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Paretic hand unimanual force control: Improved submaximal force production and regularity

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ABSTRACT

The purpose was to investigate force control capabilities in paretic hands during unimanual movements after coupled bimanual movement training and neuromuscular stimulation on impaired muscles. Nineteen chronic stroke participants completed 90 min of rehabilitation per week for six consecutive weeks. Before and after training, volunteers performed unimanual submaximal force control tasks at 5% and 50% of maximum voluntary contraction with their paretic and non-paretic hands. Force control measures included submaximal force production, force variability, accuracy, and regularity. Two major findings on paretic hands after training revealed: (a) greater submaximal force production across force levels and (b) less regular force outputs. Paretic hand control improved after coupled bimanual movement training as evidenced by submaximal force production and force regularity.

1. Introduction

An inability to voluntarily contract muscles necessary for various movements is a common motor deficit post stroke. Stroke causes hemiparesis in the upper extremities on the opposite side of the affected hemisphere (Patten et al., 2004; Cauraugh et al., 2010). A dominant characteristic of hemiparesis is partial paralysis causing muscle weaknesses and difficulty in controlling limbs. Thus, a major goal of stroke motor recovery research focuses on facilitating functional recovery in the paretic arms.

Force control capabilities in stroke survivors have been frequently investigated and a prominent finding was that more force control deficits in the paretic arms were found in comparison to non-paretic arms (Cauraugh, 2004; DeJong and Lang, 2012; Doucet et al., 2012; Kang and Cauraugh, 2014a). Overall, these studies reported that the paretic arms showed: (a) less force outputs, (b) greater force variability (e.g., increased coefficient of variation; CV), and (c) more regular force outputs (e.g., decreased approximate entropy; ApEn). Moreover, the force control measures represented motor recovery patterns in stroke survivors (Lodha et al., 2010; Kang and Cauraugh, 2014b). Specifically, better force control performances (e.g., less force variability and higher ApEn) were significantly associated with higher motor functions in a clinical assessment (e.g., higher Fugl-Meyer Assessment scores) (Lodha et al., 2010). Thus, quantifying force production during unimanual movements effectively provides a window to motor recovery progress in the paretic arms.

In addition, the temporal structure of variability is determined by computing approximate entropy (ApEn) (Pincus, 1991; Pincus and Goldberger, 1994; Vaillancourt and Newell, 2003). This force measure estimates regularity patterns of force outputs within time-series. ApEn values range from 0 to 2 and higher ApEn values indicate less regular force production than lower ApEn values (more regular force production). In stroke research, ApEn analyses are used for assessing both kinematic and kinetic variability within time-series. More regular movements indicated by less ApEn values were common in movement disorder patients and an increase in ApEn indicates more compensatory behaviors (i.e., improved motor adaptability) (Vaillancourt et al., 2001; Gil et al., 2010; Smith et al., 2011). Further, Sethi and colleagues reported that a group of stroke individuals displayed more regular joint movements in comparison to an age-matched control group at baseline. Post intervention the movement patterns were less regular (e.g., increased ApEn values) than the baseline (Sethi et al., 2013a, 2013b). For bimanual force control, ApEn post stroke was significantly less than an age-matched control group (Lodha et al., 2010). However, whether the temporal structure of force variability during unimanual paretic arm control without assistance from the non-paretic arm is improved after rehabilitation is still unclear.

Functional impairments in the paretic arm may be attributed to decreased cortical activation in the affected hemisphere and relatively higher cortical activation in the unaffected hemisphere

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post stroke (Carey et al., 2002; Bestmann et al., 2010). Additionally, these unbalanced activation patterns between hemispheres may contribute to asymmetrical inter-hemispheric inhibition. Greater inter-hemispheric inhibition from the unaffected hemisphere may interfere with feed-forward command from the affected hemisphere found in the paretic arms (Stinear and Byblow, 2004; Cauraugh and Summers, 2005; Stinear et al., 2014). Consequently, given that stroke survivors display more motor control deficits with their paretic arm than non-paretic arm, functional recovery in the paretic arm is most important for chronic stroke.

For motor recovery in the paretic arms, bimanual movement training has been extensively used because simultaneous arm movements may expedite symmetrical neural activation between the affected and non-affected hemispheres (Cauraugh et al., 2010; Stinear et al., 2014). Specifically, Cauraugh et al. (2010) reported evidence that coupled bimanual movement training with neuromuscular stimulation is an effective protocol for functional recovery in the paretic arm: (a) greater maximal isometric force outputs, (b) greater number of moved blocks, and (c) reduced motor reaction time. If stroke survivors can successfully control their unimanual force production in their paretic arms without any assistance from their non-paretic arms after training, the effectiveness of the coupled bimanual movement training will be further consolidated.

Thus, the primary purpose of this study was to investigate force control capabilities during unimanual movements to determine whether coupled bimanual movement training improves motor functions in paretic arms. Two representative target force levels (i.e., 5% and 50% of maximum voluntary contraction; MVC) were used during the submaximal force control tasks because these force levels indicate lower and upper limits of force outputs required for most daily living activities (Bestmann et al., 2010; Hu et al., 2011; Kang and Cauraugh, 2014b). Based on previous motor improvement evidence in the paretic arm after training (Chang et al., 2007; Summers et al., 2007; Cauraugh et al., 2010; Kang and Cauraugh, 2014c), we hypothesized that the coupled bimanual movement training would lead to more force control improvements in the paretic hand in comparison to the non-paretic hand and the force control improvements would be greater at 50% of MVC than 5% of MVC.

2. Materials and methods

2.1. Participants

Nineteen stroke individuals (mean age = 66.9 years; SD = 15.0 years) participated in this study. Four inclusion criteria included: (a) at least 6 months after stroke, (b) range of motion for three major upper extremities movements [e.g., wrist and fingers extension: 10° of extension from an 80° (flexion position); elbow extension: 145°–0° (neutral position); shoulder abduction: 0° (neutral position)–90°], (c) voluntary muscle contraction capacity to activate a NeuroMove^{TM} microprocessor unit for neuromuscular stimulation, and (d) intact cognitive function (Mini-Mental State Examination score ≥23) (Folstein et al., 1975). Participants were excluded if they met two criteria: (a) additional neurological or musculoskeletal impairments and (b) orthopedic injury or extensive pain in the upper extremities. Specific clinical information for the participants is shown in Table 1. Before and after training, we measured the upper extremity function score in the Stroke Impact Scale (SIS), a self-reported measure (Duncan et al., 2003). Higher score represents improved motor function (range = 0–100). Mean values of the upper extremity function score for each participant indicate that upper extremity function relatively improved after training (pre: mean = 58.2 and SD = 25.5; post: mean = 63.9 and SD = 22.7; 12 individuals increased, 4 individuals decreased, and 3 individuals no change; Table 1). All participants read and signed an informed consent form approved by the University of Florida's Institutional Review Board prior to beginning testing.

2.2. Unimanual isometric force control: paretic and non-paretic hand

To determine whether coupled bimanual movement training improves paretic hand functions, stroke participants performed isometric unimanual force control tasks with their paretic and non-paretic hands at two submaximal force levels (5% and 50% of MVC) before and after training (Hu et al., 2011; Lodha et al., 2012a). Based on previous findings (Lodha et al., 2012a; Kang and Cauraugh, 2014b), wrist and fingers extension movements were unimanually performed in an isometric force control task.

Table 1
Demographics of the stroke participants.

No.	Age (years)	Gender	Stroke type	Affected hemisphere	Time since stroke (years)	SIS (hand function; pre and post)	
1	20.0	M	H	L	1.1	55	85
2	64.0	M	I	L	13.1	15	35
3	79.8	M	I	L	0.7	25	40
4	76.8	F	I	R	1.6	80	90
5	51.0	F	H	R	1.1	40	15
6	64.8	M	I	L	1.5	25	40
7	77.5	F	I	R	0.7	80	85
8	75.3	M	I	L	7.3	75	60
9	56.8	F	I	L	5.6	100	100
10	78.1	F	I	L	0.6	45	55
11	75.5	M	I	L	7.4	60	70
12	78.2	F	I	L	0.7	55	70
13	52.3	F	I	L	0.8	15	65
14	77.8	F	I	R	2.6	50	75
15	74.5	F	I	R	8.8	80	90
16	73.0	F	I	R	7.3	80	80
17	66.6	M	I	L	3.7	70	70
18	76.8	F	I	R	1.7	90	50
19	52.4	F	I	L	0.9	65	40
Total	66.9 ± 15.0	12 F, 7 M	17 I, 2 H	12 L, 7 R	3.5 ± 3.6	58.2 ± 25.5	63.9 ± 22.7

Mean ± standard deviation; M: male; F: female; I: ischemic; H: hemorrhagic; L: left; R: right; SIS: Stroke Impact Scale.