Estimation and Evaluation of Upper Limb Endpoint Stiffness and Joint Torques for Post-stroke Rehabilitation

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Abstract—**This research was aimed to investigate biomechanical properties via estimation of upper limb endpoint stiffness and joint torques during force targeting tasks. Sixteen able-bodied subjects were recruited in the study. A 10-N force task was conducted at right and left force directions for three upper limb postures. Hand endpoint trajectories and the response forces were recorded simultaneously for each trial. The 2x2 endpoint stiffness matrix and corresponding stiffness ellipse were determined by least squares error method. Resultant shoulder and elbow torques were also calculated by inverse kinetics. Mann-Whitney U test and Kruskal-Wallis test was used to analyze the effect of movement directions and postures on endpoint stiffness and joint torques. The results indicated that the force directions and postures have significant effects on endpoint stiffness ellipse of upper limb, the shoulder and elbow joint torques during force production tasks (p<0.05). These results demonstrate the importance of the force directions and posture during performing force targeting tasks. The future work of clinical implementation suggests that upper-limb endpoint stiffness and viscosity can be measured and compared with able-bodied subjects and post-stokes.**

Keywords— **Stroke, upper-limb, endpoint stiffness, rehabilitation**

I. INTRODUCTION

Stroke is an acute onset of neurological dysfunction when blood flow to the brain is impaired by infarction or hemorrhage of cerebral arteries [1]. The most common motor deficits are characterized by hemiparesis or hemiplegia, typically on one side of the body opposite the site of the lesion [1]. The illness stages of stroke usually accompany the development of abnormal muscle tone, flexion and extension synergistic patterns [1]. Functional impairments of upper limb are always more severe than those of lower limb for deteriorated activities of daily living (ADL). It has been reported that 88% of the post-strokes suffer from paretic upper limbs in acute stages and 55-75% ones remain the paretic deficits after six months or more [2].

According to equilibrium-point control hypothesis, the neuromuscular system conducts a control mechanism based on the mechanical stability of viscoelastic properties [8]. Particularly, viscoelastic muscle properties, length-tension and force-velocity relationship, lead to joint translation and rotation. Previous researches have suggested the spring-like properties of muscles determine the individual joint stiffness. Endpoint stiffness, defined as the relationship between externally imposed displacements of the hand and the respond force generated, stabilizes the hand position. [3,4]. The resultant elastic resistance is not only due to joint stiffness, but depends on the posture-dependent joint angles and respective limb segment lengths [4, 5]. Furthermore, stability of hand can be characterized by endpoint stiffness ellipse. The major axis of the ellipse is oriented along the direction of the maximal stiffness; the minor one is oriented along the minimal stiffness, and the orientation indicated the direction of the maximal stiffness [6]. The capability to control maximum and minimum stiffness orientation could permit adjustable flexibility during tasks with direction-dependent constraints such as ball-catching, where increased joint stiffness is only required along the line of impact of the ball with the hand, or during object manipulation [7].

This research is to investigate the effects of force directions and postures on endpoint stiffness and joint torques during performing voluntary force task. More specifically, this research is aimed to:

1. Investigate the effects of voluntary force directions and postures endpoint stiffness of upper limb during force production tasks.
2. Apply endpoint stiffness ellipse to quantify stability of hand.
3. Develop a feasibility study on normal subjects.

II. MATERIALS AND METHODS

A. Endpoint stiffness modeling

The two-link and open kinematic chains was conducted to simulate the kinematic model of upper limb in this research. The upper-limb system assumes that endpoint inertia is invariant across every trail. The resulting parameterized system is shown as follows [7]:

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$$H_{ij}(s)= I_{ij}s^2+ B_{ij}s+K_{ij}\,; \tag{1}$$

where $s=2\pi f\sqrt{-1}$ *and* I_{ij}, B_{ij}, and K_{ij} represents the endpoint inertia, viscosity, and elasticity matrices, respectively. Eq. 2 shows the endpoint stiffness matrix that indicates the effects of restoring force opposite to the displacement.

$$[I_{end}]\begin{bmatrix}\ddot{x}\\ \ddot{y}\end{bmatrix}+[B_{end}]\begin{bmatrix}\dot{x}\\ \dot{y}\end{bmatrix}+[K_{end}]\begin{bmatrix}x\\ y\end{bmatrix}=\begin{bmatrix}f_x\\ f_y\end{bmatrix}\;; \tag{2}$$

where $I_{end}=\begin{bmatrix}I_{xx} & I_{xy}\\ I_{yx} & I_{yy}\end{bmatrix}$, $B_{end}=\begin{bmatrix}B_{xx} & B_{xy}\\ B_{yx} & B_{yy}\end{bmatrix}$, $K_{end}=\begin{bmatrix}K_{xx} & K_{xy}\\ K_{yx} & K_{yy}\end{bmatrix}$

indicates inertia, viscosity, and elasticity matrices, respectively.

Eq. 3 shows joint stiffness matrix related to shoulder and elbow joint torques is determined by inverse dynamics, as shown in, where the Jacobian, J, is a function of the limb segment lengths and joint angles [7]. The orientation of the endpoint stiffness ellipse is determined by the direction of the eigenvector associated with the maximum eigenvalue of the endpoint stiffness matrix. The ratio of endpoint stiffness ellipse is determined from the long axis divided by short axis and means to the shape of the endpoint stiffness ellipse.

$$\begin{bmatrix}TQ_s\\ TQ_e\end{bmatrix}=J^T K_{end}\begin{bmatrix}dx\\ dy\end{bmatrix} \tag{3}$$

where TQ_s indicates shoulder joint torque, TQ_e indicates elbow joint torque.

$$J=\begin{bmatrix}-l_h\sin(\theta_s)-l_f\sin(\theta_s+\theta_e) & -l_f\sin(\theta_s+\theta_e)\\ l_h\cos(\theta_s)+l_f\cos(\theta_s+\theta_e) & l_f\cos(\theta_s+\theta_e)\end{bmatrix}$$

where l_h refers upper arm length , l_f refers forearm length, θ_s refers shoulder joint angle , θ_e refers elbow joint angle.

B. Subjects and protocol

Sixteen subjects (nine male and seven female) ranging from 23 to 28 years-old with no history of neurological impairments were participated in this study. The protocol was approved by human experiment and ethics committee of National Cheng Kung University Hospital, ROC. The informed consent was signed by subject prior to study. Total two force directions and three seating positions for this study: D0 and D4 was right and left force direction, central position was defined subject's hand located 40 cm far in front of sternum, left and right position were defined apart one-thirds shoulder girdle width from central position, respectively. Subject accomplished with right arm 10N exertion. Table 1 shows demographic and anthropometric data for all subjects included:

1. L_h measured from right acromion process of scapula to lateral epicondyle of humerus,
2. L_f measured from the right lateral epicondyle of humerus to styloid process of radius,
3. shoulder joint angle at right position (RSangle), central position (CSangle), left position (LSangle)
4. elbow joint angle at right position (REangle), central position (CEangle),left position (LEangle).

Table 1 Demographic datas of subjects

Item	Mean	Standard Deviation
Age (y/o)	25.3	1.3
Height (cm)	167.1	6.1
Weight (kg)	61.4	8.2
L_h (cm)	30.4	1.8
L_f (cm)	26.7	1.7
RSangle (deg)	97.1	11.6
REangle (deg)	31.9	10.3
CSangle (deg)	72.3	5.0
CEangle (deg)	51.5	8.6
LSangle (deg)	51.8	13.7
LEangle (deg)	52.5	7.2

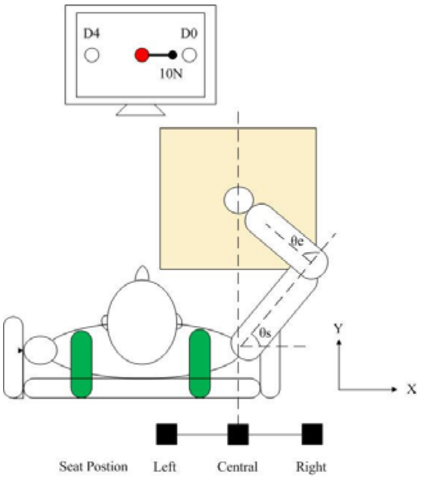

Fig. 1 Experimental setup.

There were totally 6 conditions (2 direction targets × 3 sitting position) in the experiment (Fig.1) [8]. Experiment procedures were:

1. Initial endpoint position on the screen was centered on the start window.
2. Subjects were instructed to push the robotic manipulandum according to the appearing target.

3. As subject exerted with 10-N for 6 seconds, displacement perturbation with 1cm was applied .
4. There were 8 perturbation directions from 0° to 360.

There were three trials in a set of the force production task, and every trial contained four times of the random perturbations. The subject took a rest about 30 to 60 seconds between trials for avoiding muscle fatigue.

C. Statistical analysis

Kruskal-Wallis test was used to analyze the effect of postures on endpoint stiffness and joint torques. Mann-Whitney U test was used to analyze the effect of voluntary force direction on endpoint stiffness and joint torques. The significance level was at a 0.05 level.

III. PRELIMINARY RESULTS AND DISCUSSION

This research has designed and developed a 2-D platform system for objectively endpoint assessment and training through conceptual and functional design [8], hardware selection and integration, calibration and performance testing. The hardware included 2 servo-motor and encoders (SV4835, King Right Motor Corporation, Taiwan), two force transducers (RVQ16YN, Cosmos, Jin Hua Electronic CO.LTD., Taiwan), and two slide mechanisms, one stainless steel manipulandum and iron frame. There are two mainly operating modes of this system: active and passive movement modes. The passive movement mode contains two evaluation and training functions: relaxation and force target functions. This research selects the force target function from the passive movement mode to investigate the biomechanical properties of upper-limb endpoint stiffness and joint torques during tasks.

Table 2 shows the median of endpoint stiffness matrix estimated from 6 conditions . Table 3 shows the median of long axis, orientation, and ratio of the endpoint stiffness ellipse. Table 4 shows the median of shoulder and elbow joint torques. Fig. 2 shows the endpoint stiffness ellipse of one subject (No. 12) at force direction D0 for various postures.

The results of statistical analysis have revealed that :

1. The force directions have significant effects on endpoint stiffness of upper limb except long axis length (p<0.05) , shown in Table 5.
2. The postures have significant effects on endpoint stiffness ellipse of upper limb, the shoulder and elbow joint torques (p<0.05) , shown in Table 6.

The limitations of research may include the variations in the individual limb configuration, movement velocity and small sample sizes.

Table 2 Median of endpoint stiffness matrix

Positions	Force direction	N	Endpoint stiffness matrix (N / m)
Left	D0	16	$\begin{bmatrix} -36.67 & 4.50 \\ 21.29 & 274.61 \end{bmatrix}$
	D4	16	$\begin{bmatrix} -68.03 & 9.19 \\ 26.17 & -241.59 \end{bmatrix}$
Central	D0	16	$\begin{bmatrix} -101.71 & 40.62 \\ 126.06 & -302.90 \end{bmatrix}$
	D4	16	$\begin{bmatrix} -163.09 & 56.88 \\ 141.48 & -246.81 \end{bmatrix}$
Right	D0	16	$\begin{bmatrix} -106.00 & 66.79 \\ 149.62 & -270.09 \end{bmatrix}$
	D4	16	$\begin{bmatrix} -159.67 & 75.14 \\ 147.76 & -197.66 \end{bmatrix}$

Table 3 Median of parameters of endpoint stiffness ellipse

Position	Target direction	N	Long axis (m)	Orientation (deg)	Raito
Left	D0	16	642.2	128.6	9.1
	D4	16	506.2	132.0	7.6
Central	D0	16	797.0	122.7	10.9
	D4	16	910.1	129.6	9.3
Right	D0	16	868.4	103.5	4.9
	D4	16	754.1	109.1	5.2

Table 4 Median of the shoulder and elbow joint torques

Position	Target direction	TQs (Nm)	TQe (Nm)
Left	D0	-3.39	-1.14
	D4	3.39	1.14
Central	D0	-2.11	0.77
	D4	2.11	-0.77
Right	D0	-0.98	2.05
	D4	0.98	-2.05

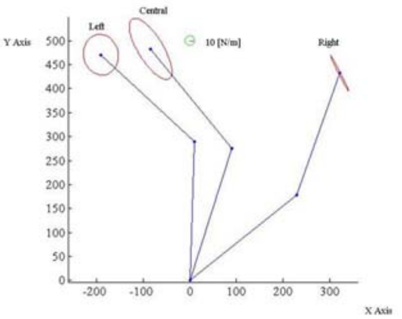

Fig. 2 Result of endpoint stiffness ellipse for subject No.12.

Table 5 Mean ranks of endpoint stiffness parameters .

	D0	D4
Long axis (m)	147.72	141.28
Orientation (deg)	147.72	141.28 *
Shape	155.92	133.08 *
TQs (Nm)	173.82	115.18 *
TQe (Nm)	74.20	214.80 *

*p< 0.05

Table 6 Mean ranks of endpoint stiffness parameters.

		Centel	Right	Left
Long axis	D0	28.38	28.69	16.44 *
	D4	29.50	27.88	16.13 *
Orientation	D0	26.06	34.38	13.06 *
	D4	27.88	33.00	12.63 *
Shape	D0	27.34	16.47	29.69 *
	D4	29.38	17.13	27.00 *
TQs	D0	25.13	38.75	9.63 *
	D4	23.88	10.25	39.38 *
TQe	D0	25.09	39.00	9.41 *
	D4	23.91	10.00	39.59 *

*p< 0.05

IV. CONCLUSIONS

The results have revealed that the endpoint stiffness model of upper-limb shows the potential advantage for functional test and evaluation in force production tasks. The upper-limb system may provide more equilibrium state due to the more isotropic endpoint stiffness ellipse, as the force direction and endpoint position are closer to shoulder joint. More subjective and objective experiments will be developed to:

1. Investigate the endpoint viscosity of the multi-joint system.
2. Compare the endpoint stiffness and viscosity variations between able-bodied subjects and post-stokes.

REFERENCES

1. O'Sullivan SB, Schmitz TJ (2003) Physical Rehabilitation: Assessment And Treatment. FA Davis, Philadelphia.
2. Cirstea MC, Ptito A, Levin MF et al (2003) ,Arm reaching improvements with short-term practice depend on the severity of the motor deficit in stroke. Exp Brain Res 152: 476-488.
3. Milner TE (2002) Contribution of geometry and joint stiffness to mechanical stability of the human arm. Exp. Brain Res 143:515–519
4. Perreault EJ, Kirsch RF, Crago PEl. (2001) Effects of voluntary force generation on the elastic components of endpoint stiffness. Exp Brain Res 141(3), pp. 312-323
5. Perreault EJ, Kirsch RF, and Crago PE. (2004) Multijoint dynamics and postural stability of the human arm. Exp Brain Res 157(4): pp. 507-517
6. Zatsiorsky VM. (2002) *Kinetics of Human Motion*. Human Kinetics, Leeds , Champaign
7. Mussa-Ivaldi FA, Hogan N, et al. (1985) Neural, Mechanical, and Geometric Factors Subserving Arm Posture in Humans. J Neurosci 5(10), pp.2732-2743
8. PR Wang, JY Chang, KC Chung (2008) Effects of Upper-Limb Posture on Endpoint Stiffness during Force Targeting Tasks, IFMBE Proc. vol. 23, 13th International Conference on Biomedical Engineering, Singapore, 2008, pp 1862–1865

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