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ORIGINAL ARTICLE

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Relationship between the modifications of bilateral deficit in upper and lower limbs by resistance training in humans

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Abstract Maximal voluntary strength of simultaneous bilateral exertion is known to be small compared to the sum of the unilateral exertions. This phenomenon is called bilateral deficit and the purpose of this study was to investigate whether it operates in both upper and lower limbs. A group of 7 female and 32 male students were divided into 4 training groups and a control group. The unilateral arm or leg training group performed maximal isokinetic arm or leg extensions using each arm or leg unilaterally. The bilateral arm or leg training group trained using bilateral extensions of both arms or legs. The groups in training continued these two types of resistance exercise 3 days a week, for 6 weeks. The control subjects did not train. The improvement in power brought about by training was compared from the viewpoint of whether the limbs (arms or legs) were trained or not and whether the mode of test power exertion (bilateral or unilateral) was the same as performed during training or not. The power in the trained limbs using the same regime as that during training (3.0% after 3 weeks, 7.7% after 6 weeks) showed the largest improvement ratio. This agrees with the *specificity theory* in resistance training. The increase in power in untrained limbs using the same regime as during training (2.1% after 3 weeks, 3.5% after 6 weeks; $P < 0.01$) and the increase in power in the untrained limbs after the opposing mode of training (1.2% after 3 weeks, 2.2% after 6 weeks; $P < 0.05$) were larger than that of the controls (−2.5% after 3 weeks, −1.1% after 6 weeks). This suggests that the effect of resistance training was transferred to the untrained limbs (i.e. to the legs in the arm training group and to the arms in the leg training group). The degree of bilateral deficit (bilateral index, BI) in the trained limbs of the bilateral training group was shifted in a positive direction (4.2% after 3 weeks, 3.7% after 6 weeks) and that in the trained limbs of unilateral training group was shifted in a negative direction (−3.0% after 3 weeks, −5.4% after 6 weeks) by 6 weeks of training. The BI in the untrained limbs of the unilateral training group was shifted in a negative direction (−1.9% after 3 weeks, −4.5% after 6 weeks) by 6 weeks of training, whereas that in the untrained limbs of the bilateral training group was not shifted in a positive direction (−0.1% after 3 weeks, −2.4% after 6 weeks). These results would suggest that bilateral deficits in the upper and lower limbs are at least partially affected by some common mechanism at a supraspinal level.

Key words Bilateral deficit · Resistance training · Lateral specificity

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Introduction

Many investigators have reported a reduction in maximal voluntary strength induced by simultaneous bilateral exertion compared with unilateral exertion (Henry and Smith 1961; Howard and Enoka 1991; Koh et al. 1993; Oda and Moritani 1995; Ohtsuki 1981, 1983; Rube and Secher 1990; Schantz et al. 1989; Secher 1975; Secher et al. 1978, 1988; Taniguchi 1997; Vandervoort et al. 1984). It has been suggested that this bilateral deficit is mediated by neural mechanisms such as interactions between the cerebral hemispheres or spinal reflexes (Ohtsuki 1983, 1994).

It has been shown that the degree of bilateral deficit (bilateral index, BI; Howard and Enoka 1991) is affected specifically by bilateral and unilateral resistance training in the upper and lower limbs (Häkkinen et al. 1996; Taniguchi 1997). Bilateral force has been found to be increased but unilateral force not to be changed by bilateral training: as a result the bilateral deficit has been decreased. Using unilateral training, opposite phenomena have been shown to occur.

If the bilateral deficit were to be mediated by reciprocal inhibition in the spinal cord, BI in upper and lower limbs should be affected independently by resistance training. However, if it were to be mediated by supraspinal mechanisms such as interhemispheric inhibition, and if this mechanism were to control bilateral deficits in both upper and lower limbs, BI in the upper and lower limbs should change in parallel with each other during resistance training.

The purpose of this study was to investigate whether the mechanism of bilateral deficit is common in upper and lower limbs, by investigating the effect of bilateral or unilateral resistance training in upper or lower limbs on the bilateral deficit in limbs that were not involved in training.

Methods

Subjects

A group of 7 female and 32 male students [mean age 20.5 (SEM 0.2) years, mean height 1.71 (SEM 0.01) m, and mean body mass 66.4 (SEM 2.2) kg] participated in the study. This study was performed in accordance with the ethical standards laid down in the Declaration of Helsinki. All the subjects gave their informed consent for participation in the study.

Apparatus

Isokinetic dynamometers, "chest force" and "kick force" (Takei Scientific Instruments Co., Ltd.) for measuring arm and leg extension power (Saito et al. 1994) were used.

The force bar or plate to which a force sensor (strain gauge) was attached, moved away at a constant velocity in a straight line on the guide rail, the velocity of the bar or plate being controlled by direct current motor resistance. The power that was exerted by the subject was obtained as the product of the force applied to the bar or plate and the velocity of the bar or plate.

In the case of arm extension, the subject sat on a seat with his/her hands grasping the bar and with his/her shoulder and elbow joints flexed. The bar position was adjusted to the level of the subject's nipple. Immediately after a starting signal, the subject pushed the bar as fast as possible.

In the case of leg extension, the subject sat on a reclining seat with his/her feet on the plate and hip, knee and ankle joints fully flexed. The plate position was adjusted 90° of the subject's knee angle. Immediately after a starting signal, the subject extended his/her legs as fast as possible.

To determine the arm or leg extension power, average power was calculated by the following equation:

$$\bar{P} = \sum_{\mathrm{i}=1}^{\mathrm{n}} (F(\mathrm{i}) \cdot v(\mathrm{i}))/n$$

where $\bar{P}$ is average power, F is force, v is velocity, and n is the number of samples that was collected every 5 ms in a single movement.

The validity and reproducibility of measurement procedures had been established in a previous study (Saito et al. 1994) as follows. Arm extension power had a high correlation coefficient ($n = 34$, $r = 0.780$, $P < 0.001$) with one-repetition maximum (1RM) of a bench press. Leg extension power had a high correlation coefficient ($n = 30$, $r = 0.614$, $P < 0.001$) with 1RM of a full squat. There was also a high correlation coefficient ($n = 30$, $r = 0.717$, $P < 0.001$) between leg extension power per unit of body mass and the height of vertical jumping. The high reproducibility was confirmed by a high correlation coefficient between the first test and the second test ($n = 45$, $r = 0.944$, $P < 0.001$ for arm extension power and $n = 40$, $r = 0.932$, $P < 0.001$ for leg extension power).

Test measurements

The subjects performed isokinetic (80 cm $\cdot$ s^{-1}) arm or leg extension power tests during unilateral and bilateral exertions in random order with more than 5-min rests between conditions. Each series consisted of six trials with 15–30 s rests in between. The maximal value was selected among the values marked in the six trials as the maximal power for each subject in each series.

After becoming fully familiarized with the apparatus and the reproducibility of measurement, all the subjects participated in the experiment. Test measurements were made before training, and 3 and 6 weeks after the beginning of training.

Training

The posture of the subjects during training and the apparatus used were the same as those used during test measurements. The subjects were divided into four training groups and a control group; bilateral arm extension training group (1 woman and 6 men), unilateral arm extension training group (1 woman and 6 men), bilateral leg extension training group (1 woman and 5 men), unilateral leg extension training group (1 woman and 5 men), and control group (3 woman and 10 men). The unilateral training groups performed maximal isokinetic (80 cm $\cdot$ s^{-1}) arm or leg extensions using each arm or leg unilaterally in three sets of six trials each day. The bilateral training groups performed maximal arm or leg extensions using both arms or legs bilaterally in three sets of six trials each day. The rests between trials and sets were 15–30 s and 2–3 min, respectively. The training groups continued this resistance training 3 days a week for 6 weeks. The control subjects did not train.

Data analysis

The power values obtained from the left unilateral, right unilateral, and bilateral exertions were used for calculation of BI. The BI in arm and leg extension power was computed as follows:

$$\mathrm{BI}\ (\%) = 100\ [\text{bilateral}/\ (\text{left unilateral} + \text{right unilateral})] - 100$$

A BI greater than 0 indicated that the bilateral values were greater than the unilateral values (bilateral facilitation), whereas a BI smaller than 0 indicated that the bilateral values were smaller than the unilateral values (bilateral deficit).

Data were classified into four categories, as shown in Table 1, from the viewpoint of whether limbs (arms or legs) were trained or not and whether the mode of power exertion (bilateral or unilateral) was the same as performed during training or not.

Similarly, BI were averaged on the basis of the categories shown in Table 2, to compare the change by training from the viewpoint of whether limbs (arms or legs) were trained or not and whether the mode of exertion in performed training was bilateral or unilateral.

Statistical analysis

Two-way repeated-measures ANOVA and the least significant difference (LSD) method were used for intracategory and intercategory comparison of power changes and BI. The 5% level of significance was chosen to indicate statistical significance.

Results

Effect of resistance training on power exertion in the same mode and in the different mode as that performed during training

Table 1 shows the power of each group in each category before training, and 3 and 6 weeks after the beginning of training. From these data the change in power in each

Table 1 Change of arm and leg extension power by resistance training in four categories from the viewpoint of limbs (trained or untrained) and mode of power exertion (same as or different from that performed during training), and one control group. *BA* Bilateral arm extension, *BL* bilateral leg extension, *UA* unilateral arm extension, *UL* unilateral leg extension

	Arm/leg extension power (W)						Ratio of after to before			
	before		after 3 weeks		after 6 weeks		after 3 weeks		after 6 weeks	
	mean	SEM	mean	SEM	mean	SEM	mean	SEM	mean	SEM
Power of trained limbs (exerted by the same mode as during training)										
BA of BA group	469	52	468	48	485	49	1.007	0.029	1.043	0.034
UA of UA group	476	48	473	40	517	52	1.010	0.034	1.090	0.031
BL of BL group	1035	123	1077	92	1142	100	1.076	0.067	1.142	0.076
UL of UL group	1150	66	1193	81	1188	71	1.036	0.029	1.033	0.014
Power of trained limbs (exerted by the different mode as during training)										
UA of BA group	494	54	481	46	497	41	0.987	0.033	1.028	0.043
BA of UA group	454	47	443	36	448	43	0.989	0.031	0.994	0.028
UL of BL group	1213	135	1182	109	1265	120	0.989	0.038	1.056	0.027
BL of UL group	1051	64	1043	76	1064	69	0.990	0.034	1.015	0.036
Power of untrained limbs (exerted by the same mode as during training)										
BL of BA group	1200	103	1201	96	1204	97	1.005	0.021	1.009	0.035
UL of UA group	1326	77	1353	66	1417	93	1.026	0.031	1.066	0.023
BA of BL group	386	53	401	57	393	52	1.034	0.023	1.025	0.032
UA of UL group	395	46	400	44	409	46	1.019	0.036	1.038	0.024
Power of untrained limbs (exerted by the different mode as during training)										
UL of BA group	1351	98	1346	104	1376	101	0.995	0.027	1.018	0.024
BL of UA group	1206	67	1199	56	1234	90	1.002	0.038	1.018	0.029
UA of BL group	395	59	410	59	418	60	1.052	0.030	1.069	0.029
BA of UL group	370	37	372	40	364	37	1.004	0.022	0.984	0.014
Power of control group										
BA of control group	382	37	379	14	373	24	0.995	0.026	0.972	0.034
UA of control group	425	22	416	18	416	25	0.986	0.030	0.979	0.026
BL of control group	920	136	885	144	921	130	0.957	0.025	1.015	0.055
UL of control group	1058	132	1019	140	1053	138	0.958	0.019	0.992	0.022

Table 2 Change in bilateral index (*BI*) by resistance training in four categories from the viewpoint of limbs (trained or untrained) and training group (unilateral and bilateral), and one control group. *A* arm extension, *L* leg extension, *BA* bilateral arm extension, *BL* bilateral leg extension, *UA* unilateral arm extension, *UL* unilateral leg extension

	BI (%)						Change of BI			
	before		after 3 weeks		after 6 weeks		after 3 weeks		after 6 weeks	
	mean	SEM	mean	SEM	mean	SEM	mean	SEM	mean	SEM
BI of trained limbs (unilateral training group)										
A of UA group	−3.7	3.8	−5.9	2.3	−12.2	3.4	−2.2	3.0	−8.5	3.3
L of UL group	−8.7	0.8	−12.7	2.5	−10.5	2.1	−4.0	2.4	−1.8	2.1
BI of trained limbs (bilateral training group)										
A of BA group	−5.4	1.8	−3.3	1.7	−3.6	2.8	2.0	2.5	1.8	3.1
L of BL group	−15.3	2.5	−8.4	1.6	−9.3	1.6	6.8	3.0	6.0	3.7
BI of untrained limbs (unilateral training group)										
L of UA group	−9.0	0.7	−11.2	1.5	−13.2	1.1	−2.2	1.7	−4.2	1.5
A of UL group	−5.5	3.0	−6.9	1.6	−10.4	2.2	−1.4	2.2	−4.9	2.0
BI of untrained limbs (bilateral training group)										
L of BA group	−11.8	1.8	−10.7	2.0	−12.7	2.4	1.1	2.4	−0.9	2.6
A of BL group	−0.5	3.1	−2.0	3.5	−4.6	3.0	−1.5	2.9	−4.1	0.9
BI of control group										
A of control group	−9.6	1.9	−8.5	3.1	−10.4	1.8	1.1	2.6	−0.8	2.1
L of control group	−13.7	3.7	−13.8	4.0	−12.2	4.1	0.0	2.7	1.5	4.5

category was calculated as the ratio of after to before training.

Two-way repeated-measures ANOVA (four training groups × three time points) was conducted for intra-category comparison of the change in power ratio. No difference was found among training groups for each category. In contrast, a significant difference among the three times was found. The ratio of power of trained limbs exerted using the same mode as during the training [TLSM, $F(2,66) = 4.963$, $P < 0.01$] increased along the time course (Fig. 1).

Since no difference was found among the power ratios in each training group for each category, two-way repeated-measures ANOVA and the LSD method were used for intercategory comparison. This indicated that a significant difference among the five categories [$F(4,375) = 5.269$, $P < 0.001$] and the three time points [$F(2,375) = 6.570$, $P < 0.01$] were found. The ratio of TLSM was larger than that of power of trained limbs exerted using the different mode from that during training (TLDM, $P < 0.01$), power of untrained limbs exerted using the different mode from that during training (ULDM, $P < 0.05$) and control ($P < 0.001$, Fig. 1). The ratios of power of untrained limbs exerted using the same mode as training (ULSM, $P < 0.01$) and ULDM ($P < 0.05$) were larger than that in the controls (Fig. 1).

Effect of resistance training on BI in trained and untrained limbs

Table 2 shows BI of each group in each category before training, and 3 and 6 weeks after the beginning of training. From these data the change of BI in each category was calculated.

Two-way repeated-measures ANOVA (two training groups × three time points) was used for intracategory comparison of the change of BI. No differences were found between training groups for each category. A significant difference among three time points was found. The BI of untrained limbs (BIUL, unilateral training group) [$F(2,33) = 4.421$, $P < 0.05$] changed along the time course (Fig. 2).

Since no difference was found between the change of BI in each training group for each category, two-way repeated-measures ANOVA and the LSD method were used for intercategory comparison. Significant differences among the five categories [$F(4,180) = 5.941$, $P < 0.001$] were found. The BI of trained limbs (BITL, bilateral training group) traced a different time course from BITL (unilateral training group; $P < 0.001$) and BIUL (unilateral training group; $P < 0.001$), and BIUL (bilateral training group; $P < 0.01$), and tended to trace a different time course from the BI of the control group (BIC; $P = 0.0608$; Fig. 2). The BITL (unilateral training group) traced a different time course from BIC ($P < 0.05$; Fig. 2). The BIUL (unilateral training group) tended to trace a different time course from BIC ($P = 0.0547$; Fig. 2).

Discussion

The ratio of ULSM increased along the time course and was the largest among the five categories. This result indicates that the power exerted in the same movement as performed during training had the largest improvement and fits the "specificity theory" in resistance training (Sale and MacDougall 1981; Sale 1986).

The ratios of ULSM and ULDM were larger than that in the control. This indicates that the effect of resistance training was transferred to the untrained limbs and would suggest the intervention of a supraspinal mechanism.

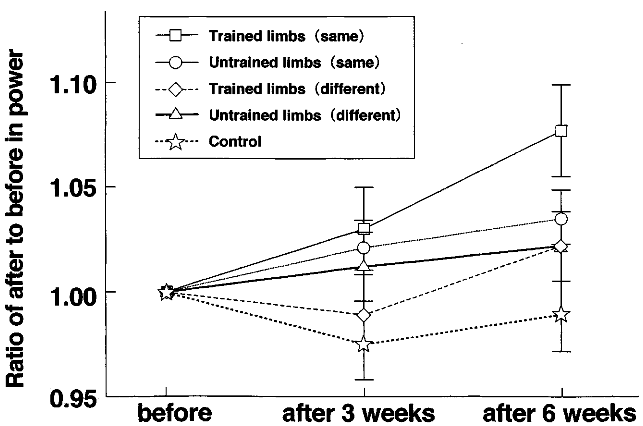

Fig. 1 Ratio of after to before power from the viewpoint of whether limbs (arms or legs) were trained or not and whether the mode of power exertion (bilateral or unilateral) was the same as that performed during training or not. Values were standardized by the values before training. Values are means and SEM

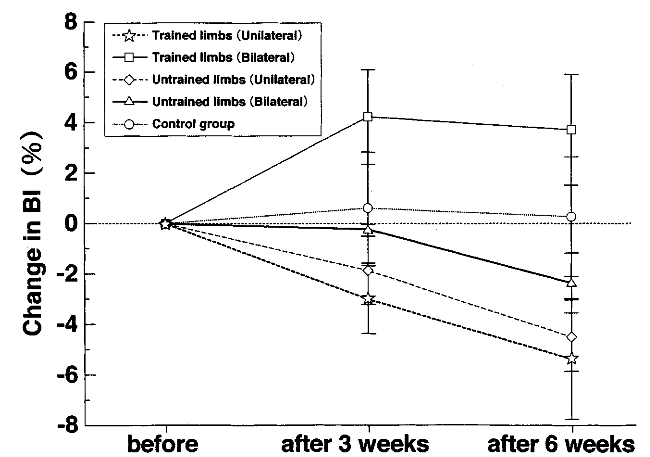

Fig. 2 Change in bilateral index (*BI*) from the viewpoint of whether limbs (arms or legs) were trained or not and whether the training was bilateral or unilateral. Values were expressed as the change from BI before training. Values are means and SEM

The change of ratio in BITL of the bilateral training group shifted in a positive direction during 6-week training and traced a different time course from that in trained limbs of the unilateral training group which was shifted in a negative direction. These results supported previous studies which have shown that BI were shifted in a positive direction by bilateral training and tended to shift in a negative direction by unilateral training (Häkkinen et al. 1996; Taniguchi 1997).

Bilateral deficit has been suspected to be mediated by neural mechanisms such as interaction between the cerebral hemispheres or spinal reflexes (Ohtsuki 1983, 1994). If bilateral deficit were to be mediated by supraspinal mechanisms such as interhemispheric inhibition, and if this mechanism were to control bilateral deficits in both upper and lower limbs, BI in upper and lower limbs would be changed inter-dependently by resistance training that is loaded on upper or lower limbs.

It is interesting that the BIUL of the unilateral training group was shifted in a negative direction by 6-week training, whereas BIUL of the bilateral training group was not shifted in a positive direction. Therefore, a positive transfer was observed between upper and lower limbs in unilateral training, but not in bilateral training. This suggests at least that the mechanism enhancing bilateral deficit is common in upper and lower limbs. The reason why transfer was not observed in bilateral training is unclear. One possible interpretation could be as follows; if the phenomenon of bilateral deficit were to be caused by the inhibitory effect of some mechanism, such as interhemispheric inhibition as has been suggested by Febert et al. (1992), Oda and Moritani (1995), and Ohtsuki (1994), the effect of bilateral training may be caused by a disinhibition of that process. It is speculated that the inhibitory effect might be common in upper and lower limbs, whereas the disinhibitory effect might be specific in trained limbs.

In conclusion, the power of the untrained limbs was increased by bilateral or unilateral resistance training. This would indicate that the effect of resistance training was transferred to the untrained limbs and would suggest a supraspinal mechanism. The BIUL of the unilateral training group was shifted in a negative direction by 6-week training, whereas the BIUL of bilateral training group was not shifted in a positive direction. These results suggested that bilateral deficits in upper and lower limbs are at least partially affected by some common mechanism at a supraspinal level.

References

Febert A, Priori A, Rothwell JC, Day BL, Colebatch JG, Marsden CD (1992) Interhemispheric inhibition of the human motor cortex. J Physiol 453:525–546

Häkkinen K, Kallinen M, Linnamo V, Pastinen U-M, Newton RU, Kraemer WJ (1996) Neuromuscular adaptations during bilateral versus unilateral strength training in middle-aged and elderly men and women. Acta Physiol Scand 158:77–88

Henry FM, Smith LE (1961) Simultaneous vs separate bilateral muscular contractions in relation to neural overflow theory and neuromoter specificity. Res Q 32:42–46

Howard JD, Enoka RM (1991) Maximum bilateral contractions are modified by neurally mediated interlimb effects. J Appl Physiol 70:306–316

Koh TJ, Grabiner MD, Clough CA (1993) Bilateral deficit is larger for step than for ramp isometric contractions. J Appl Physiol 74:1200–1205

Oda S, Moritani T (1995) Movement-related cortical potentials during handgrip contractions with special reference to force and electromyogram bilateral deficit. Eur J Appl Physiol 72:1–5

Ohtsuki T (1981) Decrease in grip strength induced by simultaneous bilateral exertion with reference to finger strength. Ergonomics 24:37–48

Ohtsuki T (1983) Decrease in human voluntary isometric arm strength induced by simultaneous bilateral exertion. Behav Brain Res 7:165–178

Ohtsuki T (1994) Change in strength, speed, and reaction time induced by simultaneous bilateral muscular activity. In:- Swinnen S, Heuer H, Massion J, Casaer P (eds) Interlimb coordination: neural dynamical, and cognitive constraints. Academic Press, New York, pp 259–274

Rube N, Secher NH (1990) Effect of training on central factors in fatigue following two- and one-leg static exercise in man. Acta Physiol Scand 141:87–95

Saito M, Yamamoto M, Yamamoto T, Inoue T, Miyashita M (1994) Isokinetic dynamometers, "Kick Force" and "Chest Force", for measuring leg and arm extension power. In: Organizing Committee of Asian Sport Science Congress, Hiroshima '94 and Japanese Olympic Committee (eds) Abstract book of Asian Sport Science Congress Hiroshima '94, Hiroshima, pp 14–20

Sale D, MacDougall D (1981) Specificity in strength training: a review for the coach and athlete. Can J Appl Sport Sci 6:87–92

Sale DG (1986) Neural adaptation in strength and power training. In: Jones NL, McCartney N, McComas A (eds) Human muscle power. Human Kinetics, Champaign, Ill., 289–307

Schantz PG, Moritani T, Karlson E, Johansson E, Lundh A (1989) Maximal voluntary force of bilateral and unilateral leg extension. Acta Physiol Scand 136:185–192

Secher NH (1975) Isometric rowing strength of experienced and inexperienced oarsmen. Med Sci Sports 7:280–283

Secher NH, Rorsgaard S, Secher O (1978) Contralateral influence on recruitment of curarized muscle fibres during maximal voluntary extension of the legs. Acta Physiol Scand 103:456–462

Secher NH, Rube N, Elers J (1988) Strength of two- and one-leg extension in man. Acta Physiol Scand 134:333–339

Taniguchi Y (1997) Lateral specificity in resistance training: the effect of bilateral and unilateral training. Eur J Appl Physiol 75:144–50

Vandervoort AA, Sale DG, Moroz J (1984) Comparison of motor unit activation during unilateral and bilateral leg extension. J Appl Physiol 56:46–51