Title: Ability to adjust reach extent in the hemiplegic arm

Article Type: Original Research

Keywords: upper limb; stroke; motor control; reach-to-grasp; reach extent

Authors: Paulette M van Vliet, PhD; Paulette van Vliet, PhD; Martin R Sheridan, PhD

Physiotherapy, Volume 95, Issue 3 , Pages 176-184, September 2009. doi:10.1016/j.physio.2009.03.004

Abstract

Background: 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.

Objective: To investigate the ability to adjust reach extent in hemiparetic subjects within 6 months after stroke.

Methods: In a repeated measures design experiment with two factors (group, target position), nine hemiparetic and nine age and gender matched healthy subjects performed 15 reaching movements, 5 to each target of 8, 13 and 18 cm from the starting position. 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 to 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. Scaling of distance moved and peak velocity to target position was not significantly different to healthy subjects. However, the distance moved, peak velocity and average velocity adjustments for each target position were significantly smaller in the stroke group.

Conclusions: Some aspects of spatio-temporal movement organisation were preserved in stroke patients when adjusting reach-to-grasp for different target positions but the magnitude of their adjustments was reduced.

* Manuscript (without Author details)

Introduction

Compared to healthy control subjects, the arm movement of patients with stroke show weakness [1], a decreased peak velocity [2 3 4], a longer movement duration [2, 4], increased segmentation of movement [2 3 5], decreased straightness of the hand path [2 5 4], 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 90º to either side. The most consistent finding was that the distance they could achieve was decreased compared to healthy controls, regardless of movement direction. Cirstea and Levin [3] also found active range of motion at the elbow and shoulder (necessary for reach extent) was decreased compared to healthy controls when 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 to control subjects in pointing movements. One strategy 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 relatively chronic patients (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. To serve this purpose however, 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 2-17 months after stroke, however this study investigated pointing movements as did those carried out 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% arms' length [12], however this study did not include a distance manipulation. 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 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 [14 15 16], but not with the explicit aim of examining the nature of movement organisation when the distance of target position is systematically varied.

The purpose of this study was to assess the ability to control movement distance in people less than 6 months after stroke.

In this study, reaching movements were to a cup placed at three different positions in front, in the sagittal plane of the body. The positions chosen were within a small range of work space to suit the less recovered movement abilities of this group compared to previous studies. Their movement organization was compared to 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 [17] and for ability to adapt to environmental perturbations [10]. Therefore we 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 to that of healthy subjects. We hypothesised that scaling of movement distance and peak velocity with target position in stroke would be restricted because of previously identified problems in the arm movements of people with stroke such as weakness, decreased peak velocity and increased variability of movement .

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 classification. Diagnosis was confirmed by CT scan where possible (Table 1).

(Table 1 near here)

The following inclusion criteria were used: 1) A score of between 3 and 7 on the arm section of the Rivermead Motor Assessment (RMA) [18]. 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 most need of rehabilitation 2) A middle cerebral artery infarct (classified by CT scan or as PACI or TACI on the Bamford classification for cerebral infarction if CT not available [19]). 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 after stroke. 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 [20]). Sensation was tested using the Nottingham Sensory Assessment (0 = sensation absent, 2 = normal (Light touch, pressure), 3 = normal (kinesthesis)) [21]. Star cancellation [22], Rey figure copy [23] and the Present Pain Index from the McGill pain questionnaire [24] 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 [25] and response to stretch [26] in the ipsilateral arm are different to that of healthy subjects. Therefore, nine healthy control subjects were recruited and matched to the hemiparetic patients for age, sex, and whether their dominant or non-dominant hand was used in the experiment. All healthy subjects were within normal range (i.e. normal mean + two standard deviations) on the Ten Hole Peg test [27]. The healthy subject group (2 women and 7 men) had a mean age of 68.5 years. The hemiparetic group (2 women and 7 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 the Nottingham City Hospital Ethics Committee.

(Table 2 near here)

Data collection

A repeated measures design with two factors (group, target position) was used. Subjects were seated on a height-adjustable chair at a table with their waist touching the table edge in front. Movement was recorded in three dimensions using a MacReflex motion analysis system [28]. The calibrated workspace measured 90 cm long by 60 cm wide and 125 cm high. Two cameras with charge coupled device, infrared flash and automatic gain control were positioned above the subject, one in front and one above the shoulder. 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 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 [29]. Harrison et al [29] report less within trial variability using the MacReflex system in comparison to the Watsmart [30] and Motion Analysis [31] systems. The mean static and dynamic constant spatial error for this experimental set-up were calculated [32] as 0.58mm and 0.88mm respectively. Variable error for the dynamic test was 0.21mm.

Procedure

The subjects' task was to reach to a plastic cup with no handle, half-filled with water (height 11 cm, top diameter 7cm , weight 0.17 kg), placed either 8, 13 or 18 cm anterior to the starting position of the hand, then take a sip of water, and replace on the table. 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). So that markers could be clearly seen by the cameras, subjects were instructed to grasp the upper portion of the cups.

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 degrees 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 the whole hand to grasp the cup.

A practise session occurred prior to the beginning of data collection, in which subjects practised grasping the cup, twice at each target position. There was a five minute rest between practice and the start of data collection. Stroke patients with a 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 total 15 trials were randomised to reduce effects of fatigue and practice on performance. Each of the nine subjects with stroke performed 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 thirty-nine coefficients and with 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.sec $^{-1}$ 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'. The z plane was not included as the task included bringing the cup to the mouth after grasp. 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 [33] or the time at which the velocity reaches a chosen low velocity or zero value [34] 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 [35]. 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 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 that of healthy subjects, so the distribution of residuals and residual plots were examined to check 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 (TPV) and percentage time to peak velocity (%TPV) (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 (in SPSS). 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 2 groups according to whether 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 hemiparesis and the within subject factor as target position.

Results

Distance moved for each of the three conditions were significantly different, as expected ($F_{2,32}$=221.6, p<0.01). Analysis indicated that there was a significant interaction for group x target position ($F_{2,32}$=3.7, p<0.05) and a post-hoc Newman-Keuls test revealed that although both groups increased the distance as required, the difference between each distance was larger in the healthy group (see Table 3). There was no significant difference between the groups for the relationship between target position and actual distance moved (p=0.54). Figure 1 shows the means and 95% confidence intervals for distance moved. These were considerably larger for the stroke group compared to the healthy group.

The movement duration for each target position was not significantly different. However, movement duration was longer for stroke subjects compared to 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 was greater as target position increased ($F_{2,32}$=44.31, p<0.01). Size of peak velocity was greater in healthy compared to stroke subjects ($F_{1,16}$=17.12, p<0.01). There was a significant group x target position interaction ($F_{2,32}$=4.81, p<0.05), with post-hoc analysis showing that although for both groups peak velocity increased as target position increased, 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 the relationship between target position and peak velocity (p=.401, Figure 2).

TABLE 3 ABOUT HERE

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 of group x target position ($F_{2,32}$=22.16, p<0.01) with post-hoc analysis revealing that the healthy group significantly increased average velocity 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 to 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 between the 18cm position and the other two positions ($F_{2,32}$=5.64, p<0.01) but there was no difference between the 8cm 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 group had impairment of spatial perception and sensation, and increased tone (Table 2). A portion of the group had neglect and pain. The effects of neglect and pain on ability to adjust reach extent were examined statistically. There was no significant difference between the subjects with or without pain. There was also no significant difference between the subjects with or without neglect.

Discussion

In this experiment, healthy subjects did not change the movement duration for different target positions. Time to peak velocity did not change significantly over 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 %TPV. The stroke subjects showed some similarities in movement organisation, with no difference in movement duration for all target positions, and no change in time to peak velocity between target positions. The adjustments of increasing size of peak velocity and a longer deceleration phase for the 18 cm position were also similar.

There were some differences compared to the healthy group, however. The main difference concerning the comparison of distance moved was that in the stroke group, the magnitude of the adjustment for each position was smaller than in healthy subjects. Thus, there was a smaller difference between the three distances actually moved by stroke patients. No significant difference between groups was evident in the 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 sufficient force, or appropriate force commands, for further away targets, compared to the healthy group (this is discussed further below). It should be noted that the larger variability demonstrated in movement distance by the stroke group may hide some residual abnormal scaling behaviour.

The adjustment in size of peak velocity and average velocity were also of a smaller magnitude in the stroke group . We hypothesised that this may be attributable to a 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 were similar (Table 3, Figure 2). Therefore, we interpret the findings for peak velocity as an indication that scaling is intact, but there is a difficulty with producing sufficient force, or appropriate force commands, to increase peak velocity sufficiently for the further targets. The scaling of peak velocity corresponds to a previously identified mechanism for controlling movement extent – pulse-height control [37] which is thought to reflect preplanning of the movement. This scaling of peak velocity to movement extent has also been demonstrated by Sainburg and Schaefer [37] for single-joint elbow extension movements in healthy subjects. We hypothesise two reasons for the smaller magnitude of peak and average velocity for the further target positions. The first is that these difficulties are likely to be caused by the weakness [25] and underactivation of muscle groups [38 39 40] typical after stroke which would limit the ability to achieve higher peak velocities. The time at which peak velocity occurred was delayed compared to 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.

The present results for healthy subjects agree with findings from previous studies by Kudoh et al [41] and Gentilucci et al [42]. However, these studies also found a longer movement duration, later time to peak velocity; results not apparent in this or a previous study by Jeannerod [43]. Since those tasks involved longer distances and smaller objects than in 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, since earlier studies recruited university students, compared to a mean age of 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. In our study, there was a significantly smaller difference between each target position in the stroke group and there was increased variance in distance moved in stroke patients (see standard deviations in table 3), suggesting that final position error (3-D distance from target) does not remain intact for these closer targets also.

An additional more recent study on acute stroke subjects [12] reports 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 a group of chronic stroke subjects was 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, though they could reach the same distance in the midline [14]. Investigation of reach-to-grasp in different directions, where the distance is systematically varied, is warranted to elucidate how direction affects the movement organisation employed over different distances.

To explain the process by which the brain applies an optimization principle to choose the best trajectory for reaching from many possible trajectories, Tanaka et al [45] have proposed a model whereby the brain tries to minimize movement duration under the constraint of meeting the accuracy requirement particular to the task and context. This differs from other optimization models [46 47] which assume that movement duration is known before optimization 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 optimization principle in programming may be preserved in stroke patients.

Regarding the clinical characteristics measured, six out of the nine stroke subjects demonstrated increased tone in the elbow flexor muscles, which could have impeded the ability to reach forward. 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.

A limitation of this study is that the number of subjects is not extensive. A study with larger numbers 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 earlier stage of recovery [35 44]. Also other movement parameters used in this study (peak and average velocity) demonstrated smaller standard deviations, in some cases being lower than the healthy group (Table 3). We also aimed to reduce variability by selecting a homogenous group with regard to time since stroke, level of motor impairment and site of lesion.

Implications

Previous research has shown that movement patterns of people with stroke can be improved with training [48]. 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 the magnitude of the adjustments for different distances was reduced suggests guidance for therapy. It is hypothesized that therapy directed towards generating the appropriate amount of force for different distances could be beneficial. Initially, strategies to increase force generation in underactive muscles could be attempted to increase the ability to reach larger distances. This could be followed by practice where the distance the patient is required to reach is systematically varied to improve the ability to adjust reach extent.

Trunk restraint has recently been demonstrated as a successful method to increase reach extent in patients with more severe arm impairment [49]. 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, however the magnitude of their adjustments for different distances was reduced.

Ethical approval

Ethical approval was granted by Nottingham City Hospital Ethics Committee

Acknowledgements

This work was conducted with the assistance of a research bursary from the Stroke Association and a grant from the Physiotherapy Research Foundation. The sponsors of the study had no involvement in study design, in the collection, analysis and interpretation of data; in writing of the manuscript; and in the decision to submit the manuscript for publication.

Conflict of interest statement

There are no conflicts of interest.

References

1. Chae J, Yang G, Park B, Labitia I. Muscle weakness and cocontraction in upper limb hemiparesis: relationship to motor impairment and physical disability. *Neurorehabilitation and Neural Repair.* 2002;16:241-248.

2. Kamper DG, McKenna-Cole AN, Kahn LE, Reinkensmeyer DJ. Alterations in reaching after stroke and their relation to movement direction and impairment severity. *Archives of Physical Medicine and Rehabilitation.* 2002;83:702-707.

3. Cirstea MC, Levin MF. Compensatory strategies for reaching in stroke. *Brain.* 2000;123:940-953.

4. Levin MF. Interjoint coordination during pointing movements is disrupted in spastic hemiparesis. *Brain.* 1996;119:281-293.

5. Archambault P, Pigeon P, Feldman AG, Levin MF. Recruitment and sequencing of different degrees of freedom during pointing movements involving the trunk in healthy and hemiparetic subjects. *Experimental Brain Research.* 1999;126:55-67.

6. Zackowski KM, Dromerick AW, Sahrmann SA, Thach WT, Bastina AJ. How do strength, sensation, spasticity and joint individuation relate to the reaching deficits of people with chronic hemiparesis? *Brain.* 2004;127:1035-1046.

7. Beer RF, Dewald JPA, Rymer WZ. Deficits in the corrdination of multijoint arm movements in patients with hemiparesis: evidence for disturbed control of limb dynamics. *Experimental Brain Research.* 2000;131:305-319.

8. Levin MF, Michaelsen SM, Cirstea CM, Roby-Brami A. Use of trunk for reaching targets placed within and beyond the reach in adult hemiparesis. *Experimental Brain Research.* 2002;143:171-180.

9. Michaelsen SM, Luta A, Roby-Brami A, Levin MF. Effect of trunk restraint on the recovery of reaching movements in hemiparetic patients. *Stroke.* 2001;32:1875-1883.

10. Scheidt RA, Stoeckmann T. Reach adaptation and final position control amid environmental uncertainty after stroke. *Journal of Neurophysiology.* 2007;97:2824-2836.

11. McCrea PH, Eng JJ. Consequences of increased neuromotor noise for reaching movements in persons with stroke. *Experimental Brain Research.* 2005;162(1):70-77.

12. Lang CE, Wagner JM, Bastian AJ, et al. Deficits in grasp versus reach during acute hemiparesis. *Experimental Brain Research.* 2005;166:126-136.

13. Kilbreath SL, Heard RC. Frequency of hand use in healthy older persons. *Australian Journal of Physiotherapy.* 2005;51:119-122.

14. Michaelsen SM, Jacobs S, Roby-Brami A, Levin MF. Compensation for distal impairments of grasping in adults with hemiparesis. *Experimental Brain Research.* 2004;157(2):162-173.

15. Lang CE, Wagner JM, Bastian AJ, et al. Deficits in grasp versus reach during acute hemiparesis. *Experimental Brain Research.* 2005;166(1):126-136.

16. Reikensmeyer DJ, McKenna CA, Kahn LE, Kamper DG. Directional control of reaching is preserved following mild/moderate stroke and stochastically constrained following severe stroke. *Experimental Brain Research.* 2002;143:525-530.

17. VanVliet PM, Sheridan MR. Coordination between reaching and grasping in patients with hemiparesis and normal subjects. *Archives of Physical Medicine and Rehabilitation.* 2007;88:1325-1331.

18. Lincoln NB, Leadbitter D. Assessment of motor function in stroke patients. *Physiotherapy.* 1979;65:48-51.

19. Bamford J, Sandercock P, Dennis M, Burn J, Warlow C. Classification and natural history of clinically identifiable subtypes of cerebral infarction. *The Lancet.* 1991;337:1521-1526.

20. Bohannon RW, Smith MB. Interrater reliability of a Modified Ashworth Scale of muscle spasticity. *Physical Therapy.* 1987;2:206-207.

21. Jackson J, Crow L. The reliability of sensory assessments in hemiplegia. Paper presented at: Eleventh Congress of the World Confederation for Physical Therapy, 1991; London.

22. Wilson B, Cockburn J, Halligan PW. *Behavioural inattention test*. Titchfield, Hante: Thames Valley Test Company; 1987.

23. Rey A. *Le test, de copie de figure complexe*. Paris: Editions Centre de Psychologie Applique.; 1959.

24. Melzack R. The short-form McGill pain questionnaire. *Pain.* 1987;30:191-197.

25. Colebatch JG, Gandevia SC. The distribution of muscular weakness in upper motor neuron lesions affecting the arm. *Brain.* 1989;112:749-763.

26. Thilmann AF, Fellows SJ, Garms E. Pathological stretch reflexes on the 'good' side of hemiparetic patients. *Journal of Neurology, Neurosurgery and Psychiatry.* 1990;53:208-214.

27. Turton AJ, Fraser CM. A test battery to measure the recovery of voluntary movement following stroke. *International Rehabilitation Medicine.* 1986;8:74-79.

28. *Qualysis User Manual for Macreflex version 2.3* [computer program]. Version. Patille, Sweden; 1994.

29. Harrison JP, Moreau S, Mansfield D. *The reliability and validity of the MacReflex motion analysis system.* [Master of Science], Simmons College; 1993.

30. Linden DWV, Carlson SJ, Hubbard RL. Reproducibility and accuracy of angle measurements obtained under static conditions with the Motion Analysis (TM) Video system. *Physical Therapy.* 1992;72(4):300-305.

31. Scholz JP. Reliability and validity of the WATSMART three-dimensional optoelectric motion analysis system. *Physical Therapy.* 1989;69:679-689.

32. Haggard P, Wing AM. Assessing and reporting the accuracy of position measurements made with optical tracking systems. *Journal of Motor Behaviour.* 1990;22:315-321.

33. Castiello U, Bennett KMB, Stelmach GE. Reach to grasp: the natural response to perturbation of object size. *Experimental Brain Research.* 1993;94:163-178.

34. Marteniuk RG, Leavitt JL, MacKenzie CL, Athenes S. Functional relationships between grasp and transport components in a prehension task. *Human Movement Science.* 1990;9:149-176.

35. Trombly CA. Observations of improvement of reaching in five subjects with left hemiparesis. *Journal of Neurology, Neurosurgery and Psychiatry.* 1993;56:40-45.

36. Snedecor SW, Cochran WG. *Statistical methods*. 6th ed. Ames, Iowa: Iowa State Univeristy Press; 1967.

37. Sainburg RL, Schaefer SY. Interlimb differences in control of movement extent. *Journal of Neurophysiology.* 2004;92:1374-1383.

38. Bourbonnais D, Noven SV. Weakness in patients with hemiparesis. *American Journal of Occupational Therapy.* 1989;43:313-319.

39. Gowland C, Bruin Hd, Basmajian JV, Plews N, Burcea I. Agonist and antagonist activity during voluntary upper limb movement in patients with stroke. *Physical Therapy.* 1992;72:624-633.

40. Fellows SJ, Kaus C, Thilmann AF. Voluntary movement at the elbow in spastic hemiparesis. *Annals of Neurology.* 1994;36(3):397-407.

41. Kudoh N, Hattori M, Numata N, Maruyama K. An analysis of spatiotemporal variability during prehension movements: effects of object size and distance. *Experimental Brain Research.* 1997;117:457-464.

42. Gentilucci M, Castiello U, Corradin ML, Scarpa M, Umilta C, Rizzolati G. Influence of different types of grasping on transport component of prehension movements. *Neuropsychologica.* 1991;29(5):361-378.

43. Jeannerod M. The timing of natural prehension movements. *Journal of Motor Behaviour.* 1984;26(3):235-254.

44. vanVliet P, Kerwin DG, Sheridan MR, Fentem PH. The influence of functional goals on the kinematics of reaching following stroke. *Neurology Report.* 1995;19(1):11-16.

45. Tanaka H, Krakauer JW, Qian N. An optimization principle for determining movement duration. *Journal of Neurophysiology.* 2006;95:3875-3886.

46. Flash T, Hogan N. The coordination of arm movements: an experimentally confirmed mathematical model. *Journal of Neuroscience.* 1985;5:1688-1703.

47. Harris CM, Wolpert DM. Signal-dependent noise determines motor planning. *Nature.* 1998;394:780-784.

48. Winstein CJ, Merians AS, Sullivan KJ. Motor learning after unilateral brain damage. *Neuropsychologia.* 1999;37:975-987.

49. Michaelsen SM, Dannenbaum R, Levin MF. Task-specific training with trunk restraint on arm recovery in stroke. Randomized control trial. *Stroke.* 2006;37:186-192.

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

Subject	Age	Weeks since stroke	Side of lesion (hemisphere)	Bamford	CT scan result
1	87	3	L	PACI	*
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 scan was not performed

PACI – Partial anterior circulation infarct

TACI – total anterior circulation infarct

Table 2 *Stroke subject characteristics*

			Spasticity			Sensation							
Subject	Hemianopia	Arm function (Rivermead)	Elbow	Wrist	Finger	Touch	Press	Kin.	2pt 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	*	*	0
5	Y	6	1+	1	0	0	0	0	0	0	42	29.5	0
6	N	4	1+	1	1	†	†	†	†	†	50	†	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§
9	N	4	0	0	1	2	2	1	1	1	45	23	0

* subject could not be tested for neglect and spatial abilities because he did not have his reading glasses

† subject could not be tested due to dysphasia

§ ‘catching’ pain which occurred occasionally in upper arm

Table 3 *Means and standard deviations of kinematic parameters. Time to peak velocity, peak deceleration and maximum grip aperture are absolute times from movement onset. These values are also expressed as percentage of total movement duration.*

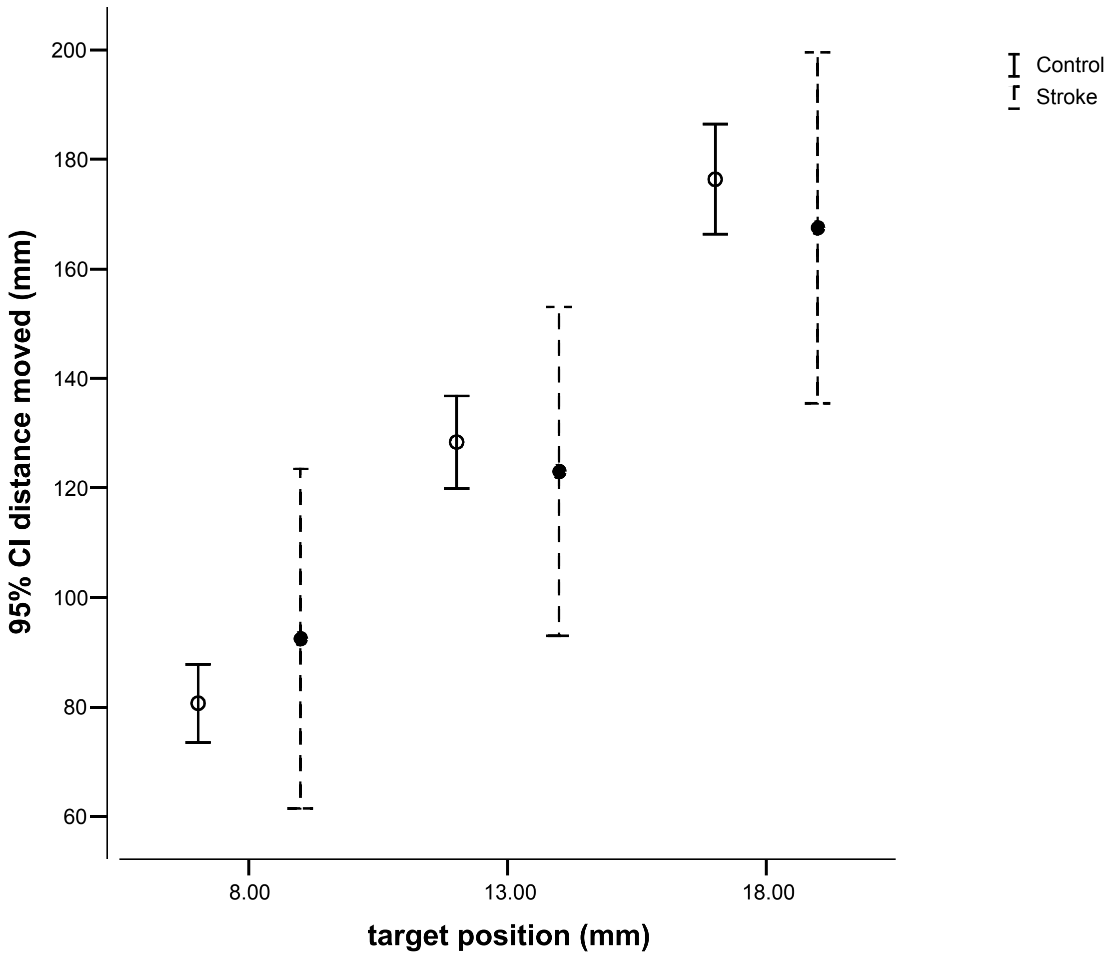
		8 cm		13 cm		18 cm	
		Mean	SD	Mean	SD	Mean	SD
Distance moved (mm)	Healthy	80.7	9.28	128.4	11	176.4	13.1
	Stroke	92.5	40.3	123	39.1	167.5	41.7
Movement duration (ms)	Healthy	1310	340	1330	380	1350	360
	Stroke	4110	2630	5000	2850	5160	2760
Transport component							
Peak velocity ($mm.s^{-1}$)	Healthy	242	72.7	325	72	384	94
	Stroke	139	65	168	77	213	88
Average velocity ($mm.s^{-1}$)	Healthy	68	21	107	34	141	38
	Stroke	35	22	37	26	46	30
Time to peak velocity (ms)	Healthy	500	160	490	270	380	70
	Stroke	1750	1470	1110	820	1440	1020
Time to peak velocity (%)	Healthy	36.4	10	32.1	7.7	29.2	3.7
	Stroke	41.3	14.3	28.6	15.3	25.5	13.1

Figure Legends

Figure 1. The mean distance moved with 95% confidence intervals for control and stroke subjects for reaching movements to the 8, 13 and 18 cm target positions.

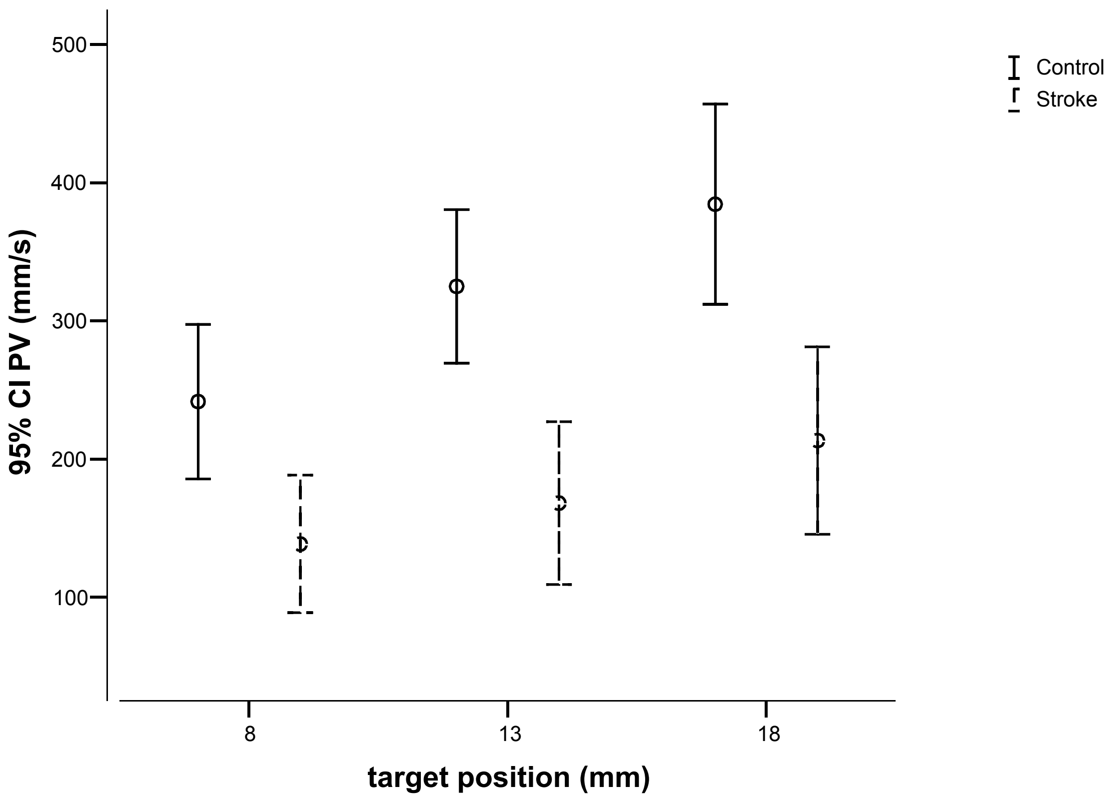
Figure 2. The mean peak velocity of the wrist with 95% confidence intervals for control and stroke subjects for reaching movements to the 8, 13 and 18 cm target positions.

Figure(s)



Control
Stroke
200
180
160
140
120
100
80
60
95% CI distance moved (mm)
8.00
13.00
18.00
target position (mm)

Figure(s)



95% CI PV (mm/s)
500
400
300
200
100
8
13
18
target position (mm)
Control
Stroke