Effects of Plyometric and Resistance Training on Muscle Strength and Neuromuscular Function in Young Adolescent Soccer Players

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Abstract

This study examined the effect of 8-weeks of resistance (RT) and plyometric (PLYO) training on maximal strength, power and jump performance compared with no added training (CON), in young male soccer players. Forty-one 11-13 year-old soccer players were divided into three groups (RT, PLYO, CON). All participants completed 5 isometric knee extensions at 90° and 5 isokinetic knee extensions at 240°/s pre- and post-training. Peak torque (PT), peak rate of torque development (pRTD), electromechanical-day (EMD), rate of muscle activation (Q30), muscle cross-sectional area (mCSA) and jump performance were examined. Both RT and PLYO resulted in significant ($p < 0.05$) increases in PT, pRTD and jump performance. RT resulted in significantly greater increases in both isometric and isokinetic PT, while PLYO resulted in significantly greater increases in isometric pRTD and jump performance compared with CON ($p < 0.05$). Q30 increased to a greater extent in PLYO (20%) compared with RT (5%) and CON (-5%) ($p = 0.1$). In conclusion, 8-weeks of RT and PLYO resulted in significant improvements in muscle strength and jump performance. RT appears to be more effective at eliciting increases in maximal strength while PLYO appears to enhance explosive strength, mediated by possible increases in the rate of muscle activation.

(*Adolescents, Strength, Isokinetic, Isometric, Electromyography, Resistance training, Plyometrics*)

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List of Abbreviations:

CMJ: Counter-movement jump

CON: Control group

DJ: Drop Jump

EMD: Electromechanical Delay

EMG: Electromyography

EMGpk: Peak Amplitude of sEMG signal

iEMG: Integrated electromyography

ITT: Interpolated Twitch Technique

LBM: Lean Body Mass

mCSA: Muscle Cross-Sectional Area

MRI: Magnetic Resonance Imaging

MVC: Maximal Voluntary contraction

PaTV: Position at Target Velocity

PBF: Percent body fat

PLYO: Plyometric Training

pRTD: Peak Rate of Torque Development

PT: Peak Torque

ROR: Rate of rise

RT: Resistance Training

RTD: Rate of Torque Development

SEC: Series Elastic Component

sEMG: Surface electromyography

SJ: Squat Jump

ttTV: Time to Target Velocity

Appendices

1.0 Introduction:

Resistance and plyometric training have been widely used among adult athletes, but much less so in children. One of the main reasons that both resistance and plyometric training have not often been recommended for children is due to an assumption among coaches or parents, supported mainly in the lay media, that children are more susceptible to injury with these forms of training (Risser, 1991). Both resistance and plyometric training carry some degree of risk associated with musculoskeletal injury. However, this risk is no greater in children than in adults and is actually lower than any other organized sports that children typically participate in (Hamill et al. 1994).

The beneficial effects of resistance training on maximal strength, and sport performance in children is well documented (Falk, B and Tenenbaum,G. 1996; Behm et al. 2008, Lloyd et al. 2014, Faigenbaum et al. 2015). Conversely, the effects of this type of training on explosive strength remains unclear (Chaouachi et al. 2014; Waugh et al. 2014). Plyometric training has been shown to increase explosive performance (e.g., sprint performance, jump height) in children, (Diallo et al 2001; Kotzamanidis, 2006) but its effect compared with resistance training is unclear. Furthermore, the factors affecting explosive strength and the effects of resistance or plyometric training on these factors in children are also not known.

1.1 Definitions:

For the purpose of this document, the following definitions of resistance and plyometric training are used:

Resistance training (RT), a more traditional style of skeletal muscle training, refers to a specialized method of physical conditioning that involves the progressive use

of a wide range of resistive loads and a variety of training modalities designed to enhance or maintain muscular fitness (Faigenbaum et al. 2009). Traditional resistance training is mainly focused on increasing maximal strength, although other goals include muscle hypertrophy or muscle endurance.

Plyometric training (PLYO), a relatively new form of skeletal muscle training, involves activities that enable a muscle to reach high force in the shortest possible time (Baechle & Earle, 2008). Plyometric training, unlike resistance training, uses dynamic movements (jumps, skips and hops) which involve rapid eccentric muscle action that is immediately followed by a rapid concentric muscle action (Faigenbaum et al. 2009). This rapid stretching and shorting of the muscle (pre-stretch) results in enhanced force generation, compared with muscle action in the absence of a pre-stretch (Faigenbaum et al. 2009).

2.0 Literature Review:

There are numerous comprehensive reviews on the development and trainability of maximal strength in children (Falk and Tenenbaum, 1996; Faigenbaum et al.2009). Therefore, the literature review below is focused on explosive strength (or force), the factors that affect it and its trainability in children.

2.1 Explosive force in children:

Explosive muscular strength is arguably one of the most important components for children involved in competitive sports. One measurement used to examine explosive strength is the rate of torque development (RTD) (Aagaard et al. 2003; Lambertz et al., 2003). The RTD is calculated as the speed at which muscle torque develops over time (Δtorque/Δtime) (Aagaard, 2003). The RTD is essential in measuring one's ability to

produce rapid and forceful movements involving contraction times from ~ 50-250 ms; for example, sprinting, jumping, kicking etc. (Aagaard, 2003). In comparison, the time it takes to develop peak torque (PT) is much longer (300ms or more). Therefore, a high RTD would allow one to attain a greater percentage of their maximal strength during short, fast movements.

2.2 Factors affecting RTD:

Factors that affect RTD include muscle fibre composition, muscle and fibre size, musculotendinous stiffness (compliance), antagonist coactivation, and degree of motor-unit activation (motor-unit recruitment, motor-unit firing frequency) (Blimke, 1989). In addition to these physiological variables that influence the RTD, various methods of skeletal muscle training have also been shown to improve explosive power in adults (Aagaard et al. 2011;Aagaard et al 2002; Behrens et al. 2014). Like adults, children have also shown improvements in explosive power as a result of different forms of skeletal muscle training. However, the majority of the studies which examine explosive power in children utilize movements that are thought to *reflect* explosive power (Diallo et al 2001; Kotzamanidis, 2006), rather than direct measurement of rate of force or toque development. Measurements typically encompass actions involving rapid torque production such as jumping (e.g., counter-movement jump, squat-jump and depth-jump).

From the limited data that are available, the effects of RT on the RTD in children remain unclear. Most studies examined indirect measures of explosive power (e.g., jumping), rather than direct measurements of RTD. In a meta-analysis examining the effects of RT in children and adolescents, Harries et al. (2012) found that training programs ranging from 6- to 16-weeks improved performance-related variables thought

to be reflective of explosive power, such as maximal jump height and sprinting velocity. Only two studies examined the effects of RT directly on explosive strength. Chaouachi et al. (2014) found that 12-weeks of RT in children improved power production during maximal knee extension at a low velocity (60°/s), but not at a high velocity (300°/s). However, it is unclear how power was determined and no possible mechanisms were investigated. In another study, Waugh et al (2014) found that 10-weeks of resistance training resulted in enhanced tendon stiffness but no apparent change in the RTD in plantar flexors among prepubertal children. Thus, more research is needed to determine how RTD is affected by resistance training in children.

Much like RT, there are limited data on the effects of PLYO on RTD in children. Traditionally, improvements in explosive strength following PLYO have been examined using indirect measures of explosiveness, such as jump height, or linear running velocity. These and other performance-related measures of explosiveness were recently reviewed by Johnson et al. (2011), who concluded that PLYO programs ranging from 8-10 weeks elicited significant improvement in performance-related variables thought to be reflective of explosive power in children. To the author's knowledge, there is only one study that has directly examined this type of training intervention and its effects on RTD in children (Chaouachi et al 2014). The authors reported that PLYO was more likely to elicit greater dynamic power during higher velocity contractions than conventional RT. However, as mentioned above, this study did not investigate possible mechanisms for performance-related changes as a result of the PLYO intervention.

The following pages discuss factors which affect RTD and the influence of resistance and plyometric training on these factors in children.

2.2.1 Muscle composition:

Human skeletal muscle is composed of various fibre types which can be classified by their contractile properties or histochemically, by their myosin ATPase activity (Baechle and Earle, 2008). A muscle fibre that produces force slowly and has a slow relaxation time is known as slow-twitch (type I). Muscle fibres that produce force rapidly and have a short relaxation time are known as fast twitch (type II) (Baechle and Earle, 2008). Type I, or slow twitch muscle fibres, are resistant to fatigue and possess a high capacity for aerobic energy supply, however they have limited potential for rapid force or torque development due to lower ATPase activity (Baechle and Earle, 2008). Type II, or fast twitch muscle fibres, are characterized as fatigable, possessing low aerobic power. However, they have the potential to develop force or torque rapidly due to their high myosin ATPase activity (Baechle and Earle, 2008). It should be noted that type II muscle fibres can be subdivided into two distinct types, type IIa (fast twitch fatigue resistant) and type IIx (fast twitch fast fatigable) (Marieb and Hoehn, 2007).

Muscle composition is commonly analyzed directly using the percutaneous muscle biopsy technique (Bergstrom, 1985). Using this technique, Harridge et al. (1996) reported that, in adult males (29.9 ± 3.9 years), muscles with higher percentages of type IIa and type IIx muscle fibres (Triceps brachii) had a greater RTD than those muscles with predominantly slow twitch type I muscle fibres (Soleus).

Assessing muscle composition in children is difficult due to ethical constraints regarding the invasive nature of the percutaneous muscle biopsy technique. Therefore, indirect methods for assessing muscle fibre composition in children must be used. The evoked twitch technique has been shown to reflect contractile properties of the muscle

(reflecting fibre type), by assessing variables such as maximal twitch force, contraction time and half-relaxation time (Grossett et al, 2005; Murphy et al. 2014). Using this technique, contractile characteristics were found to be similar in children and adults (MacDougall et al., 1981; Davies 1985; McComas et al. 1973; Paasuke et al. 2000), suggesting that muscle fibre composition is similar in children and adults.

There are few muscle biopsy studies in children which are based on relatively small sample size and in which the sample is not always representative of a healthy, normally-developing population (e.g., children with various diseases, or autopsy studies). While some studies suggest similar muscle-fibre composition in children and adults (Brooke and Engel 1969, Bell, MacDougall et al. 1980, Vogler and Bove 1985), others support as much as 10% higher type-I muscle-fibre composition in prepubertal children (Lexell et al. 1992, Jansson 1996). It is not clear to what extent such a potential muscle fibre composition difference would affect RTD.

Traditional resistance training (8-24 weeks) does not appear to influence muscle composition in adults (Hakkinen et al. 1985; Aagaard et al. 2002; Aagaard et al. 2011). Similarly, plyometric training, does not appear to demonstrate evidence of muscle fibre composition shift (Kyrolainen et al. 2005). Therefore, based on these studies in adults, any increase in the RTD from pre- to post-training intervention, appears to be influenced by factors other than changes in muscle fibre type distribution. No such studies have been performed in children.

2.2.2 Muscle and fibre size:

As muscles increase in size, they are able to produce a greater maximal force (Andersen and Aagaard 2005). In adults, there is a relationship between maximal

voluntary strength increases (MVC), and the rate at which torque is developed (Andersen and Aagaard 2006; Bell et al. 1989; Paasuke et al 2001; Hakkinen et al 1985). The increase in maximal strength is a result of both an increase in the number of contractile proteins (actin and myosin) within the myofibril and an increase in the number of myofibrils within a muscle fibre, or better known as muscle hypertrophy (MacDougall et al. 1979).

Muscle size can be assessed by examining its cross-sectional area (mCSA) using various techniques (computed axial tomography, anthropometry, magnetic resonance imaging, and ultrasonographic imaging). Studies examining mCSA have done so by comparing whole muscle size (Kanehisa et al. 1994; Kanehisa et al. 1995; Hakkinen et al. 1998) and fibre size according to type (Hakkinen et al. 1985; Harridge et al. 1996).

Traditional resistance training has consistently shown to increase muscle and fibre size (hypertrophy) in adults (Farup et al. 2014; Aagaard et al. 2011; Luthi et al. 1986). These increases in size have been accompanied by marked increases in maximal voluntary contractile strength (Farup, et al, 2014; Aagaard et al. 2011; Luthi et al. 1986). Studies examining the effects of resistance training on muscle size in children are limited. However, from the data that are available, it appears that children respond differently to resistance training than their adult counterparts. Unlike adults, resistance training in children does not appear to result in an increase in muscle size. To the author's knowledge, only two studies have demonstrated an increase in mCSA following 10-12 weeks of resistance training in children (Fukunaga et al. 1992; Mersch and Stoboy 1989). However, it should be noted that these studies are limited in terms of sample size (e.g., n=2, Mersch and Stoboy 1989) and consistency of findings among the different muscle

groups (Fukunaga et al.1992). The majority of information on children and resistance training shows that children enhance maximal strength in the absence of muscle hypertrophy (Blimke, 1992; Granacher et al. 2011). Thus, in children, a possible increase in RTD following resistance training is likely not accompanied by an increase in muscle size. The one study which reported enhanced power, presumably reflecting RTD, following resistance training, did not examine changes in muscle size (Chaouachi et al. 2014).

The relationship between resistance training-induced muscle hypertrophy and RTD is inconsistent. Some studies in adults have found an improvement in RTD, concurrent with an increase in muscle size and maximal strength in the late stages of force development (Aagaard et al 2002). However, others found an increase in RTD in the absence of muscle or fibre hypertrophy (Van Cutsem et al. 1998; Moritani and DeVries. 1979). In children, studies which examined resistance training-induced changes in muscle size, did not examine changes in RTD (Fukunaga et al. 1992; Mersch and Stoboy,1989; Granacher et al. 2011), and vice versa (Chaouachi et al. 2014).

There are few studies examining the effect of PLYO on muscle hypertrophy in adults. Kubo et al. (2007), using MRI technique of assessing whole muscle size, found that 10-weeks of PLYO induced a 5% increase in plantar flexor muscle size. Furthermore, a study by Malisoux et al. (2005) found significant increases in cross-sectional area of fast twitch muscle fibres (+20-30%) following 10 weeks of PLYO. In contrast with these findings, Kyrolainen et al. (2005) observed no changes in a fibre cross-sectional area of gastrocnemius muscle following 15-weeks of plyometric training. In children, Diallo et al (2001) reported that boys aged 12-14 years, displayed a +1.5%

increase in leg volume, estimated by anthropometry following plyometric training. However, it should be noted that the control group showed similar increases in leg volume (+1.4%). Therefore, it is likely that growth-related factors were the cause of the observed increases in muscle size. In both children and adults, plyometric training has consistently resulted in an enhancement in indirect measures of explosive strength (Diallo et al 2001; Kotzamanidis, 2006; Behrens et al. 2014). However, the relatively small change in muscle size does not appear to be the main source of influence (Kubo et al. 2007; Malisoux et al.2005; Kyrolainen et al. 2005; Diallo et al. 2001).

2.2.3 Musculotendinous stiffness (compliance):

The muscle tendon is the direct line of force transmission between the muscle and bone. Therefore, changes in the muscle tendon stiffness can influence the rate of torque production by increasing or decreasing the time between initial muscle contraction and the onset of force production. The lag time between muscle activation and the onset of torque is known as electromechanical delay (EMD), which reflects both electro-chemical processes such as synaptic transmission, propagation of the action potential, and excitation-contraction coupling, as well as mechanical processes such as force transmission along the active and the passive part of the muscle and tendon (Cavanagh and Komi 1979). Studies that have examined the relationship between tendon stiffness and EMD in children and adults have shown that as tendon stiffness increases, EMD decreases (Waugh et al 2012; Waugh et al.2013; O'Brien et al. 2010; Bojsen-Moller et al. 2005). Likewise, there is an inverse relationship between EMD and RTD. These relationships have been demonstrated in both children and adults (Waugh et al 2012; Waugh et al.2013; Bojsen-Moller et al. 2005).

Information regarding how the muscle tendon responds to resistance training is limited. Kubo et al (2001) found that 12-weeks of isometric resistance training in adults increased stiffness in tendon structures of the vastus lateralis by +7.6%, and enhanced RTD by +35%. Even greater increases were demonstrated in patellar tendon (+24%) and in Achilles tendon stiffness (+61.6%) after 9-weeks and 6-weeks of traditional resistance training (Seynnes et al. 2009 and Burgess et al 2007, respectively). In addition to these findings, Burgess et al. (2007) reported an enhancement in plantar flexors RTD by +16.7% following resistance training. All of these studies were carried out with adult men. To the author's knowledge, only one study examined the effect of resistance training on muscle tendon stiffness in children. In this study, Waugh and coworkers (2014) found that children (8.9±0.3 yrs) increased their Achilles tendon stiffness (+29%) after completing a 10-week traditional resistance training intervention. This increase was accompanied by a 13% reduction in EMD. However, the RFD did not significantly increase.

It is unclear what type of influence plyometric training has on musculotendinous stiffness. Foure et al. (2009) found that in adult men, plyometric training resulted in no change of the Achilles tendon stiffness following an 8-week plyometric training intervention. However, there were significant improvements in jump performance (squat-jumps and reactive jumps), suggesting an enhanced explosive strength. Conversely, Burgess et al. (2007) found a +29.4% increase in Achilles tendon stiffness in adult men following a 6-week plyometric training intervention, which was accompanied by an enhancement (+18.9%) in the RTD of plantar flexors. Compared with the effects of traditional resistance training (as mentioned above), the increase in Achilles tendon

stiffness was smaller (61% vs. 29%), while the increase in RTD was similar (17% vs. 19%) after plyometric training. There are no studies to the author's knowledge on the effect of plyometric training on tendon stiffness in children. In view of the disparity between training-induced changes in stiffness and RTD, it is not clear whether there are other training-induced factors that affect RTD and whether these factors are similar in children and in adults.

2.2.4 Antagonist coactivation:

When performing a rapid movement such as a soccer kick, which requires the individual to produce force as fast as possible, the agonist muscles (quadriceps) are required to contract quickly. The rapid knee extension results in stretching the opposing muscle group (hamstrings). This stretch is detected by proprioceptors in the hamstrings (muscle spindles) which results in the simultaneous activation of motor units within this muscle (Baechle & Earle 2008). This simultaneous activation of the antagonist muscles detracts from the total amount of force the agonist muscle group is producing, ultimately decreasing the torque and RTD. Some studies have reported a greater antagonist coactivation in children during both isometric and dynamic movements (Grosset et al. 2008; Lambertz et al. 2003; Frost et al. 1997), however others have not (Kellis and Unnithan B. 1999; Falk et al. 2009).

The effect of RT on antagonist coactivation has been examined in adults. Hakkinen et al. (1998) found that maximal isometric knee extension antagonist coactivation remained unchanged in adult middle-aged men after 6-months of resistance training. It should be noted that an increase in RTD by +41% was observed in this group at the end of the training period. Similarly, Aagaard et al. (2002) found that in adults, 14-

weeks of RT resulted in no change in antagonist coactivation during maximal isometric knee extension. Again, RTD was found to increase after training (+15%). On the other hand, Tillin et al. (2011) found 4-weeks of isometric RT resulted in a reduction in antagonist coactivation during knee extension in adult males, along with an increase in explosive force, specifically early in the contraction (1^{st} 50 ms). To the author's knowledge there are no studies that have examined resistance training and its effect on antagonist coactivation in children.

Plyometric training effects on antagonist coactivation have also been examined in adults. Kyrolainen et al. (2005) found that 15-weeks of explosive plyometric training resulted in enhanced RTD (+35%), along with a reduction of antagonist coactivation of the quadriceps during maximal isometric knee extension. However, this reduction did not reach a level of statistical significance. In addition, Kubo et al. (2007) found that 12-weeks of explosive plyometric training in young adult males resulted in no change in antagonist coactivation during isometric plantar flexion, but increases in jump height. These authors concluded that the increase in jump height (and presumably RTD), were not a result of decreases in antagonist activation. No studies have examined plyometric training and its effect on antagonist coactivation in children.

It would appear from the studies mentioned above that both plyometric and resistance training have a limited effect on antagonist coactivation. However, in most of these studies, coactivation was examined during isometric contractions, in which coactivation is minimal. Thus, it is difficult to draw conclusions regarding their influence on the RTD in dynamic contractions. Further research is needed to determine how training influences coactivation during dynamic contractions, particularly in children.

2.2.5 Motor-unit activation:

The motor-unit (MU) is composed of a motor-neuron and all the muscle fibres that it innervates (Baechle and Earle, 2008). All the muscle fibres of that motor-unit contract together when they are stimulated by the motor-neuron (Baechle and Earle, 2008). The degree to which motor-units are activated is arguably one of the most important factors in voluntary force development (Belanger and McComas, 1981). Motor-unit activation is contingent upon the number and types of motor-units being recruited (type I vs. type II), and the level of activation of the motor-units (firing frequency/rate coding) (Blimke, 1989). By increasing or optimizing muscle activation one is able to increase the RTD (Aagaard et al., 2002; Van Custem et al., 1998).

The degree of motor-unit activation can be assessed using various methods. One way is the interpolated twitch technique (ITT) (Belanger and McComas, 1981) which reflects motor unit activation at maximal voluntary contraction. To perform this technique, a supra-maximal stimulation (electrical or magnetic) is applied during a maximal voluntary isometric contraction (MVC). Any detectable increase in force output above and beyond what has been produced voluntarily, provides a measure of the degree of voluntary muscle activation (Belanger and McComas, 1981; Behm et al. 1996). Another less invasive way of assessing or comparing the degree of muscle activation is to examine the change in muscle activity using surface electromyography (sEMG). sEMG samples muscle activity from the skin via surface electrodes. The amplitude and pattern of the sEMG signal have been used to reflect motor unit activation (Aagaard et al., 2002; Van Custem et al., 1998).

There is evidence to suggest that children are not able to activate their motor units to the same extent as adults (Belanger and McComas, 1989; Blimkie, 1989; O'Brien et al. 2010; Ramsay et al. 1990; Grossett et al 2008). Using the ITT, Belanger and McComas (1989) compared children's and adults' ability to fully activate their plantar flexors. Belanger and McComas found that children activated their plantar flexors to a lesser degree (94%) compared to adults (99.4%). This study is often cited to demonstrate age-related differences in motor unit activation, although this difference was not statistically significant. Later studies, however, have demonstrated lower motor unit activation in children compared with adults. For example, Blimkie and coworkers (1989) reported a child muscle activation deficit in knee extensors (77.7%) compared to adults (95.3%). Likewise, O'Brien et al. (2010), using magnetic stimulation, demonstrated lower motor unit activation in boys and girls (68-75%) during knee extension compared with men and women (87%). Using surface-electromyography, Falk et al (2009) found that boys' integrated-EMG (iEMG) in the initial 30ms (Q30) of elbow flexion, reflecting the initial rise in motor unit activation, was significantly lower, compared to men's iEMG. It is possible that, due to an immature neuromuscular system, children are less able to fully activate their muscles under maximal conditions. It is not clear whether training can affect the rate of, or extent of motor unit activation in children.

Resistance training and its effect on the rate of motor-unit activation has been examined in adults. Aagaard et al. (2002), using sEMG, found that a 14-week resistance training intervention in adult males resulted in an enhancement of rate of EMG rise (RER) during isometric knee extension by +50-106%, depending on which quadriceps muscle was analyzed. The increase in RTD, however, was only +15% at the onset of

contraction (~30ms). A more recent study by Tillin et al (2012) also using sEMG, found 4-weeks of isometric strength training in young adult males, enhanced sEMG amplitude by +42% in the early phase the contraction (0-50ms). RTD also increased during this early phase, and this increase was carried over to subsequent phases (50ms, 100ms and 150ms) (RTD values not reported).

The examination of resistance training and its effect on motor-unit activation in children is limited. Ozmun and coworkers (1994) found that 10-weeks of isotonic strength training in children resulted in +27.8% increase in maximal isokinetric strength at 90°/s, an increase in iEMG by +16.8% and no evidence of muscle hypertrophy. In addition, Ramsay et al. (1990) found that 20-weeks of resistance training in young boys (9-11yrs) resulted in small increases (+13.2-17.8%) that did not reach statistical significance in motor-unit activation using the ITT. It is possible that this study was under-powered due to its small sample-size. Conversely, Waugh et al. (2014) found that 10-weeks of lower-body resistance training resulted in boys (8.9 ± 0.3 yrs) showing no significant increases in the rate of sEMG increase. Likewise, it should also be noted that there was no significant increases in RTD.

There are limited studies, all in adults, examining PLYO and its effect on motor-unit activation. Kyrolainen and coworkers (2005) examined the effect of 15-weeks of PLYO in young adult males. After 10-weeks of training, the authors reported a 74% increase in bilateral isometric knee extension RTD, which was accompanied by an increase in average-EMG (aEMG) amplitude from 317±179mV to 406±242mV. However, the latter change did not reach statistical significance. At 15-weeks of training, RTD values remained unchanged and aEMG values dropped to 374±185mV (ns). The

authors suggested that at this point participants may have reached their limit for improving neuromuscular performance. Kubo and coworkers (2007) found a +5.6% increase in the degree of activation of plantar flexors following 12 weeks of PLYO , which was accompanied by a +17.3% increase in MVC. Performance-related tests (counter-movement jump, squat jump and depth jump) significantly increased post-intervention. In children, studies that have examined the effects of plyometric training did not examine muscle activity directly. Nevertheless, in the absence of muscle hypertrophy, these studies suggested that neural adaptations are the main cause for enhanced strength and torque development (Thomas et al. 2013; Michailidis et al. 2013). More research is needed to determine how motor-unit activation is affected by plyometric training in children.

2.3 Contraction type:

The majority of the existing literature examining changes in rapid force production as a result of plyometric or resistance training used maximal isometric contractions (Aagaard et al 2002; Behrens et al. 2014; Hakkinen et al 1985;Tillin et al. 2012;Kyrolainen et al. 2005). The reasoning behind using these types of contractions is the low antagonist coactivation, thus focusing on other factors that could potentially influence the RTD. This is especially true in children as they characteristically have a higher antagonist coactivation compared to their adult counterparts (Grosset et al. 2008). However, if the goal of the study is to examine the effect of training on factors influencing RTD, then assessing isometric contractions may not be sufficiently specific to the training. Isokinetic movements offer a controlled, dynamic and a more realistic movement which, although not identical to the training exercises, resembles them to a

greater extent (compared with isometric contractions). Therefore, further studies should strive to incorporate this dynamic contraction mode to potentially determine how training type (plyometric or resistance) affects factors which influence RTD.

3.0 Statement of Problem/Purpose:

The purpose of this study was to examine the effect of 8-weeks of a plyometric or resistance training program, compared with no added training on muscle strength and rate of toque development, neuromuscular function during maximal isometric and isokinetic knee extension, as well as jump performance, in young male soccer players.

3.1 Hypothesis:

It was hypothesized that training (resistance and plyometric) will result in greater improvements in PT, RTD, neuromuscular function (EMD, iEMG), and jump performance compared with the control group. It was also hypothesized that these improvements, with the exception of PT, will be greater in the PLYO, compared with the RT group.

4.0 Methods:

4.1 Design:

The study utilized an intervention design to examine the effect of 8-weeks of training (resistance and plyometric) on muscle strength, neuromuscular function and jump performance compared with no added training, in young male soccer players.

4.1.2 Participants:

Fifty-Four 11-13 year-old soccer players were divided into three groups: RT (n = 18), PLYO (n = 18) and CON (n = 18), matched for age, body size, Y-PHV, and isometric muscle strength. All participants were high level competitive soccer players. Their training and competition often involve tasks which require maximal effort. Therefore, all participants prior to their participation in the study and assessment of muscle function had already be familiarized with a form of maximal exertion and maximal contractions.

4.1.3 Inclusion Criteria:

1. Adolescent male soccer players (11-13 yrs)
2. Train 3x/wk
3. No prior or current structured training in RT or PLYO

4.1.4 Exclusion Criteria:

1. Any risk factors and past or present muscular disease
2. Chronic/frequent use of medications that could affect neuromuscular function currently or during the preceding year.
3. Muscular or skeletal injury e.g. fractures, sprains or strains, or any injury/illness that could affect participant maximal force production

4.2 Procedure:

All tests and measurements were performed during two visits (before and after the 8-week intervention) at the Applied Physiology Laboratory at Brock University. During Visit 1, participants were informed of all tests and procedures that took place, they signed an informed consent or assent form, and were familiarized with all testing procedures. Each visit took 90 min in duration. See Measurements section for details.

4.2.1 Eight-Week Intervention Component:

All participants took part in either an 8-week training intervention (3 sessions/week) or no added training, held within BP Sports Park (CAT Soccer Field) in Welland, Ontario. Both interventions (RT and PLYO) were administered at the beginning of the regular soccer practice session after a standardized dynamic warm-up (Appendix I).

Participants completed the following activities:

Plyometric Training Intervention:

Each session consisted of a15 min dynamic warm-up followed by 30 min of plyometric training exercises. Plyometric exercises included: jumps, hops and bounds of varying volumes and intensities (Table 1.). The plyometric training protocol was structured in a manner which allowed participants to safely progress through the various exercises, as per NSCA guidelines (Lloyd et al. 2011). The training load was progressively increased by manipulating the volume, complexity of the exercises or jump height (Table 1.). Prior to each training session, participants were shown how to safely conduct all exercises in a controlled and safe manner.

Resistance Training Intervention:

Each session consisted of a 15 min dynamic warm-up followed by 30 min of on field resistance training exercises. Resistance exercises included lunges, squats and other resistance techniques, at varying volumes and intensities (Table 1.). The training load was progressively increased by manipulating the volume, weight, or complexity of the exercise (Table 1.). The resistance training protocol was structured in a manner which allowed participants to safely progress through the various exercises as per NSCA guidelines (Faigenbaum et al. 2009). Prior to each training session, participants were shown how to safely conduct various exercises in a controlled and safe manner.

Table 1- Training program volume (sets and repetitions)

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
RT								
Squats	3 set/ 12	3 set/ 12*	3 set/ 12	3 set/ 12*	3 set/ 12	3 set/ 12*	3 set/ 12	3 set/ 12*
Lunges	3 set/ 12	3 set/ 12						
Step-ups	3 set/ 12	3 set/ 12*	3 set/ 12*	3 set/ 12	3 set/ 12*	3 set/ 12		
Calf-raises	3 set/ 12	3 set/ 12*					3 set/ 12*	3 set/ 12
Sumo-Squats			3 set/ 12	3 set/ 12*	3 set/ 12	3 set/ 12*	3 set/ 12	3 set/ 12*
Bulgarian split-squat			3 set/ 12	3 set/ 12*	3 set/ 12	3 set/ 12*	3 set/ 12	3 set/ 12*
One leg sit-to-stand			3 set/ 12	3 set/ 12				
One leg squat					3 set/ 12	3 set/ 12*	3 set/ 12	3 set/ 12*
PLYO								
CMJ	3 set/ 12	3 set/ 12						
Jump tuck	3 set/ 12	3 set/ 12						
Drop jump	3 set/ 12	3 set/ 12	3 set/ 12 †	3 set/ 12	3 set/ 12 †	3 set/ 12	3 set/ 12 †	3 set/ 12
Repeated long jump	3 set/ 3x5	3 set/ 3x5						
Jump lunge			3 set/ 12	3 set/ 12	3 set/ 12	3 set/ 12	3 set/ 12	3 set/ 12
Jump pike			3 set/ 12	3 set/ 12				
Skater hops			3 set/ 12	3 set/ 12				
High-knee skip			3 set/ 12	3 set/ 12	3 set/ 12	3 set/ 12		
Triple jump					3 set/ 12	3 set/ 12		
One-leg counter movement jump					3 set/ 12	3 set/ 12	3 set/ 12	3 set/ 12
One-leg jump tuck							3 set/ 12	3 set/ 12
One-leg repeated long jump							3 set/ 12	3 set/ 12

* = Increase in weight from previous session

† = Increase in box height from previous session

4.3 Measurements:

4.3.1 Questionnaires:

Participant Screening and Medical History Questionnaire:

This questionnaire was completed during visit 1 only. This questionnaire provided medical background in order to ensure that participants were free of known injury and able to meet the demands of the training intervention and the testing (Appendix E).

The following questionnaires and measurements were assessed before and after the 8-week intervention period:

Leisure time Physical Activity Questionnaire:

The Godin Shephard Leisure Time Exercise Questionnaire (Godin & Shephard 1985): Every participant was asked to complete a self-explanatory, brief four-item query of usual leisure-time exercise habits over the past 7 days (Appendix F).

Training history:

Past and present training history was determined by a questionnaire and personal interview (Appendix G).

Pubertal Stage:

Pubertal stage was determined in accordance with secondary sex characteristics (pubic hair), as described by Tanner (1962). For this assessment, participants were asked to look at drawings of male pubic hair and check the drawing which most resembles their current stage of development on a sheet of paper (Appendix H). This was carried out in a private room to avoid any uneasiness on part of the participants.

4.4 Anthropometrics and Body composition:

Height was measured to the nearest 0.1cm using a stadiometer (Ellard Instrumentation Ltd). Weight was measured to the nearest 0.1kg using a digital scale (InBody520, Biospace CO. Ltd.). Participants removed their shoes and any excessive clothing that may significantly affect their weight.

Percent body fat was estimated using bioelectrical impedance analysis (BIA), which has previously been validated in children and adolescents (Kriemler et al. 2009). The BIA assessment required the participant to stand on a scale and grasp handles in which surface electrodes are embedded. A mild electrical current (50kHz, 800 μA) was passed through the participant's hands to their feet. This current cannot be felt and causes no harm.

All anthropometric measurements were performed by the same investigator, in order to eliminate inter-observer variability ($ICC_{(3,1)} = 1.0$, n = 10).

4.4.1 Muscle Size:

Muscle thickness (depth) was measured using real-time B-mode ultrasound (System5, GE Vingmed, Horten, Norway) with 5 MHz linear-array probe, obtaining transverse images of the vastus lateralis at rest. The scanning head of the probe was oriented along the mid-transverse axis of the muscle. All images were analyzed off-line in duplicate. Muscle thickness was measured as the distance between the adipose tissue-muscle interface. All ultrasound measurements were performed by the same investigator, in order to eliminate inter-observer variability (muscle diameter ($ICC_{(3, 1)} = 0.98$, n = 10). This measure was used for the estimation of vastus lateralis CSA: $mCSA = \pi*(\text{Muscle thickness}/2)^2$

4.4.2 Muscle Strength (Isometric and Isokinetic Testing):

All isometric and isokinetic strength measurements were performed on the Biodex System III isokinetic dynamometer (Biodex, Shirley, NY) on the right leg for consistency. The participants were seated in the chair and stabilized using an ankle Velcro strap, a strap across the hips, and two diagonal shoulder straps, which cross the chest in X fashion. The lever arm was then adjusted to a comfortable length for knee extension and knee flexion trials. The ankle support pad on the lever arm was adjusted to three centimeters superior to the most proximal point of the lateral malleolus. The axis of rotation of the lever arm was set by lining the centre of rotation with the lateral condyle of the femur. The knee was then placed in the starting position which was approximately 90° (180° = full extension).

Once the participant was seated in the chair and properly secured, they underwent a warm-up/familiarization protocol. Warm-up/familiarization trials consisted of 3 submaximal isokinetic contractions at slower velocity (180°/s), followed by 2 maximal isokinetic contractions at the testing velocity (240°/s) during both knee extension and flexion. If the participant did not feel comfortable with the set-up and isokinetic contractions at the end of the warm-up sets, additional trials were added. After the isokinetic familiarization had been completed the participant began familiarization of the isometric contractions. Warm-up/familiarization trials for the isometric contractions consisted of 3 submaximal isometric contractions followed by 2 maximal (MVC) trials at both 90 and 130° during both knee flexion and extension. If the participant did not feel comfortable with the set-up or isometric contractions at the end of the warm-up sets, additional trials were added.

After the familiarization trials, participants underwent the testing protocol which consisted of five, three second, maximal isometric knee extensions followed by five, three-second maximal isometric knee flexions, or vice versa. Contractions were separated by a minimum of 30 seconds of rest after each isometric repetition and 5 min rest between sets. Five maximal contractions were performed at a knee angle of 90° and five maximal contractions were be performed at a knee angle of 130°, in random order. Additionally, participants performed five maximal isokinetic contractions of the knee extensors and flexors at 240º/s. The order of agonist muscle contractions was also counterbalanced to completely eliminate any ordering effects. The same order of testing was used pre- and post-intervention.

Prior to each contraction, participants were verbally instructed to "kick out as fast and then as hard as possible" from a completely relaxed state. Verbal encouragement was provided, along with visual feedback displayed on the Biodex monitor. During each contraction, force and EMG signals were recorded (see below). Additional repetitions were added when contractions were deemed unfit due to reasons such as execution errors, large undulations in baseline EMG activity and abnormalities in torque and EMG traces.

4.4.3 Electromyography (EMG):

Electrode placement:

Muscle activity was recorded from the vastus lateralis muscle during all contractions using a bipolar surface electrode configuration (Delsys 2,1,Delsys Inc., Boston, MA). In preparation for electrode placement, the skin sites were cleaned with isopropyl alcohol and abrasive skin preparation gel (Nuprep, Weaver and Company, Aurora, CO, USA) to ensure all impurities that could potentially interfeasdfare with

signal transmission were removed. The electrodes were then placed parallel to the direction of the muscle fibres on the muscle belly. Exact placement was determined by manual palpation and visual inspection during a resisted isometric contraction using the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM) group recommendations for the vastus lateralis muscle (Appendix J). A reference/ground electrode was placed over the most prominent cervical vertebrae (C-7). Double-sided tape was used to secure the electrodes to the skin of the participant.

4.4.4 EMG and Torque data Acquisition:

EMG signals were band-passed filtered (20-450 Hz) using the Bagnoli-4 boamplifier (Delsys Inc., Boston,MA). All position and torque signals from the Biodex were sent to a 16-bit A/D converter (BNC-2110,National Instruments) and sampled at a rate of 1000 Hz using a Computer Based Oscillograph and Data Acquisition System (EMGworks). Recorded data were then stored for further analysis.

4.5 Analysis of Trials:

A one-way ANOVA was performed to determine if there was any statistical difference between the 5-contractions within each contraction mode (isometric KE 90°,130° and isokinetic KE 240°/s). All groups, showed statistically significant differences within each set of contraction modes. Therefore in the present study a selection of best trials was performed and used for further analysis

4.6 Selection of best trials:

All trials for both KE at both 90° and 130°, as well as isokinetic trials, were ranked according to their peak torque (PT) and peak rate of torque development (pRTD).

Both variables, PT and pRTD, were expressed as a percentage of the maximal value in the set of 5 trials. For each trial, the product of the percentage value of PT and pRTD was calculated to provide a composite score for that trial. After the composite score was calculated, trials were assigned a ranking from 1-5. The two trials with the highest composite score (ranked 1 and 2) were used for further analysis, provided the PT and pRTD were above 80% of their maximum value. Averages of all dependent variables of the two trials were calculated and used for further analysis.

4.7 Muscle Force and Electromyography (EMG) Variables & Data Reduction:

Both EMG and torque signal data were analyzed using Matlab (The MathWorks, Natick, MA).

4.8 Muscle Force Variables:

4.8.1 Peak Torque (PT):

PT was defined as the peak torque developed about a joint during a MVC (Blimke, 1989).Values were recorded from the dynamometer's torque signal and are presented in absolute values (Nm), and corrected for mCSA as a covariate. Torque kinetics were also examined by calculating the time to various percentages of PT (10-100%).

4.8.2 Position at Target Velocity and Time to Target Velocity:

In the isokinetic contractions the position at target velocity was defined as the angle (80°-150°) at which maximal isokinetic knee extension velocity (240°/s) was reached.

The time to target velocity was defined as the time from the beginning of the movement to the time that maximal isokinetic knee extension velocity (240°/s) was reached.

4.8.3 Rate of Torque Development (RTD):

RTD was defined as the speed at which torque develops over time (Δtorque/Δtime) (Aagaard, 2003) and peak RTD was determined from the first derivative of the torque trace. Values are represented in absolute terms ($Nm \cdot s^{-1}$) and corrected for PT as a covariate. RTD was also examined at various time intervals (0-50, 50-100, 100-150, 150-200, and 200-250 ms).

4.9 Electromyography (EMG) Variables:

All EMG variables were analyzed from the rectified linear envelope, which was filtered offline between 20 – 450 Hz using a high-pass Butterworth filter.

4.9.1 Electromechanical Delay (EMD):

EMD was calculated as the time difference between the onset of muscle activation and the onset of torque production (Bojsen-Moller et al. 2005; Nakagawa et al. 1996; Waugh et al. 2013). For determination of EMD, the onset of muscle activity was defined as the point at which the EMG signal is two standard deviations greater than the average amplitude of the initial 500ms of baseline activity for a consecutive duration of 100ms. The onset of torque was determined by first averaging -750 to 250ms of baseline to avoid possible torque perturbations. A reference torque level was then defined (10Nm) to avoid any baseline noise. The torque signal was then followed backwards in time until it reached the first value equal to or greater than the baseline mean.

4.9.2 Rate of muscle activation (Q30):

The rate of muscle activation was defined as the area under the rectified linear envelope of the detected sEMG signal (Konrad, 2006).The rate of muscle activation was examined in the initial 30ms (Q-30).

5.0 Performance Testing:

All participants were assessed for functional explosive leg power during a maximal counter-movement vertical jump (CMJ), squat jump (SJ) and drop jump (DJ) using the Optojump photoelectric system. The Optojump photoelectric system (Microgate, Bolzano, Italy) consists of 2 parallel bars (one receiver and one transmitter unit) that are positioned on the floor. These bars are equipped and communicate with optical infrared sensors which sample at a frequency of 1000 Hz (Microgate, Bolzano, Italy). When the communication between the 2 bars is disrupted i.e. a participant breaking the beam, a timer is activated until the disruption is removed. This can also work in reverse to detect status change i.e. timer will not begin until participant jumps and beam is mended (Microgate, Bolzano, Italy). All participants performed each jump previously listed above 3 times maximally, separated by 1-minute of rest between each trial. The best trial, defined as the maximal height achieved per a given jump, was used for analysis. The Optojump system has been shown to be both valid and reliable method to analyze vertical jump height (Glatthorn et al. 2011). Jump height was automatically calculated using a flight time algorithm i.e. Jump Height = 9.81 * (flight time) ^ 2 / 2

5.1 Counter-Movement Vertical Jump (CMJ):

The CMJ is performed when the participant starts in an upright erect position and makes a downward movement (pre-stretch) before starting to push-off (Bobbert et al, 1996). All participants were familiarized with the CMJ. Once both the participant and the investigator were confident that the movement was being performed correctly, the testing proceeded. Participants were instructed to "jump as high as they possibly could as if they were trying to try and touch the ceiling".

5.2 Squat Jump (SJ):

The SJ is performed when the participant begins in a semi-squat position, no countermovement is made before push-off (Bobbert et al, 1996). All participants were familiarized with the SJ. Once both the participant and the investigator were confident that the movement was being performed correctly, the testing proceeded. Participants were instructed to "jump as high as they possibly could as if they were trying to try and touch their head ceiling".

5.3 Drop Jump (DJ):

The Drop jump is performed when the participant begins on a raised platform (20cm). When instructed to do so, the participant jumps forward off the platform, and upon landing, performs a maximal jump (Bobbert et al. 1987). All participants were familiarized with the DJ. Once both the participant and the investigator were confident that the movement was being performed correctly, the testing proceeded. Participants were instructed to "drop off the step and quickly as fast as you can jump straight up and try to touch the ceiling".

6.0 Statistical analysis:

All statistical analyses were performed using SPSS v.20 (SPSS Inc., Chicago, IL). The data for all groups are presented as mean (M) ± 1 standard deviation (SD). An average value of the best two contractions for each action and participant was included in the statistical analyses. Group differences in muscle performance and neuromuscular function at baseline were assessed using a one-way ANOVA. The effect of the intervention was determined using a RM-ANOVA, with one within-subject main-effect (Pre/Post) and one between-subject main effect (Group). When a significant Group-by-Pre/Post interaction was observed, univariate Gain Scores were calculated, and a Bonferroni pairwise comparison was used to determine the between group differences. The effect of the intervention on torque and RTD kinetics was examined using a three-way ANOVA for repeated measures, with one between-subject main effect (group) and two within-subject main effect (Pre/Post and time). The acceptable level of significance was set at $p < 0.05$.

7.0 Results:

The study originally tested 18 participants per group. Unfortunately, due to acute injuries (concussion, muscle strain, ankle sprain, knee ligament sprain) relating to other sports in which the participants played (hockey, basketball) as well as other unforeseen circumstances (switched teams, transportation/commitment) final group sizes were n = 14, n = 13 and n = 14 for RT, PLYO and CON respectively. The present study average adherence for RT, PLYO and the CON groups were 96.7%, 97.1% and 98% respectively for total amount of training sessions attended (24 sessions).

The pattern of results was similar in the 90° and 130° isometric contraction. Therefore, only the 90° contraction results are described below. The 130° results appear in the Appendix.

7.1 Physical Characteristics:

There were no differences between groups in age, height, mass, percentage of body fat, Y-PHV, and mCSA at the start of the intervention (Table 2). There were similar increases Pre-Post ($p < 0.0001$) in age, height, mass and Y-PHV in all groups. A significant Group by Pre/Post interaction ($p = 0.04$) was observed for mCSA. However, despite the significant interaction, pairwise comparisons revealed no significant differences between groups.

Table 2 – Physical Characteristics

Physical Characteristics											
	RT		PLYO		CON		ANOVA - ONEWAY	RM-ANOVA			
	pre	post	pre	post	pre	post	Group - Baseline	Pre-Post effect	Group effect	Group x Pre-Post	Pairwise
Age, yrs	12.5 ± 0.6	12.7 ± 0.6 *	12.6 ± 0.7	12.8 ± 0.6 *	12.5 ± 0.2	12.7 ± 0.2 *	$p = 0.9$	**$p = 0.001$**	$p = 0.8$	**$p = 0.001$**	RT & PLYO > CON
Height, cm	155.1 ± 7.6	156.3 ± 8 *	157.8 ± 7.8	159.1 ± 7.8 *	152.1 ± 8.5	153 ± 8.5 *	$p = 0.2$	**$p = 0.001$**	$p = 0.1$	$p = 0.3$	N/A
Mass, kg	43.1 ± 7.1	46.1 ± 8.1*	47.2 ± 10.2	49.1 ± 10.1 *	41.3 ± 6.3	41.9 ± 6.3	$p = 0.1$	**$p = 0.001$**	$p = 0.1$	$p = 0.09$	N/A
Body fat, %	14.1 ± 4.9	14.9 ± 4.7	12.9 ± 6.3	12.8 ± 5.7	12.2 ± 5.3	11.2 ± 5.6	$p = 0.6$	$p = 0.7$	$p = 0.4$	$p = 0.05$	N/A
Y-PHV	-1.4 ± 0.5	-1.3 ± 0.6 *	-1.15 ± 0.6	-1 ± 0.6 *	-1.5 ± 0.3	-1.4 ± 0.3 *	$p = 0.1$	**$p = 0.001$**	$p = 0.3$	$p = 0.3$	N/A
mCSA, cm^2	3.1 ± 0.7	3.5 ± 0.8*	3.2 ± 1.2	3.7 ± 1.2*	3.2 ± 0.6	3.2 ± 0.5	$p = 0.2$	**$p = 0.001$**	**$p = 0.04$**	**$p = 0.04$**	N/A

*Indicates significant increase from pre-to-post intervention ($p < 0.017$)

7.2 Peak Torque:

There were no significant differences in PT between groups at baseline. The effect of the intervention on isometric and isokinetic PT was examined in absolute terms, with the change in mCSA serving as a covariate. The paragraphs below describe the statistical analysis results for each contraction separately. The full results and statistical analyses appear in Appendix A (Table 4).

KNEE EXTENSION 90°:

The RM-ANOVA analysis revealed a no significant main effect of Group in absolute PT. As expected, a significant main effect for Pre/Post was observed, reflecting an overall increase in PT in absolute values (Figure 1a). Importantly, there was a significant Group-by-Pre/Post interaction, reflecting that PT increased significantly more in the RT compared with the CON group. When the change in mCSA was added as a covariate it did not reach statistical significance ($p = 0.4$). However, the Group-by-Pre/Post interaction remained significant, with the change in PT in the RT group significantly greater than in CON. That is, this pairwise difference was observed with and the without the use of the change in mCSA as a covariate ($p < 0.05$) (Figure 1a).

KNEE EXTENSION 240°/s:

The RM-ANOVA analysis revealed a significant main-effect of Group in absolute PT. Despite the significant Group-effect, there were no significant pairwise differences between groups ($p > 0.05$ for all post-hoc group comparisons). As expected, a significant main-effect of Pre/Post was observed, reflecting an overall increase in PT in absolute values (Figure 1b). Importantly, there was a significant Group-by-Pre/Post interaction when PT was considered in absolute values, reflecting a significantly greater increase in

absolute PT in the RT group compared with CON (Figure 1b). When the change in mCSA was added as a covariate ($p = 0.5$), the Group-by-Pre/Post interaction was no longer significant ($p = 0.07$) (Table 3).

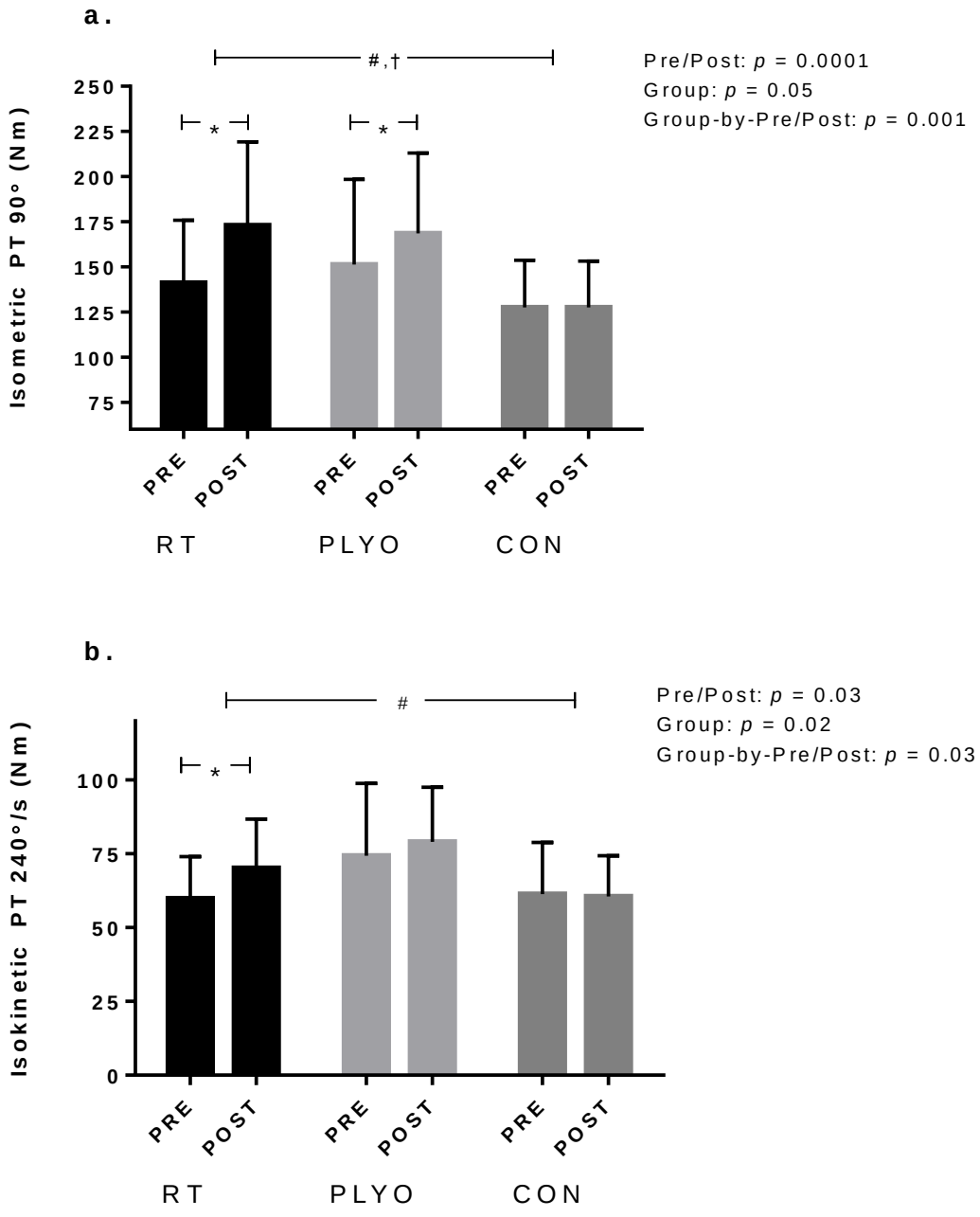


Figure 1 – Absolute isometric peak torque (PT) at 90° (a) and isokinetic PT at 240°/s (b) Pre- and Post-intervention in the Resistance training (RT), Plyometric training (PLYO) and Control (CON) groups. *Denotes significant increase within group from pre- to post-intervention ($p < 0.017$). # Denotes significant pairwise group differences in absolute changes in PT ($p < 0.05$). † Denotes significant pairwise group difference with the use of covariate (ΔmCSA) in the analysis ($p < 0.05$).*p* – values in figures are representative of data without covariate added.

7.3 Torque Kinetics:

There were no significant differences in torque kinetics between groups at baseline with the exception of time to 100% PT during isometric contractions. Therefore, isometric torque kinetics was only examined from 0-90% PT. The change in isometric and isokinetic torque kinetics from pre-to post-intervention was examined. The paragraphs below describe the statistical analysis results for each contraction separately. Figure 2 presents the mean torque kinetics for the three groups, pre- and post-intervention separately. Figure 3 presents the mean torque kinetics for each group separately. The full results and statistical analyses appear in Appendix A (Table 5a-c).

KNEE EXTENSION 90°:

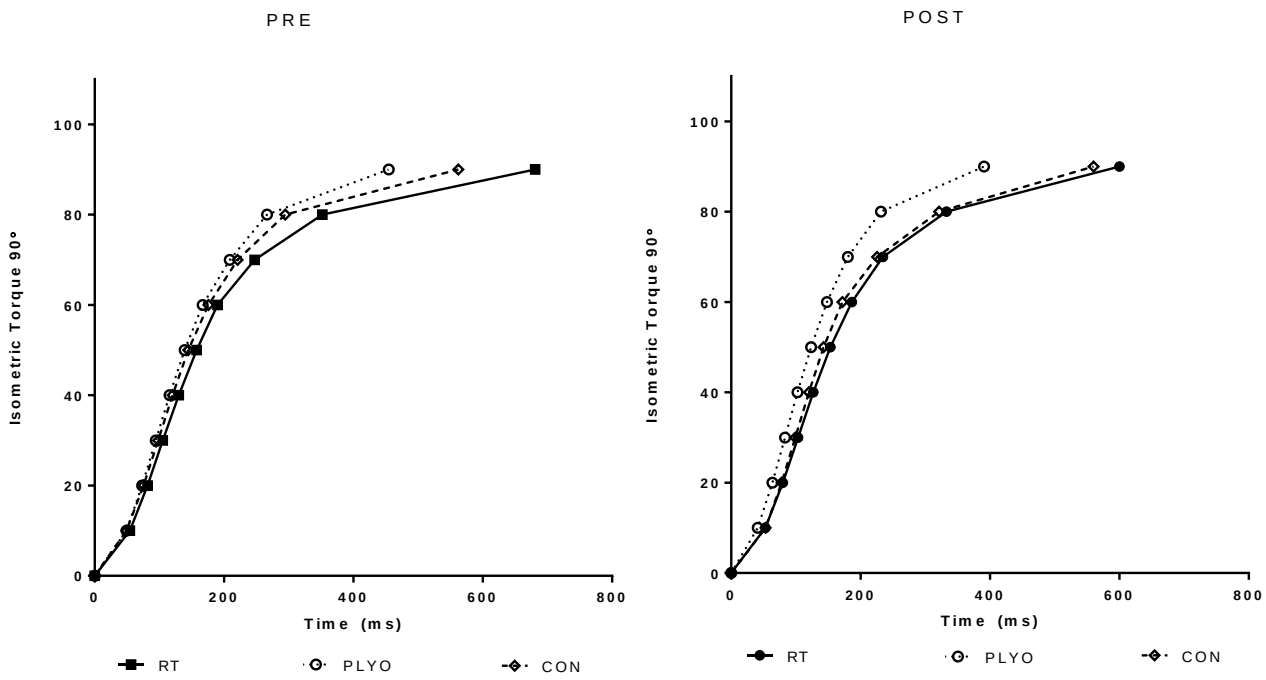
When examining the torque kinetics at isometric KE at 90°, there was no main effect for Group or Pre/Post but, as expected, there was a main effect of Time. There was no significant Group-by-Time interaction, reflecting that the increase in torque over time of contraction was similar among groups (Figure 2a). As seen in Figure-3a, the increase in torque over time appeared to be faster in the PLYO group post- compared with pre-intervention, and did not appear to change in either the RT or CON group. However, the Group-by-Pre/Post-by-Time interaction was not statistically significant ($p = 0.2$).

KNEE EXTENSION 240°/s:

When examining the torque kinetics at isokinetic KE at 240°/s, there was no main effect of Group, there was a main effect for Pre-Post and as expected, there was a main effect of Time. There was a significant Pre/Post-by-Time interaction, reflecting an overall increase in torque over time of contraction from pre-to-post intervention (Figure 2b).

group: p = 0.4
time: p = 0.0001
pre-post: p = 0.1
group x pre-post: p = 0.2
pre-post x time: p = 0.2
group x time: p = 0.3
group x pre-post x time: p = 0.6

a.



group: p = 0.8
time: p = 0.0001
pre-post: p = 0.03
group x pre-post: p = 0.4
pre-post x time: p = 0.0001
group x time: p = 0.7
group x pre-post x time: p = 0.09

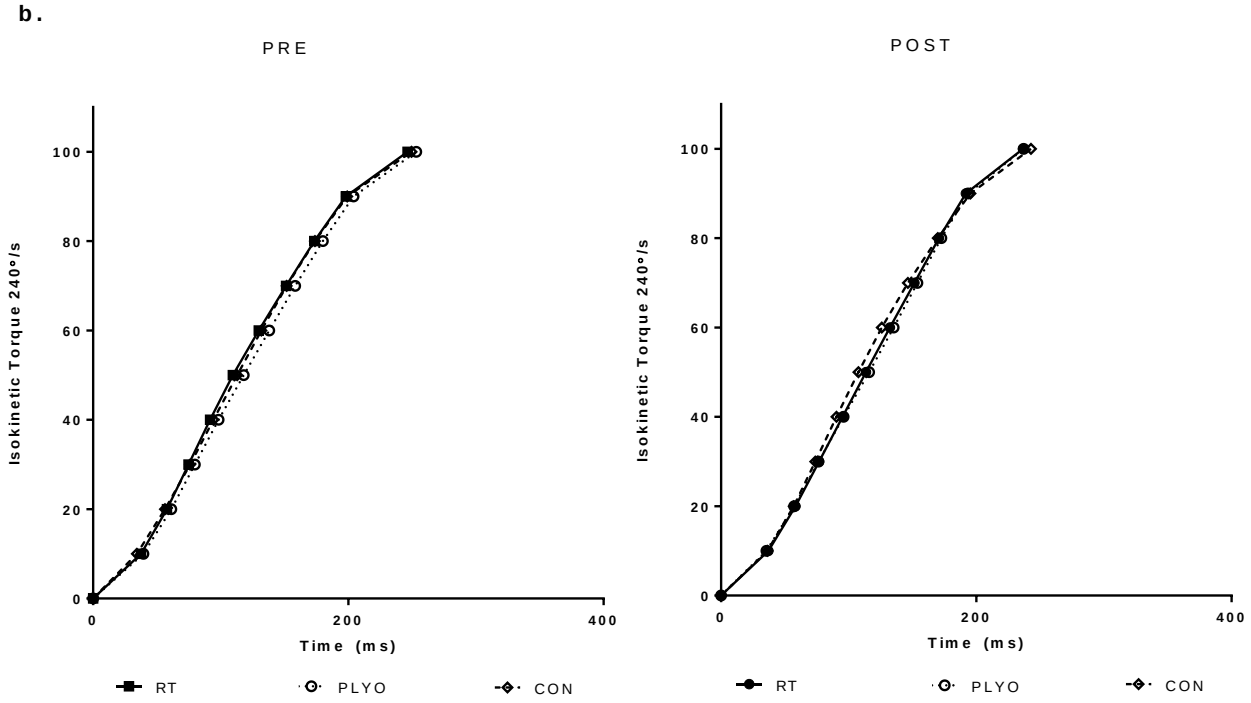
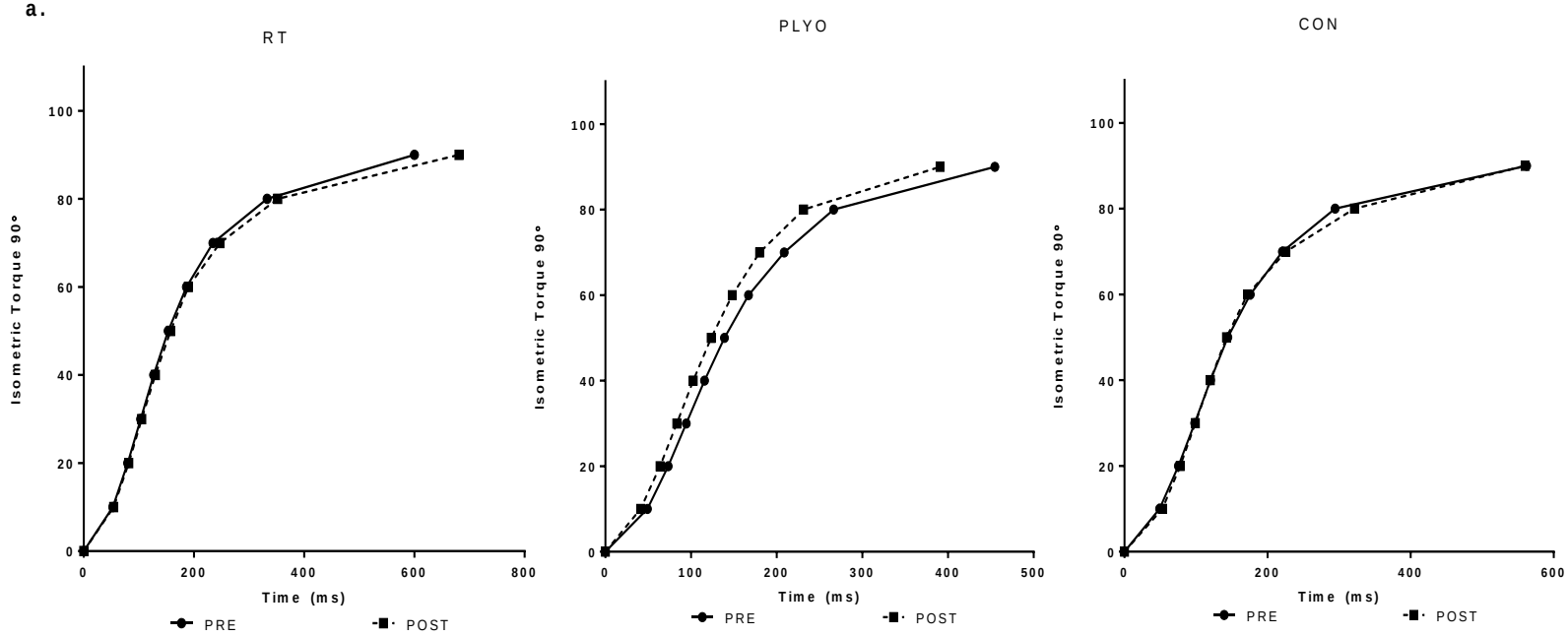


Figure 2 - Isometric (2a) and isokinetic (2b) torque (T) over the time of contraction pre-intervention (left) and post-intervention (right). Torque is expressed at percentage of peak torque

a.


RT
PLYO
CON
Isometric Torque 90°
Time (ms)
PRE
POST
0
20
40
60
80
100
0
200
400
600
800
100
300
500

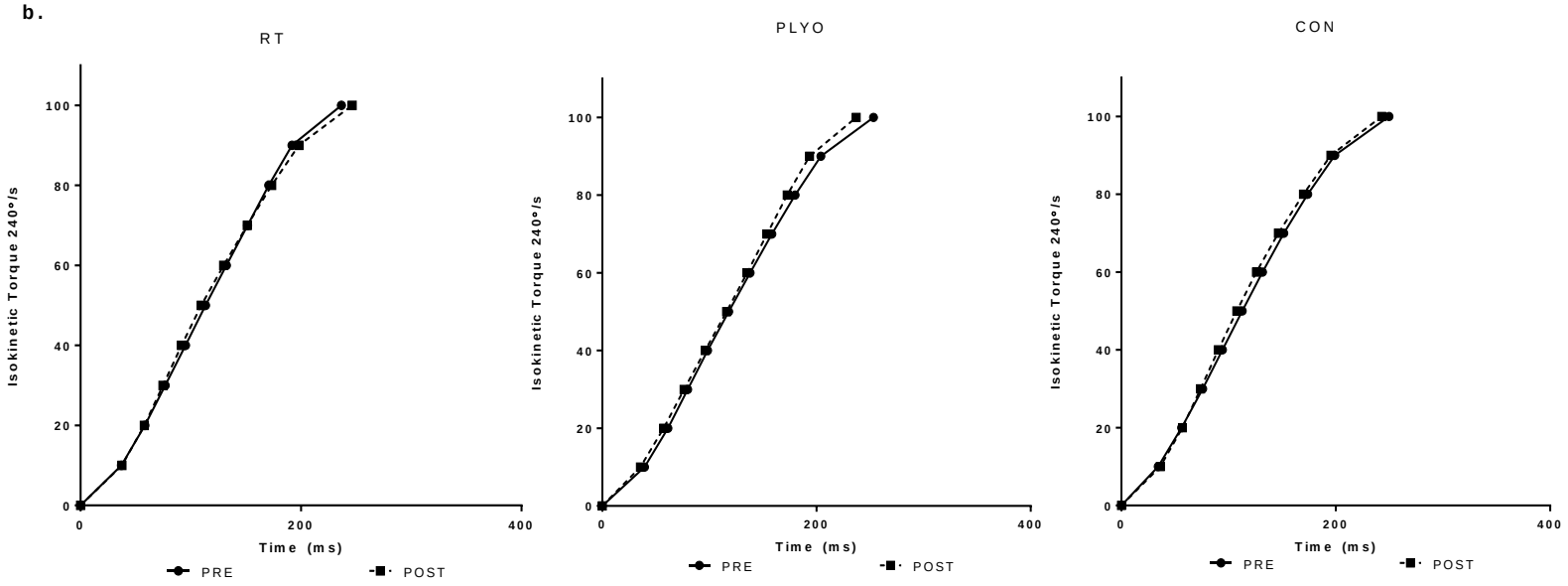


Figure 3 - Isometric (3a) and isokinetic (3b) torque (T) over the time of contraction pre-intervention and post-intervention for each group individually. Torque is expressed at percentage of peak torque

7.4 Position at Target Velocity & Time to Target Velocity:

Isokinetic KE at 240°/s total range of motion from start (80°) to full knee extension (150°) was approximately 70°. There were no significant differences in position at target velocity and time to target velocity between groups at baseline for isokinetic KE at 240°/s. The change in isokinetic KE from pre-to post-intervention was examined for the position at which target velocity occurred and the time it took to reach target velocity. The mean position at target velocity and time to target velocity for the three groups, pre- and post-intervention results and statistical analyses appear in Table 3. No significant main effects of Group or Pre/Post, nor Group-by-Pre/Post interactions were observed for either variable.

Table 3

Position at Target Velocity (PaTV) & Time to Target Velocity (ttTV)

	RT		PLYO		CON		ANOVA - ONEWAY	RM-ANOVA			
	pre	post	pre	post	pre	post	Group - Baseline	Pre-Post effect	Group effect	Group x Pre-Post	Interaction
PaTV (0°-70°)	41 ±6.4	39.9 ± 4.1	39.5 ± 6.7	36.1 ± 5.1	40.7 ± 4	40.3 ± 2.7	$p = 0.8$	$p = 0.06$	$p = 0.1$	$p = 0.3$	N/A
ttTV (ms)	244.8 ± 45.3	248.1 ± 19.9	244.5 ± 39.4	231.6 ± 30	246.8 ± 21.9	243.9 ± 18.2	$p = 0.9$	$p = 0.8$	$p = 0.9$	$p = 0.8$	N/A

7.5 Peak Rate of Torque Development (pRTD):

There were no significant differences in pRTD between groups at baseline. The effect of the intervention on isometric and isokinetic pRTD was examined in absolute terms, with the change in PT serving as a covariate. The paragraphs below describe the statistical analysis results for each contraction separately. The full results and statistical analyses appear in Appendix A (Table 6).

KNEE EXTENSION 90°:

The RM-ANOVA analysis revealed no significant main effect of Group in absolute pRTD. As expected a significant main effect for Pre/Post was observed, reflecting an overall increase in pRTD in absolute values (Figure 4a). Importantly, there was a significant Group-by-Pre/Post interaction when pRTD was considered in absolute values. That is, while absolute pRTD increased in the PLYO intervention, there were no apparent increases in CON (Figure 4a). When the change in PT was used as a covariate ($p = 0.08$), the pairwise group difference was no longer statistically significant ($p = 0.1$) (Table 6).

KNEE EXTENSION 240°/s:

The RM-ANOVA analysis revealed no significant main effect of Group in absolute pRTD. As expected a significant Pre/Post-effect was observed, reflecting an overall increase in pRTD in absolute values (Figure 4b). No significant Group-by-Pre/Post interaction was observed.

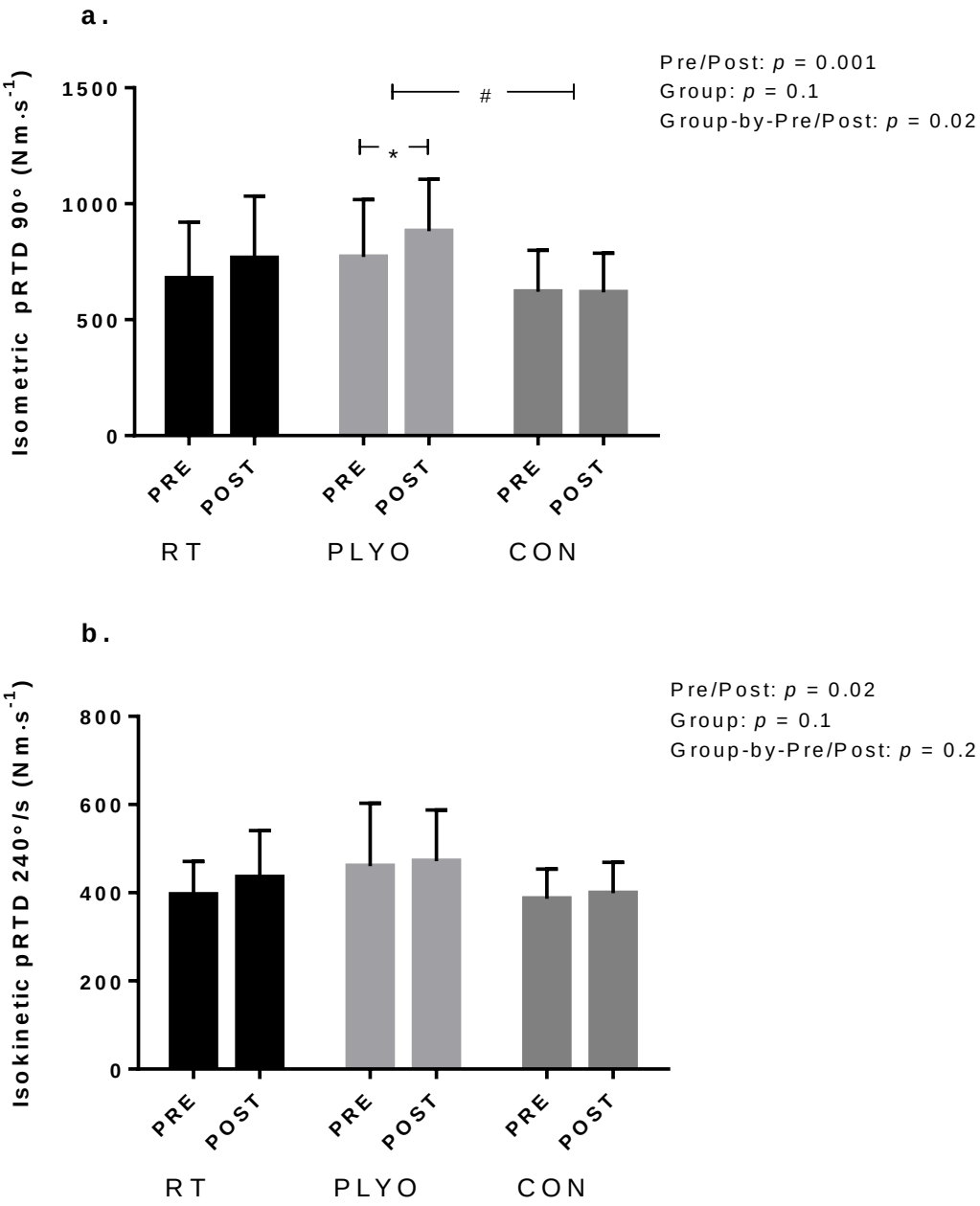


Figure 4 - Absolute isometric peak rate of torque development (pRTD) at 90° (a) and isokinetic pRTD at 240°/s (b) Pre- and Post-intervention in the Resistance training (RT), Plyometric training (PLYO) and Control (CON) groups. *Denotes significant increase within group from pre- to post-intervention (p <0.017). # Denotes significant pairwise group differences in absolute values (p < 0.05). p – values in figures are representative of data without covariate added.

7.6 RTD Kinetics:

There were no significant differences in torque kinetics between groups at baseline. The change in isometric and isokinetic RTD kinetics was examined from pre- to post-intervention. The paragraphs below describe the values and statistical analysis results for each contraction separately. The full results and statistical analyses appear in Appendix A (Table 7a-c).

KNEE EXTENSION 90°:

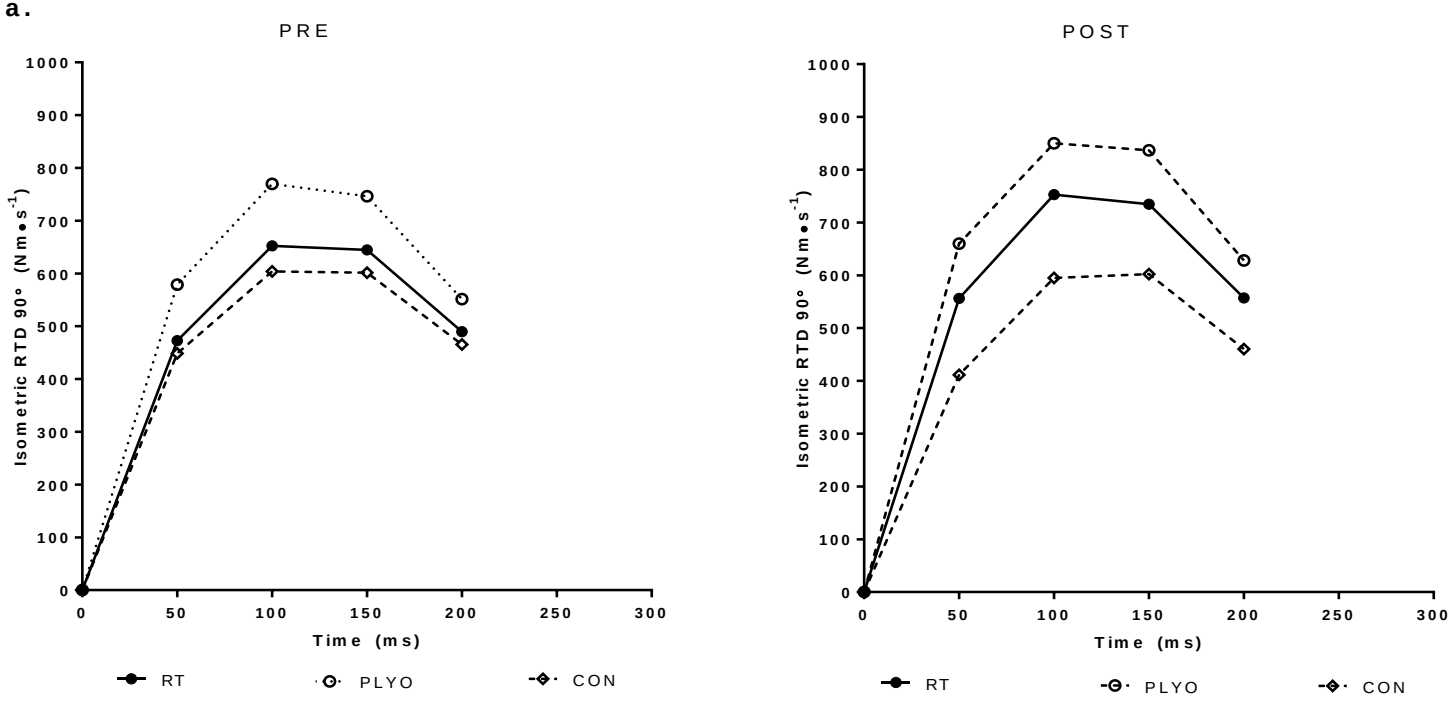
When examining the RTD kinetics at isometric KE at 90°, there was no main effect of Group ($p = 0.05$) There was a significant effect of Pre/Post, reflecting an overall faster RTD kinetics from pre-to post-intervention. As expected, there was a main effect of Time. Importantly, there was a significant Group-by-Pre/Post interaction, reflecting that there was an increase in RTD kinetics in the intervention groups, especially at 50-150 ms into the contraction, but not in CON (Figure 6a).

KNEE EXTENSION 240°/s:

When examining the RTD kinetics at isokinetic KE at 240°/s, there was a main effect of Group, reflecting a mean overall difference between groups. There was a significant effect of Pre/Post, reflecting overall faster RTD kinetics from pre-to post-intervention in all groups. As expected, there was a main effect of time. Importantly, there was a significant Group-by-Pre/Post interaction, reflecting that there was an increase in RTD kinetics in the intervention groups, especially at 100-200 ms into the contraction, but not in CON (Figure 6b).

group: p = 0.05
time: p = 0.0001
pre-post: p = 0.005
group x pre-post: p = 0.03
pre-post x time:p = 0.6
group x time: p = 0.4
group x pre-post x time: p = 0.8

a.



group: p = 0.07
time: p = 0.0001
pre-post: p = 0.0001
group x pre-post: p = 0.04
pre-post x time:p = 0.07
group x time: p = 0.02
group x pre-post x time: p = 0.01

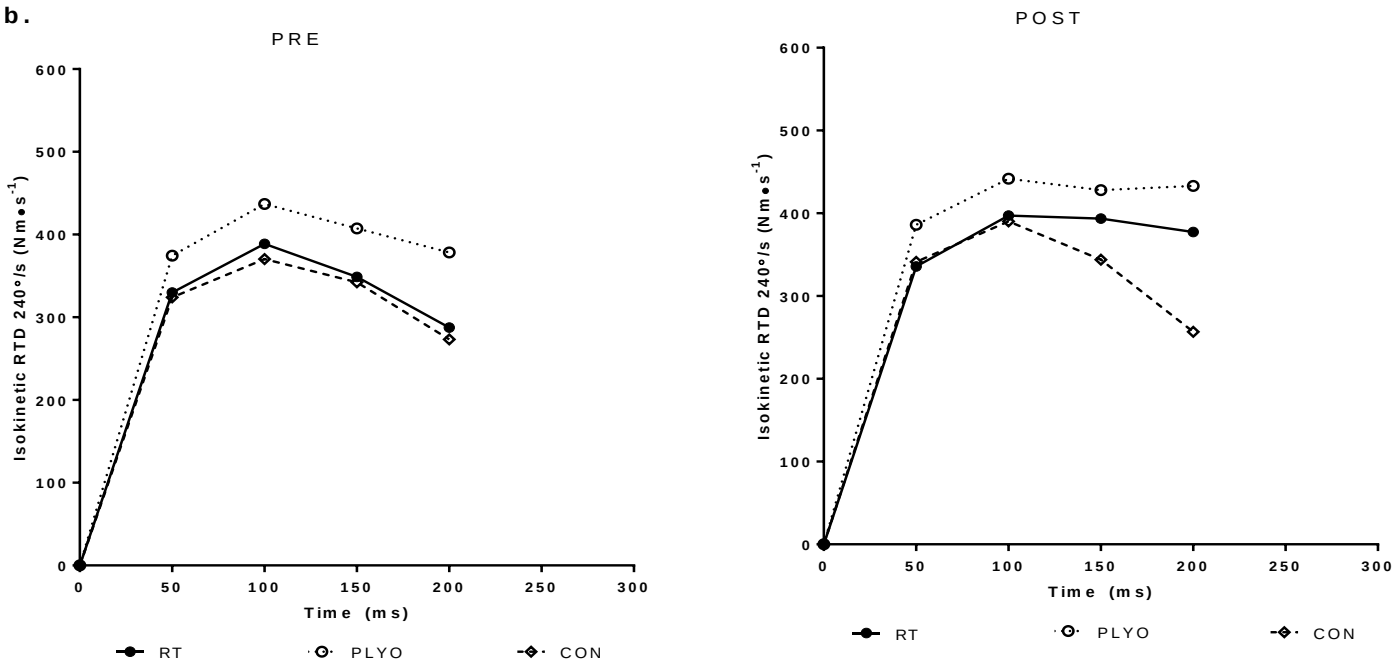
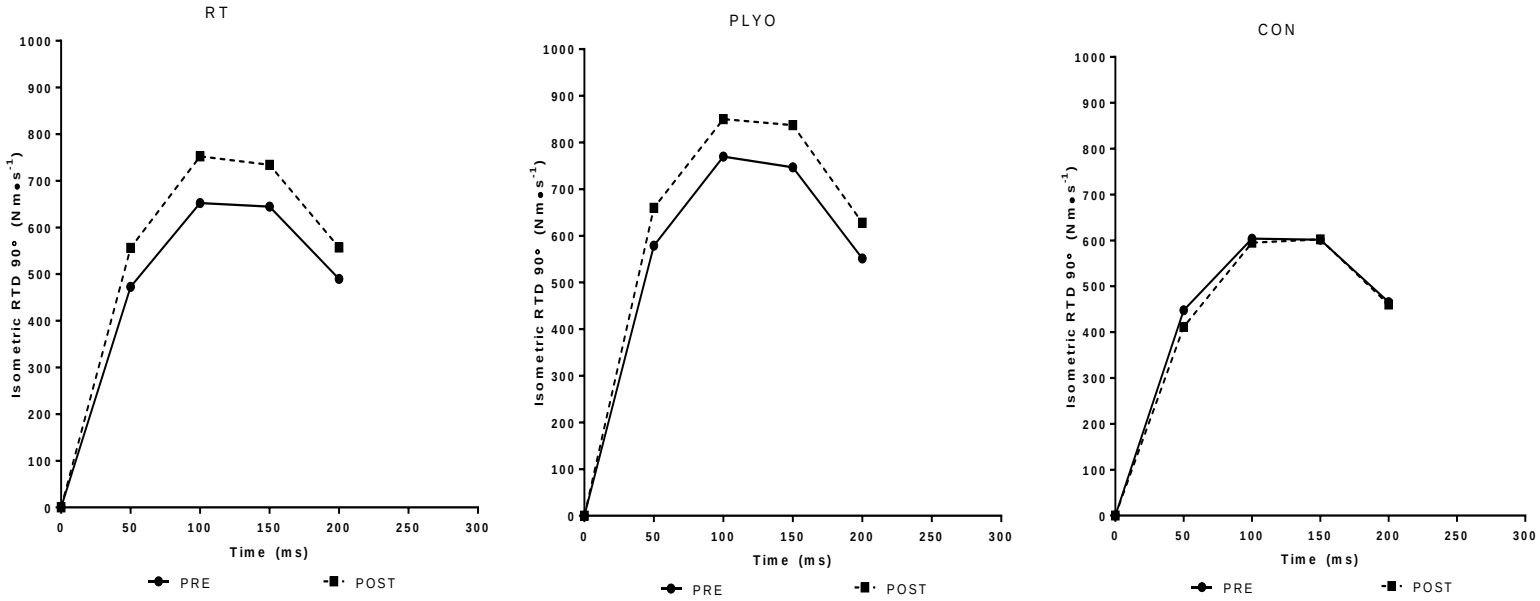


Figure 5 - Isometric (5a) and isokinetic (5b) rate of torque development (RTD) over the time of contraction pre-intervention (left) and post-intervention (right).

a.


RT
PLYO
CON
Isometric RTD 90° (Nm•s-1)
Time (ms)
PRE
POST
0
50
100
150
200
250
300
100
200
300
400
500
600
700
800
900
1000

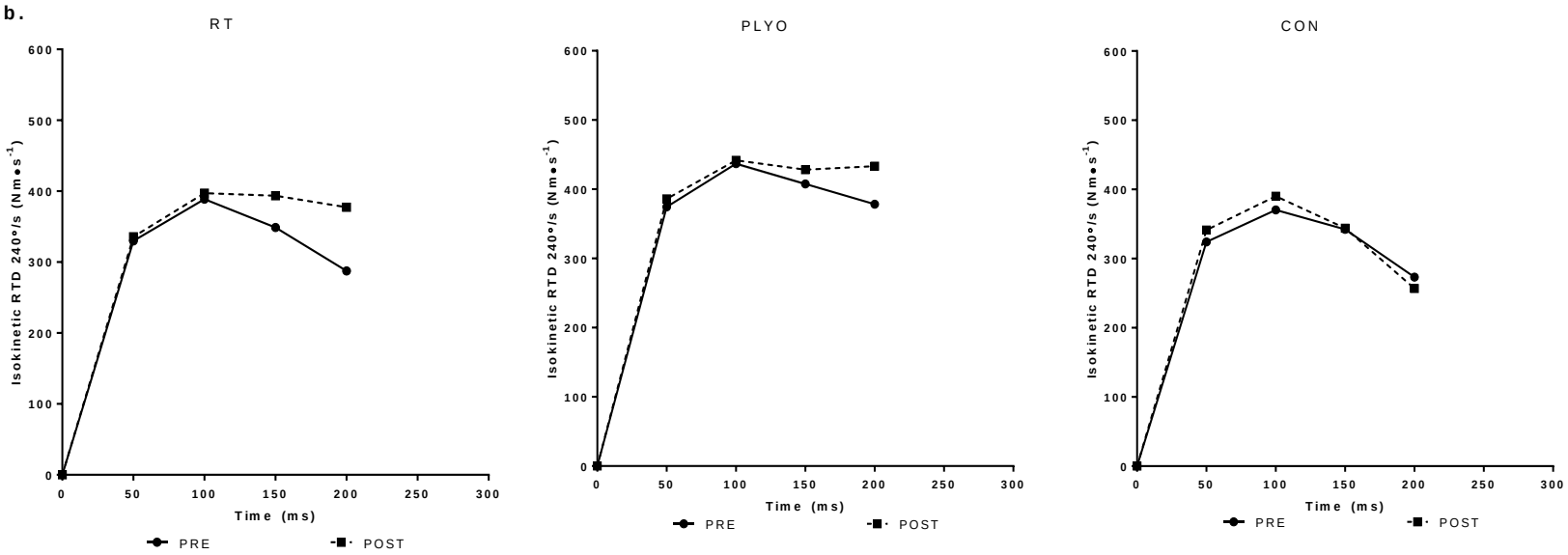


Figure 6 - Isometric (6a) and isokinetic (6b) rate of torque development (RTD) over the time of contraction pre-intervention and post-intervention for each group individually.

7.7 EMG:

7.7.1 Electromechanical delay (EMD):

There were no significant differences in EMD between groups at baseline. The effect of the intervention on isometric and isokinetic EMD was examined in absolute terms. The paragraphs below describe the statistical analysis results for each contraction separately. The full results and statistical analyses appear in Appendix A (Table 8).

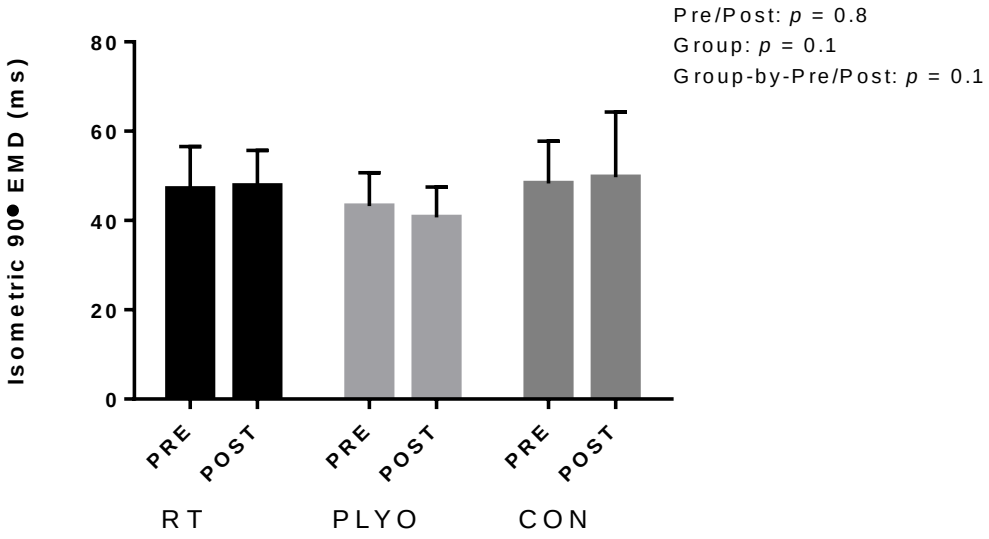
KNEE EXTENSION 90°:

The RM-ANOVA analysis revealed there was no significant main effect of Group, Pre/Post or Group-by-Pre/Post interaction when EMD was examined from pre-to-post intervention (Figure 7a).

KNEE EXTENSION 240°/s:

The RM-ANOVA analysis revealed there was a significant main effect of Group. Pairwise comparisons showed that overall, the CON group's EMD was greater than RT group's EMD. No significant main effect of Pre/Post or Group-by-Pre/Post interaction was observed from pre-to-post intervention (Figure 7b).

a.



b.

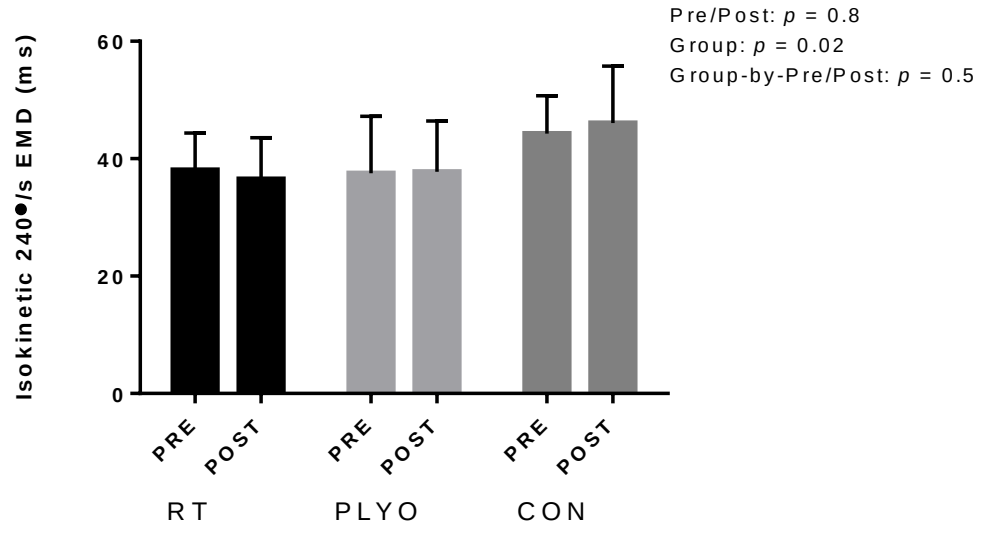


Figure 7 - Absolute isometric electromechanical delay (EMD) at 90° (a) and isokinetic EMD at 240°/s (b) Pre- and Post-intervention in the Resistance training (RT), Plyometric training (PLYO) and Control (CON) groups.

7.7.2 Rate of muscle activation (Q-30)

There were no significant differences in EMD between groups at baseline. The effect of the intervention on isometric and isokinetic EMD was examined in absolute terms and when the change in agonist peak sEMG amplitude (EMG_{pk}) was added as a covariate. The paragraphs below describe the statistical analysis results for each contraction separately. The full results and statistical analyses appear in Appendix A (Table 9).

KNEE EXTENSION 90°:

The RM-ANOVA analysis revealed there was no significant main effect of Group, Pre/Post or Group-by-Pre/Post interaction ($p = 0.1$) when absolute Q30 was examined from pre-to-post intervention. This was also the case when EMG_{pk} was added as a covariate (Figure 8a). One participant in the PLYO group had a decrease of 20% in Q30 (2.7 standard deviations below the mean change) post-intervention. When analyzed without this individual, the increase in Q30 in the PLYO group was significantly greater than in the RT and CON groups ($p = 0.01$). A significant Group-by-Pre-Post interaction remained statistically significant ($p = 0.02$) when the change in the peak EMG amplitude was accounted for (as a covariate), although pairwise comparisons were not significant (Table 10).

KNEE EXTENSION 240°/s:

The RM-ANOVA analysis revealed there was no significant main-effect of Group, Pre/Post or Group-by-Pre/Post interaction when absolute Q30 was examined from

pre-to-post intervention. As for the isometric contraction, this was also the case when EMG_{pk} was added as a covariate (Figure).

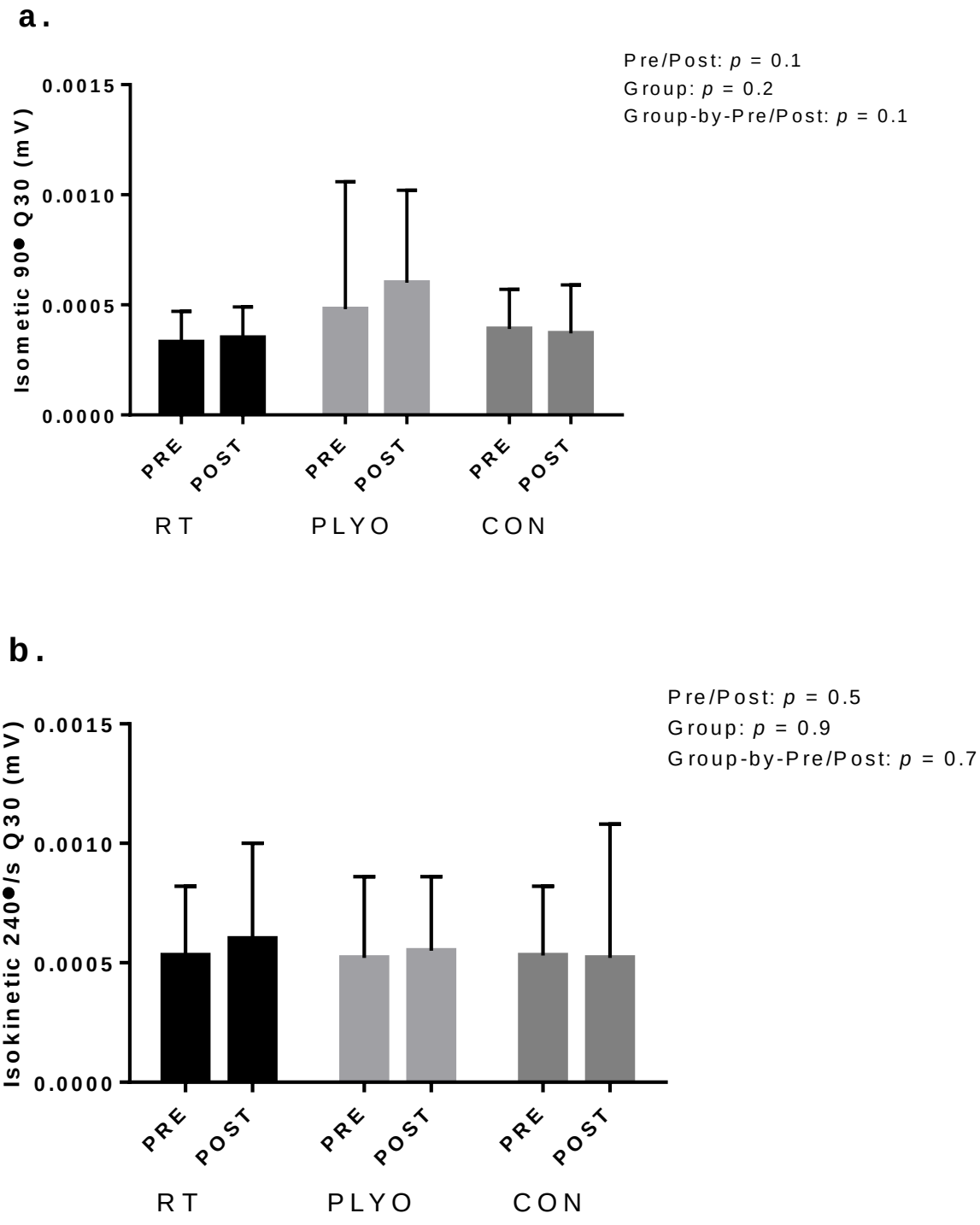


Figure 8 - Absolute isometric integrated EMG (Q30) at 90° (a) and isokinetic Q30 at 240°/s (b) Pre- and Post-intervention in the Resistance training (RT), Plyometric training (PLYO) and Control (CON) groups.

7.8 Performance Testing:

There were no significant differences in CMJ, SJ and DJ between groups at baseline.

The effect of the intervention on jump performance (CMJ, SJ and DJ) was examined in absolute terms. The paragraphs below describe the statistical analysis results for each contraction separately. The full results and statistical analyses appear in Appendix A (Table 11).

7.8.1 Counter-movement Jump (CMJ):

The RM-ANOVA analysis revealed there was no significant main effect of Group, Pre/Post or Group-by-Pre/Post interaction ($p = 0.09$) (Figure 9a).

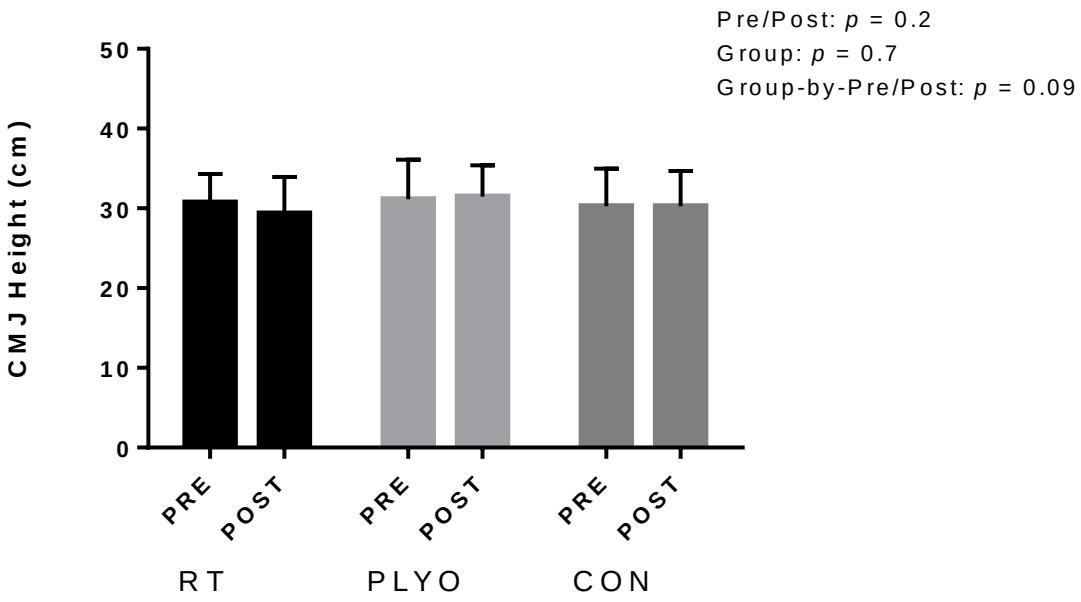
7.8.2 Squat Jump (SJ):

RM-ANOVA analysis revealed there was no significant main-effect of Group. As expected there was a significant main-effect of Time. Importantly, there was a significant Group-by-Pre/Post interaction observed, reflecting that the increase in SJ height from pre-to-post intervention was greater in the PLYO compared with the CON group (Figure 9b).

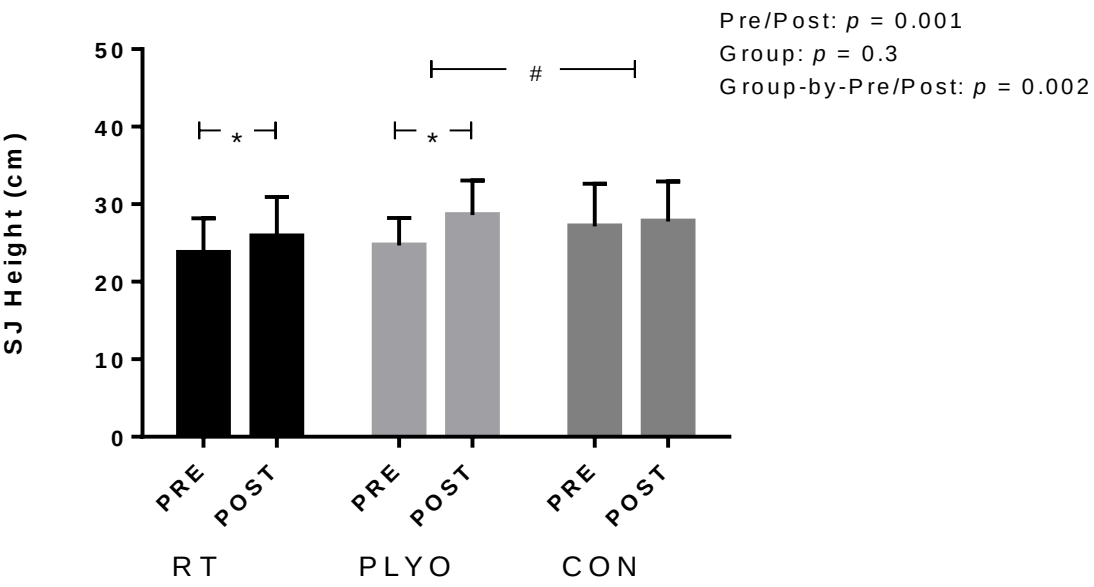
7.8.3 Drop Jump (DJ):

The RM-ANOVA analysis revealed there was no significant main-effect of Group, Pre/Post or Group-by-Pre/Post interaction when absolute DJ was examined from pre-to-post intervention (Figure 9c). However it should be noted that PLYO demonstrated a trend ($p = 0.1$) towards a greater increase in DJ height from pre-to-post intervention, compared with both, the RT and CON groups

a.


Pre/Post: p = 0.2
Group: p = 0.7
Group-by-Pre/Post: p = 0.09
CMJ Height (cm)
50
40
30
20
10
0
PRE
POST
PRE
POST
PRE
POST
RT
PLYO
CON

b.


Pre/Post: p = 0.001
Group: p = 0.3
Group-by-Pre/Post: p = 0.002
SJ Height (cm)
50
40
30
20
10
0
*
*
#
PRE
POST
PRE
POST
PRE
POST
RT
PLYO
CON

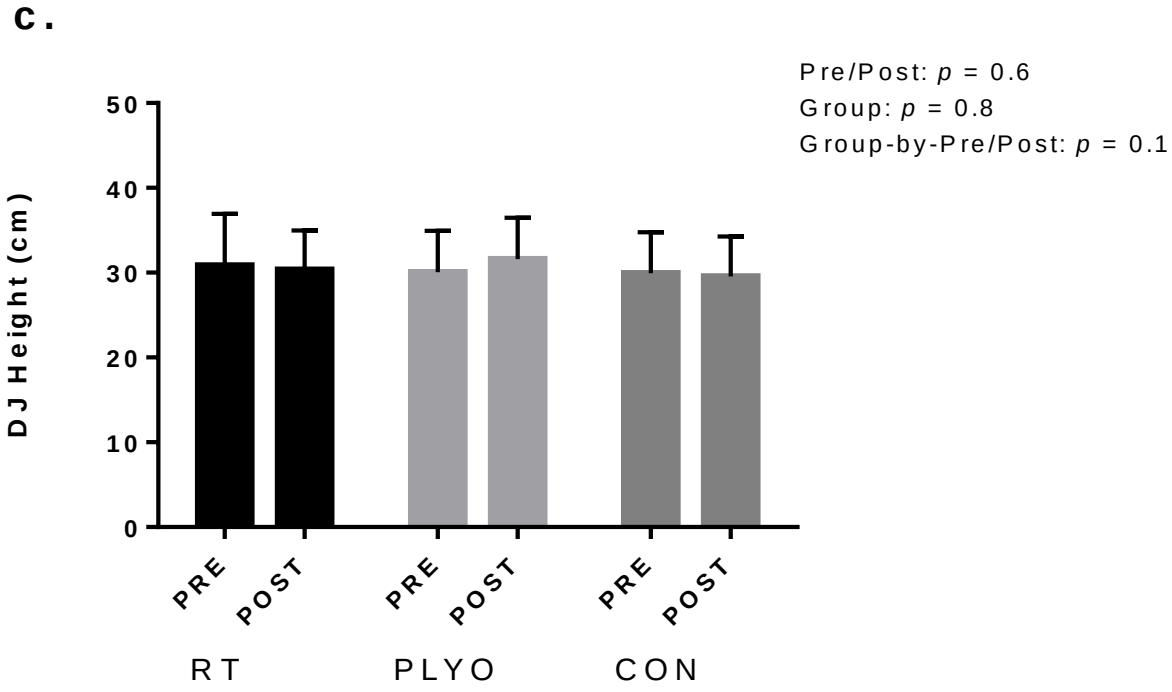


Figure 9 - Maximal jump height for Counter-movement Jump (a), Squat Jump (b) and Drop Jump (c) Pre- and Post-intervention in the Resistance training (RT), Plyometric training (PLYO) and Control (CON) groups. *Denotes significant increase within group from pre-post intervention ($p < 0.017$). # Denotes significant Group-by-Pre/Post interaction pairwise group differences in absolute values.

7.9 Correlations:

The changes in isometric and isokinetic PT, pRTD, Q30, mCSA, CMJ, SJ and DJ from pre- to post-intervention were examined to determine if any bi-variate relationships exist and whether these relationships are different between groups. The paragraphs below describe the correlations of interest. Appendix includes the correlation (*r* and *p*-values) for all correlations, for each group.

7.9.1 Peak torque and peak rate of torque development

In all participants, there was a significant positive correlation between the change in PT and the change in pRTD in both isometric KE at 90° ($r = 0.46$) and isokinetic KE at 240°/s ($r = 0.68$) (see Table 12. in Appendix A).

When each group was examined separately, there was a significant positive correlation between the change in PT and the change in pRTD only in the isokinetic contraction ($r = 0.76$, 0.71 and 0.56 for RT, PLYO and CON, respectively). In isometric contraction, a trend toward a positive correlation ($r = 0.48$, $p = 0.07$) was observed in RT (see Table 12. in Appendix A).

7.9.2 Jump performance and peak torque

In all participants, there was no significant correlations between the change in PT and the change in jump heights (CMJ, SJ and DJ) for isometric KE at 90° and isokinetic KE at 240°/s, with one exception, which occurred in the drop jump. There was a negative correlation between the change in drop jump height and the change in peak torque at KE 90° ($r = -0.36$) (see Table 13 in Appendix A).

When each group was examined separately, there was a negative correlation between the change in drop jump height and the change in peak torque at KE90° in the

RT group only (r =-0.70). There was also a negative correlation between the change in drop jump height and the change in peak torque at KE240°/s in the CON group only (r = -0.58). The other two significant correlations occurred in the squat jump: There was a negative correlation between the change in squat jump height and the change in peak torque at KE 90° (r = -0.65) and KE 240°/s (r = -0.53) in the RT group only (see Table 13 in Appendix A).

7.9.3 Jump performance and peak rate of torque development

In all participants, there was a significant correlation between the change in jump height and the change in peak rate of torque development, which occurred in isometric KE 90° (r = 0.41) (see Table 14 in Appendix A).

When each group was examined separately, there were no significant correlations between the change in any of the jumps' height and the change in peak rate of torque development, with one exception, which occurred in the SJ in the CON group only: In this group, there was a positive correlation between the change in SJ height and the change in pRTD at KE 90° (r = 0.56) (see Table 14 in Appendix A).

7.9.4 Peak torque, Peak rate of torque development and muscle size

In all participants, there was a significantly positive correlation between the change in PT for isometric KE90°and the change in muscle size (mCSA) (r = 0.42) (see Table 15 in Appendix A). In all participants, there was no correlation between the change in pRTD in any of the contractions and the change in mCSA (see Table 16 in Appendix A).

When each group was examined separately, there were no significant correlations between the change in PT in any of the contractions and the change in mCSA. Likewise, there were no significant correlations between the change in pRTD in any of the contractions and the change in mCSA (see Table 15 & Table 16 in Appendix A).

7.9.5 Peak rate of torque development and electromecanical delay

There was no correlation between the change in pRTD and the change in EMD for all contractions when all participants were considered together, nor when groups were considered separately (see Table 17 in Appendix A).

7.9.6 Peak rate of torque development and Q30

There was no correlation between the change in pRTD and the change in Q30 for all contractions when all participants were considered together, nor when groups were considered separately (see Table 18 in Appendix A).

8.0 Discussion:

8.1 Summary:

The present study was designed to determine whether 8-weeks of free-weight RT and PLYO would result in enhancements in maximal isometric and isokinetic strength (PT), explosive strength (pRTD), and jump performance, compared to no added training in adolescent male athletes, as well as investigate some of the related mechanisms. The findings demonstrate that both, RT and PLYO resulted in improved muscle performance compared with CON. More specifically, the findings suggest that RT had greater effect on PT, while PLYO had greater effect on RTD and jump performance. The greater increases in explosive strength in the PLYO group were also accompanied by a trend towards greater enhancement in the rate of muscle activation (Q30). No clear effects of training were seen on torque kinetics, although there was an apparent trend towards faster RTD kinetics in the early-mid stages of isometric contraction. Thus, 8-weeks of free-weight RT or PLYO effectively resulted in improved muscle function and performance in young male athletes, and the adaptations appear to be training mode-specific.

There are numerous studies which have examined the effects of various training, especially RT, on muscle performance in youth (see Behm et al. 2008 for review). However, this is the first study to examine the effects of PLYO in youth, not only on jump performance but also on neuromuscular function. Additionally, most previous studies have focused on field tests or on isometric contractions. In the present study, isokinetic contractions were also examined.

It should be noted that most RT studies in youth have focused on maximal strength. The current study, while measuring maximal strength, is focused on adaptations

in explosive strength, the mechanisms which may explain these adaptations, as well as their implications in terms of performance. The discussion below reflects this focus.

8.2 Peak Torque:

As expected, maximal isometric PT increased in both RT (+18%) and PLYO (+13%), compared with CON. However, pairwise comparisons were statistically significant only between RT and CON (Figure 1a). The present findings are in line with previously reported literature on the effects of RT on PT in youth (Waugh et al. 2014; Behringer et al. 2011; Behringer et al. 2010; Ramsay et al. 1990). To the author's knowledge, this is the first time PLYO and its effect on isometric PT has been examined in youth. The magnitude of the observed improvement in PT in the present study following the PLYO intervention are in line with previously reported results in adults (Kyrolainen et al. 2005; Spurrs et al. 2003).

Similarly, the maximal isokinetic PT increased in RT (+10%) and PLYO (+6%) compared with CON. However, pairwise differences were significant only between RT and CON (Figure 1b). These results are in line with Chaouchi et al (2014), who recently reported improved isokinetic PT following both, RT and PLYO in youth, although in that study, PLYO appeared to be more effective compared with RT, especially in the faster movements (300°/s vs. 60°/s). Differences in the pattern of results between Chaouchi et al (2014) and the current study may be related to the fact that in the former study, participants were younger and non-athletes and the duration of training was longer (12 vs. 8 weeks).

Overall, in the current study, in both isometric and isokinetic contractions a pattern was observed whereby RT appeared to elicit greater increases in PT following the training intervention.

The training-induced increases in maximal strength may be related to changes in muscle size. It is well documented in adults that increases in muscle size are highly related to substantial increases in maximal strength (Farup, Henrik, and Kjolhede, 2014; Aagaard et al. 2011;Andersen et al. 2009; Luthi et al. 1986; Maughan et al. 1983). Conversely, a large body of literature examining pre-pubertal children's response to RT demonstrates no change in muscle size (Falk and Tenenbaum 1996; Ramsay et al. 1990; Kraemer et al. 1989; Malina R. 2006; Ozmun et al. 1994; Blimke, 1992). In the present study, both RT and PLYO were found to result in similar increases in vastus lateralis mCSA (12% and 13%, respectively), in the absence of any change in the CON (Table 2). This result is similar to that observed by Fukunaga et al. (1992), who reported similar increases in mCSA following 12-weeks of RT (+16%) and extends it by observing a similar hypertrophic response using a different training modality. It should be noted that all participants in the current study (with the exception of four participants (two in the RT group and two in PLYO) were already pubertal at the onset of the study. To the author's knowledge there is no information which has been reported on the effects of RT on muscle hypertrophy in early adolescents (12-13yrs). Additionally, the present study is the first to report on the effect of PLYO on muscle size in youth. The literature reporting changes in muscle size in response to PLYO in adults is limited but the magnitude of improvement (+10%) is similar to those seen in the present study (Vissing et al. 2008).

The increase in isometric and isokinetic PT was related to the increase in mCSA. However, even when the change in mCSA was added as a covariate, the differences observed between groups in the increase in isometric PT remained significant, while isokinetic PT demonstrated a similar pattern ($p = 0.07$) (Table 3). This result suggests that even after correcting for changes in muscle size, additional factor(s) contribute to the different increases observed in PT between RT and CON. These factors may include different changes in the extent of motor unit activation or in co-contraction. However, these factors were not evaluated in the current study.

A limitation in the present study is that only one of the four primary muscles involved with knee-extension was investigated, and that other hypertrophic changes in the rest of the knee-extensor quadriceps muscle group could have also occurred. Future investigations regarding changes in muscle size as a result of training should attempt to include all muscles involved in the primary action to gather a full understanding of whether the magnitude of change across all primary movers has an influential role on maximal strength in youth.

8.3 Explosive strength:

8.3.1 Peak rate of torque development (pRTD):

As expected, pRTD increased significantly in both RT (+12%) and PLYO (+18%), compared to CON during isometric contraction. However, only the change in the PLYO group was found to be statistically different from CON (Figure 4a). To the author's knowledge there are no studies examining the effect of PLYO training on explosive strength in youth. Data examining pRTD and its response to RT interventions in youths are both limited and inconsistent. For example, Waugh et al (2014) is the only

study which has examined the effect of RT on explosive strength in children. Although there appeared to be increases in pRTD (along with a 20% improvement in PT), these changes did not reach a level of statistical significance. The magnitude of the increases in pRTD in the present study are in line with previous studies that have examined the effects of both types of training interventions in adults (Aagaard et al. 2002; Aagaard et al. 2011; Behrens et al. 2014; Kryolainen et al. 2005).

The pattern of change in pRTD in the isokinetic contractions was different than in the isometric contraction. That is, as opposed to the significant increase in isometric pRTD in the PLYO group, in the isokinetic contraction pRTD increased in the RT, PLYO and CON groups by 8%, 3% and 3%, respectively, with no significant difference between groups (Figure 4b). There are no previous studies which examined the effect of RT or PLYO on isokinetic pRTD in youths. However, recently Chaouachi et al (2014) examined the effects of 12 weeks of RT and PLYO on isokinetic power at slow (60°/s) and fast (300°/s) contractions. The authors do not state how power was calculated but it is assumed that it reflects explosive strength (pRTD). Chaouachi and colleagues reported that RT resulted in greater power enhancement at slow velocity, while PLYO resulted in greater power enhancement in the fast velocity contractions. The reason for the apparent contradiction between the two studies and the blunted isokinetic pRTD response in the current study may be related to the shorter training duration in the current study and the fact that participants in the current study were active athletes who engaged in additional (soccer) training.

The enhancement in isometric pRTD following training observed in the current study may be related to the observed increases in PT. In adults, it has been shown that a

positive relationship exists between PT and pRTD in adults (Andersen & Aagaard 2006; Bell et al. 1989; Paasuke et al 2001; Hakkinen et al 1985) and training-induced changes in PT are often related to changes in pRTD (Aagaard et al. 2002; Andersen and Aagaard 2006; Andersen et al. 2009). In the present study, similar to the findings in adults, a moderate positive correlation was observed between the change in PT and the change in pRTD (Table 12). Furthermore, when the change in PT was added as a covariate when examining the effect of training on isometric pRTD, the differences between PLYO and CON were no longer significant ($p = 0.1$, Table 7), suggesting that increases in isometric PT played a main contributing role in the observed enhancements in isometric pRTD. In adults, there are contrasting results regarding the influence of changes in maximal strength on improvements in pRTD. Aagaard et al (2002) observed that, following 14 weeks of RT, isometric pRTD increased even when normalized to PT. Conversely, the same group later reported a decrease in normalized pRTD (Andersen et al. 2009), while others reported no change (Haikkinen et al. 1998).

Theoretically, pRTD is influenced by tendon stiffness. A similar relationship between tendon stiffness and isometric pRTD has been demonstrated in children and adults (Waugh et al. 2013). This study, however, did not examine training-related adaptations in either tendon stiffness or pRTD. In the present study, tendon stiffness was not directly evaluated. However, musculotendinous stiffness is said to account for the majority of the EMD, along with the excitation-contraction coupling (Muraoka et al. 2004). Therefore, EMD is considered an indirect measure of muscle tendon stiffness (Muraoka et al. 2004). In the present study, there were no significant reductions in EMD during both isometric and isokinetic contractions (Figure 7). Furthermore, there were no

correlations between the change in EMD and the change in pRTD (Table 17). These results indicate that the changes observed in pRTD and the differences between groups were likely not due to an increase in muscle tendon stiffness. Notably, Waugh et al. (2014) reported that after 10-weeks of plantar flexor RT training in children, significant reductions in EMD were apparent, but these were insufficient to significantly enhance the RTD.

To the author's knowledge, no study has examined the training effect of PLYO exercise on EMD or tendon stiffness in youths. In adults, PLYO training has been shown to result in increases on muscle tendon stiffness along with increases in RTD (Grosset et al. 2009; Wu et al. 2010). However, in other studies, where changes in EMD were examined, rather than tendon stiffness, there were no changes in the RTD (Blazevich et al. 2008; Narici et al. 1996). It is possible that the magnitudes of change in EMD in the aforementioned studies were insufficient to result in significant changes in pRTD. Future research should attempt to examine the magnitude of change in tendon stiffness (and EMD) that effects changes in RTD.

The RTD can also be influenced by the rate of muscle activation (Aagaard et al., 2002; Van Custem et al., 1998), reflected by the rate of EMG increase (REI) or integrated EMG at the initiation of contraction (Q30) (Aagaard et al. 2002; Hakkinen et al. 1985). In the present study, the observed changes in Q30 during isometric contraction in PLYO, RT and CON were +20%, +5%, and -5% respectively. Despite the apparently large differences, there were no statistically significant differences between groups (Figure 8). The lack of statistical significance may be due to inter-individual variability. In the present study, one participant in the PLYO group had a *decrease* of 20% in Q30 (2.5

standard deviations below the mean change) post-intervention. When analyzed without this individual, the increase in Q30 in the PLYO group was significantly greater than in the RT and CON groups ($p = 0.01$). A significant group-by-Pre-Post interaction remained statistically significant ($p = 0.02$) when the change in the peak EMG amplitude was accounted for (as a covariate), although pairwise comparisons were not significant (Table 10). Thus, it is possible that the observed increase in pRTD in the PLYO group was due to an increase in the rate of muscle activation.

In line with the present results, Waugh et al. (2014) observed that 10-weeks of RT in children resulted in no significant increases in plantar flexor REI. Similarly, Ramsay et al. (1990) examining the effect of 20-weeks of RT in pre-pubescent boys also observed no statistically significant increases in evoked contractile properties (time to peak torque), as assessed using a twitch response. In adults, RT interventions and the influence of the rate of muscle activation on RTD is inconsistent. Increases in the rate of muscle activation have been reported in adults after RT in conjunction with marked increases in RTD (Aagaard et al. 2002; Hakkinen et al. 1985; Van Cutsem et al. 1998). However, there have also been RT studies that have found no increases in the rate of muscle activation in adults (Blazevich et al. 2008; Narici et al. 1996). The discrepancy in results in the aforementioned RT studies in adults could possibly be attributed to the differences in type of exercise (slow vs. fast movements, open vs. closed kinetic movements) and volume of training (Blazevich et al 2008). Importantly, it is possible that the velocity of movement during training affected the rate of muscle activation (and pRTD). That is, a faster and more explosive training velocity may result in greater neural enhancements (Andersen et al. 2009). In those studies where no change in REI was observed

(Blazevich et al. 2008, Narici et al. 1996), training was performed using slow movements. Similarly, in the present study, RT exercises were performed relatively slow (2 s eccentric, 1 s pause, 2 s concentric phase), which may explain the fact that no changes in Q30 were observed in the RT group.

To the author's knowledge, there are no studies examining the effects of PLYO on the rate of muscle activation, and how these changes influence RTD in youths. Data in adults are both limited and inconsistent. Behrens et al. (2014) observed after 8-weeks of PLYO a significant increase in EMG RMS, accompanied by similar increases in RTD and jump performance. The authors concluded that the neural adaptations and greater RTD contributed to the enhanced jump performance. Conversely, Kyrolainen et al. (2005) found that 15-weeks of PLYO exercise resulted in substantial increases in RTD in the absence of any significant changes in the rate of muscle activation. Kubo et al. (2007) arrived at similar conclusions as Kyrolainen and colleagues, attributing jump performance differences between PLYO and RT after 12-weeks of training, to factors other than neuromuscular enhancements. The discrepancy between these studies may be related to the duration of training. It is possible that neural enhancements are time- and volume-dependant. For instance, it is possible that neural enhancements during PLYO training are greatest at the beginning of the training programs (0-8 weeks), after which a possible muscle hypertrophy, especially of explosive type II muscle fibers may explain increases in performance. In fact, Macalouso et al (2012) demonstrated that one bout of plyometric exercise resulted in local muscle damage, particularly to type IIx muscle fibres. In the present study, training was only 8 weeks in duration. Therefore, it is possible that during this time period, enhancement in neuromuscular function is more

dominant, contributing to the increase in pRTD and jump performance (see below). Future research is needed to determine a possible time- or volume-dependent effect on neuromuscular function and how this influences the RTD and performance in both, children and adults.

8.3.2 RTD Kinetics:

RTD was examined during various time epochs to determine the acceleration of torque development over the contraction time (Andersen & Aagaard 2006). In the present study, a similar response to training was observed in RTD kinetics in both isometic and isokinetic contractions. That is, both RT and PLYO resulted in significantly faster RTD compared to the CON. This was especially apparent from 50-150ms during isometric contraction and at 100-200ms in the isokinetic contraction. Thus, it appears that both RT and PLYO resulted in a similar enhancement in terms of acceleration of torque development, and during the same time epochs.

Research examining these responses in children and youth are limited. To the authors knowledge only one study in youth has examined RTD at differing time intervals (0-50,0-100,0-200ms) and found there to be no statistically significant increases in RTD when compared to a control group (Waugh et al. 2014). In adults, Andersen et al. (2009) observed only late phase (> 100ms) RTD enhancements in response to 14-weeks of RT. Aagaard et al. (2002) and Blazevich et al (2008) observed significant improvements in RTD during the early phases of the contraction (0-100 ms) with no observed alteration in late phases of RTD (>100ms) following long (14-weeks) and short (6-weeks) duration RT programs, respectively. Oliveira et al. (2013) observed significant RTD enhancements in the early (<100ms) and late (>100ms) phases of the contraction after 6-weeks of RT.

The differing results in the aforementioned studies among adults were attributed to specificity of contraction velocity during training. Those studies which found early rises in RTD post-training, utilized an explosive form of RT, where each phase of the contraction was performed as fast as possible (Aagaard et al. 2002; Blazevich et al. 2008; Oliveira et al. 2013). Conversely, other studies, where resistance exercises were performed under a slow and controlled manner, found there to be a late phase of RTD increase (Andersen et al. 2009). In PLYO training, exercises are performed explosively throughout the movement. In adults, only early rises in RTD (0-50 ms) were observed to significantly increase as a result of PLYO training (Behrens et al. 2014). To the author's knowledge, there are no studies which have examined how RTD is affected in various time epochs as a result of PLYO in children and youth.

Early rises in RTD have been attributed to neural properties, and the late rise in RTD is related to increases in maximal strength (Andersen & Aagaard 2006; Aagaard et al. 2002). In the present study, RTD following both RT and PLYO, improved similarly in early and late time epochs. Since RT exercises were relatively slow and controlled, it would seem that the results of the present study are not in agreement with those reported in adults. Among adults, when RTD examined at different time epochs is normalized for maximal strength, those studies which focused on explosive contraction velocity training demonstrated a significantly faster normalized RTD in the early phases of the contraction (Aagaard et al. 2002; Tillin et al. 2012; Oliveira et al. 2013), whereas the slow-contraction velocity training resulted in no change in normalized RTD kinetics (Andersen et al. 2009). In the current study, when the change in PT was added as a covariate, no changes in RTD kinetics were observed across all groups. Future research

is needed to examine the mechanisms influencing early and late phases of the contraction and how these differ between training modalities.

8.3.3 Torque Kinetics:

Torque kinetics is arguably one of the most important strength parameters, as it allows for temporal visualization of how strength is developed (Aagaard et al 2002). This variable reflects the specific time history of the contraction, which is ultimately determined by all factors which influence the RTD. Much like RTD kinetics, early rises in the contraction can also be attributed to intrinsic properties (muscle composition and rate of muscle activation), and late rises are related to increases in maximal strength (Andersen & Aagaard 2006; Aagaard et al. 2002). In the present study, torque kinetics were examined in terms of the time required to reach a given percentage of PT. Thus, the effect of training-induced changes in PT are accounted for. Additionally, it is important to note that a reduction in the time required to reach a given torque percentage reflects an enhancement in torque kinetics.

When changes in torque kinetics in the isometric contractions were examined, no significant differences were observed between groups. Nevertheless, visual inspection of the mean responses (Figure 3a) reveals a pattern in which PLYO elicited faster torque-kinetics post-training compared to pre-training, whereas both RT and CON showed no apparent change from pre-to-post intervention (Figure 3a). The lack of a statistically significant difference may be related to the relatively small statistical power (partial eta = 0.04) to detect such a difference. To the author's knowledge, the present study is the first to examine how torque kinetics in children and youth responds to either RT or PLYO. In adults, Andersen et. al. (2009) observed that the slow-velocity RT resulted in no change

and even some reduction in torque kinetics following 14-weeks of training. In the present study, the response to slow-velocity RT in youth was similar to that observed by Andersen et al. (2009) in adults. Thus, it is suggested that the observed increases in pRTD and RTD kinetics from pre-to-post intervention in the RT group were largely due to increases in maximal strength.

Although information regarding the effects of PLYO training on torque kinetics is limited in children as well as in adults, insight may be gained by examining similar training modalities and sports which are characterized by similar movement velocity principles. Dotan et al. (2012), using a cross-sectional design, examined strength-normalized torque kinetics in young male gymnasts and untrained boys. Dotan and colleagues observed that strength-normalized torque kinetics were up to 20% faster in the gymnasts compared to the untrained boys. These differences between groups were attributed to observed differences in the rate of muscle activation measure (Q30), which may have been the result of the explosive nature of gymnastics training. Similarly, the previous RT studies in adults which focused on explosive fast velocity contractions resulted in early increases in strength-normalized torque-kinetics, which were also attributed to neuromuscular enhancement (increases in REI , RMS EMG) in the early phases of the contraction (Aagaard et al. 2002; Tillin et al. 2012). In the present study, statistical significance was not attained in the changes in Q30 or torque kinetics. However, the pattern of results suggests that explosive training (PLYO) may result in enhanced rate of muscle activation (Q30) and faster torque development (kinetics) during the early phase of contraction. It is possible that the magnitude of response in youth is

lower, compared with that of adults. Therefore, future studies examining the effect of explosive training on torque kinetics in youth will require a larger sample size.

8.4 Jump Performance:

To determine how each training modality affected functional explosive power, performance in three types of vertical jumps was examined (CMJ, SJ and DJ). Two of the vertical jump (CMJ and DJ) movements were used to induce the stretch-shorting cycle. During stretch-shortening cycle training (PLYO), elastic energy is stored in muscle and tendon structures in the eccentric phase (muscle lengthening) and is reused in the concentric phase (muscle shortening) (Faigenbaum et al. 2009). The other jump (SJ), was used to examine how training affected performance in the absence of an action which elicited components of the stretch-shortening cycle.

When the SJ was examined, both RT (+8%) and PLYO (+14%) significantly increased, compared to the CON (+2%) who showed little to no change. However, only PLYO was found to be statistically different from the CON (Figure 9b). Data examining both training modalities in children and adults have found similar increases in SJ performance post-training (Kubo et al. 2007; Kotzamanidis et al. 2006; Behrens et al. 2013; Diallo et al. 2001). In adults, both pRTD and PT are related to SJ performance (Kubo et al. 2007; Behrens et al. 2013). No such data are available in youth. In the present study, the change in pRTD during isometric contraction was significantly related to the improvement in SJ height in the group as a whole (Table 14). The change in pRTD in the isokinetic contraction was moderately related (r = 0.33) to the increase in SJ height only in the PLYO group. No significant correlation was observed between the change in PT and the change in SJ height. Thus, the results suggest that it is the increase in pRTD,

as seen especially in the PLYO group, which could possibly contribute to the enhancement in jump performance.

When the CMJ was examined, no significant changes were observed between groups (Figure 9a). Previous studies examining the effect of PLYO training for short (< 6 weeks) and long (6-14 weeks) durations reported significant increases in CMJ height in both youth and adults (Campillo et al. 2015; Diallo et al 2001;Kubo et al. 2007; Chaouachi et al. 2014; Thomas et al. 2009; Faigenbaum et al. 2007;Behrens et al. 2014). In the present study, there was inter-individual variability within the PLYO group, where 10 of the 13 participants improved CMJ height. It is possible that, with the relatively low sample size in the current study, the change was insufficient to statistically demonstrate the beneficial effects of the training protocol. On the other hand, RT responses were similar to previous studies which have shown RT does not consistently result in improved CMJ performance in youth and adults (Faigenbaum et al. 2007; Kubo et al. 2007).

When performance in the DJ was examined, there were no statistically significant increases amongst the groups ($p = 0.1$). Nevertheless, as was the case in the CMJ, the pattern of results was similar to that seen in the SJ. That is, the PLYO group increased in jump height by 5%, while the RT and CON groups showed little to no change (Figure 9c). As was the case in SJ, the change in pRTD was correlated with the change in DJ height, but only in the PLYO group, suggesting that an increase in explosive strength resulted in enhanced jump performance. These results are in line with previous studies in children and adults which demonstrated improved DJ performance following PLYO training (Kubo et al. 2007;Kyrolainen et al. 2005; de Villarreal et al. 2008), attributing

enhancements in DJ height to increases in pRTD (Kyrolainen et al. 2005;Kubo et al. 2007).

The specificity of PLYO training in the present study may have played a role in the observed differences in jump performance. The exercises performed during training focused on explosiveness, in both the vertical and horizontal directions, where the goal was not necessarily on maximizing jump height. This instructional specificity could possibly offer an explanation as to why the PLYO group did not demonstrate enhancements in CMJ performance. Furthermore, the CMJ exercises were included in the training program only during the initial two weeks of the intervention. It is possible that this lack of specificity in the later part of the training program resulted in an attenuated response post-intervention. An additional explanation for the lack of improvement in CMJ could be attributed to the high degree of coordination required to perform this task. A review by Behm and Colado (2012) reported that balance and coordination demands resulted in force and power decrements up to 30% in adults.

Training-induced changes in the PLYO group were most evident in SJ performance. This was likely due to the specific characteristics of the SJ, requiring relatively lower level of coordination (compared with the CMJ and DJ). The SJ allows for a clear indication of how voluntary rapid strength (explosiveness) was developed, in the absence of any counter-movement or arm-swing. This improvement was likely due, at least in part, to enhanced pRTD, and RTD kinetics in the early phases of the movement, as demonstrated in the isometric KE. These changes were accompanied by a trend toward an increase in isometric rate of muscle activation at the beginning of contraction, although this was not observed during isokinetic contraction. While it was expected that

pRTD would be affected by increased tendon stiffness, as reflected by lower EMD, this was not observed in this study. Furthermore, the effect of neuromuscular function on jump performance was not directly measured in the present study. Therefore future research should attempt to examine the effect of neuromuscular enhancements *during* the given performance task to determine its contribution.

9.0 Limitations and Future Directions

In the present study, one of the main objectives was to examine the explosive strength response to differences types of training, along with possible explanatory mechanisms. It is possible that the current sample size was insufficient to demonstrate some of the expected effects of training (RT and PLYO). However, it should be noted that the sample size was similar or even greater than most other training studies in youth. Our initial sample size calculation (Appendix) suggested that 18 participants per group should be examined. We initially tested 18 participants in each group. Unfortunately, mainly due to injuries unrelated to the present study, our final sample size was smaller than desired (RT = 14, PLYO = 13, CON = 14). Future studies should attempt to utilize a greater sample size.

The present study focused on explosive strength in terms of performance, torque measurements and possible related mechanisms (muscle size, Q30 and EMD). We did not examine tendon stiffness. Changes in EMD, which is highly related to tendon stiffness in both children and adults (Waugh et al. 2013), was used to reflect changes in tendon stiffness. No significant changes were measured in EMD. It is possible that the change in EMD is not sufficiently sensitive to detect training-induced changes in tendon stiffness. Therefore, future studies examining mechanisms responsible for training-induced

adaptations in explosive strength should also examine tendon stiffness directly. Additionally, while there is a large gap in our knowledge regarding training-induced adaptations in explosive strength, especially in children, there is also a gap in our understanding of training-induced adaptations in maximal strength (MVC), particularly in the responsible mechanisms in youth. Future studies should examine training-induced adaptations in both, maximal and explosive strength, as well as the related mechanisms.

The present study examined the effect of 8 weeks of training, assuming that neuromuscular adaptations occur relatively early in training. However, it is possible that a longer duration (or higher volume) of training is required to detect these neuromuscular changes, especially in a sample of athletes, as opposed to untrained individuals. Short duration studies in adults (< 8 weeks) have previously demonstrated training-induced adaptations in neuromuscular function (Tillin et al. 2012). However, in view of the small magnitude of the training effects and high variability in children, a longer intervention may be necessary. Future studies should examine neuromuscular adaptations over a longer duration in athletes and non-athletes. Additionally, examination of timeline of changes (i.e, measured at different intervals during training) may provide insight into the contribution of different mechanisms to improvements in performance.

In the present study we examined jump performance (open-kinetic, multi-joint movement) and explanatory factors (i.e. torque, electrical activity within the muscle) during isolated, closed-kinetic, uniplanar movements. However, training was performed using compound, multi-joint exercises. Thus, muscle assessment was not specific to the training mode. Future studies are needed to examine neuromuscular function

(force/torque, electrical activity within the muscle) during training-specific movements (i.e., during jumping).

A possible limitation in the present study is the current method used for the examination of tendon stiffness. In the present study, EMD, used to reflect tendon stiffness, was examined under voluntary conditions and was found to be unchanged post-intervention. A sensitive and precise method for EMD examination is with the use of evoked twitch contractions (Grosset et al. 2005; Murphy et al. 2014). The evoked twitch technique results in complete muscle activation, which may not occur during a voluntary maximal exertion (Grosset et al. 2005). This can allow for a more accurate and consistent assessment of EMD. Additionally, the use of evoked twitch can allow for comparison of the evoked (involuntary) torque with the maximal voluntary torque, thus allowing for some reflection on any changes in voluntary muscle activation. Future studies examining muscle activation and musculotendinous stiffness should attempt to utilize evoked contractile methods to ensure complete muscle activation, and associated maximal tendon stretch.

10.0 Conclusion:

The present study demonstrates that both, RT and PLYO effectively improved muscle performance in adolescent male athletes. More specifically, the findings suggest that RT had greater effect on maximal strength, while PLYO had greater effect on explosive strength and jump performance. The greater increases in explosive strength in the PLYO group were also accompanied by trends towards greater enhancement in the rate of muscle activation

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Appendices:

Appendix A – Tables

Table 4.

Peak Torque (PT)

	RT		PLYO		CON		ANOVA - ONEWAY	RM-ANOVA			GAIN SCORE	COVARIATE – mCSA[#]	
	pre	post	pre	post	pre	post	Group - Baseline	Pre-Post effect	Group effect	Group x Pre-Post	Interaction	Pairwise	Interaction	pairwise
90°	141.1 ± 34.7	172.8 ± 46.2 *	151.3 ± 47.1	168.5 ± 44.5 *	127.5 ± 26.1	127.5 ± 25.6	p = 0.2	***p* = 0.0001**	p = 0.05	***p* = 0.001**	***p* = 0.001**	**RT > CON**	***p* = 0.006**	**RT > CON**
130°	110.1 ± 21.5	125.1 ± 27.1 *	112.9 ± 30.2	127.5 ± 32.6 *	100.5 ± 24.2	99.2 ± 15.7	p = 0.3	***p* = 0.0001**	p = 0.06	***p* = 0.001**	***p* = 0.001**	**RT & PLYO > CON**	***p* = 0.002**	**RT & PLYO > CON**
240°/s	62.5 ± 13.2	70.2 ± 16.6 *	74.3 ± 24.5	79.1 ± 18.5	61.3 ± 17.5	60.5 ± 13.8	p = 0.1	***p* = 0.03**	***p* = 0.02**	***p* = 0.03**	***p* = 0.03**	**RT > CON**	***p* = 0.06**	N/A

*Indicates significant increase from pre-to-post intervention ($p < 0.017$)

- mCSA covariate p values: 90°: $p = 0.4$; 130°: $p = 0.5$; 240°/s: $p = 0.8$

Table 5a.

Torque Kinetics - 90° Values are mean ± SD. Values in ANOVA columns are p values.

	RT		PLYO		CON		ANOVA - ONEWAY	ANOVA - THREE WAY (INCLUSIVE)						
Time to - %	pre	post	pre	post	pre	post	Group - Baseline	Group	Time	Pre-post	Group x Pre-post	Pre-post x Time	Group x Time	Group x Pre-post x Time
10	54.3 ± 13.5	52.8 ± 10.4	49.1 ± 7.4	41.2 ± 7.3	49.1 ± 18.5	53.2 ± 17.5	0.4							
20	81.6 ± 19.3	79.8 ± 14.5	73.4 ± 9.68	63.8 ± 9.3	75.5 ± 21.9	78.1 ± 21.8	0.4							
30	105.4 ± 24.6	103.3 ± 18.5	94.5 ± 13.1	83.4 ± 11.7	98.2 ± 31.2	99.2 ± 25.1	0.5							
40	130.2 ± 31.8	126.9 ± 22.6	115.7 ± 17.3	102.6 ± 14.9	120.4 ± 42.5	120 ± 28.7	0.5							
50	157.8 ± 40.9	153.3 ± 27.2	139.1 ± 23.3	123.6 ± 19.6	144.5 ± 55.6	142.7 ± 32.9	0.5							
60	189.8 ± 52.3	186.6 ± 33.5	167.1 ± 31.7	148.2 ± 25.9	175.9 ± 83.6	172 ± 39.6	0.6	0.4	**0.0001**	0.1	0.2	0.2	0.4	0.6
70	247.3 ± 91.4	234.5 ± 44.6	208.8 ± 208.8	180.3 ± 34.7	220.8 ± 128.4	225.7 ± 71.7	0.5							
80	352.1 ± 183.7	332.8 ± 82.1	266.6 ± 83.4	231.5 ± 50.5	294.6 ± 166.5	321.4 ± 134.5	0.3							
90	681.2 ± 429.5	600 ± 232.2	454.7 ± 152.1	390.8 ± 129.3	562.3 ± 297.5	560.1 ± 228.1	0.2							
100	1854.1 ± 717.8	1739 ± 624.8	1055.1 ± 339.5	998.1 ± 432.2	1842.6 ± 644.4	1646.7 ± 497.2	**0.02**							

Table 5b.

Torque Kinetics - 130° Values are mean ± SD. Values in ANOVA columns are p values.

	RT		PLYO		CON		ANOVA - ONEWAY	ANOVA - THREE WAY (INCLUSIVE)						
Time to - %	pre	post	pre	post	pre	post	Group - Baseline	Group	Time	Pre-post	Group x Pre-post	Pre-post x Time	Group x Time	Group x Pre-post x Time
10	50 ± 13.2	48.5 ± 9.6	40.6 ± 16.1	43.3 ± 8.5	44.6 ± 15.2	54.7 ± 13.9	0.3							
20	74.9 ± 22.8	74.1 ± 15.1	64.8 ± 21.7	67.4 ± 15.4	77 ± 18.3	81.8 ± 18.4	0.4							
30	95.4 ± 22.6	94.9 ± 19.6	85.2 ± 27.1	87.9 ± 23	102.5 ± 5	104.6 ± 22.1	0.3							
40	116.3 ± 29	114.5 ± 24.2	105.7 ± 33.9	107.6 ± 30.9	126.4 ± 34.1	127.1 ± 25.9	0.4							
50	145.4 ± 55.1	135.9 ± 30.1	129.1 ± 43.8	128 ± 39.2	150.7 ± 42.3	152.6 ± 32	0.6							
60	174.2 ± 72.8	161.8 ± 38.1	155.8 ± 55.7	151.9 ± 50.1	179 ± 51.5	188.8 ± 48.1	0.9	**0.03**	**0.0001**	0.6	0.1	0.3	0.07	**0.01**
70	212.9 ± 100.7	196.6 ± 51.3	196.5 ± 85.9	194.6 ± 84.8	223.8 ± 66.2	247.4 ± 83.5	0.9							
80	307.4 ± 187.8	300.4 ± 144.7	281.6 ± 173.8	249.8 ± 140.7	333.2 ± 143.6	377.1 ± 152.5	0.9							
90	610.8 ± 370.9	594.7 ± 312.3	477.1 ± 348.7	439.9 ± 284	859.1 ± 589	932.8 ± 548.7	0.1							
100	1657.9 ± 370.9	1984.4 ± 689.8	1995.4 ± 753.2	1410 ± 682.7	2128.5 ± 506.9	1991.6 ± 524.1	0.1							

Table 5c.

Torque Kinetics - 240° Values are mean ± SD. Values in ANOVA columns are p values.

	RT		PLYO		CON		ANOVA - ONEWAY	ANOVA - THREE WAY (INCLUSIVE)						
Time to - %	pre	post	pre	post	pre	post	Group - Baseline	Group	Time	Pre/ post	Group x Pre-post	Pre-post x Time	Group x Time	Group x Pre-post x Time
10	37.6 ± 8.6	37.2 ± 14.2	39.5 ± 7.9	35.6 ± 10.6	34.4 ± 11.1	36.3 ± 12.3	0.9							
20	57.9 ± 8.5	58.3 ± 11.6	61.3 ± 10.8	57.3 ± 9.3	56.1 ± 11	56.9 ± 12.7	0.8							
30	74.8 ± 8.8	76.8 ± 12.3	79.8 ± 13.9	76.4 ± 10.3	75.7 ± 15.7	73.9 ± 16.1	0.8							
40	91.7 ± 10.2	95.2 ± 14.7	98.3 ± 17.8	95.2 ± 14.7	94 ± 21.3	90.4 ± 19.3	0.7							
50	109.6 ± 12.7	113.4 ± 16.2	118 ± 21.6	113.4 ± 16.2	112.5 ± 25.7	107.6 ± 22.8	0.8	0.8	**0.0001**	**0.03**	0.4	**0.0001**	0.9	0.09
60	129.8 ± 15.6	132.3± 17.1	138 ± 24.3	132.3 ± 17.1	131.1 ± 29.1	125.9 ± 26.7	0.9							
70	151.2 ± 18.7	151.6 ± 18.1	158.4 ± 26.1	151.6 ± 18.1	151.6 ± 31	146.5 ± 31	0.9							
80	173.4 ± 21.4	170.8 ± 18.4	180 ± 26.9	170.8 ± 18.4	173.8 ± 30.3	169.7 ± 35	0.9							
90	198 ± 22	191.9 ± 17.8	204.1 ± 27.1	191.9 ± 17.8	199.3 ± 26.1	195.4 ± 35.1	0.7							
100	246.4 ± 24.3	236.6 ± 16.9	253.3± 27.4	236.6 ± 16.9	249.3 ± 26.6	242.8 ± 35.1	0.7							

Table 6

Peak Rate of Torque Development (pRTD)

	RT		PLYO		CON		ANOVA - ONEWAY	RM-ANOVA				COVARIATE – ΔPT[#]	
	pre	post	pre	post	pre	post	Group - Baseline	Pre-Post effect	Group effect	Group x Pre-Post	Pairwise	Group x Pre-Post	pair wise
90°	677.8 ± 242.8	765.9 ± 266.9*	726.9 ± 284.9	882.9 ± 216.6*	620 ± 178.8	619.7 ± 169.2	*p* = 0.4	***p* = 0.001**	*p* = 0.1	***p* = 0.02**	**PLYO > CON**	*p* = 0.1	N/A
130°	618.2 ± 216.1	695 ± 235.7*	612.1 ± 235.8	713.2 ± 196.2*	476.9 ± 112.2	474.8 ± 124.5	*p* = 0.1	***p* = 0.003**	***p* = 0.01**	*p* = 0.06	N/A	*p* = 0.2	N/A
240°/s	395.4 ± 75.3	434.8 ± 105.9*	460.6 ± 142.5	471.4 ± 116.4	386.5 ± 67.1	396.5 ± 69.8	*p* = 0.1	***p* = 0.02**	*p* = 0.1	*p* = 0.2	N/A	p = 0.2	N/A

*Indicates significant increase from pre-to-post intervention ($p < 0.017$)

- PT covariate p values: 90°: $p = 0.08$; 130°: $p = 0.04$; 240°/s: $p = 0.5$

Table 7a.

Kinetics of RTD - 90°

	RT		PLYO		CON		ANOVA - ONEWAY		ANOVA - THREE WAY (INCLUSIVE)						
Time (ms)	pre	post	pre	post	pre	post	Group - Baseline		Group	Time	Pre_post	Group x Pre_post	Pre_post x Time	Group x Time	Group x Pre_post x Time
0-50	447.3 ± 224.6	556.3 ± 247.9	543.3 ± 211.2	661.6 ± 180.9	447.7 ± 154.1	411.5 ± 149.7	0.4	ABSOLUTE	0.07	**0.0001**	**0.002**	**0.02**	**0.04**	0.4	0.7
50-100	620.9 ± 256.2	752.6 ± 277.3	723.3 ± 290.9	852.2 ± 234.9	604 ± 193.4	595.1 ± 176.8	0.4								
100-150	614.3 ± 226.6	734.4 ± 251.3	703.2 ± 272.5	840.5 ± 222.5	601.4 ± 179.2	602.3 ± 170.1	0.5								
150-200	469.8 ± 170.5	557.1 ± 171.6	523.2 ± 178.9	636.4 ± 178.1	465.5 ± 137.4	460.1 ± 160.9	0.6	COVARIATE -ΔPT	0.2	**0.0001**	0.3	0.1	0.6	0.8	0.9
200-250	321.5 ± 139.8	369.1 ± 98.9	349.7 ± 152.1	381.6 ± 184.2	291.2 ± 80.2	274.7 ± 98	0.5								

Table 7b.

Kinetics of RTD - 130°

Time (ms)	RT pre	RT post	PLYO pre	PLYO post	CON pre	CON post	ANOVA - ONEWAY Group - Baseline	ANOVA - THREE WAY (INCLUSIVE)	Group	Time	Pre_post	Group x Pre_post	Pre_post x Time	Group x Time	Group x Pre_post x Time
0-50	407.1 ± 199.4	468.8 ± 200.6	492.4 ± 232.2	531.6 ± 179.6	321.1 ± 112.5	314.6 ± 140.2	0.1	**ABSOLUTE**	**0.01**	**0.0001**	**0.004**	0.07	0.1	**0.02**	0.7
50-100	582.3 ± 239.4	673.6 ± 249.3	600.6 ±243.8	691.3 ± 208.2	450.1 ± 137.8	455.1 ± 132.1	0.1								
100-150	581.4 ± 220.2	673.5 ± 228.1	573.2 ± 209.4	684.7 ± 183.4	464.1 ± 117.4	462.6 ± 116.7	0.2								
150-200	381.6 ± 122.8	455.9 ± 114.8	372.7 ± 107.6	479.7 ± 112.2	359.1 ± 82.5	352.1 ± 86.4	0.9	**COVARIATE - - ΔPT**	0.06	**0.0001**	0.3	0.2	0.7	0.3	0.9
200-250	231.6 ± 101.3	263.2 ± 134.1	232.6 ± 102.1	259.9 ± 134.2	211.2 ± 66.2	213.4 ± 56.5	0.8								

Table 7c.

Kinetics of RTD - 240°/s

	RT		PLYO		CON		ANOVA - ONEWAY		ANOVA - THREE WAY (INCLUSIVE)						
Time (ms)	pre	post	pre	post	pre	post	Group - Baseline		Group	Time	Pre_post	Group x Pre_post	Pre_post x Time	Group x Time	Group x Pre_post x Time
0-50	316.3 ± 86.3	335.7 ± 46.1	374.3 ± 139.7	371.4 ± 113.1	324.1 ± 81.1	341.1 ± 88.5	0.3	ABSOLUTE	0.07	**0.0001**	**0.00001**	**0.04**	0.07	**0.02**	**0.01**
50-100	372.2 ± 87.5	397.3 ± 51.9	431.6 ± 132.3	429.3 ± 121.3	370.2 ± 87.6	390.3 ± 84.9	0.2								
100-150	333.7 ± 70.6	393.5 ± 94.3	390.1 ± 136.8	424.2 ± 118.7	342.3 ± 74.7	344 ± 61.8	0.3								
150-200	273.9 ± 84.2	377.3 ± 142.6	363.6 ± 180.9	434.1 ± 127.9	273.3 ± 72.2	256.7 ± 85.1	0.1	COVARIATE - ΔPT	0.09	**0.0001**	**0.0002**	0.7	0.2	0.1	0.2
200-250	180 ± 82.8	275.9 ± 142.4	253 ± 160.2	295.8 ± 129.4	198.8 ± 98.2	153.5 ± 112.5	0.3								

Table 8

Electromechanical Delay (EMD)

	RT		PLYO		CON		ANOVA - ONEWAY	RM-ANOVA			
	pre	post	pre	post	pre	post	Group - Baseline	Pre-Post effect	Group effect	Group x Pre-Post	Pairwise
90°	47.1 ± 9.5	47.8 ± 7.91	43.8 ± 8.3	41.4 ± 7.1	48.3 ± 9.5	49.7 ± 14.6	$p = 0.3$	$p = 0.8$	$p = 0.1$	$p = 0.1$	N/A
130°	40.9 ± 7.1	38.2 ± 6	45.6 ± 12.8	42.6 ± 9.2	47.9 ± 13.8	47 ± 11	$p = 0.2$	$p = 0.03$	$p = 0.1$	$p = 0.6$	N/A
240° /s	38.1 ± 6.3	36.5 ± 7.1	37.5 ± 9.7	37.8 ± 10.5	44.3 ± 6.4	45.1 ± 9.7	$p = 0.05$	$p = 0.8$	$\mathbf{p = 0.02}$	$p = 0.5$	N/A

*Indicates significant increase from pre-to-post intervention ($p < 0.017$)

Table 9

Integrated sEMG (Q30)

	RT		PLYO		CON		ANOVA - ONEWAY	RM-ANOVA				Covariate - AMPpk	
	pre	post	pre	post	pre	post	Group - Baseline	Pre-Post effect	Group effect	Group x Pre-Post	Pairwise	Group x Pre-Post	pairwise
90°	0.00032 ± 0.00014	0.00035 ± 0.00014	0.00048 ± 0.00058	0.00060 ± 0.00044	0.00039 ± 0.00018	0.00037 ± 0.00022	$p = 0.5$	$p = 0.1$	$p = 0.2$	$p = 0.1$	N/A	$p = 0.09$	N/A
130°	0.00044 ± 0.00026	0.00052 ± 0.00029	0.00061 ± 0.00042	0.00066 ± 0.00065	0.00046 ± 0.0003	0.00039 ± 0.00035	$p = 0.3$	$p = 0.6$	$p = 0.3$	$p = 0.4$	N/A	$p = 0.3$	N/A
240°/s	0.00053 ± 0.00029	0.0006 ± 0.0004	0.00052 ± 0.00034	0.00055 ± 0.00031	0.00053 ± 0.00029	0.00052 ± 0.00056	$p = 0.9$	$p = 0.5$	$p = 0.9$	$p = 0.7$	N/A	$p = 0.8$	N/A

*Indicates significant increase from pre-to-post intervention ($p < 0.017$)

Table 10

Integrated sEMG (Q30) - with participant removed from PLYO

	RT		PLYO		CON		ANOVA - ONEWAY	RM-ANOVA				Covariate - AMPpk	
	pre	post	pre	post	pre	post	Group - Baseline	Pre-Post effect	Group effect	Group x Pre-Post	Pairwise	Group x Pre-Post	pair wise
90°	0.00032 ± 0.00014	0.00035 ± 0.00014	0.00032 ± 0.00017	0.00049 ± 0.00020	0.00039 ± 0.00018	0.00037 ± 0.00022	$p = 0.4$	***p* = 0.02**	$p = 0.5$	***p* = 0.01**	**PLYO > CON**	***p* = 0.02**	N/A
130°	0.00044 ± 0.00026	0.00052 ± 0.00029	0.00053 ± 0.00033	0.00052 ± 0.00042	0.00046 ± 0.0003	0.00039 ± 0.00035	$p = 0.7$	$p = 0.9$	$p = 0.3$	$p = 0.3$	N/A	$p = 0.5$	N/A
240 °/s	0.00053 ± 0.00029	0.0006 ± 0.0004	0.00052 ± 0.00035	0.00057 ± 0.00032	0.00053 ± 0.00029	0.00052 ± 0.00056	$p = 0.9$	$p = 0.5$	$p = 0.9$	$p = 0.7$	N/A	$p = 0.8$	N/A

*Indicates significant increase from pre-to-post intervention ($p < 0.017$)

Table 11

Performance Jumps

	RT		PLYO		CON		ANOVA - ONEWAY	RM-ANOVA			
	pre	post	pre	post	pre	post	Group - Baseline	Pre-Post effect	Group effect	Group x Pre-Post	Pairwise
CMJ	30.7 ± 3.6	29.3 ± 4.5	31.1 ± 4.9	31.4 ± 3.9	30.2 ± 4.6	30.2 ± 4.4	$p = 0.8$	$p = 0.2$	$p = 0.7$	$p = 0.09$	N/A
SQUAT	23.7 ± 4.4	25.8 ± 5.1 *	24.6 ± 3.5	28.6 ± 4.4 *	27.1 ± 5.5	27.7 ± 5.1	$p = 0.1$	$\mathbf{p = 0.001}$	$p = 0.3$	$\mathbf{p = 0.002}$	PLYO > CON
DROP	30.8 ± 6.1	30.3 ± 4.6	30.1 ± 4.8	31.6 ± 4.8	29.9 ± 4.8	29.5 ± 4.7	$p = 0.8$	$p = 0.6$	$p = 0.8$	$p = 0.1$	N/A

*Indicates significant increase from pre-to-post intervention ($p < 0.017$)

Table 12.

ΔPT vs. ΔpRTD.

	Whole group	RT	PLYO	CON
KE 90°	0**.46** (0.003)	0.48 (0.07)	0.47 (0.1)	0.24 (0.4)
KE 130°	0.27 (0.08)	- 0.08 (0.7)	0.25 (0.4)	0.24 (0.4)
KE 240°/s	0**.68** (0.0001)	**0.76** (0.002)	**0.71** (0.007)	**0.56** (0.03)

Values in parentheses are *p*-values. (*r*-values in bold are statistically significant)

Table 13.

ΔPT vs. ΔJumps.

	Whole group	RT	PLYO	CON
ΔCMJ				
KE 90°	-0.20 (0.2)	-0.06 (0.8)	-0.11 (0.7)	-0.07 (0.7)
KE 130°	0.005 (0.9)	-0.27 (0.3)	0.53 (0.06)	0.18 (0.5)
KE 240°/s	0.03 (0.8)	-0.08 (0.7)	0.40 (0.1)	-0.40 (0.1)
ΔSJ				
KE 90°	-0.08 (0.6)	**-0.65** (0.01)	-0.11 (0.7)	0.39 (0.1)
KE 130°	0.18 (0.2)	-0.22 (0.4)	0.11 (0.7)	0.02 (0.9)
KE 240°/s	0.11 (0.4)	**-0.53** (0.04)	0.43 (0.1)	0.11 (0.7)
ΔDJ				
KE 90°	**-0.36** (0.02)	**-0.70** (0.005)	-0.18 (0.5)	-0.09 (0.7)
KE 130°	0.26 (0.08)	0.09 (0.7)	0.54 (0.05)	0.22 (0.4)
KE 240°/s	0.01 (0.9)	-0.37 (0.1)	0.45 (0.1)	**-0.58** (0.02)

Values in parentheses are *p*-values. (*r*-values in bold are statistically significant)

Table 14.

ΔpRTD vs. ΔJumps.

	Whole group	RT	PLYO	CON
ΔCMJ				
KE 90°	-0.11 (0.4)	-0.46 (0.09)	0.07 (0.8)	-0.01 (0.9)
KE 130°	-0.26 (0.1)	-0.47 (0.09)	-0.24 (0.4)	0.17 (0.5)
KE 240°/s	-0.03 (0.8)	0.20 (0.4)	0.13 (0.6)	-0.05 (0.8)
ΔSJ				
KE 90°	**0.38** (0.01)	-0.19 (0.5)	0.48 (0.09)	**0.56** (0.03)
KE 130°	**0.41** (0.008)	0.23 (0.4)	0.22 (0.4)	**0.53** (0.04)
KE 240°/s	-0.02 (0.8)	-0.50 (0.06)	0.33 (0.2)	0.24 (0.3)
ΔDJ				
KE 90°	0.07 (0.6)	-0.30 (0.2)	0.28 (0.3)	-0.01 (0.9)
KE 130°	0.19 (0.2)	0.19 (0.5)	0.10 (0.7)	0.10 (0.7)
KE 240°/s	-0.16 (0.3)	-0.31 (0.2)	0.08 (0.7)	-0.43 (0.1)

Values in parentheses are *p*-values. (*r*-values in bold are statistically significant)

Table 15.

ΔPT vs. ΔmCSA

	Whole group	RT	PLYO	CON
KE 90°	**0.42** (0.006)	0.28 (0.3)	0.29 (0.3)	0.33 (0.2)
KE 130°	0.25 (0.1)	0.39 (0.1)	0.39 (0.1)	-0.45 (0.1)
KE 240°/s	0.19 (0.2)	0.44 (0.1)	0.44 (0.1)	0.51 (0.05)

Values in parentheses are *p*-values. (*r*-values in bold are statistically significant)

Table 16.

ΔpRTD vs. ΔmCSA

	Whole group	RT	PLYO	CON
KE 90°	0.03 (0.8)	0.09 (0.7)	0.09 (0.7)	-0.35 (0.2)
KE 130°	-0.09 (0.5)	-0.28 (0.3)	-0.28 (0.3)	-0.32 (0.2)
KE 240°/s	0.14 (0.3)	0.36 (0.1)	0.36 (0.1)	0.34 (0.2)

Values in parentheses are *p*-values. (*r*-values in bold are statistically significant)

Table 17.

ΔpRTD vs. ΔEMD

	Whole group	RT	PLYO	CON
KE 90°	0.007 (0.9)	-0.06 (0.8)	-0.09 (0.7)	0.35 (0.2)
KE 130°	0.09 (0.5)	-0.07 (0.7)	0.43 (0.1)	0.04 (0.8)
KE 240°/s	0.14 (0.3)	0.20 (0.4)	0.31 (0.2)	-0.03 (0.9)

Values in parentheses are *p*-values. (*r*-values in bold are statistically significant)

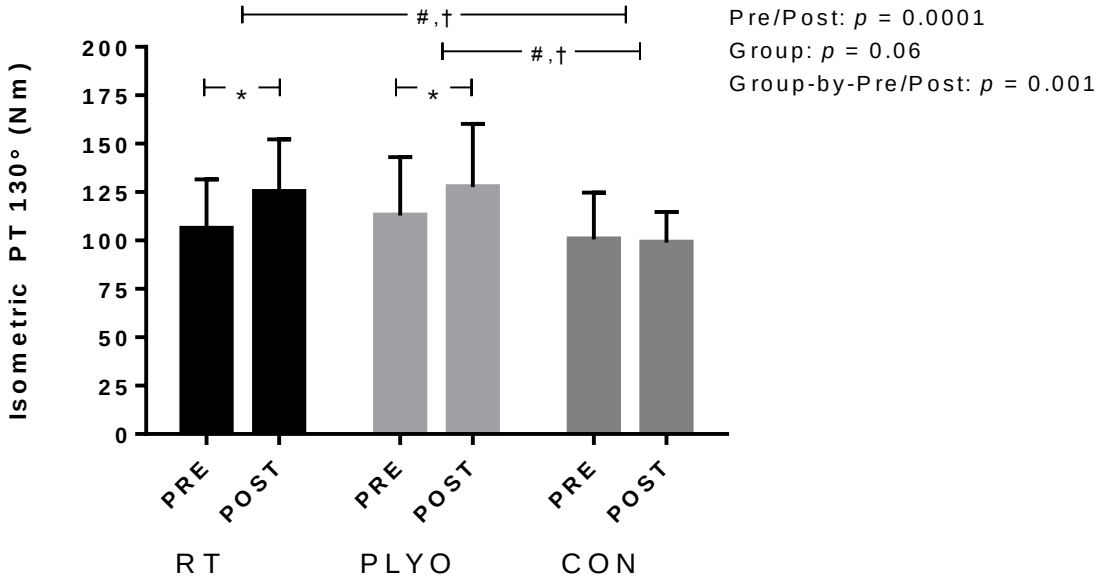
Table 18.

ΔpRTD vs. ΔQ30

	Whole group	RT	PLYO	CON
KE 90°	-0.11 (0.4)	-0.23 (0.4)	-0.42 (0.1)	-0.09 (0.7)
KE 130°	0.20 (0.2)	-0.09 (0.7)	0.26 (0.3)	-0.08 (0.7)
KE 240°/s	-0.04 (0.7)	-0.24 (0.3)	-0.53 (0.06)	0.36 (0.2)

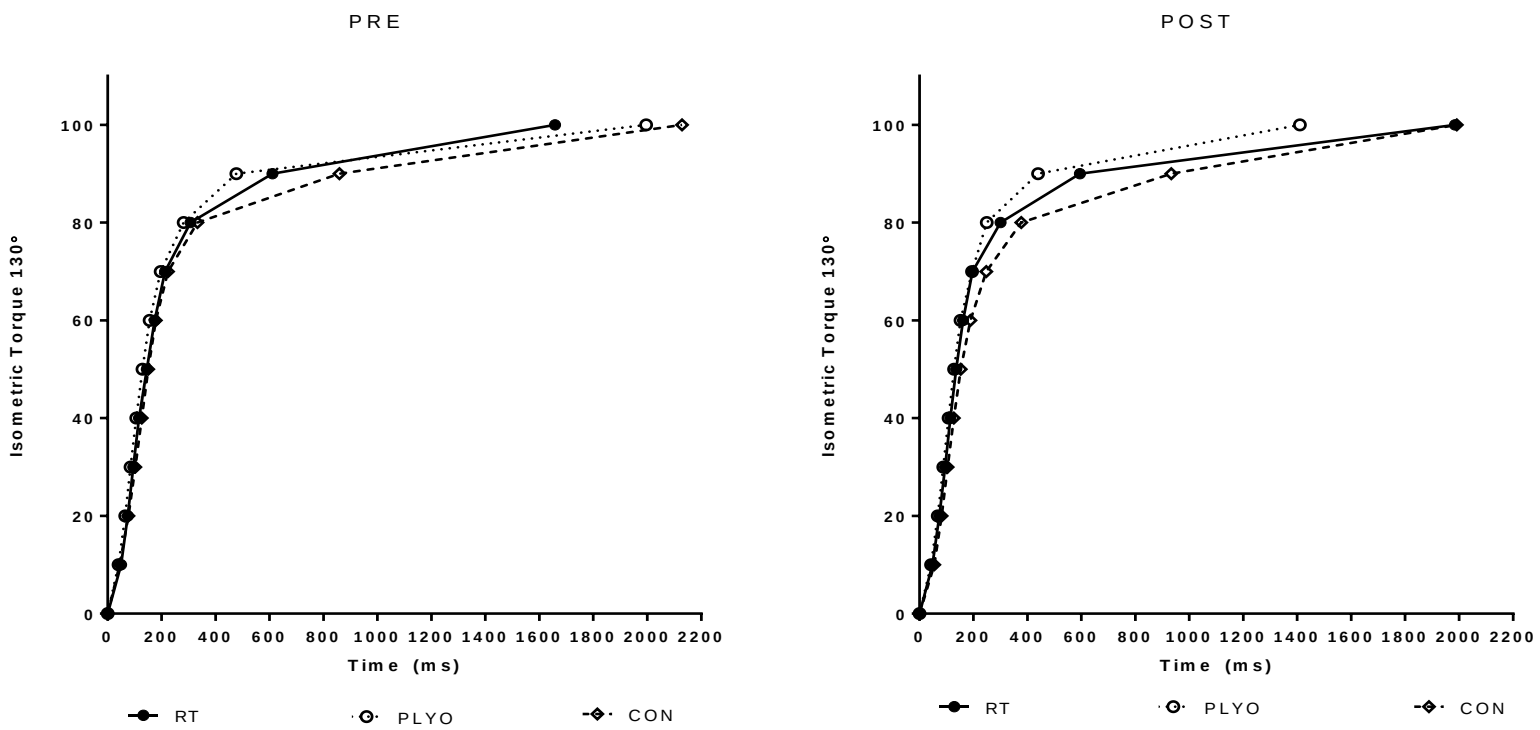
Values in parentheses are *p*-values. (*r*-values in bold are statistically significant)

Appendix B - Figures

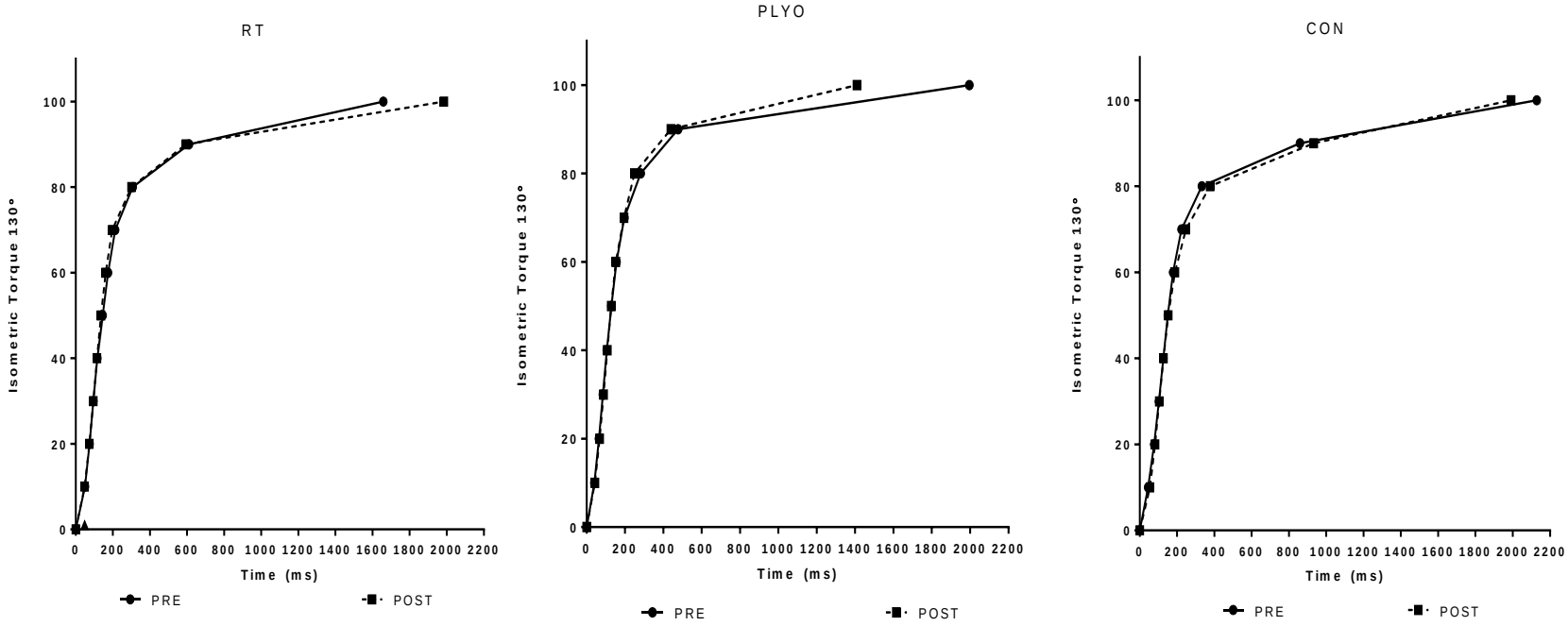


Absolute isometric peak torque (PT) at 130° Pre- and Post-intervention in the Resistance training (RT), Plyometric training (PLYO) and Control (CON) groups. *Denotes significant increase within group from pre-post intervention ($p < 0.017$). # Denotes significant pairwise group differences in absolute changes in PT ($p < 0.05$). † Denotes significant pairwise group difference with the use of covariate (ΔmCSA) in the analysis ($p < 0.05$)

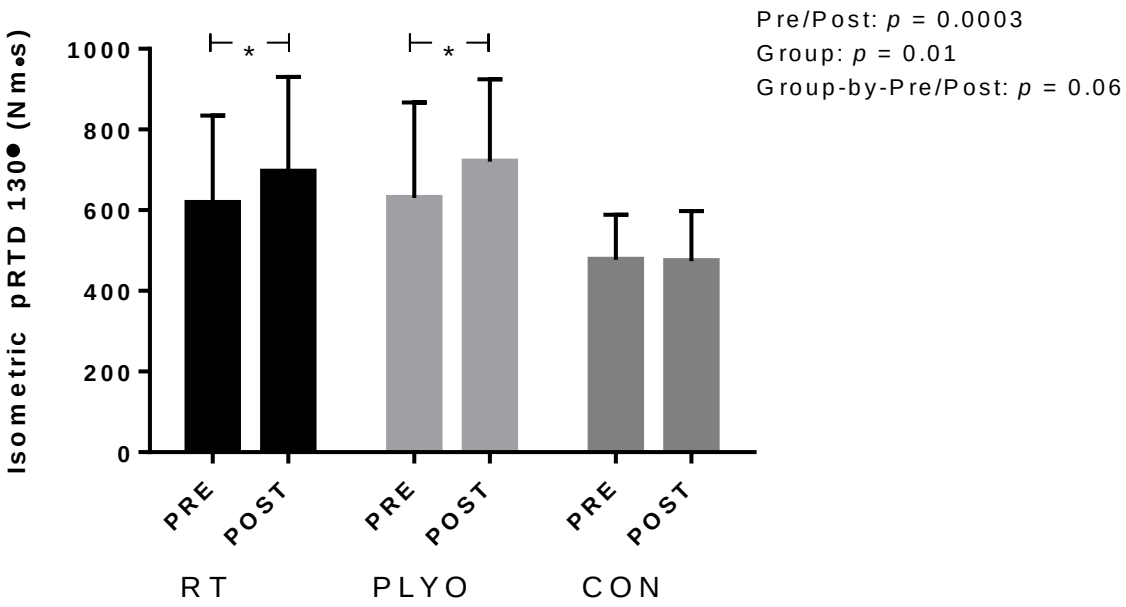
group: p = 0.03
time: p = 0.0001
pre-post: p = 0.6
group x pre-post: p = 0.1
pre-post x time: p = 0.3
group x time: p = 0.07
group x pre-post x time: p = 0.01



Isometric Torque (T) over the time of contraction pre-intervention (left) and post-intervention (right). Torque is expressed at percentage of peak torque



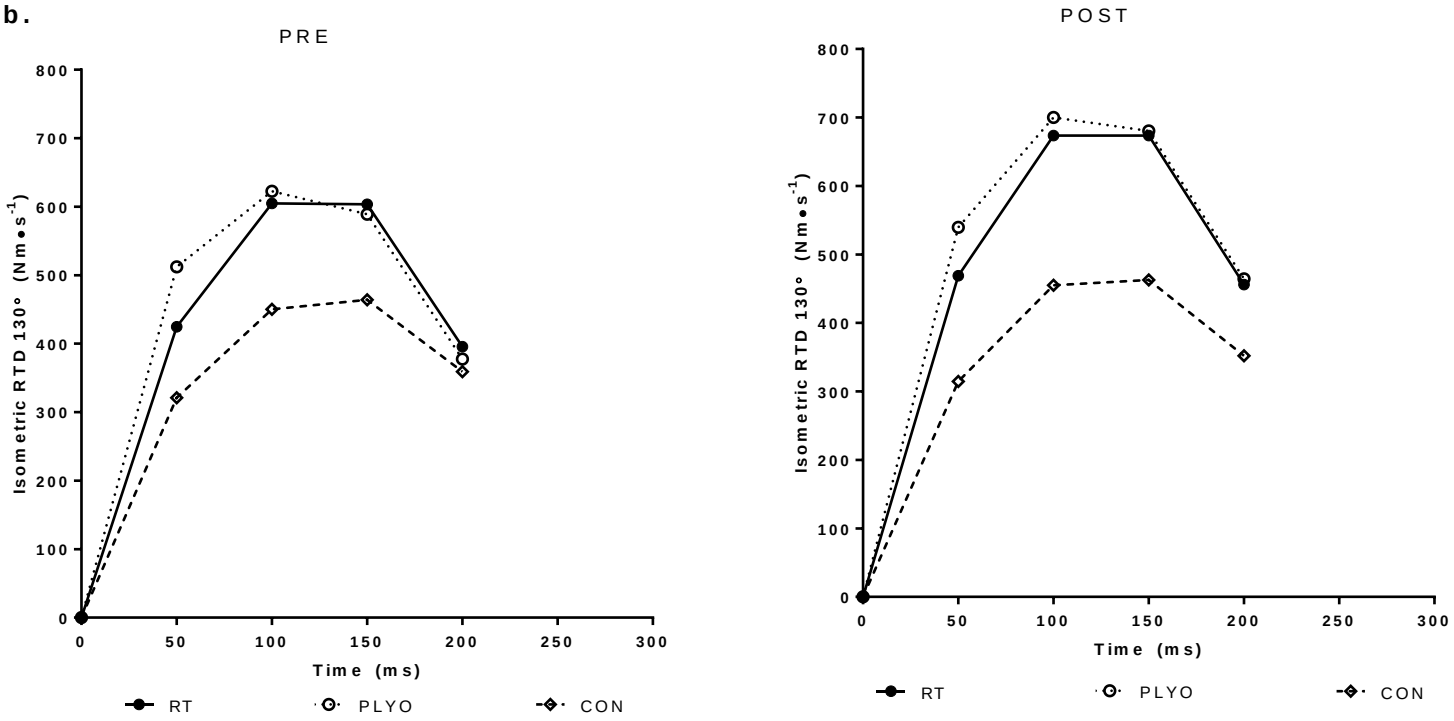
Isometric torque (T) over the time of contraction pre-intervention and post-intervention for each group individually. Torque is expressed at percentage of peak torque



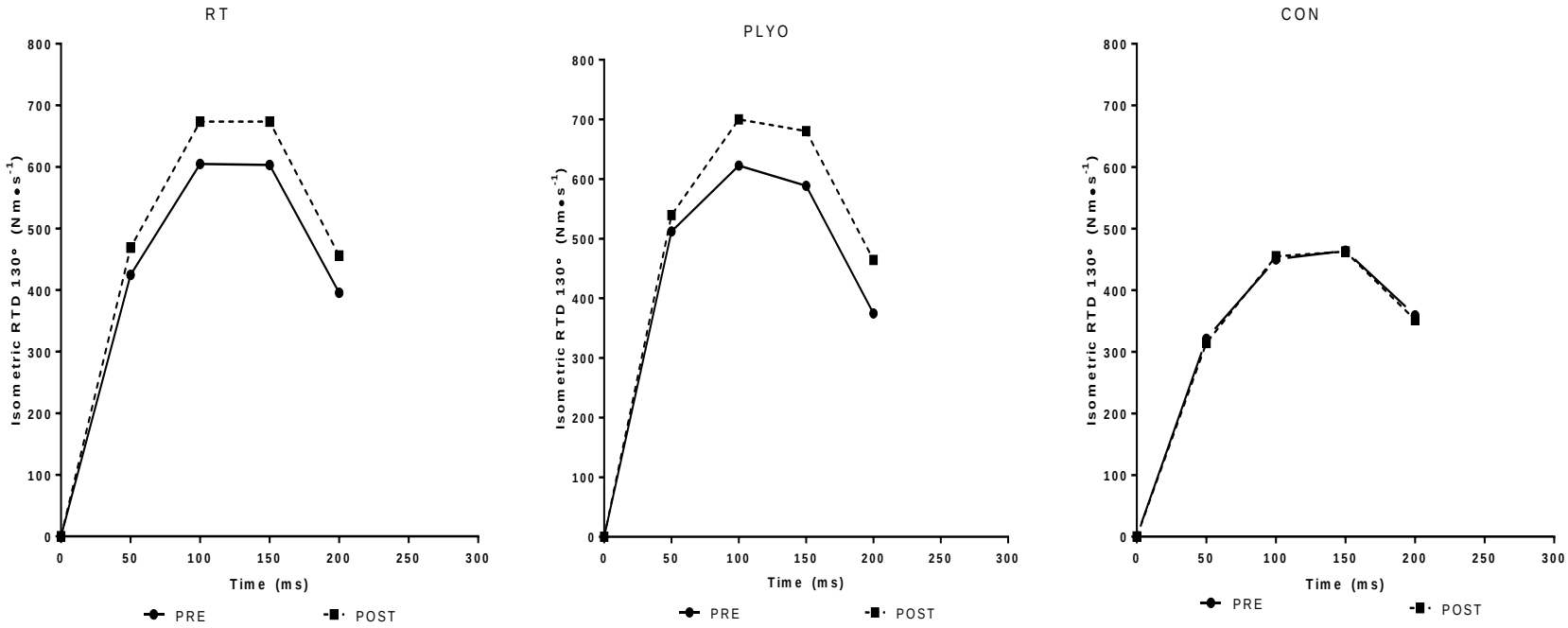
Absolute isometric peak rate of torque development (pRTD) at 130° Pre- and Post-intervention in the Resistance training (RT), Plyometric training (PLYO) and Control (CON) groups. *Denotes significant increase within group from pre-post intervention ($p < 0.017$).

group: p = 0.01
time: p = 0.0001
pre-post: p = 0.004
group x pre-post: p = 0.07
pre-post x time: p = 0.3
group x time: p = 0.02
group x pre-post x time: p = 0.7

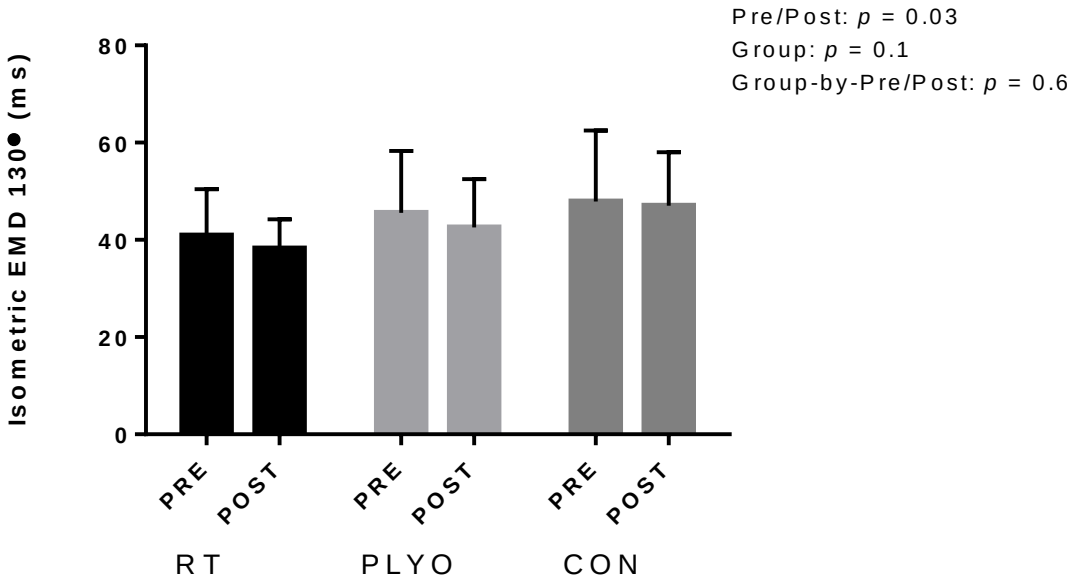
b.



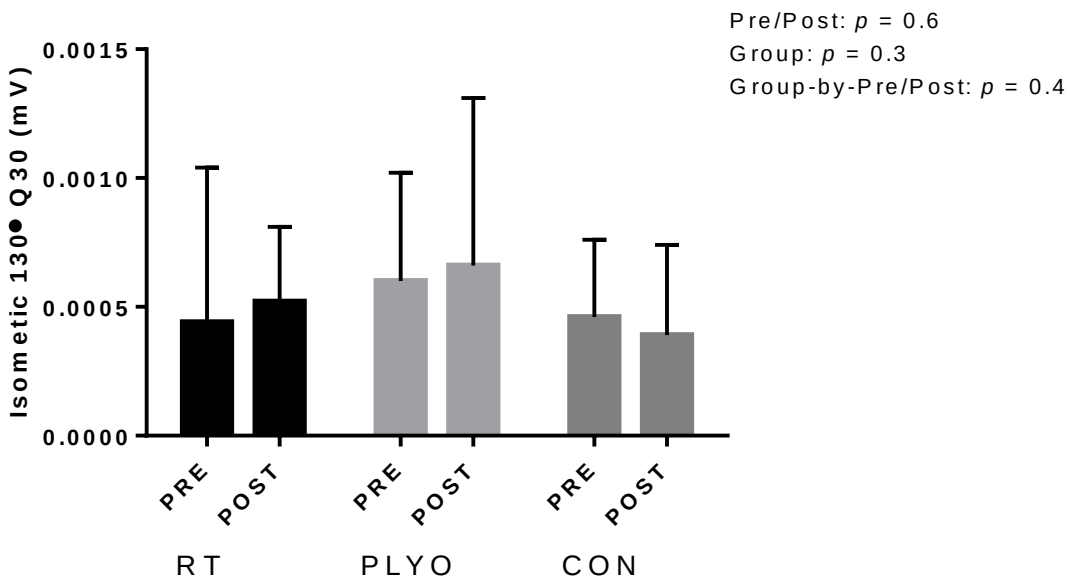
Isometric rate of torque development (RTD) over the time of contraction pre-intervention (left) and post-intervention (right).



Isometric rate of torque development (RTD) over the time of contraction pre-intervention and post-intervention for each group individually.



Absolute isometric electromechanical delay (EMD) at 130° Pre- and Post-intervention in the Resistance training (RT), Plyometric training (PLYO) and Control (CON) groups.



Absolute isometric electromechanical delay (EMD) at 130° Pre- and Post-intervention in the Resistance training (RT), Plyometric training (PLYO) and Control (CON) groups

Appendix C – Sample Size Calculation

To estimate sample size we used a recent paper by Behrens, Mau-Moeller and Bruhn (2014) for our estimation. Behrens, Mau-Moeller and Bruhn (2014) examined the effect of an 8-week plyometric intervention on leg extension RTD in competitive men volleyball players (24±3 yrs). Behrens, Mau-Moeller and Bruhn (2014) found there to be a significant improvement in the RTD during the initial 50 ms of the contraction in the plyometric training group compared with the control group who underwent no training intervention (pre ($308.7 N \cdot m \cdot s^{-1}$ difference between groups). If we estimate the standard deviation to be 250 $N \cdot m \cdot s^{-1}$ (estimated from graph), the calculated sample size is 11 individuals per groups ($\alpha = 0.05$, $1-\beta = 0.80$). It should be noted that the above sample size calculation was based on a study that examined adults and that plyometric training was compared with a non-training condition (rather than resistance training intervention). Therefore, it is possible that a greater sample size would be needed in the present study, where boys are examined, rather than men, and where ploymetric training effects are compared with resistance training effects. To account for possible lower between-group differences, as well as possible participant attrition, a sample size of 18 participants per group will be used.

(http://www.stat.ubc.ca/~rollin/stats/ssize/n2.html)

Appendix D - Informed Consent/Assent Forms

INFORMATION AND CONSENT TO PARTICIPATE IN RESEARCH

Plyometric and resistance training in children

You and your child are being invited to participate in a research study being conducted by the investigators listed below. Prior to participating in this study please read this form to find out about the purpose and the tests of this study. For the tests you will have to visit the Applied Physiology Laboratory (WH 23, Brock University). This study is part of the Faculty of Applied Health Sciences of Brock University.

INVESTIGATORS:	**DEPARTMENT:**	**CONTACT:**
Dr. Bareket Falk	FAHS, Brock University	(905) 688-5550 ex. 4979
Brandon McKinlay	FAHS, Brock University	(905) 688-5550 ex. 5623
Raffy Dotan	FAHS, Brock University	(905) 688-5550 ex. 5272
Dr. Craig Tokuno	FAHS, Brock University	(905) 688-5550 ex. 4365

PURPOSE:

The purpose of the study is to investigate muscle function response to plyometric or resistance training. Specifically, we are interested in the changes in voluntary rapid force production, that can occur after an 8-week plyometric or resistance training intervention in children.

DESCRIPTION OF TESTING PROCEDURES:

If your child agrees to volunteer for this study, he will visit our laboratory for two sessions of testing: each **60-90 min** in duration (2-3 hours in total)**.** Between testing sessions he will participate in either a plyometric or resistance training intervention (8 weeks, 3 sessions per week). At the end of the study, he will be given a summary of the findings, upon request. It is recommended that he comes prepared to exercise in athletic shoes, shorts and a short sleeved shirt.

Please note that participation in this study will not affect the status of your child within the Elite Soccer Development Academy.

Your child will undergo the measurements and procedures listed below; please note that in all questionnaires, your child may choose not to answer any question. Your child may also choose not to participate in any procedure listed below.

A. Assessments (pre- and post-training):

1. Your child will complete several questionnaires, outlining his medical history, training history and leisure-time physical activities. In all questionnaires, your child may choose not to answer any question without penalty.

2. Body Composition: we will measure your child's height, weight and body fat percentage. Body fat percentage will be estimated using skinfold thicknesses and bioelectrical impedance analysis (BIA). The BIA assessment requires your child to stand on a scale and grasp handles. A mild electrical current (50kHz, 800μA) will pass through your child's hands and feet. This current cannot be felt and causes no harm. Valid measurements require abstinence from exercise, and eating/drinking for at least 12, and 4 hours, respectively, prior to testing.

3. We will determine your child's thigh muscle thickness using the B-mode ultrasound system. This procedure involves the application of gel to the quadriceps region (thigh) of your child's legs and moving an ultrasound probe over this region. This procedure is quick and causes no pain or discomfort.

4. To assess your child's muscle activity, we will use electromyography (EMG). We will need abrade, and clean a small area on the thigh, arm and the back of the neck with alcohol and preparatory gel. We will then affix small surface electrodes to the skin on these areas using thin double-sided adhesive tape. Some redness and skin irritation may occur from this preparation process, but this will subside and can be alleviated using moisturizing lotion. The surface electrodes and EMG system records the electrical activity generated by the muscles. No electrical current is used. The recording is painless and does not involve any discomfort.

5. The measurement of your child's muscular force will involve several maximal (all out) contractions of the arms and legs (bending and straightening the elbow and the knee). It will also involve performance of maximal vertical jumps. This procedure may result in muscle soreness within 48 hours of the test. If these effects do occur, it will only be temporary.

6. A saliva sample will be collected to determine the relationship between hormonal levels (cortisol and testosterone) and muscle function during exercise. This sample will be collected using specifically designed swabs which will be brushed up against the cheek.

B. Training Protocol:

Your child will be randomly assigned to take part in an 8-week plyometric or resistance training intervention program (3 sessions/week), held within BP Sports Park (CAT Soccer Field) in Welland.

Plyometric Training Intervention:
Each session will consist of 5 minutes of warm-up, 15 minutes of plyometric training exercises, and 5 minutes of cool down. Exercises will include jumps, hops and bounds of varying volumes and intensities. The plyometric training protocol has been structured in a manner which allows your child to safely progress through the various exercises, minimizing stress placed on joints and allowing for optimal power-associated muscular adaptations to occur. Prior to the administering the intervention, your child will be properly shown how to safely conduct various exercises in a controlled and safe manner by the research team.

Resistance Training Intervention:
Each session will consist of 5 minutes of warm-up, 15 minutes of on field resistance training exercises, and 5 minutes of cool down. Resistance exercises will include lunges, squats and various resistance band/medicine ball techniques, at varying volumes and intensities. The resistance training protocol has been structured in a manner which allows your child to safely progress through the various exercises, minimizing stress placed on joints and allowing for optimal strength associated muscular adaptations to occur. Prior to the administering the intervention, your child will be properly shown how to safely conduct various exercises in a controlled and safe manner by the research team.

CONFIDENTIALITY:

All data collected during this study will remain confidential and will be stored in offices and on secured computers to which only the principal and co-investigators have access. You should be aware that the results of this study will be made available to scientists, through publication in a scientific journal but your child's name and any personal data **will not** appear in compiling or publishing these results. The name of the soccer organization may appear in the report. Data will be kept for 5 years after the date of publication, at which time all information will be destroyed. Additionally, you will have access to your child's data, as well as group data when it becomes available and if you are interested. This can be provided to you by simply contacting the principal investigator.

PARTICIPATION AND WITHDRAWAL:

You and your child can choose whether to participate in this study or not and may withdraw or remove your child's data from the study, by simply telling one of the investigators. In case you

or your child chooses to withdraw from the study by telling the investigator, you will be asked whether his data can still be used for analysis. In case your child withdraws by not showing up, partial data will be used. Your child may also refuse to answer any questions posed to him during the study and still remain as a participant in the study. The investigators reserve the right to withdraw your child from the study if they believe that it is necessary.

You child should not feel obligated to participate in the study and his decision to participate or not participate or withdraw from participation will in no way impact the standing of your child within the Elite Soccer Development Academy.

If your child choses to withdraw from the study, he will still be able to participate in the training.

COMPENSATION:

You and your child will be compensated $20 total (gift card to a local store, pro-rated in case participants do not complete the study) for travel expenses, parking and time specific to the testing sessions at Brock University. Parking expenses will be reimbursed whether you complete the study or decide to withdraw from it.

RISKS AND BENEFITS:

Participation will allow you and your child to become exposed to a research protocol, potentially improve your child's physical performance, contribute to the advancement of science, and gain personal and general knowledge about your child's fitness.

The only foreseeable risks involved in participation include:

a) Possible muscle soreness within 48 hours of training or testing. If this occurs, it will only be temporary.
b) Redness and skin irritation may result from mildly abrading the skin, cleaning the skin with alcohol, and applying surface recording electrodes with electrolyte gel. Washing the skin and applying skin lotion immediately after testing will minimize skin irritation
c) Some questionnaires may pose a potential embarrassment. In such a case, your child need not reply to any question they do not wish to. Potentially sensitive questionnaires will be filled by each participant individually, in a separate room.
d) Possible muscle fatigue from plyometric or resistance exercises. This fatigue will only be present during the initial phases of the program and is no reason for alarm. As the study progresses participants will adapt to the training stimulus and fatigue will no longer be present. This phenomenon is typical of most physical training programs. It is possible that fatigue associated with training will affect the ability of players to complete the practice. However, the coach is aware of the training programs and will be able to modify the practice workload.
e) With any participation in physical activity there is a risk of injury. Therefore, at each training session there will be one or more team members who have certified first aid training.

FEEDBACK and STUDY RESULTS:

Your child's and group results will be provided to you upon request. If any results outside the norm appear during data collection, you and your child will be informed within one month.

RIGHTS OF RESEARCH PARTICIPANTS:

You will receive a signed copy of this consent form. The study has been reviewed and received ethics clearance though the REB (file #13-305). If you have any pertinent questions about your rights as a research participant, please contact the Brock University Research Ethics Officer (905 688-5550 ext 3035, reb@brocku.ca).

INFORMATION:

Please contact Dr. Bareket Falk at 905 688-5550 (ext. 4979), bfalk@brocku.ca or Brandon McKinlay at 905 688-5550 (ext. 5623), bm13tj@brocku.ca if you have any questions about the study.

I HAVE READ AND UNDERSTAND THE ABOVE EXPLANATION OF THE PURPOSE AND PROCEDURES OF THE PROJECT. I HAVE ALSO RECEIVED A SIGNED COPY OF THE INFORMATION AND CONSENT FORM. MY QUESTIONS HAVE BEEN ANSWERED TO MY SATISFACTION AND I AGREE TO PARTICIPATE IN THIS STUDY.

SIGNATURE OF PARENT/GUARDIAN DATE

PRINTED NAME OF PARTICIPANT

In my judgment the participant is voluntarily and knowingly giving informed consent and possesses the legal capacity to give informed consent and participate in this research study.

SIGNATURE OF INVESTIGATOR DATE

INFORMATION AND ASSENT TO PARTICIPATE IN RESEARCH

Plyometric and resistance training in children

Hello,

I am Dr. Falk and I am a researcher from Brock University. I am inviting you to take part in a research study that I am doing with Brandon McKinlay who is a student at Brock. Before deciding if you want to take part please read this form to find out about the study.

Why are we doing this study?

We are doing this study is to investigate how your muscles respond to different types of physical training. We are interested in the changes in explosive power that can occur after an 8-week plyometric training (jumps, hops and bounds) or resistance training (lunges, squats and exercises using rubber bands and medicine balls).

What will happen to you if you are in the study?

If you agree to volunteer for this study, you will:

1. Visit our lab at Brock University where we will do some tests and take some measurements which are described below. Nothing you do will hurt and the tests will take about an hour or an hour and a half to complete

2. Take part in either a plyometric or resistance training program for 8 weeks (3 sessions each week). The researchers will tell you which program you will do. Please come prepared to exercise in athletic shoes, shorts and a short sleeved shirt.

3. After the 8 week training program is finished, you will visit our lab at Brock again to repeat the tests and measurements you did before.

Do you have to participate?

No. It will help our study if you volunteer but you don't have to participate. Whether or not you participate in this study will not affect your position or how people treat you within the Elite Soccer Development Academy.

If you decide to participate now and then later change your mind, you can tell the researchers that you don't want to be in the study anymore. If this happens you can still come to training if you want, you just won't come to the lab afterwards.

If there are any tests that you do not want to do or questions that you do not want to answer, you can tell the researcher and you won't have to do them

We want you to feel comfortable so remember that you can ask the researchers questions at any time.

What kinds of test and measurements will we do?

1. You will fill out several questionnaires on your medical history, training history and leisure-time physical activities. If you want, you can ask your parents to help you fill out these forms.

2. We will measure your height, weight and body fat percentage. Body fat percentage is measured using skin thicknesses and bioelectrical impedance analysis (BIA). For the BIA assessment you will stand on a scale and grasp some handles. A mild electrical current will pass through your hands and feet. You will not feel the current. It won't hurt and it won't cause any harm. Please do not exercise for at least 12 hours before testing and do not eat for 4 hours before testing.

3. We will measure your thigh muscle thickness using ultrasound. To do this we will put some gel on your thigh and then move an ultrasound wand over the area. This is quick and will not hurt.

4. To assess your muscle activity, we will use electromyography (EMG). We will clean a small area on your thigh, your arm and the back of your neck with alcohol and gel. We will then place small surface electrodes (like stickers) on your skin using thin double-sided tape. Your skin may turn red and be slightly irritated from this process, but this is temporary and can be soothed using moisturizing lotion. The EMG system records the electrical activity your muscles make. No electrical current is used. This does not hurt or cause any harm.

5. To measure your muscle strength, we will ask you to do exercises that involve bending and straightening your arms and legs. We will also ask you to do some vertical jumps. You may feel sore for a couple of days from using your muscles but this will go away.

6. We will collect a saliva (spit) sample to determine the relationship between special hormones in your body and muscle function during exercise. We will collect the sample by using swabs which will be brushed up against your cheek.

What kind of training will you do?

The researchers will assign you to one of two groups. You will train with this group 3 times a week for 8 weeks doing either plyometric or resistance training. The researchers

will pick which training you do. Training will be done at BP Sports Park (CAT Soccer Field) in Welland.

If you are assigned to the group doing **Plyometric Training,** you will do 5 minutes of warm-up, 15 minutes of training exercises, and 5 minutes of cool down. Exercises will include jumps, hops and bounds of. Before the first training session, we will show you how to do the exercises safely.

If you are assigned to the group doing **Resistance Training,** you will do 5 minutes of warm-up, 15 minutes of training exercises, and 5 minutes of cool down. Resistance exercises will include lunges, squats and resistance exercises using rubber bands and medicine balls. Before the first training session, we will show you how to do the exercises safely.

Who will know that you are in the study?

We will write papers about what we find and share the information with other researchers but when we talk about your measurements and how you did, we will not use your name.

Will you get paid for participating?

You and your parents will be given a $20 gift card to a local store (or a $10 gift card if you do not finish the entire study). We will also pay for parking when your parents bring you to the lab.

Are there good things and bad things about being in the study?

By taking part in this study, you will get to see how we do research and contribute to science. You may improve your performance and learn about your fitness.

There are some possible risks that we want you to know about:

a) Your muscles may feel tired or sore after training or testing. This is normal and should not last long. As you get used to the training exercises, your muscles will not feel as tired. Your coach will know if you take part in the study and can change your practice exercises if your muscles are feeling tired.

b) Your skin may look red and feel irritated where the surface recording electrodes are placed (on your thigh, your arm, and the back of your neck) but we will wash these areas of your skin and apply lotion to minimize any discomfort.

c) You may feel embarrassed by some of the questions on the questionnaires. You do not have to answer any question if you do not want to and you will fill out the questionnaire in a separate room by yourself (or with your parent, if you want).

d) Just like anytime you play or exercise, you may get hurt by taking part in any physical activity. If you get hurt, the researchers will make sure that you get help.

What if you have questions about the study?

You can ask us questions at any time. Just contact Dr. Bareket Falk at 905 688-5550 (ext. 4979), bfalk@brocku.ca or Brandon McKinlay at 905 688-5550 (ext. 5623), bm13tj@brocku.ca.
If you would like to find out your results or the results of the group, please ask Dr. Falk at the end of the study.
If you want to part of the study, please print your name below.

_____ _____

SIGNATURE OF PARTICIPANT DATE

_____

PRINTED NAME OF PARTICIPANT

In my judgment the participant is voluntarily and knowingly giving informed consent to participate in this research study.

_____ _____

SIGNATURE OF INVESTIGATOR DATE

Appendix E - Participant Screening and Medical History Questionnaire:

APPLIED PHYSIOLOGY RESEARCH GROUP

DEPARTMENT OF KINESIOLOGY, BROCK UNIVERSITY

Your responses to this questionnaire are confidential and you are asked to complete it for your own health and safety. If you answer "YES" to any of the following questions, please give additional details in the space provided and discuss the matter with one of the investigators. You may refuse to answer any of the following questions.

Name: ———————————————— Date: ————————————————

1. Have you ever been told that you have a heart problem?

YES NO

2. Have you ever been told that you have a breathing problem such as asthma?

YES NO

3. Have you ever been told that you sometimes experience seizures?

YES NO

4. Have you ever had any major joint instability or ongoing chronic pain such as in the knee, back or elbow?

YES NO

5. Have you ever been told that you have kidney problems?

YES NO

6. Have you had any allergies to medication?

YES NO

7. Have you had any allergies to food or environmental factors?

YES NO

8. Have you had any stomach problems such as ulcers?

YES NO

9. When you experience a cut do you take a long time to stop bleeding?

YES NO

10. When you receive a blow to a muscle do you develop bruises easily?

YES NO

11. Are you currently taking any medication (including aspirin) or have you taken any medication in the last two days?

YES NO

12. Is there any medical condition with which you have been diagnosed and are under the care of a physician (e.g. diabetes, high blood pressure)?

YES NO

Appendix F - Godin-Shepard Leisure Time Exercise Questionnaire:

GODIN-SHEPHARD LEISURE-TIME EXERCISE QUESTIONNAIRE

1. Considering a **7-day period** (a week), how many times on the average do you do the following kinds of exercise for **more than 15 minutes** during your **free-time** (write on each line the appropriate number)?

Times Per Week

2. STRENUOUS EXERCISE (HEART BEATS RAPIDLY)
(i.e. running, jogging, hockey, football, soccer, squash, basketball,

cross country skiing, judo, roller skating, vigorous swimming,

vigorous long distance bicycling)

_____

b) MODERATE EXERCISE (NOT EXHAUSTING)
(i.e. fast walking, baseball, tennis, easy bicycling, volleyball,

badminton, easy swimming, alpine skiing, popular and folk dancing)

_____

c) <u>MILD EXERCISE (MINIMAL EFFORT)</u>

(i.e. yoga, archery, fishing from river bank, bowling, horseshoes,

golf, snow-mobiling, easy walking)

_____

3. Considering a **7-day period** (a week), during your leisure-time, how often do you engage in any regular activity long enough to work up a sweat (heart beats rapidly)?

1. OFTEN	**2. SOMETIMES**	**3. NEVER/RARELY**
☐	☐	☐

Appendix G - Training History Questionnaire:

TRAINING HISTORY QUESTIONNAIRE FOR ATHELTES

Please fill in the table below to the best of your knowledge.

If you have any difficulties, discuss the matter with one of the investigators.

Activity/Sport	Level of Competition	# of years	Sessions/week	Min/session	Intensity (light, moderate, intense, very intense)	Seasonal length
Soccer						
Swimming						
Hockey						
Gymnastics						
Running						
Resistance						
Other						

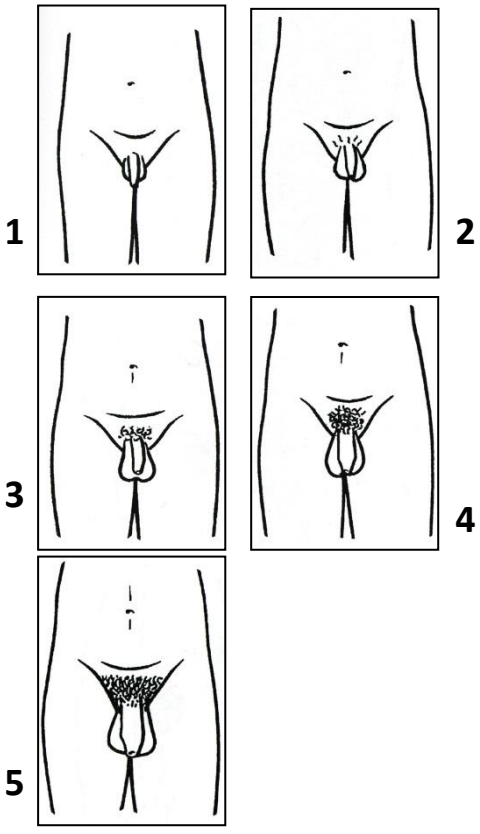
Appendix H - Pubertal Stage Questionnaire (Tanner, 1962)

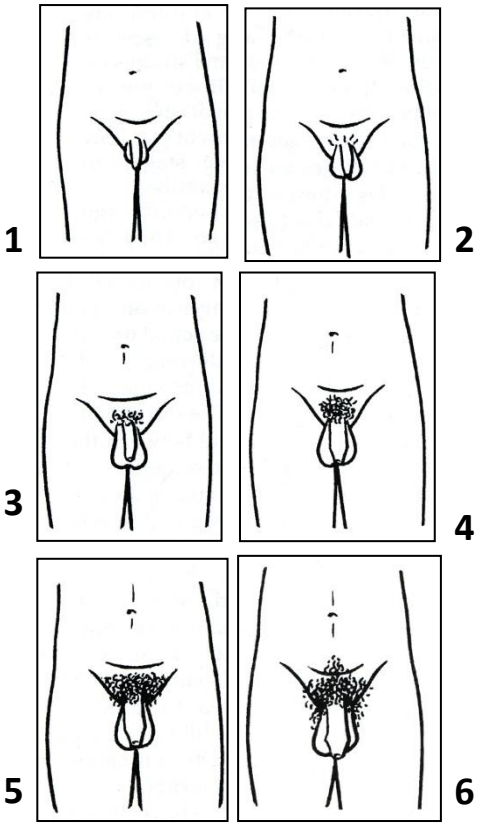
Male Pubertal Stage

This survey will be used to assess the maturational levels of the participant. For each photo choose the appropriate stage and place an X in the corresponding square.

ID: _____ Date: _____

• Please circle the box that looks most like you		• Please look at the pubic hair only • Please circle the box that looks most like you





Appendix I – Dynamic warm-up (15 min)

- Agility ladders
- High knees
- Butt kicks
- Jogging
- Frankenstein's
- Lawn bowlers
- Walking lunges
- Sideways lunges
- Fire hydrants
- Kickbacks

Appendix J – SEMIAN Guidelines

Muscle	
Name	Quadriceps Femoris
Subdivision	vastus lateralis
Muscle Anatomy	
Origin	Proximal parts of intertrochanteric line, anterior and inferior borders of greater trochanter, lateral lip of gluteal tuberosity, proximal half of lateral lip of linea aspera, and lateral intermuscular septum.
Insertion	Proximal border of the patella and through patellar ligament.
Function	Extension of the knee joint.
Recommended sensor placement procedure	
Starting posture	Sitting on a table with the knees in slight flexion and the upper body slightly bend backward.
Electrode size	Maximum size in the direction of the muscle fibres: 10 mm.
Electrode distance	20 mm.
Electrode placement	
- location	Electrodes need to be placed at 2/3 on the line from the anterior spina iliaca superior to the lateral side of the patella.
- orientation	In the direction of the muscle fibres
- fixation on the skin	(Double sided) tape / rings or elastic band.
- reference electrode	On / around the ankle or the proc. spin. of C7.
Clinical test	Extend the knee without rotating the thigh while applying pressure against the leg above the ankle in the direction of flexion.
Remarks	The SENIAM guidelines include also a separate sensor placement procedure for the vastus medialis and the rectus femoris muscle.