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RESEARCH ARTICLE

Biomechanical Evaluation of Fingers Repetitive Voluntary Tasks in Chronic Stroke Survivors

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This work involved human subjects in this research. Approval of all ethical and experimental procedures and protocols was granted by the Institutional Review Board (IRB) of Chi-Mei Medical Center, Tainan, Taiwan, under Application No. 11002-007.

ABSTRACT A chronic stroke affects hand mobility limiting the normal functioning of the finger joints. The voluntary tasks with a repetitive motion can identify the limitation in the range of motion (ROM) to enhance the hand functioning of stroke survivors. Therefore, we compared two voluntary tasks fast ball squeezing (FBS) and slow ball squeezing (SBS), and analyzed the variability of these tasks for finger pressure and ROM in chronic stroke survivors. An experimental study with 22 healthy and 39 chronic stroke participants was conducted. All of them wore an upper limb motion capture device (UMCD) to record the active (AROM) of finger joints during FBS and SBS tasks for 20 repetitions. The data were analyzed into the joint angle and pressure to compare these tasks and their variability. While comparing the FBS and SBS tasks, left-side pressure and both sides' ROM attained the level of significance ($p < 0.05$) except for right-side pressure in healthy controls. However, for stroke participants, right-side pressure and left-side ROM differed significantly. The finger pressure and ROM for the right vs. left side are changed significantly for both tasks in healthy control and stroke survivors except for SBS pressure in the stroke group ($p = 0.119$). The right FBS and SBS are more sensitive to changes in finger pressure and left SBS for ROM in healthy control while in stroke survivors, left FBS and SBS pressure and ROM are sensitive. The variability for pressure is higher and easy to detect as compared to ROM.

INDEX TERMS Active range of motion, chronic stroke, finger joints, hand function, joint angle.

I. INTRODUCTION

Stroke is a key contributing cause of death and disability [1]. The economic and social burden of stroke is quite debilitating which is further aggravated by aging, globalization, and urbanization [2]. About half of stroke people have a lifelong disability and a lower quality of life. The currently used interventions for stroke are physical therapy, neuropharmacology, robot-assisted technology, and virtual reality-based therapies [3].

Stroke survivors may present with motor impairment, muscle weakness, fatigue, and spasticity of the upper extremity (UE) [4], [5] and hand which if not treated can lead to disability and limitations in daily activities [6]. About 60% of stroke people have shortening of muscles in the first year. Wrist, metacarpophalangeal (MCP), and interphalangeal (IP) joints with their long flexors and extensors are prone to develop contractures [7].

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As spasticity is more commonly reported in the upper than the lower limb [8]. It restricts the range of motion (ROM), which is defined as a rotation around a joint, an essential part of the clinical evaluation of stroke people functioning [9], [10]. Passive ROM (PROM) is recorded when a joint is passively rotated by a therapist or external device while active ROM (AROM) is measured when a joint moves due to the contraction of the muscle [11]. The ROM of the joint is compromised by spasticity as a result of variations in muscle-tendon length in a shortened position over time [12]. For this instance, one of the studies reported that after a stroke, early quantitative measurements of hand spasticity may be able to forecast functional recovery and direct targeted rehabilitation measures [13].

The quantification of limitation in AROM in chronic stroke is studied in the previous research which explains a group of upper limb joints like shoulder, elbow, wrist, and finger functioning [14], [15], [16], [17], [18]. Clinically, functional activity questionnaire [19] and spasticity scale [20] are the most widely utilized means to record limitations in ROM after stroke. However, with the advances in technology, multiple devices with inertial measurement units (IMUs), surface electromyography (sEMG), and robots are currently being used for the quantification of AROM [14], [15], [16], [17], [18], [21], [22]. Hence, for an objective measurement of AROM, we have developed and validated a smart glove device mounted with multiple sensors to record AROM. It uses a validated method and algorithm to calculate the ROM of upper limb joints. The sensitivity and validity of this device were reported in our previously published papers [14], [17].

The limitations of hand functioning after stroke can be dealt with a rehabilitation program containing ROM exercises consisting of active and repetitive functional movements [23], [24]. The voluntary tasks used in occupational therapy [14] after stroke for upper limb rehabilitation are fast ball squeezing (FBS), and slow ball squeezing (SBS) which we employed in this study. Thus, it is important to record the AROM to know the limitation in the joint angle and estimate the joint spasticity. This idea was presented in our recent study [14] where we employed a machine learning approach to correlate the finger's spasticity score using a modified Ashworth scale (MAS) and AROM in chronic stroke survivors. Another study, which is in the process of publication utilized a regression modeling technique, generalized estimating equations (GEE) through AROM of upper limb joints to predict MAS spasticity for upper limb joints in chronic stroke survivors.

To our knowledge, no one research used the AROM to compare FBS and SBS tasks for healthy and stroke survivors. Hence, this current study primarily compared FBS and SBS tasks for healthy control and chronic stroke survivors using the finger joint pressure and AROM to determine which task is more sensitive to change in these biomechanical parameters. Because the speed of the task performed is critical for stroke survivors and has clinical implications for rehabilitation programs. For the secondary purpose, we analyzed the variability of change in finger joint pressure and AROM of these tasks.

II. METHODS

A. PARTICIPANT RECRUITMENT

This study included a total of sixty-one participants. Out of which, twenty-two were healthy controls and thirty-nine were chronic stroke survivors. This study was completed at Chi-Mei Medical Center, Tainan, Taiwan. The study procedures were carried out according to the declaration of Helsinki: Ethical Principles for Medical Research Involving Human Subjects (version October 2013) and the Institutional Review Board (IRB) of Chi-Mei Medical Center, Tainan, Taiwan (IRB code: 11002-007) approved this study.

The inclusion criteria were: 1) participants aged 20-80 years and 2) able to sit on a chair for about 40 minutes, and they were excluded if they had 1) symptoms of unilateral neglect or attention deficit, 2) cognitive or language deterioration and not be able to understand and execute the individual tasks, 3) upper-limb disability due to musculoskeletal or peripheral nervous system lesions before the onset of stroke, or 4) diagnosed with dementia or depression. An experienced researcher explained the study methods and written consent was signed by each participant shown in Fig. 1.

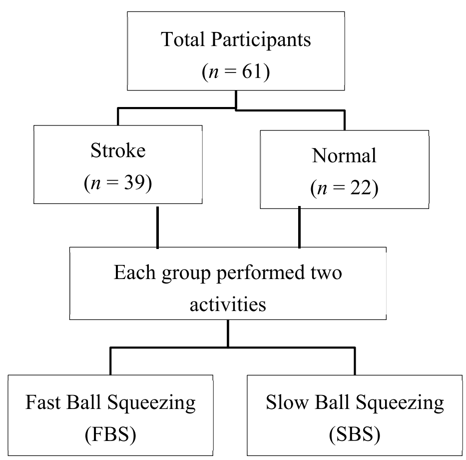

FIGURE 1. **Subject recruitment and performed activities.**

B. SPASTICITY EVALUATION

The spasticity of stroke participants was assessed using the MAS by a physical therapist, which is a common tool for clinical evaluation after a stroke. MAS is a 6-point scale and each reflects 0 = no increase in muscle tone, 1 = slight increase in muscle tone, +1 = slight increase in muscle tone reflected by a catch and release, 2 = more marked increase in the muscle tone, 3 = considerable increase in tone, and 4 = affected part rigid in flexion or extension [20], [25]. We included only the stroke participants who can perform the voluntary task with MAS 0 to 2. We presented the three categories of stroke people according to their spasticity level: 1) normal/no = 0, 2) mild = 1, and 3) moderate = +1 and 2, respectively.

C. EXPERIMENT PROCEDURE

One researcher applied an upper limb motion capture device (UMCD) to each subject with proper alignment and recorded the AROM of finger joints on both sides [14], [17]. Two tasks were used to record the hand AROM including 1) FBS and 2) SBS. These tasks are commonly employed in occupational therapy for stroke patients' rehabilitation [14]. Both FBS and SBS activities were performed on a wooden platform of $36 \times 20 \times 3$ cm^3 adjustable table with a height of 75 to 80 cm. A C-clamp holds the wooden platform to the table. The participant aligned the test forearm so that the palm was facing inward and the hand was not in contact with the platform or table. The participant gently holds the tennis ball without exerting any effort. After that, the participant squeezed the tennis ball as fast as they could 50 times in a row for FBS and squeezed slowly 50 times with the maximum force for the SBS task [14].

The UMCD consists of a sensory glove and motion tracking device (MTD-UA) mounted with 19 IMUs [14], [17] to record the raw data. The joint angles were calculated from UMCD's acceleration, angular velocity, and magnetic field strength data using a sensor fusion algorithm [26], [27], [28]. The joint angles or AROMs during FBS and SBS tasks for 20 consecutive repetitions of 14 finger joints including thumb (first metacarpophalangeal; MP1 and interphalangeal; IP), finger 2 (index metacarpophalangeal; MP2, index proximal interphalangeal; PIP2, and index distal interphalangeal; DIP2), finger 3 (middle finger; MP3, PIP3, and DIP3), finger 4 (ring finger; MP4, PIP4, and DIP4), and finger 5 (little finger; MP5, PIP5, and DIP5) joints, respectively were computed and exported into excel for further processing shown in Fig. 2.

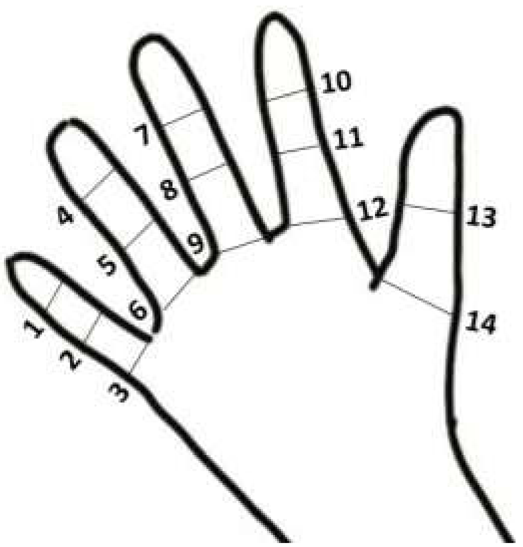

FIGURE 2. Joint angles of upper limb joints including 1: DIP5, 2: PIP5, 3: MP5, 4: DIP4, 5: PIP4, 6: MP4, 7: DIP3, 8: PIP3, 9: MP3, 10: DIP2, 11: PIP2, 12: MP2, 13: IP, and 14: MP1.

The UMCD also has a pressure ball module to record the pressure data. The hardware and software design and calibration were explained in our previous study [14]. The time series angle data of each finger joint of both sides was collected with a 50 Hz [17] sampling rate and processed as an average of 20 repetitions for FBS and SBS tasks in Matlab (R2021a, MathWorks, Inc., Natick, MA, USA). The averaged pressure and ROM data of all 14 joints were calculated as an average value into finger 1 or thumb including MP1 and IP, finger 2 with MP2, PIP2, DIP2, finger 3 with MP3, PIP3, DIP3, finger 4 with MP4, PIP4, DIP4, and finger 5 with MP5, PIP5, DIP5, respectively. Each finger pressure and ROM data were averaged for FBS and SBS tasks for both sides and statistical analysis was performed using a statistical package for social sciences (SPSS).

D. DATA PROCESSING AND STATISTICAL ANALYSIS

The 20 repetitions for change in finger pressure and ROM were compared through a paired t-test for FBS and SBS tasks between healthy control and chronic stroke survivors. The right-left side comparisons were performed using a paired t-test. The variability analysis regarding the total average of 20 repetitions of pressure and ROM for both tasks was also performed, which represents higher the variance more the spread from the mean and vice-versa [29], [30]. The steps of data processing shown in Fig. 3. The bar plots are constructed for each repetition to show the overall trend of pressure and ROM over 20 repetitions with a dotted line showing the total average for these tasks. The overall change in finger pressure and ROM for the 20 repetitions is presented in Figs. 4 and 5. The level of significance was set to $p \leq 0.05^*$, $p \leq 0.001^{**}$, and $p \leq 0.0001^{***}$.

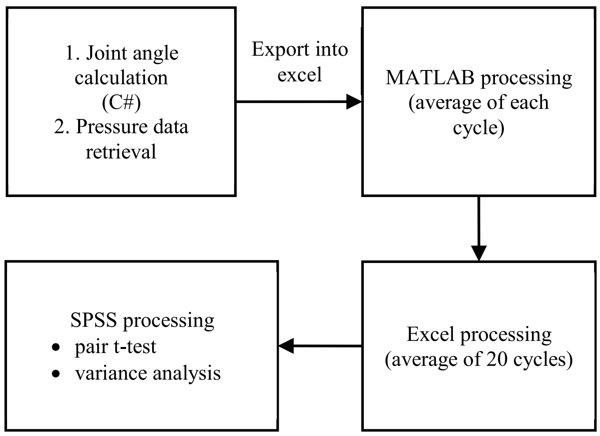

FIGURE 3. Steps of data processing.

III. RESULTS

A. DEMOGRAPHICS OF PARTICIPANTS

Out of sixty-one participants, the healthy control has twelve males and ten females while the stroke group contains twenty-nine males and ten females. The age of the subjects ranged from 45–67 years (healthy = 54.68 ± 9.63 and stroke = 56.44 ± 11.84). Most of the subjects in both groups are right-handed except for one subject in the healthy control

TABLE 1. Study demographics (*N*= 61).

	Healthy control ($n = 22$)	Stroke ($n = 39$)
Gender (Male/Female)	12/10	29/10
Age (years)	54.68±9.63	56.44±11.84
Dominant side (right/left)	21/1	34/5
Affected side (right/left/both)		19/20
Type of injury (hemorrhagic/ischemic)		11/28
Time since stroke (months)		40.31±49.45
MAS elbow (normal/mild/moderate)		7/15/17
MAS wrist (normal/mild/moderate)		17/10/12
MAS thumb (normal/mild/moderate)		21/15/3
MAS finger (normal/mild/moderate)		19/12/8

n: number of participants, MAS: modified Ashworth scale score of spasticity.

TABLE 2. Pairwise comparison of finger fast and slow ball squeezing tasks for healthy control and stroke survivors (*N*= 61).

Variables	Healthy control ($n = 22$) mean±SD	Min	Max	*p*-value
R_FBS_P	26403.19±15007.58	-318	59881	0.100
R_SBS_P	21360.94±5130.07	5239	28858	
L_FBS_P	16244.02±6035.94	776	21062	0.029*
L_SBS_P	18028.91±4510.35	2773	22401	
R_FBS_ROM	50.67±3.45	41	53	0.002*
R_SBS_ROM	48.83±1.74	43	50	
L_FBS_ROM	49.26±2.29	43	51	0.0001***
L_SBS_ROM	58.24±2.45	51	61	
	Stroke ($n = 39$)			
R_FBS_P	9983.76±2883.16	2007	11793	0.029*
R_SBS_P	10961.25±1742.45	5038	13218	
L_FBS_P	11583.79±3438.43	1152	14659	0.408
L_SBS_P	11167.37±1749.65	5122	13393	
R_FBS_ROM	45.50±1.49	41	47	0.880
R_SBS_ROM	45.53±0.75	43	46	
L_FBS_ROM	47.03±1.54	42	48	0.002*
L_SBS_ROM	48.01±0.88	45	49	

n: number of subjects, R: right side, L: left side, FBS: fast ball squeezing, SBS: slow ball squeezing, P: ball pressure, ROM: active range of motion, the level of significance was set to $p \leq 0.050^*$, $p \leq 0.001^{**}$, $p \leq 0.0001^{***}$.

and five in the stroke group, which are left-handed. Nineteen stroke participants have the right side affected and twenty have the left side affected. According to the type of stroke injury, eleven have a hemorrhagic and twenty-eight have an ischemic stroke. The included participants have had a stroke history from less than one month to around seven years, listed in Table 1.

B. COMPARISON OF FBS AND SBS HEALTHY CONTROL VS. STROKE SURVIVORS

For the comparison between FBS and SBS tasks, the finger pressure difference is higher for both groups as compared to ROM. Hence, left side pressure and both sides ROM attained the level of significance ($p < 0.05^*$) except right side pressure in healthy control. While for stroke participants, right-side pressure and left-side ROM differed significantly ($p < 0.05^*$). In healthy control, right FBS pressure and ROM are higher while on the left side, SBS pressure and ROM are higher. In the stroke group, right SBS pressure, left SBS ROM, and left FBS pressure are higher, listed in Table 2.

Overall, the finger pressure for FBS and SBS is changed side-by-side with a similar pattern. At the first repetition, the value is low, usually, it goes higher for FBS and SBS from repetition 2 to 19 and then drops for repetition 20. The finger pressure and ROM for the right vs. left side are changed significantly ($p < 0.05^*$) for FBS and SBS tasks in healthy

TABLE 3. Pairwise comparison of right and left side finger fast and slow ball squeezing tasks for healthy control and stroke patients (*N*= 61).

Variables	Healthy control ($n = 22$) mean±SD	*p*-value
R_FBS_P	26403.19±15007.58	0.0001***
L_FBS_P	16244.02±6035.94	
R_SBS_P	21360.94±5130.07	0.0001***
L_SBS_P	18028.91±4510.35	
R_FBS_ROM	50.67±3.45	0.006*
L_FBS_ROM	49.26±2.29	
R_SBS_ROM	48.83±1.74	0.0001***
L_SBS_ROM	58.24±2.45	
	Stroke ($n = 39$)	
R_FBS_P	9983.76±2883.16	0.0001***
L_FBS_P	11583.79±3438.43	
R_SBS_P	10961.25±1742.45	0.119
L_SBS_P	11167.37±1749.65	
R_FBS_ROM	45.50±1.49	0.0001***
L_FBS_ROM	47.03±1.54	
R_SBS_ROM	45.53±0.75	0.0001***
L_SBS_ROM	48.01±0.88	

n: number of subjects, R: right side, L: left side, FBS: fast ball squeezing, SBS: slow ball squeezing, P: ball pressure, ROM: active range of motion, the level of significance was set to $p \leq 0.05^*$, $p \leq 0.001^{**}$, $p \leq 0.0001^{***}$.

control and stroke participants except for SBS pressure for the stroke group ($p = 0.119$). Only, the right side FBS for the normal group and the left side FBS for the stroke participants attained higher pressure. For the healthy control, right finger pressure and ROM for both tasks are higher except for left SBS ROM. In contrast, stroke participants have higher values on the left side for pressure and ROM for both tasks, listed in Table 3.

C. VARIABILITY OF PRESSURE AND ROM IN HEALTHY CONTROL VS. STROKE SURVIVORS

For the finger pressure, the right side FBS and SBS for the healthy control while the left FBS and SBS for the stroke survivors attained higher means with greater variance. For the finger ROM, right FBS and left SBS for the healthy group and left FBS and SBS for the stroke people have shown higher variability, listed in Table 4.

TABLE 4. Variance analysis of two tasks for the healthy control and stroke survivors (*N*= 61).

Parameters	Normal ($n = 22$)			
	Mean (μ)	SD (σ)	Sum (Σ)	Variance (σ^2)
R_FBS_P	26403.2	15007.6	528063.7	↑ 225227415.7
L_FBS_P	16244.0	6035.9	324880.4	↓ 36432589.1
R_SBS_P	21360.9	5130.1	427218.9	↑ 26317651.9
L_SBS_P	18028.9	4510.4	360578.1	↓ 20343249.9
R_FBS_ROM	50.7	3.5	1013.4	↑ 11.9
L_FBS_ROM	49.3	2.3	985.2	↓ 5.2
R_SBS_ROM	48.8	1.7	976.7	↓ 3.0
L_SBS_ ROM	58.2	2.5	1164.8	↑ 6.0
	Stroke ($n = 39$)			
R_FBS_P	9983.8	2883.2	199675.1	↓ 8312627.7
L_FBS_P	11583.8	3438.4	231675.8	↑ 11822783.9
R_SBS_P	10961.3	1742.5	219225.1	↓ 3036128.9
L_SBS_P	11167.4	1749.7	223347.3	↑ 3061267.3
R_FBS_ROM	45.5	1.5	910.0	↓ 2.2
L_FBS_ROM	47.0	1.5	940.5	↑ 2.4
R_SBS_ROM	45.5	0.8	910.7	↓ 0.6
L_SBS_ROM	48.0	0.9	960.3	↑ 0.8

n: number of subjects, R: right side, L: left side, FBS: fast ball squeezing, SBS: slow ball squeezing, P: pressure, ROM: range of motion, SD: standard deviation, ↑: increasing value, ↓: decreasing value.

For the finger pressure, each repetition value is different so the overall variation among 20 repetitions regarding the total average is measured. Except for the right FBS for the healthy control, all other tasks reached higher or nearly close to the total average values for both groups, they can be shown in Fig. 4. For the finger ROM, the same pattern was noted like pressure change for both groups with higher or nearly close to the total average values. The variations in ROM are not so obvious, but the healthy control attained higher ROM than stroke survivors because it was difficult to detect a difference in ROM in stroke people for both tasks due to the limitation and weakness of the affected and unaffected sides, they can be shown in Fig. 5. The overall finger pressure and ROM change in normal and stroke participants for 20 cycles average for fast ball squeezing (FBS) and slow ball squeezing (SBS) activities are presented in Fig. 6.

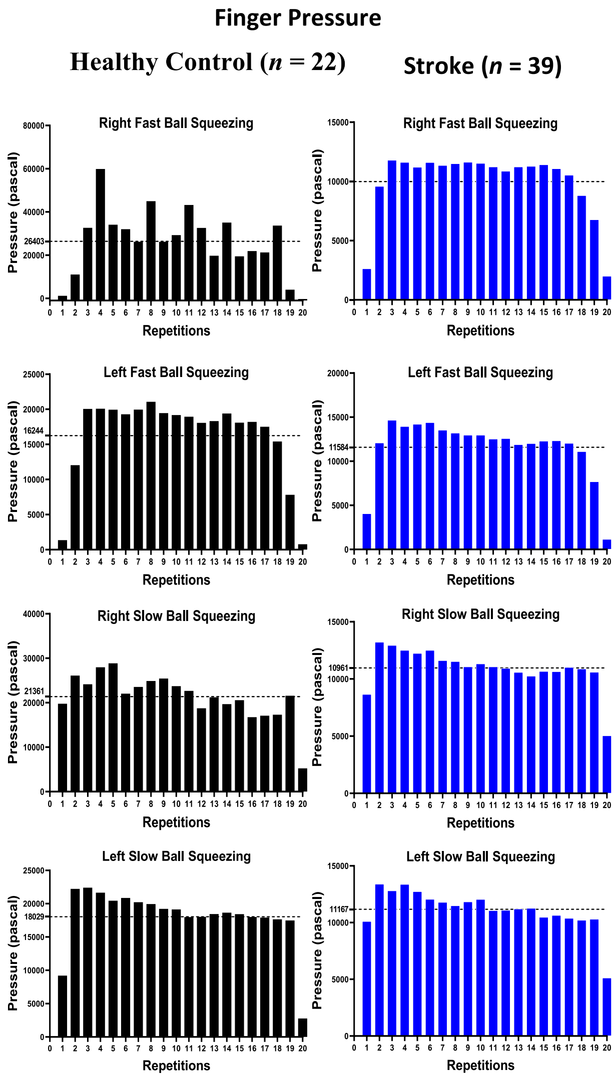

FIGURE 4. Variability analysis of finger pressure for 20 cycles average for fast ball squeezing (FBS) and slow ball squeezing (SBS) activities in healthy control and stroke participants.

IV. DISCUSSION

This is the first study that explored the change of finger pressure and ROM during voluntary tasks: FBS and SBS in chronic stroke survivors. Based on the results of this study while comparing FBS and SBS tasks, left-side pressure and both sides ROM for the healthy and right-side pressure and left-side ROM for the stroke group changed significantly ($p < 0.05^*$). The variability is higher for FBS pressure in both

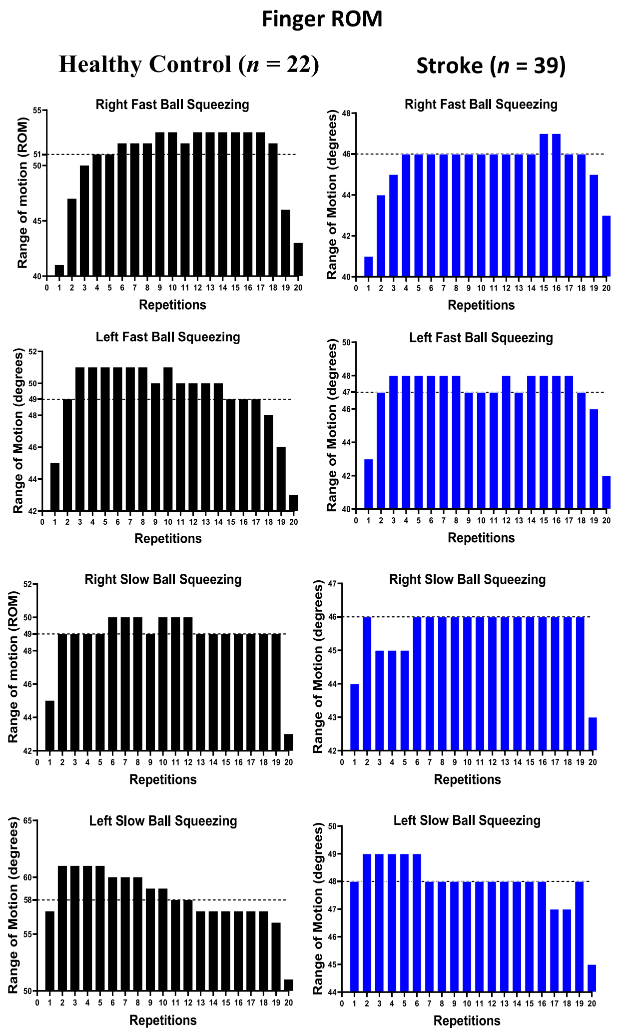

FIGURE 5. Variability analysis of finger pressure for 20 cycles average for fast ball squeezing (FBS) and slow ball squeezing (SBS) activities in healthy control and stroke participants.

groups and ROM only in healthy participants. However, the stroke participants' ROM did not differ as compared to the healthy group.

The difference in pressure and ROM in the healthy group is obvious for the FBS and SBS tasks. In the stroke group, the difference is not noticeable due to the weakness of muscles, particularly extensors, the presence of spasticity, and the co-activation of antagonistic muscles at various joints especially flexor synergy [31] contributed to reducing the functional capacity and we were unable to detect a significant difference in the pressure and ROM. In terms of the trend, stroke survivors followed a pattern similar to the healthy controls without any change in ROM for both tasks.

However, two different tasks with slow and fast speeds are performed. It is difficult to say which variable either pressure or ROM is more sensitive to change during finger movements for stroke survivors even if an obvious difference is detected for the healthy control. However, the change in finger pressure in person without stroke can be further tested in future research to implement these kinds of activities for hand-functional rehabilitation for older or stroke survivors.

A study by Beebe et al. reported that in persons with hemiparesis who experienced a stroke during the first month, the simple measure of AROM may explain 82% of the variance in upper extremity function [32]. AROM against gravity is theoretically a rapid indication of the ability of the spared motor system to activate the spinal motoneuron pools that move a particular segment in stroke survivors [33]. One study by Hsu et al. reported the use of exoskeletal robot-assisted PROM of the hand can be employed as an induction therapy for the stroke rehabilitation program [34].

The utilization of FBS and SBS tasks for stroke participants' rehabilitation suggests that pressure is more sensitive to change during fast-speed (FBS) than slow-speed (SBS) tasks. The same change is noted for stroke survivors but the underlying challenge is, that not all participants can perform fast-speed tasks. But in our study, stroke survivors with mild to moderate spasticity were included and most of them can perform the voluntary task. So, fast speed task (FBS) even though challenging can help the therapist to detect the change in pressure or ROM after several repetitions. On the other hand, a slow-speed task (SBS) would not be able to produce a notable change in pressure or ROM and will be difficult to implement for the rehabilitation program.

The variance is higher on the right side for the healthy control and on the left side for the stroke survivors for both finger pressure and ROM during FBS and SBS activities. This may be due to right-hand dominance in the healthy participants and a greater number of left-affected stroke survivors in this study.

Generally speaking, our proposed system has the following strengths and shortcomings. The main strengths are: 1) Stroke participants' pressure and AROM of finger joints can help clinicians to know the level of difficulty in performing repetitive voluntary tasks and to design an exercise program based on the objective assessment of ROM. 2) It will also help clinicians to determine the recovery time for stroke survivors to attain the required mobility level based on healthy people. The main shortcomings are: 1) This device cannot measure pressure for each finger joint which would need more research in the future to measure each joint pressure accurately. 2) This device did not include shoulder measurement as it can work for elbow, wrist, and finger joints.

In future research, we will predict fatigue using AROM, muscle strength, spasticity level, or Brunnstrom recovery stage. But in this study, we only collect pressure and AROM with mild to moderate spastic chronic stroke survivors. A study with a large sample size including mild, moderate, and severe spasticity levels to perform FBS and SBS tasks for a few days to months should be required to confirm

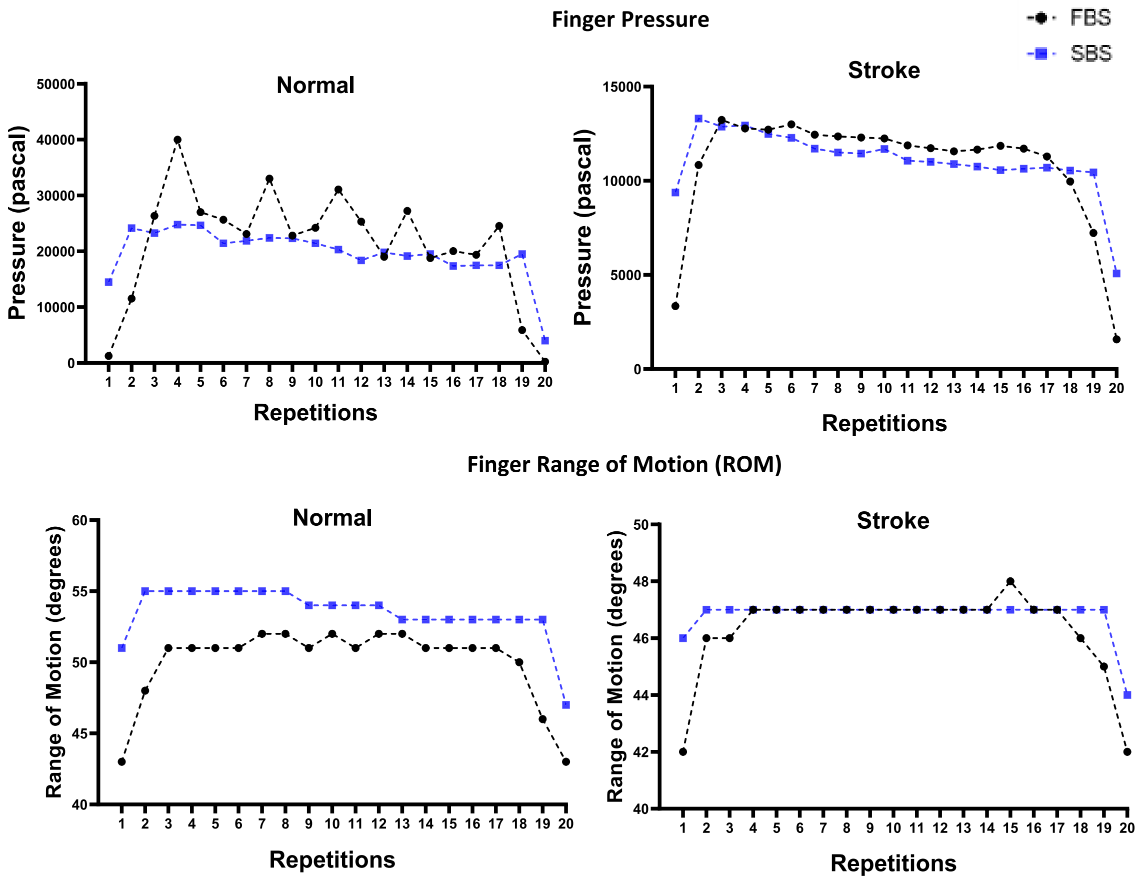

FIGURE 6. Overall pressure and ROM change in normal and stroke participants for 20 cycles average for fast ball squeezing (FBS) and slow ball squeezing (SBS) activities.

the FBS sensitivity for stroke survivors' hand rehabilitation program.

V. CONCLUSION

The right FBS and SBS tasks are more sensitive to changes in finger pressure and left SBS for ROM change in healthy control while in stroke survivors, left FBS and SBS pressure and ROM. The variability for pressure is higher and easy to detect as compared to ROM.

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