

# Study of Compensatory Strategies for Reach-to-Grasp-Pen in Stroke Patients

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## Research

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# Abstract

**Background:** In patients with post-stroke hemiplegia, coordinated reaching and grasping movements may be impaired. Patients frequently adopt compensatory strategies, which require investigation.

**Objectives:** This study examined compensatory strategies using kinematic parameters by assessing the reach-to-grasp-pen movements in stroke patients and unaffected participants – and whether such assessment distinguished between patients with different levels of stroke, and none.

**Methods:** Twelve stroke patients with mild impairment, 12 with moderate impairment and 10 healthy individuals performed a reach-to-grasp-pen task.

**Results:** Stroke patients showed longer reaching movement time, less smooth movement trajectories and more trunk rotation ( $P \leq 0.05$ ). In stroke patients, the MCP and PIP of the thumb were flexed in the starting position; the MCP and PIP joints of the index finger in the stroke group were more extended during pen grasp; the range of motion of the MCP of the middle finger and of the PIP joints of the middle, ring and little fingers became greater, suggesting a larger peak aperture ( $P \leq 0.05$ ). Greater extension was observed in the index finger at the end of the grasp, suggesting inadequate flexion ( $P \leq 0.05$ ).

**Conclusions:** The reach-to-grasp-pen task can identify patients according to stroke level and shows potential as an assessment tool.

## Introduction

Upper extremity dysfunction in post-stroke patients may lead to dependence in terms of activities of daily life (ADL), and a poor quality of life. The ability to perform ADLs is highly dependent on hand function[1] and patients often have impairments in grip strength, power and overall function of the hand that make it difficult to perform daily tasks, severely impairing their ability to perform functional activities independently and reducing their quality of life[2]. Unfortunately, the recovery of hand function recovery is among the most challenging tasks in stroke rehabilitation.

Studies have shown that patients with hemiplegia have slower, less fluid movements, lower accuracy and greater motor variability in reaching tasks compared to healthy individuals[3]. Compensatory movements are usually observed in stroke patients; for example, some use excessive trunk and/or shoulder displacement during reaching and pointing as compensations, to adapt movements in a task-dependent manner[4].

The movement of stroke patients is characterized by flexor synergy, in which the abnormal shoulder–elbow coupling reduces the available degrees of freedom(DFs), leading to a deficient spatiotemporal inter-joint coordination of reaching movements[5], and consequently more torsional and less smooth endpoint movements. Grasping function is also affected in stroke patients. During grasping tasks, patients with stroke tend to have slower hand movements, prolonged terminal phase of reaching and grasping, earlier and larger grip apertures, and a tortuous path of the hand[6]. They may also show impaired fingertip strength coordination during grasping and lifting[7]. Patients with stroke have been shown to use a variety of compensatory strategies to improve grasping function, such as reduced finger abduction, proximal interphalangeal joint (PIP) flexion, and metacarpophalangeal joint (MCP) extension during object grasping.

From a clinical perspective, clinical assessments should adequately reflect motor quality by accurately and effectively measuring movements and potentially differentiating neurological changes associated with motor recovery from compensatory strategies[8]. However, standard clinical assessments rely on clinical scales, which do not adequately reflect motor quality. Recovery of upper extremity and hand function requires therapeutic interventions that focus on

reducing movement impairment. During the first consensus meeting of the Stroke Recovery and Rehabilitation Roundtable (SRRR) group, experts suggested that quantitative movement analysis of a functional task may be useful to identify movement patterns and establish whether improvements in upper extremity and hand function are due to true motor recovery or to compensatory patterns[8]. The most common movement in kinematic studies is simple pointing or reaching. Previous studies have assessed upper limb or hand function separately, and very few studies have considered both upper limb and hand function in a single functional task[9]. Thus, from a clinical perspective, a study of functional task(s) involving both upper limb and hand function may offer greater, and valuable, insights concerning motor recovery status.

Therefore, the present study used a pencil reach and grasp method that was able to measure both upper limb and hand coordination functions. This movement is a commonly-used functional activity of daily living. The aim of this study was to identify and quantify upper extremity and hand function compensatory strategies through a reach-to-grasp-pen task in stroke patients, and to explore the use of that reach-to-grasp-pen task as a movement for use in routine upper extremity rehabilitation assessment. It was hypothesized that common compensatory strategies (flexor synergy, excessive trunk motion and finger coordination) can be identified during a reach-to-grasp-pen task, and that these strategies are affected by the level of disease.

## Methods

### 1 Participants

Twenty-four stroke patients and ten healthy individuals were recruited between 1 August 2020 and 1 December 2020. All participants' characteristics are shown in Table 1. Patients with hemiplegia and healthy individuals were recruited to participate in the study. The following study criteria rendered stroke patients eligible for inclusion: single cerebrovascular accident; haemorrhagic or ischemic; any time after stroke; left or right hemisphere affected; age between 18 and 90 years; able to sit for at least 5 minutes without trunk support; able to perform a sitting reach-to-grasp-pen task with the affected hand; and no history of complex medical conditions such as cardiac, pulmonary, or orthopaedic disease. Moderate upper extremity impairment was defined as an FMA-UE score between 32–57 and mild impairment between 58–66[10]. Patients were excluded if their medical history indicated: severe cognitive impairment (minimum mental status examination score  $\leq$  24); severe aphasia with comprehension impairment; severe neglect.

Table 1  
Characteristics of control and stroke subjects

Characteristic	Control group (n = 10)	Stroke group Mild stroke (n = 12)	Moderate stroke(n = 12)
Age,years	20.6 ± 0.69	45.16 ± 12.62	50.41 ± 12.92
Gender (Female:Male),n	0:10	2: 10	6:6
Side of the lesion (Left:Right),n	N\A	5:5	6:6
Type of stroke (Hemorrhage:Infarct) ,n	N\A	5:5	6:6
Time since stroke,months	N\A	2.41 ± 1.97	3.83 ± 3.58
FMA-UE (/66)			
Total	N\A	60.33 ± 2.70	44.08 ± 10.62
Ashworth Scale	N\A	0.25 ± 0.45	0.91 ± 0.66
Modified Barthel Index	N\A	81.25 ± 15.53	78.75 ± 16.65
Abbreviations:			
FMA-UE, upper extremity part of the Fugl-Meyer Assessment (maximal score 66), N/A not applicable			

The study was conducted in the occupational therapy department of Fujian Rehabilitation Hospital, and patients were referred by an occupational therapist. The control group was recruited at Fujian University of Traditional Chinese Medicine. The study protocol was approved by the Ethics Review Committee of Fujian Provincial Rehabilitation Hospital, and all subjects provided informed consent according to the Declaration of Helsinki.

## 2 Experimental Procedure

Patients underwent standard neurological and musculoskeletal assessments before the experiment. These included the Fugl-Meyer Assessment of Upper Extremity Motor Function (FMA-UE) and the Modified Ashworth Scale and Modified Barthel Index (MBI). During the experiment, participants sat in a straight-backed chair, with a seat 45 cm from the ground, in front of a table that was 75 cm from the ground, with their backs supported but unrestrained. In the initial position, the participant placed their test hand on the table with the forearm pronation, fingers in a fist and the wrist line near the table's edge. The upper arm was in a neutral position with the elbow flexed at approximately 90°. The participant's other hand rested on their knee. Visual inspection was performed to ensure that each trial participant had the same starting hand position. The pen container and pen were placed on the table, in front of the subject. The distance was determined according to the length of the subject's active extended arm (i.e., from the medial axilla to the distal wrist crease).

The reach-to-grasp-pen task comprised reaching, grasping the pen from the pen container, releasing the pen and returning the hand to its initial position. Participants were asked to sit against the back of the chair throughout the task, but were not restricted in their sitting position and could perform compensatory movements if needed. They were asked to begin the task following a verbal instruction from the tester, at which point they started the task at a comfortable self-paced speed. Each participant completed the task five times, and each task was recorded. Figure 1 is the schematic diagram of experimental design.

Two Azure Kinect (Microsoft, Redmond, WA, USA) and one Leapmotion (LMC, San Francisco, CA, USA) motion capture systems were used for 3D motion analysis of the torso, upper extremities and hands during the reach-to-grasp-pen task. The 3D coordinate positions of the markers were calculated immediately, throughout the motion, with high spatial resolution camera units (1 MP Time-of-flight Depth camera, 12 MP CMOS sensor rolling shutter RGB camera). The system was calibrated before each measurement and data was automatically collected by the Kinect SDK (Azure Kinect SDK 1.2, Microsoft). The captured data was transferred to MATLAB software (MathWorks Inc., Natick, Mass.) for custom analysis.

### 3 Data analysis

The endpoint parameters were calculated based on the hand markers. Each kinematic variable was calculated as the average of all motion segments for the entire task. Movement time was the time required to complete a movement segment; motion units (NMU) were calculated according to the number of velocity peaks in a motion segment and used to measure movement smoothness. A motion unit included acceleration, velocity peaks and deceleration. To define a motion unit, the local minimum and maximum values were established from the velocity distribution graph. When the difference between the minimum and the next maximum value exceeded a critical value of 20 mm / s, it was considered a velocity peak. In addition, the time between two subsequent peaks had to be at least 150 ms. These peaks reflected the repeated acceleration and deceleration on arrival, reflecting the smoothness and efficiency of the motion. The curvature index was calculated as the ratio between the total terminal path length and the straight line connecting the initial and final positions. This parameter reflected the efficiency of the motion.

Elbow joint angle and shoulder joint angle were calculated by the dot product of the vectors, defined by the coordinates of the adjacent marker points. Shoulder flexion was defined as the angle between the vector of the elbow joint and the ipsilateral shoulder marker and the vertical vector from the shoulder marker to the hip (i.e., between the straight lines through the torso). The horizontal shoulder abduction/adduction angle was measured by the angle between the vector formed by the elbow joint and the ipsilateral shoulder marker and the angle between the two shoulder crest markers. The elbow joint angle was defined by the vector formed between the wrist joint and the elbow marker, and between the elbow joint and the ipsilateral scapular marker.

In order to determine the possible compensatory movements of adjacent segments, trunk displacement and shoulder peak displacement were calculated. Torso axial rotation was defined as the rotation angle of the point sagittal line in the horizontal plane projection vector of both shoulders. Trunk flexion was defined as the maximum forward displacement from the initial position at the sternal point in the sagittal plane.

The excursion of each finger, i.e., the extent to which the thumb, index finger, middle finger, ring finger, and little finger could be flexed and extended – including the MCP, PIP, and DIP joints – was measured in the reaching and grasping task. The range of motion of the fingers was calculated as the difference between the minimum and maximum values in the finger angle data.

### 4 Statistical Analysis

Statistical analysis was performed using IBM SPSS 20.0 (IBM Corp, Armonk, NY). In the analysis of kinematic data, the mean of five records was used in the statistical calculations. The measures were expressed as mean  $\pm$  standard deviation, and the counts were expressed as rates or percentage composition ratios. One-way analysis of variance (ANOVA) was used to those compare participants who were patients with mild and moderate stroke to healthy patients, with LSD tests between groups when differences were significant and general linear model correction analysis when baseline levels were not equal. All statistical tests were performed using two-sided tests, and P values less than or equal to 0.05 were considered statistically significant for the differences tested.

## Results

### 1 Comparison of kinematic characteristics of the reaching and grasping pencil task

When participating stroke patients were compared to the control group, significant differences in movement time, movement units, curvature index, spectral arc length, forward and lateral trunk displacement, elbow extension, shoulder flexion, and shoulder abduction were identified in the stroke group; these are shown in Table 2. The mild stroke group had longer of movement time ( $P = 0.001$ ), more motor units ( $P = 0.028$ ), greater curvature index ( $P = 0.017$ ) and smaller length of spectral arc ( $P = 0.000$ ), less elbow extension ( $P = 0.048$ ), less forward trunk displacement ( $P = 0.000$ ) and more horizontal displacement ( $P = 0.006$ ). The moderate stroke group had longer movement time ( $P = 0.000$ ), more motor units ( $P = 0.000$ ), greater curvature index ( $P = 0.035$ ), and smaller spectral arc length ( $P = 0.017$ ), less elbow extension ( $P = 0.001$ ), less shoulder flexion ( $P = 0.009$ ), more shoulder abduction ( $P = 0.046$ ) and less forward displacement of the trunk ( $P = 0.005$ ). The mild stroke group showed no significant differences in trunk rotation and arm plane angle ( $P > 0.05$ ). Kinematic performance was poorer in patients with moderate stroke than in those with mild stroke, although there was no statistically significant difference.

Table 2  
Kinematic characteristics of the reach-to-grasp-pen task in healthy and stroke subjects

Parameters	Control group	Stroke group	Moderate stroke(n = 12)
	(n = 10)	Mild stroke (n = 12)	
Movement time,s	1.38 ± 0.15	2.51 ± 0.65**	2.76 ± 0.81**
Number of movement unit,n	1.10 ± 0.31	1.10 ± 0.31*	1.83 ± 0.61**
Index of curvature	1.11 ± 0.06	1.20 ± 0.03*	1.26 ± 0.33*
Spectral arc length	-1.51 ± 0.08	-1.60 ± 0.08*	-1.71 ± 0.09**
Trunk forward transition,mm	2.86 ± 0.87	0.34 ± 0.40**	0.63 ± 0.61**
Trunk lateral transition,mm	1.85 ± 1.29	4.06 ± 2.02**	3.08 ± 1.80
Range of motion, degrees			
Elbow extension	69.23 ± 7.29	58.47 ± 10.22*	50.82 ± 16.43**
Shoulder flexion	54.73 ± 7.12	48.66 ± 9.84	43.11 ± 11.37**
Shoulder abduction	9.84 ± 3.14	12.85 ± 3.55	17.61 ± 9.22*
Trunk rotation	14.91 ± 5.21	13.67 ± 4.85	13.49 ± 7.19
Arm-plane angle	23.13 ± 6.70	25.43 ± 8.68	23.21 ± 10.61
Asterisks indicate differences compared with the control group;*P<0.05 **P<0.01			

### 2 Comparison of joint angles of pen grasping strategies

To describe the pen grasping strategies of patients and controls, the differences in the metacarpophalangeal (MCP) and interphalangeal (IP) joints of the thumb, and the joint angles of the MCP, PIP, and DIP of the index, middle, ring, and little fingers at the beginning and end of the grasp were all examined.

At the grasp start position, the thumb MCP was more flexed ( $P = 0.05$ ) and the PIP was more flexed ( $P = 0.005$ ) in the mild stroke group. At the grasp end position, there was less MCP ( $P = 0.006$ ) and PIP flexion ( $P = 0.017$ ) in the index finger and less MCP flexion ( $P = 0.045$ ) in the little finger in the moderate stroke group. The remaining joint angles showed no significant difference ( $P > 0.05$ ). The grasping strategy of patients with mild stroke was closer to that of the normal group. Further details can be found in Table 3.

Table 3

Comparison of finger joint angles at the starting and end positions in grasping task in healthy and stroke subjects

Joint	Initial position of grasping			End position of grasping		
	Control	Mild	Moderate	Control	Mild	Moderate
MCP						
Thumb	9.36 ± 4.34	17.18 ± 7.83*	13.43 ± 4.65	11.51 ± 7.82	9.53 ± 6.71	10.89 ± 4.85
Index	50.55 ± 8.68	48.79 ± 13.91	39.06 ± 10.84	48.14 ± 7.82	39.03 ± 14.77	31.66 ± 13.79**
Middle	50.86 ± 6.88	54.90 ± 13.87	43.90 ± 10.26	42.93 ± 6.40	45.54 ± 11.92	38.82 ± 20.01
Ring	44.78 ± 8.35	49.51 ± 17.57	41.08 ± 14.19	53.62 ± 9.28	50.37 ± 15.06	40.23 ± 19.89
Little	43.71 ± 7.89	48.79 ± 19.90	41.56 ± 15.26	62.36 ± 9.88	57.16 ± 19.13	47.03 ± 15.77*
PIP						
Thumb	16.67 ± 7.36	28.19 ± 10.60**	24.20 ± 7.55	19.92 ± 11.69	16.18 ± 10.56	19.52 ± 7.47
Index	37.96 ± 10.42	46.30 ± 18.22	37.74 ± 12.61	53.40 ± 10.18	42.95 ± 6.89	39.59 ± 17.63*
Middle	50.06 ± 11.39	58.54 ± 16.39	56.08 ± 13.47	54.25 ± 7.39	54.95 ± 10.66	55.39 ± 19.64
Ring	50.53 ± 10.39	56.81 ± 18.05	54.16 ± 11.92	55.45 ± 5.65	53.52 ± 11.01	50.72 ± 14.44
Little	53.65 ± 8.21	57.55 ± 16.06	50.92 ± 10.30	48.93 ± 5.44	51.84 ± 9.94	47.14 ± 14.01
DIP						
Index	23.66 ± 5.19	30.93 ± 10.67	25.77 ± 7.79	39.83 ± 12.56	36.47 ± 14.70	29.92 ± 14.43
Middle	34.87 ± 10.61	37.83 ± 7.91	46.72 ± 17.90	46.43 ± 6.58	45.88 ± 12.28	44.06 ± 16.47
Ring	43.88 ± 12.51	43.59 ± 12.03	49.98 ± 17.08	50.28 ± 4.72	51.64 ± 11.11	49.86 ± 18.44
Little	48.56 ± 9.97	45.43 ± 14.26	53.78 ± 19.44	51.79 ± 8.41	51.89 ± 8.93	53.77 ± 19.13
Asterisks indicate differences compared with the control group; * $P \leq 0.05$ ** $P \leq 0.01$						

### **3 Change In Joint Angle During Grasping Task**

In terms of maximum flexion values, there was no statistical difference between the stroke and control groups, as Table 4 shows.

Table 4

Comparison of maximum flexion values, maximum extension values and joint range of motion in the stroke and control groups

	Peak Flexion, degrees			Peak Extension, degrees			Range of motion, degrees		
	Control	Mild	Moderate	Control	Mild	Moderate	Control	Mild	Moderate
MCP									
Thumb	17.16 ± 7.37	21.41 ± 7.31	19.56 ± 6.96	3.52 ± 3.10	3.44 ± 3.58	4.77 ± 3.68	13.64 ± 5.76	17.97 ± 5.87	14.79 ± 5.26
Index	56.70 ± 5.25	56.95 ± 9.34	52.31 ± 9.64	18.60 ± 6.13	10.80 ± 7.95*	12.21 ± 6.94*	38.09 ± 6.64	46.15 ± 11.72	40.10 ± 9.49
Middle	55.34 ± 4.77	66.14 ± 12.35	60.31 ± 12.15	23.24 ± 9.06	17.91 ± 12.83	18.64 ± 15.36	34.28 ± 11.72	48.17 ± 17.70*	41.67 ± 11.55
Ring	60.25 ± 6.27	65.81 ± 6.27	59.27 ± 12.15	25.96 ± 11.96	20.41 ± 15.77	19.85 ± 17.54	34.28 ± 11.72	45.40 ± 13.01	39.42 ± 9.29
Little	65.26 ± 3.96	65.88 ± 16.03	62.13 ± 11.55	26.47 ± 12.30	25.44 ± 18.08	21.31 ± 15.26	38.78 ± 11.28	40.44 ± 15.83	40.81 ± 7.41
PIP									
Thumb	29.14 ± 10.32	35.11 ± 8.88	32.37 ± 8.03	6.66 ± 5.72	5.99 ± 7.40	9.16 ± 6.58	22.47 ± 6.81	29.12 ± 7.28	23.21 ± 5.98
Index	55.69 ± 8.99	58.01 ± 11.30	53.32 ± 17.24	25.40 ± 7.08	18.12 ± 7.76*	18.24 ± 4.57*	30.28 ± 9.03	39.89 ± 10.18	36.07 ± 14.25
Middle	62.43 ± 6.91	73.43 ± 9.26	71.11 ± 15.10	33.31 ± 9.80	30.68 ± 12.67	33.93 ± 16.30	29.12 ± 7.18	42.75 ± 10.36**	37.18 ± 12.78
Ring	62.52 ± 5.28	70.47 ± 10.56	68.43 ± 8.59	38.11 ± 11.09	29.31 ± 14.86	31.49 ± 14.26	24.40 ± 8.69	41.16 ± 13.17**	36.94 ± 9.66*
Little	59.27 ± 5.83	67.95 ± 10.44	64.60 ± 2.58	36.26 ± 11.14	36.26 ± 11.14	27.45 ± 14.39	23.00 ± 6.36	41.01 ± 15.58**	37.14 ± 8.72**
DIP									
Index	41.92 ± 11.87	46.77 ± 12.23	42.07 ± 14.42	15.98 ± 4.06	10.95 ± 5.86	11.73 ± 4.14	25.94 ± 12.97	35.81 ± 10.23	30.34 ± 14.53
Middle	54.48 ± 9.09	63.80 ± 9.32	65.81 ± 15.40	23.24 ± 9.06	22.03 ± 11.89	23.99 ± 13.58	31.23 ± 14.03	41.77 ± 8.60	41.81 ± 14.44

Mean ± SD of peak flexion, peak extension and total mean range of motion (flexion minus extension) of the distal interphalangeal (DIP), proximal interphalangeal (PIP) and metacarpophalangeal (MCP) joints of each finger in the control group and patients.

Asterisks indicate differences compared with the control group; \*P<0.05 \*\*P<0.01

	Peak Flexion, degrees			Peak Extension, degrees			Range of motion, degrees		
Ring	62.53 ± 7.15	68.20 ± 8.13	70.36 ± 12.28	33.03 ± 10.08	26.70 ± 12.24	28.86 ± 14.61	29.49 ± 11.19	41.49 ± 11.56	41.49 ± 16.25
Little	66.97 ± 4.90	71.81 ± 11.15	73.85 ± 11.50	36.78 ± 8.58	31.48 ± 14.87	34.84 ± 14.16	30.19 ± 7.83	40.32 ± 12.27	39.00 ± 12.55
Mean ± SD of peak flexion, peak extension and total mean range of motion (flexion minus extension) of the distal interphalangeal (DIP), proximal interphalangeal (PIP) and metacarpophalangeal (MCP) joints of each finger in the control group and patients.									
Asterisks indicate differences compared with the control group; *P<0.05 **P<0.01									

Turning to maximum extension values, the mild stroke group had smaller maximum extension values for index finger MCP (P = 0.017) and PIP (P = 0.017) than the control group. In the moderate stroke group, the maximum extension values of the index finger MCP (P = 0.048) and PIP (P = 0.019) were smaller than those of the control group (see Table 4).

For range of motion, in the mild stroke group MCP (P = 0.010) and PIP (P = 0.006) were greater in the middle finger, PIP (P = 0.001) in the ring finger, and PIP (P = 0.001) in the little finger. The moderate stroke group had greater PIP (P = 0.012) in the ring finger and greater PIP (P = 0.007) in the little finger. The overall range of motion was greater in the stroke group than in the normal group, although this difference was not statistically significant (Table 4). Furthermore, the standard deviation was greater in the stroke group, with greater individual differences. In the healthy control group, the standard deviation of movement was smaller and consistency was better.

## Discussion

To the best of the authors' knowledge, this is the first study to extensively examine the reach-to-grasp-pen task in stroke patients with mild to moderate upper extremity motor deficits, aiming to investigate the kinematic characteristics of the upper extremity, trunk and hand during the task. The results indicate that the reach-to-grasp-pen task can reveal compensatory strategies and effectively differentiate between patients with different levels of stroke and healthy individuals. The reach-to-grasp-pen task can thus be considered as an appropriate tool for the assessment of the upper extremity in individuals with stroke.

## 1 Reaching and grasping task performance

In the present study, the stroke group showed less elbow extension and less shoulder flexion than healthy controls. Compensatory movements, including excessive shoulder abduction and trunk forward movement, were observed. Previous studies have also shown that patients with chronic moderate to severe stroke may have up to 33% increased trunk motion and/or a combination of shoulder abduction and elevation (i.e., arm plane) motion, even when reaching a target near the arm or near the arm[11]. Santos et al.[12] analysed the movement strategies of stroke patients to accomplish the task of drinking, and the affected upper extremity showed more scapular protraction and ipsilateral trunk lateral flexion than normal subjects throughout the drinking process; this was particularly pronounced during the two phases at the beginning of the movement and when the hand reached the cup. Merdler et al. [13] found higher arm abduction and less elbow extension in all target directions in the stroke group compared with the control group; the arm plane angle tended to be higher in the moderate to severe stroke group. In our study, the stroke group had less forward displacement and more horizontal displacement of the trunk. The lack of difference in trunk rotation may be due to the

fact that the task required a forward grasp of the pen. The lack of difference in arm plane angle is surprising, but probably occurred because most of the patients included in the current study were mildly impaired and already lacked capacity for synergistic movement.

For the grasping behaviour, the thumb flexion appeared to be hypertonic in the stroke group at the onset position. The thumb MCP and PIP were more flexed in the stroke group ( $P < 0.05$ ), suggesting the presence of thumb flexion muscle tone in the stroke group. Clinically, stroke patients with moderate to severe hand injury usually present with bending of the thumb to the palm of the hand and bending of the fingers to the thumb. Hyperexcitability of the thumb long flexor (FPL), which manifests as spasticity, excessive synergistic activity and delayed relaxation are thought to be responsible for this phenomenon[14]. In the present study, the flexion tone of the thumb did not seem to affect the patients' pen grasp performance, since no significant differences in MCP joint activity were observed during the task undertaken.

The stroke group did not seem able to control the scaling of the peak finger aperture during reach-and-grasp-pen task; the maximum extension values of the MCP and PIP of the index finger were smaller in the stroke group than in the control group ( $P \leq 0.05$ ), and each joint of the index finger was less flexed and more extended in the stroke group. In addition, the range of motion of the MCP and PIP joints of the middle, ring and little fingers was greater in the stroke group ( $P \leq 0.05$ ). This may be due to the lack of motor control in the stroke group, resulting in a larger range of motion. These findings suggest that the fingers of the stroke group were unable to control the size of the aperture and therefore the peak aperture was larger. A grasping motion requires precise planning and execution of hand movement toward the object and prediction of the grasping aperture for object properties. Reaching and grasping movements performed after a stroke are characterised by slow hand transmission, slow grasping apertures, inaccurate scaling of peak grasping apertures and decoupling of spatiotemporal coordination between hand transmission and grasping aperture components[6].

The ability to open the fingers during the grasping aperture component of the grasping action is altered after stroke, due to the impairment of coordination and timely activation of finger muscles in stroke patients and with the activation of more proximal muscles in the transport component of the hand, making it difficult to open the fingers accurately when approaching the grasped object. In particular, the problem of activating the finger extensors and coordinating the muscle activity between the finger flexors and extensors leads to a highly variable grasp aperture[6]. In the present study, the larger aperture may have resulted from a restricted ability to flex the index finger or from a deterioration in motor control of fingers.

In the grasp end position, the index finger MCP and PIP were less flexed in the stroke group ( $P \leq 0.05$ ); that is, in a more extended position, suggesting a problem with index finger opposition or flexion function, or just a problem with the grip strategy. One study showed that stroke patients used more MCPs for grasping[15]. This differs from the present study, possibly because Raghavan and colleagues used the task of grasping a rectangular wooden block, while the present study used a pen grasp task. Another study has proposed that mild and moderate impairments influenced patients' grasp preference. Those with moderate motor impairment primarily used the affected upper extremity and full hand grasp, whereas those with mild impairment tended to use a finger grasp[16]. However, in our study, no features of full-handed grasping were found. It is, however, possible that the patients included in this study were relatively mildly impaired.

## **2 Underlying neurophysiological mechanisms of performance deficits**

In the present study, the stroke group had more shoulder abduction and scapular elevation, which could be due to co-activation of the trapezius muscle or, possibly, co-activation of the anterior middle and posterior deltoid muscles. A previous study found that the level of upper trapezius motor unit recruitment during reaching was greater in the hemiplegic side of stroke patients than in healthy subjects, and the anterior deltoid/superior trapezius work ratio was less than in healthy subjects, suggesting that the compensatory contraction of the upper trapezius muscle in the hemiplegic side of patients was enhanced during the forward flexion reaching task[17]. In another study, the same was found for the EMG signal of the reaching action, where patients required more compensation from the trapezius muscle relative to the healthy group, and the contraction strength of other muscles was generally smaller. The lack of elbow extension in the stroke group may be due to insufficient activation of the triceps muscle. Pan et al.[18] studied the changes in muscle synergy during active reaching movements in subacute stroke survivors and observed reduced activation of the triceps, in addition to co-activation of the trapezius and deltoid muscles, and increased activation of the pectoralis major in the stroke group. Levin et al.[19] found that stroke may lead to a limitation of reciprocal inhibition and excessive co-activation of the agonist-antagonist muscles, resulting in co-activation of the biceps and triceps. This may be due to a defect in tension stretch reflex (spatial) threshold (TSRT) regulation in both muscle groups, leading to limited elbow extension.

Results from the current study show that the motor control of the fingers of stroke patients during pen grasp was reduced and the peak aperture was larger than was the case for the healthy control group. Poor motor control may be related to the loss of independent finger control[20]. Impaired independence of all fingers, including the thumb, in patients with moderate hand motor impairment due to subcortical stroke is an important cause of deficits in hand motor control[20–23]. The lack of independence is attributed to many factors, including peripheral connective tissue connections between the fingers, multifidus extrinsic hand muscles, and overlapping cortical representation of the fingers[24]. Overall, the manner in which the fingers are innervated is largely determined by central neural factors[25]. With infarction in the middle cerebral artery, the loss of higher motor planning and sensorimotor integration greatly disrupts fine force production, especially during finger independence[26]. Secondary degeneration of the corticospinal tract and loss of motor units in spinal cord segments occur in the days and weeks following ischemic injury, which also leads to permanent deficits in motor performance that can result in poor finger coordination and impaired hand function [27].

Sensory deficits may also lead to reduced finger control. Umeki et al.[28] conducted sensory training to enhance finger discrimination in patients and found that the mean change in tactile pressure threshold was significantly greater in the experimental group than in the control group. The reduction in manipulation time required for handling small balls and small metal discs that was observed in the experimental group was significantly greater than that observed in the control group. The results suggest that a sensory training program that enhances finger discrimination helps to improve not only the sensory function, but also the hand function of stroke patients, and that the improvement of somatosensory deficits after stroke reflects the control of finger movements. Sensory deficits after stroke include not only tactile loss, but also protective and proprioceptive loss. Sensory feedback information is critical because the amount of sensory feedback information generated by cutaneous sensory receptors affects the control of motor function (requiring precision).

### **3 Clinical implications**

Studies have shown that stroke patients may adopt atypical compensatory movements to perform tasks[29], and this phenomenon was also identified in the current study. Evidence suggests that the continued use of these compensatory modalities may be detrimental to true rehabilitation[30]. Replicating the correct kinematics is important for training, because restoring pre-injury kinematic movements, rather than using an altered (compensatory) kinematic approach, is fundamental to true rehabilitation[31]. Therefore, it is crucial to identify compensatory patterns.

Previous studies have identified differences between healthy controls and individuals with stroke in upper extremity, trunk, and hand kinematics using reach-to-grasp and grasp tasks, respectively. This study extends previous findings on hand function deficits in neurological patients. Our results suggest that stroke patients present with compensatory reach-and-grasp-pen strategies, abnormal upper extremity and trunk kinematic metrics, and poor hand motor control. The reach-and-grasp-pen task used in the study could be a valuable supplement to the current strategy of measuring hand compensation, and could be used to measure motor quality (i.e., trunk and arm joint displacement and intersegmental coordination) and endpoint performance (i.e., spatiotemporal quality of whole arm movement)[32], which is in line with the recent proposal arising from the first consensus meeting of the Stroke Recovery and Rehabilitation Roundtable (SRRR) to assess upper extremity motor quality by functional activity[8].

The reach-and-grasp-pen movement measures functional activity of both the upper extremity and hand compensatory strategies and is effective in differentiating between patients with different levels of stroke and controls, and may be considered by occupational therapists in clinical practice as an upper extremity assessment movement to provide a basis for rehabilitation assessment of stroke patients.

## **4 Study limitations**

The current study has several limitations. Firstly, only mild to moderate stroke patients were recruited, and the results of the study cannot be generalized to patients with severe stroke. Secondly, electromyogram(EMG) data was not recorded. Future work could combine information regarding brain networks, muscle networks and muscle synergy to better understand the neurophysiological mechanisms of the disease, and help therapists to improve treatment and rehabilitation programs.

## **Conclusions**

The study presented here has found that stroke patients showed poor endpoint performance and more trunk displacement in the upper extremity during a reach-to-grasp-pen task. There was high thumb flexion tension and poor finger motor control during pen grasp. Patients with varying degrees of stroke presented with impaired motor control of the upper extremity and hand and altered reach-to-grasp-pen strategies. The results from our study indicated that the reach-to-grasp-pen task can effectively identify patients with different levels of stroke and differentiate these from individuals unaffected by stroke, and may be considered as a routine tool for functional assessment of the upper extremity.

## **Declarations**

### **Ethics approval and consent to participate**

All participants provided written informed consent before inclusion. The study protocol of this trial was approved by the medical ethics committee of the Fujian Provincial Rehabilitation Hospital in Fujian Province, China.

### **Consent for publication**

Not applicable.

### **Availability of data and materials**

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Competing interests

The authors declare no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

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## Authors' contributions

Qiurong XIE collected, analyzed and interpreted the results of this study. Qiurong XIE also wrote the original draft of the manuscript. Yanxin ZHANG, Jia HUANG & Bo SHENG contributed to the funding, conceptualization and methodology of the study. All authors made major contributions to the manuscript. All authors read and approved the final manuscript.

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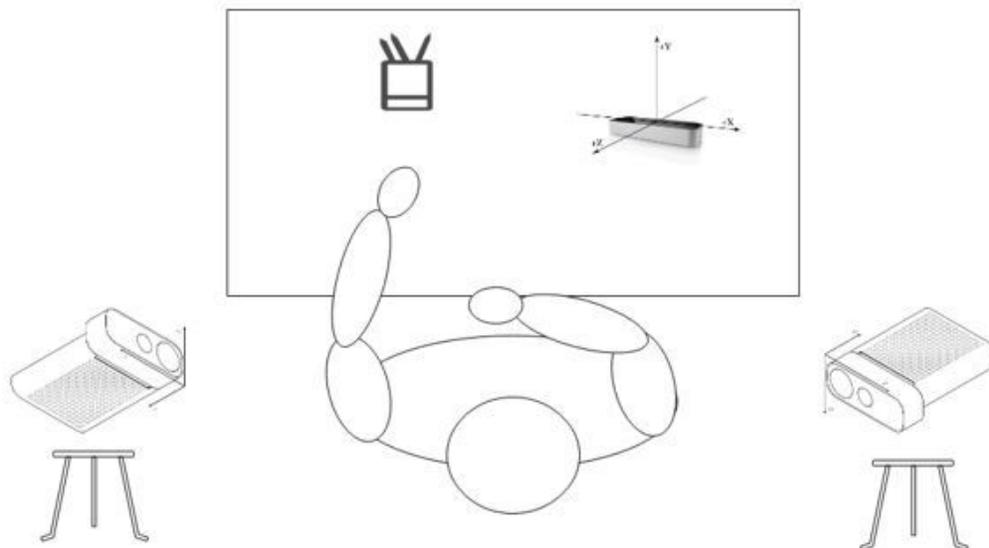
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## Figures



**Figure 1**

Schematic diagram of experimental design