The Constructs of Kinematic Measures for Reaching Performance in Stroke Patients

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Abstract

Control and movement characteristics of reaching performance are complex and challenging to understand in stroke rehabilitation. There are many kinematic variables to quantify different aspects of reaching performance. The purposes of this study were to explore the measure constructs of kinematic measures in reaching performance and to investigate the relationships between kinematic measures in reaching and clinical motor evaluation. This study recruited 40 patients after stroke and measured the subjects' paretic arm reaching performance with kinematic analysis. Findings in this study showed that variables of kinematic measures for reaching performance could be reduced to two principal conceptual measure constructs. One measure construct relates to movement speed and smoothness. The other measure construct might relate to movement strategy (feed forward or feedback control). Motor impairments scores showed significant correlations with movement speed and movement smoothness variables. This study suggests that a comprehensive kinematic measure of reaching performance should include the variables to reflect the characteristics of movement speed, movement smoothness and movement strategy.

Keywords: Stroke, Kinematics, Arm reaching, Motor impairments

1. Introduction

Reaching is a basic and important multi-joint movement of the upper extremities for independence in daily living activities such as self-feeding, grooming, toileting, dressing and environmental switch operations. Control of reaching movement requires coordination of multiple joints and involves both musculoskeletal and neural systems in the upper limbs. Patients after stroke often demonstrate residual motor impairments such as spastic or synergistic movement in the paretic upper extremities. These impairments, from mild to severe, may limit such patients in performing reaching movement. The patients often show difficulties in learning new adaptive skills, manipulation of surrounding environments and control of electronic aids in daily living activities. Kinematic measures in reaching can provide the therapist with a sensitive parameter to measure treatment efficacy and analyze the impact of different impairment levels on carrying out daily activities for patients with neurological disorders [1-3].

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The levels of motor impairment of the paretic upper limb following stroke may be influenced by severity of spasticity, motor control ability, and level of muscle weakness [4-5]. Motor assessment tools which are utilized to assess the paretic upper limb motor function during the stage of sub-acute stroke rehabilitation may include Brunnstrom's Motor Stage Assessment, Fugl-Meyer Upper Limb Motor Assessment Scale (FMA) [6-9], Modified Ashworth Scale (MAS) [10-11], grip and pinch strength assessments [12-13] and range of motion assessment, etc. These motor assessment tools all possess quantitative characteristics reflecting the degrees of impairment in specific motor capability. Validity and reliability of FMA, MAS and grip and pinch strengths are also presented in the assessment of severity of the paretic upper limb motor impairment. However, these clinical motor assessment tools are still limited to detecting the slight improvement of upper limb motor function in the late stage of upper limb rehabilitation. Kinematic assessment in reaching movement is considered as "a strategy level assessment" for upper arm function [14]. By quantification of specific reaching component in kinematics, key motor components can be identified and the influence of impairment on reach movement can be carefully analyzed [15].

Kinematic studies have always been conducted to verify the intervention effects for motor control problems and analyze the differences in reaching between normal and patients with stroke. Studies, with kinematic measures in reaching performance on subjects with stroke, have commonly found that subjects usually demonstrate increased movement duration, decreased velocity, increased movement segmentation, and increased variability in path trajectory. Furthermore, subjects with stroke always show significantly less smooth and continuous movement in path trajectory when reaching to an object with accuracy constraints [16-22].

However, the statistical verification of measure constructs in reaching movement still has not been well analyzed for patients with movement disorders. In this study, reaching movement was chosen because it involves the coordination of multiple joints and represents a basic and functional movement in daily activities [23]. In addition, it represents modeling a de-synergistic arm movement pattern that would be expected during recovery after stroke. Thus, a better understanding of the principal kinematic measure constructs in reaching will give practitioners insight into effective applications in the assessment of motor impairments. Additionally, such information can also be used to help practitioners clarify which measures are most needed to determine the changes of performance in reaching, and finally contribute to the identification of treatment efficacy for subjects with movement disorders [24].

The purposes of this study were to explore the measure constructs of kinematic measure in reaching performance and to investigate the relationships between kinematic measures in reaching and clinical motor assessments. It is expected that findings from this study will help the researchers and practitioners apply succinct kinematic measures to evaluate the treatment effects and to monitor progression of upper limbs motor impairments for patients after stroke.

2. Methods

2.1 Subjects

Forty subjects were enrolled in this study. Subjects were all from the Department of Rehabilitation Medicine in Kaohsiung Medical Hospital, Taiwan. There were 34 males and 6 females, aged from 37 to 75 years, and the mean ± standard deviation of age was 56 ± 10.54 years. Six of the 40 subjects were left-hand dominant and there were 24 subjects' dominant hands that were affected following stroke. Six of the subjects were classified as stroke of hemorrhagic type and the others were of infarction type. The duration of post incidence of stroke was from 12 days to 6 years. Criteria for inclusion of the subjects in this study included: (1) computed tomography or magnetic resonance imaging evidence of single-hemisphere involvement; (2) demonstrated reaching ability in the paretic upper limb; (3) no perceptual-cognitive dysfunction, such as loss of proprioception of the arm, apraxia, or hemispatial neglect, which could limit 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. All subjects gave informed consent, and the institutional review board of Kaohsiung Medical University approved all the research procedures applied in the studies.

2.2 Experimental protocol

The paretic upper limb motor function of all the subjects were assessed by two categories of motor function assessments. The first category was motor assessment at impairment level. MAS and the upper extremity subtest of the FMA [6] were applied, in this study, to measure the elbow muscle tone in the paretic upper limb and motor ability, respectively. The scoring in upper extremity subtest of FMA is from 0 to 66, with 66 indicating nearly normal function. Muscle tone at the elbow joint was evaluated using a six-point scale (0 = normal tone, 5 = severe spasticity) based on the Modified Ashworth Scale [10].

The second category was "motor strategies level" assessment. Kinematic measure of reaching performance of the paretic upper limb was assessed. The subject was seated in front of a rectangular experimental table with a seat belt on his/her waist to protect their sitting safety, and the seat height was adjustable so that the subject's feet were flat on the floor and the knees and hips were flexed at 90˚. At the beginning of the experimental task, the subject had to put his/her upper limbs on standard initial positions on the table, flex both elbows at 90˚. The subjects placed both wrists over the table border in a neutral position, and then the tasks required the rapid forward projection of the paretic limb so as to reach the cups at shoulder height level in front of the subject. The position of the cups was adjustable to accommodate the arm length of each subject.

It had been suggested that moving to real objects might produce better performance in stroke patients than rote and "meaningless" tasks [25], thus this study used a paper cup as the target for reaching. Each subject was requested to perform the reaching forward tasks with the paretic limb as fast as possible. Subjects had to perform five reaching trials, and a 1-minute rest period was administered between two reaching trial tasks to reduce the influence of fatigue.

At the beginning of the experiment, subjects received a brief description of the study. During the test trial, the examiner provided positive and supportive verbal feedback (e.g., "speed up a bit", "you're really doing a good job", etc.) to each subject and encouraged the subject to perform as quickly as possible. 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 task (Figure 1).

A three-dimensional optical active marker motion capture system (Visualeyez™ Hardware, PhoeniX Technologies, Inc., Burnaby, Canada) was used to collect the movement trajectories of the paretic upper limb in this study. Infrared light-emitting diodes were positioned on three anatomic landmarks of the paretic limb. The selected anatomic landmarks were as follows: the metacarpophalangeal joint of the index finger, the metacarpophalangeal joint of the fifth finger, and the middle of the 3rd metacarpal. The positions of markers on the arm were recorded at a sampling rate of 70 Hz and digitally filtered by using a low-pass second order forward and backward Butterworth filter with cut-off frequency at 5 Hz [26-27].

Figure 1. Experimental setup for stroke subjects to perform a reaching movement.

2.3 Data analysis

Kinematic data from reaching movements were analyzed by the VZAnalyzer software, V3.0 (PhoeniX Technologies, Inc., Burnaby, Canada). VZAnalyzer software gave a three-dimensional reconstruction of the marker positions. The three markers in the dorsum of the hand were modeled as a rigid-body during reaching the target. A relative velocity above or below 3% of the maximum movement velocity on the sagittal plane (Z-axis), which was parallel to the reach movement direction, was used to detect the start and end of each reaching movement. The following kinematic measure variables were derived from the marker positions to examine and quantify the paretic arm reaching movement characteristics (Figure 2): peak velocity (PV) (cm/s) [28], percentage time of reach where peak velocity occurs (%) (PTPV), movement time (sec) (MT), number of movement units (NMU), 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 [29]. 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 were used to quantify the movement smoothness [23,30-31]. NMU was 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 [30,32]. Fewer movement units indicate a smoother and more efficient reaching movement. To obtain the NJSM, a mathematical formula was used to compute the integrated squared jerk, using the trapezoidal rule, with the unit of distance/time [32]. Since integrated squared jerk increases dramatically with movement duration and the distance traveled during the movement, it was normalized in time and distance [33-34]. This was done by introducing the term t^5/s^2 into the formula for normalized jerk score. The formula was described as following:

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

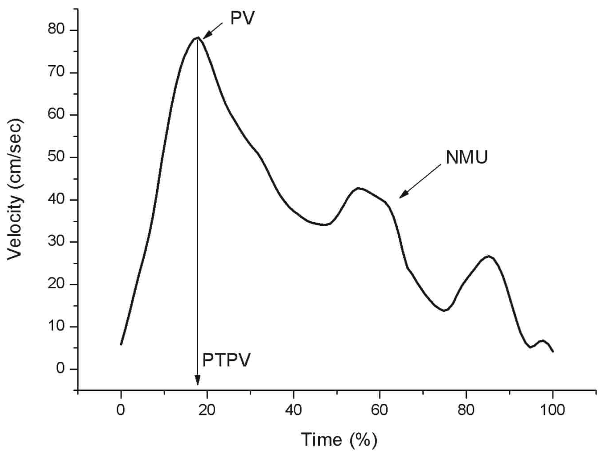

Figure 2. Kinematic variables in the velocity profile for quantifying the characteristics of paretic arm reaching movement. (NMU: number of movement units; PV: peak velocity; PTPV: percentage time of reach where peak velocity occurred.)

2.4 Statistical analysis

The data analysis method included descriptive statistics of all variables for measure in motor impairments and reaching kinematics. Principal component factor analysis with varimax rotation method was applied for exploratory factor analysis. The number of common factors was determined by setting the eigenvalues greater than 1, and variables with factor loading greater than 0.5 were considered as significant contributors to the common factor. Spearman's correlation test was performed to analyze the relationships between clinical motor function of the paretic upper limb and kinematic variables in paretic upper limb reaching performance. Statistical tests were performed with SPSS 13.0 computer package (SPSS, Inc., Chicago, USA).

3. Results

The results of descriptive statistics of the clinical motor assessments and kinematic measures of reaching from the paretic upper limb are shown in Table 1. Principal component factor analysis was used to identify the conceptual measure constructs in reaching for all subjects. The indicator of sampling adequacy (Kaiser-Meyer-Olkin measure = .63, which was greater than .6) and the identity matrix test of correlation matrix (Barlett's tests of sphericity were significant, $p < 0.01$) indicated that factor analysis was satisfactory to process our data. Exploratory factor analysis showed that there were two common factors (major conceptual measurement constructs) in the measure of paretic upper limb reaching performance. Common factor 1 included MT, PV, and NJSM (eigenvalue = 2.56). Common factor 2 included NMU and PTPV (eigenvalue = 1.16) (Table 2). The two common factors could explain 80.83% (common factor 1: 57.94%, common factor 2: 22.89%) of the total variance of reaching performance. The space of factor loading for each kinematic variables loading on the two common factors is presented in Figure 3.

Table 1. Descriptive statistics for the scores of assessment in paretic upper limb motor impairment and kinematics of reaching (n = 40).

Variables	Minimum	Maximum	Mean	SD
FMA	32	63	52.30	10.11
MAS	0	3	1.10	1.08
NMU	1	4	1.33	0.71
MT (sec)	0.29	1.83	0.79	0.35
PV(cm/sec)	35	193.47	107.84	44.08
NJSM	9.78	272.04	53.70	58.56
PTPV (%)	20.59	68.57	40.74	9.21

FMA: Fugl-Meyer Upper Limb Motor Assessment Scale; MAS: modified Ashworth Scale; NMU: number of movement units; MT: movement time; PV: peak velocity; NJSM: normalized jerk score of movement; PTPV: percentage time of reach where peak velocity occurred.

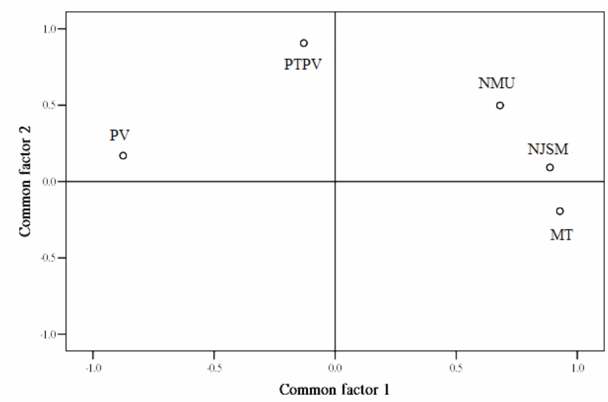

Figure 3. Plot of the kinematic reaching variables loading on the 2 common factors in space. (NMU: number of movement units; MT: movement time; PV: peak velocity; NJSM: normalized jerk score of movement; PTPV: percentage time of reach where peak velocity occurred)

The correlations between clinical motor assessments and kinematic measure are shown in Table 3. FMA was significantly correlated to NMU (r = -.45, p = .003), MT (r = -.45, p = .004), PV (r = .51, p = .001), NJSM (r = -.53, p = .001). MAS was significantly correlated to NMU (r = .40, p = .01), PV (r = -.38, p = .016) and NJSM (r = .37, p = .020).

Table 2. Common factors and factor loading of variables in kinematic measure of reaching (n = 40).

	Common factor	
	1	2
MT	**.93**	
NJSM	**.89**	
PV	**-.88**	
NMU	**.67**	**.50**
PTPV		**.72**

Common factor 1: movement speed and smoothness measure construct
Common factor 2: movement control strategy measure construct
NMU: number of movement units; MT: movement time; PV: peak velocity; NJSM: normalized jerk score of movement; PTPV: percentage time of reach where peak velocity occurred

Table 3. Correlation coefficients between clinical motor function measures and reaching kinematic measures (n = 40).

	NMU	MT	PV	NJSM	PTPV
FMA	-.45**	-.45**	.51***	-.53***	.02
MAS	.40**	.29	-.38*	.37*	.06

* p < .05 , ** p < .01, *** p < .001
FMA: Fugl-Meyer Upper Limb Motor Assessment Scale; MAS: modified Ashworth Scale; NMU: number of movement units; MT: movement time; PV: peak velocity; NJSM: normalized jerk score of movement; PTPV: percentage time of reach where peak velocity occurred

4. Discussion

Findings in this study showed that there were two common factors found in the kinematic measure of reaching. These two common factors could be applied to explain 80.83% (common factor 1: 57.93%, common factor 2: 22.89%) of the total variance of reaching performance. Additionally, both clinical motor function (FMA) and abnormal muscle tone (MAS) were significantly correlated to some of the reaching kinematic variables, such as MT, PV, and NJSM.

For a normal and well-controlled reaching, in which the motor program may not rely heavily on feedback loops to correct the ongoing movement, the movement speed was faster, smoother, the velocity profile was belly-shape and the percent time of peak velocity usually occurred between 33% and 50% [17,35-37]. The constructs of kinematic measure of reaching, for patients after stroke, may be reduced to variables relative to movement speed and smoothness measure construct [38-41], and to variables relative to movement control strategy measure construct [37,42-43]. Such finding suggests that MT, PV, NMU and NJSM are significantly correlated with measure of the characteristics of reaching performance, and these kinematic reaching variables appear to be the most important measurements to quantify the reaching performance. Additionally, a comprehensive measure of reaching performance should also include the measure of movement control strategy, which may include PTPV and NMU. Our results support that kinematic measures of movement speed, movement smoothness, and movement control strategy are needed to adequately quantify the performance of reaching in patients with stroke.

Peak velocity corresponds to the changeover between acceleration and deceleration phases, and its occurrence within the velocity profile is an indicator for type of movement control strategy [18,37,42]. Normal reaching with PTPV greater than 33% is considered to be controlled by feed forward strategy, and allows subjects to execute preplanning movement without the need of sensory feedback. On the other hand, subjects with abnormal reaching will demonstrate more than 2 movement units, and visual feedbacks are needed during performing reaching activities. The results of this study showed that PTPV and NMU were loaded on the movement control strategy common factor. Correlation analysis showed that PTPV did not correlated significantly with the motor function tests (FMA and MAS), while NMU had significant correlation with FMA and MAS. On the contrary, most of the variables, loading on movement speed and movement smoothness common factor, showed moderately significant correlations with the clinical motor function tests. Such results were in accordance with the findings in factor analysis that the two common factors would be different in dimension of measure reaching performance. Additionally, our study supported that NMU could reflect the characteristics of both measure concepts in reaching performance for patients after stroke.

The measure of NMU in reaching is determined by the number of peaks presenting in the velocity profile of the paretic upper limb reaching movement. This variable provides information about the smoothness and efficiency of a movement [30,32]. From the definition of NMU, subject with larger NMU would demonstrate longer deceleration period, and feedback control would be more dominant during performing a reaching movement [32,41]. Additionally, larger number of movement units indicates a less smooth, slower and less efficient reaching movement, which was observed in stroke patients with lower upper limb motor function and severe spasticity. This is the reason why NMU was correlated with FMA and MAS and loaded on both common factors in our study. Findings in this study indicate that use of NMU as an index to reflect the control strategy might provide more effective and valuable information than use of PTPV in monitoring of reaching performance for stroke patients.

In clinical setting, movement time or speed is an easily acquired measure to indicate the coordination skill of motor control for a specific movement or task [23]. Measure of movement smoothness is another important variable for inspecting the progression of movement control following neurological disorders [24,44-45]. The PV score may reflect the level of force generation in a reaching movement. This study found that MT, PV, NJSM, and even NMU were highly loaded on the same common factor. It demonstrated that PV was also significantly correlated to movement speed and movement smoothness. Moreover, variables loading on movement speed and movement smoothness common factor were also moderately correlated with clinical motor function scales (FMA and MAS). These findings suggests that measuring the characteristics of movement speed and smoothness will be more effective than measuring of movement control strategy in quantifying the degrees of motor impairment for reaching performance in patients with stroke.

There was a limited number of subjects for reaching observations in this study, and the reliability of variables loading on the conceptual measure constructs might be affected. Stevens [46] indicated that the number of observations required for factors to be reliable depended on the data, in particular, on how well the variables loaded on the different factors. He suggested that a factor was reliable if it had three or more variables with loading of 0.8 for any number of subjects. According to this criterion, the validity and reliability of the results of analyzing the constructs of kinematic measures in reaching performance by kinematic measures for patients after stroke in this study may be acceptable.

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