Published in final edited form as:
Conf Proc IEEE Eng Med Biol Soc. 2008 ; 2008: 3558–3561. doi:10.1109/IEMBS.2008.4649974.

Altered Multijoint Reflex Coordination is Indicative of Motor Impairment Level following Stroke

Randy D. Trumbower,
Sensory Motor Performance Program at The Rehabilitation Institute of Chicago, Chicago, IL 60611 (phone: 312-238-2227; fax: 312-238-2208)

Vengateswaran J. Ravichandran,
Sensory Motor Performance Program at The Rehabilitation Institute of Chicago and Department of Biomedical Engineering at Northwestern University, Evanston, IL 60611

Matthew A. Krutky, and
Sensory Motor Performance Program at The Rehabilitation Institute of Chicago and Department of Biomedical Engineering at Northwestern University, Evanston, IL 60611

Eric J. Perreault
Sensory Motor Performance Program at The Rehabilitation Institute of Chicago and Departments of Biomedical Engineering and Physical Medicine & Rehabilitation at Northwestern University, Chicago, IL 60611

Randy D. Trumbower: r-trumbower@northwestern.edu; Vengateswaran J. Ravichandran: vennjr@northwestern.edu; Matthew A. Krutky: ; Eric J. Perreault: e-perreault@northwestern.edu

Abstract

Following stroke, individuals often are unable to activate their elbow and shoulder muscles independently. There is growing evidence that altered reflex pathways may contribute to these abnormal patterns of activation or muscle synergies. Most studies investigating reflex function following stroke have examined only individual joints at rest. Thus, the purpose of this study was to quantify multijoint reflex contributions to the stereotyped muscle synergies commonly observed following stroke. We hypothesized that the patterns of reflex coordination mirror the abnormal muscle coactivity patterns previously reported for voluntary activation. 10 chronic stroke and 8 age-matched control subjects participated. Reflexes were elicited by perturbing the arm with a 3 degree of freedom robot while subjects exerted voluntary forces at the elbow and shoulder. The force conditions tested were selected to assess the influence of gravity and the influence of joint torque generation without gravity on reflex coordination. Reflex magnitude was quantified by the average rectified electromyogram, recorded from 8 muscles that span the elbow and shoulder. Patterns of reflex coordination were quantified using independent components analysis. Results show significant reflex coupling between elbow flexor and shoulder abductor-extensor muscles in stroke patients during isolated elbow and shoulder torque generation and during active arm support against gravity. Identified patterns of stretch reflex coordination were consistent with the stereotyped voluntary flexion synergy, suggesting reflex pathways contribute to abnormal muscle coordination following stroke.

I. INTRODUCTION

Multijoint coordination is impaired following stroke and largely restricted by abnormal patterns of muscle activation within the hemiparetic limb, clinically referred to as muscle synergies [1]. In the upper limb, this generally involves coupling of elbow flexion with shoulder abduction-extension-external rotation, and to a lesser extent, coupling of elbow extension with shoulder adduction-flexion-internal rotation [2]. This abnormal muscle coactivation leads to

perceptible weakness at the elbow, which is dependent on the torques generated at the shoulder [3]. There is growing evidence that proprioceptive feedback, mediated through stretch reflex pathways, may contribute to these muscle synergies.

Stretch reflexes are known to be disrupted following stroke. Cortical injury results in reorganization of new neural connections, which lead to changes in strength of reflex excitability and substantial influence on spinal networks [4]. Gains in proprioceptive feedback, regulated through stretch reflex pathways, are significantly enhanced, as evidenced by greater muscle activity in response to limb movement [5], but it is not clear how altered stretch reflexes contribute to impaired muscle coordination during active control of limb mechanics post-stroke. Investigations quantifying reflex function have primarily focused on passive, single joint conditions [6]. Although these studies are useful for characterizing the abnormal state of spastic muscles, their results make it difficult to fully appreciate their functional relevance under more natural multijoint conditions, relevant to control of arm posture.

Thus, this study examined the regulation of multijoint stretch reflex responses in persons with hemiparetic stroke. We hypothesized that stretch reflexes contribute to reduced limb coordination via excessive reflex coupling between muscles controlling the shoulder and elbow. This was examined during two active loading conditions. The first involved the generation of torques at the elbow and shoulder without gravity, and the second involved supporting the limb against gravity. Performance on both of these tasks is impaired following stroke. Our findings suggest that stretch reflexes contribute to abnormal muscle coupling in a load-dependent manner. This reflex sensitivity has important implications for the clinical assessment and management of stroke patients.

II. METHODS

A. Subjects

Experiments were performed on 10 adults with chronic stroke (54 ± 12 years old; Fugl-Meyer score 36 ± 11) and 8 age-matched controls. All protocols were approved by the Northwestern University Institutional Review Board, and required informed consent. Control subjects had no history of neurological impairments. Stroke subjects underwent an evaluation by a physical therapist to determine their eligibility for participation. The following inclusion criteria were used: 1) single stroke resulting in motor deficits of the arm, 2) absence of muscle tone and sensorimotor deficits in the uninvolved arm, 3) no receptive aphasia, 4) spasticity in elbow flexors/extensors with a modified Ashworth score of 1 or greater, and 5) ability to follow two-step commands. Subjects were excluded if they had history of 1) pain in upper extremity with lifting, 2) inability to attain and maintain testing position with forearm secured in a wrist orthosis, 3) inability to provide informed consent, and 4) significant musculoskeletal injuries (e.g., fracture) and/or medical complications. We recorded the Fugl-Meyer Assessment of Motor Recovery as a measure of arm motor impairment [7].

B. Equipment

Stretch reflexes were elicited using a series of ramp-and-hold displacements (Fig. 1A), applied by a 3 DOF robot [HapticMaster; FCS Control Systems, The Netherlands].

Many stroke patients have difficulty supporting their arm against gravity. Hence, arm support was provided by a customized version of the Wilmington Robotic Exoskeleton (WREX) [8]. The WREX has 4 degrees-of-freedom (DOF) allowing for shoulder flexion/extension, abduction/adduction, internal/external rotation, and elbow flexion/extension. It consists of two rigid 4-bar linkages and includes linear elastic bands that connect to these linkages, thereby providing gradable levels of gravity compensation. A 1DOF load cell [Transducer Techniques,

Temecula, CA] was used to measure the arm support provided by these elements. The sizing of the WREX was customized for each subject.

Subjects maintained a common arm posture throughout the experiment. Subjects were seated with their trunk securely strapped to a rigid chair. The tested arm was positioned such that the center of the hand was directly in line with the front of the glenohumeral joint, the shoulder abducted by 70 degrees, and the elbow flexed to 90 degrees, resulting in a shoulder horizontal flexion angle of approximately 50 degrees.

Surface electromyograms (EMGs) were recorded from 8 muscles that span the shoulder and elbow joints (Table 1). Many of these muscles have been implicated in abnormal voluntary synergies during isometric force tasks following stroke [9]. The EMG signals were recorded with bipolar surface electrodes [Noraxon USA, Inc., Scottsdale, AZ]. The resulting signals were amplified, anti-alias filtered using 8^{th} order Bessel filters with a cutoff frequency of 500Hz, and sampled at 1250Hz. A common clock was used to synchronize the EMG data with the robotic controller.

C. Experimental Protocol

We examined the effects of two voluntary loading conditions on multijoint reflex activity. The first was to assess the influence of gravity, while the second was to assess the influence of isolated torques generated at the shoulder or elbow. Gravity compensation was adjusted with the WREX to provide full, partial, or greater than full arm support while subjects were asked to remain relaxed, lift up, or press down with their arm to maintain posture, respectively. During full arm support, subjects were asked to generate flexion and extension torques of the elbow and shoulder. Visual feedback was provided to assist subjects in maintaining the desired endpoint force and arm posture. Perturbations were applied while subjects performed each force task. We used a random sequence of 12–14 ramp-and-hold perturbations oriented along the positive and negative directions of each measurement axis (Fig. 1B). The displacement (25mm) and velocity (400mm/s) of each perturbation were sufficient to elicit reflexes in able-bodied individuals [10]. The random interval between successive movements was distributed from 1.0 to 1.5sec. Each trial lasted approximately 10sec and contained 1 perturbation in one of the 6 measurement directions. A total of 42 experimental conditions were collected (7 force conditions × 6 perturbation directions).

III. DATA ANALYSIS

A. EMG processing

Reflex responses were quantified by the mean rectified EMGs for 0–100msec following perturbation onset and normalized to MVC as detailed in [11]. To quantify reflex responses relative to background muscle activity, we subtracted the mean normalized voluntary activity 50ms prior to perturbation onset from the normalized reflex responses. We also quantified the relative change in voluntary activity by subtracting the voluntary activity of the passive condition from each active condition.

B. Dimensionality reduction

The goal of this study was to quantify the reflex coordination patterns elicited in response to arm perturbations and to characterize the activation of these patterns across loading conditions. Coordination patterns and reflex activations were estimated using independent component analysis preceded by principal component analysis (ICA/PCA). This technique was selected based on previous work demonstrating its capacity to estimate EMG coordination patterns [12]. Equation (1) was used

$$\vec{E}=\sum_{i=1}^{N} c_i \vec{w}_i \quad (1)$$

to reduce the reflex EMGs (E) across muscles to N eight-muscle coordination patterns (w_i) multiplied by the activation coefficients (c_i). We determined N by applying PCA to reduce the reflex EMG data to the fewest number of orthogonal components that accounted for 90% of the data variance. ICA was applied to the reduced EMG data to determine the coordination patterns. We hypothesized that altered reflex coordination following stroke could be described either by differences in muscle patterns (w_i) or by differences in reflex activations (c_i) of similar patterns relative to controls. Reflex activations were computed using the root-mean-square of the activation coefficients for each force condition and then normalized to the root-mean-square of the activation coefficients across all subjects, force conditions, and coordination patterns.

IV. RESULTS

A. Stretch reflex characteristics

Stretch reflex responses were significantly larger in stroke subjects relative to the age-matched controls across all conditions ($p<0.05$). Typical normalized responses from a stroke subject and a control subject are shown in Fig. 2. These data were collected as subjects generated voluntary torques about the elbow while the robot perturbed their arm along both directions of the x-axis.

B. Assessment of reflex coordination patterns

We used PCA/ICA to estimate the coordination patterns of reflex activity for the two groups. The number of reflex patterns was reduced in the stroke subjects as compared to the control subjects. As shown in Fig. 3, the stroke group converged to 90% variance accounted for (VAF) earlier than the control group (*$p<0.05$). We found that the stroke subjects required 3 patterns on the average as compared to the control subjects who on average required 4 patterns (**$p<0.01$). A similar analysis on the voluntary EMG was found not to be significantly different between groups; no more than 3 patterns were necessary to account for >90% of the background EMG variance.

The reflex coordination patterns observed in the stroke group were similar to the 3 dominant patterns observed in the control group (Fig. 4). Bar heights in each pattern correspond to the relative activation of each muscle; the magnitudes of the components within each pattern vector are normalized to unity. Percentages above each pattern indicate the relative variance described by that pattern. Statistical significance corresponds to plotted values significantly different from chance (*$p<0.05$). The flexion pattern consisted of increased BRD, BI, MD, and PD activity coupled with reduced PC activity; this pattern accounted for more than twice the variance as the most similar pattern in the control group. The second pattern consisted primarily of BI, AD, and PC activity, which we defined as the shoulder flexion pattern; it accounted for similar data variance in both groups. Likewise, the third pattern consisted of TRI_L and TRI_{LAT}, which we defined as the elbow extension pattern. The fourth pattern was significant only in the control group and consisted of TRI_L, TRI_{LAT}, MD, and PD excitation, which we referred to as the extension pattern.

C. Assessment of reflex activations

Reflex activations for the same dominant set of 3 coordination patterns were significantly different between the stroke and control groups. The differences in reflex activation were most evident for the flexion pattern. Specifically, we found significantly greater reflex activation in

stroke subjects during the elbow flexion and shoulder extension torque conditions ($p<0.01$), as well as, gravity opposition ($p<0.01$). During these loading conditions, the relative voluntary activity of the elbow flexors and shoulder extensors (flexion pattern) was not statistically different between groups. Hence, the observed changes in reflex coordination were not simply due to corresponding differences in the voluntary activity of the monitored muscles.

The reflex activation of the flexion pattern in the stroke subjects, which accounted for the majority of the reflex variance, scaled with motor impairment score. The flexor pattern was greatest in response to perturbations along the -x direction, which extended the elbow and flexed the shoulder, and the magnitude of its activation scaled with Fugl-Meyer scores (Fig. 5). This relationship held only for the active task ($R^2=0.63$, $*p<0.05$), not the more commonly studied passive condition.

V. DISCUSSION

This study quantified the regulation of multi-joint stretch reflexes following stroke. Our results support the hypothesis that the impaired coordination between the elbow and shoulder that exists during voluntary muscle activation also exists in the involuntary stretch reflex responses. We found that the expression of abnormal reflex patterns was not solely due to changes in voluntary activity of muscles contributing to the clinically defined flexion synergy. Increased voluntary activity of shoulder muscles while the subjects opposed gravity or attempted to generate isolated shoulder torque coincided with increased reflex sensitivity of elbow flexors characteristic of the flexion pattern. This indicates that stretch reflex gains following stroke operate in a load-dependent manner with a bias that results in reflex patterns that mirror the abnormal voluntary flexion synergy. We did not find evidence for reflexes that resemble the abnormal voluntary extension synergy also observed following stroke, but generally weaker than the flexion synergy.

Abnormal reflex activation also was found to be related to the extent of motor impairment. The expression of a reflex bias corresponding to the abnormal flexion pattern scaled linearly with Fugl-Meyer scores during active loading. Although past studies have not observed a relationship between stretch reflexes and motor impairment, this may be due to the fact that most examined changes in reflex excitability under passive, single joint conditions. Our findings suggest that multijoint reflex coupling, under active conditions, may be a marker and possibly a contributor to altered limb function following stroke.

Acknowledgments

This work was supported by NIH grants K25 HD044720 and NS053813.

REFERENCES

1. Brunnstrom, S. Movement Therapy in Hemiplegia: A Neuropsychological Approach. New York: Harper and Row; 1970.
2. Dewald JP, Beer RF. Abnormal joint torque patterns in the paretic upper limb of subjects with hemiparesis. Muscle Nerve 2001 Feb;vol. 24:273–283. [PubMed: 11180211]
3. Beer RF, Ellis MD, Holubar BG, Dewald JPA. Impact of gravity loading on post-stroke reaching and its relationship to weakness. Muscle & Nerve 2007 Aug;vol. 36:242–250. [PubMed: 17486581]
4. Nudo RJ, Plautz EJ, Frost SB. Role of adaptive plasticity in recovery of function after damage to motor cortex. Muscle Nerve 2001;vol. 24:1000–1019. [PubMed: 11439375]
5. Thilmann AF, Fellows SJ, Garms E. The Mechanism of Spastic Muscle Hypertonus - Variation in Reflex Gain over the Time Course of Spasticity. Brain 1991 Feb;vol. 114:233–244. [PubMed: 1998884]

6. Condliffe EG, Clark DJ, Patten C. Reliability of elbow stretch reflex assessment in chronic post-stroke hemiparesis. Clinical Neurophysiology 2005 Aug;vol. 116:1870–1878. [PubMed: 15979400]
7. Fugl-Meyer AR, Jaasko L, Leyman I, Olsson S, Steglind S. The post-stroke hemiplegic patient. Scand J Rehabil Med 1975;vol. 7:13–31. [PubMed: 1135616]
8. Sanchez RJ, Liu JY, Rao S, Shah P, Smith R, Rahman T, Cramer SC, Bobrow JE, Reinkensmeyer DJ. Automating arm movement training following severe stroke: Functional exercises with quantitative feedback in a gravity-reduced environment. IEEE Transactions On Neural Systems And Rehabilitation Engineering 2006 Sep;vol. 14:378–389. [PubMed: 17009498]
9. Dewald JP, Pope PS, Given JD, Buchanan TS, Rymer WZ. Abnormal muscle coactivation patterns during isometric torque generation at the elbow and shoulder in hemiparetic subjects. Brain 1995;vol. 118:495–510. [PubMed: 7735890]
10. Lewis GN, Perreault EJ, MacKinnon CD. The influence of perturbation duration and velocity on the long-latency response to stretch in the biceps muscle. Exp Brain Res 2005 Jun;vol. 163:361–369. [PubMed: 15654583]
11. Perreault EJ, Chen K, Trumbower RD, Lewis G. Interactions with compliant loads alter stretch reflex gains but not intermuscular coordination. J Neurophysiol 2008 May;vol. 99:2101–2113. [PubMed: 18287550]
12. Tresch MC, Cheung VC, d'Avella A. Matrix factorization algorithms for the identification of muscle synergies: evaluation on simulated and experimental data sets. J Neurophysiol 2006 Apr;vol. 95:2199–2212. [PubMed: 16394079]

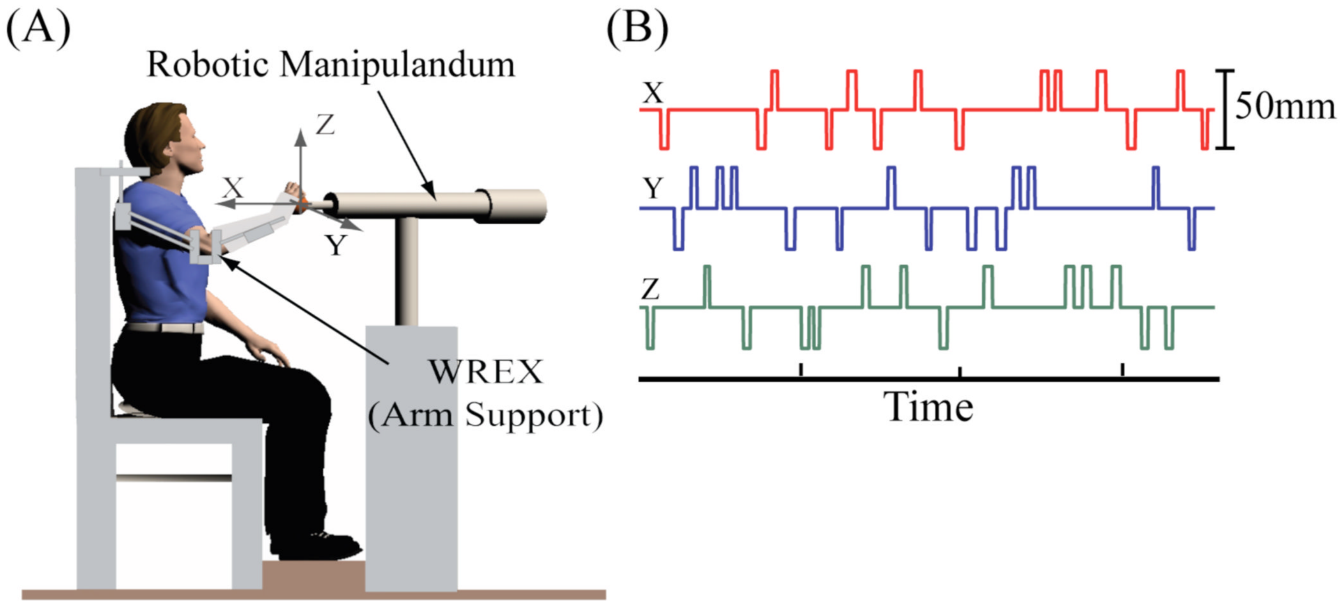

Fig 1.
Experimental setup

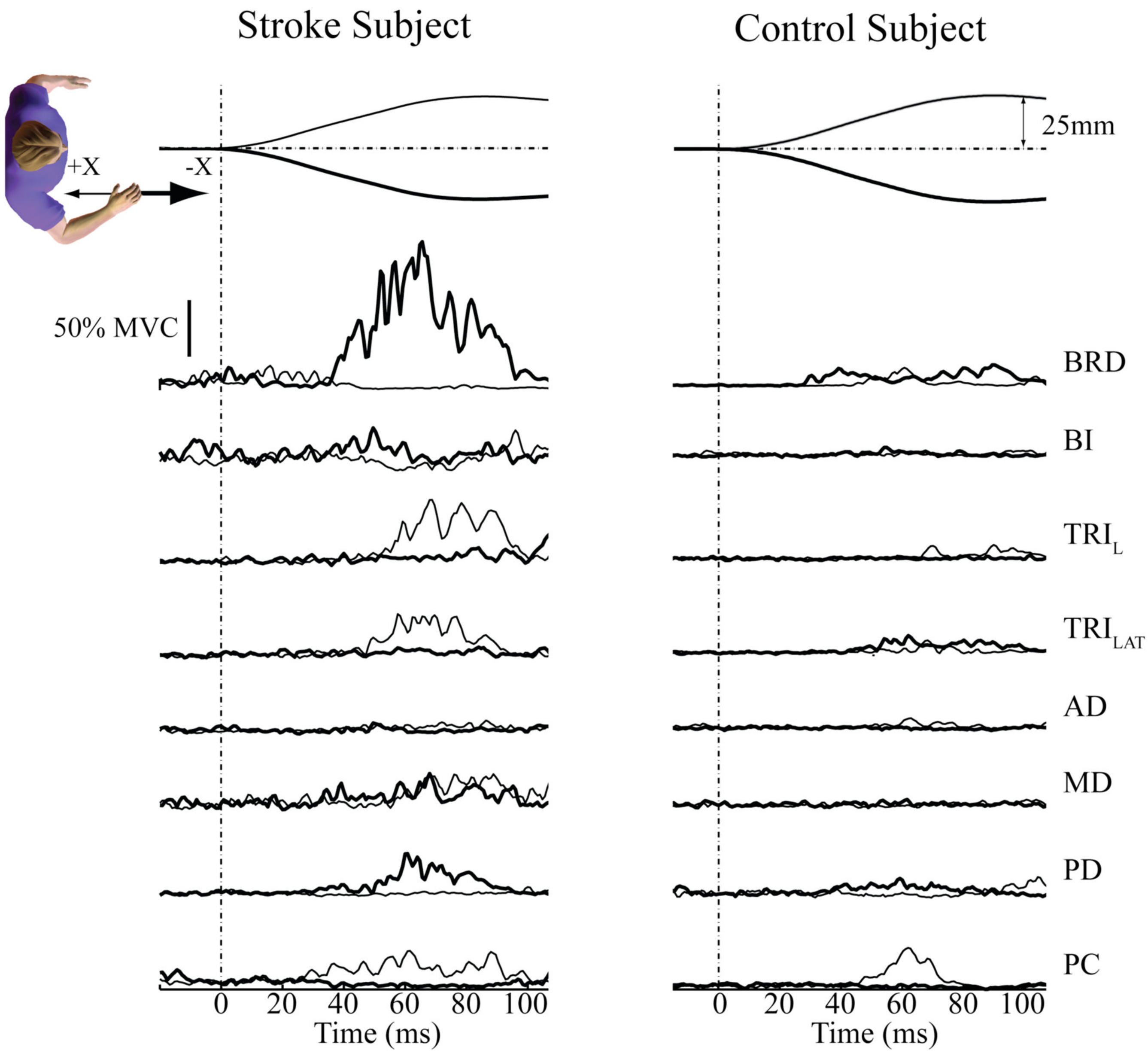

Fig 2.
Typical reflex responses

NIH-PA Author Manuscript
NIH-PA Author Manuscript

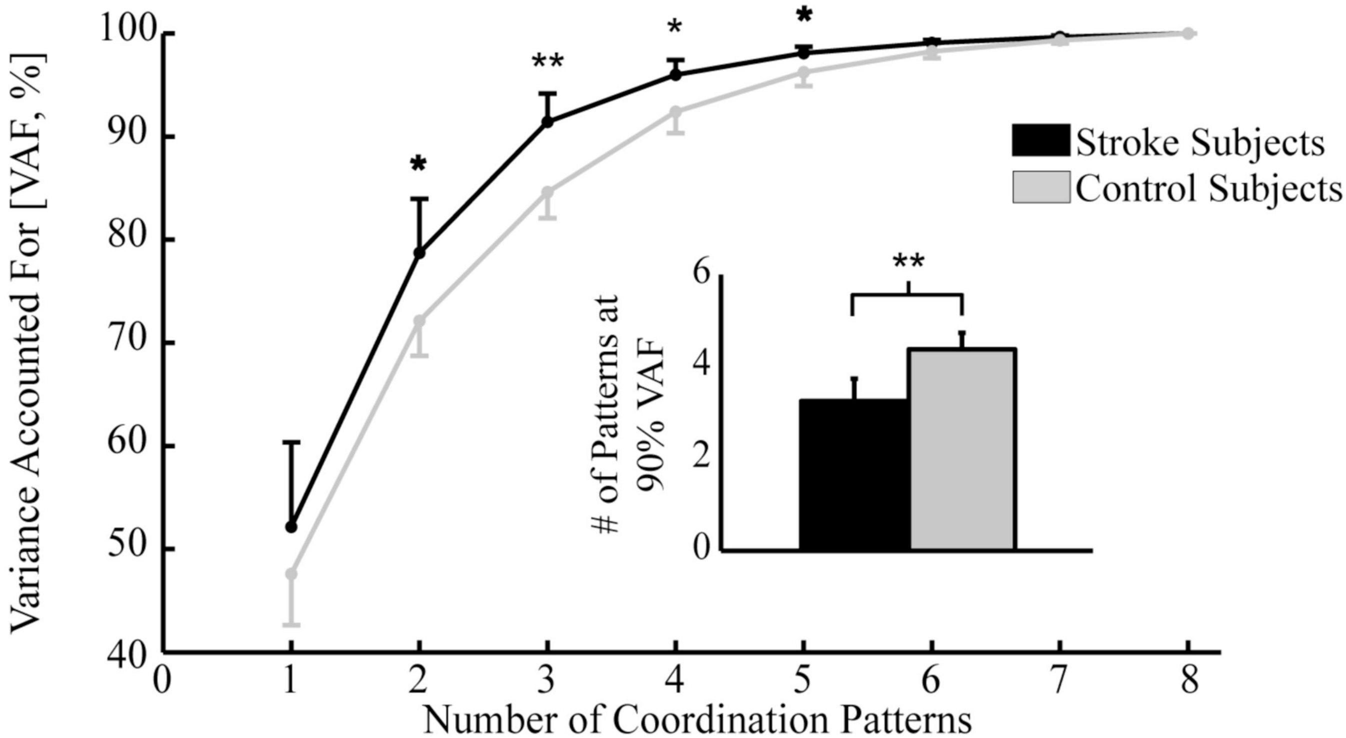

Fig 3.
Number of reflex coordination patterns

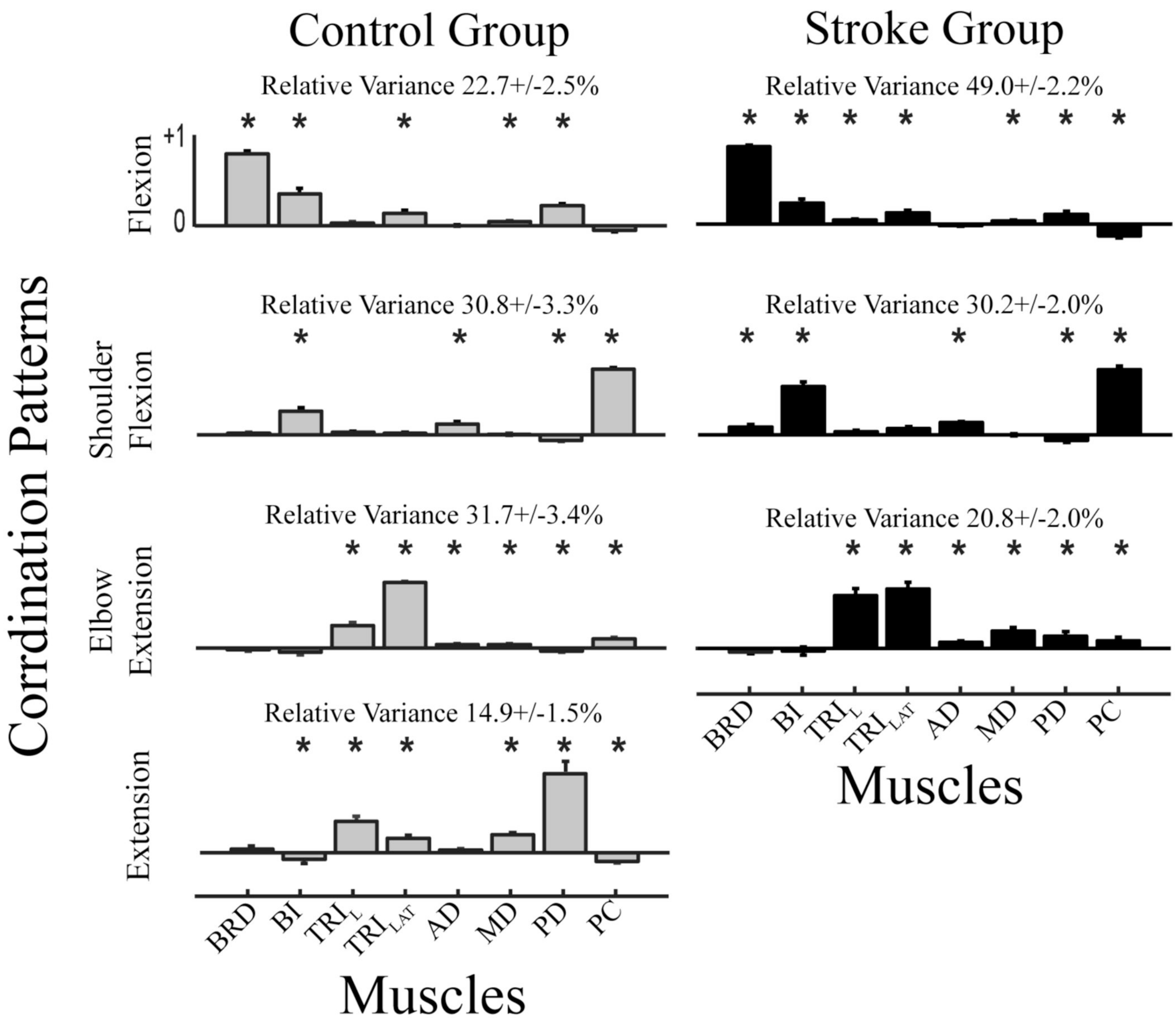

Fig 4.

Reflex coordination patterns for the stroke and control groups. Data were pooled across subjects so that a single set of patterns could be estimated for each group.

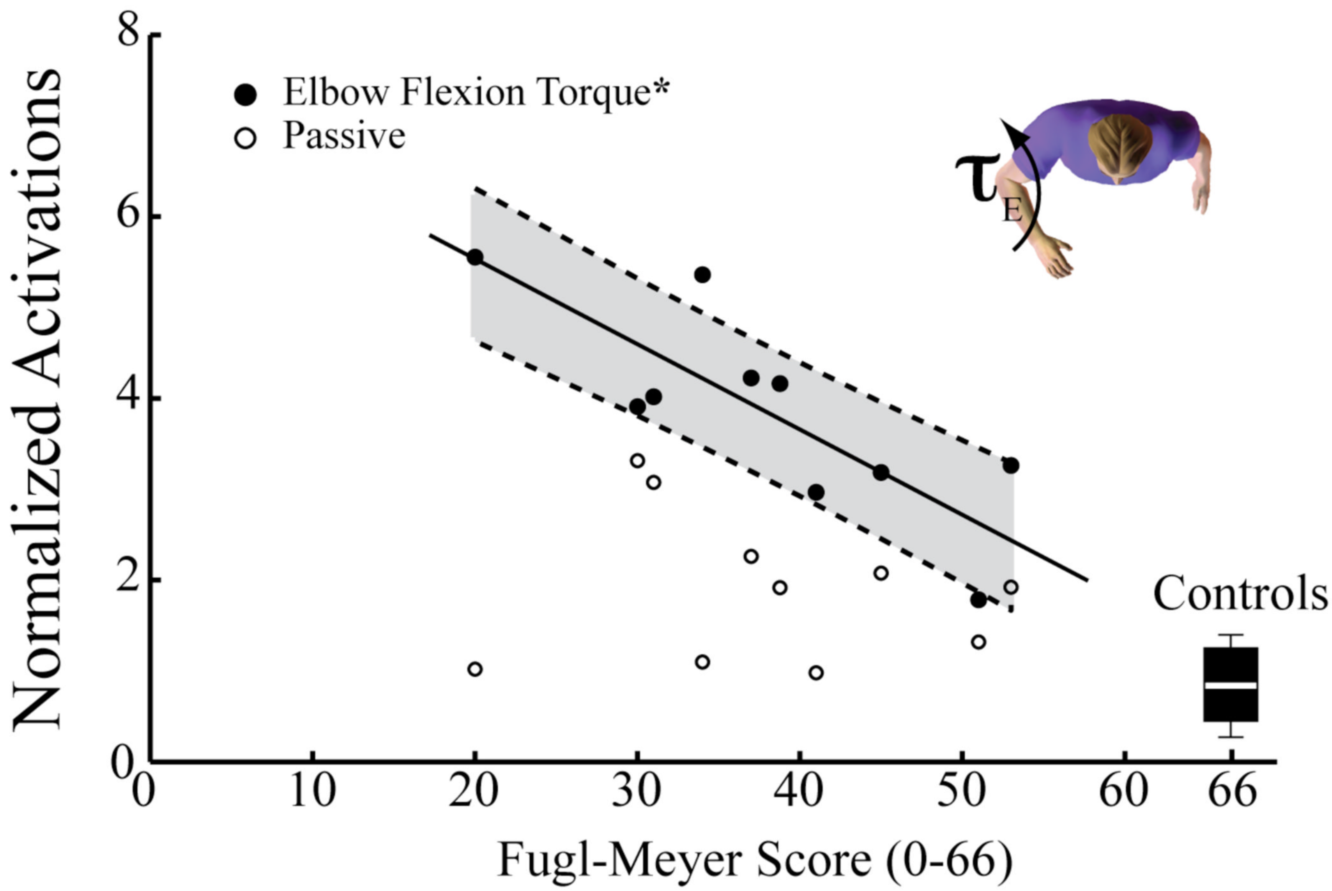

Fig 5.
Reflex activation versus Fugl-Meyer score for both passive and active conditions.

TABLE 1

Muscle Names and Abbreviations

Bracmoradialis	BRD
Biceps Brachii	BI
Triceps Long Head	TRI_L
Triceps Lateral Head	TRI_{LAT}
Anterior Deltoid	AD
Middle Deltoid	MD
Posterior Deltoid	PD
Pectoralis Clavicular Head	PC