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Ability to adjust reach extent in the hemiplegic arm

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Abstract

Objective Insufficient information exists about the ability of hemiparetic patients to adjust reach extent during early recovery from stroke. Further knowledge may suggest guidance for therapy intervention. The objective of this study was to investigate the ability of hemiparetic subjects to adjust reach extent within 6 months after stroke.
Design Repeated-measures design experiment with two factors—group and target position.
Setting Physiotherapy department.
Participants Nine hemiparetic and nine age- and gender-matched healthy subjects.
Methods Participants performed 15 reaching movements in the sagittal plane, five to each target of 8, 13 and 18 cm from the starting position.
Main outcome measures Motion analysis was used to collect information on the kinematic variables of distance moved, movement duration, peak velocity, average velocity and the timing of peak velocity. These variables were compared between the different target positions and between groups.
Results The stroke group demonstrated a longer movement duration, lower peak and average velocity, and a later time to peak velocity compared with the healthy group. In response to the change in target position, both groups increased peak velocity for each increase in target position with no significant increase in movement duration, and showed a longer deceleration phase for the 18-cm target position. There was no significant difference between scaling of distance moved and peak velocity to target position between the groups. However, stroke subjects tended to overshoot the closer target and undershoot the more distant targets. The mean difference between groups was 12 mm [95% confidence interval (CI): −17 to 50] for the 8-cm position, 5 mm (95% CI: −34 to 23) for the 13-cm position, and 9 mm (95% CI: −39 to 22) for the 18-cm position. The difference in peak velocity between each target position was smaller in the stroke subjects compared with the healthy subjects. The mean difference between groups was 103 mm/second (95% CI: −171 to −34) for the 8-cm position, 157 mm/second (95% CI: −231 to −82) for the 13-cm position, and 171 mm/second (95% CI: −262 to −80) for the 18-cm position.
Conclusions Some aspects of the movement organisation of stroke subjects were similar to that of healthy subjects. However, stroke subjects showed errors in adjusting reach extent and velocity appropriately for different distances.

Keywords: Upper extremity; Stroke; Motor skills; Hemiplegia

Introduction

Compared with healthy control subjects, the arm movements of patients with stroke show weakness [1], decreased peak velocity [2–4], longer movement duration [2,4], increased segmentation of movement [2,3,5], decreased straightness of the hand path [2,4,5], disrupted interjoint coordination between the shoulder and elbow [3,4,6], abnormal spatial tuning of elbow muscle torque [7] and an increase in variability of kinematic measures [3,5].

One aspect of arm motor control that has been insufficiently investigated in stroke survivors is the ability to adjust reach extent (how far a person can reach away from their body). Previous investigations have highlighted the fact that reach extent is a consistent problem in the arm movement of patients with stroke [2,3,5]. Kamper *et al.* [2] assessed the ability of patients to point to a screen of 75 targets in front of them and 90° to either side. The most consistent finding was that the distance they could achieve was decreased compared with healthy controls, regardless of movement direction. Cirstea and Levin [3] also found that active range of motion at the elbow and shoulder (necessary for reach extent) was decreased compared with healthy controls when

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subjects performed pointing movements across the midline in front of the body. Also, Archambault *et al.* [5] showed that patients with cortical and subcortical lesions demonstrated more errors in movement extent compared with control subjects in pointing movements. One strategy that stroke subjects commonly adopt to compensate for decreased reach extent is to recruit forward movement of the trunk [8,9].

These and other studies of reach-to-grasp in stroke [10] were conducted with patients with relatively longstanding conditions (9 to 120 months since stroke) [2,5]. There is a need to discover whether similar deficits are demonstrated at an earlier stage of recovery because kinematic performance can be significantly different in groups with different levels of impairment [10]. Also, the identification of differences between the stroke population and the healthy population is useful for developing training strategies, because it illustrates the improvements that are necessary to reach normal levels of performance. However, to serve this purpose, the information needs to be available on stroke subjects at an earlier stage of recovery to better reflect the patients that present for therapy. One study [3] examined patients at 2 to 17 months post stroke; however, this study investigated pointing movements, as did the studies by Archambault *et al.* [5], Kamper *et al.* [2] and others (e.g. McCrae and Eng [11]), but did not investigate reach-to-grasp movements. In another study investigating endpoint error (distance between the finger and target at the end of the movement) in an acute group of stroke subjects, it was found that some subjects could not reach objects placed at 90% arm's length [12]; however, this study did not vary the distance reached so does not inform about the ability to adjust reach extent. The conclusions derived from studies of pointing have not yet been investigated in reach-to-grasp movements. Since reach-to-grasp involves motor programming for hand opening and closing in addition to moving the hand forward to the target, it cannot be assumed that movement organisation (see Appendix A) for reach-to-grasp is the same as that for pointing. Reaching to grasp an object is an important movement to study because it is so common in everyday life [13]. Reach-to-grasp movements have been examined in stroke subjects [12,14,15], but not with the explicit aim of examining the nature of movement organisation when the distance of the target position is systematically varied. The purpose of this study was to assess the ability to adjust reach extent in people less than 6 months following stroke.

In this study, reaching movements were to a cup (11-cm high) placed at three different positions in front in the sagittal plane of the body. The positions chosen were within a small range of workspace to suit the less recovered movement abilities of this group compared with previous studies. Their movement organisation was compared with that of healthy control subjects. Preservation of some aspects of normal movement organisation of reach-to-grasp after stroke have been reported for coordination between reach and grasp components [16] and for ability to adapt to environmental perturbations [10]. Therefore, it was hypothesised that there would be some retention of the normal motor plan for adjusting reach extent, but that the execution of the adjustments would be impaired compared with that of healthy subjects. It was also hypothesised that scaling (see Appendix A) of movement distance and peak velocity with target position in stroke would be restricted because previously identified problems in the arm movements of people with stroke, such as decreased range of movement, decreased peak velocity and increased variability of movement, could affect the ability to generate forces that are appropriate for the required distance.

Method

Subjects

Nine patients with a diagnosis of hemiparesis were recruited consecutively from health care of the elderly wards and the physiotherapy outpatient service of one hospital, and were selected according to functional ability and stroke clas-

Table 1
Demographic data and site of lesion for the stroke group.

Subject	Age (years)	Time since stroke (weeks)	Side of lesion (hemisphere)	Bamford	CT scan result
1	87	3	L	PACI	Not performed
2	69	11	R	PACI	Right parietal and left external capsule lacunar infarcts
3	71	0.5	R	TACI	Right-sided infarct
4	89	14	R	PACI	Right anterior parietal infarct
5	73	22	R	TACI	Right thalamocapsular infarct
6	67	4	L	PACI	Multiple lacunar infarcts: deep white matter, right basal ganglia, thalamus, external capsule, corona radiata
7	77	9	R	PACI	Right infarct in middle cerebral artery territory
8	41	21	R	TACI	Right deep temperoparietal intracerebral haematoma, involving right basal ganglia
9	78	4.5	R	TACI	Parietal, cortical and deep white matter infarcts on both sides

CT, computer tomography; PACI, partial anterior circulation infarct; TACI, total anterior circulation infarct.

sification. Diagnosis was confirmed by computer tomography (CT) scan where possible (Table 1).

The following inclusion criteria were used:

(1) A score of 3 to 7 on the arm section of the Rivermead Motor Assessment (RMA) [17]. A score of 3 is described as 'lying, holding extended arm in elevation with some external rotation, the subject is able to flex and extend the elbow' and a score of 7 is described as 'Reach forward, pick up pencil, release on mid thigh on affected side five times'. Patients with this low level of recovery were chosen so that the findings would be relevant to the patients in greatest need of rehabilitation.
(2) A middle cerebral artery infarct (classified by CT scan, or partial anterior circulation infarct or total anterior circulation infarct on the Bamford classification for cerebral infarction if CT not available [18]). These patients commonly have arm impairment and constitute a large number of the patients presenting for rehabilitation.

Time since stroke was 0.5 to 22 weeks. Further details of patient characteristics are shown in Table 2. Muscle tone was assessed using the Modified Ashworth Scale (0 = no increase in muscle tone, 4 = affected part rigid in flexion or extension [19]). Sensation was tested using the Nottingham Sensory Assessment [0 = sensation absent, 2 = normal (light touch, pressure), 3 = normal (kinesthesis)] [20]. Star cancellation [21], Rey figure copy [22] and the Present Pain Index from the McGill pain questionnaire [23] were used to assess neglect, spatial perception and shoulder pain, respectively. None of the patients were apraxic. The use of the side ipsilateral to the hemisphere affected as a control was rejected, as both strength [24] and response to stretch [25] in the ipsilateral arm are different to those of healthy subjects. Therefore, nine healthy control subjects were recruited and matched to the hemiparetic patients for age, gender, and whether their dominant or non-dominant hand was used in the experiment. All healthy subjects were tested on the Ten Hole Peg test, which assesses the ability to perform repeated reach-to-grasp movements [26], and were within the normal range (i.e. normal mean ± two standard deviations). The healthy subject group (two women and seven men) had a mean age of 68.5 years. The hemiparetic group (two women and seven men) had a mean age of 71.4 years. Informed consent was obtained from all subjects according to the Declaration of Helsinki. Ethical approval was granted by Nottingham City Hospital Ethics Committee.

Data collection

Subjects were seated on a height-adjustable chair at a table with their waist touching the table edge in front. Trunk movements were not constrained, in order to reflect a naturalistic task performed in everyday life. Movement was recorded in three dimensions using a MacReflex motion analysis system (Version 2.3, Qualysis, Partille, Sweden). The calibrated workspace measured 90 cm (length) × 60 cm (width) × 125 cm (height). Two cameras with a charge coupled device, infrared flash and automatic gain control were positioned 160 cm above the table, one in front of the subject and one above the subject's shoulder, separated by a distance of 128 cm. These recorded the movement of reflective markers attached to the wrist (radial styloid process), the lateral surface of the index finger (between the distal interphalangeal joint of the finger and the finger nail), and the medial surface of the thumb (between the distal interphalangeal joint of the thumb and the thumb nail). Two on-line video processors calculated the centroid of each marker, and sent two-dimensional coordinates to a Macintosh computer for conversion into three-dimensional coordinates and storage. The '*x*' dimension represented movement in the sagittal plane, the '*y*' dimension represented movement in the coronal plane, and the '*z*' dimension represented movement in the vertical plane. The markers were sampled at 50 Hz. The likelihood of errors occurring in marker identification due to light reflections was reduced by the use of cameras with an electronic shutter with an infrared flash and automatic gain control that suppresses undesirable light sources and reflective markers which are sensitive to infrared light [28]. Harrison *et al.* [27] reported less within-trial variability using the MacReflex system compared with the Watsmart [28] and

Table 2
Stroke subject characteristics.

Subject	Hemianopia	Arm function (Rivermead)	Spasticity			Sensation							
			Elbow	Wrist	Finger	Touch	Press	Kin.	2 pt arm	2 pt finger	Neglect	Spatial ability	Pain
1	N	4	3	0	0	1	1	3	1	0	44	5	0
2	N	3	0	1	1	2	2	1	1	1	50	4.5	0
3	N	4	2	0	1	2	2	3	2	2	54	24	0
4	Y	3	2	3	1	2	1	2	2	1	–[a]	–[a]	0
5	Y	6	1+	1	0	0	0	0	0	0	42	29.5	0
6	N	4	1+	1	1	–[b]	–[b]	–[b]	–[b]	–[b]	50	–[b]	0
7	N	4	1+	0	0	2	2	2	0	1	37	19	2
8	N	8	0	0	1	2	2	3	0	1	49	21	5[c]
9	N	4	0	0	1	2	2	1	1	1	45	23	0

[a] Subject could not be tested for neglect and spatial abilities because he did not have his reading glasses.
[b] Subject could not be tested due to dysphasia.
[c] 'Catching' pain which occurred occasionally in upper arm.

Motion Analysis [29] systems. The mean static and dynamic constant spatial error for this experimental set-up were calculated [30] as 0.58 mm and 0.88 mm, respectively. Variable error for the dynamic test was 0.21 mm.

Procedure

The subjects' task was to reach and grasp a plastic cup with no handle, half-filled with water (height 11 cm, top diameter 7 cm, weight 0.17 kg), placed either 8, 13 or 18 cm anterior to the starting position of the hand, take a sip of water, and replace the cup on the table. The start position of the hand was directly in front of the elbow, and the cup was positioned directly ahead of the hand start position, so movements were in the sagittal plane and no change in shoulder rotation would normally be required to grasp the cup. This was chosen to reflect a naturalistic task performed in everyday life. The task was performed in its entirety but only the reach was analysed. The cups tapered to a slightly narrower base (5.2-cm diameter). Subjects were instructed to grasp the upper portion of the cup so that markers could be seen clearly by the cameras.

The starting position specified that the finger and thumb tips were lightly touching, the forearm was in mid-pronation, the elbow was at approximately 100° flexion and the wrist rested on a marker indicating the start position. The other arm rested in the subject's lap. Subjects were instructed to 'reach forward, pick up the cup (at the top) and have a sip of water, then place the cup on the table'. The computer emitted a tone as a signal for the subject to move. Subjects naturally used their whole hand to grasp the cup.

A practice session occurred prior to the beginning of data collection, in which subjects practised grasping the cup, twice at each target position. There was a 5-minute rest between practice and the start of data collection. Stroke patients with an RMA (arm section) score of 3 find reaching in a seated position difficult, so the number of reach-to-grasp movements was limited to fit their abilities. During data collection, five movements were made to each target position. The 15 trials were randomised to reduce the effects of fatigue and practice on performance. Each of the nine stroke subjects performed the tests in a different random order, and the random order of the control subjects was the same as that of their matched stroke subject.

Data analysis

For each recorded movement, the positions of the markers were identified manually in an editing process for three consecutive frames, after which the markers were automatically tracked through their trajectories using MacReflex software. Automatic tracking was observed on screen, and manual tracking was occasionally used when the software indicated that a marker position did not equate with the approximate position predicted by the programme tracking the marker. Two-dimensional marker positions were then converted into three-dimensional coordinates using MacReflex software. In cases where markers were invisible to the cameras, a cubic spline algorithm was applied to predict the missing values. Data were filtered using a Bartlett filter with 39 coefficients and a cut-off frequency of 10 Hz.

The trajectory, velocity and acceleration of the wrist marker were used to describe the transport component of the reach. Movement onset was determined as the time at which the three-dimensional velocity exceeded 25 mm/second using a Gaussian weighted average (average velocity value was calculated by adding the velocity value at one frame to the values at the two frames before and after the frame and dividing the total by five). The end of transport was defined as the 'first time at which the maximum distance of the wrist marker in the combined x, y (horizontal) plane was achieved'. This was easily identifiable because the xy distance decreased after the maximum distance was achieved, when the hand was brought to the mouth. The z plane was not included in the definition of end of transport, as the task included bringing the cup to the mouth after it had been grasped. Other determinants for the end of transport which have been used in investigations of normal reach-to-grasp, such as the time at which the distance between the thumb and finger markers becomes constant [31] or the time at which the velocity reaches a chosen low velocity or zero value [32], were found to be inappropriate for the functional abilities of the patients with hemiparesis. This was because the patients were occasionally unsuccessful at grasping the cup, and it is common for hemiparetic patients to reach a low or zero velocity during the reach, as their trajectory can occur in a stepwise fashion [33]. Movement duration refers to the time between onset and end of transport. The time to wrist peak velocity and wrist peak deceleration were determined and expressed in absolute and proportional (i.e. as a percentage of movement duration) terms.

Statistical analysis

A statistical comparison between patients and age-matched controls was performed using a repeated-measures analysis of variance (ANOVA) with one between-subject factor (group: stroke, control) and one within-subject factor (target position: 8, 13 or 18 cm). Movements of people with stroke can be more variable than those of healthy subjects, so the distribution of residuals and residual plots were examined to check that the data met the assumptions of constant variance, and both were satisfied. The kinematic variables inserted into this analysis were movement duration, movement distance, peak velocity, average velocity, absolute time to peak velocity and percentage time to peak velocity (expressed as a percentage of movement duration). Post-hoc Newman–Keuls tests were used to determine which conditions were significantly different from one another. The ability to scale distance moved to target position was also compared between the groups using linear regression, and tested for significance using Statistical Package for Social Sciences (SPSS Inc., Chicago, IL, USA). This was repeated for the relationship between peak velocity and target position.

In addition, comparisons were performed within the hemiparetic group data to assess the effect of neglect, spatial perception, pain and increased muscle tone on ability to adjust reach extent, where only part of the group demonstrated these impairments. For each clinical variable, patients were divided into two groups according to whether or not the patients demonstrated the particular clinical deficit. Then, repeated-measures ANOVAs were performed on the kinematic variables with the between-subject factor as presence or absence of the clinical deficit and the within-subject factor as target position.

Results

Distances moved for each of the three conditions were significantly different, as expected ($F_{2,32} = 221.6$, $P < 0.01$). There was a significant interaction between group and target position ($F_{2,32} = 3.7$, $P < 0.05$), indicating that although both groups increased the distance for each subsequent target position, the difference between each distance was larger in the healthy group (see Table 3). Results of the linear regression showed that there was no significant difference between the groups for scaling of actual distance moved to target position ($P = 0.54$). Fig. 1 shows the means and 95% confidence intervals for distance moved, and indicates greater variability in the stroke group.

The movement duration for each target position was not significantly different. However, movement duration was longer for stroke subjects compared with healthy subjects ($F_{1,16} = 15.31$, $P < 0.01$). The interaction between group and target position for movement duration was not significant. Peak velocity increased as target position increased ($F_{2,32} = 44.31$, $P < 0.01$). Peak velocity was greater in healthy subjects compared with stroke subjects ($F_{1,16} = 17.12$, $P < 0.01$). There was a significant interaction between group and target position ($F_{2,32} = 4.81$, $P < 0.05$), indicating that although peak velocity increased as target position increased for both groups, the difference in peak velocity between each target position was larger in the healthy group (see Table 3). There was no significant difference between the groups for scaling of peak velocity to target position ($P = 0.401$, Fig. 2).

Table 3
Means and standard deviations of kinematic parameters. Time to peak velocity represents absolute time from movement onset. Time to peak velocity is also expressed as percentage of total movement duration.

	8 cm		13 cm		18 cm	
	Mean	SD	Mean	SD	Mean	SD
Distance moved (mm)						
Healthy	80	9	128	11	176	13
Stroke	93	40	123	39	168	42
Movement duration (mseconds)						
Healthy	1310	340	1330	380	1350	360
Stroke	4110	2630	5000	2850	5160	2760
Peak velocity (mm/second)						
Healthy	242	72.7	325	72	384	94
Stroke	139	65	168	77	213	88
Average velocity (mm/second)						
Healthy	68	21	107	34	141	38
Stroke	35	22	37	26	46	30
Time to peak velocity (mseconds)						
Healthy	500	160	490	270	380	70
Stroke	1750	1470	1110	820	1440	1020
Time to peak velocity (%)						
Healthy	36	10	32	8	29	4
Stroke	41	14	29	15	26	13

SD, standard deviation.

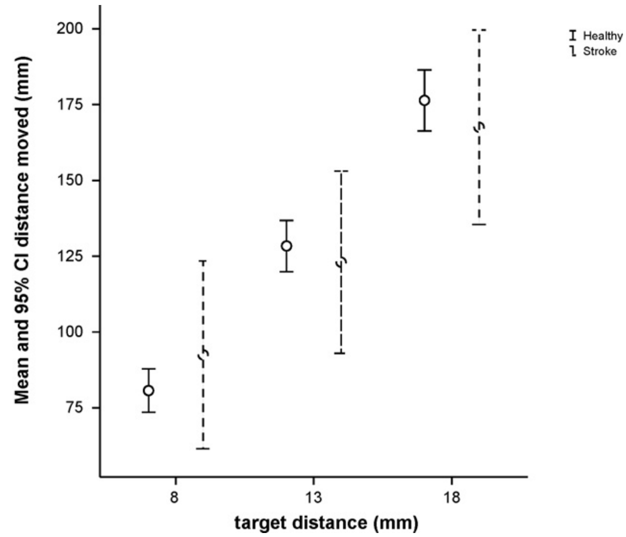

Fig. 1. Mean distance moved with 95% confidence intervals (CI) for control and stroke subjects for reaching movements to the 8-, 13- and 18-cm target positions.

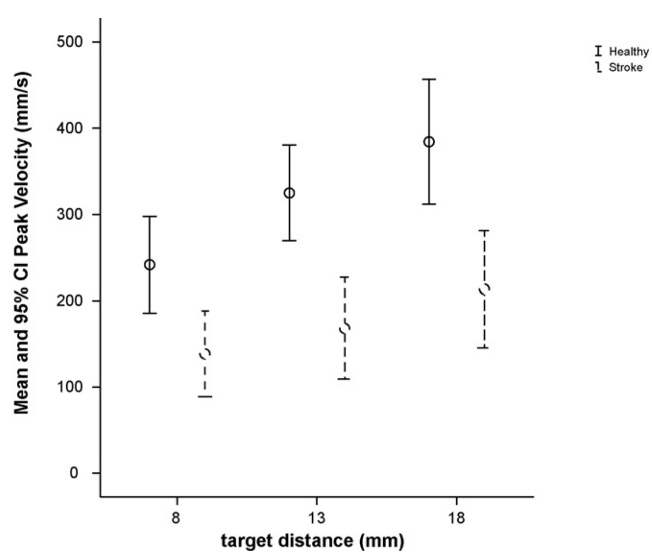

Fig. 2. Mean peak velocity of the wrist with 95% confidence intervals (CI) for control and stroke subjects for reaching movements to the 8-, 13- and 18-cm target positions.

Average velocity increased as target position increased ($F_{2,32}$ = 40.99, P < 0.01); however, average velocity was lower for stroke subjects ($F_{1,16}$ = 27.59, P < 0.01). There was a significant interaction between group and target position ($F_{2,32}$ = 22.16, P < 0.01), showing that the healthy group increased average velocity significantly as target position increased, but that in the stroke group, although the average velocity increased, the differences were not statistically significant (see Table 3).

There was no difference in time to peak velocity for target position. Absolute time to peak velocity was later in the stroke subjects compared with the healthy subjects ($F_{1,16}$ = 9.17, P < 0.01). The interaction between group and target position for time to peak velocity was not significant.

Percentage time to peak velocity occurred significantly earlier for the 18-cm position compared with the other two positions ($F_{2,32}$ = 5.64, P < 0.01), but there was no difference between the 8- and 13-cm positions. There was no difference between the groups for percentage time to peak velocity. The interaction between group and target position for percentage time to peak velocity was not significant.

The entire stroke group had impairment of spatial perception and sensation, and increased tone (Table 2). Four patients in the group had neglect and two reported pain. There was no significant difference in any of the kinematic variables (distance moved, movement duration, peak velocity, average velocity, time to peak velocity and percentage time to peak velocity) between the subjects with or without pain. Similarly, there was no significant difference for these variables between the subjects with or without neglect.

Discussion

Similarities between the stroke and healthy groups

In this study, healthy subjects showed no significant change in movement duration for different target positions. Time to peak velocity did not change significantly between the different target positions. The adjustments made for increase of position were to increase the peak velocity and to lengthen the deceleration phase, which was longer for the 18-cm position, indicated by the earlier percentage time to peak velocity. The stroke subjects showed some similarities in movement organisation, with no significant difference in movement duration for all target positions, and no significant change in time to peak velocity between target positions. The adjustments of increasing peak velocity and a longer deceleration phase for the 18-cm position were also similar.

Differences between the stroke and healthy groups in distance moved

There was a smaller difference between the three distances actually moved by stroke patients, i.e. there was a tendency to overshoot the closer target and undershoot the more distant targets. No significant difference between groups was evident in subjects' ability to scale distance moved to target position in the linear regression analysis. This finding suggests that the stroke group can scale distance moved to target position appropriately, but are unable to produce appropriate force commands, or sufficient force for more distant targets, compared with the healthy group (discussed further below). The considerable variability within the stroke group for distance moved should be noted. This indicates that this study's conclusions about distance moved need corroboration by a future study with a larger sample size.

Differences between the stroke and healthy groups in peak and average velocity

There was a smaller difference in the adjustment in peak velocity and average velocity between the three distances in the stroke group compared with the healthy group. It was hypothesised that this may be attributable to reduced ability to scale these factors for target position. However, there was no significant difference in the relationship between peak velocity and target position between the groups in the linear regression analysis, indicating that the stroke group were able to scale peak velocity to target position. The variability of the two groups for this parameter was similar (Table 3 and Fig. 2). Therefore, the findings for peak velocity are interpreted as an indication that scaling is intact, but there is difficulty with producing sufficient force, or appropriate force commands, to increase peak velocity sufficiently for the more distant targets. The scaling of peak velocity corresponds with a previously identified mechanism for controlling movement extent—pulse-height control [34] (see Appendix A), which is thought to reflect pre-planning of the movement. This scaling of peak velocity to movement extent has also been demonstrated by Sainburg and Schaefer [34] for single-joint elbow extension movements in healthy subjects. Three reasons for the smaller magnitude of peak and average velocity for the more distant target positions have been hypothesised. The first is that these difficulties are likely to be caused by the weakness [24] and underactivation of muscle groups [6,35,36] typical after stroke, which would limit the ability to achieve higher peak velocities. The time at which peak velocity occurred was delayed compared with the healthy subjects, which could also reflect underactivation. Another possibility is the presence of increased neuromotor noise after stroke [11]. Noise is present in all parts of the nervous system and can reduce the capacity to transmit information [11]. McCrae and Eng [11] found evidence that the reaching performance of stroke subjects is adversely affected by noise in both the execution of movement, where 'motor commands are sent to the muscles so the movement is actually made' [11], and the planning of arm movement. Thirdly, the accuracy requirements of grasping a cup of water are likely to present greater difficulty for stroke subjects than healthy subjects, thus causing slowness of movement in stroke subjects, in line with the speed–accuracy trade-off known to exist in the control of reaching [37].

Comparison with previous studies of reach extent

The present results for healthy subjects agree with findings from previous studies by Kudoh *et al.* [38] and Gentilucci *et al.* [39]. However, these studies also found a longer movement duration and later time to peak velocity for the more distant targets; these results were not apparent in the present study or a previous study by Jeannerod [40]. Since those tasks involved longer distances and smaller objects than the present study, it is possible that these factors are responsible for the differences between studies. A further difference was the age of the subjects; earlier studies recruited university students, whereas the mean age was 68.5 years in the present study. Earlier studies of pointing highlighted differences between the reach extent of healthy and stroke subjects, with decreased active range of motion and increase in endpoint error (distance between final endpoint position and the target) in the stroke subjects [2,3,5]. The distances in these studies explored a larger workspace, whereas subjects in the current study were reaching to closer targets. The present study adds to this knowledge about endpoint error in stroke subjects, as it demonstrates an increase in endpoint error in stroke subjects compared with healthy subjects, at closer targets than those used in previous studies.

A more recent study on acute stroke subjects [12] reported no statistically significant differences in endpoint error between stroke and control subjects, although some acute stroke subjects were unable to reach as far as the target object placed at 90% arm's length. A further study found that chronic stroke subjects were unable to reach an object placed at 90% arm's length in the ipsilateral workspace, attributable to difficulty performing shoulder abduction combined with elbow extension, although they could reach the same distance in the midline [14]. Investigation of reach-to-grasp in different directions, where the distance is varied systematically, is warranted to elucidate how direction affects the movement organisation employed over different distances.

To explain the process by which the brain applies an optimisation principle to choose the best trajectory for reaching from many possible trajectories, Tanaka *et al.* [41] proposed a model whereby the brain tries to minimise movement duration under the constraint of meeting the accuracy requirement particular to the task and context. This differs from other optimisation models [42,43] which assume that movement duration is known before optimisation begins. The model predicts a scaling relationship between peak velocity and distance of target. This relationship was demonstrated by both healthy and stroke subjects in this study, suggesting that this optimisation principle in programming may be preserved in stroke patients.

Of the clinical characteristics measured, six of the nine stroke subjects demonstrated increased tone in the elbow flexor muscles, which could have impeded the ability to reach forwards. Only three subjects showed normal kinesthesis, although one could not be tested, so it is possible that an impaired ability to utilise proprioceptive information influenced the ability to reach. It should be noted that the presence of these clinical characteristics may have an influence on reach extent that was not detected in this study because of the small number of subjects.

A limitation of this study is that the number of subjects was not extensive. A study with a greater number of subjects would be desirable given the large standard deviations found for some movement parameters (distance moved, movement duration and time of peak velocity). However, increased variability of movement performance is characteristic of the stroke population, especially at this early stage of recovery [33,44]. Also, other movement parameters used in this study (peak and average velocity) demonstrated smaller standard deviations, and in some cases these were lower than in the healthy group (Table 3). The authors aimed to reduce variability by selecting a homogenous group for time since stroke, level of motor impairment and site of lesion. This study provides preliminary data to inform hypotheses for future studies which would aim to elucidate aspects of movement deficit which could be targeted by specific rehabilitation strategies.

Implications

Previous research has shown that movement patterns of people with stroke can be improved with training [45]. Knowledge of the differences between the performance of the person with stroke and 'normal' performance can be exploited to guide the content of training, thereby facilitating the learning of more 'normal' movement kinematics. The finding that there was a tendency to overshoot the closer target and undershoot the more distant targets suggests guidance for therapy. It is hypothesised that systematic practice of reaching to objects arranged at varying distances from the body could be beneficial. This would give the person the opportunity to practice and improve their ability to adjust reach extent for different distances, and to produce peak and average velocities appropriate for the distance.

Trunk restraint has recently been demonstrated as a successful method to increase reach extent in patients with more severe arm impairment [46]. The application of trunk restraint deserves further investigation to assess its effect on the movement organisation of reach-to-grasp where both distance of target and direction of movement are varied.

To conclude, this group of subjects with stroke showed some similar spatio-temporal movement organisation to that of control subjects, but they showed errors in adjusting reach extent and velocity appropriately for different distances.

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Conflict of interest: The sponsors of the study had no involvement in the study design; the collection, analysis and interpretation of data; writing of the manuscript; and in the decision to submit the manuscript for publication.

Appendix A. Glossary

Movement organization: Planning and execution of the movement by the central nervous system.

Scaling: Ability to scale, or grade, forces appropriate to the metrics of the task.

Pulse-height control: Peak value of the initial acceleration pulse in the acceleration profile of a movement.

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