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Evaluation of Range of Motion and Muscle Strength in Stroke Patients Using a Robotic Hand Orthosis

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Abstract
Stroke-induced impairments in hand function significantly affect patients' ability to perform activities of daily living. Rehabilitation involving repetitive and task-specific exercises is essential for motor recovery. This study evaluates the effectiveness of a soft robotic hand orthosis in assessing and enhancing range of motion (ROM) and muscle strength in stroke patients. The orthosis integrates flex sensors and force-sensitive resistors to collect real-time data during flexion-extension exercises. Ten stroke patients aged 39 to 72 years participated, with stroke durations ranging from 8 to 36 months. Exercises were conducted at two speed levels, and sensor data were analyzed using regression techniques to explore associations with age and stroke chronicity. The results indicate that patients with longer post-stroke durations and older age exhibited reduced ROM and muscle strength. Performance also declined with faster movement speeds. These findings suggest that the robotic orthosis is a valuable tool for both assessment and rehabilitation, enabling objective measurement and tailored therapy based on patient-specific progress

Keywords: stroke rehabilitation, robotic orthosis, range of motion, muscle strength, sensor feedback, hand therapy

1.0 Introduction

Stroke is a leading cause of long-term disability globally, with approximately 80% of stroke survivors experiencing upper limb impairments that hinder daily functioning and quality of life (Langhorne, Bernhardt, & Kwakkel., 2011; Feigin et al., 2021). Recovery of hand function, particularly fine motor control, remains one of the most challenging aspects of stroke rehabilitation. Traditional rehabilitation strategies often rely on therapist-guided exercises, which can be limited by resource constraints, inconsistent intensity, and lack of quantitative assessment tools (Kwakkel, Kollen, & Wagenaar., 1999). In recent years, robotic rehabilitation devices (RRDs) have emerged as promising tools for enhancing post-stroke motor recovery. These devices enable repetitive, task-specific, and goal-oriented exercises—key components of effective neurorehabilitation (Mehrholz et al., 2018). Robotic hand orthoses, in particular, offer the ability to not only assist with movement but also monitor real-time biomechanical parameters such as joint angles and muscle force, thus supporting both therapy and progress assessment (Maciejasz et al., 2014).

Soft robotic orthoses, which use flexible materials and embedded sensors, are gaining attention due to their adaptability, safety, and compatibility with the human hand's complex anatomy (Polygerinos et al., 2015). These systems can be calibrated to measure range of motion (ROM) and estimate muscle strength using flex sensors and force-sensitive resistors (FSRs), providing detailed, objective data that therapists can use to tailor treatment plans.

Despite the growing availability of robotic solutions, there is still limited clinical evidence on their ability to track recovery and adjust therapy based on quantitative metrics, especially in low-resource settings. This study aims to evaluate a soft robotic hand orthosis designed to assess ROM and muscle strength in stroke patients and examine how these parameters vary with age, stroke duration, and exercise speed. The findings will contribute to the growing body of knowledge on data-driven, personalized stroke rehabilitation.

2.0 Materials and Methods

2.1 Participants

A total of ten stroke patients (7 males, 3 females), aged between 39 and 72 years, participated in this study. Participants were recruited purposively from Federal Teaching Hospital, Owerri. All patients had experienced an ischemic or hemorrhagic stroke within a time frame of 8 to 36 months prior to enrollment. Inclusion criteria required participants to (1) exhibit mild to moderate upper limb hemiparesis, (2) retain partial voluntary control of hand movements, and (3) have no severe cognitive impairment. Participants with fixed contractures, severe spasticity (Modified Ashworth Scale > 2), or other musculoskeletal disorders were excluded. Ethical approval was duly obtained from the ethics committee of Federal Teaching Hospital Owerri and written informed consent was secured from all participants.

2.2 Device Design

The robotic hand orthosis used in this study is a soft, wearable exoskeleton developed to assist and evaluate flexion-extension hand movements. A block diagram of the orthosis is presented in Figure 1 below.

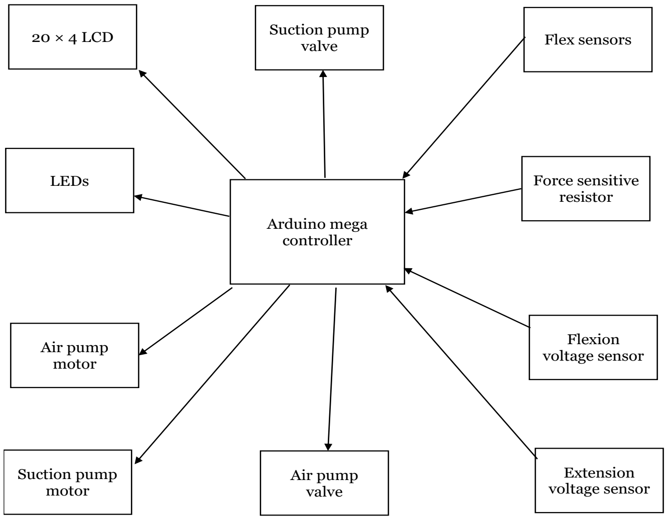

Figure 1: A block diagram of the designed Robotic Hand Orthosis

The design of the robotic hand orthosis was modelled using a combination of mechanical and electrical components integrated into a functional prototype. The orthosis consists of two flex sensors mounted on the dorsal side of the middle finger and the thumb to measure joint angle changes, with a resolution of 1° over a range of 0°–180°, a force-sensitive resistor (FSR) placed on the thumb to detect grip pressure and estimate muscle force up to 30 N, a pneumatic actuation system providing assistance via soft actuators embedded along each finger, a control system based on an Arduino Mega 2560 microcontroller, interfaced with a 20×4 LCD for feedback, and a glove designed to be lightweight (~350g), adjustable, and fabricated using silicone-based materials to accommodate various hand sizes.

The pneumatic actuators, sensors, and microcontroller were modelled in 3D CAD software for spatial arrangement and ergonomic considerations. The mechanical design focused on seamless packaging of actuators into a glove structure while allowing sufficient airflow for actuation. The glove was modelled to simulate the natural flexion and extension of fingers, with careful attention to the positioning of sensors and actuators to maintain comfort and accuracy.

The electrical circuit for the robotic hand orthosis was designed using electronic design automation (EDA) software. Electronic design automation (EDA) is a category of software tools for designing electronic systems such as integrated circuits and printed circuit boards. The circuit was designed to integrate actuators, sensors, and a microcontroller. The Arduino Mega 2560 was selected as the central processing unit due to its numerous input and output pins, necessary for interfacing with multiple sensors and actuators. Circuit simulation software, Multisim, was used to test the feasibility of the electrical connections and ensure proper communication between components. The simulation allowed for verification of voltage and current flow, relay operation, and sensor feedback prior to physical assembly. The Arduino Mega 2560 microcontroller was programmed using Arduino IDE, a C/C++-based environment. The program was designed to execute real-time control of the actuators based on sensor input. The microcontroller reads signals from the flex sensors and force-sensitive resistors, processes the data, and sends corresponding control signals to the actuators via the relay module.

The components were assembled into a cohesive unit based on the designed circuit and mechanical layout. The actuators were fitted into the rehabilitation glove, ensuring they aligned with each finger to facilitate smooth movement. Sensors were embedded into the glove, with the flex sensors placed on the fingers and the force-sensitive resistor placed at the contact points of the fingers. The electrical components, including the Arduino board, relay module, power adapter, and battery, were housed in a separate compartment to protect them from damage and ensure ease of maintenance. The LCD display was mounted for clear visibility of real-time data. Wiring was secured to prevent interference with glove movement and to ensure reliable connections between sensors, actuators, and the microcontroller.

2.3 Calibration

Sensor calibration was conducted prior to the clinical trial. Flex sensors were calibrated to degrees by using a voltage divider circuit. The flex sensor was connected in series with a 10kohms resistor. 5V was applied across the ends of the voltage divider circuit and the voltage across the flex sensor at 0 degrees and 180 degrees bend was calculated using equation 1:

$$Analog\ voltage\ across\ flex\ sensor\ = flex\ resistance/(flex\ resistance\ +\ 10kohms)\ x\ 5V \tag{1}$$

The obtained analog voltage was converted to its digital form by the arduino analog to digital (ADC) converter using equation 2:

$$voltage\ across\ flex\ sensor\ in\ digital\ form\ = Analog\ voltage\ across\ flex\ sensor/5V\ x\ 1023 \tag{2}$$

This digital voltage at 0-degree bend and 180-degree bend, was inputted in the Arduino map function to calibrate the input voltages of the flex sensor to their corresponding bending degree. Two flex sensors were calibrated according to the stated technique. One was used for the thumb movement and the other for the other fingers.

The muscle strength parameter was estimated using the force sensitive resistor (FSR), which is a sensor that changes its resistance when touched. Since the strength of the muscle at any instant of time is proportional to the touching force of the fingers, the FSR was connected in series with 10kohms resistor and voltage of 5V was applied across the voltage divider circuit. The voltage across the FSR was read from an Arduino analog pin and calibrated to touching force using known weights object and the Arduino mapped function. The voltage at 0 Newton was read (no object) and the voltage at 30 Newtons was read (an object of 30kg weight was placed on the FSR). These voltages were mapped to their corresponding force value with the Arduino map function.

2.4 Experimental Protocol

Each participant was seated in a comfortable position with the forearm supported. The robotic glove was fitted to the paretic hand. Two sets of flexion-extension exercises were performed:

- **minimum-speed trial**: 0.26 rad/s angular velocity
- **maximum-speed trial**: 1.05 rad/s angular velocity

Each trial consisted of five full cycles of finger flexion and extension, assisted by the glove. The protocol was repeated across three sessions on non-consecutive days. During each session, ROM (in degrees) and grip force (in newtons) were recorded in real-time.

2.5 Data Analysis

Descriptive statistics were computed for ROM and force data. Linear regression was used to analyse relationships between ROM, muscle strength, age, and stroke duration. Statistical significance was set at $p < 0.05$. Data analysis was performed using Microsoft Excel.

3.0 Results and Discussion

The range of motion classified by duration of stroke is presented in Table 1 and Figure 2 below.

Table 1: Range of motion of the participants classified by duration of stroke

Subject	Duration of stroke (months)	ROM of thumb (°) at minimum speed	ROM of other fingers (°) at minimum speed	ROM of thumb (°) at maximum speed	ROM of other fingers (at maximu speed
1	12	76	62	58	104
2	24	74	60	55	100
3	18	78	65	60	108
4	30	72	59	56	102
5	15	73	61	54	98
6	10	80	66	62	110
7	22	75	64	59	105
8	36	71	58	53	96
9	8	77	63	61	109
10	20	74	62	57	103

Individuals with longer stroke durations experienced more pronounced motor impairments, leading to decreased ROM. Subject 8 (Stroke Duration: 36 months) shows a notable decrease in ROM for both the thumb (71°) and other fingers (58°) at minimum speed, with even more substantial reductions at maximum speed (53° for the thumb and 96° for other fingers). On the contrary, Subject 6 (Stroke Duration: 10 months) demonstrates higher ROM (80° thumb, 66° fingers at minimum speed; 62° thumb, 110° fingers at maximum speed), indicating that shorter stroke duration correlates with better motor function and flexibility.

The polynomial equations for the range of motion (ROM) versus duration of stroke across the ten subjects in figure 2 below provide valuable insights into the device's performance under different conditions. These equations show a sixth-order polynomial relationship, indicating a complex, non-linear connection between stroke duration and the ROM achieved by various fingers (thumb and other fingers) under conditions of maximum and minimum speed. The high R^2 values for each equation—0.8577 for ROM of other fingers at maximum speed, 0.8029 for ROM of the thumb at minimum speed, 0.8463 for ROM of other fingers at minimum speed, and 0.8642 for ROM of the thumb at maximum speed—reflect a strong fit between the polynomial models and the data.

Each model predicts a reduction in ROM as stroke duration increases. This trend aligns with literature showing that prolonged stroke duration often correlates with diminished upper limb function due to factors like muscle weakness, spasticity, and joint contractures, which typically worsen over time if left untreated (Lobo et al., 2024). The high R^2 values suggest that a sixth-order polynomial accurately captures the complexities of the ROM data across the various subjects, speeds, and finger groups. Although the model captures these relationships well, it also reflects the non-linear and multifaceted nature of recovery and movement restoration in chronic stroke rehabilitation, where neural adaptations and musculoskeletal changes evolve in complex ways over time.

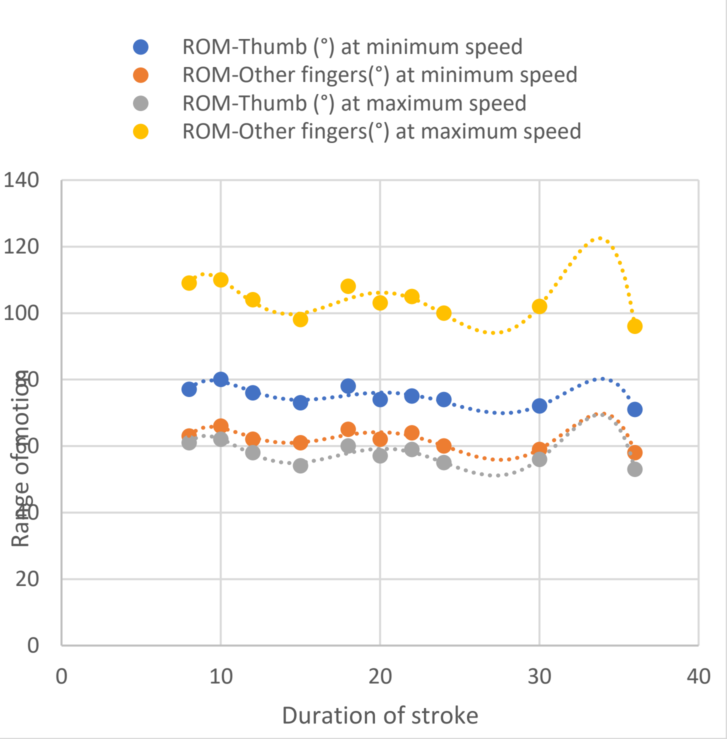

Figure 2: Range of motion of the participants classified by duration of stroke

The range of motion classified by age is presented in Table 2 and Figure 3 below

Table 2: Range of motion of the participants classified by age

Subject	Age (years)	ROM of thumb (°) at minimum speed	ROM of other fingers (°) at minimum speed	ROM of thumb (°) at maximum speed	ROM of other fingers (°) at maximum speed
1	54	76	62	58	104
2	67	74	60	55	100
3	45	78	65	60	108
4	60	72	59	56	102
5	72	73	61	54	98
6	39	80	66	62	110
7	58	75	64	59	105
8	63	71	58	53	96
9	47	77	63	61	109
10	55	74	62	57	103

From Table 2, the results indicate that older individuals generally exhibit slightly lower ROM, especially at maximum speed settings, as compared to younger individuals. Subjects aged 70+ (e.g., Subject 5, Age 72) show lower ROM in both the thumb and other fingers at both minimum and maximum speeds compared to younger subjects. Middle-aged subjects (e.g., Subject 3, Age 45) show higher ROM values than older participants, reflecting the natural decline in flexibility and motor control with aging. The polynomial equations derived for range of motion (ROM) versus subject age in figure 3 below offer a sixth-order relationship, underscoring a complex, non-linear association between age and ROM across different movement scenarios. The high R^2 values for each model—0.882 for other fingers at maximum speed, 0.9428 for the thumb at minimum speed, 0.8704 for other fingers at minimum speed, and 0.8725 for the thumb at maximum speed—indicate a strong correlation, suggesting the equations are well-suited for modelling these specific interactions. Each model reflects a trend of reduced ROM as age increases, which is consistent with prior studies indicating that aging contributes to declines in musculoskeletal strength, flexibility, and joint mobility (Takahashi et al., 2008; Daly et al., 2019). This is especially relevant for stroke rehabilitation, as older individuals often experience compounded challenges in regaining movement due to age-related muscle degradation and decreased neural plasticity.

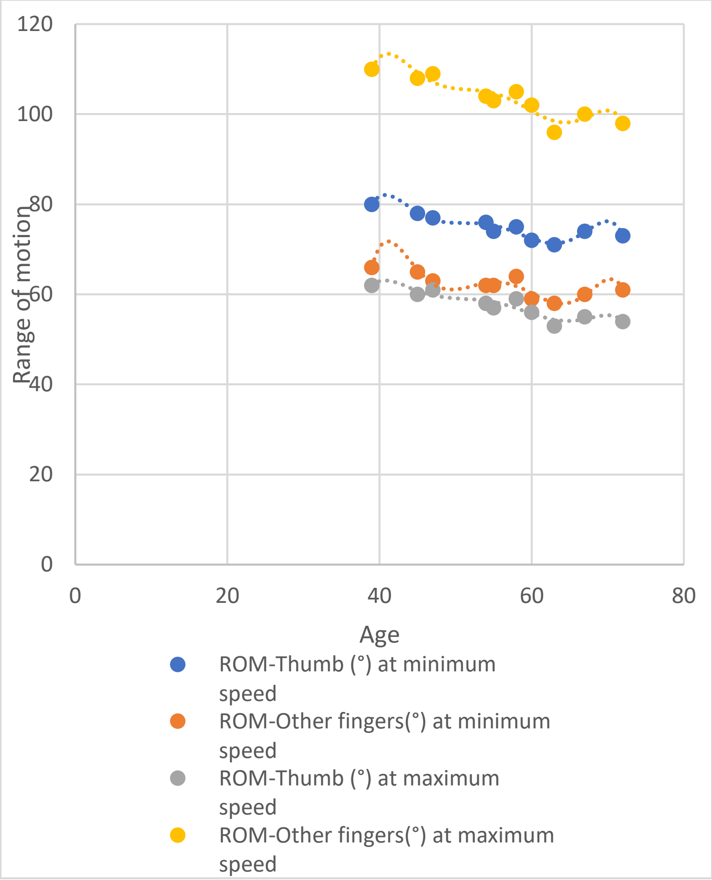

Figure 3: Range of motion of the participants classified by age

The contact force classified by duration of stroke is presented in Table 3 and Figure 4 below.

Contact force refers to the pressure or force applied by the hand during rehabilitation exercises, which is often used as a proxy for muscle strength and motor control.

Table 3: Contact force of the participants classified by duration of stroke

Subject	**Duration of stroke(months)**	**Contact force (N)**
1	12	5.5
2	24	4.3
3	18	6.1
4	30	4.0
5	15	3.7
6	10	7.4
7	22	5.0
8	36	3.5
9	8	6.8
10	20	5.3

One of the primary effects of a stroke is muscle atrophy, which occurs due to the lack of use or impaired motor control in the affected limbs. As stroke duration increases, the degree of muscle atrophy typically becomes more pronounced. When muscles are not used regularly due to weakness, spasticity, or motor control issues, they lose mass and strength. This muscle degradation leads to a reduction in the contact force generated by the subject (Bohannon, 2007). From the results obtained, it was observed that subjects with longer stroke durations exhibited lower contact force values. For example, Subject 8, who had a stroke duration of 36 months, recorded the lowest contact force of 3.5 N, indicating that extended periods of reduced motor activity and disuse had led to significant muscle weakness. In contrast, Subject 9, with a stroke duration of only 5 months, demonstrated a contact force of 6.8 N, suggesting that muscles retain more strength earlier in the post-stroke period. This inverse relationship between stroke duration and contact force is consistent with the disuse atrophy hypothesis, which posits that muscles deteriorate when they are not actively engaged in regular movement or rehabilitation exercises (Bohannon, 2007). From the results, subjects with shorter stroke durations, such as Subject 9 (5 months post-stroke) and Subject 6 (10 months post-stroke), displayed higher contact forces of 6.8 N and 7.4 N, respectively. This suggests that these subjects may still benefit from heightened neuroplasticity, allowing them to engage more effectively in rehabilitation exercises and retain better muscle strength.

The polynomial model for contact force versus the duration of stroke in figure 4 below reveals a high degree of fit and suggests a complex, non-linear relationship between stroke duration and contact force. This sixth-order polynomial suggests that contact force generally decreases as stroke duration increases, with a strong fit indicated by the R^2 value of 0.9133. The reduction in contact force aligns with the typical progression of muscle weakness and atrophy following a stroke, as prolonged disuse of affected muscles commonly leads to reduced motor strength (Ward, Brander, & Kelly, 2019; Daly et al., 2019). The sixth-order polynomial reflects a complex interaction between the contact force and duration of stroke, with multiple inflection points indicating that changes in contact force are not uniform over time. Early in stroke recovery, there may be some variability in force as muscles attempt to recover, but as time progresses, the impact of muscle atrophy and reduced neuromuscular efficiency likely become more pronounced, leading to a steady decrease in force generation capability (Mark & Taub, 2004). The curve's initial phases suggest that earlier in the post-stroke period, patients might retain higher contact forces, which could diminish more substantially with time. This supports the idea that early, intensive rehabilitation might preserve muscle strength and help maintain functional capacity in the affected limbs (Lum et al., 2012).

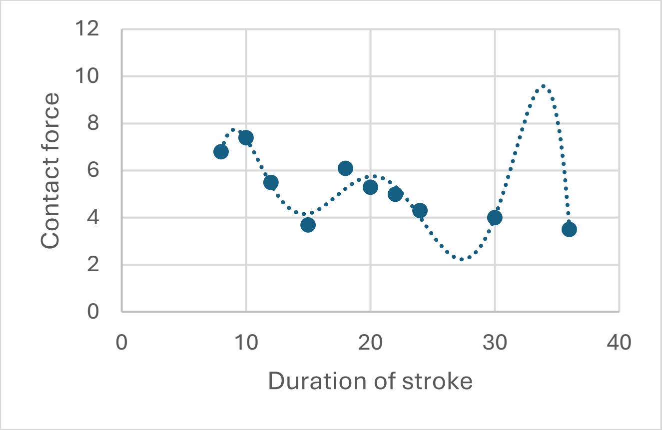

Figure 4: Contact force of the participants classified by duration of stroke

The contact force classified by age is presented in Table 4 and Figure 5 below.

Table 4: Contact force of the participants classified by age

Subject	Age (years)	Contact force (N)
1	54	5.5
2	67	4.3
3	45	6.1
4	60	4.0
5	72	3.7
6	39	7.4
7	58	5.0
8	63	3.5
9	47	6.8
10	55	5.3

In the results obtained in table 4 above, older subjects such as Subject 5 (72 years old) and Subject 2 (67 years old) exhibited lower contact forces of 3.7 N and 4.3 N, respectively. This suggests that age-related muscle weakening has a direct impact on their ability to generate force during hand movements. On the other hand, younger subjects, such as Subject 6 (39 years old), showed a significantly higher contact force of 7.4 N, indicating that younger muscles retain greater strength and functionality. The results align with research that shows muscle strength generally declines by about 1-2% per year after the age of 50, with even more pronounced declines after 60 (Janssen, Heymsfield, & Ross, 2002). Subjects 4 and 8, aged 60 years and 63 years respectively, recorded contact forces of 4.0 N and 3.5 N, demonstrating that middle-aged individuals also begin to experience reduced muscle strength and control, though not as severely as older adults. These findings suggest that in addition to muscle mass loss, the neural mechanisms responsible for controlling force generation become less effective with aging, further contributing to lower contact forces in older individuals.

The polynomial equation for contact force versus age in figure 5 below indicates a strong correlation between these two variables. This high R^2 value suggests that age has a significant impact on contact force, with a complex, non-linear relationship that includes multiple turning points. The polynomial model reflects the trend that contact force diminishes with advancing age, particularly in the later years when muscle degeneration and neuromuscular decline become more pronounced. The sixth-order polynomial highlights a non-linear decline in contact force. While the exact pattern varies, initial stages may reflect a slower decrease in force, potentially due to compensatory mechanisms, followed by a steeper decline as age progresses. This aligns with studies on muscle aging, which suggest that the initial phase of aging can be less impactful on force output, but as sarcopenia progresses, the effects on muscle strength become more drastic (Mark & Taub, 2004; Lum et al., 2012). The strong correlation (with an R^2 of 0.9677) implies that age is a critical factor to consider when designing rehabilitation programs for maintaining hand function and strength.

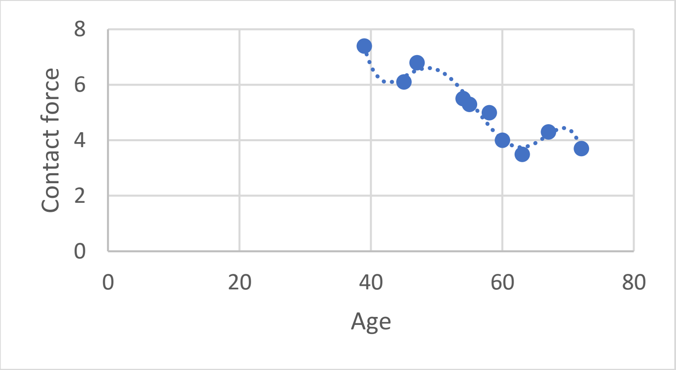

Figure 5: Contact force of the participants classified by age

4 Conclusion

A low-cost robotic hand orthosis with the ability to measure range of motion and muscle strength in real-time was successfully developed. The relationship between stroke duration and ROM was effectively modelled using a polynomial equation which revealed that individuals with prolonged stroke duration exhibited reduced ROM while those with shorter stroke durations showed improved ROM when utilizing the robotic hand orthosis. A polynomial model accurately captured the relationship between subject age and ROM showing a slight decline in ROM among older participants, particularly at maximum speed settings, compared to younger individuals. Stroke duration was also shown to have had a substantial impact on contact force, as modelled through a polynomial equation. Subjects with longer stroke durations exhibited diminished muscle strength and lower contact forces, while those with shorter durations demonstrated higher contact force capabilities. The relationship between age and contact force was similarly modelled with a polynomial equation, indicating that older participants generally exerted lower contact forces, whereas younger subjects exhibited higher contact force levels.

Declaration Statement

The authors agreed with total interest to submit the manuscript entitled, 'Evaluation of Range of Motion and Muscle Strength in Stroke Patients Using a Robotic Hand Orthosis' for publication in your reputable Institution without conflict of interest be it design and implementation, respect towards society, resources and research output and conduct without deceptive acts.

Conflict of Interest

The authors declare no conflict of interest.

Author Contribution

Darlington Chimaobi Onyido: Writing – original draft, Methodology, Conceptualization. Patrick Ugochukwu Agbasi – Supervision, Methodology, Writing – review & editing. Jovita Ada Daniel - Supervision, Methodology, Writing – review & editing. Taofik Oladimeji Azeez - Supervision, Writing – review & editing.

Boluwatife Olayiwola Demokun - Methodology. Ikechukwu William Osuchukwu - Writing – review & editing, Alice Christiana Igwe - Resources. Reyginus Onyebuchi Alaetuo: Formal analysis.

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