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ORIGINAL REPORT

EYE–HAND COORDINATION AND ITS RELATIONSHIP WITH SENSORI-MOTOR IMPAIRMENTS IN STROKE SURVIVORS

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Objective: **To investigate eye–hand coordination in stroke survivors and its relationship with sensori-motor impairments and hand functioning in daily life.**
Design: **Cross-sectional study.**
Subjects: **Fifteen subjects with stroke (mean age 62.5 years (standard deviation (SD) 7.1); time post-stroke 5.2 years (SD 3.0)) recruited by convenience sampling.**
Methods: **A fast finger-pointing task towards a moving visual target was employed to investigate the differences between the subjects' affected and unaffected hands in terms of reaction time, movement time and accuracy. Their sensori-motor impairments in tactile sensation, handgrip strength, Fugl-Meyer scores and Jebsen Taylor Hand Function Test scores were measured.**
Results: **Significant differences were found between the affected and unaffected hands in terms of movement time and accuracy in finger pointing. Movement time was significantly correlated with tactile sensitivity, handgrip strength and total Fugl-Meyer score, while accuracy correlated with tactile sensitivity and total Fugl-Meyer score. Total scores on the hand function test also correlated significantly with reaction time and movement time.**
Conclusion: **The stroke survivors had poorer eye–hand coordination, in terms of slower movement and reduced accuracy when using their affected hand. These performance measures were significantly correlated with several sensori-motor impairments. A significant correlation was also found between eye–hand coordination performance and hand function test scores.**

Key words: finger-pointing; moving target; stroke; sensori-motor function.

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INTRODUCTION

Eye–hand coordination is essential for upper extremity dexterity (1). It is defined as the use of vision to guide movements of the hand, such as reaching and grasping (2, 3); thus it requires the integrated use of eyes, arms, hands and fingers to produce controlled, accurate and rapid movements (3). It has been suggested that normal eye–hand coordination occurs in an ordered sequence as follows: (*i*) visual detection of the target; (*ii*) attention focusing; (*iii*) perceptual identification and location of the target; (*iv*) cognitive planning and programming of reaching movement; and (*v*) activation of arm muscles to initiate reaching (2). These procedures involve different systems including the sensory and perceptual systems, central processing systems, arousal and motivational systems and motor systems (4). Throughout the procedure, sensory information from proprioception and vision play an important role in guiding and adjusting the movement by providing feed-forward and feedback control (5).

A number of researchers have reported that, following stroke, visually-guided reaching and pointing movements are slower, less accurate and not as well-coordinated as those made by healthy individuals (6–11). The abnormal reaching seen in hemiparetic subjects usually occurs together with sensori-motor impairments resulting from the stroke, including dysaesthesia (6), muscle weakness (7), abnormal synergies (8–10) and lack of isolated movement (11).

Most research in this subject has studied reaching toward a static visual target. In daily living, however, reaching and grasping movements also involve moving visual targets, as in giving and receiving objects from another person, shaking hands or feeding pets. Little is known about the performance of stroke survivors in tasks that involve fast finger-pointing toward a moving target and its relationship with sensori-motor control. The present study was designed to increase our understanding of eye–hand coordination so that rehabilitation of subjects after stroke may be enhanced. Its objectives were:

- to investigate whether there are differences in eye–hand coordination performance between the affected and unaffected hands of stroke survivors in terms of reaction time, movement time and accuracy in a fast finger-pointing task towards a moving visual target;
- to determine whether there is any relationship between fast finger-pointing performance and tactile sensation, handgrip strength, or upper limb motor impairment; and
- to investigate the relationship between fast finger-pointing performance and ability in the activities of daily living.

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MATERIAL AND METHODS

Subjects and study design

Fifteen community-dwelling participants with chronic stroke (9 men and 6 women, mean age 62.5 years (standard deviation (SD) 7.1)) were recruited from 3 rehabilitation centres in Hong Kong's Community Rehabilitation Network to participate in this cross-sectional study. They underwent a balance training programme in our rehabilitation unit at the time this study was conducted. All of them had had stroke a minimum of 2 years previously (mean time since stroke 5.2 years (SD 3.0)). All subjects were able to communicate in Cantonese or English and to follow the testing procedures. Other inclusion criteria included: an Abbreviated Mental Test (AMT) score of at least 7 (12), visual acuity of at least 20/40, star cancellation test score of at least 44 out of 54 (13), shoulder flexion of at least 90°, and elbow extension deficit not more than 30°. Exclusion criteria included: hearing loss, hemianopia, visuospatial neglect, inability to perform the pointing task and missing index fingers. The study was approved by the ethics committee of The Hong Kong Polytechnic University. Written informed consent was obtained from all subjects.

Test procedures

Subjects were first screened by a physiotherapist. Then, another physiotherapist was responsible for conducting the following tests with random order. Sensori-motor performance, including tactile sensation and handgrip strength were assessed. The motor recovery of upper limb function was investigated using the arm section of the Fugl-Meyer Motor Assessment (FMA-UE). The Jebsen Taylor Hand Function Test (JTHFT) was applied to assess hand functions commonly used in activities of daily living (ADL). Subjects' eye–hand coordination performance was evaluated using fast finger-pointing tasks towards a moving visual signal.

Tactile sensation. A set of Semmes-Weinstein monofilaments was used to test the sensation threshold for fine touch. This is a standard test with high test-retest reliability (14). The monofilament was applied perpendicularly to the patient's skin until the monofilament started to bend and held in that position for approximately 1 s. Subjects were instructed to answer "yes" once they felt the pressure. If no pressure was detected, the procedure was repeated 5 times. The monofilaments were applied in descending order of stiffness until the subject no longer felt the stimulus. The previous filament was then applied again to reconfirm the sensory threshold.

Handgrip strength. The Jamar dynamometer was used to measure grip strength, which is reported to have a close association with general upper limb strength (15). Subjects were instructed to squeeze the dynamometer as hard as possible 5 times, with a rest period of 20 s provided in between to reduce the effects of fatigue.

Motor recovery. The FMA (1975 version) (16) is a measure of motor recovery after impairment for adults with hemispheric brain damage. Since this study investigated only upper limb function, only the FMA-UE was conducted. FMA is a standardized test with high inter-rater and test–retest reliability (17). The FMA-UE contains 24 items, with all items rated on a 3-point ordinal scale.

Hand function. The JTHFT is a standardized test with high intra-tester ($r=0.85$; $p>0.05$) and inter-tester reliability (intraclass correlation coefficient ranging from 0.82 to 1.00) (18). It is designed for adults with neurological or musculo-skeletal conditions involving hand disabilities. The test items include a range of fine motor, weighted and non-weighted hand function activities: (*i*) writing (copying) a sentence, (*ii*) turning over 3 × 5 cards, (*iii*) picking up small common objects such as a paper clip, bottle cap and coin, (iv) simulated feeding using a teaspoon and 5 kidney beans, (*v*) stacking checkers, (*vi*) picking up large light objects (empty tin cans), and (*vii*) picking up large heavy objects (0.5 kg tin cans) (21). The time to complete each task was recorded in seconds. The affected hand was tested first. Subjects were allowed a maximum of 180 s to complete each sub-test. If the subject could not complete the task within the time allowed, 180 s was taken as the completion time to avoid fatigue.

Eye–hand coordination. Eye–hand coordination performance was measured with a fast finger-pointing task towards a moving visual signal on a display unit (Clear Tek 3000 LCD screen, MicroTouch Systems Inc., Methuen, USA) appearing from the side contralateral to the arm being tested at a speed of 12 cm/s. The visual signal was a black circular target 1.2 cm in diameter.

The subject was seated comfortably in a non-rotating chair in front of the display unit. Their hands rested in a fixed position on the table with the elbow, hip and knee joints positioned at approximately 90º and the ankle joints in a neutral position. Foot and arm rests, when necessary, were allowed. The subject's upper trunk was stabilized by strapping it to the chair with a Velcro belt to prevent compensation of the trunk (19). As the aim was to measure electromyographic (EMG) response in the arm muscles only, any trunk movement was to be avoided.

A warning sound was given by the computer through the headphone 2 seconds before the visual signal appeared, in order to keep the subjects alert during the tests. However, some of the auditory signals were counterfeits to discourage anticipation. Instruction and familiarization trials were given before the testing began.

The affected side was tested first. During the test, the subjects were required to touch the moving visual signal appearing from the contralateral side for 10 trials. After 1 min rest, another 10 trials were conducted. Recorded encouragements, "fast and accurate" were delivered by the instructor in the middle of each set to counter any reduction in attention span.

EMG recordings

Surface electrodes were used to record EMG activities in the subjects' anterior deltoid of the tested hand. The electrode (B&L Engineering Division of Pinsco Inc., CA, USA) was positioned with electrolyte gel and adhesive tape in line with the muscle, as recommended by Cram & Kasman (20). EMG signals were recorded at a total gain of 320 times, total input impedance of >100 Megaohms, and with a bandwidth of 12–3000 Hz. The signals were sampled at 1000 Hz and stored for off-line analysis using an analogue to digital conversion card (National Instrument NI DAQCard-6024E). The EMG signals were processed using the LabView software suite (National Instrument, Texas, USA). The signals were full-wave rectified and smoothed using a second-order Butterworth low pass filter with a cut-off frequency of 10 Hz. The onset of muscle activity was identified as the point where the EMG signal fired and deviated more than 3 SD from the baseline. The point was determined using a tailor-made LabView software program, but was checked visually.

Outcome measures

The 3 outcome measures were reaction time, movement time and accuracy. Reaction time was the time between the appearance of the visual signal on the screen and the onset of EMG response. Movement time was defined in the present study as the time from the onset of the EMG response to touching the visual signal, which included the time for muscle torque generation to complete the pointing task. By convention, EMG movement time is defined as the interval from the onset to the end of the EMG signal. Because subjects with stroke showed longer biomechanical delay due to the neuromuscular dysfunctions (8–10), we included the time for generating the muscle torque required to complete the pointing task for comparison of the movement time between the subjects' affected and unaffected hands. Accuracy was defined as the absolute deviation of the subject's touching position from the centre of the visual signal.

Statistical analysis

In 2008, Chan (22) demonstrated that hand dominance does not influence performance in tests of fast finger-pointing towards moving targets in healthy older subjects. Therefore, hand dominance was not treated as a co-variate in the statistical analyses.

Paired *t*-tests were conducted to check for any influence of differences in the subjects' arm lengths. Arm length could be treated as a co-variate in the data analyses if significant differences were found. Paired t-tests were also conducted to compare the 3 outcome measures in the fast finger-pointing test (reaction time, movement time and accuracy) between the subjects' affected and unaffected hands.

Correlations between the 3 outcome measures in the fast finger-pointing test and sensori-motor impairment results were then conducted, using parametric and non-parametric statistical tests, depending on the nature of data. Pearson's product-moment coefficient of correlation was used to analyse the correlation between the outcome measures of the fast finger-pointing test and grip strength in the affected hand. Spearman's rank correlation coefficient was used to analyse the correlation between the 3 outcome measures and (*i*) tactile sensation, (*ii*) FMA (including the total score and the sub-test scores) and (*iii*) total JTHFT score. The strength of the correlation is defined by the correlation coefficient obtained as little or no ($r<0.25$), fair ($r=0.25–0.5$), moderate to good ($r=0.5–0.75$), good to excellent ($r>0.75$) relationship (23). The level of significance (α) was set at 0.05 for all statistical analysis. The data were analysed with the help of the SPSS software package (Windows statistical software, version 16.0, SPSS, Inc., Chicago, IL, USA).

RESULTS

Subjects

Fifteen subjects with stroke were recruited after screening, and their demographic data are shown in Table I. There was no significant difference in arm length between the participants' affected (mean = 68.8 cm (SD 2.2)) and unaffected sides (68.5 cm (SD 2.2); $p=0.315$)

Eye–hand coordination. Table II shows that there were statistically significant differences in movement time ($p<0.001$) and accuracy ($p=0.002$) between the affected hand and unaffected hand in the fast finger-pointing test, but there was no significant difference in reaction time. Consequently, subsequent analyses focused on correlations of movement time and accuracy with other parameters.

Correlations between movement time and sensori-motor impairment. Pearson's product-moment coefficient of correlation showed that there was statistically significant correlation between movement time and handgrip strength ($r=–0.687$, $p<0.01$; Table III) in the subjects' affected hands. The relationship was considered moderate to good. Spearman's analysis showed a statistically significant correlation between movement time and tactile sensation in the affected hand ($r_s=0.604$, $p<0.05$). Significant correlations were also found between the total FMA scores and movement time of the corresponding side using Spearman's analysis ($r_s=–0.524$, $p<0.05$). In the FMA sub-tests, movement time and wrist control (FMA Part VI) showed significant correlation ($r_s=–0.747$, $p<0.01$), while close to significant correlations between movement time and mixing synergies (FMA Part III) ($r_s=–0.507$, $p=0.054$), and coordination (FMA Part VIII) ($r_s=–0.507$, $p=0.053$) were found. Significant correlation was found between movement time and tremor (FMA Part VIII) ($r_s=–0.571$, $p<0.05$), while close to significant correlation was found between movement time and speed ($r_s=–0.507$, $p=0.054$).

Correlations between accuracy and sensori-motor impairment. Pearson's product-moment coefficient of correlation showed that there was no statistically significant correlation between accuracy and handgrip strength.

Table I. Demographic data of the subjects after stroke ($n=15$)

Characteristics	
Gender (M/F), *n*	9/6
Age, years, mean (SD)	62.5 (7.1)
Height, cm, mean (SD)	158.7 (11.2)
Weight, kg, mean (SD)	63.1 (12.9)
Hand dominance right/left, *n*	15/0
Stroke side, right/left, *n*	4/11
Arm length, cm, mean (SD)	
Unaffected side	68.5 (2.2)
Affected side	68.8 (2.2)
Visual problem, yes/no, *n*	0/15
Shoulder or arm pain, yes/no, *n*	0/15
Type of stroke (haemorrhagic/ischaemic), *n*	6/9
Years since stroke, mean (SD)	5.2 (3.0)

SD: standard deviation.

Table II. *Reaction time, movement time and accuracy during the fast finger-pointing task*

	Unaffected hand Mean (SD)	Affected hand Mean (SD)	*p*
Reaction time, ms	406.1 (124.0)	403.5 (66.5)	0.919
Movement time, ms	672.9 (217.0)	1083.73 (332.5)	<0.001†
Accuracy, mm	9.0 (1.2)	17.9 (2.1)	0.002*

*Significant at the p < 0.01 (†$p<0.001$) level.
SD: standard deviation.

Table III. *Correlations between movement time and accuracy in the fast finger-pointing task with handgrip strength, tactile sensation and Fugl-Meyer score (FMA) (total score and sub-tests scores) in the affected hand of subjects after stroke*

	Correlations with movement time of the affected hand (*p*-value)	Correlations with accuracy of the affected hand (*p*-value)
Hand grip strength#	–0.687 (0.005**)	0.080 (0.777)
Tactile sensation†	0.604 (0.017*)	0.555 (0.032*)
FMA total score†	–0.524 (0.045*)	–0.590 (0.021*)
FMA Subtests†		
Part I: Reflexes	0.483 (0.068)	–0.092 (0.744)
Part II: Flexor & Extensor Synergy	–0.312 (0.258)	–0.334 (0.224)
Part III: Mixing Synergies	–0.507 (0.054)	–0.429 (0.111)
Part IV: Out of Synergy	–0.396 (0.143)	–0.473 (0.075)
Part VI: Wrist Control	–0.747 (0.001**)	–0.593 (0.020*)
Part VII: Hand	–0.491 (0.063)	–0.358 (0.190)
Part VIII: Coordination	–0.507 (0.053)	–0.396 (0.144)
Tremor	–0.571 (0.026*)	–0.443 (0.098)
Dysmetria	0.206 (0.461)	–0.078 (0.781)
Speed	–0.507 (0.054)	–0.054 (0.849)

#Pearson's product-moment coefficient of correlation.
†Spearman's rank correlation coefficient.
*$p<0.05$, **$p<0.01$.

Table IV. *Correlation between Jebsen Taylor Hand Function Test (JTHFT) total score and performance of the affected hand in terms of reaction time, movement time and accuracy in fast finger-pointing*

	Correlation with JTHFT (total score)	*p*-value
Reaction time	0.518	0.048*
Movement time	0.661	0.007†
Accuracy	0.196	0.483

*$p<0.05$, †$p<0.01$.

Spearman's analysis revealed a statistically significant correlation between accuracy and tactile sensation ($r_s=0.555$, $p=0.032$; Table III) in the subjects' affected hands. The relationship was moderate to good.

Significant correlations were also found between total FMA score and accuracy on the corresponding side ($r_s=-0.590$, $p<0.05$). In the FMA sub-tests, only wrist control (FMA Part VI) showed significant correlation with accuracy ($r_s=-0.593$, $p<0.05$) and the relationship moderate to good.

Correlation between JTHFT total scores and reaction time, movement time and accuracy. Spearman's analysis revealed statistically significant correlations between total JTHFT scores on the affected side and reaction times ($r_s=0.518$, $p=0.048$; Table IV) as well as movement times ($r_s=0.661$, $p=0.007$), but not with accuracy ($r_s=0.196$, $p=0.483$).

DISCUSSION

The data confirm that eye–hand coordination performance with stroke survivors' affected hands was poorer in terms of increased movement time and lower accuracy than with their unaffected hands. This was in accordance with the results found by Levin (9), who used pointing movements towards stationary targets to study upper extremity control with 10 hemiparetic subjects. Levin's subjects were required to carry out planar arm reaching to 4 static targets in front of them with their trunk stabilized. In all of the hemiparetic subjects in Levin's study, movement times were significantly longer with the affected hand than with the unaffected hand. Our findings confirm this with a moving visual target. As mentioned previously, reaching in daily activities involves not only stationary objects, but moving ones also, making reaching towards moving targets a crucial function of the upper limb.

Levin (9) also found a significant correlation between movement time and the level of motor impairment as measured by the FMA. This also agrees with our present findings. This study has also shown that sensori-motor impairments including impaired tactile sensation, reduced strength, poor wrist control, poor coordination and pathological synergies may contribute to the slower and less accurate movement in fast finger-pointing tasks.

Tactile sensation

Accurate reaching relies on the integration of visual and proprioceptive sensory inputs (24). Tactile information also contributes to position sense during finger-pointing, especially when other proprioceptive sensation is not readily available (6). Proprioception is often impaired after stroke (25). As a result, more reliance may be put on tactile sensation during reaching, because the results showed significant correlations (r = 0.604 for movement time and r = 0.555 for accuracy). If there is a deficit in tactile sensory input, reaching performance is likely to be affected.

Hand grip strength

An inability to activate the agonists adequately may contribute to the poorer performance of the paretic arm. Zackowski et al. (11) found that peak reaching velocity was influenced by poor strength during reaching in 18 subjects with chronic hemiparesis. McCrea's group (7) also reported that insufficient force generation in the agonist muscles (e.g. anterior deltoid) of the paretic arm would lead to compensatory activation of additional arm muscles (e.g. the lateral deltoid). During their study, McCrea's investigators found increased activation in all the muscles of the paretic arm, contributing to the increased segmentation and longer path lengths they observed in movement trajectories during reaching. This agrees with our findings that handgrip strength, which is associated with global upper limb strength (17, 26), was significantly correlated with the movement time ($r=-0.687$).

Wrist control

The data also demonstrated that subjects with poorer wrist control tended to have longer movement times ($r_s=-0.747$) and lower accuracy ($r_s=-0.593$) during the fast finger-pointing test.

The function of visual feedback in pointing and reaching tasks may relate primarily to attaining accuracy (5). Wing & Frazer (27) have suggested that positioning the wrist during reaching may be a way to provide clear visual feedback to guide the movement and help adjust the hand and fingers. Poor control of the wrist (inability to perform wrist extension) may lead to blockage of the visual target and reduced visual feedback, which could result in a longer deceleration phase when reaching and decreased accuracy during the finger-pointing task.

Twitchell (28) suggested that recovery in hemiplegic limbs progresses from proximal to distal muscles. Those having better wrist control may recover better, thus contributing to their better performance in the fast finger-pointing task. Poor wrist control may also relate to impaired muscle strength, especially in the wrist extensors. However, further studies are needed to confirm this relationship.

Coordination

Reisman & Scholz (29) compared the inter-joint coordination of stroke survivors with that of healthy subjects using a finger-pointing task with a static target. They found that inter-joint coordination in the subjects with stroke was disrupted, resulting in more jerky and segmented hand trajectories and longer movement times. Similarly, 2 of the coordination sub-tests in the present study revealed significant correlations with the movement times in the fast finger-pointing task using a moving target: namely tremor (–0.571) and speed (–0.507).

Synergy

Levin (9) reported that hemiparetic subjects have the most difficulty in reaching for contralateral and distant targets. The finger-pointing action in this study also required subjects to reach for a moving target coming from the contralateral side. The action could be divided into 2 phases: (*i*) combined flexion of the shoulder and elbow to lift the arm; (*ii*) an isolated extension of the elbow to reach out and track the moving visual signal. In order to perform the entire task, the subjects had to activate their shoulder flexors while relaxing the elbow flexors. This pattern appears to be more difficult for hemiparetic subjects, possibly owing to "pathological synergy". Certainly in this study movement time was negatively correlated with the mixing synergy ($r=-0.507$; $p=0.054$). Several studies have reported that abnormal coupling of shoulder and elbow torques in the paretic limbs of subjects with stroke was the main factor hindering the motor control of their upper limbs (8).

ADL hand function

Total JTHFT scores were significantly correlated with reaction time ($r=0.518$) and movement time ($r=0.661$). A likely reason is that the JTHFT sub-tests involve a lot of reaching actions (30) such as picking up tin cans. Also, the nature of both tests is of the time domain. The faster the reaction time and movement time of the reaching task as measured by the fast finger-pointing task will enable the subjects to achieve shorter time while performing the JTHFT. Impaired eye–hand coordination may lead to a reduced reaching ability, which may then affect daily hand functions, as shown by the total JTHFT scores. The insignificant correlation with the accuracy of the fast finger-pointing test might be due to the fact that the objects such as bottle cap, coin and tin cans in the JTHFT are stationary, while the visual target in the eye–hand coordination test is moving. Although both tests focus on the visual-spatial domain, the accuracy achieved is different depending on whether the target objects are stationary or moving. It may imply that the test and training of the stroke survivors should include both stationary and moving targets.

Clinical relevance

The findings of this study suggest that tactile sensation, hand grip strength, wrist control, coordination, and synergies are all related to performance in rapid finger pointing towards a moving visual target, which might, in turn, affect the ADL functions of the upper limbs. Rehabilitation aimed at training each of these sensori-motor control elements, for example tactile stimulation (31) and muscle strengthening (32) may improve upper limb ADL function. However, as this current study was only a cross-sectional design, the causal relationships need to be confirmed through further prospective studies.

It should be pointed out that convenience sampling was employed in this research, and all of the participants were community walkers. It is likely that they were among the more active stroke survivors and had a higher level of function. The sample size was small, and anyone with hemianopia or visuo-spatial neglect, which are common deficits following stroke, was excluded. These deficits may affect visual perception, which is an important component in fast reaching and finger-pointing towards a moving target (5). As a result, the findings of this study may apply only to those without visual deficits. There were multiple statistical analyses performed in the correlation study, but no adjustment to the level of significance (α) was made, thus the present results should be interpreted with caution. Moreover, the objective of the present study was to investigate the difference between affected and unaffected upper limbs in stroke survivors. The difference in eye–hand performance between subjects with stroke and age-matched controls in the fast finger-pointing task towards a moving visual target is unknown; further research in this area is ongoing.

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