**EVIDENCE OF HOMOLOGOUS AND HETEROLOGOUS EFFECTS
AFTER UNILATERAL LEG TRAINING IN YOUTH**

Journal:	<i>Applied Physiology, Nutrition, and Metabolism</i>
Manuscript ID	apnm-2017-0338.R2
Manuscript Type:	Article
Date Submitted by the Author:	20-Sep-2017
Complete List of Authors:	Ben Othman, Aymen; Centre National de la Medecine et des Sciences du sport Behm, David; Memorial University of Newfoundland, Chaouachi, Anis; Centre National de la Medecine et des Sciences du sport
Is the invited manuscript for consideration in a Special Issue? :	
Keyword:	pediatrics < pediatrics, strength training < exercise, power output < exercise, resistance training < exercise, cross education

SCHOLARONE™
Manuscripts

**EVIDENCE OF HOMOLOGOUS AND HETEROLOGOUS EFFECTS AFTER
UNILATERAL LEG TRAINING IN YOUTH**

AUTHORS: Aymen Ben Othman¹, David G Behm³, Anis Chaouachi^{1,2}

AFFILIATIONS: ¹ Tunisian Research Laboratory “Sport Performance Optimisation”,
National Center of Medicine and Science in Sports (CNMSS), Tunis,
Tunisia;
²AUT University, Sports Performance Research Institute New Zealand,
Auckland, New Zealand
³School of Human Kinetics and Recreation, Memorial University of
Newfoundland, St. John’s Newfoundland

CORRESPONDING AUTHOR: David G. Behm
School of Human Kinetics and Recreation,
Memorial University of Newfoundland,
St. John’s, Newfoundland, Canada, A1C 5S7
dbehm@mun.ca
Tel: 709-864-3408
Fax : 709-864-3979

RUNNING TITLE: Youth cross education

ABSTRACT

The positive effects of unilateral training on contralateral muscles (cross education) has been demonstrated with adults for over a century. There is limited evidence for cross education of heterologous muscles. Cross education has not been demonstrated with children. It was the objective of this study to investigate cross education training in children examining ipsilateral and contralateral homologous and heterologous muscles. Forty-eight male children (10-13 years) were assessed for unilateral, ipsilateral and contralateral lower limb strength, power and endurance (1 repetition maximum (RM) leg press, knee extensors (KE) and flexors (KF) maximum voluntary isometric contractions (MVIC), countermovement jump (CMJ), muscle endurance test (leg press repetitions with 60% 1RM)), and upper body unilateral MVIC elbow flexors (EF) and handgrip strength. An eight-week training program involved two unilateral leg press resistance training groups (high load-low repetitions: 4-8 sets of 5RM, and low load-high repetitions: 1-2 sets of 20RM) and control (untrained) group. All muscles exhibited improvements of 6.1% to 89.1%. The trained limb exhibited greater adaptations than the untrained limb for leg press 1RM (40.3% vs. 25.2%; $p=0.005$), and 60% 1RM leg press (104.1% vs. 73.4%; $p=0.0001$). The high load-low repetition training induced ($p<0.0001$) greater improvements than low load-high repetition with KE, KF, EF MVIC and leg press 1RM. This is the first study to demonstrate cross education effects with children and the effects of unilateral training involve both contralateral homologous and heterologous muscles with the greatest strength training responses from high load-low repetition training.

KEY WORDS: cross education; pediatric; strength training; power output; resistance training;

51 INTRODUCTION

52 Evidence for cross education was first published over a century ago (Scripture 1894).
53 Cross education involves the performance improvement (i.e., strength, skill execution,
54 endurance) of the untrained limb after a period of unilateral practice (i.e., strength training, skill
55 learning, endurance training) (Farthing et al. 2007). Ample evidence for cross education has been
56 demonstrated in adults for contralateral homologous muscles such as the quadriceps (Goodwill
57 and Kidgell 2012, Kannus et al. 1992; Hortobagyi et al. 1997; Evetovich et al. 2001; Latella et al.
58 2012), elbow flexors (EF) (Ebersole et al. 2002; Adamson et al. 2008), and handgrip muscles
59 (Shields et al. 1999). Strength increases in the contralateral limb following unilateral strength
60 training of the ipsilateral limb has provided non-significant (Farthing and Chilibeck 2003), small
61 (i.e. 3.8-5%) (Housh and Housh 1993; Munn et al. 2005) and very large improvements (i.e. 35%,
62 52%, 77%) (Goodwill and Kidgell 2012; Hortobagyi et al. 1997). The magnitude of adaptation
63 depends on the characteristics of the intervention (e.g. different training protocols, eccentric or
64 concentric contractions) performed (Cirer-Sastre 2017), trained state of the participant (sedentary
65 or athlete), and the involved muscle groups (Hortobagyi 2005).

66 Surprisingly in the last century, cross education has not been examined with children.
67 Since neuromuscular responses to strength training can differ between children and adults
68 (Ramsay et al. 1990; Behm et al. 2008), it is not known whether this phenomenon is evident in
69 children. It could be speculated that since children's strength gains are predominantly ascribed to
70 neural adaptations (Ozmun et al. 1994; Faigenbaum et al. 1996; Falk et al. 1996; Faigenbaum
71 2000; Behm et al. 2008; Faigenbaum et al. 2009), their cross education response may exceed
72 adults. While adults also experience neural adaptations (Behm 1995, Kidgell et al. 2011, Latella

et al. 2012), they typically can access greater morphological (i.e. muscle hypertrophy) training adaptations which would not be expected to transfer to non-exercised muscles (Behm 1995).

In adults, a low repetition/high load RT program is recommended to increase maximal strength and high repetition/low load program to increase muscular endurance (Behm 1995). Other adult studies have examined cross education effects showing a proportional relationship between the applied training load and the effect achieved (i.e. high loads or intensities increase muscle strength; low loads or intensities with high repetitions increase muscle endurance) (Kannus et al. 1992; Ebersole et al. 2002; Housh et al. 1992; Housh and Housh 1993; Evetovich et al. 2001; Farthing and Chilibeck 2003). However, in 5 to 12-year-old children, Faigenbaum et al. (1999) demonstrated that high repetition/low load and low repetition/high load resistance training programs resulted in similar enhancements of maximal strength. Manipulation of the various acute resistance training variables (e.g., number of sets, repetitions, intensity, or load) are believed to influence the magnitude of strength adaptations on the trained limb (Behm 1995), and could also affect adaptations of contralateral strength (Munn et al. 2005). It is not known whether high or lower loads or intensity resistance training would similarly affect cross education or global training effects with dynamic and isometric strength, power (i.e. countermovement jumps (CMJ)) or muscle endurance with children.

According to Hortobagyi's review (2005) cross education is specific to the homologous muscle pair. However, Sariyildiz et al. (2011) did show a cross education training effect to a heterologous muscle. While there are some examples of acute non-local fatigue and stretching effects upon heterologous muscle groups (Halperin et al. 2014; Behm et al. 2016; Sambaher et al. 2016; Aboodarda et al. 2017), there is very little literature monitoring the extent of cross

education effects to heterologous muscles and no information regarding youth. Greater global or cross education responses with children would provide a rationale for a robust application of these techniques when rehabilitating unilateral injuries by training the contralateral limb. Furthermore, in youth athletic populations, the prevention techniques of unilateral overuse injuries in sports such as baseball, softball, racquet sports and others could be implemented by training the contralateral limb, decreasing the workload on the dominant over-exercised limb.

Thus, due to the absence of studies comparing the effects of different variables for equal-volume unilateral traditional resistance training in children, the aim of this study was to compare the effects of two-equal-volume unilateral resistance training programs (high load/low repetition vs. low load/high repetition) on maximal dynamic and isometric lower body muscle strength, endurance, unilateral vertical jump performance, handgrip strength and unilateral elbow flexors maximal voluntary isometric contractions (MVIC). Since the literature indicates that both cross education (Lee et al. 2007; Farthing 2009) and youth resistance training (Ozmun et al. 1994; Faigenbaum et al. 1996; Falk and Tenenbaum 1996; Faigenbaum 2000; Behm et al. 2008; Faigenbaum et al. 2009) have a high neural component, it is hypothesized that cross education effects in this population will be readily apparent in a variety of muscles and tasks.

MATERIALS AND METHODS

Participants

Forty-eight healthy male children between 10-13 years, recruited from the same public school of Bou-Arada city, Tunisia, volunteered to participate in this study (Table 1). All participants were from similar socio-economic status and had the same daily school schedules.

All of them participated in their normal physical education lessons and none were involved in any after-school activities or any formalized strength and conditioning training program. A maturity status assessment was conducted using the noninvasive technique proposed by Mirwald et al. (2002). All participants were classified at the pre-peak height velocity stage of physical maturation (Table 1). Parental and subject informed consent was obtained after thorough explanation of the objectives and scope of this project, the procedures, risks, and benefits of the study. The study was conducted according to the Declaration of Helsinki and the protocol was fully approved by the Ethics Committee of the National Centre of Medicine and Science of Sports of Tunis (CNMSS) before the commencement of the assessments. Subjects and their parent/guardian were also informed that participation was voluntary and that they could withdraw from the study at any time. None of the participants had any history of musculoskeletal, neurological or orthopedic disorders that might impair their ability to execute resistance exercise training or to perform strength and power tests.

Experimental procedures

One week before the commencement of the study, all subjects participated in three orientation sessions to become familiar with the general environment, form and technique on each test used to evaluate force and power, technique for each training exercise, equipment, and the experimental procedures to minimize the learning effect during the course of the study. Each subject's height and body mass were collected using a wall-mounted stadiometer (Easy Glide Stadiometer Perspective Enterprises, Portage, Michigan) and electronic scale (LifeSource Model UC-321P, made by A&D Company, Tokyo, Japan), respectively. Afterwards, participants' performances were tested pre- and post- the 8-week unilateral training period. The testing

protocol included assessment of lower limb unilateral strength and power (1RM horizontal leg press, maximum voluntary isometric contraction (MVIC) of quadriceps and hamstring muscles, countermovement jump (CMJ), muscle endurance test (maximum number of leg press repetitions with 60% 1RM)), and upper body unilateral MVIC strength of EF and hand grip strength. Following the initial baseline testing session, subjects were randomly divided into two unilateral resistance training groups (high load/low repetitions, $n=16$ and low load/high repetitions group $n=16$) and a control group ($n=16$) without a training program. Using a controlled randomization method, groups were matched for age, maturation status and physical characteristics. The high load/low repetition group performed 4 to 8 sets of 5 repetitions maximum (RM) of unilateral seated leg press (knee and hip extension/flexion) with 2 min rest interval between sets. The low load/high repetition group performed 1 to 2 sets of 20 RM with 2 min rest interval between sets. The volume of work during training was equal.

Training programs

The participants trained for 8 weeks, completing three sessions per week with at least 48- 72 hours of rest between sessions (totaling 24 sessions). Since with the testing periods, the duration of the experiment was 10 weeks, an 8-week training period fit into the school semester period of the participants. Subjects were randomly assigned to one of two training groups: unilateral high load-low leg press repetition group, unilateral low load-high repetition leg press group or the control group (untrained). The high load/low repetitions training group performed 4 (week 1 and 8) or 8 sets (weeks 2-7) of 5 repetitions with 2 minutes of recovery between sets. The low load/high repetitions training group was subjected to 1 (week 1 and 8) or 2 sets (weeks 2-7) of 20 repetitions with 2 minutes of recovery between sets. Progressive overload was implemented by

increasing the load by 5-10% whenever a participant could exceed the prescribed 5 or 20 repetitions. The control group was limited to their regularly scheduled physical education class. All participants complied with these instructions. Prior to each training session, the training groups underwent a 5-min warm-up including submaximal ergometer cycling and dynamic stretching. The exercise used for training was a unilateral leg press with the dominant leg in a seated position using a commercial horizontal leg press (Life Fitness Pro Horizontal Leg Press) with a range of motion 90 to 10° (0° = full knee extension). Participants in the training groups received skill-specific feedback on the quality of each movement and they were informed to never lock the knee on horizontal leg press during training or testing. The instructors recorded the training data on workout logs daily and made appropriate adjustments in training resistance and repetitions. Special attention was paid to the instructions to keep the opposite leg completely immobile and as relaxed as possible during the training. If the subject performed repetitions beyond the prescribed training zone, the weight was increased to bring the number of repetitions back within the RM training zone. Two minutes recovery was allowed between sets for both training programs.

Lower body maximal strength and muscular endurance tests

Unilateral leg press maximal dynamic strength (1 RM):

Unilateral leg strength was assessed on the horizontal leg press with a one-repetition maximum (1-RM) test as reported by Faigenbaum et al. (2003). Before attempting a 1RM, participants performed 3 submaximal sets of 1-6 repetitions with a light to moderate load, then 3 sets of a heavier load. Finally, participants performed a series of single repetitions with increasing loads. If the weight was lifted with the proper form, it was increased by approximately

1-2 kg, and the participant attempted another repetition. The increments in weight were dependent on the effort required for the lift and became progressively smaller as the subject reached 1RM. 1RM was defined as the greatest load lifted through a full range of motion (ROM) before 2 failed attempts at a given load. The exercise execution technique was standardized and continuously monitored in an attempt to assure the quality of the data. The participants were strapped into the apparatus with a seatbelt with the non-exercised leg positioned off the leg press apparatus (foot on the floor) in a relaxed state. Participants folded their arms across their chest during the procedure. Failure was defined as a lift falling short of the full ROM on at least 2 attempts spaced at least 2 minutes apart. Throughout all testing procedures, an instructor-to-subject ratio of 1:1 was maintained, and uniform verbal encouragement was offered to all subjects.

Unilateral leg press muscular endurance test

Once the 1RM was determined, 60% of this value was calculated for the local muscular endurance test. Subjects were asked to perform the horizontal leg press for as many repetitions as possible with 60% of 1RM until failure (Radaelli et al. 2015).

Unilateral isometric strength (Quadriceps and Hamstring MVIC)

Maximal isometric knee extensor and knee flexors strength were measured in both the dominant (trained) and non-dominant (untrained) limbs using a calibrated hand held dynamometer (*Microfet 2; Hogan Health Industries Inc., Draper, Utah, USA*). Specifics of the test position, stabilization, and dynamometer placement used in this study were chosen according to the instrument manual instructions as previously described (Chaouachi et al. 2017). The

dynamometer incorporates a load cell and has a digital display. The hand-held dynamometer was placed perpendicular to the anterior aspect of the tibia, just proximal of the medial malleolus for quadriceps testing and against the Achilles tendon for hamstrings testing. For quadriceps testing, participants were seated on the chair of leg extension machine, positioned so that both feet were off the ground, with hips and knees both flexed at 90°. The lever arm of the leg extension machine was fixed at 100°. The dynamometer was fixed and stabilized by the examiner between the lever arms of the machine and the specific testing placement position on the tested limb segment. The arm of the leg extension machine was fixed with a maximal load to ensure that participants performed an isometric contraction. Participants were instructed to exert maximal force against the dynamometer for a period of three to five seconds while the dynamometer was held stationary. Three consecutive trials separated by approximately 1-min for both legs and the highest values were recorded for analysis. The same procedure and instructions were utilized to measure the MVIC of hamstring muscles. Hamstring MVIC testing was performed with the subjects in a prone position on a leg flexion machine with hips in a neutral extension and knees flexed to 90°. High hand-held dynamometry reliability measurements in similar pediatric population in our laboratory have been reported elsewhere (Chaouachi et al. 2017).

Unilateral Countermovement Jump (CMJ)

The unilateral CMJ test was performed using an Ergo Jump system (Ergojump: Globus Italia, Codogne, Italy) according to the procedure described by Chaouachi et al. (2014). Participant started from an upright akimbo (hands on hip) position. Participants were encouraged to perform the eccentric phase of the jump as quickly as possible to maximize jump height. Participant self-selected the amplitude of the knee flexion of the CMJ to avoid changes in the

coordination pattern. The non-jumping leg was held in a slightly flexed relaxed position during the unilateral jump. Three trials were performed for each leg with approximately 1-min of recovery between trials and the highest jump was used for analysis.

Upper body maximal voluntary isometric contraction (MVIC)

Unilateral elbow flexors (EF) MVIC

EF MVIC strength of both arms was measured using a calibrated hand held dynamometer (Microfet 2; Hoggan Health Industries Inc., Draper, Utah, USA) as previously described (Ben Othman et al. 2017). The hand-held dynamometer was placed between the flexor aspect of the wrist and the lever of elbow flexion machine to ensure an isometric contraction. The elbow flexed at 90°, and then the participant exerted a 3-5 second MVIC against the dynamometer placed perpendicularly against the forearm. This procedure was repeated three times for both the right and left hands with an approximate 1-min rest period and the highest value was recorded for analysis. High reliability of this test in similar pediatric population in our laboratory has been reported elsewhere (Ben Othman et al. 2017).

Unilateral Handgrip strength

MVIC handgrip strength (kg) was measured using a calibrated hand dynamometer (Takei, Tokyo, Japan) as previously described (Ben Othman et al. 2017). Participants stood comfortably with the arm adducted at approximately 45°. The dynamometer was held freely without support and did not touch the subject's trunk, with constant extension of the elbow. The grip-span of the dynamometer was adjusted to each participant's hand size so that the proximal inter-phalangeal joints of the 4 fingers rested on one side of the handgrip and that of the thumb rested on the other

side. Participants were required to exert MVIC strength on the dynamometer. Three trials separated by an approximate 1min rest interval for each hand were performed, and the maximum score for each hand was recorded. Excellent MVIC handgrip strength reliability measurements in children in our laboratory have been reported elsewhere (Ben Othman et al. 2017).

Statistical Analysis

Statistical analyses were computed using SPSS software (Version 22.0, SPSS, Inc., Chicago, IL). Dependent variables underwent assumption of normality (Shapiro-Wilk test) and sphericity (Mauchley test), and when violated, the corrected value for non-sphericity with Greenhouse-Geisser Epsilon was reported. A three-way repeated measures ANOVA (2x3x2) was performed for each measure to determine the existence of significant differences between trained (dominant) and untrained (non-dominant) limbs, type of training (high load/low repetitions, low load/high repetitions and control) and time (pre- and post-training). An alpha level of $p=0.05$ was considered statistically significant. If significant main effects were demonstrated, Bonferroni post hoc analysis were conducted when appropriate. Independent t-tests were used to assess simple effects of interacting main variables. Absolute mean changes as well as contralateral homologous (cross education) and global (contralateral and ipsilateral heterologous untrained muscles) strength transfer values are reported. Contralateral strength transfer was calculated by determining the difference in changes of the experimental (high load/low repetitions, low load/high repetitions) and control groups pre- to post-training (Carroll et al. 2006, Kidgell et al. 2011). The calculation was performed as follows:

$$\frac{(\text{Exp-post-Exp-pre}) - (\text{Control-post} - \text{Control-pre})}{\text{Exp-pre} - \text{Control-pre}} * 100$$

Exp-post and Exp-pre refer to the pre- and post-test mean scores of the untrained arm for either of the experimental groups (high load/low repetitions, low load/high repetitions) while Control-pre and Control-post refer to the pre- and post-test mean scores of the control group. Relative (percentage) changes as well as the magnitude of change was calculated and reported as trivial (<0.2), small (0.2 - 0.49), medium (0.5 - 0.79) or large (≥ 0.8) effect sizes (d) (Cohen 1988). Reliability was calculated with Cronbach alpha interclass correlation coefficient (ICC).

Descriptive statistics include means $\pm$ standard deviation (SD).

RESULTS

Reliability

Reliability measures (ICC) ranged from 0.732 to 0.982 for all tests and the three training groups (Table 2).

Training Effects

Every measure (note: all measures were unilateral) expressed a significant main effect for time with pre- to post-training improvements ranging from 5.6% ($F_{(1,15)} = 20.77$; $p < 0.0001$; $d = 0.58$; elbow flexors MVIC), 8.6% ($F_{(1,15)} = 36.0$; $p < 0.0001$; $d = 0.71$; handgrip), 18.2% ($F_{(1,15)} = 122.49$; $p < 0.0001$; $d = 0.89$; CMJ), 18.9% ($F_{(1,15)} = 139.47$; $p < 0.0001$; $d = 0.90$; knee flexors MVIC), 28.2% ($F_{(1,15)} = 281.87$; $p < 0.0001$; $d = 0.95$; knee extensors MVIC), 32.7% ($F_{(1,15)} = 149.39$; $p < 0.0001$; $d = 0.91$; leg press 1RM) to 89.1% ($F_{(1,15)} = 299.23$; $p < 0.0001$; $d = 0.95$; 60% 1RM leg press) overall.

Type of Training

Except for handgrip, all measures showed a significant main effect for type of training (elbow flexors MVIC; $F_{(2,14)} = 3.92$; $p < 0.0001$; $d = 0.21$, CMJ; $F_{(2,14)} = 3.08$; $p < 0.0001$; $d = 0.27$, knee flexors MVIC; $F_{(2,14)} = 17.35$; $p < 0.0001$; $d = 0.54$, knee extensors MVIC; $F_{(2,14)} = 18.25$; $p < 0.0001$; $d = 0.55$, leg press 1RM $F_{(2,14)} = 3.21$; $p < 0.0001$; $d = 0.28$, 60% 1RM leg press $F_{(2,14)} = 26.16$; $p < 0.0001$; $d = 0.64$). Only for knee flexors MVIC did the high load/low repetition trained group provide a higher measure than the low load/high repetition training by 8.7% ($p = 0.02$). The low load/high repetition trained group did not show any advantages over the high load/low repetition training for any measure. The high load/low repetition trained group measures exceeded the control group with every measure by 24.3% ($p < 0.0001$; knee extensors MVIC), 20.9% ($p < 0.0001$; knee flexors MVIC), 11.2% ($p = 0.01$; elbow flexors MVIC), 17.6% ($p = 0.05$; handgrip), 19.1% ($p = 0.05$; CMJ), 25.6% ($p = 0.05$; leg press 1RM) and 44.1% ($p < 0.0001$; 60% 1RM leg press). The low load/high repetition training did not significantly differ from control for EF MVIC and leg press 1RM. However, the low load/high repetition training was significantly greater than control with the knee extensors MVIC (18.1%; $p < 0.0001$), knee flexors MVIC (11.7%; $p = 0.03$), CMJ (5.3%; $p = 0.05$), and 60% 1RM leg press (57.2%; $p < 0.0001$; 60%).

The pre- to post-training improvements with the high load/low repetition group measures were substantially greater than low load/high repetition (significant interactions) with knee extensors MVIC (55.1% vs. 29.4%; $p < 0.0001$), knee flexors MVIC (36.2% vs. 18.1%; $p < 0.0001$), EF MVIC (14.1% vs. 3.3%; $p < 0.0001$), and leg press 1RM (64.5% vs. 32.9%; $p < 0.0001$). Although all training improvements were significant, there were no significant differences with pre- to post-training measures of low load/high repetition versus high load/low repetition measures for handgrip (16.1% vs. 7.5%), CMJ (38.4% vs. 23.1%) and 60% 1RM leg

press (148.4% vs. 117.1%). Table 3 illustrates mean absolute vs. contralateral or global strength transfer percentage changes.

Trained vs. Untrained Limbs

With the exception of CMJ, every measure demonstrated a significant main effect for trained vs untrained limbs. Overall, the dominant trained leg exceeded the non-dominant untrained leg by 6.7% ($F_{(1,15)} = 25.32$; $p < 0.0001$; $d = 0.63$; knee extensors MVC), 3.5% ($F_{(1,15)} = 12.93$; $p = 0.003$; $d = 0.46$; knee flexors MVC), 6.9% ($F_{(1,15)} = 25.03$; $p < 0.0001$; $d = 0.63$; leg press 1RM) and 17.0% ($F_{(1,15)} = 67.4$; $p < 0.0001$; $d = 0.82$; 60% 1RM leg press). Since the upper body was not trained, these measures compared untrained dominant (ipsilateral) versus untrained, non-dominant (contralateral) changes. The dominant side showed 5.7% and 3.3% significantly greater values for handgrip ($F_{(1,15)} = 19.26$; $p = 0.001$; $d = 0.56$) and EF MVIC ($F_{(1,15)} = 22.41$; $p < 0.0001$; $d = 0.60$) respectively.

Although both the trained and untrained limbs demonstrated positive training adaptations (trained limb x time interactions), the trained limb exhibited greater training adaptations than the untrained limb only for CMJ, leg press 1RM, and 60% 1RM leg press. With the difference approaching significance for the CMJ ($p = 0.06$), the trained leg had 20.2% improvements compared to 16.3% increases for the untrained limb. For the leg press 1RM and 60% 1RM leg press, trained leg adaptations were 40.3% vs. 25.2% ($F_{(2,14)} = 58.95$; $p = 0.005$; $d = 0.80$) and 104.1% vs. 73.4% ($F_{(2,14)} = 48.86$; $p < 0.0001$; $d = 0.76$) significantly greater compared to the untrained leg respectively. There were no significant differences between the trained dominant and untrained non-dominant KE and KF MVIC forces. In addition, there was no significant

difference between untrained ipsilateral and contralateral handgrip and EF MVIC strength measures.

Trained Limb x Type of Training Interaction

With the 1RM leg press, there were significant interactions ($F_{(2,14)} = 10.49$; $p < 0.0001$; $d = 0.41$) with the trained leg whether trained with the low load/high repetition or high load/low repetition program exceeding the control group by 17.1% and 32.4% respectively. The high load/low repetition training group demonstrated 13.1% ($p = 0.03$) higher leg press forces than the low load/high repetition for the trained leg. The untrained leg with either the low load/high repetition or high load/low repetition program also significantly ($p < 0.05$) exceeded control by 10.1% and 18.6% respectively.

With the 60% 1RM leg press, the trained leg whether trained with the low load/high repetition or high load/low repetition program exceeded the control by 62.3% and 58.8% ($p < 0.0001$) respectively. There were no significant differences (2.1%) with the trained leg between the two training programs. The untrained leg with either the low load/high repetition or high load/low repetition program also significantly ($p < 0.05$) exceeded control by 51.6% and 28.5% respectively. Contrary to the 1RM leg press results, with the 60% 1RM test, the low load/high repetition training program demonstrated 18.03% significantly ($p = 0.01$) higher number of repetitions than the high load/low repetition training for the untrained leg.

Overall (all tests), when comparing the improvements of the trained to untrained leg under the high load-low repetition training program, the linear regression was $R^2 = 0.88$ with 30.5% relatively higher training increases with the trained ($53.4 \pm 50.6\%$) versus untrained ($37.1 \pm 25.5\%$) limbs. For the low load – high repetition training adaptations the overall linear

regression was $R^2 = 0.98$ with 17.9% relatively higher training increases with the trained ($47.8 \pm 51.7\%$) versus untrained ($40.5 \pm 41.3\%$) limbs.

Three way interactions are illustrated with figures 1-7.

DISCUSSION

The most important findings in the present study were 1) the evidence for cross education training adaptations in adolescent male youth, 2) that the untrained limb had relatively similar training adaptations as the trained limb for KE and KF MVIC, 3) non-local untrained muscles such as the handgrip and EF MVICs had similar dominant (ipsilateral) versus non-dominant (contralateral) increases in force output, and 4) greater strength training responses with the high load/low repetition group versus the low load/high repetition training.

To our knowledge, this is the first study to examine cross education adaptations with youth. Since Scripture's first description in 1894 (Scripture 1894), all studies have examined adult contralateral homologous (non-trained) adaptations (Hortobagyi 2005). The relative extent of contralateral training adaptations is very diverse in the adult literature with trained vs. non-trained limb improvements ranging from 46% vs. 9.2% for knee extension (Hortobagyi et al. 1992; Housh and Housh 1993; Housh et al. 1998), 41% vs. 35% for unilateral squat (Goodwill and Kidgell 2012), 20.2% vs. 5% for knee flexion (Housh and Housh 1993; Housh et al. 1998), and 48% vs. 1.2% (non-significant) for elbow flexion (Housh and Housh 1993; Ebersole et al. 2002; Farthing and Chilibeck 2003; Munn et al. 2005, Kidgell et al. 2011) strength respectively. Hortobagyi (2005) indicated that the magnitude of cross education is typically about 25%, but in some cases, force or skill transfer can reach 80%. The transfers in the present study of youth generally correspond to the aforementioned adult values. Similar relative (but not absolute)

strength training gains are found with adults and youth in trained muscle groups (Behm et al. 2008). The similarities in the extent of global or cross education training effects suggest the possibility of similar mechanisms (neural and motor learning adaptations).

In the present study, youth trained vs. non-trained leg improvements were significantly greater for the trained leg for CMJ, leg press 1RM and 60% 1RM leg press. On the contrary, there were no significant training differences with trained versus untrained KE, KF, EF MVICs or handgrip forces. There are also examples of non-significant differences in the training increases of contralateral homologous trained vs. untrained limbs in adults with 6, 7, and 8 weeks of training of isometric ulnar deviation MVIC (Farthing et al. 2005, 2007), isometric and isokinetic knee extension and flexion (Kannus et al. 1992), and EF MVIC (Adamson et al. 2008) respectively. With limited evidence for extensive pediatric muscle hypertrophy (Blimkie 1989; Faigenbaum et al. 1996; 2009; Falk and Tenenbaum 1996; Behm et al. 2008), and youth are generally less experienced or skillful in most tasks than adults, the suggestion of a strong contribution of neural adaptations (typically suggested to be increased motor unit recruitment and rate coding) with youth strength training is ubiquitously emphasized in the literature (Blimkie 1989; Ramsay et al. 1990; Ozmun et al. 1994; Faigenbaum et al. 1996; 2009; Faigenbaum 1996; Falk and Tenenbaum 1996; Hortobagyi 2005; Behm et al. 2008; Sale 1996). More recent adult research employing transcranial magnetic stimulation have reported increases in corticospinal excitability of the contralateral biceps brachii (Kidgell et al. 2011) as well as decreased corticospinal inhibition of the contralateral quadriceps (Latella et al. 2012).

In addition to possible neural adaptations, novice, untrained and non-athletic youth experience greater adaptations due to greater co-ordination and learning effects (Behringer et al. 2011; Behm et al. 2017), whereas trained youth may emphasize more neural (recruitment, and

rate coding) and morphological adaptations (Behm et al. 2017). However, the possibility of global morphological adaptations (i.e. EF, handgrip) such as untrained muscle hypertrophic responses to the unilateral leg press training program is unlikely as Beyer et al. (2016) reported no increases in contralateral lower limb muscle size or chronic hormonal profile changes following a 4-week unilateral lower body and bilateral upper body resistance training program. The present study could not ascertain whether the similar homologous cross education training effects of adults and youth could have a proportionally greater contribution from motor learning adaptations with youth.

Although Hortobagyi (2005) stated that cross education is specific to the homologous muscle, the dynamic leg press training program provided significant improvements for all the tested homologous and heterologous muscle groups and exercises whether tested with isometric or dynamic contractions. Only one adult unilateral training study (Sariyildiz et al. 2011) investigated heterologous muscle strength gains (trained wrist flexors and tested both wrist flexors and extensors). Acute adult studies have shown non-local heterologous muscle fatigue (Halperin et al. 2014; Sambaher et al. 2016; Aboodarda et al. 2015, 2017) and stretching effects (Behm et al. 2016). Ben Othman et al. (2017) induced acute unilateral KE fatigue in 10-13 year old children showing non-local muscle effects both ipsilaterally (handgrip, EF MVIC, unilateral CMJ, unilateral balance) and contralaterally (handgrip, KE MVIC, KE isokinetic torque, unilateral CMJ, unilateral balance). In agreement with training specificity (Behm and Sale 1993), the significant disparity in training improvements of the trained and untrained legs only occurred with testing measures that either exactly (leg press) or somewhat resembled (CMJ) the training exercise (leg press). However, there were no significant differences in training improvements between similar muscle groups for non-specific tests (KE, KF MVIC: isometric tests vs.

isoinertial training, uniarticular tests vs. biarticular training) or disparate, non-local, untrained, muscles for non-specific tests (EF MVIC, handgrip MVIC). It can be surmised that motor control, learning, coordination and perhaps some morphological changes were enhanced to a greater degree with the trained leg, whereas the non-local, heterologous muscle adaptations would have been more reliant upon neural adaptations (Ebersole et al. 2002; Evetovich et al. 2001; Farthing et al. 2007; Hortobagyi 2005; Kidgell et al. 2011; Latella et al. 2012; Lee and Carroll 2007). Dynamic leg press training would not have provided substantial motor learning contributions for heterologous EF or handgrip MVIC for example.

The degree of change with the muscle endurance 60% 1RM test (104.1% vs. 73.4% for trained and untrained legs) was substantially higher than the training changes for all other tests. As this test emphasized muscle endurance rather than strength, it might suggest another mechanism for cross education. Magnusson and colleagues (1996) introduced the concept of stretch tolerance to explain stretch-induced increases in ROM in the absence of changes in tissue compliance/stiffness and electromyography (EMG). They suggested that prior stretching or stretch training would allow the individual to tolerate greater pain or discomfort and thus stretch farther than before. Similarly, it could be suggested that the youth in the present study had an increase in “work tolerance”. The increased muscle endurance in the contralateral, untrained leg cannot be ascribed to enzymatic changes. It can be argued that exposure to repeated bouts of uncomfortable exertions during training allowed the youth to accommodate greater discomfort or pain and push themselves past previous limits even with untrained muscles. Children’s lack of experience can adversely affect their perception of exertion (Williams et al. 1994; Barkley 2011; Murphy et al. 2014). Whereas increased work tolerance would likely play a greater role with

enduring repeated contractions (60% 1RM), it could also play a role in tolerating the discomfort of higher intensity contractions and thus contributing to greater force outputs globally.

The final major finding was the greater strength training responses with the high load/low repetition group versus the low load/high repetition training. The greater effect of high intensity resistance training is also reported in the adult literature (Schoenfeld et al. 2014; Mangine et al. 2015; Jenkins et al. 2017). In general, the literature has previously recommended that low to moderate intensity resistance training should be implemented for youth (Faigenbaum et al. 1996; Golan et al. 1998; McNeely et al. 2002; Malina 2006). However, the Canadian Society for Exercise Physiology position stand (Behm et al. 2008) suggested that higher intensity and more advanced resistance training techniques such as plyometrics and Olympic-style lifting can also be employed. The higher load resistance training program would activate the full spectrum of low threshold type I, and higher threshold type II (slow and fast twitch respectively) motor units (Behm 1995). Other training components have also been investigated. Munn et al. (2005) reported a non-significant ($p=0.08$) cross education elbow flexor training advantage with high (5%) versus low (-1%) velocity isoinertial training. As evidenced from the strength training improvements in untrained ipsilateral (handgrip and EF) and contralateral (handgrip, EF, KE, KF) muscles, these adaptations acted globally. Whereas the high load/low repetition training provided greater strength training responses, the disparity between trained and untrained limbs was lower with the low load/high repetition training group. While the untrained limbs achieved mean 37.1% and 40.5% increases with high load/low repetition and low load/high repetition training respectively, the trained limbs achieved 53.4% versus 47.8% improvements with high load/low repetition and low load/high repetition training respectively, which contributed to the training type x trained limb disparity. Thus, irrespective of age (youth vs. adult), trained muscles

and global cross education effects demonstrate greater strength improvements with higher intensity resistance loading.

A major limitation of the present study was that EMG was not monitored during the training program with the possibility that the non-trained leg was activated by mirror activity or stabilization efforts. However, the participants were monitored by the researchers and continually exhorted to relax the non-trained limb. It was beyond the scope of this study to determine the precise neurological training adaptations.

CONCLUSIONS

Should the term cross education apply with ipsilateral and contralateral heterologous muscle training adaptations? Perhaps a more apt term would be global education or global training effects. The present study is the first to demonstrate cross or global education effects with children and illustrated that these effects act not only on contralateral homologous (cross education) muscles but also global training effects to heterologous ipsilateral and contralateral muscles. It is likely that the mechanisms for the trained muscles and contralateral homologous muscles include neural adaptations (i.e. motor unit recruitment, rate coding) and motor control / learning adaptations. The lower relative strength gains for the untrained EF and handgrip muscles (different muscles and movements; lack of training specificity) suggest that motor learning changes may not have played as much of a significant role. The greatest strength training responses involved high load/low repetition training versus the low load/high repetition training. As such, the extent of cross education effects and the greater effectiveness of high load/low repetition training illustrates similar responses between youth and adults. However, due

to the lack of adult studies examining global training effects, it is not known whether adult heterologous untrained muscles would respond similarly to youth.

CONFLICT OF INTEREST: The authors declare no conflicts of interest, financial or otherwise.

REFERENCES

- Aboodarda, S.J., Copithorne, D.B., Power, K.E., Drinkwater, E., and Behm, D.G. 2015. Elbow flexor fatigue modulates central excitability of the knee extensors. *Appl. Physiol. Nutr. Metab.* **40**: 924-30.
- Aboodarda, S.J., Sambaher, N., Millet, G.Y., and Behm, D.G. 2017. Knee extensors neuromuscular fatigue changes the corticospinal pathway excitability in biceps brachii muscle. *Neurosci.* **340**: 477-486.
- Adamson, M., Macquaide, N., Helgerud, J., Hoff, J., and Kemi, O.J. 2008. Unilateral arm strength training improves contralateral peak force and rate of force development. *Eur. J. Appl. Physiol.* **103**: 553-9.
- Barkley, J.E.R., Roemmich, J.N. 2011. Validity of a pediatric RPE scale when different exercise intensities are completed on separate days. *J. Exer. Sci. Fitness*, **9**: 52-57.
- Behm, D.G. 1995. Neuromuscular implications and applications of resistance training. *J. Strength Cond. Res.* **9**: 264-274.
- Behm, D.G., Cavanaugh, T., Quigley, P., Reid, J.C., Nardi, P.S., and Marchetti, P.H. 2016. Acute bouts of upper and lower body static and dynamic stretching increase non-local joint range of motion. *Eur. J. Appl. Physiol.* **116**: 241-9.

- Behm, D.G., Faigenbaum, A.D., Falk, B., and Klentrou, P. 2008. Canadian Society for Exercise Physiology position paper: resistance training in children and adolescents. *Appl. Physiol. Nutr. Metab.* **33**: 547-61.
- Behm, D.G. and Sale, D.G. 1993. Velocity specificity of resistance training. *Sports Med.* **15**: 374-88.
- Behm, D.G.Y., J.D.; Whitten, J.H.D.; Reid, J.C.; Quigley, P.J.; Low, J.L.; Li, Y.; Lima, C.D.; Hodgson, D.D.; Chaouachi, A.; Prieske, O.; Granacher, U. 2017. Effectiveness of Traditional Strength versus Power Training on Muscle Strength, Power and Speed with Youth: A Systematic Review and Meta-analysis. *Frontiers Exerc. Physiol.* June 2017
doi.org/10.3389/fphys.2017.00423
- Behringer, M., Vom Heede, A., Matthews, M., and Mester, J. 2011. Effects of strength training on motor performance skills in children and adolescents: a meta-analysis. *Ped. Exerc. Sci.* **23**: 186-206.
- Ben Othman, A., Chaouachi, A., Hammami, R., Chaouachi, M.M., Kasmi, S., and Behm, D.G. 2017. Evidence of nonlocal muscle fatigue in male youth. *Appl. Physiol. Nutr. Metab.* **42**: 229-237.
- Beyer, K.S., Fukuda, D.H., Boone, C.H., Wells, A.J. , Townsend, J.R., Jajtner, A.R., Gonzalez, A.M., Fragala, M.S., Hoffman, J.R. and Stout, J.R. 2016. Short-term unilateral resistance training results in cross education of strength without changes in muscle size, activation, or endocrine response. *J. Strength Cond. Res.* 30(5) : 1213-1223.
- Blimkie, C.J. 1989. Age- and sex-associated variation in strength during childhood: Anthropometric, morphologic, neurologic, biomechanical, endocrinologic, genetic, and physical

activity correlates. In: C.V. Gisolfi (Ed.), *Perspectives in Exercise Science and Sports Medicine*,
Vol. 2: Youth, Exercise and Sports, pp. 99-163. Indianapolis, IN: Benchmark Press.

Carroll, T., Herbert, R., Munn, J., Lee, M., and Gandevia, S. 2006. Contralateral effects of
unilateral strength training: evidence and possible mechanisms. *J. Appl. Physiol.* **101**, 1514–
1522.

Chaouachi, A., Hammami, R., Kaabi, S., Chamari, K., Drinkwater, E.J., and Behm, D.G. 2014.
Olympic weightlifting and plyometric training with children provides similar or greater
performance improvements than traditional resistance training. *J. Strength Cond. Res.* **28**: 1483-
96.

Chaouachi, M., Granacher, U., Makhoul, I., Hammami, R., Behm, D.G., and Chaouachi, A.
2017. Within Session Sequence of Balance and Plyometric Exercises Does Not Affect Training
Adaptations with Youth Soccer Athletes. *J. Sports Sci. Med.* **16**: 125-136.

Cirer-Sastre, R.B.-G., J.V.; Corbi, F. 2017. Contralateral Effects after Unilateral Strength
Training: A Meta-Analysis Comparing Training Loads. *J. Sports Sci. Med.* **16**: 180-186.

Cohen, J. 1988. *Statistical power analysis for the behavioural sciences*. Hillsdale N.J.: L. Erlbaum
Associates.

Ebersole, K.T., Housh, T., Johnson, G.O., Perry, S.R., Bull, A.J., and Cramer, J.T. 2002.
Mechanomyographic and electromyographic responses to unilateral isometric training. *J.*
Strength Cond. Res. **16**: 192-201.

Evetovich, T.K., Housh, D.J., Housh, T.J., Johnson, G.O., Smith, D.B., and Ebersole, K.T. 2001.
The effect of concentric isokinetic strength training of the quadriceps femoris on
electromyography and muscle strength in the trained and untrained limb. *J. Strength Cond. Res.*
15: 439-445.

- 557 Faigenbaum, A. 2000. Strength training for children and adolescents. *Pediatric Adolescent*
558 *Sports Injuries*, **19**: 593-619.
- 559 Faigenbaum, A.D., Kraemer, W.J., Blimkie, C.J., Jeffreys, I., Micheli, L.J., Nitka, M., and
560 Rowland, T.W. 2009. Youth resistance training: updated position statement paper from the
561 national strength and conditioning association. *J. Strength Cond. Res.* **23**: S60-S79.
- 562 Faigenbaum, A.D., Kraemer, W.J., Cahill, B., Chandler, J., Dziados, J., Elfrink, L.D., Formann,
563 E., Gaudiose, M., Micheli, L., Nitka, M., and Roberts, S. 1996. Youth resistance training:
564 Position statement paper and literature review. *Strength Cond.* **December**: 62-75.
- 565 Faigenbaum, A.D., Milliken, L.A., and Westcott, W.L. 2003. Maximal strength testing in healthy
566 children. *J. Strength Cond. Res.* **17**: 162-166.
- 567 Faigenbaum, A.D., Westcott, W.L., Loud, R.L., and Long, C. 1999. The effects of different
568 resistance training protocols on muscular strength and endurance development in children.
569 *Pediatrics*, **104**: e5.
- 570 Faigenbaum, A.D.W., Michelli, L.J. (1996). The effects of strength training and detraining on
571 children. *J. Strength Cond. Res.* **10**: 109-114.
- 572 Falk, B. and Tenenbaum, G. 1996. The effectiveness of resistance training in children. A meta-
573 analysis. *Sports Med.* **22**: 176-86.
- 574 Farthing, J.P. 2009. Cross-education of strength depends on limb dominance: implications for
575 theory and application. *Exerc. Sport Sci. Rev.* **37**: 179-87.
- 576 Farthing, J.P., Borowsky, R., Chilibeck, P.D., Binsted, G., and Sarty, G.E. 2007. Neuro-
577 physiological adaptations associated with cross-education of strength. *Brain Topogr.* **20**: 77-88.
- 578 Farthing, J.P. and Chilibeck, P.D. 2003. The effect of eccentric training at different velocities on
579 cross-education. *Eur. J. Appl. Physiol.* **89**: 570-7.

- 580 Farthing, J.P., Chilibeck, P.D., and Binsted, G. 2005. Cross-education of arm muscular strength
581 is unidirectional in right-handed individuals. *Med. Sci. Sports Exerc.* **37**: 1594-1600.
- 582 Golan, R., Falk, B., Hoffman, J., Hochberg, Z., Ben-Sira, D., and Barak, Y. 1998. Resistance
583 training for children and adolescents. Position Statement for the International Federation of
584 Sports Medicine: 265-270.
- 585 Goodwill A.M., and Kidgell, D.J. 2012. The Effects of Whole-Body Vibration on the Cross-
586 Transfer of Strength. *Scientific World Journal* **2012**: 1-11, 2012 doi:10.1100/2012/504837
- 587 Halperin, I., Aboodarda, S.J., and Behm, D.G. 2014. Knee extension fatigue attenuates repeated
588 force production of the elbow flexors. *Eur. J. Sport Sci.* **14**: 823-829.
- 589 Hortobagyi, T. 2005. Cross Education and the Human Central Nervous System: Mechanisms of
590 Unilateral Interventions Producing Contralateral Adaptations. *IEEE Eng Med. Biol.*
591 **January/February**: 22-28.
- 592 Hortobagyi, T., Lambert, N., Tracy, C., and Shinebarger, M. 1992. Voluntary and
593 electromyostimulation forces in trained and untrained men. *Med. Sci. Sports Exerc.* **24**: 702-707.
- 594 Hortobagyi, T., Lambert, N.J., and Hill, J.P. 1997. Greater cross education following training
595 with muscle lengthening than shortening. *Med. Sci. Sports Exerc.* **29**: 107-12.
- 596 Housh, D., Housh, T., Johnson, G., and Chu, W. 1992. Hypertrophic response to unilateral
597 concentric isokinetic resistance training. *J. Appl. Physiol.* **73**: 65-70.
- 598 Housh, D.J., Housh, T.J., Weir, J.P., Weir, L.L., Evetovich, T.K., and Donlin, P.E. 1998.
599 Effects of unilateral concentric-only dynamic constant external resistance training on quadriceps
600 femoris cross-sectional area. *J. Strength Cond. Res.* **12**: 185-191.
- 601 Housh, D.J. and Housh, T.J. 1993. The effects of unilateral velocity-specific concentric strength
602 training. *J. Orthop. Sports Phys. Ther.* **17**: 252-6.

603 Jenkins N.D.M., Miramonti A.A., Hill E.C., Smith C.M., Cochrane-Snyman K.C., Housh T.J.
 604 and Cramer J.T. 2017. Greater Neural Adaptations following High- vs. Low-Load Resistance
 605 Training. *Front. Physiol.* **8**:331. doi: 10.3389/fphys.2017.00331
 606 Kannus, P., Alosa, D., Cook, L., Johnson, R.J., Renström, P., Pope, M., Beynnon, B., Nichols, C.,
 607 and Kaplan, M. 1992. Effect of one-legged exercise on the strength, power and endurance of the
 608 contralateral leg. A randomized, controlled study using isometric and concentric isokinetic
 609 training. *Eur. J. Appl. Physiol.* **64**: 117-126.
 610 Kidgell, D.J., Stokes, M.A., and Pearce, A.J. 2011. Strength Training of One Limb Increases
 611 Corticomotor Excitability Projecting to the Contralateral Homologous Limb. *Motor Control*, **15**,
 612 247-266
 613 Latella, C., Kidgell, D.J., and Pearce, A.J. 2012. Reduction in corticospinal inhibition in the
 614 trained and untrained limb following unilateral leg strength training. *Eur. J. Appl. Physiol.* **112**:
 615 3097-107.
 616 Lee, M. and Carroll, T.J. 2007. Cross education: possible mechanisms for the contralateral
 617 effects of unilateral resistance training. *Sports Med.* **37**: 1-14.
 618 Magnusson, S.P., Simonsen, E.B., Aagaard, P., Sorensen, H., and Kjaer, M. 1996. A mechanism
 619 for altered flexibility in human skeletal muscle. *J. Physiol.* **497** (Pt 1): 291-298.
 620 Malina, R. 2006. Weight training in youth. Growth, maturation and safety: An evidence based
 621 review. *Clin. J. Sports Med.* **16**: 478-487.
 622 Mangine G.T., Hoffman J.R., Gonzalez A.M., Townsend J.R., Wells A.J., Jajtner A.R., Beyer
 623 K.S., Boone C.H., Miramonti A.A., Wang R, LaMonica .B., Fukuda D.H., Ratamess N.A. and
 624 Stout J.R. 2015. The effect of training volume and intensity on improvements in muscular
 625 strength and size in resistance-trained men. *Physiol Reports*, **3**(8) : e12472, doi:

- 10.14814/phy2.12472
- McNeely, E. and Armstrong, L. 2002. Strength training for children: a review and recommendations. *Physical Health Ed. J.* **68**: 1-6.
- Mirwald, R.L., Baxter-Jones, A.D., Bailey, D.A., and Beunen, G.P. 2002. An assessment of maturity from anthropometric measurements. *Med. Sci. Sports Exerc.* **34**: 689-94.
- Munn, J., Herbert, R.D., Hancock, M.J., and Gandevia, S.C. 2005. Training with unilateral resistance exercise increases contralateral strength. *J. Appl. Physiol.* **99**: 1880-1884.
- Murphy, J.R., Button, D.C., Chaouachi, A., and Behm, D.G. 2014. Prepubescent males are less susceptible to neuromuscular fatigue following resistance exercise. *Eur. J. Appl. Physiol.* **114**: 825-35.
- Ozmun, J., Mikesky, A., and Surburg, P. 1994. Neuromuscular adaptations following prepubescent strength training. *Med. Sci. Sports Exerc.* **54**: 510-514.
- Radaelli, R., Fleck, S.J., Leite, T., Leite, R.D., Pinto, R.S., Fernandes, L., and Simao, R. 2015. Dose-response of 1, 3, and 5 sets of resistance exercise on strength, local muscular endurance, and hypertrophy. *J. Strength Cond. Res.* **29**: 1349-58.
- Ramsay, J.A., Blimkie, C.J., Smith, K., Garner, S., MacDougall, J.D., and Sale, D.G. 1990. Strength training effects in prepubescent boys. *Med. Sci. Sports Exerc.* **22**: 605-14.
- Sale D.G, 1996. Skeletal muscle function and energy metabolism. In: D.R.L. O. Bar-Or, P.M. Clarkson (Ed.), *Exercise and the Female – A Life Span Approach*, pp. 289-359. Carmel, IN: Cooper Publishing Group.
- Sambaher, N., Aboodarda, S.J., and Behm, D.G. 2016. Bilateral Knee Extensor Fatigue Modulates Force and Responsiveness of the Corticospinal Pathway in the Non-fatigued, Dominant Elbow Flexors. *Front. Hum. Neurosci.* **10**: 18-24.

- Sariyildiz, M., Karacan, I., Rezvani, A., Ergin, O., and Cidem, M. 2011. Cross-education of muscle strength: cross-training effects are not confined to untrained contralateral homologous muscle. *Scand. J. Med. Sci. Sports*, **21**: e359-64.
- Schoenfeld B.J., Wilson J.M., Lowery R.P., and Krieger J.W. 2014. Muscular adaptations in low- versus high-load resistance training: A meta-analysis. *Eur. J. Sport Sci.* <http://dx.doi.org/10.1080/17461391.2014.989922>
- Scripture, E.W.S. 1894. On the education of muscular control and power. *Studies of the Yale Psychology Laboratory*, **2**: 114-119.
- Shields, R.K., Leo, K.C., Messaros, A.J., and Somers, V.K. 1999. Effects of repetitive handgrip training on endurance, specificity, and cross-education. *Phys. Ther.* **79**: 467-75.
- Williams, J.G., Eston, R., and Furlong, B. 1994. CERT - a perceived exertion scale for young-children. *Perceptual Motor Skills*, **79**: 1451-1458.

Table 1: Participant characteristics. Acronyms: BMI: Body mass index, PHV: peak height velocity

Groups N=16 for each group	Age (years)	Mass (Kg)	Height (cm)	BMI	Body Fat %	PHV
High load-low repetition	11.8 ± 0.6	40.1 ± 3	147.5 ± 5.5	18.5 ± 1.6	17.9 ± 3.3	-2.7 ± 0.3
Low load-high repetition	11.5 ± 0.5	38.3 ± 3.5	147.5 ± 4.7	17.7 ± 1.8	18.4 ± 2.8	-2.8 ± 0.3
Control	11.9 ± 1.2	38.8 ± 8.1	146 ± 3.5	18.2 ± 1.2	18.5 ± 2.8	-2.5 ± 1.6

Table 2: Reliability: Intraclass Correlation Coefficients Abbreviations: KE: knee extension, KF: knee flexion, EF: elbow flexion, CMJ: countermovement jump, 1RM: 1 repetition maximum, rep: repetition

	Handgrip	KE MVIC	KF MVIC	EF MVIC	CMJ	1RM Leg Press	60% 1RM Leg Press
Low Load High Rep	0.908	0.908	0.759	0.919	0.951	0.982	0.827
High Load Low Rep	0.782	0.792	0.732	0.835	0.882	0.975	0.861
Control	0.754	0.754	0.883	0.876	0.821	0.948	0.948

Table 3: The adjusted magnitude of contralateral and global strength transfer effects between groups. Absolute mean percentage differences are compared to contralateral or global strength transfer (GST) calculations. Asterisks illustrate significant differences calculated from absolute mean values. Acronyms: HL-LR: High load – low repetition, LL-HR: Low load – high repetition, MVIC: maximum voluntary isometric contraction, CMJ: countermovement jump, 1RM: 1 repetition maximum.

	HL-LR vs Control		LL-HR vs Control		HL-LR vs. LL-HR	
	Absolute	GST	Absolute	GST	Absolute	GST
Handgrip MVIC	17.6%*	3.7%	10.4%	11.1%	-8.6%	-7.4%
Knee Extension MVIC	24.3%*	55.1%	18.1%*	27.9%	25.5%*	27.2%
Knee Flexion MVIC	20.9%*	31.8%	11.7%*	16.3%	20.0%*	15.3%
Elbow Flexion MVIC	11.2%*	12.3%	4.6%	1.8%	10.8%*	10.4%
CMJ	19.1%*	20.5%	5.3%*	26.8%	-14.8%	-6.3%
Leg Press 1RM	25.6%*	44.9%	20.9%	23.3%	31.6%*	21.7%
Leg press 60% 1RM	44.1%*	69.4%	57.2%*	122.7%	-33.3%	-53.4%

FIGURE LEGENDS

Figure 1: Knee extensors MVIC

Acronyms: LL-HR: low load high repetitions, HL-LR: high load low repetitions
HR represented by grey lines or dots, LR represented by black lines or hyphens and control
represented by closed lines. Asterisk (*) indicates that HL-LR group was significantly greater
than control at post-test. Hash tag or number sign (#) indicates HL-LR significantly exceeded
LL-HR at post-test.

Figure 2: Knee Flexors MVIC

Acronyms: LL-HR: low load high repetitions, HL-LR: high load low repetitions
HR represented by grey lines or dots, LR represented by black lines or hyphens and control
represented by closed lines. Asterisk (*) indicates that HL-LR group was significantly greater
than control at post-test. Hash tag or number sign (#) indicates HL-LR significantly exceeded
LL-HR at post-test.

Figure 3: Countermovement Jump Height (CMJ)

Acronyms: LL-HR: low load high repetitions, HL-LR: high load low repetitions
HR represented by grey lines or dots, LR represented by black lines or hyphens and control
represented by closed lines. Asterisk (*) indicates that HL-LR group was significantly greater
than control at post-test.

Figure 4: 1Repetition Maximum (RM) Leg Press

Acronyms: LL-HR: low load high repetitions, HL-LR: high load low repetitions
HR represented by grey lines or dots, LR represented by black lines or hyphens and control
represented by closed lines. Asterisk (*) indicates that HL-LR group was significantly greater
than control at post-test. Hash tag or number sign (#) indicates HL-LR significantly exceeded
LL-HR at post-test.

Figure 5: 60% of 1RM Leg Press

Acronyms: LL-HR: low load high repetitions, HL-LR: high load low repetitions
HR represented by grey lines or dots, LR represented by black lines or hyphens and control
represented by closed lines. Asterisk (*) indicates that HL-LR group was significantly greater
than control at post-test.

Figure 6: Handgrip Strength

HR represented by grey lines or dots, LR represented by black lines or hyphens and control
represented by closed lines. Asterisk (*) indicates that HL-LR group was significantly greater
than control at post-test.

Figure 7: Elbow Flexors MVIC

Acronyms: LL-HR: low load high repetitions, HL-LR: high load low repetitions, IPSI: Ipsilateral arm to the trained leg, CONTRA: contralateral arm to the trained leg

HR represented by grey lines or dots, LR represented by black lines or hyphens and control represented by closed lines. Asterisk (*) indicates that HL-LR group was significantly greater than control at post-test. Hash tag or number sign (#) indicates HL-LR significantly exceeded LL-HR at post-test.

Draft

Figure 1:

Figure 2:

Figure 3:

Figure 4:

Figure 5:

Figure 6:

Figure 7: