Design and Development of Portable Wrist Rehabilitation Device for Post-Stroke Subjects: A Pilot Study

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***Abstract*—Wrist mobility is vital for post-stroke patients to carry out their daily activities. The use of robotic devices in hand rehabilitation has increased significantly in recent years, allowing patients to get training at home and effectively compensating for the therapist-to-patient ratio. Nevertheless, rehabilitation devices are expensive, cumbersome, immobile, and difficult to wear and operate. This work proposes a new method for designing a wrist rehabilitation device that uses airbag technology to minimize device weight and size. A triangular prism-shaped Neoprene (synthetic rubber) airbag is utilized in the experiment; which is inflated and deflated using a DC motorized air pump. An accelerometer sensor serves as the control input for the wrist rehabilitation exercise device. The proposed device trains the impaired hand of ten hemiplegic post-stroke patients. A goniometer and Fugl-Meyer Assessment (FMA) are used to measure wrist motion before and after the training regimen to evaluate the results. The mean angle (in degree) of wrist flexion increases from 8.6 ± 2.59 to 18.4 ± 5.19 ($p = 0.005$). Likewise, an increase in the wrist extension angle from 12.3 ± 3.62 to 17.7 ± 6.2 ($p = 0.008$) is noted. The wrist rehabilitation device is lightweight, portable, and simple to use, producing good results for hemiplegic individuals with hand disability. The suggested invention enables the user to extend their wrist's range of motion.**

***Keywords*—airbag, extension, stroke, flexion, rehabilitation, strength**

I. INTRODUCTION

Stroke is the most common neurological illness in the world, with a survival rate of 60%–75%. Eighty to ninety percent of survivors have lost some or all of their psychomotor ability [1]. Hemiplegic strokes cause paralysis on one side of the body (the upper and lower extremities), making it hard for the victim to function normally and to rely on others for performing daily tasks. For those recovering from a stroke, wrist mobility is crucial to performing everyday activities which include eating, drinking, and grooming.

The wrist is a network of tiny bones, muscles, and joints that connects the ulna and radius of the forearm to the five metacarpal bones of the hand. It provides sufficient flexibility and range of motion for the hand and forearm. The eight small wrist carpal bones join the metacarpals and forearm. The carpal bones are controlled by more than 20 carpal joints, 26 distinct ligaments, and six segments of the triangle fibrocartilage complex [2, 3]. The human wrist can flex and extend up to 85° from its neutral position [4]. Moser *et al.* [5] proved that wrist flexion and extension movement were much more significant compared to radial and ulna deviation in day-to-day activities. The author tested 20 healthy participants wearing a wrist splint and performing five tasks under five conditions. Nelson *et al.* [6] proposed that in tests involving ten participants using the Polhemus motion tracker, the maximum wrist flexion and extension needed to do 24 fundamental tasks was 50° and 51°, respectively. Using a biaxial wrist electrogoniometer, the study revealed that 54° of wrist flexion and 60° of wrist extension were required for daily activities [7]. Ten healthy individuals were examined by Palmer *et al.* [8] using a triaxial electrogoniometer. The authors found that to complete 52 basic tasks, 5° wrist flexion, and 30° wrist extension were necessary.

To recover from paralysis, physicians recommend physiotherapy exercises that involve continuous movement, which reduces stiffness and improves active motion [9, 10]. Patients seldom visit rehabilitation centers due to cost and commuting concerns. To get over this problem, researchers created rehabilitation tools that allow stroke victims to work out at home. It helps patients recover more rapidly and solves the issue of the therapist-to-patient ratio [11].

Numerous researchers employed novel approaches to create highly efficient and safe wrist rehabilitation devices [12]. The wrist rehabilitation devices and methods employed in a few research studies. Oliveira *et al.* [13] designed a cylindrical and dumbbell-shaped model for vibratory therapy, improving wrist movement. Another

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study developed a rehabilitation device combined with Functional Electrical Stimulation (FES) to reduce the spasticity of the wrist and improve muscle strength [14]. The study described a hybrid multi-segment mechanism and 3D printing technology-based rehabilitation device to assist wrist exercise with 3 degrees of freedom [15]. A study used pneumatic artificial muscles with 3D printing technology to develop an exoskeleton to improve the range of motion of the wrist [16]. Wang *et al.* [17] established a pneumatic muscle-based parallel robot for wrist rehabilitation exercises. Miller *et al.* [18] used a continuous transcranial magnetic stimulation approach to construct a robotic rehabilitation device for the wrist, which was tested on stroke survivors. Virtual Reality (VR) and computer gaming techniques were employed in several studies to create rehabilitation devices that inspired post-stroke patients to engage in daily tasks [19]. The previous wrist rehabilitation devices are bulkier, more expensive, have complicated circuitry, and are not portable.

The primary objective of this research is to construct a lightweight, portable, low-cost rehabilitation device for performing wrist exercises in stroke survivors. The proposed study shows the prototype design of a pneumatic technology-based wrist rehabilitation device. The experimental findings help individuals affected with post-stroke hemiplegia (hand impairment) to rebuild the muscle strength motor function and range of motion of the wrist.

II. MATERIALS AND METHODS

A. Prototype Design

The wrist rehabilitation device was designed with a 50° flexion and extension angle from the base of the airbag [6–8]. The dimensions of the airbag are 10 cm base and 7 cm length which are taken from the average wrist to the palm of both men and women (as reported in the anthropometry data table) [20, 21]. Fig. 1 shows the inflation and deflation of the airbag.

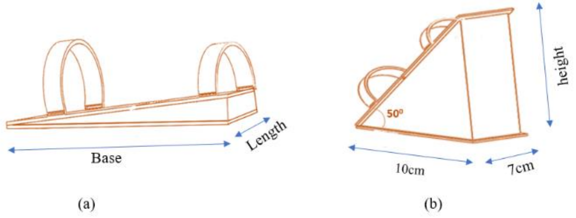


Fig. 1. Inflation and deflation of the airbag: (a) Deflation of airbag (b) Inflation of airbag.

The shape of the airbag is a triangular prism

$$AC^2 = AB^2 + BC^2 \quad (1)$$

$$\cos\theta = AB/AC \quad (2)$$

Substitute cos θ = 50° in Eq. (2)

$$AC = 15.5 \text{ cm}$$

From Eq. (1), BC = 11.8

The volume of the triangle (right angle) prism-shaped airbag V = Base area of the triangle *x* length of the airbag

$$V = \frac{1}{2}(10\times11.8\times7)$$

$$V = 413 \text{ cm}^3$$

Surface area of triangular prism

$$A = (AB+BC+AC)\ \text{Length} + (\text{Base} \times \text{Height})$$

$$A = 379 \text{ cm}^2 \text{ or } 0.0379 \text{ m}^2$$

The airbag is intended to be able to lift 400 gm, which is the typical weight of a human hand [22, 23]. The dimensions of the airbag shown in Fig. 2.

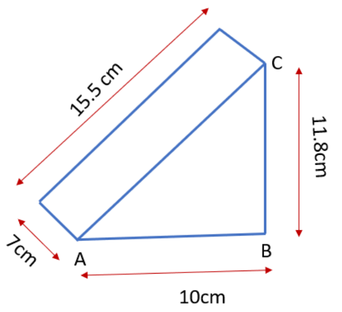


Fig. 2. Dimension of the airbag.

Force = mass×gravity
m = mass (400 gm or 0.4 kg)
g = gravity (9.8 m/s^2)
$F = 0.4 \text{ kg} \times 9.8 \text{ m/s}^2 = 3.92 \text{ N}$
Pressure = F/A
$P = 3.92 \text{ N}/ 0.0379 \text{ m}^2$
$P = 103.2$ pa required for 379 cm^2 surface area

B. Hardware

The triangular prism-shaped airbag was constructed using the Welch Allyn 5089-01 Neoprene Inflation Bladder (WEL5089-01). Chloroprene is polymerized to obtain neoprene (polychloroprene), a synthetic rubber. Neoprene is used in a variety of commercial applications, such as blood pressure monitor cuffs and knee and wrist orthopedics braces [24–28]. The airbag (synthetic rubber) is covered with nylon cloth to increase the life span of the device.

The triangular prism-shaped airbag helps to produce proper wrist flexion and extension angles from the base. Two adjustable straps are connected from this nylon cloth to tighten the hand with the device. The triangular prism-shaped airbag was inflated using an air pump DC motor (model DD370) that operated at 12V and with a maximum pressure of 1000 mmHg and a rated power of 0.12 to 0.36 W. To deflate the airbag, a solenoid valve KSV05B was used, and to control the inflate and deflate processes, a two-channel relay module (5V) was utilized. The control input is a 3-axis accelerometer (MPU 6050), which detects inclination changes of less than 1°. The accelerometer sensor was held by the patient in their healthy hand. When a patient provides a small z-axis deflection (less than 10°) using the accelerometer, the device switches to the ON state. Once the device is turned ON, the inflation and deflation process continue until the device is switched off. The device can be turned off by the patient deflecting the accelerometer again. The prototype is controlled by The Arduino Nano microcontroller board. The proposed device weighed 246 gm in total without a power bank. Fig. 3 represents a block diagram of the current study and Fig. 4 depicts the proposed device for wrist rehabilitation.

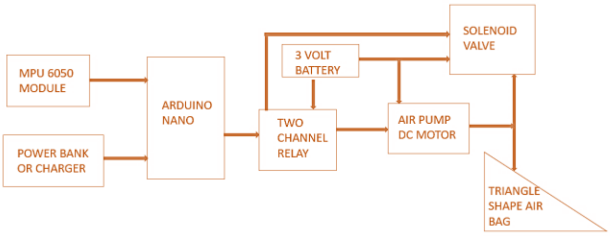


Fig. 3. Block diagram of the proposed wrist rehabilitation device.

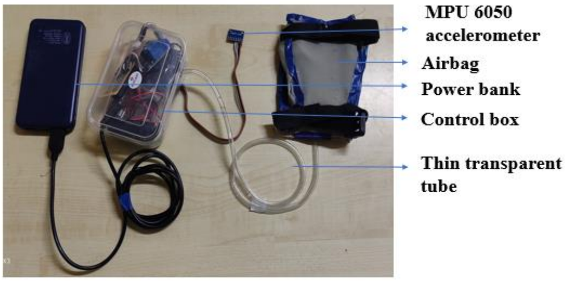


Fig. 4. The proposed device.

C. Subjects

Ten hand-impaired hemiplegic post-stroke patients were selected from SRM Medical College and Hospital. Based on patient comfort, the study was carried out at home and in the physiotherapy department of SRM Medical College and Hospital. Table I provides information regarding the subjects. The following inclusion criteria: (1) Mini-Mental State Examination (MMSE) score > 23; (2) Ashworth scale [29, 30] less than 3; and (3) hemiplegic stroke survivors (minimum of six months after stroke incidence), and exclusion criteria: (1) wrist fracture; (2) wrist inflammation; (3) patients with other neurological disease (Parkinson, spinal cord injury) were used in this study. The proposed study was approved by the Institutional Ethics Committee (IEC) of SRM Medical Hospital and Research Centre (2448/IEC/2021) and the Clinical Trials Registry-India (CTRI/2022/02/040495).

TABLE I. BASIC INFORMATION OF SUBJECTS

Number of patients	Age	Gender (Male/ Female)	Impaired hand (Left/Right)	Modified Ashworth Scale (MAS) score	Type of stroke (Ischemic/ Hemorrhage)
10	55.3 ± 14	6/4	7/3	1.2 ± 0.7	6/4

D. Experimental Setup

A physiotherapist performed a thorough physical assessment of every subject before the trial. Participants signed a consent form after learning about the protocols of the study. The participant was made to sit comfortably on the chair beside the table on which the device was placed. The forearm of the subject should be supported while they place their affected hand on the table. The two adjustable bands were used to tighten the hand with the device. The dorsal side of the wrist was put on the proposed device for performing wrist extension. In assisting wrist flexion, the device is attached to the patient’s palmar side of the wrist. The patient held the accelerometer sensor in their healthy hand to turn the device ON/OFF. The proposed device moves the patients’ affected wrists passively. Fig. 5 depicts the stroke patient wearing the proposed device and Fig. 6 shows the wrist flexion and extension of the airbag.

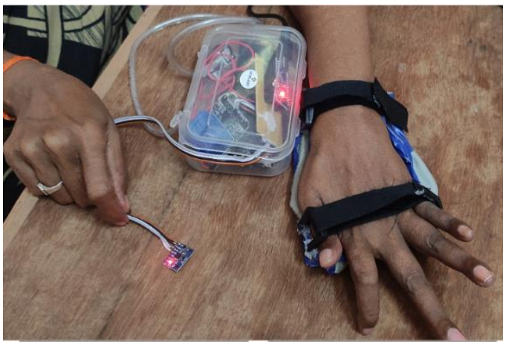
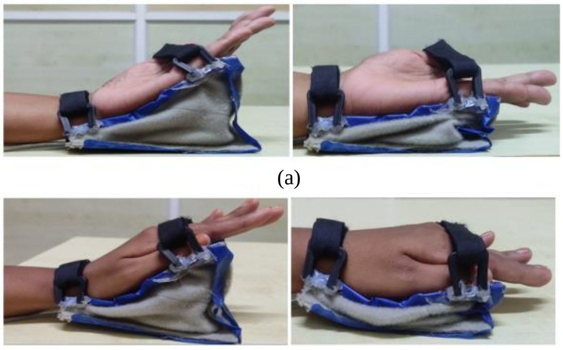


Fig. 5. A stroke patient wearing a proposed device.



(a)

(b)

Fig. 6. Inflation and deflation of the airbag for (a) wrist flexion; (b) wrist extension.

When the device is turned on, the air pump inflates the airbag, forcing the wrist to extend from its initial position. The wrist returns to its original position by deflating the airbag after 20 s. The activity persisted until the device was switched off. Over two months, the participants used the proposed device to exercise their wrists for thirty minutes a day (five days per week): 15 min of wrist flexion and 15 min of wrist extension. Using a goniometer (the gold standard), the wrist flexion and extension angles of each participant were measured before and after training sessions (at 0 weeks, 4 weeks, and 8 weeks). Similarly, the range of motion of the wrist is measured using the Fugl-Meyer Assessment (FMA) with the assistance of two skilled physiotherapists.

This study utilized a goniometer (Bos Medicare, QAS K, stainless steel) which consists of two arms (one moveable and one fixed) and one midpoint (fulcrum). The flexion and extension of the wrist were measured in the sagittal plane of motion. The midpoint of the goniometer was positioned on the triquetrum of the wrist, and its resting and moving arms were positioned parallel to the ulna and fifth metacarpal bone, respectively [31]. The movable arm of the goniometer moves manually to measure the angle of the wrist when the patient flexes or extends it. The FMA [32] is a standard clinical tool for measuring the motor function recovery of upper limbs in stroke patients. The proposed study employed the FMA to measure the affected motor functional recovery level of the wrist before and after training. A score between 0 and 2 was assigned by the physiotherapist based on the patient's performance (0-no movement, 1- partial movement, and 2-full movement). The wrist Electromyography (EMG) signal was evaluated both before and after the training using a wireless EMG sensor (Delsys-Trigno). Extensor carpi radialis is utilized for extension and flexor carpi radialis for flexion while obtaining an EMG [33].

E. Statistical Analysis

The Wilcoxson sign rank is the non-parametric assessment to analyze the enhancement of wrist flexion and extension before and after the training. The statistical significance and confidence interval were set to 0.05 and 95% for the proposed study. All statistical analyses were conducted using IBM SPSS software 23.0.

III. RESULT

The wrist flexion and extension angles of ten hand-impaired post-stroke (hemiplegia) patients measured both before and after the training using a manual goniometer are given in Table II. The average wrist extension angle (in degree) was 8.6 ± 2.59 before training, after the fourth and eighth weeks, the values were 9.2 ± 2.39 and 18.4 ± 5.19 (p = 0.005) respectively. Similarly, before exercise, the average wrist flexion angle (in degree) was 12.3 ± 3.62, at the end of the fourth week, and eighth week, it was improved to 13.9 ± 3.73, and 17.7 ± 6.2 with p = 0.008. According to this outcome, the device greatly enhanced wrist flexion and extension for patients affected by post-stroke (hemiplegia). Fig. 7 shows a graphic representation of the wrist flexion and extension angles both before and after the training. Before training, the FMA score was 6 ± 0.52 and after the fourth and eighth weeks, it was improved to 9 ± 0.32 and 23 ± 0.95 respectively with p = 0.010. Fig. 8 depicts the EMG signal of flexion and extension before and after training of the subject P01.

TABLE II. RESULT OF WRIST EXTENSION/FLEXION AND FMA

Assessments	Pre-training	After training [Four weeks]	After training [Eight weeks]	*p*-value
Wrist extension angle [degree]	8.6 ± 2.59	9.2 ± 2.39	18.4 ± 5.19	0.005
Wrist flexion angle[degree]	12.3 ± 3.62	13.9 ± 3.73	17.7 ± 6.2	0.008
FMA	6 ± 0.52	9 ± 0.32	23 ± 0.95	0.010

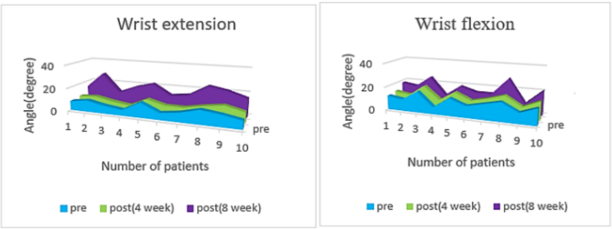


Fig. 7. Graphical representation of wrist extension and flexion angle.

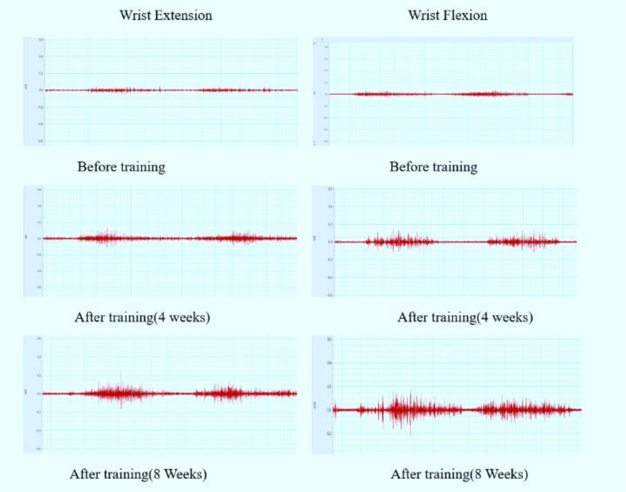


Fig. 8. EMG signal obtained from the subject during wrist extension and flexion.

IV. DISCUSSION

This research developed a portable, lightweight wrist rehabilitation device utilizing airbag technology for post-stroke (hemiplegic) patients to perform wrist exercises. The study was inspired by prior research on wrist rehabilitation devices [15, 16, 34]. This research employed synthetic rubber (neoprene), which is lightweight, chemically stable, and retains its flexibility across a wide temperature range. Physical failures such as cutting, abrasion, bending, and twisting in this material are improbable. A triangular prism-shaped airbag aids in proper wrist flexion and extension by stabilizing the air. The earlier study [35] employed more hardware and sophisticated circuits, which were overcome by airbag technology.

Wrist flexion angles (in degree) were 9.2 ± 2.39 and 18.4 ± 5.19 before and after training, respectively. Similarly, the values for wrist extension angle (in degree) before and after eight weeks are 13.9 ± 3.73 and 17.7 ± 6.2, respectively. The assessment of the range of motion in the wrist revealed improvements at the end of training using the proposed device. When compared to the previous study [19], the FMA results indicated that the proposed device yielded an improved outcome (p = 0.010). It exhibits how the outputs of the proposed device significantly improve the wrist mobility of hemiplegic patients.

The rehabilitation device generated a maximum of 48° flexion and 45° extension from the base of the airbag, achieving most of the biomechanical mobility requirements for daily work [8]. Before training, most participants had feeble EMG signals; following training, all participants had enhanced EMG signals, as seen in the graph (Fig. 8). Repeated wrist training with the proposed device improves wrist movement in hemiplegic post-stroke patients. During the examination, there were no negative effects such as discomfort, redness, or pressure ulcers. Rehabilitation devices never replace the therapist but rather assist the therapist in treating many patients efficiently at the same time.

Previous research used EMG [36], FES, and Electroencephalogram (EEG) [37] signals as device control inputs, which increases the device's complexity and makes it difficult to acquire bio-signals for some patients. The accelerometer sensor is used to turn the device ON and OFF in this proposed approach, which is relatively simple to implement. A 5V/3A mobile charger or a power bank can be used to power the proposed device.

The number of participants involved in the current study is limited to ten (a pilot study); Increasing the number of subjects might alter the findings. The performance of the device might not be generalizable when used on hand-impaired participants with other conditions as it is intended for hemiplegic post-stroke patients. The suggested device is made to bend and extend constantly by 50° from the base of the airbag. We will expand this research by including controllable pressure settings according to the patient's varying degrees of wrist motion. Future studies may include artificial intelligence with this equipment to measure wrist flexion and extension angles while the patient exercises.

V. CONCLUSION

This novel wrist rehabilitation device is portable, lightweight, simple in design, and provides effective results. The clinical evaluation using FMA and the Goniometer (gold standard), were employed in this study to demonstrate the patients' progress. Post-stroke hemiplegic patients can simply perform wrist exercises with the help of this device, improving the range of motion of the wrist. After eight weeks of training, the wrist's range of motion significantly improved compared to before training. Patients recovering from strokes will survive better if they undertake wrist exercises regularly. We intend to expand this study by utilizing artificial intelligence combined with this device to estimate the wrist angle as the patient performs their activity and also, incorporate the pressure level that can be adjusted to support varying degrees of wrist mobility of patients. We believe that this study will aid researchers working on rehabilitation assist devices for post-stroke patients. The wrist prototype video could be referred via linkage: https://drive.google.com/drive/folders/1ULJA-XozTnAiVFyjHxwQsmaAsFA7q1ep

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

All authors contributed to the study's conception and design. Porkodi Jayavel and Ashokkumar Devaraj performed device development, testing, data collection, and analysis; Porkodi Jayavel and Varshini Karthick wrote the first draft of the manuscript; all authors read and approved the final manuscript.

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