Differences in Reaching Performance Between Normal Adults and Patients Post Stroke-A Kinematic Analysis

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Abstract

Reaching is a typical functional arm movement and requires multi-joint coordination in completing daily living activities. The purposes of this study were to assess the differences in kinematics between normal and abnormal reaching during performing functional task and to use a parsimonious kinematic model to quantifying reaching control in patients post stroke. This study recruited 34 subjects, including normal adults (N = 17) and patients post stroke (N=17), and analyzed the subject's arm reaching performance with kinematic analysis. The study showed that there existed significant group differences in movement time ($F = 12.9$, $P<0.001$), peak velocity ($F = 12.57$, $P<0.001$), normalized jerk score of movement ($F = 7.97$, $P<0.01$), and number of movement units ($F = 13.77$, $P<0.001$). Our parsimonious model of kinematic measure in reaching includes two variables, peak velocity and number of movement units. This study may help therapists to identify and monitor the progression of control of reaching performance and may provide concise information to quantify the level of abnormal reaching performance in patients post stroke.

Keywords: Stroke, Kinematics, Arm reaching, Motor impairments

1. Introduction

Reach and grasp movements are basic and important upper arm motor components in completing daily living activities such as self-feeding, opening a door, operation of a button or switch etc. Patients post stroke often demonstrate unique motor impairments, such as spastic or synergistic movement, in the upper extremity during executing daily living activities. These impairments, from mild to severe, may restrict the patients from learning adaptive skills, e.g., manipulating in new environments and controlling electronic aids. Reaching has been defined as the voluntary positioning of the hand at or near a desired location so that it may interact with the environment. Performance of reach movement may be used to characterize the coordination of multiple joints and involvement of both the musculoskeletal and neural systems [1]. Thus, it is very important to evaluate reaching with quantitative method for rehabilitation practitioners and researchers to describe the coordination and functional status objectively for patients with different levels of motor impairment in the paretic upper limb.

Kinematic analysis of reaching performance provides a more sensitive way to evaluate the treatment and progression of a wide variety of motor disorder conditions. Previous studies have examined the reaching kinematics of normal, Parkinson's disease [2-4], and stroke subjects [5-6]. These kinematic studies in reaching performance have generally found that subjects with movement disorders have increased movement duration, decreased velocity, increased segmentation, and increased variability in path trajectory. Additionally, subjects with movement disorders significantly show less smooth and continuous path trajectory when reaching to an object with higher accuracy constraints [2]. Study of reaching movements with analysis of the elbow kinematics was done in patients with cerebral palsy and found ataxic subjects were characterized by lower peak velocities, prolonged durations, and increased variability compared with normal subjects [7]. Treatment effect study used kinematic evaluation to assess the effect of neurodevelopment treatment on reach movement for spastic CP and found both movement time (MT) and movement units were reduced after treatment [8]. Another kinematic study also showed that providing a task with natural and functional context for reach movement would elicit better quality of reaching in the affected and non-affected arms, particularly in the affected arm of children with spastic

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hemiparesis [9].

Assessment of reaching with kinematic analysis can be used as "a strategy level assessment" in upper arm and hand function [10]. There are many kinematic variables which can be utilized to reflect the characteristics of reaching. By quantification of specific kinematic reaching parameters, key component can be identified and the influence of motor impairment on reaching can be carefully analyzed. Consequently, specific kinematic parameters with large effect size can provide therapists with a sensitive way to measure the treatment efficacy, and to analyze the influence of different levels of motor dysfunction on upper arm control during activities with various accuracies demanded. A better understanding of this information will give insight for evaluating treatment and progression of a wide variety of motor disorder conditions, such as stroke, cerebral palsy and Parkinson's disease [7,11-12].

It is well known that abnormal movement with spasticity or synergy is one of the major motor problems for patient post stroke to execute functional reaching tasks in daily activities. Little research has been conducted to determine the sensitivity of kinematic variables for detecting normal and abnormal control of functional reaching. Thus, the purposes of this study were to assess the differences in kinematics between normal and abnormal reaching during performing functional task, to analyze the effect sizes of these significant kinematic variables, and finally to find a parsimonious kinematic model for quantifying reaching control in patients post stroke. The parsimonious kinematic model found from this study may help the therapists to effectively monitor the abnormal control of reaching performance with most sensitive and validate kinematic variables.

2. Methods

2.1 Participants

Subjects following stroke and normal age-matched adults were recruited from the hospital's outpatient rehabilitation clinics and the local community. There were totally 34 participants enrolled in this study. Seventeen normal adults and 17 patients post stroke were assigned to control (8 males, 9 females, aged from 35 to 87 years, mean age = 61.9 yrs) and experimental (14 males, 3 females, aged from 28 to 86 years, mean age = 60.7 yrs) groups, respectively. Independent t-test showed that there was no significant difference in age between control and experimental groups.

Criteria for inclusion for stroke subjects in this study included: (1) computed tomography or magnetic resonance imaging evidence of single-hemisphere involvement lasting over 6 months; (2) demonstrated affected arm reaching ability; (3) no perceptual-cognitive dysfunction, such as loss of arm proprioception, apraxia and hemispatial neglect, which limits comprehension of the experimental task; and (4) no severe concurrent medical problems, such as shoulder pain, or other neurological and orthopedic conditions affecting the arm or trunk movements. Subjects gave informed consent approved by the Institutional Review Board.

2.2 Materials and instrumentation

A three-dimensional optical motion capture system (Visualeyez™ Hardware, PhoeniX Technologies Inc., Canada) was used to collect the movement trajectories of the affected upper limb in this study. Infrared light-emitting diodes were positioned on the anatomic landmarks of the affected limb. The selected three anatomic landmarks were as follows: the metacarpophalangeal joint of the index finger, the metacarpophalangeal joint of the fifth finger, the middle of the 3rd metacarpal. The positions of markers on the affected hand were recorded at a sampling rate of 70 Hz and digitally filtered by using a low-pass 2nd order forward and backward Butterworth filter with cut-off frequency at 5 Hz.

2.3 Experimental protocol

At the beginning of the experiment, subjects received a brief description of the study. The paretic upper limb motor function of all the subjects were assessed by means of two categories of motor assessments. The first category was motor impairment level assessment, and this study used Modified Ashworth Scale (MAS), the upper extremity subtest of the Fugl-Meyer Motor Function Assessment (FMA) [13], to measure the affected upper limb's muscle tone and motor ability respectively. Ratings of functional ability of the affected upper limb of each subject were assessed prior to the study using the upper extremity subtest of the FMA to examine for the presence of synergistic and isolated movement pattern and grasp. Muscle tone at the elbow joint (flexion and extension) was evaluated using a six-point scale (0 = normal tone, 5 = severe spasticity) based on the MAS [14].

The second category was "motor strategies level" assessment. Kinematic analysis of reaching ability was assessed. During kinematic measuring, the subject was seated in front of a rectangular experimental table with a seat belt on his or her lower trunk to protect their sitting safety, and the subject's feet were flat on the floor/foot rest and the knees and hips were flexed near 90°. At the beginning of the experimental task, the table height was adjustable so that the subject had to put his or her upper limbs on standard initial positions on the table, with flexion of both elbows at 90° and forearm in neutral position. Both the subject's wrists were placed on the border of the table, which was proximal to the subject. It was suggested that moving to real objects might produce better performance in stroke patients than rote and "meaningless" tasks [15], therefore two paper cups, with the width between the two shoulders, were applied to mark the end positions for reaching. The distance of the cups was adjustable to accommodate the arm length of each subject, and the position of the cups was set at the height of shoulder level in front of the subject. The experimental subject was asked to reach for the ipsilateral target and grasp it with the paretic upper limb in a natural self-paced manner (Figure 1). A natural self-paced reaching manner was used in this study because reaching movement with such manner is less interfered by spasticity during performing activities of daily living. For subject who could not demonstrate grasp function, reaching for the target and touching it without grasping was adopted. For the control subject, reaching for the target with dominant hand or non-dominant was determined by the side of the paretic limb of the matched subject.

Figure 1. Experimental set-up and the end position for a subject performing a reaching movement.

Subjects had to perform for five experimental trials, with a 1-minute rest period administered between each trial task. The typical length of an experimental session was approximately 10 minutes, and no evidence of fatigue was observed or reported from any subject after finishing the experimental movement task.

2.4 Data analysis

Studies had reported that movement of the hand is of primary importance during rapid pointing and variations of angular trajectory without variations of the limb end-point trajectory. Thus, kinematic analysis of the end-point (hand) trajectory of reaching was adopted in this study [16-17].

Kinematic data from reaching movements were analyzed by the VZAnalyzer software, V3.0 (PhoeniX Technologies Inc., Canada). VzAnalyzer software gives a three-dimensional reconstruction of the marker positions. The palmar segment, formed by the three markers, was modeled as a rigid-body during reaching an object, and the trajectories of the marker in metacarpophalangeal joint of the index finger were used for further kinematic analysis. A relative velocity above or below 3% of the maximum movement velocity on the sagittal plane, which was parallel to the reach movement direction, was used to detect the start and end of each reaching movement. The following kinematic variables were derived from the marker position to examine and quantify the affected arm movement: movement time (MT), peak velocity (PV), number of movement units (NMU), percentage time of reach where peak velocity occurs (PTPV), and normalized jerk score of movement (NJSM).

Peak velocity, the highest instantaneous velocity during the reaching movement, is regarded as being correlated with the force generation of a movement [18]. Movement time, the duration of execution of a movement, reflects the overall speed of a movement, as a faster movement would result in shorter movement time. Both NMU and NJSM are used to quantify the movement smoothness [19-21]. NMU is determined by the number of peaks presenting in the velocity profile of the paretic upper limb reaching movement. This provides information about the smoothness and efficiency of a movement. Fewer movement units indicate a smoother and more efficient reaching movement. To obtain the NJSM, a mathematical formula was used compute the integrated squared jerk, using the trapezoidal rule, with the unit of distance/time [22]. Since integrated squared jerk increases dramatically with movement time and the distance traveled during the movement, it is useful to normalize this quantity in time and distance [23-24]. This is done by introducing the term t^5/s^2 into the formula for normalized jerk score and excludes the influence of individual differences in time and distance for each reaching performance. The formula is taken:

$$\text{NJSM}=\sqrt{\frac{1}{2}\int\left(\left(\frac{d^3x}{dt^3}\right)^2+\left(\frac{d^3y}{dt^3}\right)^2+\left(\frac{d^3z}{dt^3}\right)^2\right)dt\left(\frac{t^5}{s^2}\right)} \quad (1)$$

x: the position of the hand rigid body on the X-axis.
y: the position of the hand rigid body on the Y-axis.
z: the position of the hand rigid body on the Z-axis.
t: movement time
s: movement distance of hand

2.5 Statistical analysis

In order to obtain more stable and homogeneous spatio-temporal data, the first and the fifth trials were excluded, and the mean of the remaining trials' data was calculated for further descriptive and inferential statistics. Statistical analysis was performed with SPSS 13.0 computer package (SPSS Inc., Chicago, USA). MANOVA was utilized to test the group effects of kinematical reaching parameters respectively. Effect sizes were determined by partial eta squared. The partial eta squared is the ratio of the variation accounted for by an individual independent variable to the sum of the variation accounted for by the independent variable and the variation unaccounted for by the model as a whole. It has been suggested that for ANOVA, an effect size of 0.1 represents a small effect size; 0.25, a medium effect; and 0.4, a large effect [25]. Finally, discriminative analysis, based on Wilks' lambda and stepwise method, was utilized to determine a predictive model that was expected to find out the very sensitive kinematic parameters for discriminating effectively between abnormal and normal reaching.

3. Results

Visual inspection of typical reaching paths for both normal and abnormal subjects in velocity profile revealed that stroke patient produced lower peak velocity and less smooth reaching paths. Figure 2 shows the typical velocity vs. normalized movement time plot for normal and stroke subjects' reaching performance. In general, for a normal and well-controlled reaching, the motor program may not rely heavily on feedback loops to correct the ongoing movement, the movement speed will be faster, smoother, and the PTPV occurrence will be located in the 33~50% range [26-29]. On the contrary, stroke subjects demonstrated less smooth reaching paths, with multiple segmentations and lower peak velocity, and the PTPV was less than 30% on the plot of reaching paths.

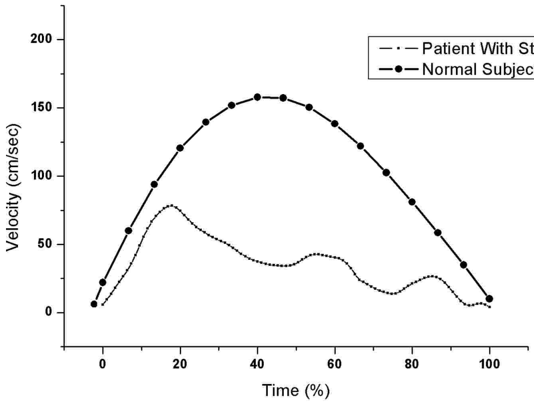

Figure 2. Typical reaching performance in velocity vs. normalized movement time plot for normal and patient post stroke.

The means and standard deviations for the kinematic variables describing the characteristics of movement patterns for normal subjects and subjects post stroke are shown in Table 1. Significant group effects are identified in Table 1 as well. There was no significant group effect in PTPV for reaching. However, patients in the post stroke group showed a prolonged MT [F(1, 32) = 12.90, P < 0.001, partial eta squared = 0.28] for reaching. Additionally, significant group effects on NMU, PV, and NJSM were also found in reaching performance [for PV, F(1, 32) = 12.57, P <0.001, partial eta squared = 0.28; for NMU: F(1, 32) = 13.77, P<0.001, partial eta squared = 0.30; for NJSM: F(1, 32) = 7.97, P<0.01, partial eta squared = 0.20]. Using NMU to measure reaching performance would obtain the greatest effect size (moderate to large) in differentiating the true differences between normal subjects and stroke subjects.

The reaching kinematic parameters were further analyzed to establish our parsimonious predictive model. Discriminative analysis with stepwise method revealed only PV and NMU left in the predictive model (Wilks' lamda = 0.59, P <0.001). The overall percentage of cases classified correctly was 73.5% (sensitivity = 64.7%, and specificity = 82.4 %). Six subjects post stroke and three normal subjects were incorrectly classified (Table 2) by the parsimonious predictive model, reflecting that PV and NMU were the best kinematic variables to use in building a parsimonious model for monitoring the control of self-pace reaching performance.

Table 2. Summary of model using NMU and PV to predict normal and abnormal reaching (N=34).

			Predicted group membership		
		Diagnosis	Stroke	Normal	Total
Observed group membership	N	Stroke	11	6	17
		Normal	3	14	17
	%	Stroke	64.7	35.3	100
		Normal	17.6	82.4	100

73.5% of observed grouped cases were classified correctively.

4. Discussion

Development of reliable and valid multi-joint biomechanical evaluation of the paretic arm movement is required, particularly for natural and goal-oriented reaching movement [30]. When reaching for an object, stroke patients with moderate motor impairment showed irregular paths profiles along with more movement corrections in the "home in" phase of reaching. This feedback control with multiple corrections significantly makes stroke subjects increase in MT and shows lower PV with less smooth reaching than those of normal subjects' reaching. In this study, the effect sizes of kinematic variables including MT, PV, NJSM and NMU to discriminate between normal and abnormal reaching were medium to large. Furthermore, from the parsimonious kinematic model built in this study, NMU and PV could be used as good indicators to quantify natural and goal-oriented reaching performance for patients post stroke.

Reaching for tasks at a self-selected pace in activities of daily living will represent more natural and functional ability in motor performance. If the reaching movement is well controlled, the motor program may not rely heavily on feedback loops to correct the ongoing movement. Consequently, the time for execution of movement will be shorter, force production will be more involved in movement. In adition movement will become smoother (i.e., fewer movement units or lower normalized jerk score of movement), and the PTPV will be greater (i.e., subject performs reaching with less dependence on on-line feedback for movement correction). Our results showed PTPV had the least effect size, and did not show any difference between normal and abnormal

Table 1. Mean ± SD of kinematic reaching variables for normal and patients post stroke (n = 34).

Variable	Normal (n=17)		Stroke (n = 17)			
	Mean	S D	Mean	SD	F	Effect size
MT (sec)	1.04	0.32	1.65	0.61	12.90***	0.28
NJSM	43.65	30.92	182.10	199.80	7.97**	0.20
PV (cm/sec)	56.36	11.98	43.43	9.07	12.57***	0.28
NMU	1.65	0.29	2.48	0.86	13.77***	0.30
PTPV (%)	33.80	7.59	36.69	13.32	0.60	0.019

MT: movement time, NJSM: normalized jerk score of movement, PV: peak velocity,
NMU: number of movement units, PTPV: percentage time of reach where peak velocity occurs.
**: P < .01, ***: P < .001.

reachings. These findings had some differences with those of other studies, which sampled from subjects with different diagnosis, such as stroke [6,20] or Parkinson's disease [2]. Our data showed that the less sensitive kinematic variable was related to measure of movement strategy. It implied that PTPV might not be appropriate to reflect abnormal reaching performance for subject with interjoint coordination problems.

This study established a parsimonious model, from the results of discriminative analysis, to differentiate normal subjects' reaching from stroke subjects' reaching. The model included NMU and PV only, and had the effectiveness of 73.5% overall correction rate to discriminate between normal subjects' reaching and stroke subjects' reaching. Careful inspection of the discrimination scores revealed that six subjects post stroke, with FMA score greater than 60 and MAS score less than two, were misclassified as normal subjects, and three normal adults, aged form 70 to 87 years, were misclassified as stroke subjects. These two factors (normal subject with age greater than 70 years old and stroke subjects with FMA score greater than 60 and minimal spasticity) would limit the sensitivity of applying NMU and PV for detecting the different performance of reaching between normal subject and patients post stroke at a self-selected pace. Therefore, practitioners should carefully judge these confounding conditions when applying this study result for clinical implications.

It is reported that control of pointing movements needs bi-level organization. One level plans the trajectory of the movement while the other specifies the interjoint coordination (movement smoothness) necessary to the completeness of goal-directed movements [32]. A previous study found that there were significant correlations between reaching kinematics (NMU, NJSM, PV) and levels of motor impairment (MAS and FMA). It revealed that subjects with higher MAS or lower FMA score demonstrated higher NMU and NJSM scores, or lower PV during performance of reaching. This study demonstrated that using PV and NMU as measure indices, in monitoring the control of reaching performance, produced the most effective and parsimonious kinematic model, which could concisely reflect the characteristics of reaching performance for stroke patients. Thus, assessment of clinical interventions, such as spasticity inhibition technique, and injection of botulinum toxin may select these reaching kinematic variables as important and sensitive indices to evaluate the effects of treatment on motor recovery and analyze the interference of spasticity on control of reaching.

Spasticity is sensitive to speed, and measurement of motor performance at a self-selected pace would diminish the disturbance of spasticity and reflect the actual ability of motor control for subjects with movement disorder. Subjects with specific motor problems (synergistic movement with spasticity vs. motor execution problem) and different commands used in the research (go at a self-selected pace vs. go as quickly as possible) are the main factors that may increase inconsistency between our results and previous results [27-29]. Another confounding factor in this study would include the use of convenience sampling, small sample size and lack of gender control. These confounding factors would limit the generalization of our research results, and precaution is needed in clinical application.

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