

The effect of unilateral training on contralateral limb power in young women and men

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ABSTRACT: The purpose of this study was to determine the effect of training of one side of the body on the muscle torques and power output on the trained and untrained side. Seventeen female and twenty-two male students were subject to a four-week knee joint power training regimen on a specially designed stand. The subjects were divided into two groups: a training group (female – N = 11 and male – N = 16) and a control group (female – N = 6 and male – N = 6). Effectiveness of power training on the stand described previously was estimated based on bilateral knee torque and power under static and isokinetic conditions. The experiment lasted for 39 days and was preceded by preliminary studies (pre-training). Control measurements in training groups were made after four weeks of training (post-training) and after the next two weeks (de-training). Power training caused an insignificant increase in force and power in both groups for the untrained leg and a significant increase in RMS EMG. Therefore, the study confirmed the hypothesis that resistance training performed in dynamic conditions can affect the contralateral limb and may also trigger delayed adaptations to training conditions during the detraining phase. Sex differences in adaptation to power training are not clear; however, the differences in gains in contralateral effects between men and women were not confirmed.

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INTRODUCTION

Cross education (CE) is the strength gain that occurs in the contralateral limb following a unilateral strength program [1]. To explain the phenomenon of CE, two distinct hypotheses were put forward. The cross-activation hypothesis proposes that unilateral strength training excites ipsilateral and contralateral cortical motor areas causing adaptations in both hemispheres. The bilateral access hypothesis maintains that the homologous untrained muscle can access the unilateral adaptations of training through interhemispheric communication from the associated motor areas [1, 2]. Currently, it is suggested that CE involves neural mechanisms [1, 3, 4] rather than muscle or morphological factors. The phenomenon of CE is widely utilized in sports or clinical rehabilitation settings due to its potential for the application in rehabilitation following a unilateral injury [5, 6].

A substantial number of studies have been conducted to confirm the existence of CE [7] using various modalities of resistance training. The increase in CE that is observed following resistance training differs between studies, which mainly stems from differences in training variables such as training load, volume, intensity, number of training sessions, exercise complexity, contraction type, training status of participants [1].

Despite a lot of studies describing CE, there is an inconsistency between their findings [1, 3, 7]. However, some evidence seems to be well established. Previous research showed that contralateral

strength gain from CE was approximately 8–18% in young participants and that cross-body transfer to the untrained limb ranged from 52% to 80% of the trained limb [3]. Manca et al. [8] showed that CE in lower limbs (16.4%) was higher than in upper limbs (9.4%). Regarding the sport level of participants, CE was lower in trained subjects than in untrained participants [9]. Moreover, the greatest CE is observed when the dominant side is trained [6] and eccentric contraction induces greater effects than concentric and isometric contraction [10].

To date, only a few studies have described different manifestations of the unilateral resistance training under dynamic conditions (e.g., power training) to stimulate cross-body transfer [11, 12]. Also, there are ambiguous results of studies comparing the magnitude of CE between sexes [13, 14]. It is not certain whether strength and power output achieved through cross education are decreased or retained during detraining. Houston et al. [15] and Weir et al. [16] found that there was no difference in maximal voluntary isometric contraction between pre-training and post-detraining levels for the contralateral limb. Conversely, Housh et al. [17, 18] observed that muscular strength increased using the only eccentric or only concentric training programme, and that power output was retained after 8 weeks of detraining in both the trained and contralateral limbs.

Due to the constant lack of indications that power output training causes beneficial effects in both the trained and contralateral limbs,

the aim of this study was to determine power gain in the contralateral limb following unilateral resistance power training of the dominant ipsilateral limb in young males and females. We also aimed to shed light on CE changes after detraining.

MATERIALS AND METHODS

Subjects

Twenty-two male and seventeen female students from the University of Physical Education in Warsaw volunteered to serve as subjects for this investigation. The subjects were divided into two groups: a training group (female – $N = 11$, age: 21.5 ± 1.5 years, height: 1.69 ± 0.06 m, and mass: 64.0 ± 8.1 , male – $N = 16$, age: 21.1 ± 2.0 years, height: 1.82 ± 0.07 m, and total body mass: 81.0 ± 4.1) and a control group (female – $N = 6$, age: 21.6 ± 1.2 years, height: 1.71 ± 0.04 m, and mass: 65.0 ± 6.1 , male – $N = 6$, age: 22.0 ± 0.8 years, height: 1.81 ± 0.02 m, and total body mass: 75.0 ± 5.0). The participants were familiarized with the purpose of the experiment and gave their written consent to take part in the study. This study was approved by the University research ethics committee and all the subjects read and signed an approved informed consent document. All the subjects were right-leg dominant based on their preferred leg to kick a ball. Sample size calculations were established on the average effect sizes for changes in the magnitude of strength transfer following a long-term unilateral power training program. Using previous cross-education data in healthy untrained adults [19], we estimated that ten participants in each group would provide at least 80% power (95% confidence interval) to detect 16% cross transfer of strength and 18% transfer of power using a repeated measures design (G*Power 3.1.7 software).

Testing procedures

The experiment lasted for 39 days and was preceded by preliminary studies (pre-training). Control measurements in training groups were made after four weeks of training (post-training) and after the next two weeks (de-training). The control group was tested at preliminary studies and after four weeks of training but performed no training. Preliminary measurements were carried out one week before training in the following order: bilateral knee torque under isometric conditions (IMT) at the 90° of knee flexion as well as bilateral knee torque (IKT) and power (IKP) under isokinetic conditions. The order of testing for the limbs was randomized. The isometric strength tests and isokinetic tests were performed on a calibrated Biodex System 3 Pro (Biodex Medical System Inc. USA). The first measurements were performed to familiarize the participant with the procedure. After 10 minutes of rest, measurements were repeated twice with an interval of 2 minutes. The contraction with the highest torque and power output was taken as the representative score. The test velocity of knee extension under isokinetic conditions was set as 240 deg/s based on the mean velocity during motion with training resistance. The pre-training order of testing for each subject was also followed during the post-training and detraining test sessions. During pre-training, post-training and

detraining measurements sessions, EMG of vastus lateralis was measured. Bipolar surface EMG recordings were obtained using self-adhesive pairs of disposable Ag/AgCl surface electrodes (Blue Sensor M-00-S, Ambu, Denmark). The raw SEMG signal was recorded at the sampling rate of 1000 Hz, amplified (differential amplifier, CMRR > 130 dB, total gain 1000) with a bandwidth from 20 to 500 Hz, analog-to-digital converted (14-bit) using an eight-channel Noraxon Tele Myo 2400 system (Noraxon USA Inc., Scottsdale, AZ; 1500 Hz). Before electrode placement, the skin area was shaved, cleaned with isopropyl alcohol, and abraded with coarse gauze to reduce skin impedance. The electrodes (11 mm contact diameter and a 2 cm center-to-center distance) were placed along the presumed direction of the underlying muscle fiber according to the recommendations by SENIAM. The root-mean-square (RMS) was measured simultaneously during IMT and IKT tests. The percentage of muscle activity (% RMS) was defined as the RMS ratio of the IKT and IMT and was used for later analysis. Following standard procedures, all the electrodes were located on the right and left side of the body.

Training protocol

During four weeks, volunteers participated in the training on the stand described previously [19]. The subjects were seated with their torsos strapped to the backrest of the device and were instructed to hold tightly to the sides. The backrest was adjusted so that the anatomical axes of the knees were aligned with the mechanical axis of the device. Resistance was created using elastic bands attached between lever arm and the wall. A shin pad was attached to the lever arm for placement against the subject's right leg. The shin pad was at a fixed distance from the axis of rotation and, therefore, not adjustable; however, positioning was consistent for each subject across all tests so that strength tests across time were not affected by the inter-subject differences in lever leg length. The value of mechanical resistance was established based on the IMT test as 30% of IMT value. Resistance training took place five times a week for four weeks and consisted of 4 sets of 10 extensions and flexion in the knee joint each with 120-sec interval between the sets. The training exercise involved the fastest possible right knee extension. Before every training session, the participants performed a 2-minute light warm-up with little resistance (5% of IMT) on the training device. During the detraining period, each subject continued with their normal level of daily physical activity and did not participate in any other strenuous activities.

Statistical analysis

Normality and homogeneity of variances were confirmed with the Shapiro-Wilk and Levenes tests, respectively. To test differences in IMT, IKT and IPT, 2×3 repeated-measures (2×2 in the control group) ANOVAs (SIDE [body side: Right and LEFT] \times TIME [Pre, Post and Ret]) were used. Post-hoc comparisons were performed with a NIR Fisher test. Cohen's d effect size (d) was calculated [20]. Parametric effect sizes were defined as large ($d > 0.8$), moderate (d between 0.8 and 0.5), small (d between 0.49 and 0.20), and trivial

($d < 0.2$) [20]. An alpha of 0.05 was used to determine statistical significance. The statistical analysis of the results was carried out using STATISTICA v. 13 (StatSoft Inc., Tulsa, OK, USA, 2017).

RESULTS

Isometric strength and isokinetic strength and power

ANOVA test results, effect sizes and post hoc test results for IMT, IKT and IKP are shown in Table 1. ANOVA revealed a statistical influence of TIME on IMT, IKT and IKP in the trained leg in the male group and IKT and IKP in the female group. Post-test results of IMT (men – 12% ($p < 0.003$), women – 10% (n.s)), IKT (men – 9% ($p < 0.05$), women – 5% (n.s)) and IKP (men – 11% ($p < 0.03$), women – 7% (n.s)) increased significantly in the trained leg only in men. In the contralateral leg, an increase was also observed but it was insignificant in IMT (men – 5%, women – 1%), IKT (men – 4% women – 0%) and IKP (men – 4%, women – 1%). An insignificant decrease in IMT from DET to POST was observed during detraining, both in men (trained – 0.7%; untrained – 3%) and women (trained – 7%;

untrained – 0.7%), while IKT (trained – 3%; untrained – 0%) and IKP (trained – 2%; untrained – 4%) still improved in men. The, ANOVA did not prove any significant influence of TIME on the untrained leg. Also, we did not find any statistical influence of SIDE differences between trained and untrained legs in both groups of women and men. A slight fluctuation of values reaching up to 2% was noted for most indicators in the control group. The presented differences were not statistically significant and fell within the typical variability and measurement error of research methods. Based on the results obtained in the control group, it could be assumed that participation in typical activities included in the study plan did not exert a significant influence on the growth indicators monitored in training groups.

EMG activity

The RMS EMG (Table 2) significantly increased from POST to PRE in the trained limb (22% ($p < 0.0001$) – men, 13% ($p < 0.0001$) – women) and contralateral limb as well (9% ($p < 0.0001$) – men,

TABLE 1. Changes in variables at PRE-training, POST-training, post-detraining (DET) and ANOVA results in trained (men (M) and women (W)) and control (C) groups; r – right leg, l – left leg, ns – not significant. Data are presented as mean ± SD

variable	Pre	Post	Det	Side effect	Time effect	Post hoc	
M	IMT-r [Nm]	265 ± 36	296 ± 42	294 ± 41	F(1, 30) = 2.185, p = 0.149	F(2, 60) = 8.37, p ≤ 0.001	POST-PRE p < 0.003; d = 0.63
	IMT-l [Nm]	260 ± 35	272 ± 49	264 ± 46			ns
	IKT-r [Nm]	169 ± 25	184 ± 24	189 ± 22	F(1, 30) = 2.423, p = 0.130	F(2, 60) = 7.396, p < 0.001	POST-PRE p < 0.05; d = 0.46
	IKT-l [Nm]	165 ± 19	171 ± 28	171 ± 28			ns
	IKP-r [P]	248 ± 59	275 ± 59	281 ± 62	F(1, 30) = 0.729, p = 0.399	F(2, 60) = 5.192, p < 0.001	DET-PRE: p < 0.004; d = 0.54
	IKP-l [P]	242 ± 57	251 ± 56	261 ± 71			ns
W	IMT-r [Nm]	146 ± 22	161 ± 26	149 ± 28	F(1, 20) = 0.312, p = 0.582	F(2, 40) = 2.726, p = 0.077	ns
	IMT-l [Nm]	145 ± 30	146 ± 36	145 ± 37			ns
	IKT-r [Nm]	94 ± 16	99 ± 13	97 ± 13	F(1, 20) = 1.637, p = 0.215	F(2, 40) = 4.191, p = 0.0023	ns
	IKT-l [Nm]	91 ± 18	91 ± 16	93 ± 14			ns
	IKP-r [P]	176 ± 59	188 ± 33	183 ± 42	F(1, 20) = 0.533, p = 0.473	F(2, 40) = 3.602, p = 0.036	ns
	IKP-l [P]	171 ± 49	172 ± 39	173 ± 34			ns
C	IMT-r [Nm]	208 ± 83	210 ± 67	-	F(1, 22) = 0.006, p = 0.938	F(1, 22) = 0.248, p = 0.623	ns
	IMT-l [Nm]	207 ± 63	207 ± 62	-			ns
	IKT-r [Nm]	136 ± 42	139 ± 43	-	F(1, 22) = 0.596, p = 0.448	F(1, 22) = 0.088, p = 0.769	ns
	IKT-l [Nm]	125 ± 42	122 ± 39	-			ns
	IKP-r [P]	220 ± 56	214 ± 51	-	F(1, 22) = 0.415, p = 0.526	F(1, 22) = 1.089, p = 0.308	ns
	IKP-l [P]	205 ± 50	202 ± 53	-			ns

TABLE 2. Changes in muscle activity (% RMS) at PRE-training, POST-training, post-detraining (DET) and ANOVA results in trained (men (M) and women (W)) and control (C) groups; r – right leg, l – left leg, ns. – not significant. Data are presented as mean ± SD

variable	Pre	Post	DET	Side effect	Time effect	Post hoc	
M	%RMS-r [%]	69 ± 7.6	84 ± 5.2	81 ± 7.7	F(1, 30) = 23.750, p < 0.0001	F(1, 60) = 99.933, p < 0.0001	POST-PRE p < 0.0001; d=2.30 DET-PRE p < 0.0001; d = 1.57
	%RMS-l [%]	65 ± 5.7	71 ± 4.4	69 ± 4.6			POST-PRE p < 0.0001; d = 1.17 DET-PRE p < 0.0001; d = 0.77
W	%RMS-r [%]	54 ± 2.6	61 ± 2.8	59 ± 2.3	F(1, 20) = 2.49, p = 0.130	F(1, 40) = 30.06, p < 0.0001	POST-PRE p < 0.0001; d = 2.59 DET-PRE p < 0.0001; d = 2.03
	%RMS-l [%]	54 ± 3.1	58 ± 2.4	57 ± 5.2			POST-PRE p < 0.0001; d = 1.44 DET-PRE p < 0.0001; d = 0.70
C	%RMS-r [%]	59 ± 5.9	58 ± 5.5	-	F(1, 22) = 0.116, p = 0.736	F(1, 22) = 0.083, p = 0.776	ns
	%RMS-l [%]	57 ± 5.4	59 ± 6.3	-			ns

7% (p < 0.0001) – women) only in training groups. After detraining, increases in the RMS were not significantly changed in the trained limb (-4% (ns) men, -3% (ns) women) and still were significantly higher than during PRE in the trained and contralateral limb. ANOVA proved a statistical influence of SIDE differences between trained and contralateral legs in both female and male groups. An advantage of muscle activity (%RMS) in the trained limb occurred in posttest and detraining tests, both in trained men (POST – 16%, p < 0.001; DET – 15%, p < 0.001) and women (POST – 5%, p=0.066; DET – 3%, p=0.232). We did not find any statistical influence of SIDE and TIME differences between right and left legs in the control group.

DISCUSSION

The main finding of the present study was that results confirm delayed adaptations to power training during the detraining phase, but only in the case of strength and power measured in dynamics. It is common knowledge that power is an essential element of sports training because it allows athletes to achieve high sports results. Training load used in this study was individualized, so each of the participants achieved maximum power output in each set of exercises. The differences in specificity of training for the trained versus untrained limbs suggest that there may be differences in neural mechanisms involved in strength gains in the trained and contralateral limbs [21]. Farthing and Chilibeck [10] claim that cross-education was the greatest with the most unfamiliar type of training (fast-velocity training), which indicates that learning may play a large role in cross-education. This hypothesis is only partly confirmed by the results of our study. Only the EMG results increased significantly for the contralateral limb in both groups as a result of power training. None of the strength

and power indicators increased significantly after training in woman group. However, the present study shows that unilateral resistance power training results in an increase in isometric knee extensor strength in both the trained (men – 12%, women – 10%) and contralateral untrained (men – 5%, women – 1%) limbs but statistically significant only in men. In the control group, there was no significant increase (1%) in the mean IMT values between week 0 and week 4, which suggests that the magnitude of the strength gain in the contralateral limb (5%) is a meaningful increase. It should be noted that the training protocol may be a contributing factor, inducing greater cross education of muscular strength. The testing specificity of force is considered to be important for evaluating the effect of cross education and in particular the similarities in muscle contraction during training and measurement. Hortobagyi et al. [22] reported that quadriceps strength in the contralateral untrained limb increased by 15% with isometric testing and by 23% with eccentric testing after 6 weeks of unilateral eccentric training. Farthing and Chilibeck [10] found CE to be highly specific, since cross-body transfer to the untrained limb occurred mainly in the homologous muscle group, with the same velocity or joint angle used in training. These findings suggest that the magnitude of the cross education effect is changeable and it depends upon the testing specificity, which is consistent with the results of our research.

It has been proven that neural adaptation to resistance training is not confined to the muscles directly involved in exercise, but becomes expressed in a spatially specific manner in the contralateral homologous muscle in the form of increased voluntary force and neural activation. There is now evidence that practice of elementary movements with loads ranging between 20 and 100% of maximum

voluntary contraction at a wide range of contraction velocities cause adaptations in the excitability of spinal reflexes, corticospinal pathways and cortical networks controlling the trained muscle [23]. Zijdwind and Kernell [24] and Sehm et al. [25] observed electromyographic (EMG) activity in the contralateral muscle during unilateral contractions in resistance training. The “associated activity” that appears in the resting limb during motor practice with the other limb can reach 20% of MVC [22, 24]. How such inadvertent brain activity can increase MVC force of the untrained or casted limb is unclear [26]. However, CE in our research can support this hypothesis. Post-training and detraining increases of RMS EMG the in trained and contralateral limb were statistically significant in the groups of women and men. Thus, despite the lack of a significant increase in contralateral strength and power, we probably saw an improvement in neuromuscular coordination expressed by a significant increase in EMG after resistance training in both limbs.

In the present study, the comparison between sexes did not reveal significant differences for the magnitude of the training adaptation. The strength gain in men and women was 12% and 10%, respectively. To date, only a few studies have included sex comparisons [13, 14]. Hubal et al. [13] found significantly higher CE in females (21%) compared to males (16%). In contrast, Tracy et al. (1999) noted lower CE in females (32%) than in males (36%). Both studies revealed significant differences between females and males. Similarly, in our study there was no significant difference in the magnitude of CE between sexes.

Despite the abundance of studies on CE of muscular strength, only a few have investigated CE during detraining [18, 27, 15, 21, 28]. The findings of those studies are conflicting. Shaver [27] observed a loss of training-induced strength gain in the contralateral limb, while Houston et al. [15] and Housh et al. [18] reported that strength gain induced by CE was retained during detraining. Narici et al. [21] also reported a decrease in isometric maximal voluntary contraction in the contralateral untrained limb during detraining. Our results on CE during detraining are similar to those reported by Shaver [27] and Narici et al. [21]. An insignificant decrease from POST to DET of RMS EMG and IMT in trained and contralateral legs was observed in both sexes, whereas IKT and IKP increased even more in the group of men in both the trained and contralateral limbs. The study by Shima et al. [28] provides another example of CE changes in the untrained limb after detraining. The researchers observed differences in individual maximal voluntary isometric contraction which increased in three out of nine subjects and decreased in the other six subjects. Furthermore, approximately the same rate of strength gain by CE as the rate of decreases in strength gain in the contralateral limb was observed following the same detraining time periods. In the present

study, no such dependency was found although the duration of the detraining period was only 2 weeks, while the training period lasted 4 weeks.

The resistance training protocols used were focused on maximal strength and power output development. The results of the present study confirm the hypothesis that resistance training performed in dynamic conditions can affect the contralateral limb. Unfortunately, we can only fully confirm this hypothesis based on CE obtained from EMG measurements. The likely reason for the absence of differences in the strength (power) gain could be too short training period, as evidenced by the fact that strength and power grew even during the detraining period. Mixed data were shown in previous studies on effects of longer periods without exercising after muscle strength or muscle power training in healthy older adults. However, significantly different after-training delayed adaptations in peak and mean muscle power output were shown between low-intensity and high-intensity muscle strength training groups in favor of the latter [29]. In this study, we used a resistance-training machine with elastic bands. All lower extremity exercises were performed with individual maximal power adjusted by increasing the tension of pulling forces of the elastic bands (resistance). The training method used in our research exerted a positive influence on detraining adaptations to power training, but only in the case of strength and power measured in dynamics. The equality between sexes in the magnitude of CE observed in this study is inconclusive; however, we do not confirm CE differences between women and men. The results prove that this type of training can be used in sport as a supportive method during training with one of the limbs immobilized for various reasons (injury, pain).

CONCLUSIONS

1. The results confirm the contralateral effects of resistance power training.
2. Sex differences in adaptation to power training are not clear; however, the differences in gains in CE between men and women were not confirmed.
3. The results confirm delayed adaptations to power training during the detraining phase, but only in the case of strength and power measured in dynamics.

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