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The effect of unilateral and bilateral strength training on the bilateral deficit and lean tissue mass in post-menopausal women

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Abstract Some have observed maximal strength of simultaneous bilateral homologous limb contraction is less than the sum of strengths of right and left limbs contracting alone; a phenomenon referred to as the bilateral deficit (BLD). There is controversy on whether there is a BLD for all exercises. We assessed whether a BLD occurs across different exercises (leg press, knee extension, and lat pull-down), whether the BLD could be altered with unilateral or bilateral training, and whether unilateral versus bilateral training was more beneficial for increasing lean tissue mass (LTM). Post-menopausal women (~57 years) were randomized to bilateral ($n=14$) and unilateral ($n=12$) training, or non-training control ($n=24$) groups. Bilateral training involved seven exercises performed with bilateral contractions (two sets, 3 days week⁻¹, 26 weeks). Unilateral training involved the same exercises performed with one limb at a time. A BLD was found for leg press and lat pull-down, but not for knee extension. Bilateral training decreased the BLD; whereas unilateral training had minimal effect on the BLD. The unilateral-training group had a greater increase in lower-body LTM compared to the control group ($P<0.05$); however, there were no differences between unilateral and bilateral training groups. Both training groups had greater increases in LTM of the upper- and whole-body compared to the control group. We conclude that the BLD is apparent for some exercises (i.e., the leg press and lat pull-down) but not others (i.e., knee extension). Bilateral training reduces the BLD; whereas unilateral training has minimal effect on the BLD.

Keywords Old · Bilateral index · Muscle · Female

Introduction

Muscular strength is an important component for physical activity and for the performance of tasks of daily living. A phenomenon that is commonly observed is that maximal strength generating capacity is compromised when homologous limbs contract bilaterally. This is referred to as the bilateral deficit (BLD), and occurs when the maximal voluntary strength of simultaneous bilateral contraction is less than the sum of the strengths of right and left limbs when contracting alone (Howard and Enoka 1991; Jakobi and Chilibeck 2001; Kawakami et al. 1998). Henry and Smith (1961) first observed a BLD while examining grip strength. Since then, BLD has been shown in both large and small muscle groups (Howard and Enoka 1991; Koh et al. 1993; Oda and Moritani 1994; Schantz et al. 1989; Secher et al. 1988; Vandervoort et al. 1984), athletic and non-athletic populations (Secher et al. 1988; Schantz et al. 1989), and in male and female subjects (Schantz et al. 1989); however, there is some controversy as to the existence of the BLD with some studies not showing a BLD (Jakobi and Cafarelli 1998; Haikkinen et al. 1995, 1996a, b, 1997; Vandervoort et al. 1987). We have recently reviewed studies of the BLD and found that certain movement patterns [i.e., leg press (combined knee and hip extension)] frequently exhibit a BLD while others such as knee extension usually do not (for review, see Jakobi and Chilibeck 2001). It is thought that the BLD is caused by neural inhibition when attempting to contract two homologous limbs simultaneously (Vandervoort et al. 1984; Herbert and Gandevia 1996; Kawakami et al. 1998; Khodiguian et al. 2003; Oda and Moritani 1995). Complex exercises where movement is required at multiple joints, such as the leg press, may require a greater neural involvement than simple exercises (i.e., single joint exercises) such as knee extension (Chilibeck et al. 1998). Exercises involving movement at more than one joint may therefore be more susceptible to a BLD.

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There is controversy as to whether a BLD exists in older individuals. There is some evidence the BLD may be related to inhibition of fast-twitch motor unit recruitment during bilateral contractions (Kawakami et al. 1998; Vandervoort et al. 1984). Older individuals may have a reduced number and size of fast-twitch muscle fibers (Lexcel 1993); therefore, one would expect that the BLD would be less prominent in older compared to younger individuals. Studies are mixed on the existence of the BLD in older individuals. Owings and Grabiner (1998) and Kuruganti et al. (2005) found a BLD with knee extension or flexion, Hernandez et al. (2003) found a BLD with elbow flexion in older adults, while Hakkinen et al. (1995, 1996a, b, 1997) did not observe a BLD during knee extension. Since there are age-related changes to the neuromuscular system and consequently, strength and function, it is important to examine whether this neural phenomenon does occur in older populations.

The BLD is reduced with bilateral training and increases with specific unilateral training (Taniguchi 1997). This may have implications when recommending appropriate training for those involved in sports where unilateral contractions predominate (i.e., boxing, cycling, running) compared to sports where bilateral contractions predominate (i.e., weight lifting, rowing). Specific training may also be important for performance of certain activities of daily living (i.e., bilateral contractions of the legs when rising from a chair).

Given that one may be able to produce greater force when performing unilateral contractions, it has been suggested that unilateral training may be of greater benefit if an individual is attempting to build muscle mass (Jakobi and Chilibeck 2001; Vandervoort et al. 1987). This hypothesis has never been tested with a rigorous training program. This training strategy may be of benefit for individuals such as the elderly, who have reduced muscle mass.

The purpose of this study was to determine whether a BLD actually occurs in an aging population, whether bilateral and unilateral training can change the BLD and whether unilateral training can be used as a strategy for increasing muscle mass in post-menopausal women. Our hypotheses were: (1) the BLD would be evident in multi-joint exercises such as leg press or lat pull-down (combined elbow flexion and shoulder adduction), but absent in single joint exercises such as knee extension; (2) bilateral training would reduce the BLD; whereas unilateral training would increase the BLD; and (3) unilateral training would be more beneficial for increasing muscle mass than bilateral training.

Methods

Subjects

Women who were not previously involved in formal strength training were recruited through newspaper ads and posters. All participants gave their informed consent

prior to their inclusion in the study. The study was approved by the University of Saskatchewan Biomedical Ethics Committee for Research in Human Subjects.

The subjects were simultaneously participating in another study examining the effects of the exercise training and a bisphosphonate on bone mineral density (BMD) (Chilibeck et al. 2002). Subjects were randomized to exercise and non-exercise training groups based on the design of this study. Subjects in the exercise groups were then randomly assigned to perform unilateral or bilateral training for 26 weeks.

There were initially 57 subjects who began the study and the subjects were randomly assigned to either the bilateral ($n=15$) or unilateral ($n=14$) training groups, or a non-training control group ($n=28$). Two subjects withdrew from the unilateral group, citing lack of time and interference with work, one subject in the bilateral group withdrew because she broke her ankle in an accident unrelated to the training program, one subject from the control group withdrew because her family physician prescribed hormone replacement therapy which was an exclusion criterion for the bone mineral study, and three subjects in the control group were lost to follow-up. The number of subjects who completed the study therefore included 14 in the bilateral training group, 12 in the unilateral training group and 24 in the control group. The subjects in the unilateral training group had an age of 54.8 ± 6.5 years, mass of 70.3 ± 13.7 kg, and height of 165 ± 6 cm, subjects in the bilateral training group were 55.8 ± 8.2 years, 71.5 ± 13.4 kg, and 165 ± 4 cm, and subjects in the control group were 58.8 ± 6.7 years, 69.5 ± 9.8 kg, and 163 ± 6 cm.

Strength and BLD assessment

The one repetition maximum (1-RM) of bilateral and unilateral strengths were assessed before and after training for leg press and knee extension (Hammer Strength, Life Fitness; Franklin Park, IL, USA) and for lat pull-down (using Lever equipment, Pulse Fitness Systems, Winnipeg Manitoba, Canada) for the training groups. For unilateral strength, both limbs were tested separately in random order. Because the unilateral testing was quite time consuming and strength was not expected to increase in the control group, this group was only assessed for bilateral strength on the leg press and lat pull-down. The leg press, lat pull-down, and knee extension machines had split lever arms, which allowed the subjects to do either unilateral or bilateral testing. These machines were altered so that they had plates and pins to join the levers together for bilateral testing. The order of the bilateral and unilateral efforts was randomized. The test order of the machines was consistent with the leg press first, lat pull-down second, and knee extension last. A standard warm-up consisted of riding a cycle ergometer for 5 min followed by leg and arm stretches. In order to familiarize the subjects with the movements a warm-up was done on each machine before the 1-RM testing. The subjects performed ten repetitions at a light weight and then a couple of single repetitions at

progressively heavier weights. During the 1-RM testing, with each successful attempt the weight was increased by 2–10 kg, depending on the ease with which the subject performed the movement. It took approximately six to eight attempts to reach the participant's 1-RM. A successful attempt for the leg press and knee extension included the subjects extending their legs to the required position. The seat for leg press was adjusted so the participant's knees were in approximately 90° of flexion for the start of the movement. A hip belt was worn during the leg press and knee extension tests to try to eliminate excessive hip movement. For the knee extension and leg press, the subjects had to move from approximately 90°–10° of knee flexion. For knee extension there were stoppers placed at the top end of the range of motion (approximately 10° of flexion) and the subjects had to touch the stoppers for a successful attempt. For lat pull-down, the participants started with their arms above their head with a slight bend in their elbow joint. The seat was adjusted to a height which made the elbow position possible. For a successful attempt the participant had to pull the lever down to their chin. During each of the tests, there was a 2-min rest interval between each attempt to avoid muscle fatigue. The reproducibility of 1-RM testing was determined on ten of the women for measures of leg press and lat pull-down and for eight women for knee extension. This involved performing the strength tests on two separate days, 1 week apart. To calculate reproducibility, the method error of repeated measurements was used, expressed as a coefficient of variation (Chilibeck et al. 1994). For bilateral and unilateral leg press the coefficients of variation were 3.0 and 2.7%, respectively. For bilateral and unilateral knee extension the coefficients of variation were 4.3 and 3.7%, respectively. The coefficient of variation was 1.9% for both bilateral and unilateral lat pull-down.

As an index of the BLD, we calculated a bilateral index. The bilateral index, which is a ratio between bilateral and unilateral strengths, was calculated from the left unilateral, right unilateral and bilateral 1-RM values. The bilateral index is computed as:

$$\text{Bilateral index (\%)} = 100 \times (\text{bilateral strength}) \times (\text{right unilateral strength} + \text{left unilateral strength})^{-1} - 100$$
 (Howard and Enoka 1991; Taniguchi 1997, 1998).

A negative bilateral index will indicate the bilateral strength is less than the sum of unilateral strengths (i.e., BLD). A positive index will indicate the bilateral strength is greater than the summed unilateral strengths (i.e., bilateral facilitation) (Taniguchi 1997).

Lean tissue mass and bone density

Bone mineral-free lean tissue mass (LTM) was assessed by dual energy X-ray absorptiometry on a Hologic QDR 2000 densitometer both before and after training for the whole body (excluding the head), lower (legs) and upper (arms and trunk) body. All scans were analyzed by the same individual, who was blind to the group assignments. Reproducibility was assessed by measuring ten subjects on two occasions, 1 week apart. The coefficients

of variation were 4.1% for the arms, 1.2% for the legs, 0.7% for the trunk and 0.5% for the whole body. BMD was simultaneously assessed, with additional scans for the lumbar spine and proximal femur. Coefficients of variation for these measurements were 0.7% for lumbar spine BMD, 1.0% for proximal femur BMD, and 0.5% for whole-body BMD.

Training

Subjects trained three times per week for 26 weeks. At least 1 day of rest was given between training sessions. Exercises included leg press, knee extension, and hamstring curl (knee flexion) on Hammer Strength equipment (Life Fitness; Franklin Park, IL, USA) and lat pull-down, biceps curl, shoulder press, and chest press on Lever equipment (Pulse Fitness Systems; Winnipeg Manitoba, Canada). These machines had split lever arms, which allowed the subjects to do either unilateral or bilateral training. The unilateral training was done on both sides separately. Electromyographic measurements showed that during unilateral exercises, there was minimal activation (i.e., minimal contraction for stabilization) of the non-exercising limb (Chilibeck et al. 2004). In addition to the above exercises, subjects also performed back extension, and unilateral hip extension, flexion, adduction, and abduction on Lever equipment. Each exercise was performed with eight to ten repetitions for two sets. During the first 2–3 weeks of training there was an accommodation period. During the first week the subjects performed only one set of 12 repetitions for each exercise. The weights for the leg press, lat pull-down and knee extension were approximately 50–60% of the subjects' 1-RM. For the other exercises, a weight was selected which allowed the subjects to perform 12 repetitions. After the subject completed three training sessions a second set of one exercise was added for the fourth session. After that a second set of one exercise was progressively added until each of the exercises was performed with the required two sets. The weight was adjusted in accordance to the individual's strength increases so the subject was only able to perform eight to ten repetitions. Once the subject was able to perform ten repetitions with good form, the weight was increased by 1.1 kg per side. The subjects were supervised during every training session to ensure proper form and lifting techniques.

Statistical analyses

A one-factor analysis of variance (ANOVA) was used to analyze differences between groups for strength measures, bilateral index, LTM, mass, height, and age at baseline. To determine if the bilateral index was significantly different from zero, a dependent (one-sample) *t*-test was used to assess baseline bilateral indexes for leg press, knee extension, and lat pull-down exercises. If the bilateral index was significantly less than zero, this would indicate there was a BLD for that exercise.

The changes in bilateral index (for leg press, knee extension, and lat pull-down), individual measures of strength, LTM (for whole, lower, and upper body), and bone density between groups were assessed with two-factor ANOVA with repeated measures on the second factor (time, pre/post training). To clarify differences between groups change scores for LTM were analyzed by a one-factor ANOVA. Change scores for LTM were determined by subtracting post-training scores from pre-training scores. Relative changes in each strength measure were determined by subtracting the post-training strength from the pre-training strength, dividing by the pre-training strength, and multiplying by 100 (to obtain a percentage change score). Differences between groups for percent change in strength were analyzed with a one-factor ANOVA. To determine whether there was a difference in the time course for training between groups and whether the unilateral group was training with greater loads as predicted, training loads for the leg press, knee extension, and lat pull-down were expressed relative to pre-training 1-RM and analyzed with a two-factor (group \times time) ANOVA with repeated measures on the second factor (time; pre-, mid-, and post-training). Tukey post hoc tests were used when main effects or interactions were significant. Pearson correlation coefficients were determined between pre-training bilateral indexes and changes in the bilateral index with training to determine if initial BLDs would influence the degree to which the BLD could be changed with training. Results were expressed as means \pm SD, except for some figures where means \pm SEM were used for clarity. Significance was set at $\alpha \leq 0.05$.

Results

Baseline

There were no differences at baseline between groups for all measures. The baseline bilateral indexes for leg press

($-12.7 \pm 6.9\%$) and lat pull-down ($-8.8 \pm 7.8\%$) were significantly different from zero ($P < 0.001$) indicating a BLD for these exercises. All subjects had a BLD for leg press exercise, while 22 of 26 subjects had a BLD for the lat pull-down. The baseline bilateral index for knee extension ($-4.3 \pm 12.6\%$) was not significantly different from zero ($P = 0.095$). Fourteen of the 26 subjects had a BLD for knee extension.

Training

There was no difference between groups for attendance to training sessions. The unilateral group had an attendance rate of 82% (range 63.8–97.1%) while the bilateral group had an attendance rate of 76% (range 57.7–95.7%).

Measures for bilateral and unilateral strength before and after training are shown in Table 1. The unilateral and bilateral training groups increased strength for all measures ($P < 0.01$) with no differences between training groups. Relative (percent) changes for most measures were in the expected direction (i.e., greater relative changes for bilateral strength in the bilateral training group and greater relative change in unilateral strength in the unilateral group) but differences between groups were not significant because of high variability. There were no changes in the control group.

There were group \times time interactions for the bilateral indexes for leg press ($P < 0.05$) (Fig. 1), knee extension ($P < 0.01$) (Fig. 2), and lat pull-down ($P < 0.01$) (Fig. 3). The bilateral index for the leg press and knee extension increased significantly in the bilateral group ($P < 0.05$) and the bilateral indexes for all exercises were significantly different between groups after training ($P < 0.05$). For the bilateral group, the initial bilateral index was negatively correlated with changes in the bilateral index (leg press $R = -0.75$, lat pull-down $R = -0.90$, knee extension $R = -0.84$; all $P < 0.01$), implying that those with a large BLD could change their BLD with greater ease with bilateral training.

The time course for training showed little differences in progression between groups for the leg press and lat

Table 1 Pre- and post-strength measures for bilateral and unilateral test exercises (kg)

	Bilateral group				Unilateral group				Control group			
	Pre	Post	%	Range	Pre	Post	%	Range	Pre	Post	%	Range
Bilateral leg press	113 \pm 36	147 \pm 41	35 \pm 37	11–157	99 \pm 28	125 \pm 33	27 \pm 8	16–41	109 \pm 29	116 \pm 27	8 \pm 15	–20–53
Unilateral right leg press	65 \pm 19	80 \pm 20	27 \pm 25	0–100	56 \pm 13	72 \pm 19	28 \pm 7	15–39				
Unilateral left leg press	64 \pm 19	79 \pm 21	27 \pm 26	0–107	56 \pm 15	71 \pm 15	28 \pm 10	11–43				
Bilateral knee extension	37 \pm 12	48 \pm 12	42 \pm 60	0–235	37 \pm 85	51 \pm 15	29 \pm 21	0–61				
Unilateral right knee extension	20 \pm 5	23 \pm 5	17 \pm 29	0–109	19 \pm 5	27 \pm 11	26 \pm 16	–5–56				
Unilateral left knee extension	19 \pm 6	21 \pm 7	18 \pm 37	0–134	19 \pm 5	27 \pm 11	30 \pm 20	9–67				
Bilateral lat pull-down	39 \pm 7	48 \pm 9	37 \pm 44	6–178	38 \pm 8	53 \pm 15	28 \pm 16	0–56	33 \pm 15	32 \pm 15	1 \pm 29	–87–57
Unilateral right Lat pull-down	22 \pm 4	26 \pm 5	35 \pm 63	0–66	22 \pm 5	31 \pm 10	28 \pm 10	13–43				
Unilateral left lat pull-down	20 \pm 3	24 \pm 4	40 \pm 77	–5–301	20 \pm 5	30 \pm 10	33 \pm 16	14–59				

Values are means \pm SD

% percent change from pre- to post-training

Range The range of percent change

All measures increased over time for the training groups; whereas there were no changes in the control group

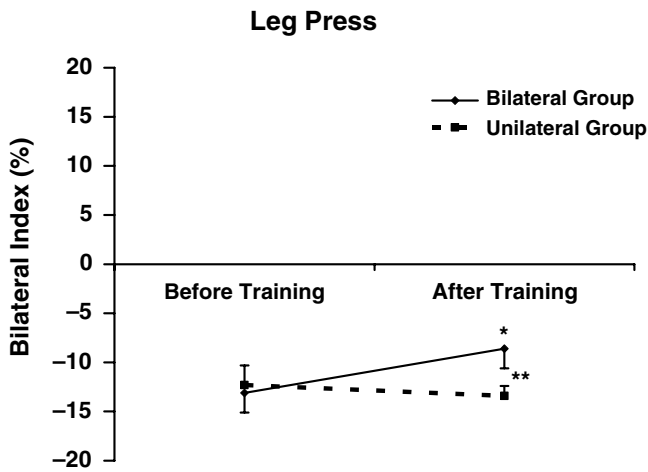


Fig. 1 Leg press bilateral index for the bilateral-training and unilateral-training groups before and after training. *The bilateral group increased the bilateral index with training ($P < 0.05$). **The bilateral index was significantly different between groups after training ($P < 0.05$). All values are means \pm SEM

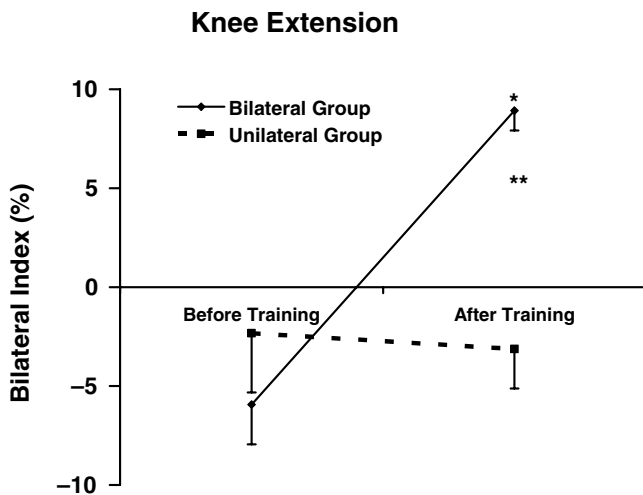


Fig. 2 Knee extension bilateral index for the bilateral-training and unilateral-training groups before and after training. *The bilateral group increased the bilateral index with training ($P < 0.05$). **The bilateral index was significantly different between groups after training ($P < 0.05$). All values are means \pm SEM

pull-down; however, the groups differed for the knee extension training load ($P < 0.05$), with the unilateral group having a higher load at all three measurements (pre-, mid-, and post-training) for knee extension (unilateral group: pre = $53 \pm 8\%$, mid = $72 \pm 12\%$, post = $87 \pm 17\%$ of pre-training 1-RM; bilateral group: pre = $47 \pm 12\%$, mid = $63 \pm 23\%$, post = $67 \pm 26\%$ of pre-training 1-RM).

Lean tissue mass before and after training is shown in Table 2. One subject from the control group was removed because she had a large increase in body mass over the study (11.1 kg) and therefore was considered an outlier. There were group \times time interactions for lower-body ($P < 0.05$), upper-body ($P < 0.01$) and whole-body

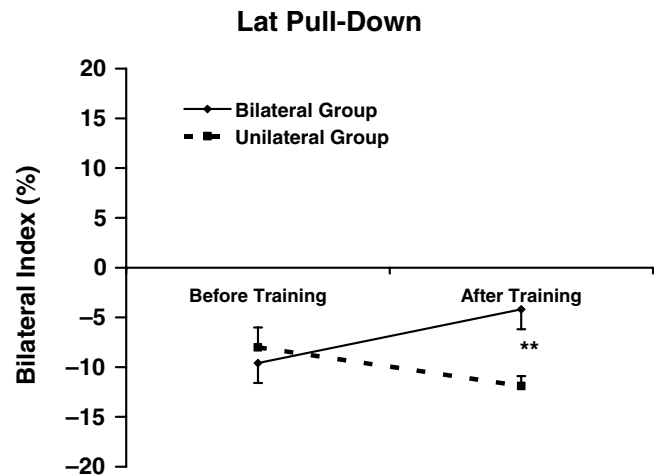


Fig. 3 Lat pull-down bilateral index for the bilateral-training and unilateral-training groups before and after training. **The bilateral index was significantly different between groups after training ($P < 0.05$). All values are means \pm SEM

($P < 0.01$) LTM. The bilateral and unilateral groups increased all measures for LTM over time, while there were no changes in the control group (Table 2). Change in lower-body LTM was greater in the unilateral training group compared to the control group ($P < 0.05$; Fig. 4a) but there were no differences between bilateral and unilateral training groups. Change in upper-body and whole-body LTM was greater in unilateral and bilateral training groups versus the control group ($P < 0.01$; Fig. 4b, c). There were no changes in BMD in any of the groups (Table 3).

Discussion

Our first hypothesis was that a BLD would be evident for complex exercises such as leg press (i.e., combined hip and knee extension) and lat pull-down (i.e., combined elbow flexion and shoulder adduction), but not for a simple, single joint exercise such as knee extension. Our hypothesis was based on a review of the literature that showed all studies of leg press exhibiting a BLD (Jakobi and Chilibeck 2001). Also, it is thought that the BLD is due to neural inhibition during bilateral compared to unilateral contractions (Vandervoort et al. 1984). The nervous system may be more involved during contractions that involve movement at multiple joints (Chilibeck et al. 1998); therefore, exercises that involve movement at multiple joints may be more susceptible to a BLD than exercises that involve movement at a single joint. Our results support this hypothesis: the bilateral index was negative for the leg press and lat pull-down indicating the existence of a BLD; whereas the bilateral index was not significantly different from zero for knee extension. The existence of the BLD in individuals was consistent for the leg press, with all subjects having a

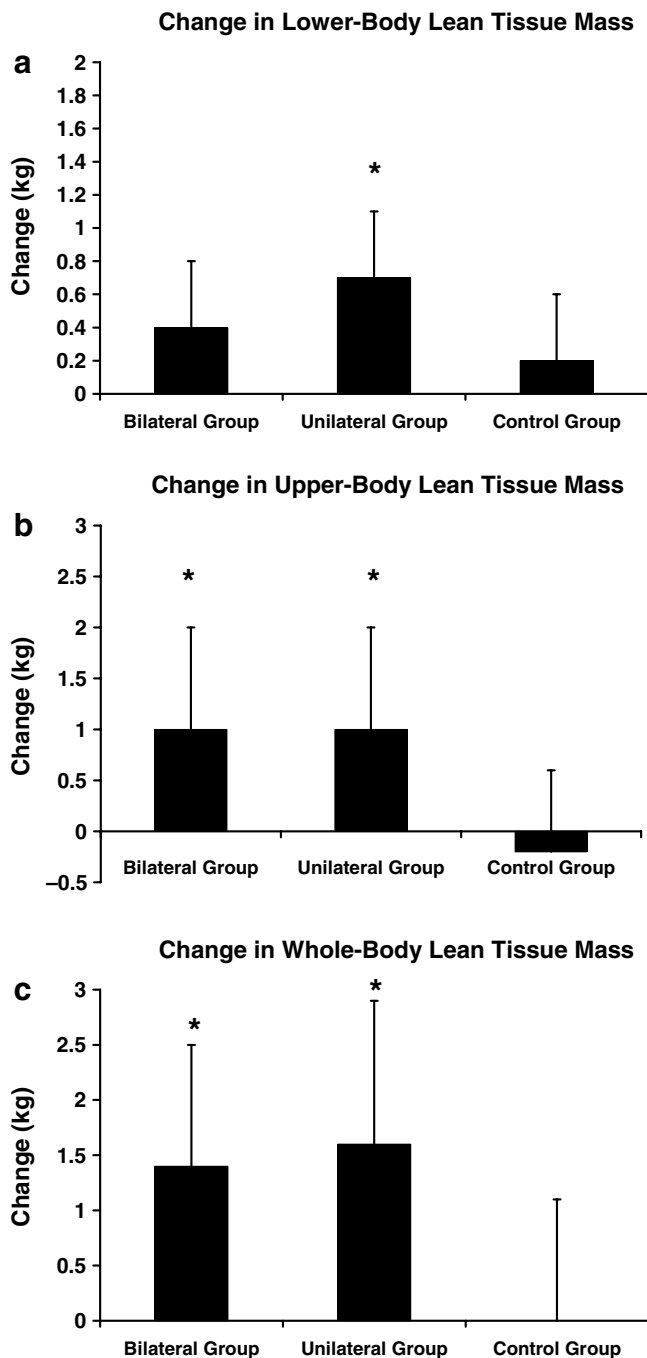


Fig. 4 Changes in **a** lower-body, **b** upper-body, and **c** whole-body lean tissue mass over the training program. *Greater compared to the control group ($P < 0.05$). All values are means \pm SD. *Note:* One outlier was removed from the control group

BLD. Twenty-two of 26 subjects had a BLD for lat pull-down; whereas 14 of 26 subjects had a BLD for knee extension. The current study is unique in that it is the first study to indicate in post-menopausal women that the BLD can exist for certain movement patterns, but not for others. Our findings are in agreement with other studies that have assessed the BLD for different exercises within younger subjects. For example, Schantz et al. (1989) found a BLD for leg press, but not knee extension

in young men and women, similar to our results for these two exercises. Taniguchi (1998) found a BLD for leg press and bench press in young men and women, similar to our findings for leg press and the multi-joint upper-body movement of lat pull-down. In contrast, Secher et al. (1988) found a BLD for leg press, but not for bench press in a group of younger subjects. The existence of a BLD for the leg press and lack of BLD for knee extension is quite consistent across the literature (Jakobi and Chilibeck 2001). While there is disagreement on whether a BLD exists for complex upper-body exercises, it is clear from studies that have found a BLD that the BLD is smaller compared to leg press within the same subjects (i.e., the current study and Taniguchi 1998).

Previous research has indicated that bilateral training of the upper and lower limbs results in the bilateral index moving in the positive direction (i.e., decreasing the BLD), while unilateral training results in the bilateral index moving in the negative direction (i.e., increasing the BLD) (Taniguchi 1997, 1998). Our second hypothesis that changes in the BLD are specific to type of training was based on these findings. The results for leg press and knee extension of the bilateral group from our study support this hypothesis. The bilaterally trained group was able to decrease their BLD for leg press and knee extension; whereas unilateral training had little effect on the BLD. For the bilateral group the change in bilateral index was inversely correlated with initial bilateral index for all three exercises ($R = -0.75$ to -0.90) implying that those with a greater BLD can more easily reduce the BLD with bilateral training. Our findings are in agreement with two other studies of training in older individuals. Hakkinen et al. (1996a) trained a group of middle-aged and elderly men and women with bilateral and unilateral knee extension. In order to quantify their BLD results they used a bilateral to unilateral strength ratio, which is similar to the bilateral index. They determined after 12 weeks of training that the bilateral to unilateral strength ratio increased 7% in the bilateral training group and decreased 2% in the unilateral training group. Recently, Kuruganti et al. (2005) also showed bilateral knee extension training was effective for reducing the BLD in older individuals. These studies and our results imply that one can reduce the BLD, but not increase it significantly. This has important implications for activities that involve mainly bilateral contractions of the lower body (i.e., two-legged jumping, rowing, or activities of everyday living such as rising from a chair). If one wants to improve force output during these types of contractions it would be best to train bilaterally rather than unilaterally. Our study incorporated the longest training duration (6 months) of unilateral compared to bilateral training and therefore provides important information on the extent to which the BLD can be changed. Measurement of bilateral versus unilateral strength in athletes that have been exposed to long durations of bilateral training indicate that the BLD can be eliminated and that it may be possible for long-term bilateral training to result in a bilateral facilitation (i.e., where

Table 2 Pre- and post-training measures for lean tissue mass (kg)

	Bilateral group		Unilateral group		Control group	
	Pre	Post	Pre	Post	Pre	Post
Lower-body	11.7±2.2	12.0±2.2**	11.6±1.6	12.3±1.8*	11.1±1.9	11.3±1.9
Upper-body	23.5±3.0	24.4±3.4*	23.7±2.5	24.6±2.9**	22.1±3.3	22.1±2.9
Whole-body	35.2±5.4	36.4±6.1*	35.3±4.4	36.8±4.9*	34.9±5.3	34.9±5.1

Note: one outlier was removed from the control group

Values are means ± SD

Significant difference between pre- and post-training * $P < 0.01$; ** $P < 0.05$

Table 3 Pre- and post-training measures for bone mineral density (g/cm^2)

	Bilateral group		Unilateral group		Control group	
	Pre	Post	Pre	Post	Pre	Post
Proximal femur	0.875±0.136	0.877±0.123	0.891±0.080	0.897±0.092	0.868±0.121	0.871±0.115
Lumbar spine	0.893±0.147	0.880±0.128	0.938±0.125	0.948±0.123	0.944±0.138	0.955±0.151
Whole-body	0.986±0.088	0.979±0.086	0.999±0.108	0.997±0.098	0.989±0.088	0.990±0.084

Values are means ± SD

bilateral strength is actually greater than summed unilateral strengths) (Howard and Enoka 1991; Secher 1975).

Our third hypothesis was that unilateral training would result in a greater increase in LTM compared to bilateral training. This was based on the reasoning that if a BLD existed for most exercises, then one would be able to train with higher loads if participating in unilateral, compared to bilateral training. Our results partially support our hypothesis. The unilateral group was able to train with greater loads for the knee extension exercise, but not the leg press or lat pull-down (see Results). Only unilateral training was effective for increasing lower body LTM to a greater extent compared to the control group (Fig. 4a); however, there were no differences for changes between the unilateral and bilateral training groups for lower body LTM. Unilateral and bilateral training were effective for increasing LTM in the upper body and whole body compared to the control group and there were no statistical differences between unilateral and bilateral training (Table 2, Fig. 4).

Bone mineral density did not change over the 26 week training program (Table 3). Bone turn-over is relatively slow; therefore, a longer duration of training is most likely necessary to increase BMD (Chilibeck et al. 1995).

Typical of an older population, there was much variation in the response to training, with a wide range of changes in strength across the groups (Table 1). Although the increase in LTM with training was statistically significant the changes were small. Overall, the relative increases in strength (~25%) were substantially larger than the increases in LTM (~4%). This implies that adaptations in the nervous system or learning how to better perform the exercises had a greater impact for improving strength than changes in muscle mass. Previous research has indicated that the increase in strength for older subjects during short-term training is dependent mainly on neural factors (i.e., increased maximal

muscle activation) whereas for younger subjects the increase in strength is due to neural factors initially and then muscle hypertrophy after about 4 weeks (Moritani and deVries 1980).

In conclusion, a BLD can exist with certain movement patterns, but be absent in others within the same individual. Our results indicated a BLD during leg press and lat pull-down, but not during knee extension. Training with bilateral contractions can lessen the BLD; whereas training with unilateral contractions maintains the BLD but does not increase it significantly. Only unilateral training was effective for increasing lower-body LTM compared to a control group; however, there were no differences between unilateral and bilateral training for increasing LTM of the lower-body or upper-body.

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