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Abstract

Cross-education has been extensively investigated with adults. Adult studies report asymmetrical cross-education adaptations predominately after dominant limb training. The objective of the study was to examine unilateral leg-press (LP) training of the dominant or non-dominant leg on contralateral and ipsilateral strength and balance measures. Forty-two youth (10-13 years) were placed (random allocation) into a dominant (n=15) or non-dominant (n=14) leg-press training group or non-training control (n=13). Experimental groups trained 3 times per week for 8 weeks and were tested pre-/post-training for ipsilateral and contralateral 1-repetition maximum (RM) LP, knee extensors (KE) and flexors (KF) maximum voluntary isometric contractions (MVIC), countermovement jump (CMJ), triple hop test (THT), elbow flexors (EF) MVIC and handgrip MVIC, as well as Stork and Y balance test. Both dominant and non-dominant LP training significantly ($p<0.05$) increased both ipsilateral and contralateral lower body strength (LP 1RM [Dominant:59.6-81.8%; Non-dominant:59.5-96.3%], KE MVIC [Dominant:12.4-18.3%; Non-dominant:8.6-18.6%], KF MVIC [Dominant:7.9-22.3%; Non-dominant:non-significant-3.8%]), and power (CMJ: Dominant:11.1-18.1%; Non-dominant: 7.7-16.6%]) with the exception that non-dominant LP training demonstrated a non-significant change with the contralateral KF MVIC. Other significant improvements were with non-dominant LP training on ipsilateral EF 1RM (6.2%) and THT (9.6%). There were no significant changes with EF and handgrip MVIC. The contralateral leg Stork balance test was impaired following dominant LP training. KF MVIC exhibited the only significant relative post-training to pre-training (post-test/pre-test) ratio differences between dominant versus non-dominant LP cross-education training effects. In conclusion, children exhibit symmetrical cross-education or global training adaptations with unilateral training of dominant or non-dominant upper leg.

Key Words: resistance training; cross-education; youth; strength; power; balance

Introduction

Cross-education has been extensively investigated since before the 20th century (Scripture 1894). It involves the performance improvement of the untrained limb after a period of unilateral practice (i.e., strength, acceleration, skill, endurance) (Hortobagyi 2005; Carroll et al. 2006; Farthing et al. 2007; Farthing 2009; Hester et al. 2018). Substantial evidence for cross-education has been demonstrated in adults for contralateral homologous muscles such as the quadriceps (Kannus et al. 1992; Hortobagyi et al. 1997; Evetovich et al. 2001; Goodwill et al. 2012; Latella et al. 2012), elbow flexors (EF) (Ebersole et al. 2002; Munn et al. 2005; Adamson et al. 2008), and hand grip muscles (Shields et al. 1999; Manca et al. 2016). While Farthing et al. (2003) demonstrated both non-significant (with slow velocity eccentric training) and significant cross-education effects (high velocity eccentric training) in the same study, other reports have shown increases ranging from small (i.e. 3.8-5%) (Housh et al. 1993; Munn et al. 2005) to very large improvements (i.e. 35%, 52%, 77%) (Hortobagyi et al. 1997; Goodwill and Kidgell 2012). In addition, unilateral eccentric contractions of the dominant forearm were reported to spare contralateral muscle volume after four weeks of forearm immobilization (Andrushko et al. 2018b).

Cross-education has been sparingly examined with children. In one of the few studies to examine cross-education in children, Ben Othman et al. (2018) had 10-13 year old children perform unilateral, dominant leg, resisted leg press actions over 8 weeks (3 x week) and tested both contralateral and ipsilateral homologous (1-repetition maximum [RM] leg press, knee extensors [KE] maximum voluntary isometric contractions [MVIC] and countermovement jump [CMJ]) and heterologous lower body muscles (knee flexors [KF] MVIC). In addition, they tested contralateral and ipsilateral heterologous upper body muscles (elbow flexors [EF] and hand grip

MVIC). The global (contralateral and ipsilateral, homologous and heterologous muscles) training effects were ubiquitous with significant strength improvements with the untrained muscles that were within 10% of the trained muscles from unilateral, dominant limb, leg press training. These similar global training adaptations may reflect more malleable central nervous system (CNS) adjustments with children versus adults. As these non-local or global training effects have been sparsely examined in the literature (adult or children) (Sariyildiz et al. 2011), there is a need to replicate and further examine the reliability and validity of these findings (Halperin et al. 2017). Greater global training effects with youth would have important applications for the rehabilitation of unilateral injuries, prevention of limb asymmetry and unilateral overuse injuries (i.e. baseball, softball, racquet sports).

In the adult literature, the cross-education effect after unilateral strength training of the dominant limb is quite potent (Farthing et al. 2005; Farthing et al. 2009; Farthing et al. 2011; Andrushko et al. 2018a) when compared to lesser or non-significant improvements with unilateral training of the non-dominant limb (Imamizu et al. 1995; Stoddard et al. 1996; Farthing 2009; Parmar et al. 2009). However, not all cross-education studies show greater transfer after dominant limb strength training. Recent work by Coombs et al. (2016) reported symmetrical cross-education after dominant or non-dominant training in right-handed individuals with a hand-held weight, wrist extension task. Coombs et al. suggested that the characteristics of the task and the training paradigm (e.g. metronome-paced) could account for some discrepancy across studies. With respect to the task, (Farthing, 2009) theorized that the degree of strength asymmetry prior to training could also influence the directionality of effects. It has been suggested that unilateral strength training involves a substantial motor learning component (Farthing et al. 2007; Farthing 2009). Since children's motor learning patterns are less consolidated (Behm et al. 2008; Faigenbaum et al. 2015) and may be more amenable to training or adaptable than adults (Behm et al. 2008; Ben Othman et al. 2017; Ben Othman et al. 2018), it might suggest that their global training or cross-education adaptations may not exhibit the same degree of uni-directionality. Although, the prior Ben Othman et al. (2018) study used similar testing measures, training protocol, and population, they only trained the dominant leg. To our knowledge, there are no studies examining the directionality of cross-education in lower limbs, and very few studies investigating children. Such an investigation will provide greater insights into the adaptability and CNS training transferability with children.

Hence, it was the objective of this study to examine whether healthy children exhibited global training (contralateral and ipsilateral homologous and heterologous muscles) directionality (dominant versus non-dominant leg press training). A second objective was to investigate the reproducibility of the testing measures following a similar training protocol within the same laboratory, researchers and youth population. This is important because replication studies verify probability of error in the testing of null hypotheses, or the likelihood of a Type I or Type II error. With reference to the literature (Behm et al. 2008; Ben Othman et al. 2017; Ben Othman et al. 2018), we hypothesized that unlike adults, there would be less evidence of directionality and more global (non-local) training effects due to higher plasticity in the children's developing nervous system.

Methods

Participants

Forty-two 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. They were not involved with any other extracurricular training programs. 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 participant 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. Participants 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 withdrew from the training study. 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, balance and power tests.

Place Table 1 approximately here

Experimental procedures

One week before the commencement of the study, all included children participated in three orientation sessions to become familiar with the general environment, form and technique of each test (force, power and balance techniques), equipment, and the experimental procedures to minimize the learning effect during the course of the study. Each participant'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. Post-testing, the researchers conducting the tests were blinded to participants' group allocation. The testing protocol included assessment of lower limb unilateral strength in the form of 1RM horizontal leg press, maximum voluntary isometric contraction (MVIC) of knee extensors (KE: quadriceps) and knee flexors (KF: hamstring muscles), and upper body unilateral MVIC strength of elbow flexors (EF) and hand grip strength as well as an EF 1RM and proxies of muscle power (countermovement jump [CMJ], triple hop test [THT]). Balance was tested with the Standing Stork and Y balance tests. Following the initial baseline testing session, participants were randomly divided into two unilateral resistance training groups (dominant limb leg press training, n=15 and non-dominant limb leg press training n=14) and a control group (n=13) without a training program. Footedness and handedness were assessed by Waterloo Handedness and Footedness questionnaires respectively to determine the dominant upper and lower limb. Using a controlled randomization method, groups were matched for age, maturation status and physical characteristics. The training groups performed 3-4 sets of 6-10 RM of unilateral horizontal seated leg press (knee and hip extension/flexion) with 2 min rest intervals between sets (Table 2). The training program was periodized and the volume of work during training was equal between the experimental groups.

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). Three sets of 8, 9, 10, and 6 repetitions were completed in weeks 1-4 respectively, followed by 4 sets of 8, 9, and 10 repetitions in weeks 5-7 respectively with a reduction to three sets of 6 repetitions in the final week 8. Two minutes recovery was allowed between sets for both training programs. Two to five days after the last training session, post-training was performed using the same timeline and procedures as during the pre-test. Progressive overload of the dominant and non-dominant leg press group was implemented by increasing the load by 5-10% whenever a participant could exceed the prescribed 6-10 repetitions. All trained participants attended at least 85% of the training sessions (missed no more than 3 sessions). The control group was limited to their regular daily activity (no structured or systematic training or activity).

Before each training session, the training groups performed a specific warm-up consisting of submaximal ergometer cycling for 5 minutes before dynamic stretching. The exercise used for training was a unilateral leg press with either the dominant or non-dominant leg in a seated position using a commercial horizontal leg press (Life Fitness Pro Horizontal Leg Press) with a range of motion from 90 to 10° (0° = full knee extension). The load lifted for the 1RM test or RM repetition was the sum of additional plate load and weight of the leg press machine lever (3 kg) and plate carrier (11 kg). Participants in the training groups received skill-specific feedback on the quality of each movement. The instructors recorded the training data and made appropriate adjustments in training resistance and repetitions. Special attention was paid to the instructions to keep the contralateral leg completely immobile and as relaxed as possible during the training. The arms were placed across the chest during the leg press repetitions to ensure that the youth did not provide a strength training stimulus to the arms or hands by stabilizing. If the participant performed repetitions beyond the prescribed training zone, the weight was increased to bring the number of repetitions back within the RM training zone (6-10).

Lower body maximal strength and power tests

Unilateral leg-press maximal dynamic strength (1-RM)

Unilateral leg strength was assessed on the horizontal leg-press with a 1-RM test. Before attempting a 1-RM, 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. 1-RM 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. Throughout all testing procedures, an instructor-to-participant ratio of 1:1 was maintained, and uniform verbal encouragement was offered to all participants.

Unilateral isometric strength (knee extensors and flexors MVIC)

Maximal isometric knee extensor and knee flexors strength were measured in both the dominant and non-dominant limbs using a calibrated hand-held, load cell 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; 2018; Ben Othman et al. 2018). 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 the 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 3-5 seconds. 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°. The same researcher performed all hand-held dynamometry measures. High hand-held dynamometry reliability measurements in a similar pediatric population in our laboratory have been reported elsewhere (Chaouachi et al. 2017; 2018; Ben Othman et al. 2018).

Unilateral countermovement jump (CMJ)

The unilateral (single leg) CMJ test was performed using an Ergo Jump system (Ergojump: Globus Italia, Codogne, Italy) according to the procedure described previously (Chaouachi et al. 2014). Participants started from an upright akimbo position. Participants 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. High reliability of this test (ICC=0.95) in a similar pediatric population in our laboratory has been published previously (Chaouachi et al. 2014; Ben Othman et al. 2017).

Triple hop test

With the triple hop test (THT), the tape measure was fixed to the ground, perpendicular to a starting line. Participants were instructed to stand behind the starting line with their non-dominant leg forward and the dominant leg off the ground and the reverse procedure when testing the dominant leg. The subject performed three consecutive maximal hops forward on the same leg to reach the maximal horizontal distance. Arm swing was allowed. The investigator measured the distance hopped from the starting line to the point where the heel hit on the completion of the third and final hop. Previous test - retest reliability scores for balance measures from our laboratory with a similar pediatric population have been high (ICC=0.89) (Chaouachi et al. 2017).

Upper body strength tests (elbow flexion [EF] 1-RM)

The dynamic strength of the dominant and non-dominant EF was assessed by 1-RM performing a seated unilateral elbow-flexion exercise on a preacher-curl bench on a standard elbow flexion machine (Life Fitness Pro Elbow Flexion Machine, Brunswick Corp., Mettawa Illinois, USA). The right or left arm was positioned against the preacher bench pad with the chest against the pad, holding the lever arm of the machine. Before attempting a 1-RM, participants performed three submaximal sets of one to six repetitions with a relatively light load. Participants then performed a series of single repetitions with increasing loads. If the participant successfully completed one contraction without assistance until complete elbow flexion was achieved, weights were raised slightly (0.5 kg), and the participant again attempted to complete one repetition. Failure was defined as a lift falling short of the full range of motion (10° to full flexion, 0° full extension, to prevent locking at the elbow joint) on at least two attempts spaced at least two minutes apart. The same investigator measured 1-RM for a participant and ensured that the arm not being tested was relaxed and placed in neutral position behind the back. Throughout all testing procedures, an instructor-to-subject ratio of 1:1 was maintained, and uniform verbal encouragement was offered to all participants. High reliability of this test (ICC=0.85) in a similar pediatric population in our laboratory has been published previously (Chaouachi et al. 2014; Ben Othman et al. 2017).

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; 2018; Chaouachi et al. 2018). The hand-held dynamometer was placed between the flexor aspect of the wrist and the lever of the elbow flexion machine to ensure an isometric contraction. The elbow was 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 (ICC=0.84-0.92) in a similar pediatric population in our laboratory has been reported elsewhere (Ben Othman et al. 2017).

Unilateral hand grip MVIC

MVIC hand grip strength (kg) was measured using a calibrated hand dynamometer (Takei, Tokyo, Japan) as previously described (Ben Othman et al. 2017). Participants stood with the arm adducted at approximately 45°. The dynamometer was held freely without support and did not touch the participant'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 four fingers rested on one side of the hand grip and that of the thumb rested on the other side. Three trials separated by an approximate 1 min rest interval for each hand were performed, and the maximum score for each hand was recorded. Excellent MVIC hand grip strength reliability measurements in children in our laboratory have been reported elsewhere (ICC=0.78-0.91) (Ben Othman et al. 2017).

Y balance test

The Y balance test was used to assess dynamic postural control for both legs and has been reported to possess high reliability (ICC=0.92-0.93) with similar pediatric populations (Hammami et al. 2016a; Chaouachi et al. 2017). To perform the Y balance test, participants stood on the dominant leg, with the most distal aspect of their great toe on the center of the footplate from the Y balance test kit. The participants were then asked to push the reach-indicator block with the free limb in the anterior, posterior medial, and posterior lateral directions in relation to the stance foot on the central footplate, while maintaining their single-limb stance. The average maximum normalized reach across the three directions was calculated in order to record a composite score for each participant. Y balance measures were normalized by dividing each excursion distance by the participant's leg length, then multiplying by 100. Thus, normalized values can be viewed as a percentage of excursion distance in relation to the participant's leg length (Hammami et al. 2016a). Following the completion of the test trials, each participant was given a 1-minute rest period and then conducted two test trials in each direction.

Standing stork test

Static balance was assessed for both legs utilizing the Stork stand balance protocol. To perform the Stork stand test, participants stood akimbo with their opposite foot against the inside of the supporting knee. On the command, the subject raised the heel of their foot from the floor and attempted to maintain their balance as long as possible. The trial ended if the participant either moved his hands from his hips, the ball of the dominant foot moved from its original position, or if the heel touched the floor. The test was timed using a stopwatch. The recorded score (duration in seconds) was the best of three attempts. Previous test- retest reliability scores (ICC=0.75-0.89) for balance measures from our laboratory with a similar pediatric population have been high (Chaouachi et al. 2014; 2017; Hammami et al. 2016b; 2016c).

Statistical analyses

Statistical analyses were computed using SPSS software (Version 24.0, 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 (3x2x2) was performed for each measure to determine the existence of significant differences between groups (control, dominant leg press trained and non-dominant leg press trained limbs), tested leg (dominant and non-dominant limb) and time (pre- and post-training). Since the dominant limb is typically stronger in absolute values than the non-dominant limb, we also wanted to examine the relative (%) training-related changes of the two limbs to determine if relative training responses were significantly different; unencumbered by the absolute dominant versus non-dominant limb differences that would influence the three-way ANOVA. Thus, a second two-way repeated measures ANOVA (3x2) was performed for each measure to evaluate significant differences in the relative (normalized to pre-test: post-training / pre-training values) ratio of training adaptations between groups (control, dominant leg press trained and non-dominant leg press trained limbs) and tested limb (dominant and non-dominant limbs). If significant ($p \leq 0.05$) main effects were demonstrated, Bonferroni post hoc analysis and corrections were conducted. For significant interactions, independent t-tests were used to assess differences between groups, legs or time. Overall main effects and interaction effect sizes were computed from eta^2 using the SPSS ANOVA output. The effect size (d) magnitude of change for specific within group significant interactions were calculated (mean of A – mean of B / standard deviation of pooled means) 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).

Results

Dominant and non-dominant leg-press training responses

Within group pre-post interactions: The control group exhibited no significant changes over time. Three way interactions (trained group x tested limb x time) demonstrated that dominant limb, leg press training significantly increased both ipsilateral and contralateral lower body strength measures (leg press 1RM [$F_{(2,24)}$=49.88; p<0.0001], KE MVIC [$F_{(2,24)}$=15.85; p<0.0001], KF MVIC [$F_{(2,24)}$=8.89]). Non-dominant leg press training showed similar responses with the exception of a non-significant change with the contralateral (dominant) KF MVIC. The only significant improvement in upper limb strength measures was with non-dominant leg press training on ipsilateral (non-dominant) EF 1-RM ($F_{(2,24)}$=30.12; p=0.004). A similar ipsilateral training effect was seen with the THT with significant pre- to post-training test increases observed with non-dominant leg press training on ipsilateral (non-dominant) THT for distance performance. CMJ demonstrated significant ($F_{(2,24}$= 4.43; p=0.023) increases with both dominant and non-dominant leg press training for both the ipsilateral and contralateral legs. The Stork balance test exhibited a near significant ($F_{(2,24)}=3.24$; $p=0.057$) impairment following dominant leg press training when testing the contralateral (non-dominant) leg but no balance deficits with the ipsilateral dominant leg (see Table 2 and Figure 1 for details of all tests).

Main effects: Significant main effects for time were detected for all strength and power measures except EF 1-RM (p=0.069), and the Stork Test. There were significant main effects for the tested limb with higher values for the dominant tested KE MVIC, KF MVIC, EF MVIC, and hand grip MVIC, but a lack of significance with EF 1-RM, CMJ, THT, Stork test and Y balance test. Main effects for trained leg were observed only with the leg press 1-RM (Table 3).

Place tables 2 and 3 approximately here

Relative (normalized to pre-test) training responses

Training and testing limb interactions: When comparing the relative (%) post-training test results to pre-training measures (post-test/pre-test), there were no significant differences between dominant versus non-dominant leg press cross-education training effects for leg press 1-RM, KE MVIC, EF MVIC, hand grip MVIC, EF 1-RM, CMJ, THT, Standing Stork or Y balance test. The two-way ANOVA (trained groups x tested limb) showed that significant interactions were evident with dominant leg press training when comparing training and testing of the dominant limb to cross-education effects (training of one limb and testing of the contralateral limb) (see results with asterisks in Table 4 and Figure 1).

There were significant differences with KF MVIC as the dominant leg press training with testing of the contralateral (non-dominant) KF demonstrated superior results compared to the i) non-dominant leg press training with testing of the contralateral (dominant) KF as well as with ii) non-dominant leg press training with testing of the ipsilateral (non-dominant) KF. There were also significantly greater training adaptations with the dominant leg press training when testing the ipsilateral (dominant) KF compared to i) non-dominant leg press training and testing the contralateral (dominant) KF, and ii) non-dominant leg press training and testing the ipsilateral (non-dominant) KF. Hence, with the two-way ANOVA, there was a significant interaction effect ($F_{(1,13)}$=16.92 ; p=0.001) showing that when testing knee flexion MVIC, the dominant leg press training was superior to non-dominant leg press KE training (Table 4).

Non-dominant leg press training only demonstrated superior relative training effects when the trained and tested leg were the same and then compared to a cross-education training effect (dominant trained leg with testing of the non-dominant leg) for leg press 1-RM, KE MVIC, and THT (Table 4).

Main effects: KF MVIC was the only test to show a significant main effect of the directionality of leg training with greater relative training increases with dominant leg training. Main effects for the tested limb appeared with greater non-dominant leg relative training adaptations with the leg press 1-RM, and triple hop test. Greater dominant tested limb relative training adaptations occurred with the KF MVIC and the Y balance test (see Table 5 for all main effect details). An illustrative summary of training effects are found in figure 1.

Place tables 5 and 6 and figure 1 approximately here.

Discussion

The major findings in the present study were that children did not exhibit a trained limb preference for the transfer of training effects from dominant or non-dominant legs to contralateral or ipsilateral homologous and heterologous muscles, with the exception of testing the knee flexor MVIC. Secondly, the global (contralateral and ipsilateral, homologous and heterologous muscles) training effects of unilateral leg press training were evident with lower limb training specific (leg press 1-RM) and non-specific (KE MVIC, KF MVIC, CMJ) actions but were generally not evident with upper limb tasks (exception: improved EF 1-RM with non-dominant training and testing of ipsilateral [non-dominant] limb). Finally, there were no training-related improvements with the Y balance test and Stork test.

Many adult cross-education studies demonstrate a uni-directional (Farthing et al. 2005) training transfer with the dominant limb training providing significantly greater contralateral gains in comparison to unilateral training of the non-dominant limb (Housh et al. 1992; Imamizu and Shimojo 1995; Stoddard and Vaid 1996; Farthing 2009; Parmar et al. 2009). However, Coombs et al. (2016) reported symmetrical cross-education after dominant or non-dominant training of adults proposing that the task and the training paradigm (e.g. metronome-paced) could account for some differences between studies. Secondly, this occurrence is predominately examined with the upper limbs of adults (i.e. EF and hand muscles) (Farthing et al. 2005). As to be expected, there was some evidence in the present study of dominant limb training superiority when testing the trained (dominant or ipsilateral) limb and comparing to a cross-education effect (train the non-dominant limb and test the contralateral, untrained, dominant limb) (Table 5). For example, leg press training improvements were 81.8-96.3% (large magnitude) when the trained and tested legs and actions were the same but were only 59% (large magnitude) improved with cross-education effects (testing of contralateral leg press). Leg press training adaptations exceeded all other measures. This greater leg press training to testing adaptation can be attributed to the concept of training specificity (Behm et al. 1993) as this testing measure replicated the training protocol.

The general lack of cross-education training effect directionality with leg press training in children in this study suggests that in accordance with our hypothesis, the child's CNS may be more adaptable than in adults (Behm et al. 2008; Ben Othman et al. 2017; 2018). The specific location of this process was beyond the scope of this study. However, in a number of adult studies, cross-education effects occur without increases in electromyographic (EMG) activity suggesting that cross-education would be more likely attributed to increased activation of the motor cortex (Hortobagyi et al. 2003; Farthing et al. 2005). Farthing in his review (Farthing 2009) explains that a mechanism of cross-education would be related to plasticity of the cortical pathways involved in motor planning input as well as plasticity in the motor command of the motor cortex increasing agonist activation (Hortobagyi et al. 1997; Farthing et al. 2007) and decreasing co-contractions (Carolan and Cafarelli 1992). Based on adult research, increases in corticospinal excitability (Kidgell et al. 2011; Leung et al. 2018) and decreased corticospinal inhibition (i.e. short interval cortical inhibition) of the contralateral limbs (Latella et al. 2012; Leung et al. 2018) could contribute to enhanced motor unit recruitment and rate coding-induced increases in strength and power (Behm 1995; Behm et al. 2008) with the training effects observed with children in this study. However, a meta-analysis by Manca et al. (2018) indicated that the magnitude of corticospinal excitability did not correlate with cross-education changes. Lagerquist et al. (2006) hypothesized that the cross-education effect of a 5 week adult strength training program may be due more to supraspinal than spinal mechanisms as they did not detect significant changes in the H-reflex of the contralateral untrained soleus. Although, there is still strong evidence for a central neural origin of cross-education, the lack of correlations in the Manca et al. (2018) review could not establish a mechanistic link with the increased corticospinal excitability.

Whether global strength enhancement is achieved from the proficiency model (task acquisition with the more proficient system provides a better stored motor program for the opposite limb) or the cross activation (motor programs for a skill or task are stored in both hemispheres with unilateral acquisition) model (Parlow et al. 1989; Farthing 2009), the strength data from the current study suggests that in comparison to adults, children's access to or storage of motor cortical programs seems to be more equitably distributed (right and left cortices) or more easily accessed from either side. The children's greater plasticity may be related to the ongoing and greater degree of growth and development of the CNS (Falk et al. 2003; Faigenbaum et al. 2009; Behm et al. 2010b).

The only consistent exception to the equivalence of global training effects was the predominance of dominant leg press training on the relative training adaptations for KF MVIC. Dominant leg press training with testing of either the contralateral or ipsilateral KF exhibited significant, moderate to large magnitude training gains compared to the non-significant and trivial magnitude non-dominant leg press training changes with testing of the dominant and non-dominant knee flexors respectively. This predominance of dominant limb training adaptations to non-dominant limbs is quite common in the adult literature. Dominant limb training effect predominance may have only occurred with the knee flexors since flexor motoneurones have a greater proportion of monosynaptic corticospinal connections, leading to higher monosynaptic excitation compared to more disynaptic and polysynaptic inhibition of the extensors (Phillips et al. 1964; Palmer and Ashby 1992). Sainburg (2005) postulates a dynamic dominance, indicating that the dominant limb has greater control over the efficient and accurate coordination of muscle forces especially with multi-joint limb movement or interaction forces. Meanwhile, the nondominant limb is more attuned for positional control. With adults, stronger transfer effects observed from the dominant arm training to both contralateral limb extensors and flexors (Housh et al. 1992; Imamizu and Shimojo 1995; Stoddard and Vaid 1996; Farthing 2009; Parmar et al. 2009) may reflect the stronger established neural networks from decades of dominant limb task preference. However, with youth, this dominance preference would not be as well established (Bishop et al. 1996; Bryden et al. 2006; Corbetta et al. 2006; Bryden et al. 2011), resulting in less entrenched neural networks. Thus, cross-education or global training effects may be more limb equitable with youth with the exception of a less inhibited, more excitable flexor contralateral flexor network pathway that may be more susceptible to dominant limb transfers with children.

Whereas Ben Othman et al. (2018) reported global training adaptations from dominant limb leg press training resulting in increased strength of both the lower (leg press 1RM, KE MVIC and KF MVIC) and upper limbs (EF and hand grip MVIC), the training in the present study generally did not improve EF and hand grip MVIC, although there was an increase of EF 1-RM with non-dominant training and testing of ipsilateral [non-dominant] limb. As Halperin et al. (2017) emphasized, the replication of experiments are at the heart of science and allows for confirmation or refutation of outcomes. The general lack of EF and hand grip MVIC improvements are surprising as the children were of a similar age group, physiological maturity stage, trained status, same city and tested by the same researchers with the same equipment as the prior Ben Othman et al. (2018). In addition, the number of participants were quite similar with 16 per group in the prior Ben Othman study and 14 and 15 per training group in the present study. A possible difference was that the children who experienced more global training effects in the prior study were trained and tested during the school year when they had supervised and structured physical education classes during each week, compared to free play time for children in present study. Although more structured physical education classes could provide a greater motor learning emphasis that might facilitate the more global transfer of skills; in neither study did the control groups exhibit significant gains in strength, power or balance. Hence, this conjecture is unlikely. A second difference was that the present study had a lower volume of training. In the prior study with greater global training adaptations, the children performed 40 repetitions per session from training weeks 2-7 of an 8 week program. The children in the present study performed 24, 27, 30, 18, 32, 36, 40, and 18 repetitions from week 1 to 8 respectively. Hence, higher volumes of training may significantly impact the global impact of unilateral training in children. This possibility needs to be further investigated.

Furthermore, these differences highlight the need for replication studies. Since we had access to the prior Ben Othman data, the dominant leg press training data were integrated with the present data for the EF and hand grip MVIC to observe if a greater study population (n=46) would still provide global training effects (dominant leg press training effects upon the upper body). For both integrated measures, a two-way ANOVA (2 testing limbs [dominant and non-dominant] x 2 times) demonstrated significant ($p<0.0001$) overall training gains (main effects for time: EF: eta^2: 0.35: hand grip: eta^2: 0.45) but no significant interactions. Thus, the evidence for global training effects were weaker when both studies were combined and a larger population was analyzed. While recruiting 13-15 participants (or less) is ubiquitous within the exercise sciences, many multi-site, medical interventions recruit hundreds of participants. These present and integrated results demonstrate the importance of either larger samples or basing our theories and applications on meta-analyses with much greater population access. Further investigations are necessary to assess the reliability of upper body strength improvements following unilateral lower body training with children.

The Stork test did not significantly improve and actually was impaired with dominant leg press training with testing of the contralateral non-dominant leg. The leg press training was performed on a resistance machine with minimal stability or balance requirements. Although, strength and power increases were observed with training, the Stork balance test does not necessitate substantial muscle contraction strength. Hence, with such lack of training specificity (Behm and Sale 1993), it is not surprising that there was no significant improvements with training. On the other hand, dominant leg press training resulted in a near significant interaction ($p=0.068$) Y balance test improvement (3.3%-4.1%). The Y balance test does necessitate higher leg strength in order to stabilize the stationary leg, while the other leg reaches out to greater distances from the centre of gravity. The farther the movement of the reaching leg from the centre of gravity would create higher disruptive torques to the individual's balance, which could be compensated to a greater extent by a stronger leg. However, strictly speaking, the balance findings were non-significant and would be in accord with the concept of training specificity (Behm and Sale 1993). Unilateral strength training on a stable leg press device did not significantly improve a complex task such as balance, which involves not only strength, but the integration of proprioceptive and vestibular afferents culminating in an appropriate motor command to deal with equilibrium perturbations (Behm et al. 2017).

A similar argument could be made for the lack of significant gains in 3 of 4 triple hop tests (significant improvement only with non-dominant leg press training and testing the ipsilateral [non-dominant] leg). Although both the CMJ and triple hop tests would involve power, the CMJ is stationary, whereas the triple hop test is a dynamic translation of the body. Higher performance on this test would involve not only power but balance and stability. It is well established that an unstable base decreases force, power, angular velocity and range of motion

(Behm et al. 2006; Drinkwater et al. 2007; Behm et al. 2010a). Although the present study did show global transfers of strength and power, the lack of balance or stability enhancement could have nullified gains in three of the four THT.

A limitation of the study was the lack of mechanistic measures (laboratory equipment constraints) to identify the underlying processes involved with the present findings. Furthermore, with the analysis of 10 measures, there might be a risk of Type I error for instance with non-dominant leg press training on ipsilateral (non-dominant) EF 1-RM. As a precautionary note, all trainers, coaches and researchers should only employ resistance training programs that are within a child's or adolescent's capacity and involves gradual progression under qualified instruction and supervision with appropriately sized equipment (Behm et al. 2008). However, if these recommendations are followed, resistance training is safe and effective in youth which is why it has been endorsed by several entities (e.g. American Academy of Pediatrics, National Strength and Conditioning Association, Canadian Society for Exercise Physiology, British Association of Sport and Exercise Science)(Behm et al. 2008, Faigenbaum et al;. 2009, Lloyd et al. 2014).

Conclusions

The children in this study did not exhibit directionality of cross-education after unilateral leg training. The results showed that children had similar global training results whether the dominant or non-dominant leg was trained. Hence, children with unilateral injuries that prevent them from training a particular limb, whether it is the dominant or non-dominant limb can continue to train unilaterally and expect strength training benefits bilaterally.

Conflict of interest statement

The authors declare no conflicts of interest, financial or otherwise.

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Table Legends

Table 1a: Participant characteristics and limb dominance

Table 2: Absolute means, standard deviations, percentage (%) pre-post-training changes, p values and observed statistical power (OP) for dominant and non-dominant leg press training with testing of the contralateral (cross-education) and ipsilateral limbs. Shaded cells highlight significant pre- to post-training changes. within either the dominant or non-dominant training programs. There were no significant interactions within the control group. 1-RM: 1 repetition maximum, KE: knee extensors, KF: knee flexors, EF: elbow flexors, MVIC: maximum voluntary isometric contraction, CMJ: countermovement jump. d: effect size

Table 3: Main effects with three-way ANOVA for time, trained leg and tested limb. 1-RM: 1 repetition maximum, MVIC: maximum voluntary isometric contraction

Table 4: Analyses of significant relative (normalized to pre-training scores: post/pre-training ratio) trained leg to tested leg interactions. Asterisks illustrate where the trained leg with testing of the same trained leg (ipsilateral training effect) had a significantly higher ratio (greater extent of training adaptations) than with a cross-education training effect (trained leg with testing of the untrained contralateral leg). Shaded rows highlight where the dominant trained leg group exhibited greater relative training adaptations than the non-dominant trained leg group irrespective of whether it was comparing an i) similar ipsilateral training response, ii) similar cross education response, or iii) dominant cross-education to non-dominant ipsilateral training response. As there were no significant control group differences, this table reflects the experimental groups (dominant versus non-dominant training).

Table 5: Relative (two-way ANOVA: normalized to pre-test: post-training / pre-training) main effects and interactions for trained leg and testing limb. 1-RM: 1 repetition maximum, EF: elbow flexors, MVIC: maximum voluntary isometric contraction. Arrow indicates the percentage change in values for the dominant versus non-dominant limb. Specific post-hoc interactions (trained leg dominance x testing limb dominance) are illustrated in Table 5. As there were no significant control group differences, this table reflects the experimental groups (dominant versus non-dominant training).

Figure Legends

Figure 1: Relative (post-pre-training ratio) training responses.

A. All significant leg press training responses occurred with the lower limb measures (cross-education) but generally no global training effects with the exception of significant training improvement with elbow flexors (EF) 1RM: (Non-dominant leg press training and testing of non-dominant elbow flexors), THT (non-dominant leg press training effects upon non-dominant THT) and lack of significant training improvements with knee flexors (KF) MVIC (non-dominant leg press training effects upon dominant KF MVIC).
B. There were no significant dominant limb training predominance (no directionality of cross-education).
C. Asterisks (*) illustrate where ipsilateral training responses (i.e. Dominant leg press training effects upon dominant limb or non-dominant leg press training effects upon non-dominant limb measures) were significantly greater than cross-education responses of the contralateral limb (i.e. dominant leg press training effects upon non-dominant leg measures or non-dominant leg press training effects upon dominant limb measure).
D. The hashtag (number sign: #) indicates that the triple hop test (THT) non-dominant ipsilateral training response (non-dominant leg press training effects upon non-dominant THT) was significantly great than the other three training THT responses.
E. The vertical arrow bar designates that it was only with knee flexion (KF) MVIC that the dominant leg press trained limb significantly exceeded the non-dominant leg press trained limb (cross-education dominant limb predominance).
F. As there were no significant changes with control group, their data is not included in this figure.

Table 1: Participant characteristics. Non-DOM: non-dominant, BMI: Body mass index, PHV: peak height velocity

Groups		**Age (years)**	**Mass (kg)**	**Height (cm)**	**BMI (kg/m²)**	**PHV (years)**
Dominant-leg	(n=15)	11.7 ±0.8	41.3±7.6	150.3±8.6	18.2±2.9	-2.3±0.5
Non-DOM leg	(n=14)	11.4±0.7	39.9±7.8	147.3±6	18.3±2.8	-2.4±0.5
Control	(n=13)	11.3±0.5	38.6±5	146.3±6.5	18±2	-2.7±0.3
Limb dominance		**Dominant leg-press training group**		**Non-dominant leg-press training group**		**Control group**
Right leg dominant		(n=11) = 73%		(n=11) = 78.5%		(n=11) = 84.6%
Left leg dominant		(n=4) = 26.6%		(n=3) = 21.5%		(n=2) = 15.4%
Right hand dominant		(n=13) = 86.7%		(n=12) = 85.7%		(n=11) = 84.6%
Left hand dominant		(n=2) = 13.3%		(n=2) = 14.3%		(n=2) = 15.4%

Table 2: Absolute means, standard deviations, percentage (%) pre-post-training changes, p values and observed statistical power (OP) for dominant and non-dominant leg-press training with testing of the contralateral (cross-education) and ipsilateral limbs. Shaded cells highlight significant within group pre- to post-training changes within either the dominant or non-dominant training programs. There were no significant test leg x time interactions within the control group. 1-RM: 1 repetition maximum, KE: knee extensors, KF: knee flexors, EF: elbow flexors, MVIC: maximum voluntary isometric contraction, CMJ: countermovement jump. d: effect size

	Dominant leg-press (knee extensors) training				Non-dominant leg-press (knee extensors) training				Control			
Tested Limb	Dominant (DOM) Pre	Non-dominant (ND) Pre	DOM Post Ipsilateral Effects	ND Post Cross-Education	Dominant (DOM) Pre	Non-dominant (ND) Pre	DOM Post Cross Education	ND Post Ipsilateral Effects"	DOM Pre	ND Pre	DOM Post Cross-Education	ND Post Ipsilateral Effects
Lower Limb Strength Tests												
Leg Press 1RM	54.4 ±6.9	54.6±6.8	98.9±15.1 81.8% $p<0.0001$ d=4.4 OP: 1.0	87.1±11.8 59.6% $p<0.0001$ d=1.66 OP: 1.0	50.8 ±8.6	49.3 ±9.1	81.1±14.6 59.5% $p<0.0001$ d=2.61 OP: 1.0	96.9±14.7 96.3% $p<0.0001$ d=4.0 OP: 1.0	51.9 ±5.8	50.9 ±5.3	52.1 ±4.9	51.8 ±3.9
KE MVIC	353.7 ±70.5	329.3 ±69.8	418.6 ±70.4 18.3% $p<0.0001$ d=0.92 OP: 0.966	370.3 ±67.6 12.4% $p<0.0001$ d= 0.60 OP: 0.966	341.7 ±55.8	325.0 ±60.9	371.4±57.6 8.6% $p=0.01$ d=0.53 OP: 0.993	385.7±66.3 18.6% $p<0.0001$ d=0.95 OP: 0.993	369.4 ±33.1	367.9 ±32.5	372.9 ±38.2	377.5 ±30.5
KF MVIC	170.3 ±26.7	167.9 ±20.7	208.4 ±30.4 22.3% $p<0.0001$ d=1.3 OP: 0.933	181.3 ±20.1 7.9% $p<0.0001$ d=0.65 OP: 0.93	182.9 ±39.6	174.1 ±34.8	185.4±41.2 Non-sig	180.7±35.3 3.8% $P=0.002$ d=0.18 OP: 0.425	180.5 ±19.4	180.8 ±24.1	184.2 ±14.3	181.5 ±22.7
Upper Limb Strength Tests												
EF MVIC	140.3 ±28.1	138.6 ±25.9	146.06 ±27.6 Non-sig	143.8 ±27.9 Non-sig	140.07 ±21.2	134.3 ±23.8	145.5 ±26.0 Non-sig	138.14 ±25.3 Non-sig	140.8 ±20.2	132.5 ±17.3	140.7 ±19.1	133.5 ±17.2
Hand grip MVIC	21.9 ±4.8	21.1 ±5.1	22.9±5.3 Non-sig	21.9±5.1 Non-sig	20.9 ±4.8	20.8 ±4.2	21.9±4.9 Non-sig	22.4±4.8 Non-sig	22.5 ±4.6	21.8 ±3.9	22.7 ±5.3	22.2 ±4.4
EF 1-RM	5.8 ±1.4	5.8 ±1.2	6.03 ±1.2 Non-sig	6.0 ±1.2 Non-sig	6.1 ±1.4	5.8 ±1.4	6.1±1.3 Non-sig	6.2±1.1 7.4%	6.0 ±1.04	5.9 ±1.01	6.2 ±0.98	6.1 ±0.97

								p=0.004 d=0.32 OP: 0.585				
Power Tests												
CMJ	12.4 ±2.6	12.8 ±2.1	14.6±2.6 18.1% p<0.0001 d=0.84 OP: 0.607	14.2±1.8 11.1% p=0.0008 d=0.72 OP:0.607	13.5 ±3.9	12.8 ±3.6	14.5±3.7 7.7% p=0.0002 d=0.26 OP: 0.64	14.9±3.4 16.6% p<0.0001 d=0.6 OP: 0.648	12.6 ±2.7	12.3 ±2.5	12.9 ±12.5	12.5 ±2.4
Triple Hop	442.4 ±39.9	440.5 ±39.7	457.4 ±46.1 Non-sig	457.7±36.3 Non-sig	428.1 ±53.8	406.7 ±62.8	433.6±54.3 Non-sig	445.6±48.2 9.6% p=0.0002 d=0.65 OP: 0.843	423.8 ±36.3	426.3 ±41.3	430.7 ±39.3	432.5 ±43.7
Balance Tests												
Stork Test	6.6 ±2.9	7.3 ±2.8	7.1±3.8 7.7% Non-sig	6.6±2.5 -9.9% p=0.05 d=0.26 OP: 0.70	6.9 ±3.7	7.3 ±4.6	7.6±3.6 Non-sig	7.5±4.3 Non-sig	6.3 ±2.5	6.3 ±2.5	6.5 ±2.6	6.6 ±2.3
Y Balance	0.92 ±0.06	0.93 ±0.07	0.96±0.06 4.1% p=0.068 d=0.66 OP: 0.45	0.95±0.06 3.3% p=0.068 d=0.31 OP: 0.45	0.92 ±0.08	0.92 ±0.6	0.95±0.09 Non-sig	0.97±0.06 Non-sig	0.9 ±0.06	0.9 ±0.06	0.9 ±0.07	0.9 ±0.06

Table 3: Main Effects with three-way ANOVA for Time, Trained leg and Tested limb. 1-RM: 1 repetition maximum, MVIC: maximum voluntary isometric contraction

Measures	Main Effects for Time (pre- to post-training)	Main Effects for Trained Leg DOM: dominant; ND: non-dominant	Main Effects for Tested Limb DOM: dominant; ND: non-dominant
Lower Limb Strength Tests			
Leg Press 1-RM	$F_{(1,12)} = 521.18$ $p<0.0001$; eta^2: 0.97 50.5%↑	$F_{(2,24)} = 43.02$ $p<0.0001$; eta^2: 0.78; DOM: 45.0%↑; ND: 37.2%↑ > Control	Non-significant
Knee Extensor MVIC	$F_{(1,12)} = 43.58$ $p<0.0001$; eta^2: 0.78 9.4% ↑	Non-significant	$F_{(1,12)} = 13.29$ $p=0.003$; eta^2: 0.52 DOM: 3.2%↑ > ND
Knee Flexor MVIC	$F_{(1,12)} = 44.12$ $p<0.0001$; eta^2: 0.79 5.8%↑	Non-significant	$F_{(1,12)} = 13.45$ $p=0.003$; eta^2: 0.53 DOM: 4.4%↑ > ND
Upper Limb Strength Tests			
Elbow Flexor MVIC	$F_{(1,12)} = 6.04$ $p=0.03$; eta^2: 0.33 2.8%↑	Non-significant	$F_{(1,12)} = 30.12$ $p<0.0001$; eta^2: 0.71 DOM: 3.8%↑ > ND
Elbow Flexor 1-RM	Non-significant $p=0.069$; eta^2: 0.25	Non-significant	Non-significant
Handgrip MVIC	$F_{(1,12)} = 29.7$ $p<0.0001$; eta^2: 0.71 3.5%↑	Non-significant	$F_{(1,12)} = 7.76$ $p=0.016$; eta^2: 0.39 DOM: 2.3%↑ > ND
Power Tests			
Countermovement Jump	$F_{(1,12)} = 126.86$ $p<0.0001$; eta^2: 0.91 9.5%↑	Non-significant	Non-significant
Triple Hop Test	$F_{(1,12)} = 44.87$ $p<0.0001$; eta^2: 0.79 3.6%↑	Non-significant	Non-significant
Balance Tests			
Stork test	Non-significant	Non-significant	Non-significant
Y balance test	$F_{(1,12)} = 10.65$ $p=0.007$; eta^2: 0.47 2.3%↑	Non-significant	Non-significant $p=0.078$; eta^2: 0.24

Table 4: Analyses of significant relative (normalized to pre-training scores: post/pre-training ratio) trained leg to tested leg interactions. Asterisks illustrate where the trained leg with testing of the same trained leg (ipsilateral training effect) had a significantly higher ratio (greater extent of training adaptations) than with a cross-education training effect (trained leg with testing of the untrained contralateral leg). Shaded rows highlight where the dominant trained leg group exhibited greater relative training adaptations than the non-dominant trained leg group irrespective of whether it was comparing an a) similar ipsilateral training response, b) similar cross-education response, or c) dominant cross-education to non-dominant ipsilateral training response. As there were no significant control group differences, this table reflects the experimental groups (dominant versus non-dominant training).

Leg Press 1RM Significant Interaction Effect: $F_{(1,13)} = 53.59$; $p<0.0001$			
*DOM Train–DOM Tested (1.8±0.25) > ND Train-DOM tested (1.6±0.19)	p=0.01	d=0.87	12.5%
*ND Train-ND tested (1.98±0.29) > DOM Train–ND Tested (1.6±0.21)	p=0.003	d=1.52	23.7%
Knee Extension MVIC Significant Interaction Effect: $F_{(1,13)} = 39.32$; $p<0.0001$			
*DOM Train–DOM Tested (1.2±0.09) > ND Train-DOM tested (1.09±0.11)	p=0.01	d=1.1	10.1%
*ND Train-ND Tested (1.19±0.1) > DOM Train-ND Tested (1.13±0.11)	p=0.03	d=0.4	5.3%
Knee Flexion MVIC Significant Interaction Effect: $F_{(1,13)} = 16.92$; $p=0.001$			
a. DOM Train–DOM Tested (1.23±0.15) > ND Train-ND tested (1.04±0.04)	p=0.0003	d=2.0	18.2%
b. DOM Train–ND Tested (1.08±0.04) > ND Train-DOM tested (1.01±0.04)	p=0.001	d=1.75	6.9%
c. DOM Train–ND Tested (1.08±0.04) > ND Train-ND tested (1.04±0.04)	p=0.02	d=1.0	3.8%
*DOM Train–DOM Tested (1.23±0.15) > ND Train-DOM tested (1.01±0.04)	p<0.0001	d=2.3	21.7%
Countermovement Jump (CMJ) Height Significant Interaction Effect: $F_{(1,13)} = 10.23$; $p=0.007$			
*DOM Train–DOM Tested (1.19±0.1) > ND Train-DOM tested (1.08±0.06)	p=0.001	d=1.4	10.1%
Triple Hop Test (THT) Significant Interaction Effect: $F_{(1,13)} = 7.82$; $p=0.015$			
ND Train-ND tested (1.1±0.08) > DOM Train–DOM Tested (1.03±0.06)	p=0.08	d=1.0	6.7%

DOM Train: Dominant leg-press trained leg; DOM Tested: Dominant tested leg
ND Train: Non-dominant leg-press trained leg; ND Tested: Non-dominant tested leg
MVIC: Maximal voluntary isometric contraction; 1-RM: 1 repetition maximum; d=effect size

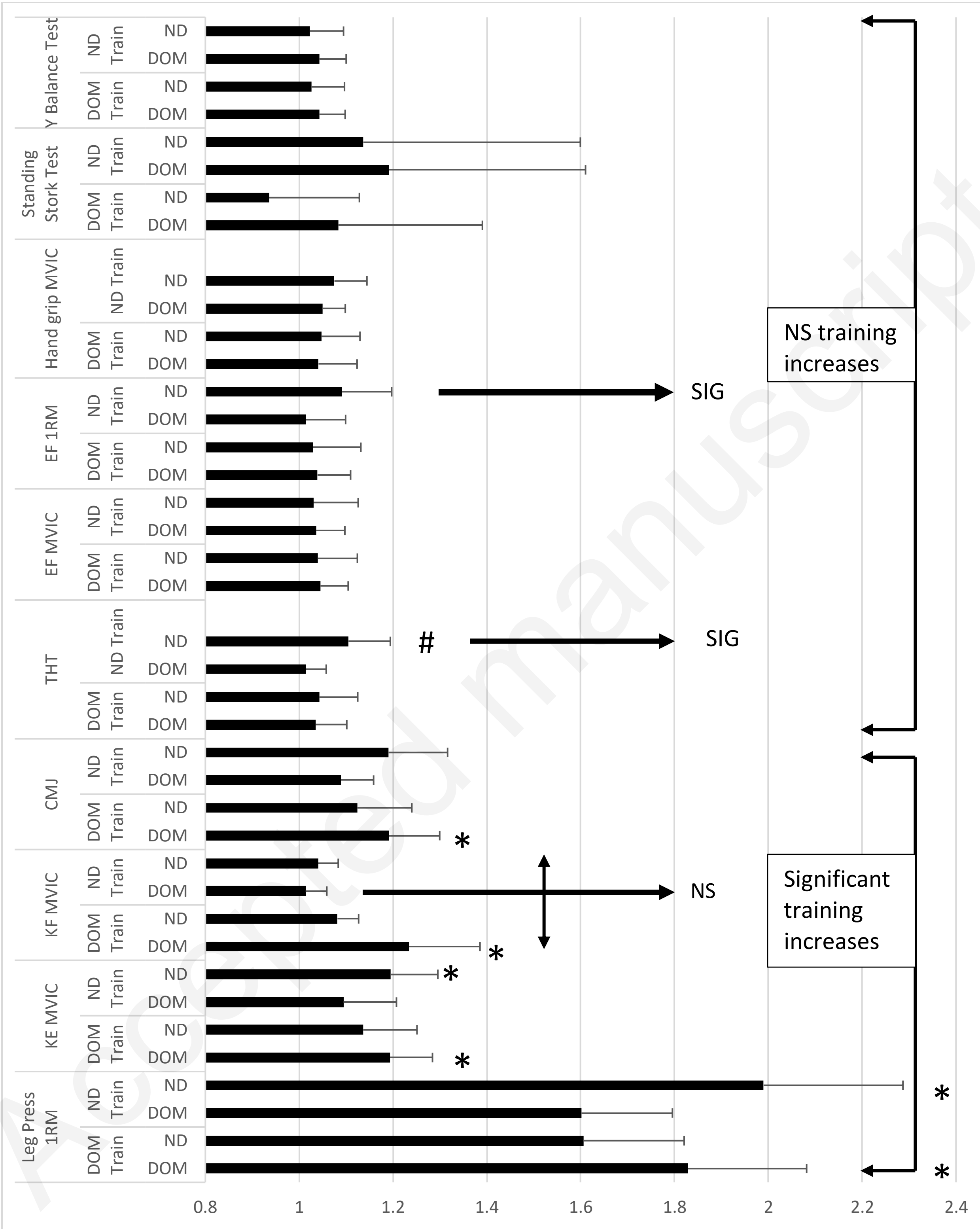
Table 5: Relative (two-way ANOVA: normalized to pre-test: post-training / pre-training) Main effects and interactions for trained leg and testing limb. 1-RM: 1 repetition maximum, EF: elbow flexors, MVIC: maximum voluntary isometric contraction. Arrow indicates the percentage change in values for the dominant versus non-dominant limb. Specific post-hoc interactions (Trained Leg Dominance x Testing Limb Dominance) are illustrated in Table 5. As there were no significant control group differences, this table reflects the experimental groups (dominant versus non-dominant training).

Relative Measures Normalized to pre-test	Main Effects for Trained Leg Arrow indicates change of dominant in relation to non-dominant limb	Main Effects for Testing Limb Arrow indicates change of dominant in relation to non-dominant limb	Interactions (Trained Leg Dominance x Testing Limb Dominance)
Lower Limb Strength Tests			
Leg-Press 1-RM	Non-significant	$F_{(1,13)} = 4.86$ $p=0.04$; 4.4%↓ $eta^2=0.272$ OP=0.532	$F_{(1,13)} = 53.59$ $p<0.0001$ $eta^2=0.805$ OP=1.00
Knee Extension (KE) MVIC	Non-significant	Non-significant	$F_{(1,13)} = 39.32$ $p<0.0001$ $eta^2=0.752$ OP=1.00
Knee Flexion (KF) MVIC	$F_{(1,13)} = 45.4$ $p<0.0001$; 11.4%↑ $eta^2=0.77$ OP=1.00	$F_{(1,13)} = 7.08$ $p=0.02$; 5.7%↑ $eta^2=0.353$ OP=0.692	$F_{(1,13)} = 16.92$ $p=0.001$ $eta^2=0.56$ OP=0.96
Power Tests			
Countermovement Jump (CMJ)	Non-significant	Non-significant	$F_{(1,13)} = 10.23$ $p=0.007$ $eta^2=0.44$ OP=0.84
Triple Hop Test (THT)	Non-significant	$F_{(1,13)} = 4.53$ $p=0.053$ 4.8%↓ $eta^2=0.259$ OP=0.505	$F_{(1,13)} = 7.82$ $p=0.015$ $eta^2=0.376$ OP=0.73
Upper Limb Strength Tests			
EF MVIC	Non-significant	Non-significant	Non-significant
EF 1-RM	Non-significant	Non-significant	Non-significant
Handgrip MVIC	Non-significant	Non-significant	Non-significant
Balance Tests			
Stork test	Non-significant	Non-significant	Non-significant

Y balance test	Non-significant	$F_{(1,13)} = 3.83$ p=0.03 1.9%↑ eta^2=0.31 OP=0.61	Non-significant

Figure 1: Relative (post-pre-training ratio) training responses.

A. All significant leg-press training responses occurred with the lower limb measures (cross-education) but generally no global training effects with the exception of significant training improvement with elbow flexors (EF) 1-RM: (non-dominant leg-press training and testing of non-dominant elbow flexors), THT (non-dominant leg-press training effects upon non-dominant THT) and lack of significant training improvements with knee flexors (KF) MVIC (non-dominant leg-press training effects upon dominant KF MVIC).
B. There were no significant dominant limb training predominance (no directionality of cross-education).
C. Asterisks (*) illustrate where ipsilateral training responses (i.e. dominant leg-press training effects upon dominant limb or non-dominant leg -press training effects upon non-dominant limb measures) were significantly greater than cross-education responses of the contralateral limb (i.e. dominant leg-press training effects upon non-dominant leg measures or non-dominant leg-press training effects upon dominant limb measure).
D. The hashtag (number sign: #) indicates that the triple hop test (THT) non-dominant ipsilateral training response (non-dominant leg-press training effects upon non-dominant THT) was significantly greater than the other three training THT responses.
E. The vertical arrow bar designates that it was only with knee flexion (KF) MVIC that the dominant leg-press trained limb significantly exceeded the non-dominant leg-press trained limb (cross-education dominant limb predominance).
F. As there were no significant changes with the control group, their data is not included in this figure.


Y Balance Test
Standing Stork Test
Hand grip MVIC
EF 1RM
EF MVIC
THT
CMJ
KF MVIC
KE MVIC
Leg Press 1RM
ND Train
DOM Train
ND
DOM
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
SIG
#
SIG
NS
*
NS training increases
Significant training increases