31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

Preliminary trial of symmetry-based resistance in individuals with post-stroke hemiparesis

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Abstract— **We tested a novel control strategy for robotic rehabilitation devices used by individuals with post-stroke hemiparesis. Symmetry-based resistance increases resistance when limb forces become more asymmetric during bilateral exercise. The underlying rationales for the control mode are that it will guide patients to increase paretic limb activation while teaching them to accurately gauge paretic limb force production relative to the non-paretic limb. During a one day training session, seven subjects post-stroke performed lower limb extensions in symmetry-based resistance mode on a robotic exercise machine. Subjects improved lower limb symmetry from 28.6%±3.9% to 36.2%±4.3% while under symmetry-based resistance training (ANOVA, P=0.03), but did not maintain the improved lower limb symmetry during a constant resistance post-test. Two subjects that showed the large improvements in symmetry during the one day session performed additional days of training. Those results suggest that some patients demonstrate long lasting benefits with symmetry-based resistance training.**

I. INTRODUCTION

Stroke is a leading cause of serious, long-term disability in the United States with 5.8 million patients with stroke [1]. More than half of these individuals experience moderate to severe impairments that limit their mobility and functionality. These impairments include weakness and impaired coordination, proprioception and force scaling abilities [2-4].

Stroke patients impaired force scaling abilities are less understood. When post-stroke patients are asked to produce a force in their paretic limbs equal to the force in their non-paretic limbs, they often overestimate the force produced in their paretic upper limbs [5,6] and paretic lower limbs [7]. A disparity exists between patient's perceived force levels and actual force levels. Such force mismatches in the lower limbs can affect patients' ability to be mobile, stand from a seated position, and recover from falls. For example, if a patient with stroke needed to take a step to prevent a fall, sending too low of an efferent command to the lower limb muscles would lead to inadequate extension torques about the joints and the patient could fall.

Strength training and aerobic exercise can help post-stroke patients regain strength and mobility [8-10]. Patients usually exercise two to three days per week and can increase motor recruitment of both the paretic and non-paretic limbs without an exacerbation of spasticity [11, 12]. Increasing muscle strength leads to concurrent increases in functional abilities such as sit-to-stand performance, gait speed, and dynamic balance [6, 9, 13].

Therapy may also include audio and/or visual biofeedback training focused on patients' muscle activation or limb forces. Some studies have shown that visual biofeedback can improve stance symmetry and decrease sway during standing compared to similar therapy without feedback [14, 15]. These improvements occur over long training periods of up to 60 minutes a day, 3 to 5 days a week, for 4 to 6 weeks [16, 17]. However, recent systematic reviews of the literature conclude that audio/visual biofeedback of muscle activation and/or limb forces are not very effective for motor recovery after stroke [18, 19]. One potential reason for this is that audio/visual biofeedback requires increased cognitive involvement of cortical brain regions that are not directly involved with the motor task. Patients may benefit more from an alternative type of therapy that acts to influence proprioceptive feedback given its proximity to the basic neural control architecture. Proprioceptive feedback is encoded at the spinal cord level along with motor neuron activation patterns [20, 21], resulting in shorter feedback pathways than audio or visual feedback pathways.

Symmetry-based resistance has the potential to provide proprioceptive biofeedback to patients without requiring involvement from audio/visual cortical centers. With symmetry-based resistance, task resistance increases with the magnitude of the limb force asymmetry during bilateral exercise. This control mode could benefit the patient by evoking enhanced muscle activation in the paretic limb during exercise. In addition, it could help patients calibrate their force production in their paretic limb with the force production in their non-paretic limb. Applied to lower limb extensions, individuals exercise with the goal of producing equal lower limb forces during movement. If they exercise with equal forces, resistance is at a baseline value and subjects perform the minimal mechanical work. If their lower limb forces become asymmetric, a real-time controller increases resistance causing subjects to perform more mechanical work. This novel control strategy has previously been tested on neurologically intact individuals that typically demonstrate a slight asymmetry during lower limb exercise [22]. Subjects altered their lower limb forces

Manuscript received April 7, 2009. This work was supported in part by National Institutes of Health R01 NS045486 and an award from the American Heart Association.

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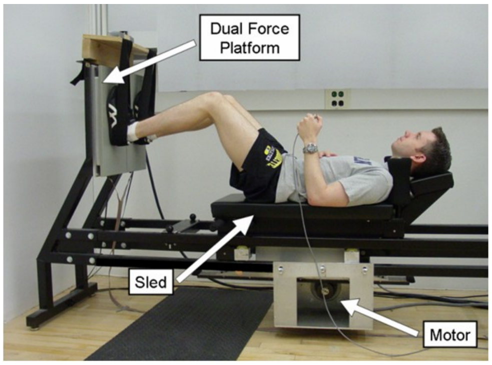

Fig. 1. Lower limb robotic exercise machine.

towards a target symmetry within a single training session [22].

The goal of this study was to perform a preliminary trial of lower limb exercise with symmetry-based resistance in individuals with post-stroke hemiparesis. In the current study, symmetry-based resistance training was tested as a means of addressing subjects' impaired force scaling abilities. Individuals post-stroke could use the proprioceptive feedback received during training to reduce the mismatch between the forces they think they are producing and the forces they are actually producing. We hypothesized that lower limb exercise with symmetry-based resistance would result in more symmetric lower limb forces when subjects performed extensions against a constant resistance.

I. METHODS

A. Subjects

We recruited 7 individuals (5 females, 2 males) with stroke-induced hemiparesis (age: 48 ± 20 years, mean ± s.d.). A physiatrist at the University of Michigan evaluated each subject for inclusion criteria and study participation. Inclusion criteria consisted of: 1) at least six months post-onset of a single neurologic insult that included ischemic or hemorrhagic type strokes, 2) between the ages of 18 and 85 years, 3) free of any musculoskeletal injuries or deformities, 4) presented no spastic hypertonia in the lower limbs, and 5) adequately able to comprehend our instructions. All subjects gave written informed consent approved by the Institutional Review Board for Human Subject Research at the University of Michigan Medical School. A physical therapist evaluated subjects' lower extremity physical capabilities through use of the lower limb and balance portions of the Fugl-Meyer Clinical Assessment (Table I). Based on comments from subjects, we noted various subject sensory deficits including reduced cutaneous sensation and impaired force perception. No subjects reported impaired sense of limb motion and position.

B. Experimental Design

Subjects exercised on a robotic lower limb exercise machine (Fig. 1) [22]. The machine included a dual force plate (Model Dual Accu-Gait, AMTI, Watertown, MA) to capture individual foot forces during exercise.

Maximum Strength Testing

First we assessed subjects' isokinetic maximum strength during lower limb extensions on the exercise machine in isokinetic mode. In this mode, the computer controlled resistance so movement velocity remained constant. We instructed subjects to push as hard as they could only during the extension phase and relax during the flexion phase. Subjects performed two trials each of right limb only, left limb only, and bilateral maximum voluntary contraction (MVC) trials. We randomized the trial order and verbally encouraged subjects to push as hard as they could throughout each contraction. Subjects rested three minutes or more between each MVC trial.

Lower Limb Extensions

Subjects performed one set of ten bilateral lower limb extensions on the robotic exercise machine in isotonic mode pre- and post-training. In isotonic mode, the resistance for continuous lower limb extensions remained constant and was equal to 60% of the paretic limb bilateral MVC force.

TABLE I. SUBJECT CHARACTERISTICS

Subject	**Age (yrs)**	**Gender**	**Paretic Side**	**Postonset (mos)**	**Lesion Location**	**Type of Stroke**	**Fugl - Meyer***	
							Lower Extremity	**Balance**
1	73	F	L	156	Right hemisphere	Ischemic	22	8
2	52	F	R	11	Left basal ganglia	Hemorrhagic	31	9
3	22	M	R	37	Left thalamus extending into the pons	Hemorrhagic	21	3
4	69	F	R	12	Left hemisphere	Ischemic	23	9
5^	54	M	L	29	Right parietal lobe	Ischemic	23	10
6^	22	F	L	37	Right temporal lobe	Ischemic	29	11
7	47	F	L	24	R-MCA-internal capsule/basal ganglia	Hemorrhagic	34	14

Abbreviations: Sex (F: female, M: male), Paretic Side (L: left, R: right)
*Fugl-Meyer Clinical Assessment: Lower extremity motor score (0-34), Balance motor score (0-14)
^Subject participated in four week training protocol.

We instructed and frequently verbally reminded subjects to try to produce equal forces throughout the movement. Since this was a bilateral task, if subjects were able to produce equal forces in their limbs they would have only needed to produce force equal to 30% of the paretic limb bilateral MVC force in each limb (i.e. a total resistance of 60% was equal to 30% force in each limb). We instructed subjects to extend their lower limbs completely but to not lock out their knees), flex to knee and hip angles of 90 degrees, and match their movement speed to a metronome set to 0.33 Hz.

In between the pre- and post-test, subjects performed lower limb extensions on the exercise machine in symmetry-based resistance mode. Movement timing and range of motion were the same as the pre- and post-test trials. The control algorithm used for symmetry-based resistance determined resistance levels in real-time based on individual's instantaneous lower limb symmetry (Fig. 2a). Lower limb symmetry was calculated according to (1).

$$\mathrm{Sym}_i = \frac{F_{\mathrm{Paretic}}}{F_{\mathrm{Paretic}} + F_{\mathrm{Non-paretic}}} \times 100\% \tag{1}$$

The resulting signal ranged from 0% to 100% with 50% representing perfect symmetry in lower limb forces. In symmetry-based resistance mode, resistance followed the shape of standard normal distribution curve reflected over the horizontal axis (Fig. 2b). The resistance, R, in percent maximum force ability of the paretic limb, was calculated according to (2) and (3).

$$R = -K \times \exp\left[-\frac{4.5 \times (50 - \mathrm{Sym}_i)^2}{(50 - \mathrm{Sym}_{\mathrm{RMS}})^2} \right] + S \tag{2}$$

$$K = \frac{S - B}{\sqrt{0.32\pi}} \tag{3}$$

where K was the controller gain. B and S were baseline and saturation resistances set to 60% and 100% of the bilateral maximum force ability of the paretic limb, respectively. This limit was set to ensure that subjects had the capability to produce equivalent forces in their paretic and non-paretic limb. $\mathrm{Sym}_{\mathrm{RMS}}$ was the root mean squared symmetry value measured for each subject during the pre-test and Sym_i was the instantaneous lower limb symmetry calculated in real-time from Equation 1. After the real-time controller calculated load the signal was passed through a 2nd order low pass Butterworth filter (1 Hz cutoff). The signal was then sent to the motor drive. The overall result of (2) and (3) was that resistance was at a minimum with perfect lower limb force symmetry and increased to saturation as lower limb forces became asymmetric (Fig. 2b).

Initially, we allowed subjects to explore what symmetry-based resistance felt like by instructing them to vary their non-paretic and paretic limb forces and experience the resistance feedback. We explicitly told subjects that exercising with equal forces in their lower limbs would result in a lower exercise resistance. The exploration lasted for two minutes and subjects were not under the constraints of movement timing or range of motion described previously. Subjects then performed four sets of ten repetitions of lower limb extensions with the symmetry-based resistance controller. We verbally reminded subjects to produce equal forces during exercise. We allowed subjects to rest between sets for three minutes or longer if necessary. Including the rest period, the lower limb extension protocol lasted approximately one hour.

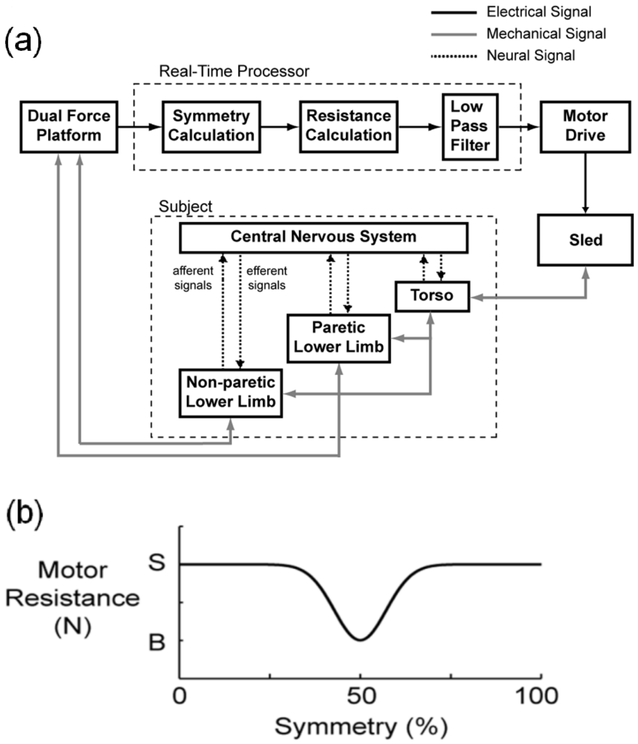

Fig. 2. Symmetry-based resistance controller. a) A dual force platform recorded forces during extensions and sent data to a real-time processor and output to the motor drive. The subject sensed resistance through afferent signals and output motor efferent signals. b) Motor resistance vs. lower limb symmetry for symmetry-based resistance mode. Motor resistance (R) was set to a minimum baseline value (B) when lower limb forces were equal and increased until saturation (S) as limb forces became more asymmetric.

4 Week Training Protocol

In order to investigate the retention effects of exercise with symmetry-based resistance, subjects who showed greater than a 30% improvement in pre- to post-test lower limb symmetry values returned to the laboratory for further training. Two of the seven subjects showed this trend and returned to the laboratory for one day a week for three additional weeks of training (four weeks total). During day one and four subjects performed both the maximum strength testing and the lower limb extension protocol (Table II). During day two and three subjects only performed the lower limb extension protocol.

TABLE II. EXPERIMENTAL PROTOCOL

Day 1 & 4	Maximum Strength Testing Right limb only, left limb only, and bilateral maximum voluntary contractions, 2 trials each
Day 1 – 4	Lower Limb Extensions Pre-test: Extensions against a constant resistance, 1 set of 10 repetitions Training: Extensions in symmetry-based resistance mode, 4 sets of 10 repetitions Post-test: Extensions against a constant resistance, 1 set of 10 repetitions

C. Data Acquisition and Analysis

We recorded dual force plate data sampled at 1000 Hz throughout all trials on the exercise device (Fig. 1). Non-paretic and paretic limb MVC force was determined as the maximum force measured during the two trials [23, 24]. We calculated normal force (force vector in the direction of movement), total resultant force (sum of the normal force vector combined with shear force vectors), and total resultant force direction (0 degrees represented the normal direction). During lower limb extensions, we identified cycle timing from motor encoder data and averaged individual foot force data only across the extension phase of each cycle. We calculated root mean square (RMS) symmetry during the extension phase to capture the variability. As this value approached 50%, it represented a change in foot forces towards perfect symmetry (i.e. producing equivalent forces in both the non-paretic and paretic lower limbs). We averaged individual foot forces and RMS symmetry for the last five repetitions within each set to eliminate possible high variability of initial repetitions. Subjects were excluded from the study if their lower limb forces during the pre-test of the lower limb extensions resulted in greater than 45% symmetry as these subjects did not properly represent the stroke population with hemiparesis. Three out of the ten subjects were excluded from the analysis for this reason.

For the lower limb extension training with symmetry-based resistance, we performed a repeated measures ANOVA limb by set (included training, pre-test, and post-test sets) to test for significant differences in lower limb forces. We performed a repeated measures ANOVA by set to test for differences in RMS symmetry values. When the ANOVAs indicated significance ($P<0.05$), we used Tukey-Kramer Honestly Significant Difference (THSD) post-hoc tests ($P <0.05$). Post-hoc power analyses were carried out where appropriate.

II. RESULTS

A. Maximum Strength Testing

Subjects isokinetic bilateral and unilateral maximum strength showed significant differences between limbs (ANOVA $P<0.0001$) (Table III). Peak paretic limb forces were significantly lower than non-paretic by 47% during bilateral isokinetic MVC conditions (THSD $P<0.05$).

TABLE III. PEAK FORCE RECORDED DURING ISOKINETIC MAXIMUM VOLUNTARY CONTRACTIONS

Condition	**Non-paretic Limb Peak Force (N)**	**Paretic Limb Peak Force (N)**
Unilateral MVC	644 ± 214	326 ± 204*
Bilateral MVC	548 ± 212	286 ± 145*

Values are mean ± s.e.m.

*Post-hoc (THSD) analysis indicates significant decrease in paretic limb force compared with non-paretic limb force within a condition ($P<0.05$).

B. Lower Limb Extensions

During the pre-test when individuals with post-stroke hemiparesis attempted to generate equal lower limb forces, they produced significantly different limb forces (ANOVA $P<0.001$) (Fig. 3). The paretic limb produced significantly less normal force during exercise. When subjects performed lower limb extensions with symmetry-based resistance, there was no significant increase in normal force produced by the paretic limb (THSD $P>0.05$). The average amount of resistance subjects exercised against increased from 474N ± 102 N (mean ± s.e.m) during pre- and post-training to 693N ±71 N during exercise with symmetry-based resistance (Sets 1-4). Comparing the average normal limb force pre- to post-training within the one day session, there were no significant differences for both non-paretic and paretic limbs (THSD $P>0.05$ for both limbs). Further force analysis revealed that for the normal force in the non-paretic and paretic limbs accounted for greater than 96% and 95%, respectively, of the total resultant force during all lower limb extensions. Results comparing total resultant force magnitude during the pre-test, training, and post-test showed similar trends as the normal force magnitude reported.

Fig. 4A shows one subject's lower limb symmetry during the lower limb extension pre-test, training with symmetry-based resistance, and post-test. Subjects' goal was to

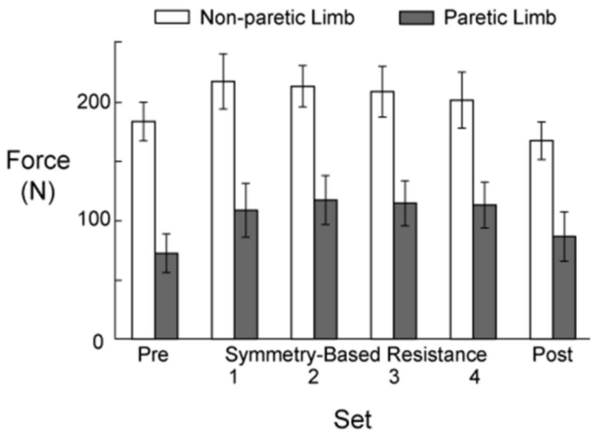

Fig. 3. Average forces during lower limb extensions for all subjects during the one day training session. White columns represent non-paretic limb forces and grey columns represent paretic limb forces. Error bars are standard error of the mean. The non-paretic limb generated significantly more force than the paretic limb during the pre- and post-test as well as during symmetry-based resistance training (ANOVA, $P<0.001$).

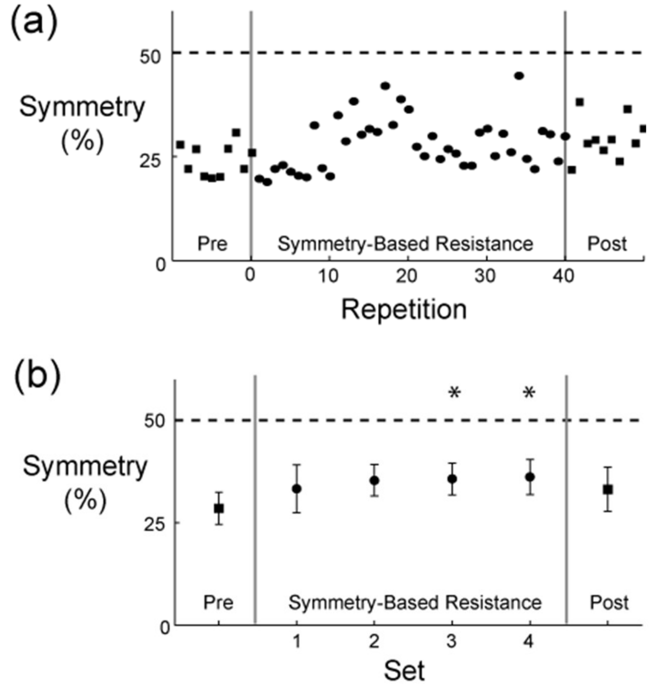

Fig. 4. Symmetry values for subjects during the one day training session. The dashed line represents subjects' goal of 50% symmetry. The pre- and post-test lower limb extensions were against constant resistance. The symmetry-based resistance controller was turned on for Sets 1-4. a) Symmetry vs repetition for a typical subject. b) Symmetry vs. set for all subjects. Subjects exercised with significantly higher lower limb symmetry values during Sets 3 and 4 compared to the pre-test values (ANOVA, *: P=0.0262).

exercise with 50% symmetry or equal lower limb forces. Subjects increased their lower limb symmetry values during exercise with symmetry-based resistance for Set 3 and 4 compared to the pre-test against constant resistance (ANOVA P=0.0262) (Fig. 4B). Lower limb symmetry values for the pre-test were 28.6% ± 3.9% for the pre-test, 36.2% ± 4.3% during the last set of symmetry-based resistance training (Set 4), and 33.2% ± 5.4 % during the post-test.

C. 4 Week Training Protocol

The two subjects with stroke-induced hemiparesis that trained for four sessions had average lower limb symmetry values of 34.2% ± 4.2% for the pre-test on Day 1 of training. These subjects showed substantial improvement within the one day of training, having post-test symmetry values of 48.3% ± 3.9%. The subjects also demonstrated retention of symmetry-based resistance training throughout testing Days 2-4 (Fig. 5). During the lower limb extension pre-test against constant resistance on Day 4, subjects exercised at lower limb symmetry values of 50.7% ± 3.1%.

III. DISCUSSION

During lower limb extensions, individuals with post-stroke hemiparesis did not produce equal forces even though they believed their forces were equal. Previous studies have reported similar results in both the upper and lower limb of these patients [5-7]. Based on subjects comments, when the symmetry-based resistance controller was turned on, all subjects were able to feel the change in resistance (i.e. they knew when the resistance increased or decreased). During Set 3 and 4 of exercise with symmetry-based resistance, subjects were able to improve their lower limb symmetry. However, these improvements were small in magnitude for the group as a whole. The improvement in lower limb symmetry represented a smaller difference between the forces the subjects thought they were producing and the forces they actually produced. The increase in lower limb symmetry did not demonstrate carryover as subjects did not produce significantly different symmetry values when comparing the single day pre- to post-test values for lower limb extensions against a constant resistance.

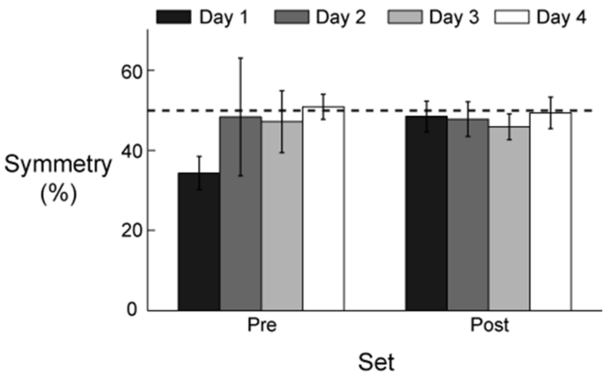

Fig. 5. Symmetry values for the two subjects in the four week training protocol. The dashed line represents subjects' goal of 50% symmetry. Data represents on the pre- and post-test lower limb extensions against a constant resistance. Black columns represent Day 1, dark grey columns represent Day 2, light grey columns represent Day 3, and white columns represent Day 4. Subjects demonstrated retention of symmetry-based resistance training throughout testing Days 2-4.

Analysis of the total resultant force vectors during lower limb extensions revealed that subjects did not have problems with producing force in the plane of movement. A previous study has shown that individuals with post-stroke hemiparesis have coordination impairments that lead them to produce inappropriate paretic limb forces during pedaling [25]. These subjects had a hard time directing their foot forces to a given direction. The subjects in the current study did not present this problem during lower limb extensions. One possible explanation is that performing lower limb extensions is a simpler task compared to pedaling. Pedaling may require more coordination in order to move the legs in different directions and constantly change force direction.

Subjects who returned to the laboratory for a total of four training sessions did show pre- to post-training improvement in lower limb symmetry and of increased paretic limb force. These subjects also showed retention of training as their lower limb symmetry values during the no feedback pre-test improved from Day 1 to Day 4. Our studies of exercise with symmetry-based resistance have some limitations. The studies report data for seven subjects for one day training and two subjects for four week training. However, we achieved statistical power of 0.78 for the one day training protocol. This suggests that longer training may be necessary to see pre- to post-training results if they will occur in post-stroke hemiparesis subjects. Testing more subjects for the longer training protocol seems to be warranted based on these preliminary results. Another limitation was that our subjects had a large range of functional impairments. Results may have differed if we used a stricter inclusion criteria based on functional abilities.

IV. CONCLUSION

An advantage of long-term training on the exercise machine with symmetry-based resistance would be the potential for strength augmentation. Traditionally, strength training regimens in individuals post-stroke were thought to increase spasticity and decrease functional abilities [11]. Studies now show that strength training has positive benefits such as increasing motor recruitment, muscle strength, and functional abilities without increasing spasticity [9, 11, 13, 26]. Computer-controlled exercise machines have the potential of enhancing the neural component of strength training beyond that which is possible with normal exercise machines. Populations of individuals post-stroke are very diverse in functional abilities and impairments. Targeting interventions for patients based on preliminary test may help tailor therapies to groups of patients. Future studies could compare groups of subjects exercising with symmetry-based resistance, audio/visual force feedback, or pure strength training to assess which type of training, if any, could produce the most benefit in the least amount of training time for different groups of patients.

ACKNOWLEDGMENTS

The authors would like thank Antoinette Domingo, Pei-Chun Kao, and the rest of the members of the University of Michigan Human Neuromechanics Laboratory for help with data collections and the subjects for their participation.

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