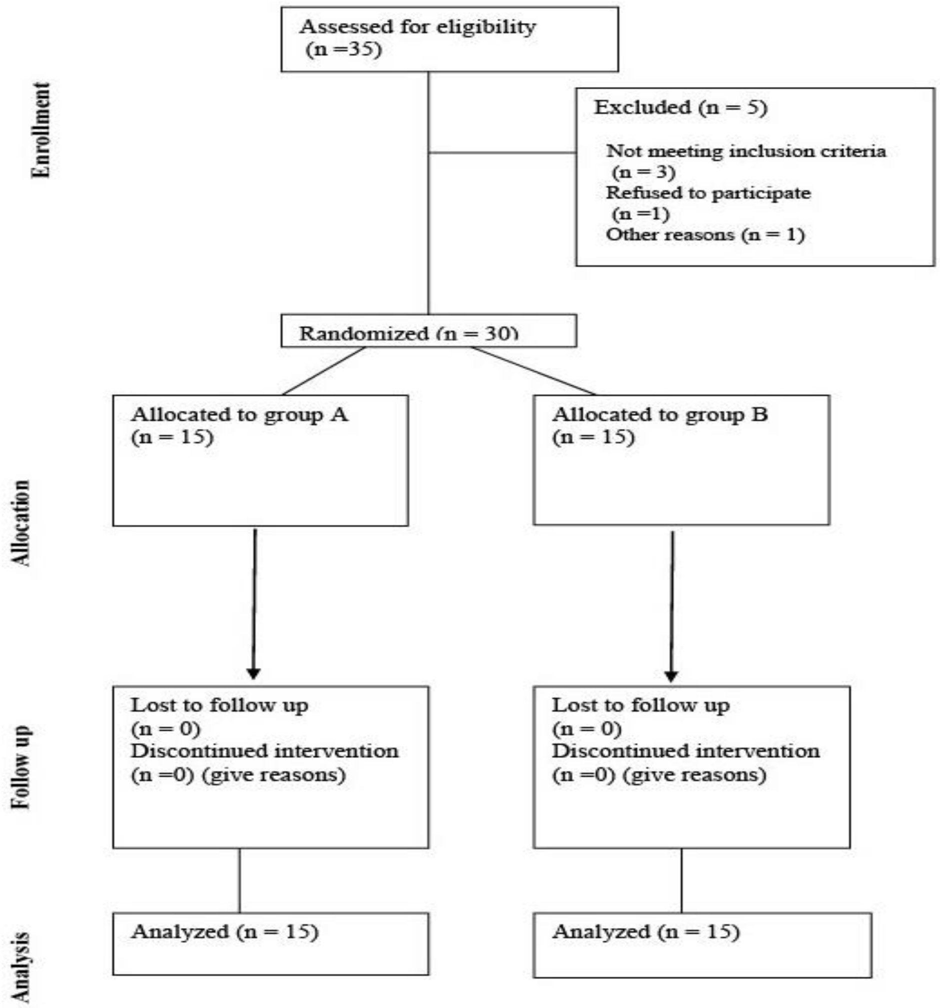

Figure 1. CONSORT flow diagram

2.2. Instruments

2.2.1. Assessment instruments

JAMAR Hand-held Dynamometer: This hand dynamometer is perfect for regular evaluations of hand function and grip strength, giving CHTs, OTs, and PTs a simpler way to monitor and record patients' progress. In addition, a dual-scale readout showing isometric grip force between 0 and 200 pounds is included in this hand strength test. With five adjustable degrees of grip positions, it can be used to evaluate peak strength and isometric force. With ease, the handle may be adjusted in half-inch increments from 1 3/8" to 3 3/8". This facilitates monitoring recovery and strength over time (Roberts et al., 2011).

2.2.2. Treatment instruments

SYREBO Hand Rehabilitation Device: This device was manufactured by SIYI intelligence company in 2021 in China to rehabilitate stroke patients, it consists of a soft robotic glove incorporated with unidirectional and bi-directional molded elastomeric fabric-based actuators. These soft fabric actuators allow the device to be lightweight, so it doesn't hinder the patient's movement.

A base glove with connection points (such as straps or hook-and-loop fasteners) for modular, separate finger actuators makes up the device design. Three layers of fabric and two airtight bladders positioned in between each fabric pocket compose each fabric-based actuator. By using an air pump to selectively pressurize these bladders, finger extension, and flexion can be achieved. The actuators are made to perform intricate motions that resemble the natural movements of the hand by utilizing the material characteristics of each fabric layer (such as stiffness and anisotropy) and introducing geometric design factors into the structure (such as pleats) (Fig. 2).

The soft robotic glove can lift and hold light objects because it is made to exert enough force on each finger to open and close. The glove can hold variously shaped things because of its naturally conforming structure. It has been shown that a healthy user of the glove can grab an object with a force of 15 N, which is equivalent to an average of roughly 30% of an adult's greatest pinch force. When the user kept their muscles relaxed and the glove was pressurized to 172 kPa (25 psi), the integral of contact pressure was recorded using an incredibly thin pressure mapping sheet wrapped around a 76 mm cylinder (Fig. 2).

A transportable and independent control box was created in order to operate the glove. The box includes an electric air pump, battery pack, control electronics, exhaust, and fill air manifold. It also has seven solenoid valves attached to control the airflow of seven pneumatic channels, which are in turn connected to pneumatic actuators. The electric pump was turned on and the solenoid valves were operated by a pressure control loop. To minimize complexity, the single-finger actuators are either linked with joint pneumatic channels or operated separately (Fig. 2).

When the flexion of the middle finger, index, and thumb are all activated simultaneously, the glove executes a three-point pinch hold. The glove executes a palmar grasp when all flexion actuators, involving the ring and pinky fingers, are activated. By alternately pressing and depressing the agonist and antagonist actuators, two buttons were able to initiate the opening (finger extension) and closing (finger flexion) actions of the hand. As a safety precaution and to release any remaining air in the bladders when no active assistance was required, a third button was added (Fig. 2).

With the help of this hand robot, specific fingers can receive carefully chosen instruction along with frequent, repeating workouts. This device has two modes for active-assisted exercise: position-controlled and isometric. It also provides visual assistance during computer games that focus on finger extension and flexion. Also, it contains a mirror mode which allows the paretic hand to move just like the non-affected hand. This is accomplished by wearing the sound hand a soft glove with motion sensors attached to it, these sensors detect the hand motion and transmit it to the unit of the robotic glove where it can be translated into movement of the glove of the patient hand (Fig. 2).

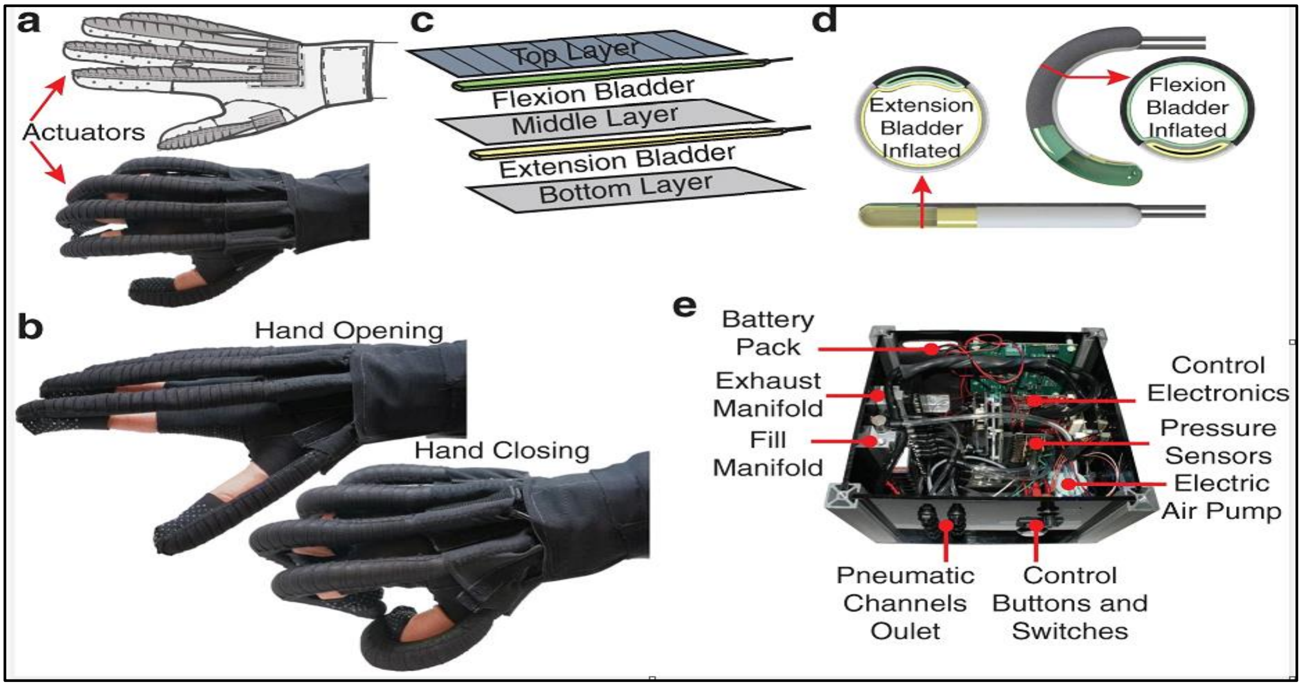

Figure 2. The fabric-based soft robotic actuators, adopted from (Cappello et al., 2023).

2.3. Procedures

2.3.1. Assessment procedures

Hand grip strength: Hand grip strength was measured by a JAMAR hand-held dynamometer as the following:

1. We demonstrated how to hold the dynamometer to the participant and explained how the dial registers the best result by squeezing as tightly as possible.
2. The patients sat comfortably in a chair with back support and fixed arm rests.
3. Use the same style of chair (low-backed, with fixed armrests) for every measurement.
4. The participants were asked to rest their forearms on the arms of the chair and keep their feet flat on the floor
5. Their wrists should be just over the end of the chair’s arm, thumb facing upwards.

6. They placed their thumb around one side and their fingers around the other side of the handle.
7. Turn the dial to make sure the red needle is in the"0" position.
8. Repeat the measurement with the left hand after starting with the right.
9. When the subject is holding the dynamometer, the measurer should support its weight by placing it on their palm, but they shouldn't be preventing the instrument from moving freely.
10. For optimal results, squeeze for as long as you can and as tightly as you can, until the needle stops rising. Squeeze with the traditional words, "Squeeze...harder, harder...and stop squeezing."
11. Read the measurement (in kg) from the dial after the needle stops rising, then note the result to the nearest 1 kg. The result is displayed in kg on the outer dial and in lb.
12. Record three measurements for each hand, alternating sides.

Hand function: Hand functions will be graded by performing Fugl-Meyer Scale (FM) test to assess sensorimotor function of upper limb and each patient takes agrade equals to his performance according to the scale. The Fugl-Meyer Assessment uses a three-point ordinal scale to score performance on each task:

0 points: Cannot perform the task.

1 point: Performs the task partially.

2 points: Performs the task fully.

The scores for each domain are summed up to generate a total score.

2.3.2. Treatment procedures

Group A: Every patient received five sessions per week for four weeks. The session was divided into two parts: a standard physical therapy program and robotic rehabilitation training. The standard physical therapy program was:

- Strengthening shoulder flexors, elbow extensors, and wrist extensors.
- stretches for the elbow flexors, wrist flexors, and shoulder adductors.
- Attempting to bear weight on the afflicted upper limb for ten seconds while sitting, then letting go of the pressure: the patient did this. The number of repetitions for each patient ranged from five to 10, depending on their capacity.
- Proprioceptive neuromuscular facilitation techniques using active extension of the wrist
- Bobath technique using distal key point (the thumb).

Group B: Every patient received five sessions per week for four weeks. The session consisted of a standard physical therapy program.

Robotic rehabilitation training: by SYREBO Hand Rehabilitation Device

The patient relaxed in a supine position or sitting position according to his/her preferences. The patient put the rehabilitation glove on the affected hand with the fingers reaching the top of the glove then the Velcro on the back of the wrist tightened, the soft glove was put on the other non-affected hand and its strap also tightened the control unit was set on mirror mode as the robotic device imitated the movement from the sound hand to the affected hand, the patient was instructed that when the device was on, he extended the sound hand so that the device can imitate it then when the movement of the rehabilitation glove occurs, patient started to extend the affected hand as the device helped him during the task. The time of robotic rehabilitation was thirty minutes (Fig. 3).

Figure 3. Robotic rehabilitation training by SYREBO Hand Rehabilitation Device, adopted from (Kim et al., 2022)

2.4. Outcome measures

Hand grip strength by hand dynamometer.

2.5. Sample size

An a priori analysis is performed to determine the required sample size for the study groups through G*POWER statistical (G*power version 3.1). Using data from the upper limb Fugl-Meyer test from Youssef et al., 2021, a two-sided t-test with an α error probability of 5% a power of 80%, and an effect size of 1.1 was then carried out, resulting in a sample size of 15 subjects per group.

2.6. Statistical analysis

The subjects' characteristics were compared between groups using descriptive statistics and unpaired t-tests. A mixed MANOVA was used to examine the relationship between time and treatment-dependent variables, as well as the effects of time (before versus post) and treatment (between groups). All statistical tests had a significant level of $p < 0.05$. The Statistical Program for Social Sciences (SPSS) version 25 for Windows was used to conduct all statistical analyses.

3. RESULTS

3.1. Basic characteristics of participants

In our analysis, we included 30 cases. The mean age of the included patients was 57.2 ± 3.8; The mean age of the control group was 56.9 ± 3.5 while the mean age of the treatment group was 57.4 ± 4.2 with no significant difference observed between both groups regarding the age P-value= 0.7. Out of all cases, we included cases 21 were females and 9 were males. The percentage of males in the control group was 33.3% while the percentage of the males in the treatment groups was 26.7% with no statistically significant difference (P >0.05).

We evaluated the Jamar dynamometer before and after the intervention. The pre-interventional dynamometer measure of the control groups was 2.79 ± 1.36, while in the treatment group, it was 2.81 ± 1.33 with no significant difference between both groups P = 0.9. Concerning the Fugl Meyer the pre-treatment scale was 48.6 ± 13.08 while in the treatment group it was 48.13 ± 12.70; P-value = 0.9 (Table 1).

Table 1. Basic characteristics of participants

Variables	Control	Treatment	P-value
Age	56.9 ± 3.5	57.4 ± 4.2	0.7
Gender			
Females	10 (66.7%)	11 (73.3%)	0.69
Males	5 (33.3%)	4 (26.7%)	
Comorbidities			
Hypertension	6 (20%)	5 (16.6%)	
Diabetes	3 (10%)	4 (13.3)	
Hyperlipidemia	4 (13.3%)	5 (16.6%)	
Liver cirrhosis	1 (3.3%)	0 (0%)	
Others	1 (3.3%)	1 (3.3%)	

Note. Data are represented as mean and standard deviation or frequency and (%).

3.2. Outcome measures

3.2.1. Jamar dynamometer

The comparison of grip strength measured by the Jamar dynamometer between the conventional mirror and robotic mirror techniques showed a statistically significant difference. The mean grip strength using the conventional mirror was 4.64 ± 1.7, while the mean grip strength using the robotic mirror was 6.52 ± 2.2. The mean difference was 1.87, with a 95% confidence interval (CI) of 0.39 to 3.35, and a p-value of 0.015. This indicates a significant improvement in grip strength when using the robotic mirror compared to the conventional mirror (Table 2, Figure 4).

3.2.2. Fugl Mayar Scale

The comparison of motor function as measured by the Fugl-Meyer scale between the conventional mirror and robotic mirror techniques revealed a statistically significant difference. The mean score on the Fugl-Meyer scale for the conventional mirror was 79.6 ± 16.62, while the mean score for the robotic mirror was 62.93 ± 17.44. The mean difference was 16.67, with a 95% confidence interval (CI) of 3.9 to 29.4, and a p-value of 0.012. This indicates a significant reduction in motor function when using the robotic mirror compared to the conventional mirror (Table 2, Figure 5).

Table 2. Comparison of grip strength and motor function between conventional and robotic mirror techniques

	Conventional mirror	**Robotic mirror**	**Difference (95% Cl)**	**P-value**
	Mean ± SD			
Jamar dynamometer	4.64 ±1.7	6.52 ± 2.2	1.87 (0.39, 3.35)	**0.015***
Fugl mayar scale	79.6 ± 16.62	62.93 ± 17.44	16.67 (3.9 ,29.4)	**0.012***

*Note. SD; standard deviation, Cl; confidence interval; *Significant at p < 0.05.*

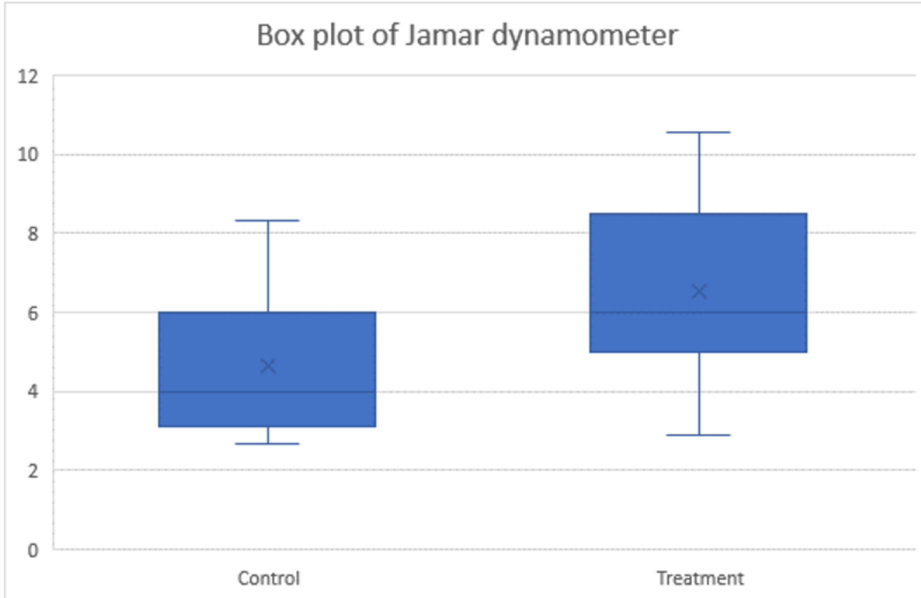

Figure 4. Box plot of the Jamar dynamometer

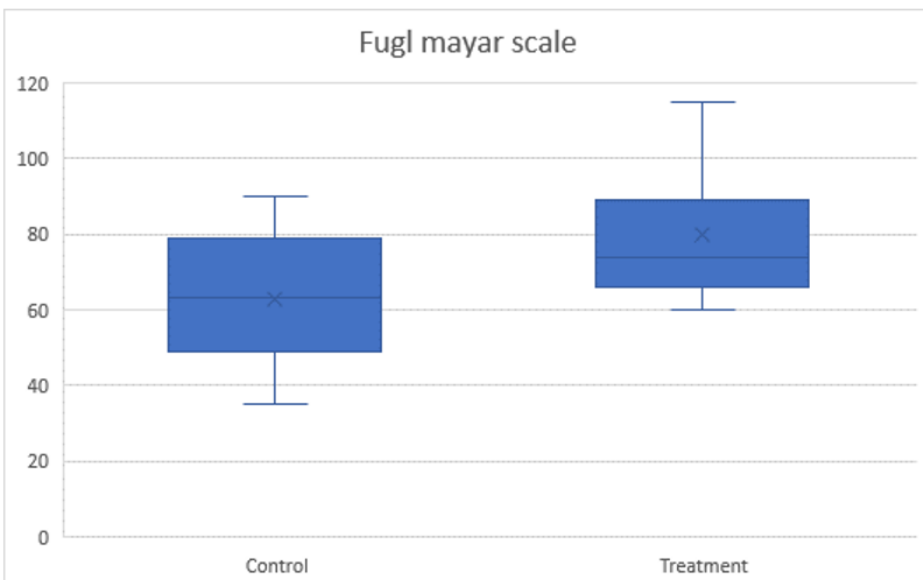

Figure 5. Box plot of the Fugl Matar scale

4. DISCUSSION

In this prospective group study, we attempted to assess the potential benefits of adding robotic rehabilitation training to a conventional physical therapy program compared with a conventional physical therapy program alone with regard to the change in upper limb grip strength and motor ability. The results indicate that the patients in the group that underwent the combined therapy (Group A) had a statistically significant improvement in grip strength when tested by the Jamar dynamometer and in motor function when evaluated by the Fugl-Meyer scale than the group who had only conventional physical therapy (Group B).

These findings are consistent with existing literature, which states that robotic-assisted therapy improves motor function and functional outcomes. For example, Lum et al. (2002) investigated the effectiveness of robot-assisted movement therapy for upper limb recovery after stroke against the conventional therapy approach. Accordingly, their findings suggested that the subjects who underwent robotic-assisted training displayed better motor activity and, therefore, had higher grip strength and motor function in the robotic group.

Kwakkel et al. (2008) published a systematic review of the impacts of robot-assisted stroke rehabilitation on the upper extremity motor functions. In their review, comprising multiple randomized controlled trials, they established that robot-assisted therapy offered better motor improvement as opposed to non-robot-aided therapy. This finding corroborates our study in which Group A which underwent robotic rehabilitation together with conventional physiotherapy improved significantly more than Group B which underwent conventional physiotherapy.

Similarly, a pilot randomized controlled trial by Hsieh et al. (2020) assessed the levels of treatment intensity in upper limb robot-assisted therapy for chronic stroke patients. In their study, they concluded that increased intensity of robotic therapy was beneficial in enhanced grip strength and dexterity reaffirming our conclusions of throper’s robotic assisted therapy.

Additionally, in their systematic review on the effectiveness of robotic arm in rehabilitation of chronic stroke patients, Lo et al. (2010) concluded that robotic therapy offered significant benefits in motor recovery as opposed to conventional therapy. This study supports our findings and highlights the possibility of using robotic devices, such as the SYREBO Hand Rehabilitation Device in rehabilitation.

A meta-analysis conducted by Mehrholz et al. (2018) also summarizes stable evidence indicating the beneficial value of the application of robotic-assisted upper limb training. In their review of several studies, they confirmed that robotic therapy increased motor function and levels of functional independence in stroke survivors, similar to what was found in our work.

Similarly, another study conducted by Colombo et al. (2007) examined the applicability of robotic devices for upper limb rehabilitation in subacute stroke patients. They also identified that patients qualified to attend robotic therapy showed more enhanced motor changes and participated in self-maintenance tasks than the patients who received conventional therapy. In agreement with our findings, this study placed focus on the aspect of increased functional performance associated with robotic intervention during rehabilitation.

In a study conducted by Laco et al. (2024), it showed that the effects of robotic therapy improved rehabilitation of the upper extremity in chronic stroke patients. They noted increased useful limb movements and muscle strength in patients using robotic therapy of the upper extremities; supporting our conclusion that the SYREBO Hand Rehabilitation Device can effectively complement standard physical therapy to achieve better outcomes. Moreover, the use of robotic rehabilitation has been extended to other neurological conditions beyond stroke.

For instance, Calabrò et al. (2016) studied the effects of robotic-assisted therapy in patients with multiple sclerosis, finding notable improvements in motor function and quality of life. Although our study focused on patients with upper limb impairments, the broader application of robotic rehabilitation across various conditions further validates its efficacy and potential benefits.

The improvements observed in Group A can partially be explained by the inherent characteristics of robotic rehabilitation. First, the mirror mode function of the SYREBO device enables bilateral movement training that, as previous evidence proved, improves motor recovery through interhemispheric interactions and plasticity (Stinear et al., 2012). This helps in motor relearning for the affected hand as the device mimics the movements of the non-impaired hand. Second, the repetitive and intensive nature of robotic therapy provides consistent proprioceptive feedback and enhances motor learning. This intensive training paradigm is crucial for motor recovery, especially in the early stages of post-injury or post-stroke, where neuroplasticity is at its peak (Patton et al., 2006).

Another critical factor that needs to be considered in this context is patient involvement and motivation towards the rehabilitation process. Some robotic rehabilitation devices like the SYREBO Hand Rehabilitation Device, include play-like features that would make the therapy sessions seem more like play, thus being interesting to patients. This could result in higher compliance with therapy schedules and practices, which are underlying prerequisites for enhancing the manner and extent of rehabilitation. Maclean et al., also revealed that patient’s motivation and involvement in the rehabilitation process is an important factor in predicting effective rehabilitation outcomes (Maclean, 2000).

Despite the promising findings, this study has several limitations. The sample size was relatively small, and the study was conducted over a short period. Future research should include larger sample sizes and longer follow-up periods to confirm the long-term benefits of robotic rehabilitation.

Additionally, the study did not account for the potential placebo effect or patient motivation, which could have influenced the outcomes.

5. CONCLUSIONS

In conclusion, this prospective group study provides evidence that combining robotic rehabilitation with a standard physical therapy program yields superior improvements in grip strength and motor function compared to standard physical therapy alone.

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AUTHOR CONTRIBUTIONS

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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