

# Symmetry-based resistance as a novel means of lower limb rehabilitation

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## Abstract

Robotic devices hold much promise for use as rehabilitation aids but their success depends on identifying effective strategies for controlling human–robot interaction forces. We developed a robotic device to test a novel method of controlling interaction forces with the intent of improving force symmetry in the limbs. Users perform lower limb extensions against a computer-controlled resistive load. The control software increases resistance above baseline in proportion to lower limb force asymmetry (balance between left and right limb forces). As a preliminary trial to test the device and controller, we conducted two experiments on neurologically intact subjects. In experiment 1, one group of subjects received symmetry-based resistance while performing lower limb extensions ( $n = 10$ ). A control group performed the same movements with constant resistance ( $n = 10$ ). The symmetry-based resistance group improved lower limb symmetry during training (ANOVA,  $p < 0.05$ ), whereas the control subjects did not. In experiment 2, subjects ( $n = 10$ ) successfully used symmetry-based resistance to alter their lower limb force production towards a target asymmetry (ANOVA,  $p < 0.05$ ). These studies suggest that symmetry-based resistance may hold rehabilitation benefits after orthopedic or neurological injury. Specifically, performing strength training therapy with this controller may allow hemiparetic individuals to focus better on increasing strength and neuromuscular recruitment in their paretic limb while experiencing symmetric limb forces.

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## 1. Introduction

Strength training is beneficial to rehabilitation after neurological or orthopedic injury. This training can increase muscle strength in the affected limb(s) by increasing motor neuron recruitment and muscle size (Dodd et al., 2002; Jacobs and Nash, 2004; Jan et al., 2004; Patten et al., 2004). When one limb is more affected than the other limb, an imbalance in limb forces

can arise during functional tasks. One way that therapists have attempted to overcome this type of limb asymmetry is to provide patients with audio and/or visual feedback about muscle activation or limb force. Neurologically impaired individuals who are provided with visual force feedback while standing and performing upper limb tasks improve stance symmetry and decrease sway compared to subjects receiving similar therapy without feedback (Sackley and Lincoln, 1997; Wong et al., 1997). Sit-to-stand training with audio feedback of paretic lower limb loading shows increased improvement toward symmetric body weight distributions over no feedback controls (Engardt et al., 1993). Although these results show improvements after

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training with feedback, they occur over relatively long training periods. Training sessions range between 45 and 60 min a day, 3 to 5 days a week, for 4 to 6 weeks (Bourbonnais et al., 2002; Engardt et al., 1993). An alternative type of therapy that reduces training time could speed patients' motor recovery and decrease therapy costs.

Robotic devices can yield functional benefits for patients when training task-specific exercises (Reinkensmeyer et al., 2004). The devices can impose novel force fields to shape motor output while completing a task. During a bilateral steering task, the force-cue mode implemented in the Driver's Simulation Environment for Arm Therapy (Driver's SEAT) uses resistance torques that allow steering motions to be produced only by the paretic upper limb (Johnson et al., 2005). With these force cues, hemiplegic subjects increased the productive use of their paretic upper limb over trials without force cues. Resistive force fields can also strengthen patients' muscles. Devices such as upper extremity manipulanda and lower extremity locomotor devices are showing promise, although to date the results are very joint specific (Hesse et al., 2001; Krebs et al., 2005; Lum et al., 2002). These results suggest that multiple types of robotic exercise machines will likely be necessary for rehabilitation (Krebs et al., 2005).

We built a lower limb robotic device that uses a novel control strategy for increasing force symmetry during bilateral lower limb extensions. The device features a motor to provide real-time control of resistance and a force platform to measure limb forces. Control software calculates the difference between the target and actual center of pressure location. This difference is multiplied by a gain and then added to a baseline resistance. In effect, the motor increases resistance in proportion to lower limb force asymmetry. Subjects training with the symmetry-based resistance perform the least effort against the device when they produce symmetric forces.

This study reports initial results from neurologically intact subjects using the device. In the first experiment, two groups of 10 subjects performed bilateral lower limb extensions during a single testing session. One group received symmetry-based resistance and the other group received constant resistance. Both groups were asked to perform lower limb extensions as symmetrically as possible. We hypothesized that the symmetry-based resistance group would increase lower limb symmetry within the single testing session more than the control group as a result of the variable resistance. In the second experiment 10 subjects attempted to produce an asymmetry of foot forces using symmetry-based resistance, again in a single testing session. We hypothesized that these subjects would learn the appropriate relative sense of effort in the two limbs to produce the target asymmetry. Some neurologically impaired subjects perceive symmetric force production as an asymmetry.

Thus, testing neurologically intact subjects as they learn to produce a force asymmetry may provide a good indication of the learning effects using the symmetry-based resistance controller.

## 2. Methods

We modified a commercially available exercise machine (Plyo-Sled, Lifestyle Sports, Dunkirk, NY) (Fig. 1). Subjects recline on a sled resting on low friction rollers and place their feet on a vertical footplate to perform bilateral lower limb extensions. We added a computer-controlled electrical motor (MT706C1-R1C1 Goldline XT Servomotor, Kollmorgen, Northampton, MA) to control resistance in real-time. A horizontal rack affixed to the sled was driven by a pinion on the motor to transform rotational motion of the motor to linear motion of the sled. We attached a force platform (Model OR6-7MA, AMTI, Watertown, MA) to the footplate to capture center of pressure during movement. From center of pressure calculations the controller determined the relative symmetry between right and left foot forces.

Real-time control of motor resistance was achieved with two desktop PCs in a host-target configuration with RT-Lab Solo software (Opal-RT Technologies, Quebec, Canada). The symmetry-based resistance controller adjusted resistance according to the location of the center of pressure detected by the force platform (Fig. 2A). The resistance,  $R$ , in percent body weight, was calculated according to the following equations:

$$R = K|\text{COP} - T| + B, \quad (1)$$

$$K = \frac{S - B}{1.5|\text{COP}_{\text{avg}} - T|}, \quad (2)$$

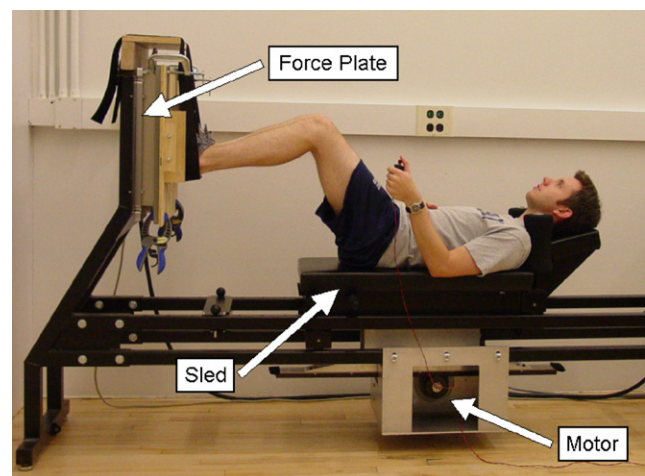


Fig. 1. Lower limb robotic device in use by a neurologically intact subject. A force platform measured lower limb forces while a computer controlled motor adjusted resistance in real-time.

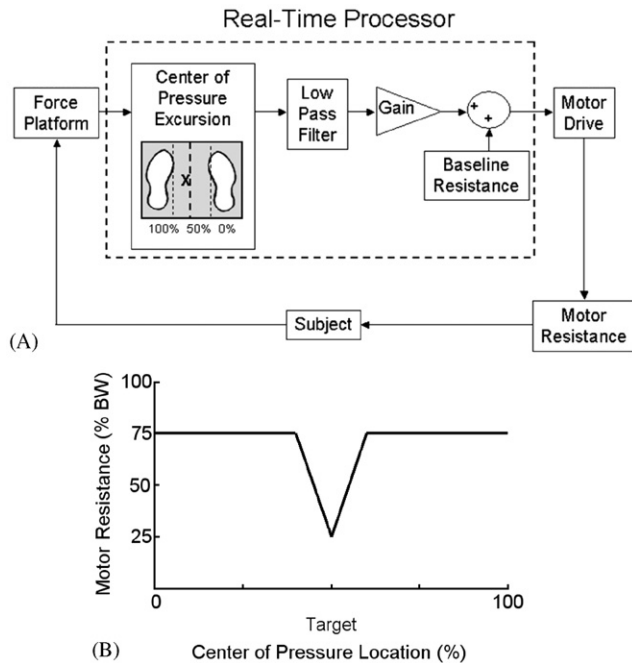


Fig. 2. (A) Diagram of the symmetry-based resistance controller. A force platform recorded foot forces during bilateral lower limb extensions and sent data to a real-time processor. The real-time processor calculated center of pressure location in percent distance from the non-dominant foot (sample asymmetry of center of pressure location at 60% denoted by the X). The center of pressure excursion was calculated as the difference between the center of pressure location and the target. After low pass filtering, the signal was multiplied by the gain to produce the motor command. A baseline resistance was added to the signal before output to the motor drive. Subjects performed extensions with least effort if they generated the necessary lower limb forces to move their center of pressure to the target. (B) Plot of motor resistance as a function of center of pressure location for the symmetry-based resistance controller. Motor resistance is at a minimum when the center of pressure location is at the target (i.e. 50% for perfect symmetry). As the center of pressure moves away from the target, the motor resistance increases until saturation at 75% body weight.

where COP is the instantaneous center of pressure low-pass filtered at 5 Hz,  $K$  is the controller gain, and  $T$  is the target symmetry (i.e. 50% for perfect symmetry). The symbol  $COP_{avg}$  is the center of pressure location averaged over the entire first set of extensions. The symbols  $B$  and  $S$  are the baseline and saturation resistance as a percentage of body weight. Eq. (1) determines the motor resistance by multiplying the difference between the center of pressure and the target by a gain and adding a baseline resistance. As the center of pressure moves away from the target, motor resistance increases until saturation (Fig. 2B). If foot forces were the same (i.e., subject's center of pressure remained directly between his/her feet), motor resistance remained at baseline. If foot forces were unequal (i.e., subject's center of pressure moved away from center towards one of the feet), the computer increased motor

resistance above baseline. The resistance was proportional to the amount of asymmetry in the subject's foot forces thereby providing immediate information about force symmetry in the subject's lower limbs. Subjects could perform extensions with minimal resistance if they generated equal forces at their left and right feet.

Thirty neurologically intact subjects gave written informed consent and participated in this study (14 male and 16 female; age:  $26 \pm 3.0$  years, mean  $\pm$  s.d.). The human subject review board at the University of Michigan Medical School approved the protocol.

### 2.1. Experiment 1

The purpose of experiment 1 was to determine whether subjects could become more symmetric in their lower limb force production with symmetry-based resistance. Twenty subjects were randomly placed in two groups. One group experienced the symmetry-based resistance and the other was a control group with constant resistance. All subjects performed five sets of 20 lower limb extensions with rest between sets. Subjects' foot placement had an inter-foot distance equal to their anterior superior iliac spine (ASIS) width. We tracked center of pressure location as a percentage of inter-foot distance with 0% being at the non-dominant foot center. The non-dominant foot was determined as the foot that produced the least amount of force during set 1. We set the target for symmetry at 50% of inter-foot distance. Subjects extended to full knee extension and flexed to a knee angle of approximately 90 degrees, matching movement speed to a metronome set at 0.33 Hz.

The symmetry-based resistance group performed the first set of lower limb extensions against a constant baseline resistance equal to 25% of their body weight (Fig. 3A). During the second, third, and fourth sets, the symmetry-based resistance controller was turned on. Resistance increased in real-time above baseline in proportion to lower limb asymmetry. We set the saturation resistance equal to 75% body weight. We informed subjects that the resistance would vary based on their force symmetry and their goal was to perform extensions with increased symmetry and therefore decreased resistance. In the fifth set, we turned the symmetry-based resistance controller off and set the resistance to a constant 25% body weight. We included this set to assess subject performance without the controller.

The control group performed set 1 against a constant resistance equal to 25% body weight (Fig. 3A). During the second, third, and fourth sets the resistance did not change with foot force asymmetry and was equal to the average resistances of the symmetry-based resistance group (43%, 42% and 43% body weight, respectively). We informed subjects of the new constant resistance levels. In the fifth set, we set the resistance to a constant

Experiment 1 Protocol					
	Set 1	Set 2	Set 3	Set 4	Set 5
Symmetry-Based Resistance Group	25% BW	SBR	SBR	SBR	25% BW
Control Group	25% BW	43% BW	42% BW	43% BW	25% BW
No. of repetitions	20	20	20	20	20
Instructions	Symmetric	Symmetric	Symmetric	Symmetric	Symmetric

(A)

Experiment 2 Protocol					
	Set 1	Set 2	Set 3	Set 4	Set 5
Symmetry-Based Resistance Group	25% BW	SBR	SBR	SBR	25% BW
No. of repetitions	20	20	20	20	20
Instructions	Symmetric	Asymmetric	Asymmetric	Asymmetric	Asymmetric

(B)

Fig. 3. Protocol for experiments 1 and 2. All sets of extensions included 20 repetitions. (A) The symmetry-based resistance group received constant resistance for sets 1 and 5. In sets 2–4 they received symmetry-based resistance (SBR) where the amount of resistance increased with asymmetric foot forces. The control group received constant resistance at varying percentages of their body weight (BW) for all sets. Instructions to subjects of both groups were to perform all sets of extensions symmetrically. (B) Subjects received constant resistance for sets 1 and 5. In sets 2 through 4 they received symmetry-based resistance (SBR) where the amount of resistance increased as their center of pressure location moved away from the target force asymmetry. Instructions to subjects were to perform extensions of set 1 symmetrically, in sets 2 through 4 they were to learn the asymmetry in force production, and in set 5 they were asked to reproduce the asymmetry.

25% body weight to assess performance after training. As with the symmetry-based resistance group, we frequently verbally reminded subjects to perform extensions symmetrically.

## 2.2. Experiment 2

The purpose of experiment 2 was to determine if neurologically intact subjects could learn an asymmetry of foot forces using the symmetry-based resistance controller. Ten subjects performed five sets of 20 lower limb extensions with rest between sets (Fig. 3B). We changed the target in the symmetry-based resistance controller from 50% to 33%. During the second, third, and fourth sets when subjects received symmetry-based resistance, we informed subjects that they were to learn the asymmetry in force production by attempting to minimize device resistance. We did not explicitly inform subjects where the new target was, which foot had to produce more force, or how much more force that foot had to produce. We assessed subject performance without the controller in the fifth set by asking subjects to reproduce the asymmetry against a constant resistance of 25% body weight.

## 2.3. Data collection and analysis

For both experiments, we collected force and center of pressure readings using a force platform (Fig. 1). We

normalized center of pressure data to individual stance width to reduce intersubject variability. We identified extension cycle timing from motor encoder data. We also calculated the root mean square (RMS) center of pressure excursion to capture the variability. We normalized RMS center of pressure excursion to the average value of the first set to reduce intersubject variability. This resulted in a first set average value of 100% for all subjects. A decrease in this value represented a change in foot forces towards the target. We averaged center of pressure and RMS center of pressure excursion for the entire last 10 repetitions within each set to eliminate possible high variability of initial repetitions.

For experiment 1, we collected electromyography (EMG) data from all subjects in the symmetry-based resistance group to ensure that any changes in limb symmetry were not due to muscle fatigue. We recorded surface EMG (Model CP511, Astro-Med Inc., West Warwick, RI) from the left vastus lateralis using bipolar surface electrodes. The EMG amplifier had a bandwidth of 30 - 1000 Hz. We calculated the mean power frequency of EMG within each set by plotting the power spectral density and calculating which frequency corresponded to the mean value. As the vastus lateralis muscle fatigues, the power spectrum of EMG shifts towards lower frequencies (Arendt-Nielsen and Mills, 1988). Due to equipment malfunction, we analyzed EMG data for only seven of the 10 subjects.

In experiment 1, we used a repeated measure ANOVA (subject by group by set, with subject nested within group) to test for differences in average center of pressure location and normalized RMS center of pressure excursion (JMP IN software, SAS Institute, Inc., Cary, NC). We performed a repeated measure ANOVA (subject by set) for the symmetry-based resistance group to test for differences in EMG mean power frequency. When the ANOVA indicated significant differences ( $p < 0.05$ ), we used a Tukey-Kramer HSD post hoc test to determine differences between sets ( $p < 0.05$ ).

In experiment 2, we used a repeated measure ANOVA (subject by set) to test for differences in average center of pressure location and normalized RMS center of pressure excursion. As in experiment 1, we then used a Tukey-Kramer HSD post hoc test to determine differences between sets ( $p < 0.05$ ).

## 3. Results

### 3.1. Experiment 1

Subjects in the symmetry-based resistance group improved force symmetry as measured by average center of pressure location while control subjects did

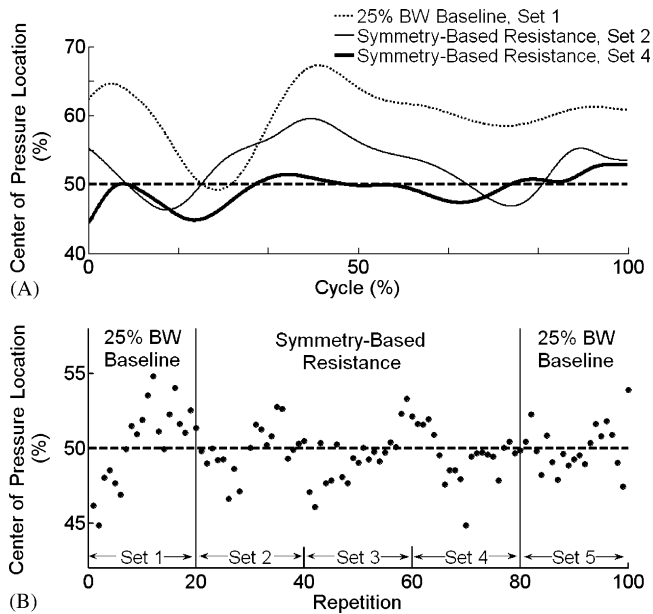


Fig. 4. (A) Plot of center of pressure location as a function of percent of lower limb extension for one subject throughout three repetitions. Lower limb flexion is the first 50% of the cycle and extension is the last 50% of the cycle. Data represent center of pressure location during the last repetition of set 1 against 25% body weight resistance (dotted line), first repetition of set 2 with the symmetry-based controller turned on (thin solid line), and last repetition of set 4 with the symmetry-based controller (thick solid line). The subject's center of pressure location moved closer to the target of 50% symmetry by the end of set 4. (B) Average center of pressure location data for a typical subject with the symmetry-based resistance controller in experiment 1. The dashed line represents the target for symmetry of 50%. This subject was better at producing symmetric forces about the target by set 4 (indicated by reduced scatter of set 4 compared to set 1).

not (ANOVA,  $p < 0.001$ ). Fig. 4 shows example data from one subject in the symmetry-based resistance group. On average, the symmetry-based resistance group had center of pressure locations closer to 50% for sets 3 and 4 than for set 1 (Tukey HSD,  $p < 0.05$ ) (Fig. 5A). The average center of pressure location for these subjects was  $52.5\% \pm 0.73\%$  (mean  $\pm$  s.e.m.) for set 1 and decreased to  $50.2\% \pm 0.63\%$  during set 4. The control group did not improve with training ( $p < 0.05$ ), perhaps due to lack of concentration. Comparing the symmetry-based resistance and control groups showed no significant difference of average center of pressure location between groups during set 1 ( $p > 0.05$ ). By sets 3 and 4, the symmetry-based resistance group was significantly closer to 50% than the control group ( $p < 0.05$ ) (Fig. 5A). During the last set, however, there was no significant difference between groups ( $p > 0.05$ ).

Center of pressure excursion demonstrated similar trends as average center of pressure (Fig. 5B). We collected this measure to further describe symmetry levels by capturing the variability in the center of pressure. In sets 3 and 4, the symmetry-based resistance

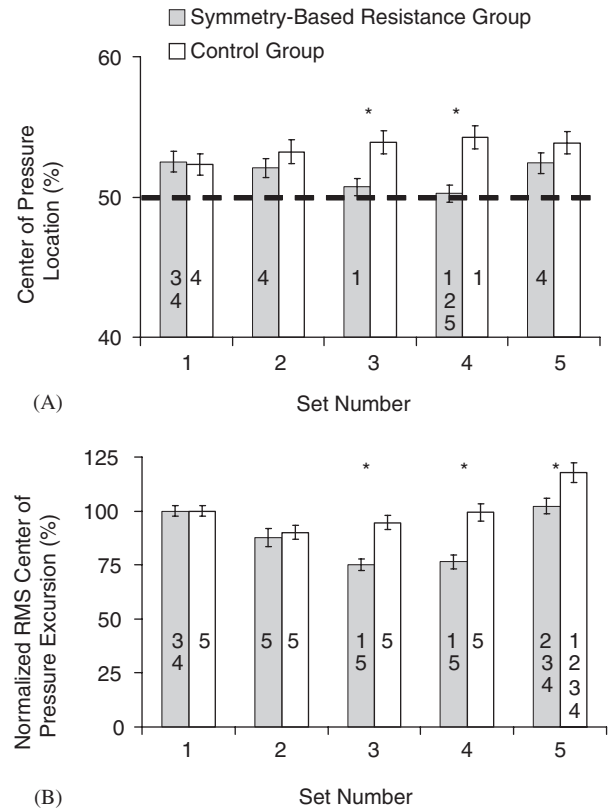


Fig. 5. Averaged center of pressure location and normalized RMS center of pressure excursion for all subjects in experiment 1. Gray columns represent the symmetry-based resistance group and white columns represent the control group. Numbers within each bar indicate which sets are significantly different from the current set (Tukey HSD,  $p < 0.05$ ). Error bars are standard error of the mean. (A) Mean center of pressure location significantly decreased in the symmetry-based resistance group ( $p < 0.05$ ). In contrast, the control group did not improve in symmetry. In sets 3 and 4, the symmetry-based resistance group was significantly better at producing symmetric forces than the control group (\*:  $p < 0.05$ ). (B) Normalized RMS center of pressure excursion showed results similar to the center of pressure location with one addition. The symmetry-based resistance group was significantly better at producing symmetric forces than the control group in sets 3–5 (\*:  $p < 0.05$ ) rather than just sets 3–4.

group significantly reduced their center of pressure excursion from set 1 ( $p < 0.05$ ). The control group did not improve with training ( $p > 0.05$ ). During set 5, the center of pressure excursion for the control group significantly increased compared to set 1 ( $p < 0.05$ ). Overall, there was a significant difference between the two groups during sets 3, 4, and 5 ( $p < 0.05$ ).

EMG results from the vastus lateralis muscle of subjects in the symmetry-based resistance group showed no significant change in EMG mean frequency (ANOVA,  $p > 0.05$ ). These results indicate that these subjects were not fatigued by the end of training. EMG mean frequencies for sets 1–5 were  $80.6 \pm 4.0$  Hz,  $78.3 \pm 4.5$  Hz,  $79.7 \pm 3.8$  Hz,  $81.4 \pm 4.0$  Hz, and  $81.1 \pm 4.0$  Hz, respectively.

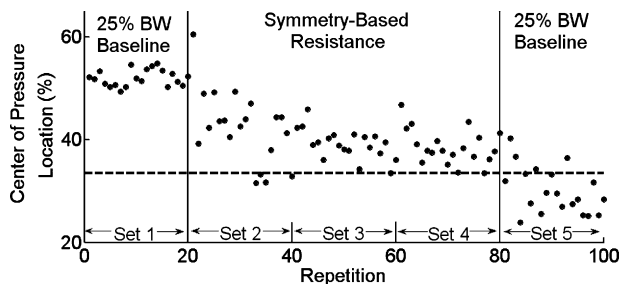


Fig. 6. Average center of pressure location data for one subject with the symmetry-based resistance controller in experiment 2. The dashed line represents the target for asymmetry of 33%. With training, the subject was able to produce asymmetric forces near the target. When asked to reproduce the asymmetry during set 5, the subject showed carryover of the training.

### 3.2. Experiment 2

With the symmetry-based resistance controller on, subjects shifted their average center of pressure location towards the target of 33% (ANOVA,  $p < 0.001$ ). Fig. 6 shows data of one subject learning the asymmetry. The trend towards the target is clearly evident. For all subjects, the average center of pressure location in the first set was  $55.3\% \pm 0.5\%$  (Fig. 7A). The second, third, and fourth sets decreased significantly from set one towards the target ( $p < 0.05$ ) and by set four the average center of pressure location was  $44.6\% \pm 0.7\%$ . In set five when the symmetry-based resistance controller was turned off and subjects were asked to reproduce the asymmetry, the average center of pressure location was  $41.1\% \pm 1.6\%$ . This value was significantly lower than that of set one ( $p < 0.05$ ), demonstrating a carryover of asymmetry.

Center of pressure excursion (as calculated from the target asymmetry) also decreased with training (Fig. 7B). With the symmetry-based resistance controller turned on, this value decreased during sets two, three, and four ( $p < 0.05$ ). The normalized RMS center of pressure excursion for set five was significantly less than set one ( $p < 0.05$ ), showing a carryover of training.

## 4. Discussion

Our results show that neurologically intact subjects training with the symmetry-based resistance controller shifted their center of pressure location towards the targets. In experiment 1, the symmetry-based resistance group increased lower limb symmetry within the single testing session. This increase in symmetry, however, was not maintained when the symmetry-based resistance controller was turned off. In experiment 2, subjects learned the appropriate relative sense of effort in the two limbs to produce the target asymmetry. When subjects were asked to reproduce the asymmetry, they did show

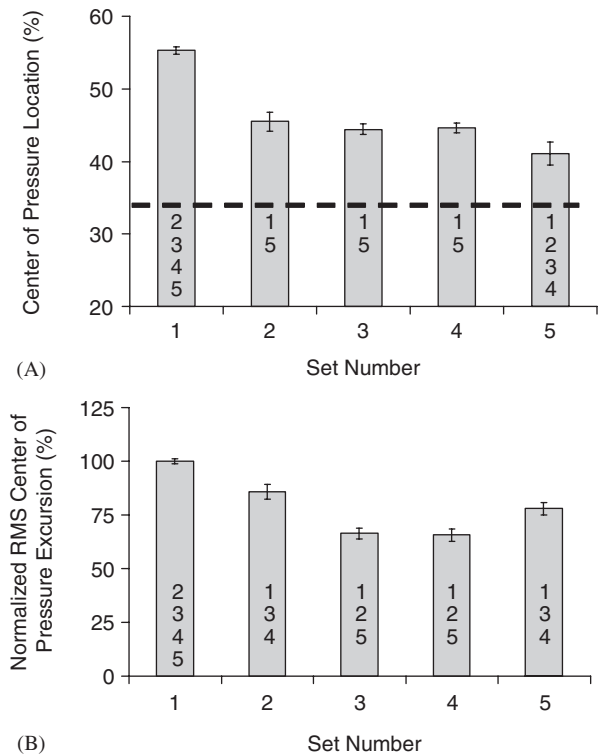


Fig. 7. Averaged center of pressure location and normalized RMS center of pressure excursion for all subjects in experiment 2. During sets 2 through 4, all subjects received symmetry-based resistance about the targeted asymmetry of 33%. Numbers within each bar indicate which sets are significantly different from the current set (Tukey HSD,  $p < 0.05$ ). Error bars are standard error of the mean. (A) Mean center of pressure location shows a significant decrease towards the asymmetry with training ( $p < 0.05$ ). In set 5, subjects showed carryover of the training and were able to reproduce the asymmetry without the symmetry-based resistance controller. (B) Normalized RMS center of pressure excursion decreased in sets 2, 3, 4, and 5 from initial values in set 1 ( $p < 0.05$ ).

carryover of training. Subjects altered lower limb force production towards the asymmetry without the symmetry-based resistance controller.

One explanation for why the symmetry-based resistance controller was effective in the neurologically intact subjects is the principle of least effort. The principle states that while performing a task, humans prefer movements that require the least amount of physical energy to achieve a goal (Almasbakk et al., 2000). Symmetry-based resistance directs subjects into altering limb symmetry towards the target by this principle. Subjects performed extensions against minimal resistance and therefore least effort when they increased lower limb symmetry. Symmetry-based resistance may have an advantage over audio and/or visual feedback because proprioceptive mapping to muscle recruitment is much more direct than audio/visual sensory mapping to muscle recruitment. Motor neuron activation and muscle forces are encoded at the spinal cord level (Bizzi

et al., 2002; Bosco and Poppele, 2001), resulting in a more natural proprioceptive feedback loop for symmetry-based resistance. The rate of motor learning may be faster for symmetry-based resistance than for audio and visual feedback techniques.

In all likelihood, experiment 1 did not demonstrate carryover for the symmetry-based resistance group because of the relatively small changes in symmetry required to match the target. All subjects exhibited symmetry levels close to the target in set 1. The symmetry-based resistance controller was able to increase symmetry slightly, but the resolution of the training effect was not great since the change in center of pressure location was only 2% of the distance between the feet. In experiment 2, the asymmetry target was much further away from subjects' initial symmetry levels. The subjects made a change in center of pressure location of 10% of the distance between the feet. The resolution for the second experiment was better because of the magnitude of the targeted change.

Neurologically impaired individuals may benefit from symmetry-based resistance therapy. Subjects in the second experiment demonstrated carryover to what they perceived as an asymmetry. Individuals with hemiparesis sense symmetry in force development as a perceived asymmetry and the magnitude of targeted change would likely be large. Although the principle of least effort may not hold for neurologically impaired users, practice with symmetry-based resistance may allow them to gain a better sense of relative effort for comparable forces in their paretic and non-paretic limbs (Rode et al., 1996). This could enable them to produce symmetric forces in other functional movements when they have a need (e.g. sit to stand transition). In addition, exercise with symmetry-based resistance may enhance recruitment of the paretic limb during therapy and lead to greater strength gains than traditional strength training with a constant resistance. Further testing on neurological populations is warranted to test these hypotheses.

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