Comparisons of Countermovement Jump and Isokinetic Performances in Youth Athletes: Maturation and Early Sport Specialization Considerations

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Thesis Abstract

This thesis examines the impact of maturation status and single versus multiple sport participation on the physical performance of adolescent athletes across 6 studies. *Study 1 investigated the test – retest reliability of isokinetic knee flexion and extension, countermovement jump (CMJ)performance and muscle architecture in adolescents.* Eight ultrasound variables, nine CMJ variables and six isokinetic variables were found to be reliable among this subject group and were subsequently used in the remaining studies. *Study 2 investigated the relationships between isokinetic knee flexor and extensor peak torques, muscle architecture and CMJ performance in adolescent athletes.* The results showed that there were moderate to strong correlations between vastus lateralis muscle thickness and knee extension peak torque at $60°\cdot s^{-1}$ and $300°\cdot s^{-1}$ and CMJ height and its determinants (i.e., take-off velocity, propulsion impulse) mean and peak propulsion power, mean and peak propulsion force, mean and peak braking force. *Before examining the impact of maturation and sport specialization on physical performance a defined method to establish peak height velocity (PHV) was required (study 3). Using a group (n = 65) of adolescent subjects* PHV somatic measurement methods were compared. The results indicated that the equations for PHV estimates in males cannot be used interchangeably and for females even though no statistically significant differences were observed there was a large mean difference between the ages calculated by the different PHV equations. Therefore, practitioners should use consistent methods and only make comparisons with literature that uses the same equation. *Study 4 compared isokinetic peak torque and CMJ variables between athletes of different peak height velocity stages using* the Mirwald equation (2002). The results showed adolescents that are post-PHV perform better than the subjects that are pre or circa-PHV. *Study 5 compared isokinetic peak torque and CMJ performance between average and late maturers based on* the Mirwald equation (2002). The results indicate no significant or meaningful differences between the subjects that are classified as average maturers to those that are considered late maturers. The final study *(study 6)* evaluated subjects based on if they participated in one or multiple sports throughout the year. Subjects that were single sport athletes significantly and meaningfully outperformed multi-sport athletes in the CMJ and isokinetic performance variables. The results of this thesis show that maturation timing as well as participating in a single sport have an impact on how an athlete performs while completing countermovement

jumps and isokinetic dynamometer testing. Since most current research concludes that being a single sport athlete leads to negative affects more research needs to be completed since in this study the subjects did outperform the multiple sport athletes. Future research should examine more performance variables to understand the effects of single versus multiple sport participation as adolescents transition through their maturation in order to make it the safest, healthiest and most beneficial transition.

Chapter 1: Introduction

Currently millions of children are participating in sports worldwide, with 30-45 million in just the United States alone (Brenner, 2016). In 1993, Ericsson et al. published a paper that stated that to become a master of a skill you must put in 10,000 hours of deliberate practice of that specific skill. Even though this research was conducted within the music industry it has transferred into the world of sports to achieve elite performance. This "10,000-hour rule" in turn may have led to an increase in single-sport participation and therefore becoming a single sport athlete at a younger age. Research has been completed to evaluate how early specialization and how being a single sport athlete impacts an individual's participation in sport and how it may increase drop out and injury risk rates (Enoksen, 2011; Indriðadóttir et al., 2015). However, there has been little research on how early sport specialization impacts an athlete's performance in their sport (Fransen et al., 2012).

Dropout rates among all sports show an average dropout rate of 4-5% every year, which is similar to the participation percentage decrease (The Sport & Fitness Industry Association, 2020). Mollerlokken et al. (2015) conducted a systematic review to evaluate drop-out rates among youth soccer athletes ages 10-18 years of age and found an average dropout rate of 26.8% for females and 21.4% for males. These dropout rates are the concern of coaches, trainers and researchers that are trying to improve youth sport participation and develop long-term athletes in a safe, healthy, and enjoyable way. This dropout trend within adolescent athletes has been shown to have a connection between early sport specialization and the demands, stress and higher injury rates that relate to the focus on a single sport early on in adolescents (Enoksen, 2011; Fransen et al., 2012; Indriðadóttir et al., 2015).

In 1988, Patriksson evaluated a group of 657 Swedish youth athletes between the ages of 7 and 18. After six months 13% of the athletes had dropped out and stopped participation in any sport but that half of those athletes returned to a sport (either the same sport or different) within a year. Previous research has listed reason for dropout that range from boredom, not feeling good enough, not liking teammates or coaches, playing other sports, not having enough time, too expensive and injury to name a few (Carlman et al., 2013; Crane & Temple, 2015; Maffulli et al., 2009; Patriksson, 1988).

Maffulli et al. (2009) reported that 8% of Australian adolescent athletes dropped out of their sport due to injuries. Brenner (2016) further examined injury in sport and stated that

~50% of the injuries acquired by these adolescents are from overuse injuries which could be caused by early specialization and single sport focus at too early an age. Hall et al. (2014) and Jayanthi et al. (2015) both conducted studies to evaluate the impact of single sport participation on injury rate. These studies were conducted on subjects ages 12-15 and found that the subject competing in a single sport were one and a half to two times more likely to encounter an injury than those competing in multiple sports (Hall et al., 2014; Jayanthi et al., 2015). The results from Jayanthi et al. (2015) revealed that the older subjects in the study were more likely to be injured than the younger athletes. Based on these results questions arise about the impact of an individual's maturation timing on their sport performance and how that may influence injury. Researchers have evaluated the impact of peak height velocity (PHV) and whether being pre, circa or post-PHV impacts an adolescent athlete (Beunen & Malina, 1988; Malina et al., 2003; Philippaerts et al., 2005; Towlson et al., 2020). Researchers have also evaluated the impacts of being an early, average, or late maturer based on when an individual hits their PHV (Hägg & Taranger, 1991; Till et al. 2017). The results of these studies indicate that maturation phase and timing do affect the performance of these adolescent athletes. The post PHV subjects can create greater forces than the pre and circa-PHV groups and the subjects that do mature later and may be left behind because it took them longer to mature, eventually do "catch up" and in some cases outperform the early and average maturers (Beunen & Malina, 1988; Hägg & Taranger, 1991; Malina et al., 2003; Philippaerts et al., 2005; Till et al. 2017; Towlson et al., 2020). The impacts of PHV may also be seen in the older athletes having a greater chance of injury (Jayanthi et al. 2015). These impacts of maturation timing likely influence on performance but have not been evaluated in relationship to sport specialization and the implications that may have based on the physical changes already occurring in a maturing body.

Based on these past studies there has been more interest in why single sport specialization increases the chance of injury among the youth athlete population. It is also of interest to the long-term athlete development advocators since injury has been shown to be one of the reasons for individuals to drop out of sports. There is a current misconception that to receive a college athletic scholarship or a club contract one must concentrate solely on one sport. The strive to get scholarship money or a contract is a driving force in athletes focusing on participating in just one sport. More research has shown that early sport specialization is not necessary to reach elite status in most sports (Bell et al., 2018; LaPrade, Agel and Baker, 2016; Moesch et al., 2011). Bell et al. (2018) and LaPrade et al. (2016) found that being a multiple sport athlete as an adolescent does not prevent success in most sports that one would specialize in later in life. Certain sports like gymnastics, figure skating, diving and even some swimming disciplines have been shown to have the best success when an individual is still in their adolescent phase and therefore, specialization might need to take place earlier for these individuals. However, with these sports have seen higher dropout rates, gymnastics 20%, than some other sports. These findings were also consistent with the results of Moesch et al. (2011) who found that the athletes that had reached elite status had specialized later in their adolescents and had not participated in as many sport specific training hours as the near elite athletes did. These results show that it is not essential for most athletes to specialize in a specific sport early in their adolescents.

Even though this research exists the number of early specialized and therefore, single-sport athletes is on the rise. This could be due to the Ericsson (1993) article of needing 10,000 hours to master a skill, but it could also be due to financially not being able to afford more than one sport, not having access to the equipment or facilities needed or simply just not having enough time to participate in many sports. The Sport & Fitness Industry Association reported that the number of sports individuals ages 13-17 are participating in is ~1.75, which is the lowest it has been in the last 10 years. The issue with playing one sport is that the constant repetitive motions repeated when completing the same athletic movement in a sport can cause strain and stress injuries (LaPrade, Agel and Baker, 2016). Playing multiple sports could increase the amount of time and individual is competing in sports which may increase injury however, this has little to no research currently to support the claim. Injuries do, however, cause long absences from the sport and can lead an athlete to drop out from the sport (Witt & Dangi, 2018). The early specialization trend is starting to cause concern among researchers, especially those interested in the long-term athlete development, because >25% of youth athletes are dropping out of sports every year which can cause health issues now and in the future for these individuals (Sport & Fitness Industry Association, 2020).

With all the research associated with reasons for dropout from sport among adolescent athletes, there is minimal research on the performance and physical attributes of the athletes participating in single or multiple sports and the differences that may exist between these groups. Therefore, research should be conducted to see if athletes who specialize early and participate in only one sport are developing differently than those late specializers playing multiple sports. Current research findings illustrate that there is a problem with early specialization and the influence is plays on athletes getting injured and/or dropping out from sports all together but there is no current research explaining what potential physical attributes may be contributing to these problems. This research would be able to help coaches, trainers and athletes examine the physical changes among adolescents as they are growing and what training and practices would best benefit the growth of these maturing athletes.

The published research currently investigates the implications of early sport specialization (Bell et al., 2018; LaPrade, Agel and Baker, 2016; Moesch et al., 2011). Most of the research is looking at injury and dropout rates and the negative impacts of specializing in sport at an early age. There is little research on the physical performance differences between individuals that participate in one sport versus those who participate in multiple sports. Therefore, research should be completed to examine if a single-sport athlete "makes" it and becomes an elite athlete and does not drop out or get injured, are performing the tasks of their sport at a higher level than those who did not specialize as early.

Most laboratory-based athlete research in the past has involved countermovement jump (CMJ), isokinetic dynamometer and muscle architecture ultrasound assessments to evaluate an athletes force and power outputs (Aagaard et al., 1998; Aagaard et al., 2001; Blazevich et al., 2003; Blazevich et al., 2007; Brockett et al., 2004; Christou et al., 2006; Comfort et al., 2014; Cormack et al., 2008; Croisier et al., 2008; Devan et al., 1998; Graham-Smith et al., 2013; Grygorowicz et al., 2010; Hewett et al., 2008; Kannus, 1991; Potier et al., 2009; Magalhães et al., 2004; Marginson & Eston, 2001; McMahon et al., 2018; Myer et al., 2009; Paasuke et al., 2001; Rosene et al., 2001; Secomb et al., 2015 & Seynnes et al., 2006; Tauchi et al., 2008; Vuk et al., 2015). These tests have been used to evaluate performance outputs between athletes in different sports and athletes in different positions within the same sport. The research results have also been used to help determine potential muscle imbalances or strength deficiencies and the possible effects that could have on injury rate. However, none of the research evaluates the performance differences between single and multiple sport youth athletes. Past research results have shown how different types of training can impact the performances of these tests and therefore have been considered important testing measures to determine athletic performance abilities in athletes (Aagaard et al., 1998; Aagaard et al., 2001; Blazevich et al., 2003; Blazevich et al., 2007; Brockett et al., 2004; Christou et al., 2006; Comfort et al., 2014; Cormack et al., 2008; Croisier et al., 2008; Devan et al., 1998; Graham-Smith et al., 2013; Grygorowicz et al., 2010; Hewett et al., 2008; Kannus, 1991; Potier et al., 2009; Magalhães et al., 2004; Marginson & Eston, 2001; McMahon et al., 2018; Myer et al., 2009; Paasuke et al., 2001; Rosene et al., 2001; Secomb et al., 2015 & Seynnes et al., 2006; Tauchi et al., 2008; Vuk et al., 2015).

Given the outcomes of the past research this thesis investigated the potential muscle and performance differences between single-sport and multiple-sport youth athletes. Due to time restrictions of a PhD, it was not possible to conduct a longitudinal study that would enable a researcher to follow youth athletes through their maturation and the impact switching from a multiple sport athlete to a single sport athlete might have on a specific individual and if it was more likely to lead to injury or dropout. Therefore, since there is a lack of research involving single versus multiple sport athletes in general an initial plan to examine muscle differences and imbalances, and power and force output between these two groups was created for this thesis to start the examination with these individual groups. The original study outline is presented in Figure 1.1. As the thesis progressed and variables were found to not be reliable the outline changed which is addressed at the end of each individual studies chapter.

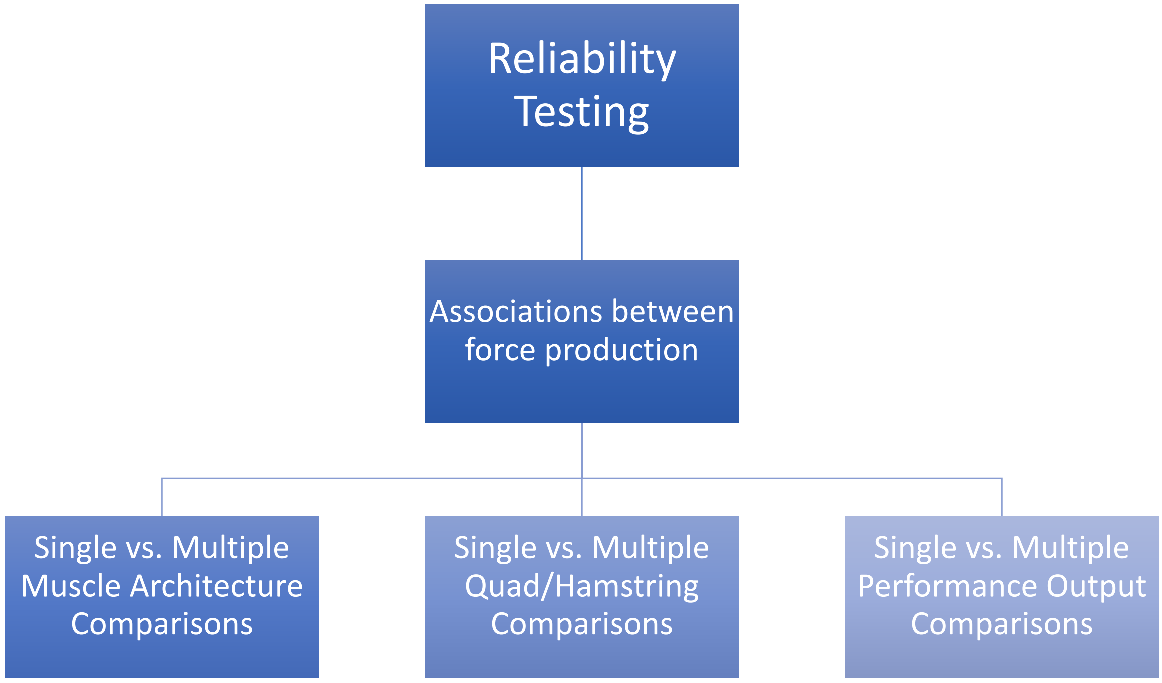


Figure 1.1: Schematic Diagram Illustrating the Planned Sequence of Experimental Studies on Youth Athletes Ages 13-18.

Chapter 2: Literature Review

2.1: Long Term Athlete Development

Researchers and coaches are always trying to create a successful athlete which can be as simple as enhancing an individual's sport skills or improving their physical performance in relation to measurable activities such as jump height, sprint speed and/or one repetition max lifts. A successful athlete may also be considered an individual that is participating in activities to live a healthier life or participate in lifting or movement sessions to avoid injury. The term successful can have a myriad of meanings for youth athletes because some youth want to become professional athletes, whereas for others the importance of their involvement in exercise is to lead a healthier lifestyle (Lloyd et al., 2015). Therefore, training programs need to be created that not only help produce elite athletes but also encourages children to continue to participate in sport and exercise for the rest of their lives (Balyi and Hamilton, 1999; Côté et al., 2007; Lloyd and Oliver, 2012; and Lloyd et al., 2015).

Many researchers have approached this question and have different tactics to achieving the objective (Ericsson et al., 1993; Balyi and Hamilton, 1999; Côté et al., 2007; Lloyd and Oliver, 2012; and Lloyd et al., 2015). One of the first formal ideas presented for creating elite level performances by individuals was created by Ericsson et al. (1993). Ericsson et al. (1993) theory is based on creating expert performance, in musicians, which has later been applied to athletes based on a specific number of deliberate practice hours. Ericsson et al. (1993) found that practicing around 7,000 to 8,000 deliberate practice hours over 10 years created an expert musician. Ericsson et al. (1993) has been cited for many years because of the research on the number of deliberate practice hours required to reach a level of expertise. The number of hours however, that has been associated with becoming an elite athlete has been increased to 10,000 hours and even referred to as the "10,000-hour rule" (Baker & Côté, 2003). This number seems to be an arbitrary number that is much higher than research has stated it needs to be. According to Ericsson et al. (1993) around 7,000-8,000 hours of deliberate practice produced an expert musician while Baker and Côté (2003) observed that elite team sport athletes were performing an average of around 4,000 hours of deliberate practice. However, Baker and Côté (2003) did find that the elite athletes had an average of 20 years of participation in their sport and the non-elite athletes had an average of 12 years of participation in their sport. Based on the average age of the groups the elite athletes started participating in their sport around the age of 7 years and the non-elite athletes started a few years later around 11 years of age. However, the authors do not specify if the subjects were single sport athletes so it is unknown if recommendations would be made to specialize early or to focus on deliberate practice hours later in adolescents. More information is needed to be known about the breakdown of these athletes to gain additional knowledge for the best approach to training throughout adolescents. Baker and Côté, (2003) showed that the deliberate practice hours are greatly less than those suggested by Ericsson et al. (1993) to create elite athletes but it is still important to participate in deliberate practice for the development of skill.

Baker and Côté, (2003) along with Ericsson et al. (1993) defined deliberate practice as those activities that are designed to improve current performance that is effortful and not inherently enjoyable. The improvement of current performance would indicate enhanced accuracy and speed of cognitive, perceptual and motor task abilities in laboratory-based testing. Also, the deliberate practice idea is based on the perception that this time should be focused and effortful, which in turn means it might not be inherently enjoyable. For children up to the age of 10 this idea from Ericsson et al. (1993) is vastly different than the FUNdamental stage presented by Balyi and Hamilton (1999). By expressing this theory of deliberate practice Ericsson et al. (1993) are stating that the path to elite performance does not involve fun or an experimentation of multiple activities. The path to being elite is focused and deliberate. Ericsson et al. (1993) stated that 10 years of devotion to a talent and deliberate practice is needed to become elite. This is contrasted by the following LTAD models who predominately state that there is a place for fun and activity experimentation prior to the need for deliberate practice, where a child will then specialize and have a single focus.

Ericsson et al. (1993) completed two studies to evaluate the differences between the elite, good and average violinists and pianists. These levels of expertise were defined by the musician's teachers. Both studies concluded that the elite and average musicians had accumulated a statistically different number of deliberate practice hours. The first study showed that the best (elite) violinists had accumulated an average of 7,410 hours of practice, good violinists had an accumulated average of 5,301 hours and the average violinists averaged 3,420 hours of practice. These totals were all calculated for the number of hours accumulated prior to the age of eighteen years. Since this study shows that the different groups started their training at approximately the same age it was concluded that the cause for the differences in achieved levels of expertise on their instrument was due to the number of deliberate practice hours.

The second study evaluated twelve expert pianists and twelve amateur pianists. This study did show a difference in starting age between the experts and amateurs (Ericsson et al., 1993). The experts had started playing at an average age of 5.8 years old and all had more than 14 years' experience with an average of 19.1 years of experience. Whereas the amateurs started playing at an average of 9.9 years of age with a very vast range of experience ranging from 5-20 years. This study also concluded that the expert pianists had a statistically greater number of deliberate practice hours per week than the amateurs. The experts averaged 26.71 hours of solo practice per week and accumulated and average of 7,606 hours of practice prior to the age of 18 years. This was drastically different from the amateurs who only spent an average of 1.88 hours per week on solo practice and accumulated only 1,606 hours of deliberate practice prior to 18 years of age. Therefore, this study for Ericsson et al. (1993) also provided evidence that the number of deliberate practice hours was the prominent factor between expert and amateur pianists.

The two studies of Ericsson et al. (1993) however, were focused on how to create elite musicians, not elite athletes. One difference between creating elite musicians and elite athletes is the difference in motor skills between the two tasks. Playing the piano and becoming an expert musician requires fine motor skills, whereas athletic movements and becoming elite in a sport, predominately requires gross motor skills. Fine motor skills involve precise movements that use small muscle groups (Seashore, 1942). Gross motor skills involve vigorous contractions of large muscle groups (Seashore, 1942). Based on these definitions by Seashore (1943) the difference between the two types of skills (piano playing & sports) are apparent. Athletes do require the use of both gross and fine motor skills however most performance tasks that an athlete would be evaluated on would be gross motor skills such as, acceleration, deceleration, change of direction, agility, jumping and running (Fransen et al., 2012; Lloyd and Oliver, 2012). Therefore, to make a connection between musicians' fine motor skills and athletes that predominantly use gross motor skills is nearly impossible based on the vast differences in the muscle movements required to complete the different tasks.

Ericson et al. (1993) used research by Kaminski et al. (1984), Sack (1980), Monsaas (1985) and Klinkowski (1985) to try and connect their research to sport. The issue with these comparisons to sport are all the studies are based on sports that are considered early specialization sports as defined by Balyi and Hamilton (1999). These sports are when elite levels of performance are typically reached at a young age and therefore must be specialized in at an earlier age as well. Swimming, gymnastics, figure skating and tennis all fall under this category of early specialization sports and therefore this research indicates that they do start at a younger age, but the research does not specify if they are the only activities these subjects are participating in.

Overall, Ericsson et al. (1993) were researching what it took to become an elite musician not an elite athlete. The conclusion of Ericsson et al. (1993) is that there needs to be 10 years dedicated to deliberate practice to reach an elite level. This, however, is looking at skill level and not necessarily physical development. The research is showing that the amount of time needed to become elite is just based on the number of practice hours. This research did not necessarily show how one developed into an elite musician. These researchers do not state a specific number of practice hours but based on the findings the elite musicians had completed almost 8,000 hours of deliberate practice in 10 years to become elite. It has been adapted to be the ”10,000 hour rule” which means an individual would complete 10,000 hours of deliberate practice, which would break down to 1,000 hours per year, to become elite in your chosen sport. Therefore, using the Ericsson et al. (19993) research is difficult when creating the best approach to LTAD. Since playing an instrument is typically fine motor skills and there is little variation in movements, deliberate practice hours of an instrument can create an elite musician. However, when looking at LTAD a more specific breakdown of practice focus needs to be completed to encompass the variety of gross motor skills required to become an elite athlete. The focus of upcoming research needs to include late specialization sport (typically team sports) and deliberate practice hours for skills that are not necessarily fine motor skills, like playing the piano, to focus on gross motor skills like throwing, catching, kicking etc. that will improve their athletic development. Ericsson et al. (1993) give a great base of knowledge to support “practice makes perfect” but it now needs to be applied to sports, long-term athlete development, and the healthiest ways to produce elite athletes.

Balyi and Hamilton (1999) created an LTAD model that was separated based on a sport being categorized as an early specialization sport or a late specialization sport. Early specialization sports were classified as those sports that are typically dominated by athletes of a younger age like gymnastics, figure skating and diving. Late specialization sports include team sports, athletics, cycling and rowing. Balyi and Hamilton's (1999) LTAD model is relatively similar for both groups, but the early sport specialization path suggests that due to the limited time the youth athletes have to become elite they have to skip what the researchers call the FUNdamental stage of development and start with the training to train stage to reach a professional level sooner (for an overview of the LTAD Model refer to Figure 2.1.1 and Figure 2.1.2). This LTAD models FUNdamental stage is suggested to be from age 6-10 for both males and females and should primarily focus on agility, balance, coordination, and speed. Due to the need for these abilities to be met earlier in development, early specialization athletes need to combine this phase with the training to train phase. For late specialization, however, Balyi and Hamilton (1999) suggest that the training to train stage should not begin prior to age ten to help prevent early burn out, drop out or the inability to reach the next phase in the model which is training to compete. Balyi and Hamilton (1999) suggest that the training to train stage should be ages 10 – 14 for boys and 10 – 13 for girls. In this phase, the athletes learn how to train, and they also learn basic skills for a specific sport. The athletes are introduced to technical and tactical skills for the sport as well as how to warm up/cool down, stretch, hydrate, eat properly, recover, regenerate, and mentally prepare for their chosen sport/s. For this stage, the training to competition percentage split is 75%/25%. This is the stage in which Balyi and Hamilton (1999) believe specialization in a single sport needs to occur. They believe that the focus should be on training and not competition for this age, but that one sport needs to be the focus of both training and competition. The time frame of when an athlete should transition from a multiple sport athlete to a single sport athlete is where researchers have a difference in opinion when it comes to long-term athlete development. It is a debated topic of conversation in which most researchers in the field have varying beliefs and paths that they believe are the most effective in creating long term athletes. The topic has become a more recently discussed issue due to the increases in injury and burnout and will continue to be until more comprehensive research model is completed to determine definitive training methods (Lonsdale, Odge and Role, 2009; Hall et al., 2015; and Jayanthi and Dugas, 2017).

Early Specialization Model	Late Specialization Model
1. Training to Train 2. Training to Complete 3. Training to Win 4. Retirement/Retaining	1. FUNdamental 2. Training to Train 3. Training to Compete 4. Training to Win 5. Retirement/Retraining

Figure 2.1.1: Difference in the Long-Term Athlete Development model based on early or late specialization (Balyi and Hamilton, 1999)

For the Balyi and Hamilton (1999) LTAD model as the adolescent athlete ages, they transition into stage three which is focused on training to complete. This stage will occur from 14-18 years of age for boys and 13-17 years of age for girls (Balyi and Hamilton, 1999). During this LTAD model stage training and competition percentage should be a 50/50 split and the individuals are focusing on high intensity and sport-specific training. This is when Balyi and Hamilton (1999) believe development needs to start to be individually based to create a better environment for improvement. Stage four is when the athletes train to win. For males this occurs over the age of 18 and females over the age of 17 (Balyi and Hamilton, 1999). All the athlete's physical, technical, tactical, and mental capacities are now fully established, and training is now solely focused on optimizing performance for competition. Training to competition ratio is now 25%/75% with most focus on the competitions. The final stage, stage five, is the retirement phase which is when athletes have retired from competition but may still participate in the sport.

This model for LTAD only focuses on competitive athletes and not creating physically active individuals for a lifetime of activity. Therefore, it only has stages for the development of competitive athletes. This model is therefore incomplete in creating individuals for a life of physical activity (Balyi and Hamilton, 1999). It also has the adolescent athletes focused on a single sport at a relatively early age. Balyi and Hamilton (1999) also stated that individuals participating in early specialization sports need to focus on a single sport up to four years earlier than the sports categorized as late specialization sports. However, this model is not based on any laboratory testing it is just based on the ideas and reviews of previous research. To create a stronger model, the LTAD model needs to be supported with longitudinal research to provide sufficient and appropriate data to support the model's ideas.

FUNdamental	Training to Train	Training to Compete	Training to Win
Chronological/Biological Age *Male & Female 6-10* FUN and participation General, overall development Athleticism: ABC's of running, jumping and throwing ABC's of movement Agility, Balance, Co-ordination and Speed Speed, power and endurance through FUN and games Proper running, jumping ad throwing technique Medicine ball, Swiss ball and own body exercises for strength Introduction to simple rules and ethics of sport Talent Identification NO periodization, but well-structured programs Sport participation 5-6 times per week	Biological Age *Male: 10-14 Female: 10-13* Emphasis on general physical conditioning Shoulder, elbow, core, spine and ankle stability FUNdamental technical skills progressively more specific skills toward the end of the stage FUNdamentals of tactical preparation Participation in complementary sports; (similar energy system and movement pattern requirements) Individualization of fitness and technical training Introduction to mental preparation FUNdamentals of ancillary capacities Recruitment Single Periodization Sport-specific training 4 times per week, with participation in other sports	Chronological/Biological Age *Male: 14-18 Female: 13-17* Sport and individual specific physical conditioning Shoulder, elbow, core, spine and ankle stability Sport-specific technical and playing skills under competitive conditions Advanced tactical preparation Individualization of technical-tactical skins Advanced mental preparation Sport and individual specific "ancillary capacities" Specialization Double or Multiple Periodization Sport-specific technical, tactical and fitness training 6-9 times per week	Chronological Age *Male: 18+ Female: 17+* Maintenance (or possible improvement) of physical capacities Shoulder, elbow, core, spine and ankle stability Further development of technical, tactical and playing skills Modelling all possible aspects of training and performance Frequent prophylactic breaks All aspects of training are individualized Develop further "ancillary capacities" (there in no "ceiling limit") High Performance Triple or multiple periodization Sport-specific technical tactical and fitness training 9-12 times per week

Figure 2.1.2: Overview of Long-Term Athlete Development (Balyi and Hamilton, 1999)

Balyi and Hamilton further adapted their LTAD model to address physical changes that occur during adolescents and the possibility to enhance development throughout adolescents (2004). This model started to address ages and maturation timing and how these physical changes impact how a youth athlete should be approaching training as they grow and develop. Balyi and Hamilton also addressed the fact that maturation and growth are very individualized and specific to the one athlete and therefore the "model" will change depending on the subject (2004). Since this original LTAD model was presented, many researchers have attempted to adapt and enhance the model to be a better tool for coaches and trainers to use to develop their athletes.

After Balyi and Hamilton (1999) presented their LTAD model research Côté et al. (2007) created their development model of sports participation (DMSP). Côté (1999) had previously coined the term deliberate play and used it to create separation from the deliberate practice ideas from Ericsson et al. (1993). Deliberate play is a form of sporting activity that involves early development physical activities that are intrinsically motivating, provide immediate satisfaction, and are specifically designed to maximize enjoyment (Côté, 1999). This idea of deliberate play and Ericsson et al. (1993) idea of deliberate practice was at the center of the DMSP.

Côté et al. (2007) believed there to be three outcomes for youth athletes involved in sport and reflected that in their DMSP. After entry into sport at the approximate age of five, Côté et al. (2007) believed that children needed to decide to specialize early or to enter into the "sampling years" of sport. If the athlete chooses to specialize early, they will be focusing on only one sport and have a high amount of deliberate practice hours and a low amount of deliberate play hours from the age of 6 until the child reaches adulthood. Côté et al. (2007) believed the probable outcomes of this path is elite performance. However, due to the early specialization, reduced physical health and reduced enjoyment are also probable. Wall and Côté (2007) also support that early specialization can be linked to drop out and decreased participation in sport. In the long term, this could create individuals who are less motivated to work out and stay healthy later in life.

The other two paths of the DMSP start in the sampling years from the age of 6 and continue until around the age of 11 (Côté et al., 2007). These researchers believed the sampling years involve several sports, a high number of deliberate play hours and a low number of deliberate practice hours. According to the DMPS, at around the age of 12, a youth athlete needs to decide whether or not to pursue elite performance or continue as a recreational participant. If the athlete chooses recreational participation, they will continue high amounts of deliberate play and low amounts of deliberate practice and shift focus to activities that promote health and fitness. This should create a life-long recreational athlete with enhanced physical health and enjoyment in physical activity (Côté et al., 2007).

The third and final path created by Côté et al. (2007) is elite performance through sampling. Again, at around age 12, the youth athlete chooses to pursue elite performance. Once he/she has decided this path the athlete shifts into the specializing years. In this phase, deliberate play and deliberate practice are balanced and the athlete starts to reduce involvement in several sports. The next phase of this path is the investment years. This should be implemented around the age of 15 according to Côté et al. (2007). The athletes in the investment years should now be focused on a single sport and transition to a high amount of deliberate practice and a low amount of deliberate play. By taking this path Côté et al. (2007) believed that the probable outcomes would be elite performance. However, unlike the early specialization path to elite performance these athletes are predicted to have enhanced physical health and enhanced enjoyment of the sport which should allow for continue participation in healthy physical activities for a lifetime.

As was the case with Balyi (2001), Côté et al. (2007) try and support their DMSP with previous research results. However, no longitudinal study has been conducted to reliably test this model to see its impact on youth athletes. This model states that at age 12 an individual needs to decide whether or not to become a single sport athlete and follow a path to pursue elite performance. This is a very young age to be making a decision that may impact the rest of this athlete's life. Côté et al. (2007) do suggest that multiple sports can be played until the athlete is 15 years old but then needs to change to a single sport athlete. Not only is this also a young age to be making such important decisions these models do not consider the potential benefits that can come from participating in different sports. Being a multiple sport athlete can help an individual with spatial awareness, hand eye coordination, muscle balance, agility, and strength gain. These important athletic properties can vary from sport to sport and therefore, help improve your overall performance. This is another aspect to consider with LTAD but seems to not play a significant role in creating the current development models. Therefore, due to these open-ended questions more research is needed to find the best approach to LTAD.

Lloyd and Oliver (2012) published their LTAD model known as the Youth Physical Development Model (YPDM). These researchers focused on defining how physical qualities and an individual's maturation phase should be addressed and the require adjustments to training based on these categories. The physical qualities Lloyd and Oliver addressed with their model are functional movement skills, sport specific skills, mobility, agility, speed, power, strength, hypertrophy, and endurance. The YPDM also addresses the structure of a practice that incorporates Balyi and Hamilton's idea of what training should look like as an athlete grows (2004).

According to Beunan and Malina (2005) the onset of the adolescent growth spurt occurs around two years earlier in girls (about 10 years old) than in boys (around 12 years). Also, girls typically experience peak height velocity (PHV) at an earlier age as well (12 years for girls and 14 for boys). Therefore, Lloyd and Oliver (2012) YPDM is the same for both sexes however, the onset of changes to the physical development focus' are at an earlier age for girls compared to the boys (approximately 1-2 years before) to account for the maturation differences.

During early childhood, which is specified from ages 2-4 for both boys and girls, Lloyd and Oliver (2012) believe the main focus for physical qualities development needs to be on fundamental movement skills and strength. Fundamental movement skills are meant to focus on improving gross motor skills which can also be improved by helping the athletes gain strength. Practice during early childhood should be unstructured and little focus should be on sport specific skills, mobility, agility, speed, power, hypertrophy, endurance, and metabolic conditioning (Lloyd and Oliver, 2012).This is the first model that incorporated development for children at this young of an age. Later in the YPDM skill development is incorporated but the main focus of this model is on physical development. Part of this model does incorporate sport specific skills but most of the development breakdown has a goal of improving physical and athletic movements and strength.

The next age period in the YPDM is the middle childhood phase. For boys, this period is 5 thru 11 years of age and for the girls it is 5 to 9 years (Lloyd and Oliver, 2012). This phase is where the separation between boys and girls starts based on the fact that girls start to physically mature around 2 years younger than boys and may start around the age of 9. During this phase training will start with little structure and slowly progress to moderate structure. The focus for this stage is predominately on movement qualities and more focus should also be made on mobility, agility, speed, power, and strength. Fundamental skills during training transition from more important than sport specific skills to less as the athlete ages, and hypertrophy, endurance and metabolic conditioning should continue to have minimal focus (Lloyd and Oliver, 2012).

The third and fourth phases of the YPDM are adolescence and adulthood (Lloyd and Oliver, 2012). These phases are discussed together since most transitions of focus occur during adolescence and are continued to adulthood. For boys, the adolescence phase is from approximately 12 – 20 years old and adulthood starts at 21. For girls, the adolescent age range is approximately 10 – 19 and adulthood begins at 20 years of age (Lloyd and Oliver, 2012). For both adolescents and adulthood, the sport specific skills are more important than the fundamental movement skills. Mobility also becomes less important and should have little focus during these two phases. Agility and speed transition from highly important to moderately important in the middle of adolescents. Strength and power, however, continue to be of high importance for physical development in these stages. Hypertrophy becomes highly important during the middle of the adolescent phase when the child has reached their peak height velocity. Peak height velocity is the point of pubescents when the tempo of growth is the greatest (Malina et al., 2004). Going into adulthood hypertrophy then transitions back to medium importance. Endurance and metabolic conditioning transition from little importance to medium importance from the middle of the adolescent phase and continue into adulthood. Lastly, training becomes highly structured and just prior to adulthood becomes very highly structured (Lloyd and Oliver, 2007).

Lloyd and Oliver (2012) focused on the importance of the maturation phase into their LTAD model. Lloyd and Oliver (2012) also stated that even though they have given age ranges, individual athlete maturation needs to be observed and adaptations should be made to the individual's YPDM to accommodate the athlete's specific needs based on if they are early or late maturing individuals. This model does not specify what kind of athletes are being developed and what following this plan achieves. Does this model help create elite athletes or physically fit people until the age of 18. The naming of these models as "Long Term Athlete Development" is also misleading since all the models only show a focus on subjects from infancy to around 18 years of age. It could be that if one follows this model as a child, they will in turn continue to be an active and healthy person but is not apparent within the details of the models. Also, with the desire of youth athletes to become elite in their sport these models do not specify if following them will just create a healthy athletic individual or if the model will create an elite athlete. As research advances more connections are being made and applied to create more encompassing LTAD models; however, there is still no research demonstrating that following one of the models creates an elite athlete. It is all circumstantial based on various results from other cross-sectional research.

After these past research results, scientists realized that something needed to be done to blend all the previous LTAD models that were based on talent and athletic development. Therefore, Lloyd et al. (2015) created the composite youth development model (CYDM). Lloyd et al. (2015) found it important to create the CYDM to demonstrate how existing models of youth development and talent development can be adapted and integrated to provide an overall pathway for the complete development of youth athletes (Lloyd et al., 2015). The CYDM is composed of Lloyd and Oliver's YPDM (2007) and Côté et al. DMPS (2001). Additional parameters were also added to account for the psychosocial development of athletes to create motivation for a lifetime engagement in sports and physical activity.

The psychosocial development is lined up with the talent development phases of the DMPS model. For the CYDM however, a change was made to the terminology of the original DMPS to account for the years prior to the start of that model. For ages 2-6, Côté et al. (2001) had not specified any phase or stage to occur in athlete development. Therefore, the CYDM termed this early childhood phase as the "investment years" and the third phase of the DMPS is referred to as the specializing or recreational years. Lloyd et al. (2015) thought it was important to term this early childhood phase the investment years because it is crucial for children to "invest" in the exploration and learning of a broad range of fundamental skills in fun-based learning environments that will serve as a strong foundation for more advanced movement skills later in life. This phase lines up with the exploration and social interaction phase of the psychosocial development. The investment years phase should have an emphasis on promoting fun and social interaction to help young children enjoy the learning of new skills and to encourage the interaction process with their peers (Lloyd et al. 2015).

In the CYDM, after the investment years phase, children ages 6-12 are encouraged to move into the sampling years as shown in the DMPS model(Lloyd et al., 2015). This also falls under the middle childhood phase of the YPDM, and the focus of psychosocial development should be peer relationships, empowerment and self-esteem. Enhancing self-worth and self-esteem in children at this age is important to offset the potential negative consequences that can occur when children start to compare themselves to their peers. It is also important to empower youth at this age to encourage them to begin to take responsibility for their own learning process (Lloyd et al., 2015).

As a child transitions into either the specializing phase or the recreational phase in the DMPS model, they are entering their adolescence phase and continuing into adulthood based on the YPDM model. In this part of the CYDM if a child chooses to follow a recreational path it is important that their psychosocial development continues for this group of non-competitive athletes, so they remain motivated for a lifetime engagement in recreational sports and physical activity. If a child chooses to specialize in a sport, psychosocial development needs to continue to enhance peer relationships, self-esteem and empowerment, but the individual's development should also add sport-specific psychological skills in an attempt to maximize sport performance (Lloyd et al., 2015).

The CYDM was a great step in creating an all-encompassing LTAD model that combines talent, psychosocial and physical development of youth athletes. It is the first model to express the importance of each aspect of development together in a model however, the outcomes of following the model are still not conclusive. As was the case with the previous research no longitudinal research has been conducted to follow the development of a youth athlete across time to see how the model works or impacts their life as an athlete. The CYDM also does not address if following one of these paths will create an elite athlete. Based on Ericsson et al. (1993) and the 10-year rule, if an athlete starts sports around age 6 and puts in a substantial number of deliberate practice hours, by age 16 they should be elite. However, Ericsson et al. (1993) doesn't account for the psychosocial phases or the promotion of LTAD and the enjoyment of participating in physical activities for a lifetime. The current research is all circumstantial in relation to athletes. There are models that try and help with the development of these adolescent athletes but there is currently no proof or data to support the supposed outcomes of these models.

The CYDM by Lloyd et al. (2015) also does not address the early sport specialization athletes. As stated previously, some sports may require children to specialize earlier than these models would want them too. Therefore, if we know some athletes, like gymnasts and figure skaters, are going to specialize early, we need to manipulate their training model to create healthy and motivated long-term athletes. Côté et al. (2007) did address early sport specialization but determined the path would probably create reduced physical health and reduced enjoyment. This is not an ideal outcome for LTAD however, the number of youth athletes starting to specialize early is on the rise with the idea that it will create elite athletes. This trend will be discussed in the upcoming chapter. With this increasing number of athletes however, there are more injuries and burnout which do not help create lifelong athletes or individuals interested in a lifetime of healthy physical activity. The trend in early sport specialization shows the increasing need for definitive LTAD models to promote and create healthy youth athletes. This, however, requires empirical evidence and data that can prove these models are accurate and if followed can produce elite athletes that not only have the talent, but are well rounded athletes prepared for the high demands placed on these athletes. It is also important that these athletes continue a healthy lifestyle after their competitive playing career has come to an end.

The idea behind LTAD models is important to help with the guidance of youth development however, there are still some underlying issues with the models. As expressed in the paper by Ford et al. (2011) the most important idea behind any LTAD model is the understanding that they need to be adapted to every individual subject. Currently it seems the models are used as a concrete approach to LTAD, and the coaches and trainers are not adapting them to their athletes. This may be a limitation on the data provided in the models or the coaches and trainers inability to interpret the models and fit them to their athletes (Ford et al., 2011). Therefore, all youth subjects should have their peak height velocity determined and have their training and development plan made specifically for them. Also, there are some models that address early specialization sports and how that may impact what an individual's model. However, there is no model that addresses the optimal time of switching to a single sport focus when it isn't a sport like gymnastics or figure skating where optimal performance occurs at a younger age. The models also need to address what happens when you follow these plans, are you going to become an elite athlete or just a fit individual. Until these gaps can be addressed it is difficult to individualize them to a subject because there are unknowns that may impact when transitions should be made. That is why the currently proposed research is important to see if any physical difference exist between adolescents competing in a single-sport versus those competing in multiple sports. There is a need for data to support the potential use of LTAD models to develop the most useful and comprehensive path for youth athletes so they can develop in a safe and healthy way.

2.2: Early Sport Specialization

Some long-term athlete development (LTAD) models address early sport specialization and its potential negative impact on youth athletes; however, there is an increasing number of athletes that are starting to specialize at an earlier age (Fransen et al., 2012; Post et al., 2017). The reasons why some athletes are encouraged to specialize early are not concrete, but the increasing need to create elite athletes to gain a college scholarship and/or to make an elite club team may be potential causes. However, there is a large number of athletes' that dropout of their sports at young ages (Lonsdale et al., 2009). Sport injury, which can be related to overtraining and burnout (known effects of early sport specialization), create an increase in dropout. Indriðadóttir et al. (2015) show that 8.4% of sports injuries led to that individual to dropping out from their sport. Enoksen (2011) also showed that injury was the most prevalent reason for dropout in young athletes. Enoksen's 25-year study, using questionnaires and interviews, which occurred in 1983 and 1989 respectively, showed that 14.5% and 9.8% of the athletes dropped out of sport due to injury. Therefore, for this whole study that meant that 24.3% of the athletes in the study (67 of 276) dropped out of sports due to injury. Indriðadóttir et al (2015) and Enoksen (2011) show that injury is an issue with youth athlete and has led to an increase in drop out levels among this age group. Injury and athlete dropout are disadvantages to early sport specialization and this chapter will examine both the advantages and disadvantages that surround the participation in a single sport.

Due to the research completed by Côté et al. (2007) on their developmental model of sport specialization, early specialization became a focus of scientific discussion. Côté at al. (2007) defined early specialization as a high volume of deliberate practice and a low amount of deliberate play in one sport with the focus of practice being on performance as early as age six or seven. Deliberate practice is defined as any activity designed to improve current performance that is effortful and not inherently enjoyable (Ericsson et al., 1993). Deliberate play is defined by Côté (2007) as a form of sporting activity that involves early developmental physical activities that are intrinsically motivating, provide immediate satisfaction and are specifically designed to maximize enjoyment. Support for early specialization assumes that specialization and deliberate practice in one sport is the superior way to develop elite athletes versus deliberate play which includes involvement in various sporting activities during childhood. It is assumed based on Ericsson et al. (1993) 10-year rule, which has been translated into 10,000 hours of deliberate practice is the best way to promote elite performance in adolescents as they transition to adults. Recently this theory has been questioned and research has started to look into whether or not it is necessary to specialize in a single sport at such an early age to achieve elite status (Côté et al., 2009; Lonsdale et al., 2009; Moesch et al., 2011; Fransen et al., 2012; Hall et al., 2015; and Post et al., 2017).

Côté, Lidor and Hackfort (2009) created a position paper for the International Society for Sports Psychology to develop views on the best ways to create elite performers and athletes that continue athletic participation after they have stopped competitive involvement. As stated previously these positions apply to sports in which peak performance occurs after maturation. Therefore, sports like women's gymnastics and women's figure skating, where peak performance occurs prior to full maturation, were not the focus of this research because they do not have advantages to early diversification and sampling other sports (Côté et al., 2009). Using previous research, Côté et al. (2009) created seven postulates or theories to encourage childhood sport programs to focus on the development of sport skills while maximizing participation and minimizing drop out. The first postulate is based on previous research that looked at ice hockey, field hockey, basketball, net ball, baseball, tennis, triathlon and rowing athletes (Soberlak and Côté, 2003; Baker, 2003; Gilbert et al., 2002; Hill, 1993; Côté 1999; and Baker et al., 2005). After Côté et al. (2009) reviewed these studies, they determined that early diversification (sampling) did not hinder elite sport participation in sports where peak performance is reached after maturation. The second postulate states that early diversification (sampling) is linked to a longer sport career and has positive implications for long-term sports involvement. Based on the review, Côté et al. (2009) theorized that early specialization has been shown to shorten peak performance, increase drop out/burn out, and increase risk and occurrence of injuries in young athletes. Côté et al. (2009) and therefore, concluded that sports where peak performance is reached after maturation will generally have a longer career than athletes from sports where specialization prior to maturation is the common path athletes take. Post et al. (2017) completed research based on questionnaires completed by 2,011 youth athletes ages 12-18 years. This questionnaire determined the athlete's specialization level and whether it had an impact on sport-related injuries for those athletes over the past year of their participation in sport. The results of this study showed that highly specialized athletes were more likely to have had a previous injury. Athletes who played their primary sport more than 8 months out of the year and also participated in their primary sport for more hours per week than their age had higher injury risk (Post et al., 2017).

The third postulate created by Côté et al. (2009) states that early diversification (sampling) allows participation in a range of contexts that most favorably affect positive youth development. This postulate suggest that early diversification has the potential to promote a broader spectrum of developmental experiences and outcomes more than early specialization. According to Busseri at al. (2006) and Fredricks & Eccles (2006), adolescents that are involved in varied activities score more favorably on personal and social measures such as well-being and positive peer relationships compared to those who specialize. The results of the two studies by Busseri at al. (2006) and Fredricks & Eccles (2006) show support for early diversification for development mentioned in postulate three.

Postulates four and five both consider the importance of deliberate play. Postulate four states that high amounts of deliberate play during the sampling years build a solid foundation of intrinsic motivation through involvement in activities that are enjoyable and promote intrinsic regulation (Côté et al., 2009). Postulate five states that a high amount of deliberate play during the sampling years establishes a range of motor and cognitive experiences that children can ultimately bring to their principal sport of interest (Côté et al., 2009). Both postulates address the importance of deliberate play in creating self-motivated, well-rounded athletes that love to compete and enjoy the sport they are playing (Côté et al., 2009). These postulates show the importance of sampling and enjoying playing to help develop athletes that will be involved in sport after competitive retirement.

The last two postulates address the ages in which children should change from diversification to specialization. Postulate six proclaims that around the end of primary school (about age 13), children should have an opportunity to either choose to specialize in their favorite sport or to continue in sport at a recreational level (Côté et al., 2009). The final postulate, postulate seven, states that late adolescents (around age 16) have developed the physical, cognitive, social, emotional, and motor skills needed to invest their effort into highly specialized training of one sport (Côté et al., 2009).

Just like the previous writing mentioned involving LTAD in the previous chapter, Côté et al. (2009) review of early specialization is based on research that is mostly cross-sectional and not longitudinal. The statements made about best practices for development do have research to support the claims of their research, but more research is needed to follow athletes throughout their development to have more concrete data about the effects of early specialization. This review by Côté et al. (2009) includes little research about the physical differences and muscular characteristics (e.g., force production characteristics, architecture, fiber types) that may lead to more successful athletes. This research is needed to narrow down if there are performance differences between single and multiple sport athletes or if there are any physical reasons behind the higher rate of injuries in single, early sport specialization athletes. This research also did not include information about the early specialization sports such as gymnastics and figure skating. Even though these early specialization sports typically reach elite status prior to full maturation, the athletes in these sports still suffer from overuse injury and burnout. These sports should also have a model or path to help athletes have long term athletic involvement. Therefore, Côté et al. (2009) have made a great initial review about the disadvantages of early specialization but more research is needed to be able to determine the exact reasons behind those issues.

The second postulate from Côté et al. (2009) addresses the idea that early specialization can lead to athlete burnout. Lonsdale, Hodge and Rose (2009) completed research to investigate athlete burnout in elite sport. In 1997, Raedeke defined athlete burnout as a syndrome characterized by: (1) emotional and physical exhaustion, (2) sport devaluation; and (3) a reduced sense of accomplishment. Using this definition Lonsdale et al. (2009) used a questionnaire with a group of 201 athletes to determine their level of burnout. All of the athletes had participated in their sport for 9.5 years. The study also used two different questionnaires to evaluate the basic needs satisfaction and motivation of the subjects. These questionnaires assessed perceptions of autonomy, competence, and relatedness, as well as amotivation, external regulation, introjected regulation, identified regulation, integrated regulation, and intrinsic motivation (Lonsdale et al., 2009). This research concluded that it is important for athletes to have both intrinsic and extrinsic motivation to participate in sport. An athlete's sport environment should also promote needs satisfaction which will lead to more self-determined motivation and therefore help prevent athlete burnout (Lonsdale et al., 2009). Lonsdale et al. (2009) study showed that the "I do it for the love of the game" mentality is not the only influence, and that outside or extrinsic factors also play a role to minimize burnout and that an athlete wants to achieve goals and express a sense of self, so they feel accomplished in a sport (Lonsdale et al., 2009). Athletes who were motivated to participate by complying with demands or avoiding guilt and shame were more likely to report burnout symptoms (Lonsdale et al., 2009). These results show that positive, needs based environments are the best to limit athlete burnout. This research helps define signs and symptoms of burnout that athletes might be having. However, the research is only looking at single sport adult athletes who have been participating in one sport for 9.5 years. Further research is needed to determine if multi-sport athletes show similar response and if any connections can be made between burnout, injury, performance, or dropout from the sport among this group as well.

In 2011, Moesch et al. completed research to evaluate elite sport performance through athletes that were either early or late specialization athletes. The athletes examined participated in the sports of cycling, kayaking, sailing, skiing, swimming, track and field, triathlon, and weightlifting. The basis of their research was on the early specialization and early diversification paths of the DMSP model from Côté et al. (2007). To perform their research Moesch et al. (2011) created an online questionnaire for a group of 243 Danish athletes to complete. Of the 243 athletes, 148 athletes were considered to be elite and the other 95 athletes were near elite. This designation meant the elite athletes had placed in the top 10 in a world championship competition, won a medal at a European championship or won a medal at a junior championship, if the athlete was under 21 years of age (Moesch et al., 2011). The near-elite athletes had not accomplished these parameters in their designated sport. The questionnaire focused on six categories: biographical information, practice hours within their main sport, involvement in other sports, career development, weekly training schedule and athletic success. The results showed that the elite athletes had specialized in a single sport later in life than the near-elite athletes. It also concluded that the near-elite athletes spent more hours practicing at a younger age. At 18 years of age the two groups had a similar number of practice hours but then the elite athletes started to have more (Moesch et al., 2011). This may have some connection to dropout and certain athletes not being able to reach the elite level. This research supports the idea that late specialization does not delay athletic development. Also, less training at earlier ages and specialization later in life can be more beneficial for children who want to become elite athletes (Moesch et al., 2011). This study is helpful in the effort to improve athlete development, but more research is needed to support the claims presented in this study. This article could have also drawn a connection between practice hours and dropout. However, the proper questions were not asked to be able to draw that conclusion. As with the other studies it is cross-sectional and therefore relying on recall data from the subjects to answer the questionnaires. More longitudinal research studies are needed to collect more reliable data to examine trends of youth athletes.

Wall and Côté (2007) conducted a study that looked at 12 active and dropout male minor ice hockey players. The parent most involved with their child's participation in ice hockey was interviewed and questioned to determine if any connections could be made between training/game schedules and the individuals that had dropped out of the sport. The results showed that there was one clear difference between the active and dropout groups that focused on deliberate practice. The players who ended up dropping out of their sport began off-ice training at a younger age and participated in more off-ice training than their active player counterparts (Wall &Côté, 2007). Even though this study has a very small sample size it begins to show that the added hours of deliberate practice (effortful and not inherently enjoyable) lead to over training and eventual dropout from the sport for these athletes. More subjects are needed to draw a more definitive conclusion about over training and dropout, but the results of this study indicate that early specialization and earlier deliberate practice in adolescents have increased the chances of dropout from the sport.

Fransen et al. (2012) also conducted a study using the DMSP model from Côté et al. (2007) to evaluate athletes that either followed an early diversification path or an early specialization path to achieve elite performance. Fransen et al. (2012) tested a group of boys ages 6-12 participating in soccer to see if any physical fitness and gross motor coordination differences existed between those two groups. Three age groups were formed (6-8, 8-10, 10-12) and 1162 children were tested. This research looked at the athlete's anthropometry, strength, flexibility, speed and agility (actually change of direction), cardiovascular endurance, and motor coordination. For muscular and endurance strength sit ups and pushups were used to assess the athletes as well as handgrip strength and standing broad jump for static strength and explosive strength respectively (Fransen et al., 2012). For flexibility, a sit and reach test were used, for speed and agility, a 10 x 5-meter shuttle run and for cardiovascular endurance an endurance shuttle run test was used. The last category of testing was for gross motor coordination where four different tests were used: walking backwards on a balance beam, moving sideways on boxes, hopping for height on one leg, and jumping sideways (Fransen et al., 2012).

Critiques of this research are focused on the limitations of some of the testing protocols. Fransen et al. (2012) used hand grip strength and standing broad jump for static and explosive strength. Both tests are reliable in their own right but not in comparison to one another. The hand grip strength test looks at upper body strength and has shown relevance to overall muscle strength in youth athletes (Milliken et al., 2008). However, hand grip strength cannot be used to compare strength when hand grip strength is an upper-body static strength test and is was being compared to lower body explosive strength test (standing broad jump). Furthermore, muscle and endurance strength were measured based on pushups and sit ups. These tests are reliable tests when looked at individually for an athlete’s strength abilities. However, in this research pushups and sit ups were combined with broad jump and handgrip strength to evaluate an individuals’ overall strength. Therefore, “overall strength” in this study was an evaluation of four different muscle groups testing four different types of strength. This measurement could become very biased based on the sports the individuals are participating in. For example, swimmers may have much stronger upper-body strength where soccer players may have stronger lower-body strength. Therefore, it is difficult to use these groups of tests to make an accurate comparison between athletes. In addition to the strength tests the Eurofit 10 X 5 shuttle run test was used to evaluate agility. The shuttle run test is a reliable and valid test but in the context of this research is not used properly for evaluation of the subjects. These researchers defined it as a test for speed and agility when in reality it is a test for speed and change in direction. Agility is measured when the subject is responding to a stimulus which was not used in this research (Sheppard and Young, 2005). Therefore, when evaluating the results of this study to other research studies the differentiating of results between agility and change of direction may lead to confusion and/or improper comparisons.

Fransen et al. (2012) used self-reported physical activity assessments for their study. The boys were categorized into four groups; single sport participants involved in few hours of sport per week (SSF); single sport participants involved in many hours of sport per week (SSM); multiple sport participants involved in few hours of sports per week (MSF); and multiple sport participants involved in many hours of sports per week (MSM) (Fransen et al., 2012). This research does not specifically define the number of hours that would categorize an athlete as having few or many hours per week and is a major critique of the research. There are cut-offs used for the hours categorization, but future research would have a difficult time comparing results to this study based on the limited details of the specific hours of sport the subjects completed per week. To determine the difference between few and many hours single sport participants ages 6-8 had a median of 3 hours per week, less than 3 hours was considered few, more hours were considered many. For single sport athletes ages 8-10 and 10-12 a mean of 4 hours of practice per week was used. For multiple sport athletes ages 6-8 it was 5 hours per week, 5 ½ hours per week for 8-10 years of age and 6 hours per week for 10-12 years of age. For all age groups, the athletes that participated in more hours per week achieved better scores for strength and gross motor coordination. Therefore, this research does emphasize the positive effect of spending more hours a week in sports and how that can improve an individual's performance (Fransen et al., 2012). This research shows that the variation of activity and participation in sport for more, but not excessive, amounts of time help develop better sport skills, motor functions and strength (Fransen et al., 2012).

Differences in testing performance between single sport and multiple sport athletes were not seen until the subjects fell into the 10-12 year-old age group. The differences existed in strength, speed and agility, and gross motor control, with the multiple sport athletes performing the tests better than the single sport athletes (Fransen et al., 2012). Based on research from Côté et al. (2009) the boys participating in more than one sport were exposed to a greater number of physical, cognitive and psycho-social environments which is what allowed them to have better performances in the tests compared to the single sport athletes in this study.

Overall, the researchers concluded that the multiple sport participants with many hours per week jumped farther and had better gross motor coordination than all other groups (Fransen et al., 2012). Gross motor coordination was evaluated by having the subject's complete four tests: walking backwards along a balance beam, moving sideways on boxes, hopping for height on one foot, and jumping sideways were the evaluations used. A team of trained supervisors evaluated each test and appointed scores for the ability of the subjects to complete these tests. The results of this study showed that the multiple sport athletes were able to complete these tests at a higher ability than the other subjects (Fransen et al., 2012).

This study was focused on a very young group of boys which in turn means that more research is needed to broaden the subject pool. Future research should be done to incorporate female athletes as well as youth athletes between the ages of 13-18 to help gain a better picture of the physical ability differences between single-sport and multiple sport youth athletes as they transition thru their adolescents. More research is also needed to define the fine line between the time needed to improve and be a better athlete and when an athlete is spending too much time, participating in too high of intensity training and/or too high a training load in their sports. One side of this theoretical line can result in athletes who enjoy their sport whereas the other side can result in injury, burnout, and eventual dropout from the sport.

In 2015, Hall et al. addressed the question of whether or not sport specialization causes more injuries with a group of 546 adolescent female athletes participating in basketball, soccer, and volleyball players. Based on self-reporting from the subjects, 357 were considered multiple sport athletes and 189 single sport athletes. The methods for this study consisted of the subjects completing the anterior knee pain scale, the international knee documentation committee form, supplying a standardized history and physician-administered physical examination, medical history information and the subject's anthropometric data (Hall et al., 2015). Based on the questionnaires it was concluded that single sport athletes had an increased risk and incidence for anterior knee pain compared to multiple sport athletes. Single sport athletes had a 1.5 times greater risk of patellar-moral pain and 4 times greater risk of Osgood Schlatter Disease and Sinding Larsen Johansson/ Patellar Tendinopathy (Hall et al., 2015). This research suggests that there may be a link between single-sport athletes being more at risk of injury. The results of this research, however, only addresses females and their increase in injury so it is unknown if males experience the same issues. The research also only mentions that the subjects are middle school and high school aged. For more complete information, it would have been useful to separate the subjects into age groups and/or stage of peak height velocity to see if all ages show the same outcome or if there is a transition based on age and maturity that affects injury risk. Lastly, this research is strictly questionnaire based and future research needs to address what physical differences may cause single sport athletes to be at higher risk of knee injury or pain. Muscle differences, strength imbalances, and force and power outputs need to be tested to see if they are contributing factors to why more single sport athletes are prone to injury. The research shows that single sport athletes are at higher risk but now the research needs to be done to address what physical differences are causing these issues among these specific groups of athletes (Côté et al., 2009; Lonsdale et al., 2009; Moesch et al., 2011; Fransen et al., 2012; Hall et al., 2015; and Post et al., 2017).

Post et al. (2017) completed research to address the association between sport specialization and training volume in relation to injury occurrence in youth athletes. This research addresses the growing concern that specialized training in sport can lead to an increase in the chance for injury (Post et al., 2017). Even though medical organizations, doctors and researchers have warned against the effects of sport specialization it does not seem to change the trend of increasingly more athletes becoming single sport athletes. Therefore, this research was conducted to try and give more supporting data to limit sport specialization training to minimize the risks of injury to youth athletes. This study examined 2,011 youth athletes ages 12-18 who all completed a questionnaire regarding their specialization status, yearly and weekly sport participation volume and injury risk (Post et al., 2017). Of the 2,011 youth athletes 989 were female and 1,022 were male. Using the Jayanthi et al. (2015) definition of high, moderate, and low degrees of specialization, Post et al. (2017), analyzed the results of the questionnaire. To be considered highly specialized the athlete had to participate in year-round training for more than 8 months, focus on one single sport, and have quit all other sports to pursue a single sport. Moderately specialized athletes adhere to two of these and low specialization athletes meet one of these criteria (Jayanthi et al., 2015). The current research by Post et al. (2017) resulted in highly specialized athletes being more likely to report a previous injury or overuse injury to have occurred in the previous year compared to athletes who were categorized in the low specialization group. This research also concluded that athletes who participated in their primary sport more than 8 months a year and/or participated in their primary sport for more hours than their age per week were more likely to report an injury (Post et al., 2017). Therefore, Post et al. (2017) concluded that high levels of specialization resulted in a history of injuries, independent of age and sex. If an athlete exceeded the volume of participation recommendations, they were more likely to have a history of overuse injury (Post et al., 2017). This research was able to address that sport specialization and injury was not dependent on age or sex and effected these athletes in the same way. However, as addressed with previous research in this chapter the subjects completed a questionnaire and no laboratory testing. Laboratory testing that could be completed to examine physical differences between the single-sport and multiple sport athletes are the isokinetic dynamometry tests, countermovement jump tests and ultrasound test. The resulting output variables of these tests will help examine muscle balance, muscle architecture, and force production characteristics to see if any physical differences can be associated with the trend that exists between sport specialization athletes and their increase in injury and dropout rates. Ultrasound testing can examine muscle thickness, pennation angle and fascicle length which can evaluate differences in strength and force production abilities between subjects. Countermovement jumps and isokinetic dynamometry can examine power, force and torque production between subjects. Using these three laboratory testing performance evaluations can be made between single and multiple sport athletes to shed some light on the physical implications that may exist depending on what type of athlete you are.

Most of the current research on sport specialization has been based on questionnaires (Côté et al., 2009; Lonsdale et al., 2009; Moesch et al., 2011; Fransen et al., 2012; Hall et al., 2015; and Post et al., 2017). This has begun to answer questions about the problems that may be associated with specializing in a single sport. The results of current research shows how youth athletes who specialize earlier, have a higher number of deliberate practice hours, and exceed volume of participation recommendations have an increase in injury and are more prone to dropout (Côté et al., 2009; Lonsdale et al., 2009; Moesch et al., 2011; Fransen et al., 2012; Hall et al., 2015; and Post et al., 2017). The current research addresses some issues that may occur based on being a specialized or single sport athletes. The current research also typically evaluates differences in early sport specialization athletes. These athletes that specialize early typically do so around 6 years old which is why Fransen et al. (2012) performed their testing on subjects ages 6-12 years old. These subjects were predominantly pre-peak height velocity which has been shown as a time when functional movement skills should be focused on according to Lloyd et al. (2015). Therefore, it makes sense that from 10-12 years of age the subjects who participated in various activities performed better than the single sport subjects. However, the question still exist about how single sport and multiple sport athletes perform later in their adolescents and through their PHV transition. There may also be confusion with early sport specialization and single sport specialization. An early sport specialized athlete is in fact a single sport athlete however and individual athlete can become a single sport athlete later in adolescents. The question remains when the ideal timing is to become a single sport athlete to avoid the higher risks of injury and dropout. At some point an individual has to focus on a single sport if they want to become elite (go to college or join a club) in a sport but no performance research has been conducted to evaluate the differences between single and multiple sport adolescents going through their PHV stages. Therefore, the current research will evaluate performance outputs using ultrasound, countermovement jump, and isokinetic dynamometer analysis of single and multiple sport athletes.

2.3: Adolescent Maturation

When evaluating adolescent athletes, it is important to understand their physical development and maturation phase, as muscular development, and the associated force production characteristics, can be influenced by their growth (Philippaerts et al., 2006). As an adolescent progresses through their growth spurt, known as peak height velocity (PVH) there is an increase in an individual's limb length. This increase in limb length enables an individual to go through a larger range of motion during their performance of athletic tasks, e.g., the countermovement during a jump. If a subject is able to optimize their range of motion, they have potential for greater acceleration because they are able to apply force across a greater range of motion and potentially for a longer duration. Increased range of motion and therefore duration for force application would in turn cause a greater impulse, with acceleration over a greater range of motion resulting in a faster take-off velocity, leading to a greater jump height (Kirby et al., 2011). Once an adolescent reaches peak weight velocity (which occurs after PHV) the larger forces produced due to increase in the individual's mass now need to be used to offset the increased range of motion. Since more force is required to move the larger mass of the individual a subject may see a plateau in their relative strength changes and jump height (Philippaerts et al., 2006). These physical changes through individuals' growth spurts may should cause adaptations to training measures, which may involve decreasing certain aspects of training, to help a subject progress through their growth period while continuing to improve their performance outputs (Morris et al., 2018).

Morris et al. (2020) observed that many adolescents do not improve their relative strength as they transition through their growth spurt even when structured training is performed, which may highlight limitations in current training practices. This is concerning due to the greater physical demands on the athletes as they grow and not being able to adapt and prevent injuries if not training properly through their growth. Adolescents may reach their PHV at different ages compared to other peers of the same chronological age. Mirwald et al. (2002) gave an example of two adolescent boys who at pre peak height velocity and post peak height velocity had nearly identical heights and weights to one another. These individuals however hit their PHV two years apart from one another. This difference in PHV occurring at different ages has an impact on what training and abilities these adolescents have as they mature through their PHV (Mirwald et al., 2002 & Lloyd et al., 2015). Hägg and Taranger (1991) and Till et al. (2017) expressed the importance of allowing children to all transition through their PHV before evaluating their full athletic potential. This is due to the fact that some of the children could hit their PHV 2-3 years after their peers but have been shown to “catch-up” and be successful athletes. However, if they are “put off” of discouraged from competing because they are smaller or always playing against bigger opponents they may drop out and no longer participate in sport (Hägg and Taranger, 1991; Till et al., 2017). Therefore, when evaluating adolescents, it is important to use a valid and reliable measurement to help determine the growth phase of an individual at their specific time of testing, peak height velocity (PHV) along with skeletal age, sexual age and other somatic assessments like PHV which include, growth rates and adult stature predictions, have been used in studies to provide this information for researchers (Beunen & Malina, 1988; Mirwald et el., 2002; Philippaerts et al., 2006; Rumpf et al., 2012; Lloyd & Oliver, 2012; Lloyd et al., 2014; Lloyd et al., 2015; & Mills et al., 2017).

Adolescents competing in sport are categorized by age groups because it is an easy way to place athletes in a competing category. Age categorization is currently a debated topic because it does not account for the physical development of the athletes, but it is the simplest way to separate adolescents for sports (Abbott et al., 2019; Cummings et al., 2017; Malina et al., 2019). Recently, researchers have started to consider bio-banding, which groups athletes by their maturation status and not their chronological age (Cummings et al., 2017). For certain aspects of training, such as strength and conditioning, certain practice drills or training games, adolescents could be separated by different maturation phases. Future goals could include separating the children by maturation phase for competition. Separation based on maturation phase may allow athletes to acquire better skill development that they otherwise might not obtain if they are early or late maturing adolescents. The early maturing child may be physically stronger than the rest of their age group and therefore physically dominate the game and not feel the need to develop their skill base. Whereas a late maturing child may not be able to keep up with the physical demands of the sport and could lose confidence or interest in the sport (Cummings et al., 2017). This idea of bio-banding has caused an increase in the need to be able to determine an athlete’s maturation status at any given time (Cummings et al., 2017). Lloyd et al. (2014), Malina et al. (2015), and Mills et al. (2017) in turn have reviewed the different maturation assessments, including which method is considered the “gold standard” and which methods are most practical for day-to-day use by coaches and trainers. The researchers have stated that the gold standard of predicting biological age would be to determine skeletal age by way of radiograph image analysis (Lloyd et al., 2014 & Mills et al., 2017); however, cost, accessibility, and qualified clinicians to evaluate the scans make this method difficult to apply to youth athletics. Sexual age can also be considered to assess maturation phase using the Tanner method and the females age at menarche.; however, this also requires qualified and experienced doctors and may present an uncomfortable situation for some of the adolescent subjects (Lloyd et al., 2014). Therefore, given the previous information somatic assessments, such as growth rate, peak height velocity predictions and adult stature predictions, can be measured and determined on any given day and have become a commonly used measurement tool to determine biological age of adolescents (Lloyd et al., 2014; Malina et al., 2015; & Mills et al., 2017).

Growth rate assessments involve researchers gathering longitudinal anthropometric measurements of limb length, mass, and height to growth curves to determine when an adolescent is approaching, currently in, or past their PHV (Lloyd et al., 2014). This assessment would require a subject to report frequently to have their measurements taken. Growth rate calculations also involve numerous measurements such as, breadths, widths and lengths of specific individual landmarks, overall stature and body mass, and the sum of skinfold measurements to determine adiposity. These measurements are then used to apply the current subject to the growth curves to determine their PHV. These various measurements would cause a longer duration laboratory session to be able to collect this data which could cause issues with clubs and teams whose time for training and conditioning may already be limited. Also due to the added time commitment the subject’s compliance might not be perfect and therefore could create missing data and result in less accuracy in the assessment of the individual’s maturity status.

For adult stature predictions researchers can take a single measurement of the subject height and weight at the current time and apply it to their parent’s heights to determine what their predicted adult height will be (Khamis and Roche, 1994). Predicted height can be very important in the world of sport to see how a specific athlete might mature and develop. This could help determine potential positions to focus on for specific sports or the athlete’s ability to deal with the physical demands of a sport (Khamis and Roche, 1994). The predicted height has been more recently used by researchers to find the percentage of adult height at the given moment. This in turn would help coaches and trainers determine where in their maturation an individual might be (Lloyd et al., 2014 & Ryan et al., 2018)). The researchers, trainers and coaches can measure an individual's height in a training session or laboratory session and then find the percentage of their current height. If they are below 89% then the adolescent is prepubertal, 89 – 95% of predicted adult height means the adolescent is in their pubertal growth spurt and 95% or greater means they have are past their growth spurt. The concerning issue for this method of assessment is that not all subjects know their birth parents, some children are adopted, or a parent has not been present in their life, so the practitioner would be unable to gather accurate adult heights to perform this assessment. This assessment also just tells you what phase of maturation an individual is in and not a potential age of when a subject may hit or has hit their PHV. Allowing for a predicted age for PHV and not just the maturation phase of the athlete would allow practitioners, coaches, and trainers to develop a better training plan for that individual.

The last somatic assessment for predicting PHV is to use regression equations (Mirwald et al., 2002 & Moore et al., 2015). This somatic assessment allows an individual's PHV assessment to be completed without any longitudinal study or the need to collect data on parents that might not be available or accurate. The regression equations allow for an age estimate of the subject's maturation phase at the time of testing which should allow for more accurate and safer training methods to be applied to the subject. The Mirwald et al. (2002) PHV equations are calculated within ±1 year of PHV 95% of the time, which the researchers believe to be a sufficient level of accuracy to be able to categorize athletes by their different developmental phase. This accuracy rate of ±1 years is also where criticism of regression equations begins. Some researchers believe this is not an accurate enough measure to predict PHV and would like a more valid measurement (Koziel & Malina, 2018 & Moore et al., 2015). However, all biological age assessments pose difficulty in some way to practitioners, coaches, and trainers. Assessments such as skeletal age can be expensive and along with sexual age require professional examiners. The anthropometric measurements involved with growth rate, especially skinfolds and measurements at specific landmarks would involve good subject compliance over the maturation phases as well as a training session time for practitioners, coaches and/or trainers to collect the data to ensure the measurements are taken properly.

The adult stature predictor along with PHV assessments produce more raw data, in that it is just a calculated number, however, they are easier for coaches and trainers to complete and measure (Lloyd et al., 2014). Lloyd et al. (2014) considered all of these assessments and determined that if you are completing a cross sectional assessment or a first-time assessment of an individual that using age at PHV would be the recommended assessment. The reasoning behind this decision is that there is no previous information needed to find PHV and only measurements taken on the day of the assessment are needed (Lloyd et al., 2014). PHV assessment allows the practitioner to compare subjects at a single date and would provide coaches and trainers an idea of an athlete's biological age to be able to create a better starting point for training and strength and conditioning workouts. All the other PHV assessments require multiple laboratory visits or time set aside at practice as well as additional information that doesn't involve the tested subject (i.e., parents height) to complete the calculations to determine maturation status (Lloyd et al., 2014).

Beunen and Malina (1988) performed a review of previous PHV literature and found that between the various methods for determining PHV the average PHV typically occurred in girls during the later months of their 11th year and in boys around the age of 14. The research articles used in this review included subjects from Europe and North America. The researchers of this review recommend that going forward practitioners, coaches and trainers should not have one set development training model for children because they are all maturing at different rates, and therefore, should have different training focuses based on their biological age (Beunen and Malina, 1988). This article states that the different sexes did mature and reach their PHV at similar times based on the sex of the individual but not at the exact same time which showed there is not a definitive age for PHV for each gender (Beunen and Malina, 1988). This time frame for PHV give an approximation as to when a subject could be approaching PHV but emphasized that each individual is different. Knowing this, researchers, coaches, and trainers still need to further evaluate individuals based on their age and path to PHV. Furthermore, Sherar et al. (2005) examined three longitudinal studies and found that the differences between the age of PHV being achieved can vary between 3 years in boys and 2 and a half years in girls. These two articles show that a trainer or coach working with a U13 boys sport team could have individuals in all three phases of maturation; pre, post and circa PHV (Beunen and Malina, 1988 & Sherar et al. 2005). Therefore, researchers such as Khamis and Roche (1994), Mirwald et al. (2002) and Moore et al. (2015) have provided PHV calculation equations that can be used to determined PHV using a single measurement session for an athlete. These equations can allow coaches and trainers to have a better understanding of the athletes they are working with and make a positive training environment. This will enable coaches and trainers to create more precise training programs for the individual youth athletes that can help prevent injuries and create a healthier athlete.

To initially address the need for PHV calculations for adolescents, Khamis and Roche (1994) created a method to determine what phase of maturation an individual is in. Using the current height and mass of the subject along with the subject's parents' height. Khamis and Roche (1994) were able to determine if an individual was pre, during or post their PHV. The ability to place an individual in a maturation phase enables trainers and coaches to individualize training based on maturation phase and monitor the potential impact on motor skill or sports performance. However, this method may lack inclusivity, as some individuals might not know their birth parents or may only know one of their parents and thus, presents a major issue in this method of analysis. Due to this potential complication in data collection, other methods have since been developed that rely on collecting data from variables that are only obtained from the subject. Furthermore, the Khamis and Roche (1994) method also only categorizes the phase of an adolescent and does not provide an actual age at which an individual will or did reach their PHV.

Philippaerts et al. (2006) conducted a mixed longitudinal study to evaluate physical performance based on PHV difference in a group of youth soccer players. Fifty-one of their subjects were tested over 5 years and 25 were tested over 4 years. The subjects (n=76) performed the full battery of Eurofit testing procedures in one testing session once a year, which included the flamingo balance, bent arm hang, standing long jump, sit-ups for 30 seconds, 10 x 5 m shuttle run, plate tapping (the time for a subject to touch 2 cones on either side of their stationary hand placed on the table 25 times), sit and reach, and endurance shuttle run (Philippaerts et al., 2006). The Eurofit testing has been used in studies to determine athletic differences between groups of individuals and has been determined to be a reliable set of tests (Tsigilis et al., 2002). Tsigilis et al. (2002) completed a between session reliability study using physical education university students. Flamingo balance and plate tapping were found to have an ICC value that was close to or below 0.7 which would be considered poor reliability where the rest of the test were above an ICC value of 0.8 and considered moderately to highly reliable. Erikoğlu et al. (2015) performed a studied that compared 13 youth soccer players to 13 sedentary youth individuals (mean age for both groups was ≈ 13 years) using the Eurofit battery of testing but replaced the standing long jump with the vertical jump. The results showed that the soccer subjects performed the flamingo balance, medicine ball throw, 20 m sprint and 20 m shuttle run significantly better than the sedentary subjects. However, there were no differences between the groups while performing the vertical jump, sit and reach, sit-ups or plate tapping tests (Erikoğlu et al., 2015). This research calls into question the validity of the tests being used in the Eurofit tests for athletic purposes since the results show that only 50% of the tests were significantly different between athletes and non-athletes.

Philippaerts et al. (2006) do show the impacts of the PHV timing on the performance of certain physical tests however these researchers improperly refer to the rate of change between the variable measurements as velocity changes between the measurements. The only measurement that did not reach the greatest rate of change at the time of PHV was the sit and reach test. The sit and reach performance did not reach its maximum rate of change until twelve months after PHV was achieved (Philippaerts et al., 2006). The difference in timing of leg growth and trunk growth (being on different sides of the individual's peak height velocity) may be the cause of limited flexibility until the whole body has completed peak growth rate (Philippaerts et al., 2006). This reduction of ROM could also be based on the muscle tendon relationship through the adolescent phases. Muscles tend to grow in length, thickness and cross-sectional area along with the bones, but the tendons do not adapt to the adolescent changes as quickly (Mersmann et al., 2015). Therefore, as the individual grows the stiffness of the tendon is greater which causes a greater strain within the muscle (Mersmann et al., 2015). This stiffness within the tendons could also be reasoning behind the reduced range of motion (Mersmann et al., 2015).

One of the measurements that was added to this study not associated with the original Eurofit battery of tests was the vertical jump. The vertical jump, if performed correctly, can be a useful test to all coaches and athletes across all sports, as the test measures neuromuscular function of the subject (Philippaerts et al., 2006). For this research the vertical jump was recorded using the best jump height of three attempts; however, there was no other information given as to how the jumps were performed or how the jump height was measured. Therefore, it is not known what instructions were given to the subjects regarding arm swing or squat distance which could have an impact on the jump results. The researchers of this study also incorrectly use the term “explosive strength” as the definition of data output shown by the vertical jump (Winter et al., 2015). This phrase seems to be used by coaches and trainers to help explain and/or visualize what the test is measuring however it is not a term that should be used during research studies. Even with the limited information about how the jumps were performed the results of the vertical jump test did show that the rate of change of jump height increased in relation to the individual getting closer to PHV. Once the individual reaches PHV the rate of change of jump height starts to decline (Philippaerts et al., 2006). This does not mean that the subject is jumping lower it simply states that the gains in jump height are not as drastic as they were during PHV.

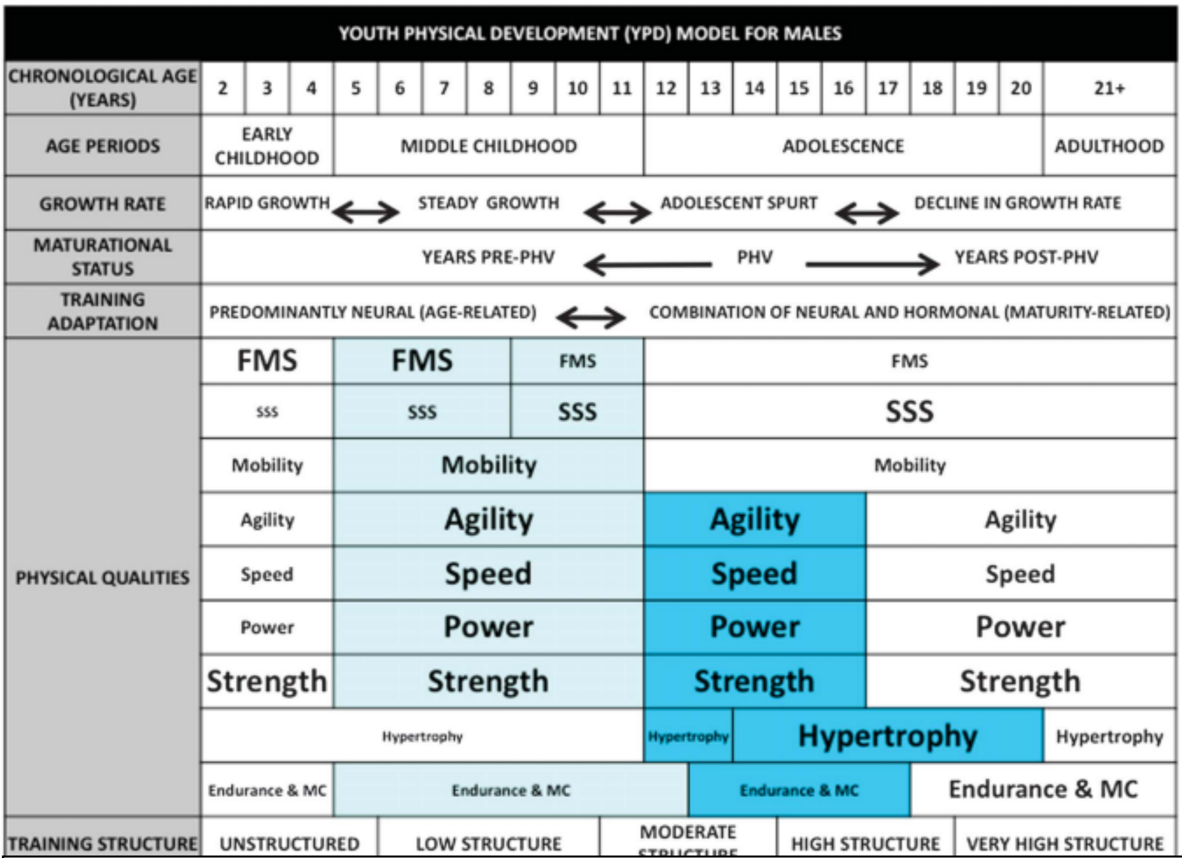
When observing how the adolescent body is changing throughout PHV the lower limbs growth spurt is prior to overall PHV, where the trunk growth spurt is after overall PHV (Philippaerts et al., 2006). Due to the changes in height and mass, as an individual transitions through their maturation phase it is imperative to look at relative net impulse and its components (relative mean force and duration) so that a more detailed and appropriate analysis can be made of the performances of the adolescents(McMahon et al., 2017). Relative net impulse will account for the changes in mass and will allow for a greater understanding of how velocity at take-off affects the individuals jump height. If mass is included in these evaluations, it will seem as though the heavier subjects are producing more force simply because they weight more but it will not be helping with the understanding of how the subject is performing based on their phase of maturation (Kirby et al., 2011; McMahon et al., 2017). This research does show the initial analysis of how neuromuscular function varies depending on where an individual is in relation to the PHV. The results of the different tests in this study show that the largest gains in performance are made prior to PHV and smaller performance gains are made after PHV (Philippaerts et al., 2006). These results highlight the importance of continuing to analyze and evaluate adolescent athletes and the impact of maturation on their performance abilities. This study was a longitudinal study which did create a potential for a more accurate PHV measurement of the subjects (Philippaerts et al., 2006). This study was completed over a 5-year span where the measurements were taken once a year. The researchers also produced 6-month averages based on the yearly measurements to create data that could be closer to an individual PHV if it was reached closer to a half year age (Philippaerts et al., 2006). This method means that some individuals PHV and data points were estimated and may not be as accurate compared to the individuals whose PHV occurred closer to the times when the measurement were collected. In future studies more frequent measurement sessions should occur throughout the year to be able to observe more accurate timing and evaluations of the adolescents as they transition through their maturation phases.

In 2002, Mirwald et al. performed a study to create an easier way to calculate PHV. Prior to this research PHV was a measurement that was acquired during a longitudinal growth study involving repeated measurements for many years to pinpoint and determine when a child had reached their PHV (Mirwald et al., 2002). Using previous data from three different longitudinal studies, Mirwald et al. (2002) created an equation by using an algorithm that can be used to determine how long until or how far past an individual is from their PHV. The total subject count for this study was two hundred boys and one hundred sixty-one girls with a combined total of two thousand eight hundred and eighty-two observations for data collection. Using this data Mirwald et al. (2002) created a regression line using fifteen independent variables to determine the maturity off set of the subjects. The maturity off set is how far an individual is to or from their PHV. These independent variables consisted of age, height, sitting height, subischial leg length, and weight. From these five variables ten interactions were also created to account for the fifteen total independent variables (Mirwald et al., 2002). The results of this study have created a method of measurement of an individual that is a non-invasive, single-session measurement to determine their timing to or from PHV and to determine if the subject is an early, late, or average maturer (Sherar et al., 2005). PHV calculations are important when dealing with adolescents since during their maturation phases muscle architecture and muscle strength are changing and may influence their athletic performance and muscle susceptibility to injury (Philippaerts et al., 2006).

Since Mirwald et al. (2002) created their algorithm, some researchers have questioned the reliability and effectiveness of the PHV regression equation (Moore et al., 2015 & Koziel and Malina, 2018). Moore et al. (2015) found evidence that the Mirwald at al. (2002) equation may be overfitting the data and only be truly applicable to the subjects that were used for their study. Therefore, Moore at al. (2015) redeveloped the equation and simplified the number of measurements needed to be taken of the subjects. Their original equations used only age and sitting height for males and age and height for females. To simplify the equations even more they developed one for males that was just age and height and eliminated sitting height (Moore et al., 2015). In 2018, Koziel and Malina (2018) performed a study to validate the maturity offset prediction equations by both Mirwald et al. (2002) and Moore et al. (2015). The results found that the equations were found to be most accurate when determining average maturing adolescents near their actual time of PHV. Early and late maturing individuals and those farther away from their actual PHV had greater error in predictions (Koziel and Malina, 2018). Both equations tended to overestimate the age at PHV when the subjects were early or late maturing or far away from PHV (Koziel and Malina, 2018). Even with critiques these equations are still the simplest and most accessible way to determine PHV and they still play in important role in the ability to help define the maturation status of adolescents. Future researchers just need to be aware of the limitations of the somatic assessment approach and understand what the data is presenting when it is analyzed and reviewed.

The training programs are also not consistent across all the research articles which means there is not a uniform approach to the training interventions. This causes an issue when reviewing articles because a researcher cannot be sure if the training program or the maturation phase is the cause for differences in the data. Based on the reviewed articles however, the results showed that pre-PHV adolescents had the most improvement in sprint times when they participated in plyometric training. Plyometric training was also most effective for the circa-PHV group as well (Rumpf et al., 2012). The post-PHV group showed the most improvements with combined training methods (Rumpf et al., 2012). Even though some of the reviewed articles did not supply in depth details about their training interventions, the current results show that developmental stage does have an impact on the effectiveness of certain training methods. However, this research uses a rough assessment of PHV by categorizing subjects under the age of 12 as pre-PHV, between the ages of 13-15 as circa-PHV and over 16 years as post-PHV. Since the reviewed research articles did not account for actual PHV of the subjects and used chronological age is it not possible to know if all the subjects in the research are placed in the correct maturation phase. Another problem presented with this study is only impacts on sprint speed are assessed. There are many other aspects of sport such as strength, power and agility that should also be examined during the different stages of adolescents based on a child's PHV. Therefore, knowing PHV is the most effective way to categorize adolescent children, not chronological age, future research should use PHV and evaluate performance implications based on their PHV timing. However, this study showed the importance of examining and testing athlete throughout their PHV journey and how different training interventions can impact performance at different PHV phases.

Since PHV has become a way of determining maturation phases more recent sport development models have used PHV to adapt training to the proper phase of development for adolescents. When Lloyd and Oliver (2012) created their youth physical development model they allowed for adjustment in training methods based on whether or not the individual athlete is an early or late maturer. Lloyd and Oliver (2012) believe this would be determined based on the individual athletes PHV. If the adolescent athlete is an early maturer then Lloyd and Oliver (2012) believe that the athletic focus can be modified to include the training that is more beneficial during that phase of development. Lloyd and Oliver (2012) state that the training areas most affected by developmental stages are fundamental movement skills, sport specific skills, mobility, and hypertrophy. These areas will therefore see a shift in training focus based on an individual's PHV timing. A few years after Lloyd and Oliver (2012) created the youth physical development model, they collaborated with other researchers to create the long-term athletic development model that also expresses the importance of training adjustments being made based on maturity level (determined by PHV) and what the best training approach is for those specific athletes (Lloyd et al., 2015). Figure 2.3.1 shows the importance of training methods used to best fit the growing athlete and what methods should be used to create the healthiest, strongest and best physically prepared athelte while their bodies develop and mature (Lloyd et al., 2015). Figure 2.3.1 expresses the imprortance surrounding the proper training methods for aging adolescents and the importance of being able to determine PHV (Lloyd et al., 2015).



FMS = fundamental movement skills; MC = metabolic conditioning; SSS = Sport Specific Skills

Figure 2.3.1: The Youth Physical Development Model (Lloyd et al., 2015)

Based on initial research to develop a PHV equation (Mirwald et al., 2002) and continued research using it as a factor for adolescents training, (Lloyd & Oliver, 2012; Lloyd et al., 2015; Philippaerts et al., 2006; and Rumpf et al., 2012) the importance of maturation phase for athletic development has become a vital part of training focus. The research shows the importance of not defining an adolescent athlete by chronological age because muscle and body development for training could cause decreases in the interest of the sport, potential injury and lead to drop out if the focus is not appropriate for the individuals maturity phase.

This review chapter addresses all the different techniques that are possible to use to determine an adolescents PHV. It is determined that the most practical assessments for trainers and coaches are the somatic measurements of growth rate, PHV algorithms and adult stature predictions (Lloyd et al., 2014). The PHV and adult stature predictions are ones that can easily be calculated based on simple measurements that can be obtained in a short time frame by a trainer or coach. Future research should examine the exact output and meaning of these different somatic measurements to produce a systematic approach to the appropriate time to use the different measurements to assure an individual proper PHV. This will allow coaches and trainers to create the best approach to training for these adolescent athletes. The current research will examine the PHV algorithms and adult stature predictions within the current subject pool to determine the most appropriate strategy for categorizing the athletes into maturation phases (pre, circa or post) and maturation timing (early, average or late).

2.4: Ultrasound Assessments of Muscle Architecture

In the last 20 years ultrasound has started to become a common method for evaluating muscle structures in individuals. Ultrasound is a non-invasive way to examine an individual's muscle thickness (MT), fascicle length (FL) and pennation angle (PA) of specific muscle structures. These variables all play a pivotal role in the function of a muscle. Muscle thickness is defined as the perpendicular measurement of the muscle from the superficial aponeuroses to the deep aponeuroses. Pennation angle is measured from the insertion angle of the muscle fascicles into the deep aponeuroses. Finally, fascicle length is measured from the insertion points of the muscles into the superficial to the deep aponeurosis. An entire fascicle length may not fit into the scan image and is therefore calculated using muscle thickness multiplied by the sin of the pennation angle (Raj et al., 2017). Muscle thickness can also be referred to as the cross-sectional area of the muscle and is proportional to the force created by the specific muscle (Lieber & Fridén, 2000). Fascicle length or fiber length is proportional to the absolute maximum contraction velocity of the muscle (Lieber & Fridén, 2000). The final measured value, pennation angle, shows the proportion of force transmitted to the muscle tendon (Lieber & Fridén, 2000). These three values have been used to evaluate and compare individuals force production and strength as well as their potential susceptibility to injury.

Based on the research previously conducted using ultrasound, the most important task is finding the appropriate location for scanning the muscle area that is being examined. The process of measurement needs to be conducted accurately and consistently to create reliable data for testing. The most common lower limb muscle involved in ultrasound research has been the vastus lateralis (VL). The VL measurement is taken at the mid-point of the muscle. The research has taken a few different approaches to finding the mid-point however, the most common way was to measure the VL from the greater trochanter to the lateral epicondyle of the femur. Once this measurement is taken the halfway point is found and the ultrasound scans are recorded at that location (Aagaard et al., 2001; Blazevich et al., 2007; Secomb et al., 2015). Two other commonly scanned lower limb muscles in ultrasound studies are the biceps femoris (BF) and medial gastrocnemius (MG). For the BF researchers typically measure from the lateral tibial condyle to the ischial tuberosity and find the halfway measurement. Researchers have also been known to find the halfway point between the tibial condyle and the greater trochanter and then sliding the ultrasound probe medially to find the belly of the

BF where the scans are then taken (Potier et al., 2009). The MG is found at 30% of the tibial length with the probe rotated medially from the apex of the muscle to the belly of the MG (Legerlotz et al., 2010). It can also be taken as the halfway point between the medial femoral condyle and the MG distal muscle tendon junction (McMahon et al, 2015). For the MG another critical part to ensure an accurate measurement is that the subject's foot is hanging off the scanning table to ensure a neutral position, so the foot is neither plantarflexed or dorsiflexed and the gastrocnemius is in a relaxed state.

Strength effects of muscle architecture research has evaluated changes in MT, FL, and PA before and after strength training (Aagaard et al., 2001; Blazevich et al., 2003; Blazevich et al., 2007; Potier et al., 2009; Secomb et al., 2015 & Seynnes et al., 2006). Aagaard et al. (2001) completed a study of eleven male subjects evaluating the effects of a fourteen-week resistance training program on the vastus lateralis muscle. These subjects had an average age of 17 years old and had not previously participated in a resistance training program. The resistance training program for this study consisted of thirty-eight supervised sessions over the fourteen-week period to ensure consistency and accuracy within the training program. The training regime started with lower loading weight and higher repetitions and advance to heavier weight loadings at four-six repetition maximums. The exercises performed for this study were hack squats, incline leg press, isolated knee extension, hamstring curls and calf raises (Aagaard et al., 2001).

The results of this study showed significant increases in the MT, FL and PA measurements after the subjects completed the resistance training program. Due to these anatomical and physiological muscle changes there was also an increase in maximum contractile muscle strength (Aagaard et al., 2001). Based on this research conclusions can be made that training-induced alterations to an individual's workout can be made to increase muscle strength. This research also shows that a larger cross-sectional area (or MT), increased FL and an increased PA are the physiological changes within a muscle that cause the increase in muscle strength (Aagaard et al., 2001). This research however has a small non-diverse population. Only eleven male subjects between the ages of 22-23 were tested. This is a very narrow subject set and should be expanded to see if similar effects can be seen across different ages and sexes. This study also only examined the vastus lateralis muscle group and therefore other muscles should be involved in future research to evaluate the effects of training on all muscle groups and not just one. Based on these limitations more research needs to be conducted to expand the subject pool and examine other muscle groups to see if they also have the same effect to training as the vastus lateralis did in this study.

More research has been performed showing the effects of training and muscle architecture of the vastus lateralis muscle based on the manipulation of force and power. Blazevich et al. (2007) evaluated the influence of concentric and eccentric training on the vastus lateralis muscle. This study evaluated recreationally active males and females. A total of thirty-two subjects were tested with twelve men and twelve women being placed in the training groups and four men and women being in the non-training control group. The subjects were first familiarized with both concentric and eccentric testing on an isokinetic dynamometer prior to the strength measurement being recorded (Blazevich et al., 2007). Peak strength, muscle size, and muscle architecture were measured prior to the start of the training program for this study. Measurements were also taken at five and ten weeks while the subjects were participating in the training program and then tested again at the end of a three-month (fourteen week) post training “detraining” period (Blazevich et al., 2007). The subjects were split into one of three groups: the concentric only group, the eccentric only group or the control group. The concentric and eccentric groups completed a ten-week, maximal effort, concentric or eccentric contraction repetitions, based on their assigned group, three times per week (Blazevich et al., 2007).

The results showed that muscle architecture (including FL, PA and MT) and muscle strength increased in both the concentric and eccentric resistance training groups. In this research no significant differences were found between the two resistance training groups, however, both had significant increases compared to the control group (Blazevich et al., 2007). This research shows the positive impact of resistance training on strength outputs as well as how it effects muscle architecture changes that allow for the strength gains. Even though this research did look at male and female subjects the results did not compare between sexes. These results can help future training programs but could be more applicable if there had been a breakdown of comparisons between sexes. Also, the subjects tested were in a narrow age range in their twenties. More research should be conducted to evaluate resistance training effects on adolescents in all phases of maturation to see if there would be similar strength gains on these subjects. This research also only addressed one muscle group therefore, future research should focus on other muscles not included in the quadriceps.

In 2009, Potier et al., examined the biceps femoris (BF) to see if muscle architecture can be manipulated by eccentric strength training to potentially create hamstrings with lower susceptibility to injury. This research had twenty-two subjects around thirty years of age with no pre-existing musculoskeletal injuries. The subjects only participated in the study training program and had no additional weight training of their lower limbs throughout the duration of the study (Potier et al., 2009). The study consisted of sixteen females and six males with nine females and two males in the control group and seven females and four males in the experimental group. The tests were only performed on the subjects' dominant leg and were taken before and after the eight-week eccentric strength training program (Potier et al., 2009). The subjects performed a one-repetition max eccentric hamstring curl to test for maximum strength and a passive knee extension test to evaluate flexibility and range of motion (Potier et al., 2009). Ultrasound images were also taken of the BF where FL and PA were measured. The subjects were then divided into the control group and the experimental group. The experimental group participated in eccentric 1RM weight training where once the subject was able to complete 1RM without difficulty another repetition was added. Only repetitions increased in this study, weight was never added to the repetitions (Potier et al., 2009). The results showed a significant (mean 13.8 ± 2.3 kg) increase in 1RM max in the experimental group with no significant changes found in the control group (Potier et al., 2009). The experimental group also had a significant increase in range of motion (ROM). There was a significant increase in FL in the experimental group from pre to post training measurements. However, the control group also had an increase in FL which resulted in no significant differences between the two groups. No differences were found between the PA in either the pre or post-test group or between the experimental or control groups (Potier et al., 2009).

This research shows the improvement that can be made in strength and ROM with the implementation of eccentric training (Potier et al., 2009). However, some additional research should be done to truly understand the effects of eccentric training on individuals. This study discusses the commonality of hamstring strain in athletes but does not specify whether or not the subjects are athletes. The age range given is also broad and was stated to be between twenty and fifty years of age with a mean that fell around thirty years old (Potier et al., 2009).

This is a very wide age range especially when athlete injury is the apparent focus of the research. This study also has both male and female subjects in both groups for initial testing to see effects of this training is acceptable but should be evaluated separately in the future to see if differences occur between sexes. The increase in both control and experimental groups fascicle length between weeks one and eight might show the inaccuracy of their method of measuring. Since the FL for the BF cannot be fully seen in the image, line extensions were created until intersections were made between superficial and deep aponeuroses along a fascicle line in the scanned muscle. Since both groups had increases and no significant difference between groups but all other tests expect PA showed difference, more questions arise about the accuracy of the ultrasound measurement and if muscle thickness should have been evaluated as a more accurate measurement. This study shows the potential risks of using ultrasound and the need for more universal methods to ensure accurate measurements of the muscles being tested.

A more recent study did evaluate muscle structure and strength in a group of adolescent athletes (Secomb et al., 2015). In this study thirty junior competitive surfing athletes (twenty-three male and seven females) with an average age of 14.8 years participated in this research. The athletes partook in ultrasound assessments of their VL and lateral gastrocnemius (LG) as well as a countermovement jump (CMJ), squat jump (SJ) and isometric mid-thigh pull (IMTP). All of these tests were completed in a single testing session (Secomb et al., 2015).

This study showed that muscle thickness of the VL and LG as well as the pennation angle of the VL were significantly related to peak force (PF) produced in the countermovement jump, squat jump and isometric mid-thigh pull. Results also showed that leg stiffness had a significant relationship with thickness of the VL and LG muscles and pennation angle of the VL. Peak force in the CMJ, SJ and IMTP also had significant relationships with leg stiffness (Secomb et al., 2015). Secomb et al. (2015) concluded that muscle thickness had a stronger correlation with peak force (r =0.54-0.77) than pennation angle (r = 0.51-0.53) but that positive correlations exist between muscle architecture and the impact it has on the performance during a CMJ, squat jump and isometric mid-thigh pull. These observations are likely explained by Narici et al. (1989) who concluded that increases in cross-sectional area of the muscle (muscle hypertrophy) were only accountable for 40% of the overall muscle strength increase and that 60% was due to other muscle architectural changes within the muscles. The researcher express the importance of evaluating all aspects of the muscle architecture and not just muscle thickness (Narici et al., 1989). The researchers did not account for changes in adolescent maturation phase and its potential effect on muscle architecture and PF. Males and females also reach their maturation phases at different times in development and therefore, even though there may still be significant correlations between these tests and PF, a more integrated break down by maturation and sex could be beneficial. These researchers also averaged the right and left leg VL and LG for the muscle thickness and pennation angle which is assuming that the subjects have balances muscles between their legs (Secomb et al., 2015). This is an assumption that could affect testing results since most athletes have a dominant and non-dominant leg that can have effects on muscle architecture and in turn have an effect on PF. More detailed analysis needs to be made between sexes and maturation status to continue the evaluation of adolescent youth athletes.

In 2021, Radnor et al. conducted a study they did evaluate the differences between subjects at different stages of maturation. The study was conducted on male athletes whose mean ages for the different groups were ~12 years of age for the pre-PHV group, ~14 years of age for the circa-PHV group and ~16 years of age for the post-PHV group. These subjects all participated in ultrasound scans of the vastus lateralis and medial gastrocnemius, countermovement jumps and sprint assessments. This study also included a cross-sectional study as well as a longitudinal study (Radnor et al., 2021). The longitudinal study consisted of two testing sessions that were 18-month apart from one another. The results of this study showed the importance testing adolescent subjects. In the cross-sectional study the post-PHV subjects performed better during the jumping and sprinting tests and had greater muscle thickness and fascicle lengths in the vastus lateralis compared to the pre and circa-PHV subjects (Radnor et al., 2021). Longitudinally all groups performed their jumps and sprints better and saw increases in their vastus lateralis thickness and fascicle length (Radnor et al., 2021). The results of this study not only showed the differences between phases (pre, circa and post) of individual subjects but also how maturing through a phase or continuing in the post-PHV phase impacts the muscle architecture and jump and sprint variables. This research has helped highlight the importance of following subjects through their adolescent growth spurt and the ability to help subjects improve with strength training programs that involve both heavy load and high-speed movements (Radnor et al., 2021). These results show the impact muscle architecture has on sprint speed and jumping performance. Muscle thickness had the greatest impact on greater performance in the individuals jumps and fascicle length in sprint speed and should be considered as critical evaluation for talent identification and performance outputs in adolescents (Radnor et al., 2021). This study only addresses boys so future research needs to be completed to address adolescent females to see if the correlations are the same within the different sex.

Ultrasound is a reliable method for evaluating the muscle thickness, pennation angle and fascicle length of specific muscles but needs to be used in conjunction with other laboratory testing, like isokinetic dynamometry peak torque outputs and countermovement jumps, to create more meaningful data to examine the potential difference between adolescent athletes (Aagaard et al., 2001; Blazevich et al., 2003; Blazevich et al., 2007, Potier et al., 2009; Secomb et al., 2015 & Seynnes et al., 2006). Past research has shown that ultrasound has an important place in the evaluation of strength and training adaptations for athletes because it enables the assessment of the impacts of increasing muscle thickness, fascicle length, and pennation angle have of force and power output (Aagaard et al., 2001; Blazevich et al., 2003; Blazevich et al., 2007, Potier et al., 2009; Secomb et al., 2015 & Seynnes et al., 2006). Being able to observe these physiological changes can help coaches and trainers know what training adaptations are most beneficial for athletes.

Recently ultrasound researchers have started to question the reliability of between session scan evaluations (Franchi et al., 2019, Ripley et al., 2022). These researchers have found that when the ultrasound probe length is less than 6 cm overestimations of fascicle lengths which could lead to misleading data (Franchi et al., 2019, , Ripley et al., 2022). These studies have brought into light the potential of using larger probe lengths so that there is a larger field of view or to use the extended field of view methodology that creates a visual of the whole muscle which enables more accurate measurements to be made (Franchi et al., 2019, , Ripley et al., 2022). The current research thesis will use ultrasound scans based on the previous studies showing the correlation between muscle architecture variables and performance outputs (Aagaard et al., 2001; Blazevich et al., 2003; Blazevich et al., 2007, Franchi et al., 2019; Potier et al., 2009; Radnor et al., 2021; Ripley et al., 2022; Secomb et al., 2015 & Seynnes et al., 2006). The research conducted by Radnor et al. (2021), Franchi et al.

(2019), and Ripley et al. (2022) was completed at the same time as the current thesis but enhances the importance of ultrasound scans in the analysis of athletic performances of subjects. However, current research does not thoroughly address the differences muscle architecture differences between single sport and multiple sport adolescent athletes. Therefore, to help evaluate athletes that are single sport or multiple sport athletes who are at different stages of their maturation, ultrasound muscle architecture will be evaluated in this thesis.

2.5: Countermovement Jump Assessment

The countermovement jump (CMJ) has been used in research to evaluate the neuromuscular function of athletes (McMahon et al., 2018). Some researchers have previously referred to the neuromuscular function as the "explosive strength" of an athlete which is more of a physical characteristic of how the movement is completed and easily explained and understood by coaches and athletes but should not really be referred to this way in scientific literature. (Winter et al., 2015). The evaluation of force and power production during a CMJ has been used to assess differences in athletic performance between various groups of subjects (Christou et al., 2006; Comfort et al., 2014; Cormack et al., 2008; McMahon et al., 2018; Paasuke et al., 2001; Secomb et al., 2015; Tauchi et al., 2008; Vuk et al., 2015). Countermovement jumps performed on force plates have produced a wide variety of output data. This data has been critiqued and reevaluated so that the most affective variables are examined to be able to compare athletic performance between subjects or subject groups.

Power is one of these variables that has been critiqued because the power generated by a subject can be manipulated by how a CMJ is performed (Markovic et al., 2013). Therefore, Markovic et al. (2013) observed subjects performing CMJs and saw that the power changes were relatively small and dependent on the load applied to the athlete during a jump. After a training period the subjects had an increase in strength but minimal gains in power output. The changes in the CMJ kinematics and kinetics like depth of the CMJ squat, movement duration and ground reaction forces had a larger influence on the jump height increases in this study (Markovic et al., 2013). However, if there were two subjects that had the same movement time and jump height, but one weighed more than the other, the heavier subject is going to produce more power simply because of the additional mass. This example and the study by Markovic et al. (2013) show that power has a place in the research but the effects of how a jump is performed (i.e., jump strategy) and how those movement changes impacts impulse (and the component parts; force and time) can be more effective in the evaluation of the CMJ. Using power as an example it is shown that when reviewing CMJ there are two main points a researcher should focuses on and be cautious of when evaluating methods and analysis. These two foci are testing methods and data analysis (including the variables selected).

Testing methods, the first foci, should focus around whether or not the subjects used an arm swing while performing the CMJ. A proper CMJ should be performed without an arm swing to enable the evaluation of the lower limb without the momentum caused by the use of an arm swing (Cormack et al., 2008). Lees, Vanrenterghem & De Clercq (2004) have shown the importance of making sure there is no arm swing to prevent momentum from those movements. An arm swing will skew the jump height and forces data acquired in the jump. If the arm swing is negated then the only forces created by the subject during the jump of by the leg muscles of the subjects (Cormack et al., 2008). Past researchers have used arm swing and no arm swing interchangeably or without proper explanation in the testing procedure or methods (Santos & Janeria, 2008). Therefore, if the jump procedure or method is not clearly defined and if a practitioner or coach reviews the study it could cause confusion while evaluating the results and data and how it should best be used. Unknown jump methodology may also create an inability for data comparison and review between other jump research. Therefore, the verification of which CMJ method was conducted during a research study needs to be of the utmost importance for researchers when they are performing, evaluating or reviewing jumping test research. McMahon et al. (2017) commented on a review of CMJ jump height data and how it was acquired. These researchers express their concerns surrounding what jump system was used to during testing and how jump height was eventually calculated. Some of the jump systems use flight time to calculate jump height which can be manipulated by how a subject lands, if they land flat footed or tucked their legs prior to landing, the flight time would be longer and therefore an inaccurate jump height would be recorded (McMahon et al., 2017). Therefore, velocity at take-off should be used for a more accurate jump height but not all jump systems have this as an output variable. With the different jump systems and evaluation of the results McMahon et al. (2017) explained that comparisons between the testing systems and the corresponding data cannot be made. Therefore, based on the importance of the jump methodology and the effect it can have on data output it is important to be aware of these issues while performing article reviews on this topic. Researchers and evaluators therefore need to be diligent when evaluating and performing the CMJ to ensure a thorough review and application of the CMJs performed.

The second area of focus when reviewing CMJ literature is the different phases of the jump and the coinciding variables used during analysis (McMahon et al, 2018). Recently researchers have started to consider the different phases of the CMJ and the different forces, velocities, and power outputs to enable a more thorough understanding of the neuromuscular function and jumping mechanics used in a CMJ (McMahon et al., 2018). Prior to McMahon et al., (2018) creating the different phases, most data output was broken down by the eccentric or concentric contraction of the CMJ motion. The lowering phase or unweighting and braking phases would be considered the eccentric contraction of the motion and the raising or propulsion phase would be the concentric contraction (McMahon et al., 2018). McMahon et al. (2018) determined that since it is not certain that all muscles associated with the eccentric and concentric movements are acting in those particular contractions that it should not be the way to describe the phases. Therefore McMahon et al. (2018) created the following phases during the countermovement jump to ensure more concise descriptions.

McMahon et al. (2018) evaluated a CMJ force-time curve and determined there to be six different phases in the jump. The first phase is the weighted phase. This phase should be conducted while the subject is stood as still as possible for at least a second on the force plate (McMahon et al., 2018). This phase ensures an accurate bodyweight calculation so that the onset of movement of the CMJ can be determined and derive the subjects body mass from the measurement for application in further calculations (McMahon et al., 2018). Body mass is the division of the subject's body weight (which is a force represented by newtons) by gravity or 9.81 $m \cdot s^{-2}$. This calculation leaves the researchers with a body mass in kg and can be used in calculations to determine forces or variables relative to the subject's mass. This allows for the comparing of athletes of different sizes based on relative outputs with the negation of mass (McMahon et al., 2017 & Morris et al., 2020).

Following the weighing phase is the unweighting phase of the CMJ which begins at the onset of movement. The onset of movement is defined as the instant the force readings drop below the bodyweight force of the subject and continues until the instant at which force output returns to the subject's body weight (McMahon et al., 2018). This phase has negative acceleration and negative direction. If a subject is able to create a greater net impulse in this phase there is a greater negative velocity. This in turn requires the subject to apply and equally large net impulse in the braking phase (next phase) to reduce the momentum back to zero to continue a greater magnitude of force to eventually lead the subject to jump. The net impulse in this phase reflects on the impact of the stretch-shortening cycle of the jump muscles and how they are loaded to enable braking and eventual propulsion in the jump (McMahon et al, 2018).

The third phase of the CMJ is the braking phase, where the subject decelerates and achieves a velocity of zero at the bottom of their countermovement (McMahon et al., 2018). The transition from the unweighting phase to the braking phase is at the instant of peak negative velocity. This phase has previously been referred to as the eccentric phase of the movement (Aboodarda et al., 2013; McMahon et al., 2017; Toumi et al., 2004). This is because the leg extensors are acting in an eccentric contraction to decelerate the subject (McMahon et al., 2018). However, all muscle of the leg may not be acting in an eccentric way and the eccentric phase may have included the unweighting phase as well which is why McMahon et al. (2018) have renamed and redefined these phases to help minimize future confusion while performing analysis involving a CMJ. During the braking phase a subject may apply a larger force for a shorter period of time or a smaller force for a longer period of time which will change the shape of the force-time curve. The difference in force and time applications can be used to evaluate different jumping styles and how they affect the jump height of an individual (McMahon et al., 2018).

The propulsion phase is the fourth phase of the CMJ which is when the subject forcefully extends their lower limb joints (knee, hip, ankle) to move their mass upward (McMahon et al., 2018). This phase occurs once the subject has achieved a positive velocity after zero-velocity was achieved at the end of the braking phase and continues until the subject has achieved complete separation from the force plate, also known as the moment of take-off (McMahon et al., 2018). Impulse is the variable that is most important during the CMJ propulsion phase. The application of force over time and the manipulation of the two during the propulsion phase are the variables that, when manipulated, should enable the improvement of jump performance (McMahon et al., 2018).

The next phase is the flight phase and is the fifth phase of the sequence. This phase is represented by the moment of take-off until the instant of touchdown (McMahon et al., 2018). Jump height can be calculated in this phase by using either flight time and/or take-off velocity (Moir, 2008). There are other calculations to find jump height however these two methods seem to be the most commonly used (Moir, 2008). To calculate jump height based on flight time one would use the equation JH = $\frac{1}{2}g(\frac{t}{2})^2$ where g=gravity and t=flight time. If one chose to use take-off velocity, then jump height would be calculated using the equation JH = $\frac{TOV^2}{2g}$ where TOV=take-off velocity and g=gravity. The sixth and final phase of the CMJ is the landing phase where the subject decelerates from the flight phase and returns to their weighted phase measurement (McMahon et al., 2018). This phase can help with evaluations of landing styles and force application to the leg joints while landing. This in turn could help evaluate more efficient and safer ways to land from a jump (McMahon et al., 2018).

The understanding of these different phases throughout a CMJ enables a researcher to evaluate more specific variables and data outputs produced by the force plate during a CMJ. Force, impulse, power, velocity, and the time duration of the different movement phases are variables should be analyzed during a jump. Force and time will create the impulse variable in the different phases and velocity at take-off will determine the overall jump height acquired by the subject. This will enable a better understanding of jumping mechanics and how different variables may play different roles in the success of a subjects jump. In the past the most important variable for coaches and athletes was jump height because of the vital role it can play in sport. However, with additional evaluations of these phases and variables within the phases there can be a more thorough understanding of what influences the athletes jump height. This will enable an athlete to focus on certain aspects of their jump to achieve a greater jump height as well as allow coaches and trainers better insights into where improvements need to be made throughout the jump.

As mentioned previously there has been an increase in the number of variables and calculations that are being produced from the CMJ data outputs. Therefore, along with different phases of the jump these calculations and variables also need to be included as an area of focus while examining past literature. The first step in examining CMJ's with force platforms is to examine the sampling frequency used during the jump. This frequency indicates the number of force samples taken in each minute. Street et al. (2001) and Owen et al. (2014) determined that for the calculated force variables to be valid and reliable the sampling frequency needed to be at least 1000 Hz. This simply means that 1000 samples per minute need to be recorded for the testing variables calculated from this data to be reliable and valid. These researchers showed that a sampling frequency less than 1000 Hz has less accuracy in jump height of the subjects and therefore can lead to misinformation about the subjects jumping performance (Street et al. 2001 & Owen et al. 2014). Street et al. (2001) and Owen et al. (2014) showed that if the sampling frequency is less than 1000 Hz the instant of take-off and landing have a higher probability of being inaccurate because there are less force data samples taken off of the force plate. Therefore, when using flight time to calculate jump height it can become a skewed variable and can produce a less accurate jump height. The CMJ has been used frequently in research because it is typically a very basic movement skill for most athletes and is easy for the subjects to perform. However, examining the methods involved in conducting a countermovement jump, there are many ways that this relatively easy testing method can be conducted improperly which causes issues with accuracy and comparison among other studies.

As stated prior the main output focus of CMJ analysis used to be jump height (Linthorne, 2001). For athletes and coaches, it was an easy test that enabled them to examine how high an athlete could jump. In many sports jump height is important for success and therefore, many didn't think there was any need for more data output or analysis. In 2001, Linthorne examined the most reliable method of calculating jump height between three calculations obtained using the ground reaction forces collected by a force platform. The three different calculations were the flight-time method, the impulse-momentum method and the work-energy method (Linthorne, 2001). Of these three calculations the most reliable jump height was recorded was the impulse-momentum method of calculation. Due to the calculations and data outputs the researcher also started to examine the force-displacement graphs to analyze the differences between a CMJ and a Squat Jump (Linthorne, 2001). This examination showed that the CMJ enables the subject to create more force due to the unweighting and braking phase which in turn propels the subject into a higher jump (Linthorne, 2001). Based on the results of this research it can be beneficial to have a more in-depth data output to examine force-time, acceleration-time, velocity-time, displacement-time and force-displacement curves generated from the data of the CMJ to see what roles these variables may have in the success or failures of an athletes jump. Since this research by Linthorne (2001) was completed, researchers have started to examine more than just the jump height of athletes (Christou et al., 2006; Comfort et al., 2014; Cormack et al., 2008; McMahon et al., 2018; Paasuke et al., 2001; Secomb et al., 2015; Tauchi et al., 2008; Vuk et al., 2015). The number of variables that can be examined is quite extensive and should be narrowed down based on what the researcher is specifically looking to examine during their research. However, in 2018 Chavda et al. produced an article to show many of the different jump characteristics can be examined using the force-time curve using the six phases of the countermovement jump developed by McMahon et al. (2018).

Cormack et al. (2008) completed a reliability study on fifteen elite Australian Rules Football players. The players partook in three familiarization sessions to become comfortable and efficient with the CMJ movement where all the subjects were instructed to hold their hands in place on their hips during the entire jump (Cormack et al., 2008). This research evaluated the reliability of a single CMJ as well as five continuous CMJ repetitions. The data collected over the five CMJs created an average of the jumps for the variables analyzed. The results of this study showed that CMJ can be a reliable testing method for jump height, flight time, peak power, relative peak power, mean power, relative mean power, peak force, relative peak force, eccentric time, concentric time and flight time (Cormack et al., 2008). Jump height, power variables and force variables are the most reliable of the data points collected (Cormack et al., 2008). This study also evaluated reliability between morning and afternoon sessions as well as different day sessions. The subjects had a very controlled workout schedule and the results showed there were no significant differences between morning and afternoon sessions or day to day sessions (Cormack et al., 2008). These results show the reliability of the CMJ test. An issue with this study however is that the subject pool is made up of elite athletes. The subjects compete at the highest level of their sport and can perform basic athletic movements. These athletes were also given three familiarization sessions as well as three submaximal jumps prior to the analyzed jump. This helps with testing reliability because the subjects have practiced the test and know what is expected and required during the testing. This type of preparation protocol is ideal when testing but is not always feasible. Therefore, reliability testing should be completed without familiarization sessions to see if the test can be reliable when a researcher only has access to their subjects for one session. Also, different sexes and age groups should be evaluated to see if the test is reliable across various subject pools.

Further research by Tauchi et al. (2008) examined the performance of CMJ's between elite and healthy male adolescents. This research had 120 elite alpine skiers, fencers, soccer players, weightlifters, track and field sprinters or jumpers (aged 18-24) who were compared to 316 healthy males aged 19-20 years (Tauchi et al., 2008). Two vertical jump tests were performed: a CMJ and a five-repeated rebound CMJ's. The jumper's arms were set at the hips to control for the effect of arm swing. During the testing three of each jump were performed unless one was unsatisfactory to the researcher. If a test was considered unsatisfactory the subject was asked to repeat the jump until a satisfactory jump was completed (Tauchi et al., 2008). The results showed that for both the single CMJ and the five repeated CMJs, the elite athletes had significantly higher jump heights compared to the healthy male group. The elite group also had a shorter contact time during the five repeated CMJ's. This result shows that the elite athletes have more explosive speed and turnover than the healthy male group (Tauchi et al., 2008). This research shows that strength and agility differences exist between healthy males and elite male athletes, by way of jump height. More research should be done to see where the muscular differences exist in the lower limbs to create these differences. Future research should examine quadricep and hamstring strength differences and potential muscle thickness, fascicle length and pennation angle differences through ultrasound. These tests have the potential to show why significant differences exist between these two groups. Future tests should also include females to determine if the same differences exist within this subject group. The subjects of this study are also said to be adolescent athletes however, the subjects tested are quite late in adolescents at age 19 and 20 and might be considered past adolescents by some. All subjects tested would be well past their peak height velocity. Therefore, future research should include younger subjects who are at different stages of PHV to see the effects of age on CMJ as well.

Research has also started to use CMJ's to compare laboratory tests and training manipulations to see if the CMJ can be used to observe strength differences among testing subjects (Comfort et al., 2014; Christou et al., 2006; Paasuke et al., 2001; Secomb et al., 2015; & Vuk et al., 2015). In 2001, Pääsuke, Ereline and Gapeyeva performed a study to examine knee extensor muscle strength and vertical jumping performance in pre and post-pubertal boys. This study examined twenty-eight boys, fourteen of which were classified as pre-pubertal and had an average age of 11.4 years. The other fourteen tested were considered post-pubertal and had an average age of 16.4 years (Pääsuke et al., 2001). Using a Cybex II dynamometer the two groups of boys had their knee extensor muscles tested isokinetically in a concentric motion at 60°·s^{-1}, 180°·s^{-1} and 240°·s^{-1}. The subjects also had isometric testing with the knee angle at 90° to test for maximum isokinetic force and rate of force development (Pääsuke et al., 2001). The vertical jump tests conducted were the squat jump, CMJ and drop jump. For all three jumps the subjects were instructed to keep hands on their hips throughout the jumps to eliminate the influence of arm swing on the jumps (Pääsuke et al., 2001). The results of the study showed that there was a strong relationship between an increase in body mass and an increase in isokinetic strength (Pääsuke et al., 2001). Therefore, since the post-pubertal boys had a body mass average of approximately seventeen kilograms more than the pre-pubertal boys their isokinetic strength is also greater (Pääsuke et al., 2001). This study also showed that pre-pubertal boys had 15-17% lower jump heights than the post-pubertal boys. The researchers believe this is due to the post-pubertal boys having an increase capacity for rapid neural activation (Pääsuke et al., 2001). This study shows that post-pubertal boys have a higher jump height and absolute isokinetic and isometric strength, but their relative strength based on body weight was not significantly different. The post-pubertal boys would have gone through their PHV so even though their relative strength was the same as the pre-pubertal boys they would have been taller and have the potential to have a greater range of motion in their CMJ. This greater range of motion allows the subject to have a greater impulse because they are able to apply forces for a longer period of time which may be the reasoning the post-pubertal boys were able to jump higher. Therefore, more research should be done to evaluate links between the CMJ and isokinetic testing performed in this study to see if a more detailed analysis can be made correlating the two tests. This research also only examined males subject therefore, future research should be conducted with the inclusion of the female sex to see if similar results are shown in that population of subjects.

Marius et al. (2006) evaluated eighteen male soccer players with an average of 4.3 years of training experience and ranging between 12-15 years of age to determine the effects strength training might have on the physical capacities of adolescent soccer players. These two groups were divided evenly into a strength and soccer training group, just a soccer training group, and a control group that consisted of eight boys (Marius et al., 2006). To evaluate the impacts of the sixteen-week strength training program on this subject pool the following tests were completed; maximum strength (1 RM bench press and leg press), vertical jump performance (squat jump, CMJ and repeated jumps for 30 seconds), 10 m and 30 m sprints, 10 x 5 m agility test, sit and reach test and a slalom dribble test to evaluate soccer technique. The results of this study showed improvements in agility, flexibility and strength of lower limbs for both soccer groups during this study which shows that consistent training in a sport can help improve some physical aspects of an athlete (Marius et al., 2006). In the strength group vertical jump performance significantly increased in terms of jump height, maximal force and power (Marius et al., 2006). These researchers showed the positive impacts of strength training on adolescent athletes using laboratory tests which included the CMJ (Marius et al., 2006). Using this information future goals would be to create more effective training protocols based on the results shown in the laboratory tests to improve all athletes. This study however has a small population of subjects and also only used male subjects. The age range of the boys might also be a concern because between the ages of 12 and 15 these boys could be pre, circa or post-PHV. Therefore, PHV should be considered in the future to see if there are different effects on the jumping and training manipulation based on where adolescents are in their maturation.

In 2020, Morris et al. evaluated the difference between maturity offset and age of youth male soccer players. The results of this study showed that the subjects did not demonstrate differences in relative strength or relative force between age groups (Morris et al., 2020). These results contrast those of the study by Christou et al. (2006) that showed sport training alone and strength training as an addition to sport training can improve an athlete's performance in leg press strength, bench press strength, CMJ jump height, and squat-jump jump height. The Christou et al. (2006) study was a small sample size and therefore maybe with a larger experimental group the results may change. Also, Morris et al. (2020) stated that their athletes were elite level athletes where Christou et al. (2006) only stated that their subjects were soccer players. Analysis of past research by Rhea (2004) demonstrated that trained and untrained individuals can both increase strength via strength training but that the untrained subjects have a greater overall potential for change in strength. This differentiation might mean that the non-elite subjects have greater improvements to be made. However, the impact of strength training on performances like the CMJ should continue to be evaluated to see if athletes can be developed in a better and healthier way.

Comfort et al. (2014) analyzed the relationship between speed, vertical jumps and lower body strength within a group of youth male soccer players (average age of 17.2 years).

To evaluate these athletic abilities 5 meter and 20 meter sprints, squat jump, CMJ and a regression equation analysis of 5RM failure progression squat to determine the 1RM back squat load, were administered. This research showed the importance strength plays in athletic movements such as speed and jumping performance (Comfort et al., 2014). The results of this study showed moderate to strong correlations between strength and athletic movement performance (Comfort et al., 2014). Strong correlations were found between strength and jump performance (r = 0.762) and strength and sprint speed (r = -0.596) (Comfort et al., 2014). The more successful subjects performing these tests were also the subjects that were considered elite in comparison to the sub-elite group (Comfort et al., 2014). This research evaluates just males who were most likely past their PHV so future research should be done with younger age groups as well as with females to see if the trends are consistent throughout adolescents and between sexes.

Secomb et al. (2015) uses countermovement jump as part of the overall analysis of athletic performance conducted to examine muscle structure relations with lower-body strength, force production and eccentric leg stiffness in adolescent athletes. The CMJ was used in conjunction with a squat jump (SJ) and an isometric mid-thigh pull (IMTP) to evaluate lower-body strength and explosiveness (Secomb et al., 2015). This study tested thirty competitive male and female surfing athletes with an average age of 14.8 ± 1.7 years (Secomb et al. 2015). In relation to the CMJ this study showed significant relationships between muscle thickness in both the vastus lateralis and lateral gastrocnemius with the peak force created in the CMJ as well as the SJ and IMTP. This result shows the importance of leg thickness and the ability to produce stronger dynamic and isometric forces (Secomb et al., 2015). These relationships are important moving forward to help evaluate adolescent athletes. This study is testing adolescent athletes that may be transitioning through PHV, but no data is presented to confirm the maturation phase of the subjects. Therefore, future researchers should examine how muscle thickness is affected by both maturation phase transitions and training programs to see what benefits truly exist with the training at the different stages of maturation. A wider age range and PHV calculation as well as muscle thickness measured with ultrasound and leg circumference should be used to create a more accurate analysis of adolescent athletes.

In 2015, Vuk et al., evaluated if load and body size would have an effect on knee extensor muscle strength and movement performance. This study tested 66 young and healthy men aged 22 ± 4 years with athletic backgrounds (Vuk et al., 2015). This study had five different loading conditions for the CMJs: zero load (100% BW), two negative loads (85% and 70% BW) and two positive loads (115% and 130% BW). For each one of these loads 3 consecutive trials were performed with breaks between each different load. After performing the CMJ sequence, the subjects then performed an isokinetic dynamometer test to determine the subjects concentric quadricep strength of the subject's non-dominant leg at $60°\cdot s^{-1}$ (Vuk et al., 2015). The results of this study showed that peak power and jump height (found from isokinetic dynamometer and CMJ respectively) were independent of the external loads applied during the jumping phase (Vuk et al., 2015). These results showed that relative strength would be a better means for comparing individuals for strength measures versus absolute strength. This idea has been supported within two studies conducted by McMahon et al. (2017) and Morris et al. (2020). The results of these studies showed there were significant and meaningful differences between the CMJ variables in the tested groups when absolute values were used. However, when relative values (variables divided by body mass) were calculated and assessed there were less or no significant differences found between the CMJ performance variables (McMahon et al., 2017 & Morris et al., 2020). The research also exhibits the importance of relative leg strength and its impact on jump performance. Relative strength, therefore, should be used as the means of evaluation and comparison of subjects across sexes and ages. However, this study only evaluated males that have achieved and surpassed their PHV by many years and therefore more research should be done across various ages and sexes to evaluate if relative strength measures can truly be used to compare all types of subjects in an accurate and reliable way.

All the previously mentioned studies have shown the importance CMJ's can play in the evaluation of athletes. Peak force and jump height are two integral measurements for the evaluation and comparison of athletes' abilities. These CMJ results can also be used in conjunction with other laboratory tests such as ultrasound and isokinetic dynamometers, to examine performance abilities between subject groups. More research needs to be done across ages and sexes to truly find the best integration of the CMJ into the evaluation of athletes. Maturation phases should be evaluated farther based on the physical changes that occur while an individual transitions from pre to post-PHV. Some research has been completed on subjects that fall within these age groups but are not specifically looking at the groupings based on PHV. Pääsuke at al. (2001) had subjects that were pre- and post-PHV however, there were no subjects within the growth spurt period to enable evaluation of what happens while the subjects is growing rapidly. Marius et al. (2006) and Secomb et al. (2015) performed their research on adolescents between 12 and 15 years of age which is right when most adolescents are in their PHV ranges. These studies, however, did not account for PHV phase of the subjects, which based on research from Beunen & Malina (1988), Malina et al. (2003), Philippaerts et al. (2005) and Towlson et al. (2020), was a mistake since as a subject transitions through PHV they produce increased forces which would impact CMJ performances. The changes in height and weight as an adolescent grows are the reasons there are impacts on the athlete's performance abilities and should be examined to make sure training and practices are conducted in the safest and most effective way. The CMJ should be used in the future because it is a simple task that most individuals can complete, especially athletes. The previous research has shown the variables that impact jump heigh and play pivotal roles in an individual's performance abilities. The more research completed using CMJ will enable coaches, trainers and practitioners to better evaluate and find ways to adjust an individual's training and conditioning to create a more successful athlete.

Therefore, moving forward with the current thesis, based on past research showing how the CMJ can be used in conjunction with ultrasound measurements and isokinetic dynamometer, it seems imperative to use it while evaluating the differences between single sport and multiple sport athletes (Christou et al., 2006; Comfort et al., 2014; Cormack et al., 2008; McMahon et al., 2018; Paasuke et al., 2001; Secomb et al., 2015; Tauchi et al., 2008; Vuk et al., 2015). However, no research has been conducted comparing single sport athletes to multiple sport athletes. Based on the information that can be provided using these three testing procedures it is important to start to examine the physical impacts of being a single or a multiple sport athlete to determine the best development strategy for athletes as they transition through their adolescents. This advancement in research would help add to the LTAD models and hopefully help develop healthy athletes that are able to compete at the level they aspire too.

2.6: Isokinetic Dynamometer Assessment

Isokinetic dynamometry has long been used to measure torque and isometric force production, and to evaluate lower limb muscle torque and muscle balance in an effort to determine reliable measurements that may identify athletic performance and athletes that may be at higher risk of lower extremity injuries (Wilk, 1998). When muscle balance is used for evaluation of the lower limb muscles hamstring to quadriceps (HQ) ratio is used. Originally the H/Q ratio was evaluated as the concentric force production of the flexor and extensor muscles which is now referred to as the conventional H/Q ratio (Wilk, 1998; Devan at al., 2004; Myer et al., 2009; Magalhães at al., 2004; Rosene et al., 2001; Hewett at al., 2008; & Grygorowicz at al., 2010). The research conducted has determined that an H/Q ratio greater than 60% at $60°·s^{-1}$ or 85% at $300°·s^{-1}$ during concentric assessment has been shown to be related to improved knee stabilization which has been reported to reduce the risk of potential knee and hamstring injuries (Croisier at al., 2008 & Devan et al., 2004). Along with H/Q ratios, peak torque (PT) has been evaluated to compare strength of the quadriceps and hamstrings between groups of subjects. The importance of this data is reviewed and critiqued in the following chapter.

The study in which Wilk (1998) creates the percentages acceptable for the concentric H/Q ratios was a reliability study that consisted of 24 subjects performing knee extension and flexion movements on an isokinetic dynamometer. The subjects tested at $60°·s^{-1}$, $180°·s^{-1}$, $360°·s^{-1}$ and $450°·s^{-1}$. The number of subjects is sufficient to complete a reliability study however, it is an extremely low number of subjects to create normative data values in which future research is based. Each subject was tested twice with two days' rest between each test. Analysis of the data using Pearson correlation coefficients showed the Biodex to be a reliable testing device; however, reliability should be determined by running an intraclass correlation coefficient (Wilk, 1998). Pearson's correlation should only be used when determining the linear association between two variables (Liu et al., 2016) as it only provides information regarding the magnitude of the correlation between variables and not agreement (reproducibility) between them (Koo & Li, 2015; Lui et al., 2016; Weir, 2005). Therefore, when correlation and reproducibility are being examined in test-retest research the ICC analysis should be used (Koo & Li, 2015; Lui et al., 2016). The ICC accounts for both correlation and agreement as well as error which evaluates the differences between the true and observed scores (Koo & Li, 2015; Lui et al., 2016; Weir, 2005). The ICC should also be presented with the

95% confidence interval range to truly express a more accurate range of correlation and agreement for the variables being tested (Koo & Li, 2015; Lui et al., 2016; Weir, 2005).

The research by Wilk (1998) also only states that the analysis of data on multiple trials show that the Biodex Isokinetic Dynamometer is a reliable test device. This means the study does not state if the H/Q ratio is a reliable and valid testing measurement. Also, the normative values for one of the H/Q ratios was for 300°·s^{-1} which was not actually performed by the subjects during testing. The study shows that the subjects completed a 360°·s^{-1} test instead. Therefore, it is unclear if the percentage for H/Q ratio values should be for 360°·s^{-1} or if the test was performed at 300°·s^{-1} and just reported inaccurately. Either way it is not consistent, and research has since been performed using both 300°·s^{-1} and 360°·s^{-1} with the expectations that the H/Q ratio should be the same percentage even though other research has shown that and increase in angular velocity increases H/Q ratios. Therefore, Wilk's (1998) research is creating inconsistent variables that are being used as normative values for both velocities. In research this creates disjoint and confusion among presented research and how to properly test for the normative strength ratio at these speeds. This research also does not state if the subjects are male or female which is also a cause for concern since research has shown difference in strength capacities based in sex (Hewett et al., 2007). Therefore, a normative value that does not consider sex differences may be too broad to use across sexes. It is something that needs to be observed and re-evaluated prior to using these H/Q ratio percentages as the industry standard for research.

More recently, researchers have begun to examine the functional H/Q ratio, which divides the ratio into a concentric/eccentric evaluation of the agonist/antagonist relationship. This allows a functional evaluation of the muscles based on their movement pattern and muscle activation during common sporting tasks (Croisier at al., 2008 & Aagaard et al., 1998). For the functional ratio values should be closer to a 1:1 relationship, where the torque of the antagonist muscle during an eccentric action is equal to the force of the agonist muscle during a concentric action. This ratio demonstrates that the antagonist muscle can generate adequate force to counteract the agonist. The functional H/Q ratio theoretically make the most sense to test based on the muscle relationships of the hamstring and quadriceps working in an agonist and antagonist fashion during movement. However, it has been shown that eccentric testing requires extensive familiarization for the subjects to be performed correctly, especially in adolescent subjects (Kellis et al., 1999). Therefore, if there are minimal testing session opportunities concentric testing may be a better way to ensure more reliable data of the subjects (Kellis et al., 1999). Also, the conventional H/Q ratio accounts for the changes in force application depending on the angular velocity. When the angular velocities are lower the subjects are able to produce greater concentric force than when the angular velocities are greater (Andrade et al., 2012). It has been shown that quadriceps concentric peak torque decreases at a greater rate than the hamstrings concentric peak torque which is what leads to the greater H/Q ratio percentages as angular velocity increases (Andrade et al., 2012). Functional ratios have also been shown to range from 0.60 – 1.60 and increase as angular velocity increases (Baroni et al., 2020). Therefore, the assumption of the functional ratio needing to be at 1:1 should be re-evaluated so that a better understanding of the impacts isokinetic movements can have on peak torque and its relationships to sport performance.

Other measurements used to evaluate the lower limb muscles are the isometric peak force, angle of peak force, peak torque, angle of peak torque, average peak torque and angle of crossover (Brockett et al., 2004; Kannus, 1991; Eston, 2001; & Jones at al., 2013). If research using isokinetic dynamometry can identify differences in performance output between different groups and subjects that may be at a higher risk of injury, then it should be used to evaluate youth athletes transitioning through their maturation phases and how that physical change effects performance output.

Using the isokinetic dynamometer, researchers have selected various angular velocities to test their subjects. These angular velocities typically range from $30°\cdot s^{-1}$ to $450°\cdot s^{-1}$. The higher testing velocities are meant to simulate fast athletic movement for the subjects and typically range from $240°\cdot s^{-1}$ to $450°\cdot s^{-1}$ (Wilk, 1998). Wilk (1998) states that individuals estimated angular velocity while walking is $233°\cdot s^{-1}$, where a running individual may reach velocities of $1200°\cdot s^{-1}$. The dynamometer is unable to simulate a “running” angular velocity, but researchers select the higher velocities in an attempt to create fast motion movements in a laboratory setting. However, it has been shown that training at a lower angular velocity can show improvements at higher velocities so it may not be necessary to test at the faster velocities if it is not producing useful or reliable data (Bell & Wenger, 1992; Taboković et al., 2016). The issue with the higher angular velocities is that a subject might not be able to reach the set velocities during the movement phase of the test, or if they do reach the velocity, it is for a short time over a small percentage of the range of motion (Baltzopoulos & Brodie, 1989). There is also potential that a subject’s peak torque is not reached during the time frame in which the subject is at the tested velocity (Baltzopoulos & Brodie, 1989). Therefore, even though the higher velocities simulate faster athletic movements lower angular velocities are used in conjunction with the higher velocities to produce a more comprehensive analysis of the strength and torque measurements of an individual. When the velocity is lower a subject is able to reach the testing velocity faster and able to sustain that speed for a longer period of time. This means that there is a much greater possibility of the peak torque occurring at the set angular velocity. Typically, the angular velocities that achieve this need to be between $30°·s^{-1}$ to $180°·s^{-1}$ (Baltzopoulos & Brodie, 1989).

As subjects' transition from a lower velocity to a higher velocity the force production decreases. This is due to the muscle activation and biomechanics of the muscle groups being tested. Kellis and Baltzopoulos (1997) performed a study using electromyography (EMG) during isokinetic testing to support this claim. They determined that even though there is increased EMG activity at faster concentric speeds due to there being higher activation of the motor units the torque decreases. This is because the force at the higher speeds is decreased because the crossbridges within the muscle fibers are unable to produce the higher torques as the angular velocities increase (Kellis & Baltzopoulos, 1997). The changes in torque based on angular velocity also has an impact on the H/Q ratios, as shown by Hewett et al. (2007), as the angular velocity increases the H/Q ratio increases as well, which is the reasoning behind the different percentages based on different velocities presented by Wilk (1998).

The changes in the torque and H/Q ratios based on the angular velocity shows that not one singular isokinetic measurement can be used to evaluate an individual. Grygorowicz et al. (2010) states that a cross examination of all the data together is required to perform a comprehensive analysis for an individual. Grygorowicz et al. (2010) tested a group of healthy athletes and a group of injured athletes by evaluating their H/Q ratios as well as their relative peak torque. Relative peak torque is the subjects peak torque acquired from the isokinetic dynamometer divided by the subject's mass in kilograms. This value allows a strength comparison among individuals of the same sex (Grygorowicz et al., 2010). If Grygorowicz et al. (2010) had only observed the H/Q ratios it would have appeared that the injured athletes had more balanced H/Q ratio and therefore a lower likelihood of injury. However, evaluating the relative torque values shows that the injured group is much weaker than the healthy group (Grygorowicz et al., 2010). Therefore, it is important to state that even though an athlete might appear to have ideal H/Q ratios this value may be misleading because the athlete is just weak. This could lead to the inability to deal with the stresses of their sports, performance detriments and greater risk of injury. This research shows that isokinetic dynamometer data can be useful if used properly and in conjunction with multiple data points to create a well-rounded overview of the subject tested.

The purpose of this chapter is to review and critique part research involving isokinetic dynamometry data. The review of these articles will conclude the best approach for using isokinetic data to find the best ways to evaluate athletes at greater risk of injury.

Conventional H/Q Ratio:

The most commonly used method to date to examine lower-limb muscle balance has been the conventional H/Q ratio. This ratio is the comparison of the hamstring and quadriceps muscle strength in a concentric analysis. The ratio is determined by the concentric hamstring peak torque being divided by the concentric quadricep peak torque. Devan et al. (2004) conducted a study to determine if athletes with H/Q ratios lower than a certain percentage at a specific angular velocity ($60°\cdot s^{-1}$ and $300°\cdot s^{-1}$) were at an increased risk of lower-leg injury. Wilk (1998) stated that the expected ratios for normal knee muscle structure would have an H/Q ratio of 60-69% at $60°\cdot s^{-1}$ and 80-95% at $300°\cdot s^{-1}$. This study by Wilk (1998) was not a longitudinal prospective study and therefore, it is not known if the subjects in this study with the lower H/Q ratios ended up with injuries.

These normative values created by Wilk's (1998) research have been used in various research articles to evaluate how H/Q ratios influence injury risk (Devan et al., 2004; Myer et al., 2009; Magalhães et al., 2004; Rosene et al., 2001; Hewett et al., 2008 and Grygorowicz et al., 2010). Subject information, methods and results from reviewed research addressing the conventional H/Q ratio can be found in Table 2.6.1.

The most common differences between the conventional H/Q ratio studies were the subjects tested, types of injuries evaluated, and the number of repetitions performed by the subjects to gain the peak torque for the quadriceps and hamstrings. Devan et al., (2004) assessed 53 female athletes, across 5-repetitions of concentric knee flexion/extension at $60°\cdot s^{-1}$ and 15 repetitions of concentric knee flexion/extension at $300°\cdot s^{-1}$. The subjects were tested prior to the start of their sports season and did not have injuries at the time of testing. During the season the athletes were observed for overuse injuries which are those injuries not induced by direct trauma to the athletes during their season. The overuse injuries observed in this study were tendonitis of the knee, patellofemoral syndrome, and iliotibial band friction syndrome. The results of this study showed that 8 out of 20 athletes that suffered from one of the overuse injuries had an H/Q ratio below 60% at $60°·s^{-1}$ and all subjects had below 80% at $300°·s^{-1}$.

Myer et al. (2009) performed their research on 132 male and female high school or collegiate soccer and basketball players who were tested and then observed for the occurrence of an anterior cruciate ligament (ACL) injury. The isokinetic testing performed by the subjects for this research was 10-repetitions of concentric knee flexion/extension at $300°·s^{-1}$. Of the 132 athletes tested 22 female athletes suffered ACL injuries after the testing. Evaluation of their data showed that the injured athletes had a lower H/Q ratio because they had weaker hamstrings compared to the non-injured group. According to Wilk's (1998) normative data however, the uninjured group still fell below the 80% recommended ratio at $300°·s^{-1}$. The uninjured athletes at $300°·s^{-1}$ had an H/Q ratio just above 60% where the athletes that suffered ACL injuries had an H/Q ratio average of 56%. This research shows that the differences between the injured and uninjured athletes relate to the difference in hamstring strength and not H/Q ratio percentage. This research supports the idea that the H/Q ratio alone should not be used to determine athletes at risk of injury and that a more comprehensive analysis of the information behind the H/Q ratio should be used as well.

Magalhães et al. (2004) evaluated 28 elite male volleyball and 46 elite male soccer players. The subjects performed concentric knee flexion/extension movements on the isokinetic dynamometer. The subjects completed 5-repetitions at $360°·s^{-1}$ and 3-repetitions at $90°·s^{-1}$. The purpose of this study was to evaluate the peak torques and H/Q ratios between athletes in different sports as well as comparing these values among athletes participating in the same sport but in different playing positions. The results of this study showed that volleyball players had significantly higher quadricep torque than the soccer players but there were no significant differences in the hamstring torques which caused significant differences in the H/Q ratio between the sports at the lower angular velocity. The study also revealed that there were no significant differences between soccer athletes playing different positions. This research shows that certain considerations should be made based on the sport the athletes are participating in. Even though this research did not evaluate injury it shows that the different athletic movements required for different sports can have an impact on the hamstring and quadricep torque production as well as H/Q ratios.

In 2001 Rosene et al. performed a study on 81 collegiate athletes (26 males, 55 females) with no history of knee or thigh injury (volleyball, soccer, women's basketball and women's softball). These researchers looked at the H/Q ratios between the different sports and evaluated the subjects by having them perform concentric knee flexion/extension isokinetic testing at $60°·s^{-1}$, $120°·s^{-1}$, and $180°·s^{-1}$. The results of this study showed no significant differences in H/Q ratios between the athletes in different sports or different sex. This research did not address the potential effect the H/Q ratios may or may not have on injury prevention because the athletes were not followed or evaluated for this purpose. However, if one was to compare the average H/Q ratios in this study to Wilk's (1998) normative values one would see that most of the athletes' H/Q ratios fall below the recommended 60% at $60°·s^{-1}$. This research again puts into question the reliability of Wilk's normative values.

Grygorowicz et al. (2010) performed a concentric knee flexion/extension H/Q ratio study on 48 collegiate age athletes, who were separated into 3-groups: Group A – 16 healthy subjects (no symptoms or past history with musculoligamentous injuries), Group B – 16 subjects with minor injuries (knee sprains, contusions or hamstring sprains), Group C – 16 subjects with significant (meniscus, cartilage and ligamentous injuries). All of these subjects performed 5-repetitions at $60°·s^{-1}$ and 10-repetitions at $120°·s^{-1}$. This study took into consideration the relative strength of the subjects and the impact that this data might have on the H/Q ratios and injury occurrence. The results showed that the uninjured athletes had significantly higher relative strength values than the two injured groups. The H/Q ratios however, showed that the injured groups prior to injury had higher H/Q values. Until this research was completed it was assumed that higher H/Q ratios would mean that this group of athletes would be at a lower risk of injury. However, with the addition of the relative strength variable it was observed that the injured athletes were significantly weaker and therefore less capable of dealing with the stresses of sport which led to them being more prone to injury. This research is highly significant because it expresses the importance of the full evaluation of the data received from the isokinetic data to make a comprehensive evaluation. Relative strength in this research shows that a stronger athlete, even one with a lower H/Q ratio, may be less susceptible to injury and that weaker athletes, even if they have a higher H/Q ratio, can be more prone to injury. This is important for future evaluation of H/Q ratios and isokinetic peak torque while evaluating athletes and the importance it may play in the evaluation of an individual's risk of injury and performance.

A review of twenty-two conventional H/Q ratio studies by Hewett et al. (2008) included 1,568 healthy subjects (1,145 male, 423 female) and compared H/Q ratios between sexes. The review of research concluded that as the isokinetic velocity got faster there were significant changes in H/Q ratios. At the faster velocities there was a significant difference in H/Q ratios between sexes, but this was not the case at the lower velocities. All of these concentric H/Q research articles had different ways of approaching the use of their isokinetic dynamometer and its importance and how it impacts athletes. The results of these studies can also be observed in Table 2.6.1.

Analysis of the several studies utilizing the H/Q ratio highlights several key points for consideration in future research. Therefore, based on research done after Wilk (1988) it seems that even though H/Q ratios may show some value in understanding athlete muscle balance and performance the strength or weakness of an individual may be more important in the analysis of athletic performance abilities and injury risk than the H/Q ratio.

Author(s) / Year Published	Subject Information	Methods (for knee joint)	Results	Sports	Injury Increase (Y or N)
Wilk (1998)	24 subjects	Concentric Flex/Ext - 60°·s^{-1}, 180°·s^{-1}, 360°·s^{-1} and 450°·s^{-1}	Expected H/Q ratios: 60°·s^{-1} - 60%-69%, 300°·s^{-1} - 80%-95%	N/A	N/A
Devan, Pescatello, Faghri & Anderson (2004)	53 Female Division 1 athletes	Concentric Flex/Ext - 5 reps @ 60°·s^{-1}, 15 reps @ 300°·s^{-1}	8 of 10 overuse injuries occurred in athletes with H/Q ratios less than 60% @ 60°·s-^{1} and all 10 had H/Q ratios lower than 80% @ 300°·s^{-1}	Field Hockey, Soccer and Basketball	YES
Myer, Ford, Barber Foss, Lui, Nick & Hewett (2009)	132 subject (110 Females and 22 Males (controls)) High School and College Athletes	Concentric Flex/Ext - 10 reps @ 300°·s^{-1}	Females who suffered an ACL injury had a 15% decrease in hamstring strength compared to the male and female control group	Soccer and Basketball	YES
Magalhães, Oliveira, Ascensão & Soares (2004)	75 elite Portuguese athletes	Concentric Flex/Ext - 5 reps @ 360°·s^{-1}, 3 reps @ 90°·s^{-1}	Significantly lower H/Q ratio for volleyball vs. soccer @ 90°·s^{-1} H/Q ratio but no difference @ 360°·s^{-1} H/Q ratio	Soccer and Volleyball	N/A
Rosene, Fogarty, & Mahaffey (2001)	81 male and female collegiate athletes	Concentric Flex/Ext - 5 reps @ 60°·s^{-1}, 10 reps @ 120°·s^{-1}, 15 reps @ 180°·s^{-1}	No significant H/Q ratio differences between sports, female athletes were 1.3%-2.4% more likely to be injured vs. male athletes. No difference between dominant and nondominant legs.	Men's Volleyball, Women's Volleyball, Men's Soccer, Women's Soccer, Women's Basketball, Women's Softball	Yes
Grygorowicz, Kubacki, Pilis, Gieremek & Rzepka (2010)	48 athletes divided into 3 groups (Group A were 16 healthy subjects, Group B were 16 subjects with minor lower limb injuries, Group C were 16 subjects with significant lower limb injuries)	Concentric Flex/Ext - 5 reps at 60°·s^{-1} and 10 reps at 120°·s^{-1}	The healthy group (Group A) had statistically higher values in H/Q ratios and average peak torque (APT) compared to the injured group (Group C).	Various Sports	Significant lower limb injuries (meniscus, cartilage and ligamentous injuries) lead to greater imbalances in the quadriceps and hamstrings and should be addressed prior to return to sport.
Hewett, Myer & Zazulak (2008)	1568 subjects (1145 males, 423 females)	Concentric Flex/Ext - ranges from 30°·s^{-1} to 360°·s^{-1}	Males had significant increases in H/Q ratio in males between 30°·s^{-1}, 60°·s^{-1}, 180°·s^{-1}, 240°·s^{-1}, and 360°·s^{-1}. Females did not show any significant differences in H/Q ratios between velocities. The men showed significantly greater H/Q ratios compared to females at 60°·s^{-1}, 120°·s^{-1}, 300°·s^{-1}, and 360°·s^{-1}.	Not Defined	Not Specified

Table 2.6.1: Summary of Conventional Hamstring /Quadriceps Ratio Isokinetic Studies

Functional H/Q Ratio:

Much of the existing research utilize the functional H/Q ratios alongside the conventional H/Q ratio to compare the two ratios. Aagaard et al. (1998) first applied the functional H/Q ratio using 9 male and female track and field athletes, using two velocities (30°·s^{-1} and 240°·s^{-1}). No repetition data was provided for this research. Based on the peak moments produced concentrically the conventional ratio was 50% at 30°·s^{-1} and 61% at 240°·s^{-1}. The functional ratios produced peak torque ratios of 61% at 30°·s^{-1} and 101% at 240°·s^{-1}. This shows that using the functional ratio does produces a ratio closer to 1:1 at higher velocities, in line with the researchers' hypotheses (Aagaard et al., 1998). The lower velocities however had functional ratios closer to that of the conventional ratios and not a ratio close to 1:1 like the higher velocities. This research by Aagaard et al. (1998) shows the differences between how concentric and eccentric H/Q ratios differ between velocities. In the eccentric evaluation of this study as the velocities increased the force produced by both the quadriceps and hamstrings increased. For the concentric movements however, the forces produced both decreased as the velocities increased. This relationship is present because eccentric contractions involve the lengthening of the muscle and concentric contraction involves the shortening of the muscles. Therefore, eccentrically the forces produced are in direct relation to the velocity of the movement (a lower velocity a lower force and a higher velocity a higher force). This relationship is important, but more research needs to be done on the functional ratio to evaluate the differences between the velocities used for the testing and the potential for normative data values to be produced for this specific ratio.

Croisier et al. (2008) performed a prospective study using 462 professional football players from the Belgian, Brazilian and French professional leagues, to evaluate the importance of the functional H/Q ratio in relation to the potential prevention of hamstring injuries. All the subjects were assessed during preseason with either the Cybex Isokinetic Dynamometer or the Biodex Isokinetic Dynamometer, performing 3 concentric repetitions at 60°·s^{-1} and 5 concentric repetitions at 240°·s^{-1} followed by eccentric repetitions performed at 30°·s^{-1} (3-repetitions) and 120°·s^{-1} (4-repetitions).There were 4 groups created for evaluation; Group A consisted of no preseason imbalances, Group B had preseason imbalances and did no training to fix the imbalances, Group C had imbalances and completed training until tests showed their imbalances were fixed, Group D had imbalances and completed training but did not have testing feedback to determine if the imbalances had been addressed. The athletes that had preseason imbalances and either did no compensatory training or did training without any evaluation of the success of the training intervention were 3-5 times more likely to suffer from a hamstring injury during their season. Typically, research has eccentric and concentric contractions completed at the same velocities for comparison and creation of the H/Q ratios. This research used different velocities for the lower and higher speeds at the different contractions. The higher velocities were 240°·s^{-1} for the concentric velocity and only 120°·s^{-1} for the eccentric contraction. The lower velocities were 60°·s^{-1} for the concentric contraction and 30°·s^{-1} for the eccentric contraction. The problems surrounding this research is that the groups were created based on different types of imbalances. This is problematic because there is no way to tell which imbalance was most prevalent in the injured players because it just states that they had preseason imbalances in 2 or more areas. A subject could have had a bilateral strength deficit, conventional H/Q ratio imbalance and/or a functional H/Q ratio difference. The conventional ratio imbalance was also specified as athletes below 45% which is 15% lower than the 60% recommended in previous research (Wilk, 1998). Looking at the use of the functional ratio in this study the researchers used two different speeds within the ratio. The ratio was determined by using the eccentric hamstring peak torque at 30°·s^{-1} and concentric quadriceps peak torque at 240°·s^{-1}. The researchers expressed that even though hamstring injuries occur at a higher velocity the reliability of eccentric contractions is greater at lower velocities. Therefore, they chose 30°·s^{-1} for the eccentric contraction velocity. When the knee muscle joint is flexing or extending it is at a constant speed for both muscle groups so the calculation of a functional H/Q ratio using different speeds between the agonist and antagonist muscle group seems to make little sense. Therefore, the explanation for the 30°·s^{-1} to have a more accurate measurement is fine but there is no reason to create the H/Q ratio with the higher concentric velocity. Therefore, even though the research states this as a functional H/Q ratio it is unlike other research and has no supporting evidence that is should be calculated this way. The research also states that the players with mixed (functional) H/Q ratios of greater than 140% did not sustain any muscle injuries of the hamstring. This, however, shows that the subjects had a set cut off where it could be seen that the subjects who met or were above a certain percentage were more likely to have injury free seasons. There is a brief overview of these studies that can be seen in Table 2.6.2.

The importance of injury prevention is to ensure the athlete' are healthy and can compete throughout their entire season. If there is a testing method that allows for evaluation of such parameters, it could make a massive impact on the training of athletes. Currently, the H/Q ratio seems to have a lot of questions surrounding the best approach to assess these athletes. More research should be done across difference groups, including adolescents, to see if there are more accurate variables that can be used with the isokinetic dynamometer to help these subjects as they grow and develop.

Table 2.6.2: Summary of Functionals Hamstring/Quadricep Ratio Isokinetic Studies

Author(s) / Year Published	Subject Information	Methods (for knee joint)	Results	Sports	Injury Increase (Y or N)
Croisier, Ganteaume, Binet, Genty & Ferret (2008)	462 professional male athletes in Belgium, Brazil and France split into 4 groups - Group 1 had no preseason imbalances, Group 2 had preseason imbalances but no compensating training, Group 3 had preseason imbalances and compensating training but no further isokinetic testing to evaluate training progress, Group 4 had preseason imbalances and compensating training until they met normalized values(individuals were considered imbalanced if they met 2 of the following; a bilateral difference of 15% or more in the hamstrings concentrically and/or eccentrically, a concentric H/Q ratio of less than .47 or .45 on Cybex or Biodex respectively, or a mixed H/Q ratio of .80 or .89 they were added to either group 2, 3 or 4).	Concentric Flex/Ext - 3 reps @ $60°\cdot s^{-1}$, 5 reps @ $240°\cdot s^{-1}$ Eccentric Flex - 3 reps @ $30°\cdot s^{-1}$, 4 reps @ $120°\cdot s^{-1}$	Athletes with preseason strength imbalances that did not complete corrective training were 4-5% more likely to suffer a hamstring injury during their season (corrective training included manual, isotonic, or isokinetic strengthening based on the team trainer or physical therapists recommendations)	Soccer	YES
Aagaard, Simonsen, Magnusson, Larsson & Dyhre-Poulsen (1998)	9 Athletes (4 female and 5 male)	Maximal concentric and eccentric quadriceps and hamstring muscle strength was obtained using the maximal force moments during flex/ext of the knee at $30°\cdot s^{-1}$ and $240°\cdot s^{-1}$	Conventional concentric H/Q ratios were 0.5 @ $30°\cdot s^{-1}$ and 0.61 @ $270°\cdot s^{-1}$ based on the subjects peak torque. Functional ratios (H_{ecc}:Q_{con}) were 0.61 @ $30°\cdot s^{-1}$ and 1.01 @ $270°\cdot s^{-1}$	Track and Field (pole vault, long jump and high jump)	N/A

Non-H/Q Ratio Isokinetic Dynamometer Testing Research:

Additional isokinetic dynamometer research has been conducted to examine other data points collected during the testing session. The data points observed in these research articles consist of angle specific torques, peak torque angles, relative peak torque, angle-torque curves and angle of crossover axis (Brockett et al., 2004; Kannus, 1991; Eston, 2001 & Graham-Smith et al., 2013). A brief summary of these article can be seen in Table 2.6.3.

Brockett et al. (2004) used angle-torque curves to determine lower limb muscle function. The angle-torque curve is a measure of the muscle torque as a function of knee joint angle that is produced when the muscle is maximally activated during isokinetic movement (Brocket et al., 2004). Brockett et al. (2004) tested twenty-seven healthy elite and sub-elite Australian football league and track & field athletes and nine previously injured athletes who had suffered multiple hamstring strain injuries (HSI) over the previous 4-5 years. The injuries had taken subjects out of at least a week of training or competition and their most recent HSI had occurred within the last competitive season. The subjects completed seven concentric flexion and extension repetitions at $60°\cdot s^{-1}$ for both the left and right legs. Once the data was collected the angle and torque curves were evaluated between the uninjured and injured athletes. It was found that the injured hamstrings reached optimum peak torques around 12° earlier than the uninjured leg, although the quadriceps showed no difference in the angle torque curve between the injured and uninjured groups. The maximum torque reached was not significantly different between the injured group and the uninjured group. This research shows that athletes who suffer from HSI, even months after the injury, have not fully recovered and could be more susceptible to re-injury due to the reduced angle of peak torque (Brockett et al., 2004). This is important because hamstring injuries typically occur at the end of the swing phase therefore, an individual would want to have an increased angle of peak torque to decrease HSI risk. This research was completed post injury, so it is unknown if the athletes had weaker or unbalanced hamstrings that initially led to the injury. More longitudinal, prospective research should be completed to follow athletes from before injury to post injury to evaluate muscle torques throughout the process.

Another testing measurement that has been researched is the angle of the knee when peak torque occurs and how that may affect stability of the knee (Kannus, 1991). Kannus (1991) evaluated the differences between subjects with one injured knee and one knee that had lateral collateral ligament (LCL) insufficiencies. Twenty-one subjects (9 men and 12 women) with a mean age of thirty-five performed 6 repetitions at $60°·s^{-1}$ and $180°·s^{-1}$. The results showed no significant differences between the peak torque or angle of peak torque between the injured and uninjured legs (Kannus, 1991). This research shows that isokinetic testing might not be the most appropriate test to determine subjects who are at a higher risk of LCL injury because the measurements did not show any significant differences. The research does not address what the subject's values were prior to injury or if the subjects were undergoing rehabilitation which could affect the leg muscle balance. The research also only looks at injured individuals and therefore is difficult to say if these subjects showed differences from uninjured athletes. More research needs to be completed looking at the knee angle of peak torque and its relevance in diagnosis of risk of lower-limb injury. Research should also be done to compare different age groups using angle of peak torque analysis.

Marginson and Eston (2001) investigated the relationships between torque and joint angle between boys and men, testing eight boys (mean age 9.3 years) and eight men (mean age 21 years) using the isokinetic dynamometer. This study used isometric (non-movement) forces to evaluate the torques provided at different angles. When the knee was in full extension it was considered to be at 0° for this study. From that position the knee began flexion, and the dynamometer was moved to 20°, 40°, 60°, 80°, 90° and 100°. At these angles 2-3 second maximal contractions of the quadriceps were made against the isometric dynamometer lever. Since the men would have stronger absolute strength, the torques were converted to percentages of peak torque to better compare the relative torque of the groups. The results showed that during ascension of the limb the boys had a lower relative torque until the limb passed 80° then the boys stayed mostly level as the men decreased. Marginson and Eston (2001) explained this relationship was due to lower muscle stiffness in boys. This research shows that even though boys have a lower torque output for most of the ascending torque curve that the curves are similar in shape. This research only examines the quadricep torque and more research should be completed to compare hamstring strength as well as the resulting H/Q ratio between the adult and youth subjects. Due to maturation, there are biomechanical differences in muscles that should continue to be evaluated also to see if measurements can be made to help determine athletes at risk of injury across all age levels.

Graham-Smith et al. (2013) performed research that addressed the criticism of isokinetic testing that has been made in regard to the H/Q ratios in past research. These past research studies only presented the relationship between peak torque values that may occur at different angular positions during flexion and extension of the knee but does not account for the torque produced throughout the whole contraction. This observation in the ratio evaluation makes it difficult to compare subjects because the torque-angle plots can have so much variability (Graham-Smith et al., 2013). Therefore, as a solution to this problem these researchers proposed a dynamic control profile. This subject profile represents the net joint torque over the entire range of motion. For this study the net joint torque was the evaluation of eccentric flexor to concentric extensor (Graham-Smith et al., 2013). This research proposes that the closer the angle of crossover is to 90° of flexion the greater the range of motion compensated by the hamstrings is during quadricep torque. The crossover is when the net torque crosses zero on the x-axis (Graham-Smith et al., 2013). For this study twenty-three male athletes completed two testing sessions, seven days apart, where the right leg hamstrings and quadriceps were tested both concentrically and eccentrically at $60°\cdot s^{-1}$. From these values concentric H/Q ratios and dynamic control ratios, peak torques of the flexor and extensors at 30°, 40°, and 50°, and the angle of crossover were also identified (Graham-Smith et al., 2013). The results of this study suggest that these variables are reliable measures of muscle balance (Graham-Smith et al., 2013). Therefore, since crossover angle is reliable it may be a useful indicator of normal hamstring function and can be used to help restore hamstring function back to normative values to help reduce risk of another injury (Graham-Smith et al., 2013). Additional longitudinal research including the angle of crossover variable and its ability to highlight injury risk should be conducted. van Dyk et al. (2017) found that the isokinetic testing variables used in the past to determine potential injury risk, especially hamstring injuries, were found to not show any difference between players that became injured and players that stay uninjured over two seasons. These results show that more research should be done with the isokinetic dynamometer since many studies have shown greater injury risk based on isokinetic output (Brockett et al., 2004; Kannus, 1991). This leaves questions about past and future studies and being able to determine what should be used going forward.

Table 2.6.3: Non-Hamstring/Quadricep Ratio Isokinetic Studies

Author(s) / Year Published	Subject Information	Methods (for knee joint)	Results	Sports	Injury Increase (Y or N)
Brockett, Morgan & Proske (2004)	27 athletes (Elite and Sub Elite): 9 had a clinical history of 4-5 years of multiple hamstring strains	Concentric Flex/Ext - 7 reps @ $60°·s^{-1}$	Uninjured subjects reached optimum torque angles between 16-34° - so it was concluded that a typical value should be within range of 20° and any individual who are significantly above this value could be at greater risk of injury.	Australian Rules Football (23 Athletes) and Track and Field (4 Athletes)	Individual athletes with peak torque angles being reached significantly above 20° are at a higher potential risk of hamstring strain
Kannus (1991)	21 subjects (3-top level athletes, 8 competitive athletes, 5 recreational athletes and 5 non-athletes were tested)	Concentric Flex/Ext - 6 reps @ $60°·s^{-1}$ and $180°·s^{-1}$	There were no significant differences between the uninjured and injured limbs for peak torque or angle-specific torque.	Not Specified	The injured subjects had chronic post traumatic (8 ± 2 years from injury) partial or total LCL tear that had not been surgically fixed. This research showed that the injured lateral collateral ligament leg did not show differences to the non injured leg. Therefore, peak torque may not be a good determinant of injury risk for the LCL. The research does not state if rehabilitation was a part of the individuals recovery but there had been significant time between injury and testing. The individuals did have lower torque values (in comparison to other research) which might show weakness of an athlete and therefore lower differences in torque.
Marginson & Eston (2001)	8 boys (average age of 9) and 8 men (average age of 21)	Two - 3 second isometric quadricep extensions at 20°, 40°, 60°, 80°, 90° and 100°; 0° = full extension.	Both men and boys had a relative torque increase until optimal joint angle was achieved. Then the torque began to decrease. Men produced a higher percentage of their maximal torque prior to the production of their maximum torque after maximum torque was achieved the boys did not drop in percentage of maximum torque as much as the men.	Not Specified	May show that muscle stiffness in boys can impact the relative torque produced by them being lower in the angles closer to full extension. The stiffer muscles could potentially lead to injury during the younger ages. This is speculation from the researchers based on biomechanical knowledge but no data was provided in this research article to prove this hypothesis.
Graham-Smith, Jones, Comfort & Munro (2013)	23 male (average age 23)	4 maximal effort concentric and eccentric quadricep and hamstrings isokinetic peak torque measurements were taken at $60°·s^{-1}$.	That angle specific torque ratios may be more useful than peak torque ratios. Also that the angle of crossover (the point at which the net joint torque crosses zero on the x-axis) may be a helpful indicator for normal hamstring function in recovery and future prevention on a recurring injury.	Soccer and Rugby	These measures may provide more insight when screening athletes for hamstring injury risk. However, since this research was strictly to examine the reliability of various muscle balance ratios and to compare the dynamic control profile to other measures of muscle balance, more research is needed in order to determine the importance of these ratios in relation to injury.

Conclusion:

The Wilk normative values for H/Q ratios tend to be questioned based on the results of the research presented above. Various studies have presented other ways to evaluate this commonly researched value (Devan et al., 1998; Myer et al., 2009; Magalhães et al., 2004; Rosene et al., 2001; Grygorowicz et al., 2010; Hewett et al., 2008; Croisier et al., 2008; Aagaard et al., 1998; Brockett et al., 2004; Kannus, 1991; Marginson & Eston, 2001; Graham-Smith et al., 2013). Continued research is needed to increase the understanding and importance of the data produced by the isokinetic dynamometer. Based on the review of these studies the important analysis for future research is too included is creating variables in relative terms based on the subject's mass and size. This will allow for comparisons made between sexes, age and sports to see how those aspects influence performance abilities. Isokinetic dynamometer data can be useful if used properly and in conjunction with multiple data points to create a well-rounded overview of the subjects being tested.

Recently, McKinlay et al. (2018) evaluated the impact of resistance training and plyometric training on strength, explosiveness and jump performance within a cohort of 41 male, adolescent soccer players. The players were between the ages of 11 and 13 years. Evaluations were made before and after an 8 week training intervention using the isokinetic dynamometer, ultrasound, CMJ and SJ. The study resulted in both training groups showing significant increases in muscle strength and jump performance. The plyometric training group improve more (but not significantly) with their jump performance, but the free-weight resistance training group showed more improvement (but not significant) in peak torque. All groups showed increases in muscle thickness of the vastus lateralis. This study shows the importance of using various tests to enable researchers to narrow down what is causing the improvements in these subjects. This study only tests male subjects who are most likely all pre-PHV. Therefore, future research should include females and subjects throughout their maturation phases. Using these testing methods, it would be helpful to see how these testing outputs may change while a subject is going through their growth phase. Impacts of training interventions during growth phase also may help improve LTAD development and training practices to best support youth athletes during their "adolescent awkwardness" stage of life.

Chapter 3: Methods

Youth athletes ranging from 13 to 18 years (n = 64, mean ± SD: age: 15.1 ± 1.6 years, height: 168.2 ± 8.1 cm, mass: 60.1 ± 9.6) volunteered to participate in this research [n = 27 male (age 15.15 ± 1.81 years, height 171.3 ± 10.37 cm, body mass 86.68 ± 5.59 kg) female, n = 38 (age 15.08 ± 1.48 years, height 166 ± 5.17 cm, body mass 86.8 ± 4.19 kg)]. The subjects were selected from different high school and club sport teams in the area. Due to the age of the subjects, it was more difficult to get subjects to the facility because it was not at a practice and was an additional trip that needed to be taken to get the subjects tested. Subjects <18 years of age had parental permission to participate in the study, with parents providing written informed assent and subjects who were 18 years old providing written informed consent. The institutional review boards of the University of Salford (Appendix A) and SUNY Upstate (Appendix B) provided ethical approval. Ethical approval for two universities was needed since the research testing occurred at the Institute for Human Performance research facility at SUNY Upstate in New York and the data collection was part of the thesis research for a PhD that would be obtained through the University of Salford.

The current research thesis consisted of six individual research studies. The final study layout can be seen in Figure 4.5.1 at the end of Chapter 4. The same subjects were used across all six studies and categorized into the applicable categories based on the research question for each individual study. The subjects reported to the facility to participate in a 45-minute to hour long testing session. The first task for the subjects was to compete a questionnaire (Appendix C). Once the questionnaire was completed the standing height and sitting height were collected for the subjects. The first test completed was the ultrasound scans of the subjects VL, BF and MG. Once the ultrasound scans were completed the subject participated in a warm-up. The warmup consisted of a three-minute no-resistance stationary bike ride and five minutes of dynamic stretching. Once the warmup was completed the subjects then completed the countermovement jump testing followed by the isokinetic dynamometer testing. Once the isokinetic testing was finished the testing session was complete and the subject was released. A summary of the six studies is shown in Figure 3.1.

Studies and Methods		
Study	**Summary**	**Data Used for Study**
Test-Retest Reliability Study (Chapter 4)	11 Subjects completed ultrasound scans of the VL, BF and MG, Countermovement Jump and Isokinetic Dynamometer testing to examine reliability of the tests being used fir this study.	**Ultrasound:** Muscle Thickness, Pennation Angle and Fascicle Length for the Vastus Lateralis, Biceps Femoris and Medial Gastrocnemius. **Countermovement Jump:** Jump Height, Take-off Velocity, RSI Mod, Mean & Peak Propulsion Power, Propulsion Impulse, Braking Impulse, Mean & Peak Propulsion Force, Mean & Peak Braking Force, Propulsion & Braking Time Phase, Total Time to Take-off and Countermovement Depth **Isokinetic Dynamometer:** Right and Left Knee Extension and Flexion Peak Torque and Angle of Peak Torque for 60°·s-1 and 300°·s-1, Right and Left H/Q Ratios at 60°·s-1 and 300°·s-1.
Correlation Study (Chapter 5)	64 Subjects completed ultrasound scans of the VL, BF and MG, Countermovement Jump and Isokinetic Dynamometer testing to examine reliability of the tests being used fir this study.	Reliable variables from study one were used which included: VL Muscle Thickness, Absolute and Relative Peak Torque Knee Extension at 60°·s-1 and 300°·s-1, and Absolute and Relative; Jump Height, Take-off Velocity, Mean and Peak Propulsion Power, Propulsion Impulse Mean and Peak Propulsion Force, and Mean and Peak Braking Force.
Peak Height Velocity Comparison (Chapter 6)	27 Males and 38 Females had their anthropometric data collected and analyzed to determine their Peak Height Velocity (PHV) timing using the Mirwald, Moore and Khamis and Roche equations.	Anthropometric data of standing height, sitting height, mass, and age at time of their testing session (using years and months for a more precise age).
Pre, Circa and Post PHV Comparisons between CMJ and Isokinetic Tests (Chapter 7)	27 Male Subjects were tested using the CMJ variables and isokinetic dynamometer variables.	**Countermovement Jump:** Jump Height, Relative Mean and Peak Propulsion Power, Relative Propulsion Impulse, Relative Mean and Peak Propulsion Force, Relative Mean and Peak Braking Force. **Isokinetic Dynamometer:** Relative Right, Left and Average Knee Extension Peak Torque at 60°·s-1 and 300°·s-1, Relative Right, Left and Average Knee Flexion Peak Torque at 60°·s-1.
Average vs. Late PHV Comparisons between CMJ and Isokinetic Tests (Chapter 8)	53 Subjects (15 Males and 38 Females) were separate into Average (34 subjects) and Late (19 subjects) maturers and tested using the CMJ variables and isokinetic dynamometer variables.	**Countermovement Jump:** Jump Height, Relative Mean and Peak Propulsion Power, Relative Propulsion Impulse, Relative Mean and Peak Propulsion Force, Relative Mean and Peak Braking Force. **Isokinetic Dynamometer:** Relative Right, Left and Average Knee Extension Peak Torque at 60°·s-1 and 300°·s-1, Relative Right, Left and Average Knee Flexion Peak Torque at 60°·s-1.
Single vs. Multiple Sport athlete Comparisons between CMJ and Isokinetic Tests (Chapter 9)	53 Subjects (15 Males and 38 Females) were separate into Single-Sport (13 subjects) and Multiple-Sport (40 subjects) athletes and tested using the CMJ variables and isokinetic dynamometer variables.	**Countermovement Jump:** Jump Height, Relative Mean and Peak Propulsion Power, Relative Propulsion Impulse, Relative Mean and Peak Propulsion Force, Relative Mean and Peak Braking Force. **Isokinetic Dynamometer:** Relative Right, Left and Average Knee Extension Peak Torque at 60°·s-1 and 300°·s-1, Relative Right, Left and Average Knee Flexion Peak Torque at 60°·s-1.

Procedures

3.1: Anthropometric Measurements:

3.1.1: Standing Height: Height was recorded while subjects were stood next to a wall with a measuring tape on the wall (a stadiometer was not available at the testing facility, so this method was used). They were instructed to have heels, buttocks, shoulders and head pressed against the wall to ensure an erect position. They were also measured without shoes on to eliminate inaccurate measurements due to thickness of shoe soles. Once the proper stance was obtained and the subject was centered on the measuring tape their height was recorded.

3.1.2: Sitting Height: Sitting height was taken in the same was as standing height. However, subjects were instructed to sit on the floor with their buttocks, shoulders and head against the wall to again insure an erect position. The subjects were instructed to have their legs either bent or straight, whichever allowed their buttocks to be pressed firmly against the wall.

3.1.3: Mass: Mass was recorded as an average of the weighing phase during the 3 countermovement jump trials. The subjects were instructed to stand still for at least one second prior to jump to ensure the ability to accurately calculate the mass of the subjects ($N/9.81 m \cdot s^{-1}$) and to ensure that center of mass velocity was zero prior to analyzing the force-time data to calculate the CMJ variables. The average of the three measurements were taken to have a single body mass calculation.

3.1.4: Maturation Status: The subjects had their height measured by the researcher using a measuring tape on a wall in the laboratory. The subjects were instructed to remove their shoes and stand with their backs against the wall. They were then instructed to have 4 points of contact (heels, buttocks, shoulders and head) against the wall to ensure proper posture. Their standing height was then measured. Then the subjects were instructed to sit on the floor and with bent or straight legs (whichever way ensured their buttocks could be pressed against the wall) and maintain 3 points of contact (buttocks, shoulders, head) for the researcher to measure the subject's sitting height. The subjects' age was determined by calculating the year plus month age of the subject at the time of testing. For example, if a subject was 14 years and 8 months their day of testing age would be 14 + (8/12) for an age of 14.67 years old. With the collection of subject age, standing height and sitting height the researcher then proceeded to calculate predictive PHV age using the Mirwald equations for male and female subjects (Mirwald et al., 2002). The Mirwald regression equation was determined to be an appropriate

PHV measurement based on the results of the Chapter 6 research from this thesis. The following equations were the calculations used:

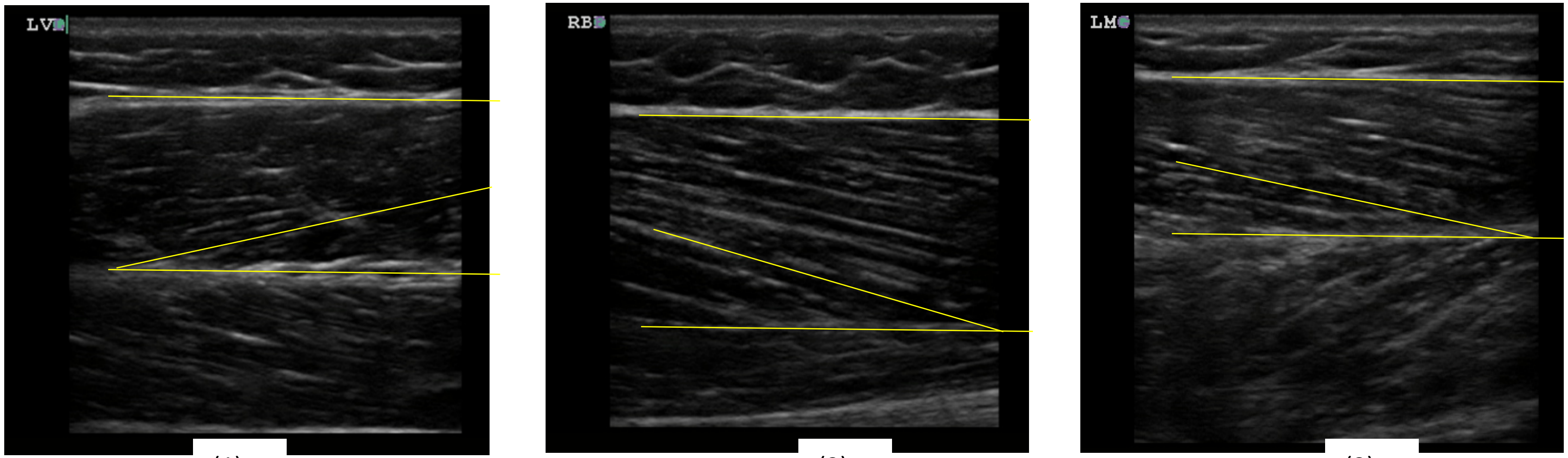
Mirwald Girl: Maturity Offset = -16.364 + 0.0002309·Leg Length and Sitting Height interaction + 0.006277·Age and Sitting Height interaction + 0.179·Leg by Height ratio + 0.0009428·Age and Weight interaction

Mirwald Boy: Maturity Offset = -29.769 + 0.0003007·Leg Length and Sitting Height interaction – 0.01177·Age and Leg Length interaction + 0.01639·Age and Sitting Height interaction + 0.445·Leg by Height ratio

The average age of an adolescent to hit PHV for girls is age 12 and for boys is age 14. Therefore, if the predicted PHV age calculation falls within ±1 year of these ages a subject would be considered an average maturer. If the subjects predicted PHV fell before age 11 for girls and 13 for boys, they would be considered early maturers and if predicted PHV fell after age 13 for girls and 15 for boys they would be considered late maturers. Based on these equations the subjects were categorized as pre, circa or post PHV. Subjects were classified as pre PHV if their age at the testing date was more than a year less than their estimated age of PHV, during PHV subjects would be subjects had an estimated PHV that was between ± 1 year of their testing date age and post PHV subjects would have a testing date age greater than one year from their estimated PHV age. Pre, Circa and Post-PHV subjects were found only among the male subjects and were used during the Chapter 7 of this study. Also based on the results of Chapter 7, significant and meaningful differences were found between pre-, circa- and post-PHV subjects which resulted in Chapter 8 and Chapter 9 only considering subjects who are in their post-PHV stage. For this subject testing pool there were also no subjects that were considered early maturers and therefore the analysis for Chapter 8 was only completed between average and late maturers.

3.2: Ultrasound Measurements:

The first test that was administered was the ultrasound scans of three specific muscles crossing the knee joint. The scans were administered using a Sonosite M-Turbo ultrasound unit with a 6 MHz – 13 MHz, 4.5 cm x 1 cm linear transducer (Sonosite Inc. Bothell, WA). This was completed prior to any physical activity to minimize the effect on muscle architecture (Lieber & Fridén, 2001). Three scans were taken of each of the subject's dominant and non-dominant vastus lateralis, biceps femoris and medial gastrocnemius muscles. For all scans the ultrasound probe was placed parallel to the measured muscle and perpendicular to the skin. The VL scans were taken with subjects laying in a supine position with their legs straight and muscles relaxed. The probe was placed half-way between the greater trochanter and the lateral condyle of the femur (See Figure 3.2.1 for an example scan of the VL). The BF and MG scans were taken with subjects laying in a prone position with their feet hanging just off the table to allow the MG muscle to be in a relaxed position. The BF scans were taken midway between the lateral condyle of the knee and the ischial tuberosity (See Figure 3.2.1 for an example scan of the BF). The MG muscle was scanned first by finding the apex of the two gastrocnemius muscles and then moving medial to the muscle belly where the scans were taken (Lieber & Fridén, 2001) (See Figure 3.2.1 for an example scan of the MG). Three scans were taken on each muscle and then analyzed using the ImageJ software. Within the ImageJ software the tester can set the scan depth of the picture to the scan depth that the probe was set at for the scans. For this study the scan depth was set at 4 cm and therefore the image was calibrated at that depth so that an accurate measurement could then be taken. Using ImageJ software muscle thickness and pennation angle were measured from each image. Muscle thickness was measured between the superficial and deep aponeurosis layers in the middle of the muscle scan. The pennation angle of the muscle was measured as the angle between the muscle fascicle insertion point into the deep aponeurosis. The fascicle length of the muscle was then calculated using the muscle thickness divided by the sine of the pennation angle (Lieber & Fridén, 2001; McMahon et al, 2016). For each session three measurements were taken of the MT and PA of each scan and these measurements were then used to calculate the FL. These three scans were then averaged for a single measurement for each scan and then finally all three scan averages were averaged to create a single measurement for MT, PA and FL for each of the three muscles (VL, BF and MG). Finally, the measurements from each session were then compared to each other to determine reliability.



(1) (2) (3)

Figure 3.2.2: Ultrasound scans of the vastus lateralis (1) biceps femoris (2) and medial gastrocnemius (3)

3.3: Countermovement Jumps:

After a 3-minute warm up on a cycle ergometer and 5-minute lower limb dynamic stretching the subjects completed 3 countermovement jumps. Prior to the recorded jumps the subjects performed a practice jump to familiarize them with the requirements of the jump. The subjects were instructed to place their hands on the hips throughout the movement. The subjects were also instructed that the squat depth was at their discretion, and they were told to jump as high as possible. Once the subjects stepped on the force plate, they stood still for one second so that the subject's weight could be recorded and to ensure accurate measurements for the movement onset threshold. After the subject was still for at least one second, they were instructed to jump. The subject then repeated the jump two more times. The subjects were given a 30 second rest between each jump. The countermovement jumps were completed on a Kistler model 9287 portable force plate at 1080 Hz, in line with recommendations from Street et al. (2001) and recorded via BioWare Version 5.3.0 software. The variables of interest were consistent with previous work from McMahon et al. (2017) and included jump height, take-off velocity, reactive strength index modified (RSImod), peak propulsive power, mean propulsive power, propulsion impulse, braking impulse, propulsion mean force, propulsion peak force, braking mean force, braking peak force, propulsion phase time, braking phase time, time to take-off and countermovement depth.

Center of mass (COM) velocity throughout the sampling period was determined by dividing vertical force data (minus body weight) by body mass and then integrating the product using the trapezoid rule (Owen et al., 2014). Instantaneous power was determined by integrating COM velocity and then calculated by multiplying vertical force and velocity data at each time point and COM displacement was determined by double integration of the vertical force data. The onset of movement for each CMJ trial was considered to have occurred 30 milliseconds prior to the instant when vertical force had reduced by five times the standard deviation of body weight, as derived during the silent period (Owen et al., 2014). The unweighting phase of the CMJ was considered to have occurred between the onset of movement and the instant of peak negative COM velocity (which occurs when the vertical force equals body weight again) (McMahon et al., 2017). The braking phase of the CMJ was defined as occurring between the instants of peak negative COM velocity and zero COM velocity. The concentric phase of the CMJ was deemed to have occurred between the instant that COM velocity exceeded 0.01 m·s^{-1} and the instant of take-off (McMahon et al., 2017). The instants of take-off and touchdown were defined as the instants that vertical force had fallen below and above, respectively, a threshold equal to five times the standard deviation of the residual force which was calculated during the first 300 milliseconds of flight phase of the jump (i.e., when the force platform was unloaded) (McMahon et al., 2017).

The instants of take-off and touchdown were defined as the instants that vertical force had fallen below and above, respectively, a threshold equal to five times the standard deviation of the residual force which was calculated during the first 300 milliseconds of flight phase of the jump (i.e., when the force platform was unloaded) (McMahon et al., 2017). Final calculations are made for the jump impulse during the propulsion and braking phases. For each of the phases the mean force and phase duration are multiplied to determine the phase impulse. Countermovement depth was determined by using the displacement calculated between the onset of movement and the onset of the propulsion phase. This displacement was calculated using the previous displacement value plus the subjects' velocity at the sample/the sample rate. Jump height was determined using the subject's flight time during their CMJ. This is calculated by taking the $(t^2 \cdot g)/8$ where t = flight time and g = acceleration due to gravity. Modified reactive strength index (RSImod) was calculated by dividing jump height (determined based on take-off velocity) by total movement time.

3.4: Isokinetic Dynamometry:

Following the CMJ testing the subjects were seated in the isokinetic dynamometer ([IKD] Biodex System 3 Multi-Joint System, Biodex Medical Systems, Shirley, NY) with a hip joint angle of around 90° and knee flexion uninhibited by the seat pad. The shin pad was placed 1-2 cm proximal to the lateral malleolus and secured to the leg. To minimize upper body movements, straps around the shoulders, waist and thigh secured the subject to the dynamometer chair and subjects were also directed to hold onto the handles with both hands. The knee joint axis of rotation (lateral condyle) was aligned with the dynamometers axis of rotation and checked prior to every test. The subjects performed 3 warmup repetitions at 50% effort prior to each of the different angular velocities on each leg. The subjects then completed one set of 5 repetitions at 60°·s^{-1}. The subject was then given a minute-long rest and then completed 5 repetitions at 300°·s^{-1} test after their warm-up repetitions. Then the machine was reconfigured, and the subject completed the same testing sequence for their left leg. The isokinetic testing was always performed on the right leg first and then the left leg. While performing the tests, the subjects were encouraged by the researcher to give maximal effort. Torque-angle data were gravity corrected through the Biodex software 3.43, which computed the peak torque, angle of peak torque and H/Q ratio. The software has a correction setting known as isokinetic windowing that ensures that the peak torques recorded were obtained during the isokinetic speeds in which there were being tested. This eliminated potential peak torques that were acquired during the accelerating or decelerating phases of the knee extension or flexion to produce a peak torque output that occurred at the tested isokinetic velocity. Gravity correction was obtained by weighing the subject's leg at 0° leg flexion (full extension) and this correction was then applied to the output data. These variables were then recorded in an Excel sheet from the data output sheet on the IKD (Wilk, 1998).

Chapter 4: Test–retest reliability of isokinetic knee flexion and extension, countermovement jump performance and muscle architecture in adolescents.

4.1: Abstract:

The aims of this study were to determine test-retest reliability and measurement error of concentric isokinetic knee flexion and extension assessments, countermovement jump (CMJ) performance and assessment of lower limb muscle architecture in youth athletes. *Methods:* Eleven subjects had 3 ultrasound scans of their vastus lateralis (VL), biceps femoris (BF) and medial gastrocnemius (MG) muscles on their left and right legs to determine fascicle length (FL), muscle thickness (MT) and pennation angle (PA). Subjects then performed three CMJs and five continuous concentric isokinetic contractions of the knee flexors (Flex) and extensors (Ext) at 60°-s^{-1} and 300°-s^{-1} to determine peak torque (PT), knee angle of peak torque (APT) and hamstring/quadriceps peak torque ratio (H/Q) *Results:* The following variables were found to be reliable (intraclass correlation coefficient [ICC] 95% confidence intervals [CI]; % coefficient of variation [CV]); left MG FL (0.97[0.88-0.99]; 1.8%), right VL MT (0.95[0.72-0.98]; 3.4%), left VL MT (0.92[0.72-0.98]; 4.2%), right BF MT (0.96[0.85-0.99]; 4.2%), left MG MT (0.95[0.85-0.99]; 1.8%), right VL PA (0.87[0.62-0.96]; 4.3%), right MG PA (0.92[0.74-0.98]; 2.2%), left MG PA (0.91[0.72-0.98]; 3.4%), jump height (0.89[0.57-0.98]; 4.4%), take-off velocity (0.91[0.62-0.98]; 2.4%), mean propulsion power (0.95[0.79-0.99]; 7.1%), peak propulsion power (0.99[0.88-0.995]; 4.9%), propulsive impulsive (0.99[0.95-0.998]; 2.2%), mean propulsion force (0.97[0.84-0.998]; 4.7%), peak propulsion force (0.95[0.78-0.99]; 4.9%), mean braking force (0.93[0.66-0.99]; 5.6%), peak braking force (0.95[0.79-0.99]; 5.0%), right PT Ext 60°-s^{-1} (0.94[0.78-0.98]; 6.2%), left PT Ext 60°-s^{-1} (0.84[0.52-0.95]; 10.9%), right PT Ext 300°-s^{-1} (0.91[0.72-0.98]; 5.6%), left PT Ext 300°-s^{-1} (0.90[0.69-0.97]; 5.9%), right PT Flex 60°-s^{-1} (0.91[0.70-0.94]; 7.5%) and left PT Flex 60°-s^{-1} (0.89[0.65-0.97]; 6.1%). *Conclusion:* Based on these results, assessment of adolescents' lower limb muscle structure, CMJ and isokinetic assessments resulted in twenty-three of fifty-three variables demonstrating acceptable reliability (ICC lower bound 95% >0.50, %CV < 15% and an effect size < 0.06). These variables can be used to evaluate adolescent athletes' lower limb muscle structure, power, torque and force production.

4.2: Introduction:

In sports science it is imperative to have measurement tools and methods that result in accurate and reliable data along with low measurement error, in order to obtain data sets that can be used to monitor adaptations to training and competition, provide research and determine possible trends and differences among the tested subjects. Isokinetic dynamometry of torque production, force plate assessments of CMJ, and muscle architecture assessed via ultrasonography have been shown to be reliable in adults (Cormack et al., 2008; Croisier et al., 2008; Devan et al., 2004; Lieber & Fridén, 2001); however, minimal research has been conducted with adolescent subjects (Forbes et al., 2009 and Lloyd et al., 2009).

Isokinetic dynamometry has long been used to evaluate lower limb muscle balance as well as torque production at joints to determine measurements that can identify athletes at risk of potential lower extremity injuries (Wilk, 1998). Quadricep and hamstring imbalances have been associated with hamstring strain injuries and knee injuries such as ACL tears (Croisier et al., 2008; Devan et al., 2004). The imbalance between the quadricep and hamstring muscles increase risk of lower limb injuries because the torque created around the knee joint by the quadricep force production cannot be properly slowed or accounted for by the counteracting force generated by the hamstring muscles (Croisier et al., 2008; Devan et al., 2004). This research however did not evaluate adolescent athletes. Therefore, it is important to evaluate lower limb muscle torque with this group of subjects to evaluate its importance in this subject group.

Countermovement jump (CMJ) tests can be used to evaluate an individuals' dynamic lower limb force production. Force plate analysis has been shown to be a reliable and valid method to examine CMJ kinetics (Cormack et al., 2008). There are many variables that can be calculated from force plate data of a CMJ (McMahon et al. 2017). Lake (2020) has expressed the importance of different output metrics (this is immediate feedback for an athlete and coach and includes variables such as jump height), driver metrics (helps identify what an athlete may need to work on to improve for example force production) and strategy metrics (these metrics help researchers explain the athlete's performance by evaluating time phases and movement depth) to evaluate an individual's CMJ. Lake (2020) expressed the importance of evaluating and comparing variables that fall within each of the categories of metrics. Evaluating the variables within each category of the CMJ enables a researcher to determine the potential changes to an individual's jump strategy throughout the different jumps. For example, an individual might complete three CMJs and have a similar jump height or a different jump height in all three jumps. However, by evaluating the driver metrics and strategy metric variables, like braking or propulsion forces and phase times or countermovement displacement, a researcher may be able to determine the most efficient mode of jumping for an individual subject.

Muscle architecture has previously been used to determine muscle function (Lieber & Fridén, 2001). Muscle architecture is defined as the arrangement of muscle fibers within a muscle relative to the axis of force generation (Lieber & Fridén, 2001). A diagnostic ultrasound machine can be used to observe and measure the cross-sectional area, fiber length and pennation angle of a muscle. Past research has shown that these ultrasound measurements of a muscle can be related to the muscle's strength and power. Muscles with larger cross-sectional areas have been shown to produce greater torque in an isokinetic testing session (Lieber & Fridén, 2001 and Wickiewicz et al., 1984). This set of data is then used to evaluate muscle function. The cross-sectional area is proportional to muscle force, fiber length is proportional to absolute muscle contraction velocity and pennation angle dictates the proportion of force transmitted to the tendon (Lieber & Fridén, 2001).

Most of the current reliability research was completed on adult athletes. Therefore, the aim of this study is to determine the test – retest reliability and measurement error of isokinetic dynamometer measurements of knee joint torques, force plate measurements of CMJ and muscle architecture measurements among a group of adolescent subjects. This research will determine both within- and between-session reliability of these testing variables for a group of adolescent athletes. It is hypothesized that since these testing methods have been proven to be reliable in adult subjects that they will also be reliable within this subject group of adolescent athletes and therefore appropriate to use for future research (Croisier et al., 2008; Devan et al., 2004; Cormack et al., 2008; Lieber & Fridén, 2001) and monitoring changes in performance.

4.3: Methods:

4.3.1: Experimental Approach:

A cross-sectional, repeated measures design was used to determine between-session reliability and measurement error for concentric isokinetic flexion and extension torques at $60°\text{-}s^{-1}$ and $300°\text{-}s^{-1}$, muscle architecture measurements (muscle thickness, pennation angle and fascicle length for the vastus lateralis, biceps femoris and medial gastrocnemius) and CMJ performance (jump height, take-off velocity, reactive strength index modified (RSImod), peak propulsive power, mean propulsive power, propulsion and braking impulse, propulsion mean and peak force, braking mean and peak force, propulsion phase time, braking phase time, time to take-off and countermovement depth), in youth athletes.

4.3.2: Subjects:

Healthy youth athletes ranging from 13 to 17 years (n = 11, mean ± SD: age: 16 ± 1.26 years, height: 171.83 ± 10.15 cm, mass: 61.50 ± 10.52 kg) volunteered to participate in this study (body mass was calculated using the force output from the force plate during the still phase of the CMJ testing divided by $9.81 m \cdot s^{-1}$ to determine the subjects' mass in kg). The subjects in this study participated in soccer, volleyball, athletics, lacrosse, basketball, baseball, tennis, horseback riding and hockey. Nine of the athletes were multiple sport athletes and two were single sport athletes. One of the subjects was far enough past the age of peak height velocity (PHV) that a maturity-offset age calculation was not given. However, the other 10 subjects had an average maturity-offset of 1.8 years (±1.03 years from PHV). All subjects and their guardians signed the informed consent and parental assent forms and the study received ethical approval from both the University of Salford and the State University of New York at Upstate Medical University research ethics committees. For the CMJ analysis only 8 subjects were used due to output error for 3 subjects during their second testing session. All subjects were middle or high school athletes without any known lower limb injuries. Subjects were instructed to maintain their regular training practices during the experiment but asked to not participate in any vigorous physical activity 24 hours prior to their testing session.

4.3.3: Procedures: Subjects were tested during two identical testing sessions held no more than a month apart (13.7 ± 8.9 days). Most were under two weeks, but a few subjects were not able to get back to the facility until a little less than a month after their original testing session. All testing and measurements were conducted by the same experimenter to avoid intertester variability. Time of day was also standardized between testing sessions to remove the effect of circadian rhythms on performance.

4.3.3.1: Anthropometric: Height, sitting height, mass and PHV were all collected for this study. Refer to Chapter 3: Section 3.1 for more details on how these measurements were acquired.

4.3.3.2: Ultrasound: The first test that was administered were ultrasound scans. This was completed prior to any physical activity to minimize the effect on muscle architecture (Lieber

& Fridén, 2001). Three scans were taken of each of the subject's dominant and non-dominant vastus lateralis, biceps femoris and medial gastrocnemius muscles. For all scans the ultrasound probe was placed parallel to the measured muscle and perpendicular to the skin. For each session each scan had three measurements taken of the MT and PA which then calculated the FL which was recorded in Excel. These three scans were then averaged for a single measurement for each scan and then finally all three scan averages were averaged to create a single measurement for MT, PA and FL of the VL, BF and MG muscles. Finally, the between session averaged were then compared for reliability. For more detail refer to Chapter 3: Section 3.2.

4.3.3.3: Countermovement Jumps: After a 3-minute warm up on a cycle ergometer and 5-minute lower limb dynamic stretching the subjects completed 3 CMJ. The subjects were instructed to place their hands on the hips and not use them in their jumping movement. The subjects were also instructed that the squat depth was at their discretion, and they were told to jump as high as possible. Once the subjects stepped on the force plate, they stood still for one second to record weight and then were then instructed to jump. The subject then repeated the jump two more times with 30 second rest between each jump. Briefly, data was analyzed using a forward dynamics approach with jump height calculated from velocity of center of mass at take-off (See Chapter 3, Section 3.3 for more detail).

4.3.3.4: Isokinetic Dynamometry: The subjects then completed the isokinetic testing. The subjects performed 3 warmup repetitions at 50% effort prior to each of the different angular velocities on each leg. The subjects then completed one set of 5 repetitions at $60°\cdot s^{-1}$. The subject was then given a minute-long rest and then completed 5 repetitions at $300°\cdot s^{-1}$ test after their warm-up repetitions. Then the machine was reconfigured, and the subject completed the same testing sequence for their left leg. While performing the testing the subjects were given encouragement by the researchers. For more in depth methodology refer to Chapter 3: Section 3.4.

4.3.4: Statistical Analyses: All statistical analyses were performed using IBM SPSS Statistics version 26. Between-session reliabilities were calculated via intraclass correlation coefficients (ICC) and associated 95% confidence intervals (CI) along with percentage coefficient of variation (%CV). The ICCs were interpreted in line with recommendations from Koo and Li

(2016) based on the lower bound 95%CI; < 0.5, between 0.5 and 0.74, between 0.75 and 0.9, and > 0.90 are indicative of poor, moderate, good, and excellent reliability, respectively. Lubans et al. (2011) stated that the %CV can be acceptable at values < 20% based on the changes that can occur during adolescent changes. For the %CV it has also been stated that values of < 10% are good for variable variation (Cormack et al., 2008) and McMahon et al., (2018) specified that a %CV of < 5% is considered excellent reliability and < 10% is acceptable.

Shapiro Wilk's tests of normality were performed to determine the distribution of the data. If the data were determined to be normally distributed paired sample t-tests and Cohen's *d* effect sizes were completed to determine if there were any differences between testing sessions and the magnitude of those potential differences. If a variable was determined to not be normally distributed a Wilcoxon non-parametric test was run in place of the paired samples t-test. Effect sizes for the non-parametric tests were determined using $Z/\sqrt{n}$. An *a priori* alpha level was set at $p < 0.05$ and effect size values were interpreted as trivial (< 0.19), small (0.20 – 0.59), moderate (0.60 – 1.19), large (1.20 – 1.99), and very large (2.0 – 4.0) (Hopkins, 2002). Standard error of the means (SEM) and smallest detectible difference (SDD) were also calculated to determine the potential random error scores between testing sessions (Comfort and McMahon, 2015). SEM was calculated using the formula: (SD [pooled] × $\sqrt{1 - \text{ICC}}$),and SDD was calculated using the formula (1.96 × [$\sqrt{2}$]) × SEM. The SEM and SDD were also expressed as a percentage of the variable mean.

4.4: Results:

Within session reliability was run and all the variables and found to be moderately to highly reliable. Therefore, since all the variables were found to have acceptable within session reliability, the between session reliability tests were run.

Fascicle lengths across the three different muscle groups between sessions were evaluated based on the variables lower bound 95% CI of the ICC, highlighting that left MG (0.97 [95% CI < 0.88]) was the only reliable variable. The left MG FL also demonstrated no significant or meaningful difference between the testing sessions ($p > 0.05$, $d < 0.19$), and an acceptably low %CV (1.8%), although the ICC revealed poor reliability (Table 4.4.1).

Table 4.4.1 - Descriptive and Between Session Reliability Statistics for Fascicle Length

Variable	Session 1 (Mean ± SD)	Session 2 (Mean ± SD)	Mean (Mean ± SD)	ICC (95% CI)	% CV	T-Test (*p*)	Cohen's *d*	% SEM	% SDD
Right VL	6.76 ± 0.76	6.81 ± 0.89	6.79 ± 0.83	0.61 (0.02-0.88)	4.8%	0.83	0.06	4.3%	11.8%
Left VL	6.48 ± 1.08	6.32 ± 1.24	6.40 ± 1.16	0.72 (0.20 - 0.92)	7.2%	0.58	0.14	4.8%	13.3%
Right BF	7.68 ± 1.64	7.91 ± 1.31	7.80 ± 1.48	0.76 (0.31 - 0.94)	6.5%	0.51	0.15	3.5%	9.8%
Left BF	8.16 ± 1.53	8.17 ± 1.15	8.17 ± 1.34	0.70 (0.14 - 0.92)	7.4%	0.98	0.01	3.5%	9.6%
Right MG	4.73 ± 0.78	4.69 ± 0.42	4.71 ± 0.60	0.54 (-0.09 - 0.85)	5.3%	0.83	0.06	4.1%	11.3%
Left MG	4.53 ± 0.69	4.58 ± 0.72	4.56 ± 0.71	0.97 (0.88 - 0.99)	1.8%	0.79	0.08*	0.7%	2.1%
Red = poor reliability (lower bound 95% CI < 0.50); yellow = moderate reliability (lower bound 95%CI 0.50-0.74; green = good-excellent reliability (lower bound 95%CI ≥0.75).									
*Represents a non-parametric test where effect size was calculated by $Z/\sqrt{n}$									

Four muscle thickness variables demonstrated moderate to excellent reliability (0.92-0.96 [95%CI < 0.72]), including the right and left VL, right BF and the left MG, in addition, there were no significant or meaningful differences between sessions ($p > 0.05$, $d < 0.19$), along with acceptably low variability (CV < 10%) (Table 4.4.2).

Table 4.4.2 – Descriptive and Between Session Reliability Statistics for Muscle Thickness

Variable	Session 1 (Mean ± SD)	Session 2 (Mean ± SD)	Mean (Mean ± SD)	ICC (95% CI)	% CV	T-Test (*p*)	Cohen's *d*	% SEM	% SDD
Right VL	1.97 ± 0.38	1.92 ± 0.44	1.95 ± 0.41	0.95 (0.84 - 0.99)	3.4%	0.25	0.12	0.6%	1.7%
Left VL	1.94 ± 0.40	1.91 ± 0.40	1.93 ± 0.40	0.92 (0.72 - 0.98)	4.2%	0.65	0.07	0.9%	2.4%
Right BF	2.15 ± 0.30	2.16 ± 0.29	2.16 ± 0.30	0.96 (0.85 - 0.99)	4.2%	0.65	0.03	0.8%	2.2%
Left BF	2.17 ± 0.27	2.21 ± 0.27	2.19 ± 0.27	0.78 (0.33 - 0.94)	3.4%	0.52	0.15	2.0%	5.5%
Right MG	1.56 ± 0.14	1.54 ± 0.17	1.55 ± 0.16	0.60 (0.01 - 0.86	3.9%	0.70	0.13	2.2%	6.1%
Left MG	1.60 ± 0.17	1.57 ± 0.16	1.59 ± 0.17	0.95 (0.84 - 0.99)	1.8%	0.28	0.18	0.7%	1.8%
Red = poor reliability (lower bound 95% CI < 0.50); yellow = moderate reliability (lower bound 95%CI 0.50-0.74; green = good-excellent reliability (lower bound 95%CI ≥0.75).									
*Represents a non-parametric test where effect size was calculated by $Z/\sqrt{n}$									

The pennation angle of the right VL and the right and left MG demonstrated moderate reliability (0.87-0.92 [95%CI < 0.62]) with no significant or meaningful differences between session ($p > 0.05$, $d < 0.19$), along with acceptably low variability (CV < 10%) (Table 4.4.3).

Table 4.4.3 - Descriptive and Between Session Reliability Statistics for Pennation Angle

Variable	Session 1 (Mean ± SD)	Session 2 (Mean ± SD)	Mean (Mean ± SD)	ICC (95% CI)	%CV	T-Test (*p*)	Cohen's *d*	% SEM	% SDD
Right VL	17.14 ± 3.10	16.67 ± 3.47	16.91 ± 3.29	0.87 (0.62 - 0.96)	4.3%	0.37	0.14	2.2%	6.1%
Left VL	17.71 ± 2.72	17.88 ± 1.93	17.80 ± 2.33	0.59 (-0.06 - 0.88)	5.5%	0.81	0.07	4.7%	13.0%
Right BF	17.01 ± 3.71	16.23 ± 2.42	16.62 ± 3.07	0.69 (0.17 - 0.91)	5.4%	0.35	0.25	4.5%	12.5%
Left BF	15.87 ± 2.62	15.93 ± 2.01	15.90 ± 2.32	0.79 (0.35 - 0.94)	5.3%	0.92	0.03	3.3%	9.2%
Right MG	19.48 ± 2.66	19.38 ± 2.06	19.43 ± 2.36	0.92 (0.74 - 0.98)	2.2%	0.74	0.04	1.9%	5.4%
Left MG	20.98 ± 2.67	20.62 ± 3.34	20.80 ± 3.01	0.91 (0.72 - 0.98)	3.4%	0.35	0.12	1.5%	4.1%

Red = poor reliability (lower bound 95% CI < 0.50); yellow = moderate reliability (lower bound 95%CI 0.50-0.74; green = good-excellent reliability (lower bound 95%CI ≥0.75).

*Represents a non-parametric test where effect size was calculated by $Z/\sqrt{n}$

Overall, nine CMJ variables were found to be reliable. Output metric variables jump height, take-off velocity, mean propulsion power, peak propulsion power and propulsive impulse were found to be reliable (0.89 - 0.99 [95% CI < 0.57]), with no significant or meaningful differences between session (p > 0.05, d ≤ 0.44) and acceptably low variability (CV < 10%) (Table 4.4.4). The driver metric variables (mean and peak propulsion force and mean and peak braking force) were also found to be reliable (0.93-0.97[95% CI < 0.66]), with no significant or meaningful differences between session (p > 0.05, d < 0.19), along with acceptably low variability (CV < 10%) (Table 4.4.4).

Table 4.4.4: Descriptive and Between Session Reliability Statistics for Countermovement Jump Variables

Variable	Session 1 (Mean ± SD)	Session 2 (Mean ± SD)	Mean (Mean ± SD)	ICC (95% CI)	%CV	T-Test (p)	Cohen's d	% SEM	% SDD
Output Metrics									
Jump Height (m)	0.25 ± 0.05	0.23 ± 0.04	0.24 ± 0.45	0.89 (0.57 - 0.98)	4.4%	0.23	0.44	2.8%	7.7%
Take-off Velocity ($m \cdot s^{-1}$)	2.24 ± 0.24	2.27 ± 0.18	2.26 ± 0.21	0.91 (0.62 - 0.98)	2.4%	0.48	0.14	1.0%	2.7%
RSI Mod	0.30 ± 0.11	0.32 ± 0.06	0.31 ± 0.09	0.69 (0.08 - 0.93)	13.8%	0.38	0.23	6.0%	16.8%
Mean Propulsion Power (W)	1420.19 ± 544.43	1443.80 ± 459.32	1432.00 ± 501.88	0.95 (0.79 - 0.99)	7.1%	0.58	0.05*	1.5%	4.0%
Peak Propulsion Power (W)	2796.39 ± 993.87	2822.06 ± 863.85	2809.23 ± 928.86	0.97 (0.88 - 0.995)	4.9%	0.76	0.03	0.7%	2.0%
Propulsive Impulse (Ns)	139.20 ± 40.71	140.73 ± 38.21	139.97 ± 39.46	0.99 (0.95- 0.998)	2.2%	0.45	0.04	0.3%	0.9%
Braking Impulse (Ns)	53.75 ± 17.46	59.97 ± 19.05	56.86 ± 18.26	0.92 (0.17 - 0.99)	8.0%	0.01	0.34	2.7%	7.7%
Driver Metrics									
Mean Propulsion Force (N)	1128.73 ± 327.39	1138.87 ± 290.83	1133.80 ± 309.11	0.97 (0.84 - 0.99)	4.7%	0.75	0.03	0.8%	2.2%

Peak Propulsion Force (N)	1416.18 ± 377.65	1422.31 ± 341.85	1419.25 ± 359.75	0.95 (0.78 - 0.99)	4.9%	0.89	0.02	1.1%	3.1%
Mean Braking Force (N)	858.97 ± 218.17	906.28 ± 220.45	882.63 ± 219.31	0.93 (0.66 - 0.99)	5.6%	0.12	0.22	1.3%	3.5%
Peak Braking Force (N)	1151.66 ± 319.07	1182.80 ± 298.80	1167.23 ± 308.94	0.95 (0.79 - 0.99)	5.0%	0.48	0.10	1.5%	4.2%
Strategy Metrics									
Propulsion Time Phase (s)	0.28 ± 0.06	0.27 ± 0.04	0.275 ± 0.05	0.68 (0.05 - 0.92)	9.6%	0.32	0.20*	5.0%	13.7%
Braking Time Phase (s)	0.23 ± 0.06	0.21 ± 0.04	0.22 ± 0.05	0.13 (-0.62 - 0.74)	17.0%	0.43	0.39	12.4%	34.4%
Total Time to Take-off (s)	0.91 ± 0.15	0.83 ± 0.08	0.87 ± 0.12	0.34 (-0.24 - 0.80)	10.0%	0.12	0.67*	6.3%	17.4%
Countermovement Depth (m)	-0.28 ± 0.08	-0.27 ± 0.06	-0.275 ± 0.07	0.78 (0.24 - 0.95)	11.3%	0.48	0.14*	5.6%	15.4%
Red = poor reliability (lower bound 95% CI < 0.50); yellow = moderate reliability (lower bound 95%CI 0.50-0.74; green = good-excellent reliability (lower bound 95%CI ≥0.75).									
*Represents a non-parametric test where effect size was calculated by $Z/\sqrt{n}$									

For the isokinetic assessment right limb concentric peak torque during extension and flexion at 60°·s^{-1} resulted in reliable measurements (0.84- 0.94 [95% CI < 0.52]). At 300°·s^{-1} concentric extension was also found to be reliable for the right and left legs (0.89-0.91 [95% CI > 0.69]), with no significant or meaningful differences between session ($p > 0.05$, $d < 0.19$), along with acceptably low variability (CV < 10%) (Tables 4.4.5, 4.4.6 and 4.4.7). Left peak torque during concentric extension had a CV of 10.9%. This variable will still be considered reliable based on its closeness to the accepted %CV and meeting all the other statistical reliability assessments.

Table 4.4.5 - Descriptive and Between Session Reliability Statistics for Concentric Extension

Variable	Session 1 (Mean ± SD)	Session 2 (Mean ± SD)	Mean (Mean ± SD)	ICC (95% CI)	%CV	T-Test (*p*)	Cohen's *d*	% SEM	% SDD
Right PT 60°-s^{-1}	160.28 ± 45.08	157.93 ± 43.60	159.11 ± 44.34	0.94 (0.78 - 0.98)	6.2%	0.65	0.05	1.8%	5.0%
Left PT 60°-s^{-1}	152.16 ± 42.69	144.99 ± 43.88	148.58 ± 43.29	0.84 (0.52 - 0.95)	10.9%	0.36	0.17	1.5%	4.1%
Right Angle of PT 60°-s^{-1}	75.18 ± 5.86	75.45 ± 7.29	75.32 ± 6.58	0.55 (-0.07 - 0.86)	4.4%	0.89	0.04		
Left Angle of PT 60°-s^{-1}	78.36 ± 8.31	81.18 ± 7.39	79.77 ± 7.85	0.11 (-0.50 - 0.65)	7.8%	0.39	0.36		
Right PT 300°-s^{-1}	83.41 ± 21.85	86.79 ± 28.95	85.10 ± 25.40	0.91 (0.72 - 0.98)	5.6%	0.53	0.19*	1.2%	3.5%
Left PT 300°-s^{-1}	76.39 ± 23.02	81.02 ± 25.71	78.71 ± 24.37	0.90 (0.69 - 0.97)	5.9%	0.16	0.20	0.5%	1.4%
Right Angle of PT 300°-s^{-1}	82.73 ± 6.20	80.45 ± 4.66	86.59 ± 5.43	0.59 (0.07 - 0.87)	3.5%	0.15	0.42		
Left Angle of PT 300°-s^{-1}	77.09 ± 5.11	79.09 ± 5.75	78.09 ± 5.43	0.65 (0.16 - 0.89)	4.0%	0.16	0.37		
Red = poor reliability (lower bound 95% CI < 0.50); yellow = moderate reliability (lower bound 95%CI 0.50-0.74; green = good-excellent reliability (lower bound 95%CI ≥0.75).									
*Represents a non-parametric test where effect size was calculated by $Z/\sqrt{n}$									

Table 4.4.6 - Descriptive and Between Session Reliability Statistics for Concentric Flexion

Variable	Session 1 (Mean ± SD)	Session 2 (Mean ± SD)	Mean (Mean ± SD)	ICC (95% CI)	%CV	T-Test (*p*)	Cohen's *d*	% SEM	% SDD
Right PT 60°-s^{-1}	102.85 ± 27.72	104.92 ± 27.59	103.89 ± 27.66	0.91 (0.70 - 0.94)	7.4%	0.59	0.07	0.9%	2.6%
Left PT 60°-s^{-1}	100.28 ± 24.89	99.98 ± 22.38	100.13 ± 23.64	0.89 (0.65 - 0.97)	6.1%	0.93	0.01	1.5%	4.1%
Right Angle of PT 60°-s^{-1}	47.45 ± 8.08	40.09 ± 9.02	43.77 ± 8.55	-0.04 (-0.4 - 0.49)	17.9%	0.08	0.86		
Left Angle of PT 60°-s^{-1}	51.45 ± 6.50	44.91 ± 12.24	48.18 ± 9.37	0.55 (-0.02 - 0.85)	14.5%	0.02	0.67		
Right PT 300°-s^{-1}	66.14 ± 14.02	70.42 ± 18.25	68.28 ± 16.14	0.74 (0.31 - 0.92)	7.5%	0.25	0.26	6.8%	18.8%
Left PT 300°-s^{-1}	64.46 ± 12.63	67.15 ± 11.86	65.81 ± 12.25	0.54 (-0.05 - 0.85)	9.9%	0.47	0.22	5.8%	16.2%
Right Angle of PT 300°-s^{-1}	42.64 ± 5.66	41.18 ± 6.27	41.91 ± 5.97	0.64 (0.12 - 0.87)	7.5%	0.15	0.24		
Left Angle of PT 300°-s^{-1}	43.73 ± 5.58	44.37 ± 10.00	44.05 ± 7.79	0.60 (0.002 -0.87)	8.1%	0.63	0.14*		

Red = poor reliability (lower bound 95% CI < 0.50); yellow = moderate reliability (lower bound 95%CI 0.50-0.74; green = good-excellent reliability (lower bound 95%CI ≥0.75).

*Represents a non-parametric test where effect size was calculated by $Z/\sqrt{n}$

Table 4.4.7 - Descriptive and Between Session Reliability Statistics for Hamstring/Quadricep Ratios

Variable	Session 1 (Mean ± SD)	Session 2 (Mean ± SD)	Mean (Mean ± SD)	ICC (95% CI)	%CV	T-Test (*p*)	Cohen's *d*	% SEM	% SDD
Right H/Q Ratio 60°-s^{-1}	64.61 ± 6.84	67.11 ± 7.53	65.86 ± 7.19	0.47 (-0.11 - 0.82)	7.0%	0.53	0.35	6.9%	19.1%
Left H/Q Ratio 60°-s^{-1}	66.77 ± 7.35	70.87 ± 9.68	68.82 ± 8.52	0.59 (0.02 - 0.85)	7.1%	0.15	0.48	6.3%	17.5%
Right H/Q Ratio 300°-s^{-1}	80.50 ± 9.82	82.46 ± 7.76	81.48 ± 8.79	0.51 (-0.09 - 0.84)	6.3%	0.48	0.22	4.4%	12.1%
Left H/Q Ratio 300°-s^{-1}	86.87 ± 13.40	88.10 ± 8.47	87.49 ± 10.94	0.57 (-0.03 - 0.87)	6.7%	0.71	0.12	0.6%	1.5%

Red = poor reliability (lower bound 95% CI < 0.50); yellow = moderate reliability (lower bound 95%CI 0.50-0.74; green = good-excellent reliability (lower bound 95%CI ≥0.75).

*Represents a non-parametric test where effect size was calculated by $Z/\sqrt{n}$

4.5: Discussion:

The aim of this investigation was to evaluate the reliability of vastus lateralis, biceps femoris and medial gastrocnemius ultrasound scans, CMJ and isokinetic testing variables in a group of adolescent subjects. Twenty-three of the fifty-three variables were found to be reliable with no significant or meaningful differences between sessions. The ultrasound variables that met these criteria were the left MG FL, right VL MT, left VL MT, right BF MT, left MG MT, right VL PA, right MG PA and left MG PA. CMJ resulted in reliable jump height, take-off velocity, mean propulsion power, peak propulsion power, propulsion impulse, mean propulsion force, peak propulsion force, mean braking force and peak braking force. The isometric dynamometer resulted in six isokinetic measurements to be reliable. At 60°·s^{-1} right PT Ext, right PT Flex, left PT Ext, left PT Flex and at 300°·s^{-1} right PT Ext and left PT Ext were the variables found to be reliable.

Previous reliability research for muscle architecture has resulted in more variables being considered reliable (König et al., 2013; Marzilger at el., 2017). However, these studies typically only used one statistical test to examine and determine reliability. König et al., (2013) and Marzilger et al., (2017) studies both found MT, PA and FL reliability using ICC values. König et al., (2013) tested the left MG, whereas Marzilger et al. (2017) examined the vastus lateralis. These researchers, however, did not look at both right and left limbs so it is not known if both limbs were found to be reliable since in the current study certain muscles were not found to be reliable from right to left leg. ICC values for MT, FL and PA for these studies were between 0.82 – 0.97, 0.77 – 0.90 and 0.47 – 0.90 respectively (König et al., 2013 & Marzilger at el., 2017). The ICC values of the past research did not include the 95% CI and therefore may or may not have fallen within the reliable ranges for ICC values determined by Koo and Li (2016). This could have caused more variables in the past studies to be reliable than defined in this study and should be considered when one is examining these studies. These studies were also conducted on subjects aged 27 - 30 and not on an adolescent population of subjects.

The limitation of ICC values not being represented by the 95% CI and potentially affecting the genuine reliable variables is also present in the Feiring et al., (1990), Gross et al., (1991) Li et al., (1995) and Maffiuletti et al. (2007) research conducted using isokinetic dynamometry. These studies were all conducted on subjects between the ages of 20 and 42 which are all above the 18 year old cut off for adolescent consideration. In these past research studies, the ICC values for 60°·s^{-1} during the extension phase were recorded between 0.83 – 0.98 and 0.84 – 0.99 during the flexion stage (Feiring et al., 1990; Gross et al., 1991; Li et al., 1995; Maffiuletti et al., 2007). Feiring et al. also examined 300°·s^{-1} and found ICC values of 0.97 and 0.82 for extension and flexion respectively. Maffiuletti et al. (2007) reported 60°·s^{-1} torques of 3.2%CV for extension and 3.1%CV for flexion. These research studies also only used one or two statistical tests to determine reliability of these variables and were also performed on subjects that were not categorized as adolescents. Since body changes are so prevalent and dynamic in the growth and changes of an adolescent going through puberty it is imperative to determine the reliability of measurements in this specific group since adult subjects are less likely to be fluctuating in mass and size as much as a pubescent adolescent.

In past research CMJ testing has typically used more than one statistical reliability analysis to determine variable reliability (Cormack et al., 2008; Markovic et al., 2004; McMahon et al., 2018; Nuzzo et al., 2011). Markovic et al. (2004) and Nuzzo et al. (2011) used both ICC values and %CV to determine reliability however they did not use the 95% CI which could cause a misrepresentation of that data as described above. Markovic et al. (2004) and Nuzzo et al. (2011) only evaluated jump height of their subjects and determined ICC values to be 0.87 – 0.95 with %CV values between 2.8% and 7.6%. Cormack et al. (2008) presented their reliability with %CV and typical error of the means. Cormack et al. (2008) did evaluate more than just jump height in their study. For jump height, peak power, peak force and mean force the %CV in Cormack et al. (2008) were all found to be ≤ 5% and therefore considered reliable. However, Cormack et al. did not include ICC values or effect size for this research. McMahon et al. (2018) has the most complete reliability assessment for CMJ addressing all the forementioned reliability statistical needs to complete a thorough analysis of the research data. This research completed by McMahon et al. (2018) examined jump height, take-off velocity, peak eccentric force, peak concentric force, concentric impulse and peak concentric power that match the current studies reliable CMJ variables. These variables had ICC values > 0.92 and %CV values < 5% (McMahon et al., 2018). These previous research studies did start to address the need to have more than one statistical analysis run to determine the true reliability of a testing variable. Aside from McMahon et al. (2018) these previous CMJ studies were conducted on subjects ages 19-24. Therefore, the current research used various reliability statistics to ensure the future research of adolescent athletes uses the most accurate variables for testing.

The ultrasound measurements resulted in the most unreliable variables in the current study. This is likely due to the higher probability of human error that occurs while performing an ultrasound test. This is the test that relies most on the examiner and involves more calculations and measurements to calculate the fascicle length variable. The FL calculation involves using the measurements of the muscle thickness divided by the sine of the pennation angle. Due to the division of two previously measured variables the measurement errors are compounded and creates a larger error for the FL. Therefore, the FL would result in the lowest number of reliable variables. For this study the test-retest did occur within two weeks but for a maturing adolescent that could be another reason for the lower reliability between sessions due to their growth over that time. Past research also did not have the examiner holding the ultrasound probe and instead had a fixed strap to hold it on their subjects (König et al., 2013 & Marzilger et al., 2017). Research has also presented the changes in adipose tissue in adolescents which may have an impact on reliability in between sessions and why one limb might have been reliable where the other was not (Orsso et al., 2020). Orsso et al. (2020) states that adipose tissue is gained at low rates until a child hit puberty. At the time of puberty the females then tend to have rapid increased in adipose tissue where the males tend to have decreases (Orsso et al., 2020). These changes in adipose tissue gains or losses during puberty could have an impact on reliability of an ultrasound scan that is based on subject who are in or around their puberty onset. All these reasons could cause this study to result in a lower number of reliable variables. However, with the eight ultrasound variables that were found to be reliable in this study the most useful for future research would be the right and left VL muscle thickness. These variables will be able to be used in conjunction with the other tests to see if quadriceps muscle thickness plays a role in CMJ and isokinetic torque production. This would allow future research to examine individual limb impacts compared to the specific muscle (VL) during jumping and isokinetic movement. The VL measurements can be used to see if the specific muscles between left and right leg play a role in torque output and leg dominance. This can also be used to evaluate the impact of bilateral deficiencies and its potential impact on CMJ data.

For the current study the isokinetic variable at 60°·s^{-1} that were found to be reliable were the flexion and extension for both right and left legs at peak torque. The current study ICC values > 0.84 and were comparable to the previous studies that had ICC values > 0.83. The current studies reliability is specified as moderate instead of good and excellent due to the 95% CI which was not included in the previous studies (Feiring et al., 1990; Gross et al., 1991; Li et al., 1995; Maffiuletti et al., 2007). For 300°·s^{-1} extension ICC values from past research showed an ICC value of > 0.97 where the current research was above 0.69 for both left and right leg however that was the 95% CI value (Feiring et al., 1990). Feiring et al. (1990) had a much lower ICC value (0.82) for flexion at 300°·s^{-1} which is close to the current study, but the 95% CI made the current variables unreliable. The current study had less reliable variables when the 95% CI was considered and therefore brings to the forefront the true reliability of the past research variables. Future research can be used especially with the 60°·s^{-1} variables since it is able to examine bot the agonist and antagonist muscles during that movement.

The CMJ resulted in the most reliable variables for the current study and compared to the previous studies (Cormack et al., 2008; Markovic et al., 2004; McMahon et al., 2018; Nuzzo et al., 2011). The current study had ICC values similar and within the ranges of the past research. However, due to the 95% CI for the ICC that is reported for the current study some of the variables became moderately reliable instead of good-excellent reliability like the past studies have indicated. Jump height, take-off velocity, mean propulsion power, peak propulsion power, propulsion impulse, mean propulsion force, peak propulsion force, mean braking force and peak braking force all had 95% CI ICC values > 0.62 which is lower than previous results that were > 0.82. Some of these reliable measurements have created similar results because they impact one another. The mean propulsion forces are a component of calculation of propulsion impulse and therefore, has an impact on the reliability of propulsion impulse. Then propulsion impulse is divided by the subject's mass to determine velocity at take-off. Take-off velocity is then used to calculate the subjects jump height. Therefore, seeing all these relationships between these variables enables us to see the relationships between measurements and how they impact one another. The variables that were found to not be reliable for CMJ involved calculations using multiple variables which can compound errors or dealt with temporal aspects of the jump. When a subject is told to jump higher their total force production will likely not be affected which is why those variables were reliable.

However, the subjects are more likely to adjust how low they squat which will in turn affect the time the subject takes during their braking and propulsion phase. Therefore, those variables would have found to be unreliable. The current study reliable variables had more comparable %CV values with all reliable variables being < 7.1% and the past research being all < 7.6%. Therefore, the current CMJ study has created similar reliability results to past research only with a group of only adolescent subjects.

When comparing the current study to the previous study it is seen that the ICC values for all three muscle architecture measurements and isokinetic measurements fall within previous research ICC value (Feiring et al., 1990; Gross et al., 1991; König et al., 2013; Li et al., 1995; Maffiuletti et al., 2007; Marzilger at el., 2017). The reason the current research resulted in less reliable variables is because the current research used 95% CI for the ICC which caused the variables to then be considered unreliable. It is unknown how interpreting the ICC based on the lower bound 95% CI of the ICC would have affected the reliability presented by the previous researchers. When comparing past research to the current study the detailed analysis of reliability and the need to meet four criteria to be considered reliable seems to be the reasoning for the lower number of acceptable values compared to the previous studies. With the left MG FL, right VL MT, left VL MT, right BF MT, left MG MT, right VL PA, right MG PA, left MG PA, jump height, take-off velocity, mean propulsion power, peak propulsion power, propulsion impulse, mean propulsion force, peak propulsion force, mean braking force, peak braking force, right and left PT extension and flexion at $60°\cdot s^{-1}$ and right and left PT extension at $300°\cdot s^{-1}$ found to be reliable among adolescent athletes in this current study they can be used in future research of the adolescent population.

4.5.1: Limitations and Areas of Future Research

For this study even though the number of subjects is appropriate for a test-retest reliability study and falls in line with the number of subjects used in previous studies it is still a small sample of subjects tested (Cormack et al., 2008; Gross et al., 1991). Therefore, future research could be conducted on a larger sample of adolescents to see if there is a change in reliability of the variables based on the possibility of lowering the range of the 95% CI in the ICC values by limiting the power of outliers. Another potential limitation is the calculation of jump height in the CMJ. Past research has commonly calculated jump height based on flight time like the current study (Cormack et al., 2008; McMahon et al., 2018). Jump height based on flight time has been determined to be a reliable variable but can also be skewed if the subject tuck their legs during their jump (Cormack et al., 2008; McMahon et al., 2018). Therefore, this could be a potential limitation for this study even though the subjects were instructed to not tuck their legs during their CMJ. In the current study an outlier would have a significant impact due to the smaller sample size whereas in a larger sample group the outlier would have less of an impact on the overall outcome of the variables.

Another limitation for this study was the accessibility of subjects. It was difficult to get the subjects into the facility once let alone twice within a two-week span. The average number of days between testing session was 13.7 ± 8.9 days. The subjects were instructed to participate normally in their athletic practices and games prior to testing day. On testing day, they were instructed to not participate in any vigorous exercise prior to their testing session. Ideally a test-retest reliability study would have a set time difference between the first and second testing sessions however for this study access to the subjects was at the discretion of the parents and their willingness to bring them back to the testing facility. This was found to be a difficult task for this study and is the reasoning behind the low subject numbers for the test-retest reliability study.

The researcher for this study did have experience with the usage of muscle structure ultrasound scanning and how to find the anatomical positions for the scans. However, there had not been formal training or supervision for any of the testing. This is most likely the reasoning behind the ultrasound scans not being as reliable between sessions. The vastus lateralis has simplest anatomical positioning for the probe which is why this muscle would have had the highest number of reliable variables. Also, typically if a testing method that has been shown to be reliable within other groups of subjects another study would have been run to check the results of the current study. However, due to the global Covid-19 pandemic the testing facility was closed, and it was not possible to run another reliability study.

However, there is a significant number of variables from this study that were found to be reliable and therefore can be used in future research. These reliable variables can start to enable coaches and athletes to better understand their muscle balance, strength and muscle architecture and its potential influence on sport performance and/or susceptibility for injury.

These evaluations will also be able to be used to examine the impact of developmental stages on the adolescent body with respect to athletic performance in future studies.

Future research should also consider familiarization sessions for the athletes. These sessions will allow them to be more comfortable with what is expected during the testing session. Also, if these sessions can occur eccentric contractions may be more feasible for analysis since it is not a common movement action and needs practice to perfect for testing (Graham-Smith et al., 2013). The adolescent age group would benefit from familiarization sessions because for many it is the first time they are in a laboratory testing session. Therefore, a familiarization session would be beneficial and likely improve reliability. However, again for this study accessibility to the subjects was not easy and therefore limited to one session for data collection only.

4.5.2: Conclusions

The left MG FL, right VL MT, left VL MT, right BF MT, left MG MT, right VL PA, right MG PA, left MG PA, jump height, take-off velocity, mean propulsion power, peak propulsion power, propulsion impulse, mean propulsion force, peak propulsion force, mean braking force, peak braking force, right and left PT extension and flexion at $60°\cdot s^{-1}$ and right and left PT extension at $300°\cdot s^{-1}$ were found to be reliable variables for this population of adolescents. Future research can now be conducted on this adolescent population using these reliable variables.

Transition from Chapter 4 to Chapter 5

The results of the study impacted the initial research plan of the thesis. Originally the flow of studies was meant to examine the differences between H/Q ratios as well as muscle architecture differences between single and multiple sport athletes. This initial plan was intended to examine if there were muscle balance differences between these two groups that may be a cause of the single sport athletes being more susceptible to injuries. However, since the H/Q ratios and many of the muscle architecture values were found to be unreliable the thesis shifted focus to the maturation phases of the athletes and how the growth spurt affects adolescents and then eventually how that may play a role in differences in single-sport versus multiple-sport athlete performance outputs. The new study flow diagram can be seen in Figure 4.5.1.

Chapter 4 of this thesis examined the test-retest reliability of muscle architecture, countermovement jumps and isokinetic dynamometer data. The reliable variables from these tests were taken forward into chapter 5 to examine if there could be relationships between these tests. The reasoning behind this examination was to see if tests such as countermovement jump (CMJ) that may be easier for more subjects, coaches and practitioners to perform when laboratory access is not possible can be found to have relationships with muscle architecture and isokinetic dynamometer. The CMJ requires force development in order to accelerate during a jump in order to achieve a greater jump height. These forces and torques about the knee joint can also be examined during an isokinetic dynamometer which can help examine how the quadriceps and hamstring muscle may impact the jump height. Muscle architecture scans can then help evaluate the impact muscle thickness, fascicle length and pennation angle have on force production. These results could help with improvement of training practices without the need for expensive and difficult sessions. These could be used for quick analysis of a simple testing measure like CMJ to help monitor athletic develop in a more efficient way. Therefore, chapter 5 examines the potential relationships and correlations between the CMJ, isokinetic dynamometer and muscle architecture measurements.

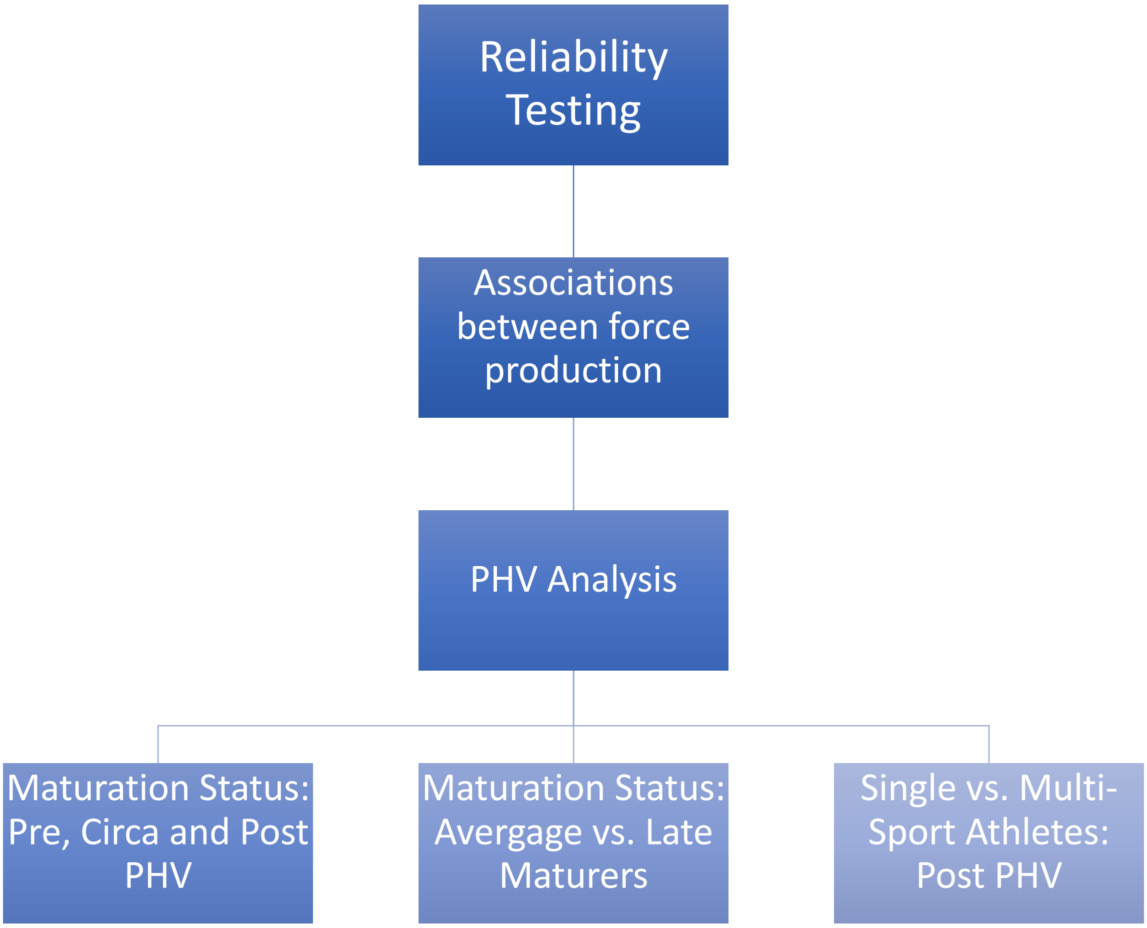


Figure 4.5.1: Schematic Diagram Illustrating the Final Sequence of Experimental Studies on Youth Athletes Ages 13-18 (PHV = peak height velocity).

Chapter 5: Correlations between Isokinetic Knee Flexor and Extensor Torques, Muscle Architecture and Countermovement Jump Performance in Adolescent Athletes.

5.1: Abstract:

The aims of this study were to determine the associations between isokinetic knee extensor peak torque (PT), countermovement jump performance variables and muscle architecture in adolescent athletes. *Methods:* Variables previously determined to be reliable in this cohort (vastus lateralis [VL] muscle thickness [MT], jump height, take-off velocity, mean and peak propulsion power, propulsion impulse, mean and peak propulsion force, mean and peak braking force, knee extension PT [at $60°{\cdot}s^{-1}$ and $300°{\cdot}s^{-1}$]) were used. Mean values were also calculated for the right and left leg MT and knee extension PT. Relative values were also calculated for CMJ variables and isokinetic variables, where appropriate. *Results:* Left VL MT moderately correlated with left knee extension PT at $60°{\cdot}s^{-1}$ and $300°{\cdot}s^{-1}$ (r = 0.534, 0.414 respectively, $p < 0.001$). Right vastus lateralis MT moderately correlated with right extension PT at $60°{\cdot}s^{-1}$ and $300°{\cdot}s^{-1}$ (r = 0.478, 0.411 respectively, $p < 0.01$). Mean VL MT moderately correlated with mean extension PT at $60°{\cdot}s^{-1}$ and $300°{\cdot}s^{-1}$ (r = 0.505, 0.432 respectively, $p < 0.01$). Mean VL MT also had moderate correlations with the mean and peak propulsion power, propulsion impulse, mean and peak propulsion force, mean and peak braking force (r 0.496-0.536, $p < 0.001$). Mean PT at $60°{\cdot}s^{-1}$ and $300°{\cdot}s^{-1}$ had moderate to strong correlations (r 0.516-0.794, $p < 0.001$) with jump height, take-off velocity, mean and peak propulsion power, propulsion impulse, mean and peak propulsion force, mean and peak braking force. Lastly, relative PT at $60°{\cdot}s^{-1}$ and $300°{\cdot}s^{-1}$ had moderate correlations (r 0.402-0.635, $p < 0.05$) with relative mean and peak propulsion power, propulsion impulse, relative mean and peak propulsion force, relative mean and peak braking force. *Conclusion:* There are moderate to strong correlations between VL MT, knee extension PT at $60°{\cdot}s^{-1}$ and $300°{\cdot}s^{-1}$ and CMJ height, take-off velocity, mean and peak propulsion power, propulsion impulse, mean and peak propulsion force, mean and peak braking force variables.

5.2: Introduction:

Researchers have reported that an athlete's force production characteristics are associated with athletic tasks such as jumping and running (De Ruiter et al., 2006; Schons et al., 2018; Zaras et al., 2020). Force production and jumping can be analyzed using the equation force = mass x acceleration. If two subjects have the same mass but one can produce more force over a given duration, then that subject will demonstrate greater acceleration due to the direct relationship of this equation. If a subject can accelerate more efficiently then they will most likely be the more successful athlete due to a greater ability to jump higher and accelerate faster during a sprint. This association between force production, acceleration and mass is why researchers have examined the relationships between testing platforms that are associated with or produce force and acceleration of athletes (Alegre et al., 2014; De Ruiter et al., 2006; Schons et al., 2018; Wickiewicz et al., 1984). The capability of an athlete to create a larger force is then transferred into the training of that athlete. Creating a training program for an athlete that focuses on their ability to create rapid and maximal force production has now become a main emphasis for coaches and trainers of athletes (Alegre et al., 2014; De Ruiter et al., 2006; Earp et al., 2010; Schons et al., 2018; Zaras et al., 2020).

Researchers have demonstrated that larger muscle cross sectional areas (CSA), greater muscle thickness (MT) longer fascicle lengths (FL) and greater pennation angles (PA) can all play a role in greater force production in either countermovement jumps (CMJ) or isokinetic dynamometer movements (Alegre et al., 2014; De Ruiter et al., 2006; Earp et al., 2010; Schons et al., 2018; Wickiewicz et al., 1984; Zaras et al., 2020). This association between muscle architecture and CMJ performance and isokinetic quadricep and hamstring peak torques has now become a focus of training programs due to its importance for athletic success. For a coach, trainer or athlete to be able to gain information about the subject's athletic performances based on a singular test that could be performed by all athletes could have a great impact on the development of athletes. However, these relationships have not been thoroughly explored in the adolescent subject group.

De Ruiter et al. (2006) and Schons et al. (2018) assessed athletes in their 20's to determine isokinetic torque and CMJ variables. These studies focused on the force production and its impact on jumper performance. De Ruiter et al. (2006) examined unilateral isometric knee torque bilateral CMJ and concluded that the torque values taken during a unilateral (one-legged) isometric knee session were proportional to the subjects jump height during their bilateral (two-legged) CMJ (r = 0.76 at 90° and r = 0.86 at 120°). This research not only compared unilateral movement to a bilateral action, but it also set parameters for knee angle in the CMJ. This is important to note and could be important to apply while critiquing jump strategy and the most effective way to jump higher. However, athletes do not have limitations of knee angle or how far they can squat while they are performing a jumping task in their sport and therefore it might not reflect the true jumping capabilities. Further research by Schons et al. (2018) reiterated that the greater power generated during a CMJ was created by the subject that created greater peak torque at $180°\cdot s^{-1}$ of the subjects' dominant leg ($r = 0.610$). Both studies evaluated the unilateral torque created by the subjects' dominant leg in the isokinetic dynamometer to the bilateral variables obtained during the CMJ. This choice of evaluation should be further researched since while you perform a CMJ both legs are producing forces to complete the jump. Therefore, a peak torque average of both right and left legs should be used to see if correlations can still be made when both legs are being compared to the CMJ jump height.

Researchers have reported relationships between isokinetic peak torque and muscle architecture (MT, PA and FL) of the quadriceps (vastus lateralis [VL], vastus intermedius [VI], vastus medialis [VM] and rectus femoris [RF]) and hamstrings (biceps femoris [BF]) during the isokinetic assessments (Alegre et al., 2014 and Wickiewicz at al., 1984). Wickiewicz et al. (1984) determined a proportional relationship between muscle CSA and the torque characteristics; however, did not specify an *r* value to express the magnitude of the correlation. The researchers simply stated that there appeared to be a correlation and therefore more research needs to be completed to determine the significance of these relationships. Alegre et al. (2014) researched the effect of resistance training on muscle architecture and isokinetic peak torque (PT) also reporting correlations between muscle thickness and peak torque which concluded that there was a proportional relationship and that the larger the increase in muscle thickness based on the resistance training group the larger the increase in peak torque (Alegre et al., 2014). This research also did not specify a specific *r* value for correlation between thickness and peak torque they just observed that the group with resistance training increased both thickness and torque significantly more than the other group ($p < 0.05$).

Research has also been conducted to determine associations between countermovement jump (CMJ) performance and lower limb muscle architecture. Zaras et al., (2020) completed a study in which young adult females (age: 23.5 ± 6.3 years) conducted weightlifting tasks as well as CMJ and muscle architecture scans and resulted in correlations between the CSA are of the individual quadricep muscles (VL, VI, VM and RF) with the power production in the CMJ (Zaras et al., 2020). CMJ power was associated with vastus lateralis (VL) MT (r = 0.540), PA (r = 0.470) and FL (r = 0.658) (Zaras et al., 2020). The correlation values, r = 0.618, 0.797, 0.506 and 0.315 for the VL, VI, VM, and RF respectively, show that there is a relationship between the CSA and muscle architecture of the quadricep muscles and CMJ power production. However, it would have been advantageous to look at other CMJ output variables since power output does not always result in a higher jump height (McMahon et al., 2017). Since ultimately athletes are trying to jump higher to gain an athletic advantage in their sport the need for this correlation is also needed. An athlete might have better jump mechanics but produce less power and potentially still jump higher than someone with more power production but worse jump mechanics (McMahon et al., 2017). Earp et al. (2010) found correlations between the LG PA, MT and FL and CMJ jump height, peak power and relative power. This study resulted in r^2 – values of 0.186, 0.152 for LG PA and FL respectively in relationship to CMJ jump height and 0.210 and 0.416 for LG MT and MG PA respectively with absolute power. The coefficient of determination values (r^2) found in this study show that only 15.2 - 41.6% of the shared variance is explained by these results. This is a relatively weak correlation however, the researchers expressed that even though their r^2 – values showed weak correlations they were still found to be significant. Both studies exhibit correlations between a subjects' muscle architecture and CMJ performance; however, there are still research questions that can be answered about these relationships especially in conjunction with adolescents.

The aim of this study was to determine correlations between CMJ, muscle architecture and isokinetic knee extensor torque among a population of adolescent athletes that have previously been found within older athlete populations. It is hypothesized that there would be a correlation found between the adolescent subject muscle thickness, CMJ variables and isokinetic peak torque, in line with previous research (Alegre et al., 2014; De Ruiter et al., 2006; Earp et al., 2010; Schons et al., 2018; Wickiewicz et al., 1984; Zaras et al., 2020).

5.3: Methods

5.3.1: Experimental Approach: A cross-sectional single session research study was completed using adolescent athletes. Subjects completed testing that resulted in concentric flexion and extension using the isokinetic dynamometer at 60 $°\cdot s^{-1}$ and 300$°\cdot s^{-1}$, muscle architecture measurements of muscle thickness, pennation angle and fascicle length for the VL, BF and MG as well as jump height, take-off velocity, reactive strength index modified (RSI Mod), peak propulsive power, mean propulsive power, propulsion impulse and braking impulse, propulsion mean force, propulsion peak force, braking mean force and braking peak force, propulsion phase time, braking phase time, time to take-off and countermovement depth from the countermovement jumps. Appropriate variables (peak torque, CMJ peak and mean power, impulse ($Ns \cdot kg^{-1}$) and force variables) were also ratio scaled (absolute value / body weight). Relative values were calculated to normalize these variables and eliminate the potential increase in strength based due to higher body mass.

Based on a previous reliability study (Test-retest reliability of isokinetic knee flexion and extension, countermovement jump performance and muscle architecture in adolescents) where 23 variables were found to be reliable in adolescent athletes (based on ICC and %CV values) these variables that were used to determine correlations in this study.

5.3.2: Subjects: Healthy youth athletes ranging from 13 to 18 years (n = 64, mean ± SD: age: 15.1 ± 1.6 years, height: 168.2 ± 8.1 cm, mass: 60.1 ± 9.6) volunteered to participate in this study. Within this group of subjects 52 were multiple sport athletes and 12 were single sport athletes participating in 25 different sports (soccer, volleyball, athletics, lacrosse, basketball, baseball/softball, football, tennis, horseback riding, swimming/diving, hockey, golf, wrestling, dance and gymnastics). All subjects and their guardians signed the informed consent and parental assent forms and the study received ethical approval from both the University of Salford and the State University of New York at Upstate Medical University research ethics committees. All subjects were middle or high school athletes without any known lower limb injuries. Subjects were instructed to maintain their regular training practices during the experiment but asked to not participate in any vigorous physical activity 24 hours prior to their testing session.

5.3.3: Procedures: Subjects were tested in one 45-minutes testing session.

5.3.3.1: Anthropometric: Height, sitting height, mass and PHV were all collected for this study. Refer to Chapter 3: Section 3.1 for more details on how these measurements were acquired.

5.3.3.2: Ultrasound: The first test that was administered were ultrasound scans. This was completed prior to any physical activity to minimize the effect on muscle architecture (Lieber

& Fridén, 2001). Three scans were taken of each of the subject's dominant and non-dominant vastus lateralis, biceps femoris and medial gastrocnemius muscles. For all scans the ultrasound probe was placed parallel to the measured muscle and perpendicular to the skin. For each session each scan had three measurements taken of the MT and PA which then calculated the FL which was recorded in Excel. These three scans were then averaged for a single measurement for each scan and then finally all three scan averages were averaged to create a single measurement for MT, PA and FL of the VL, BF and MG muscles. Finally, the between session averaged were then compared for reliability. For more detail refer to Chapter 3: Section 3.2.

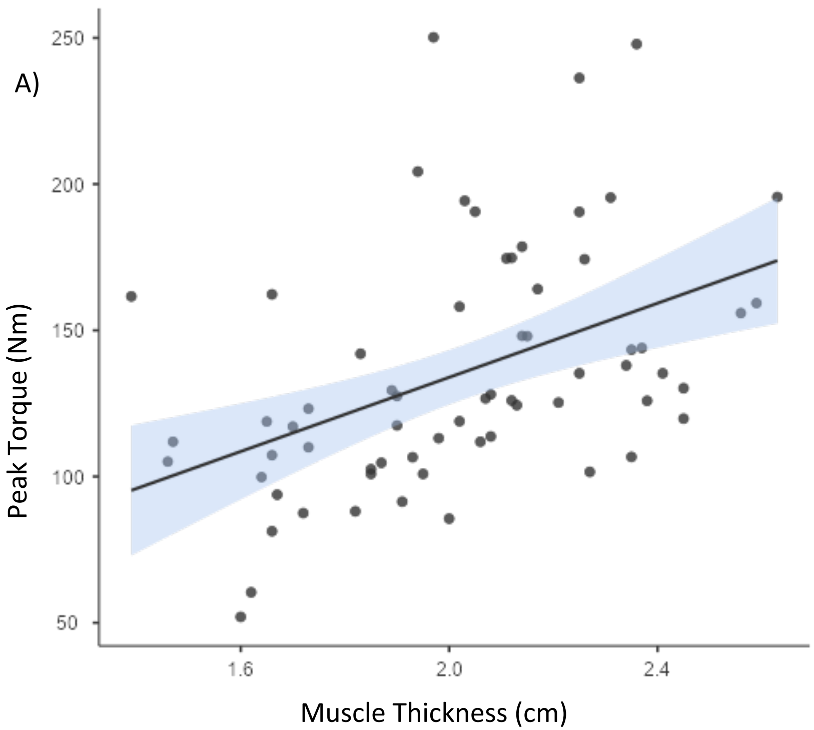
4.3.3.3: Countermovement Jumps: After a 3-minute warm up on a cycle ergometer and 5-minute lower limb dynamic stretching the subjects completed 3 CMJ. The subjects were instructed to place their hands on the hips and not use them in their jumping movement. The subjects were also instructed that the squat depth was at their discretion, and they were told to jump as high as possible. Once the subjects stepped on the force plate, they stood still for one second to record weight and then were then instructed to jump. The subject then repeated the jump two more times with 30 second rest between each jump. Briefly, data was analyzed using a forward dynamics approach with jump height calculated from velocity of center of mass at take-off (See Chapter 3, Section 3.3 for more detail).

5.3.3.4: Isokinetic Dynamometry: The subjects then completed the isokinetic testing. The subjects performed 3 warmup repetitions at 50% effort prior to each of the different angular velocities on each leg. The subjects then completed one set of 5 repetitions at $60°\cdot s^{-1}$. The subject was then given a minute-long rest and then completed 5 repetitions at $300°\cdot s^{-1}$ test after their warm-up repetitions. Then the machine was reconfigured, and the subject completed the same testing sequence for their left leg. While performing the testing the subjects were given encouragement by the researchers. For more in depth methodology refer to Chapter 3: Section 3.4.

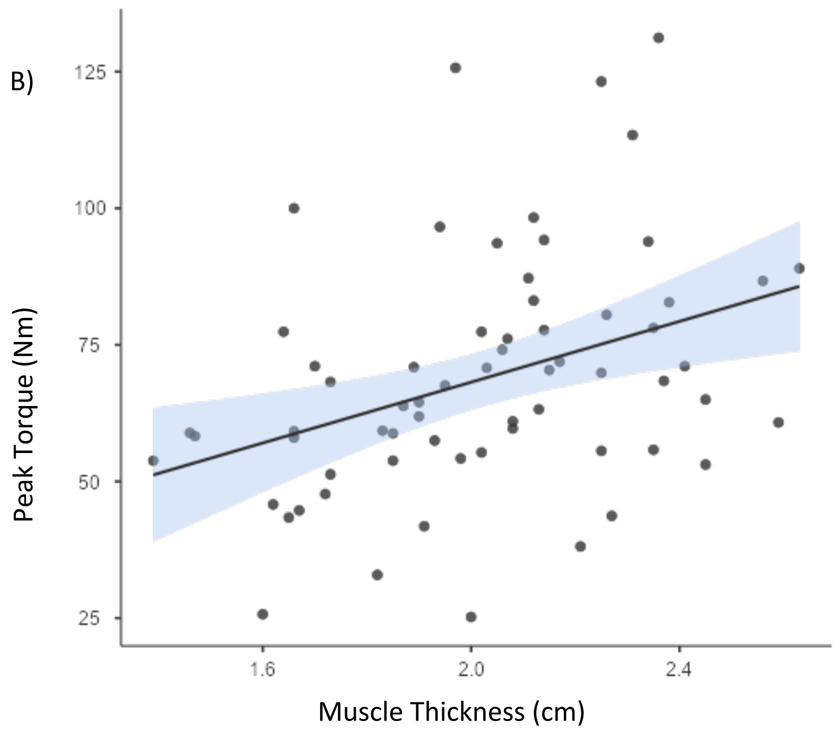
5.3.4: Statistical Analyses: All statistical analyses were performed using IBM SPSS Statistics version 26 and Jamovi version 1.6.13. For the isokinetic variable and ultrasound variables correlations were calculated based on a unilateral comparison between the individual's right or left legs. For correlations with the CMJ variables, the averages of the right and left leg measurements for peak torque and muscle thickness were calculated to create a single measurement to compare with the bilateral measurement of the CMJ. Shapiro Wilk's test for normality was performed to determine the distribution of the data. If both the variables were found to be normalized data sets then Pearson's correlation analyses (*r* – value, including the associated 95% confidence intervals) was performed to determine relationships between the different testing methods (Crawford, 2006). Pearson correlation values of $r \leq 0.35$ are considered to represent low or weak correlations, $r = 0.36 - 0.67$ moderate correlations, $r = 0.68 - 0.89$ strong correlations and $r \geq 0.9$ very high correlations (Crawford, 2006). If one of the variables being used for correlation calculation was found to not be normally distributed then Spearman's correlation analyses was run (*r* – value, including the associated 95% confidence intervals). The previously mentioned parameters for Pearson correlation value definitions were also used for the Spearman *r*-values. Due to the multiple correlations being run simultaneously the Bonferroni correction was conducted to account for the family-wise error rates. For the left and right leg analysis 12 correlations were performed on each leg. Therefore, the calculated correlation *p*-values were multiplied by 12 and then if the value was still $p < 0.05$ it was a significant correlation variable. For the average correlations calculated between testing platforms 42 comparisons were made and relative leg analysis had 27 comparisons were performed. These corrected *p*-values determined the final set of significant correlations run for this study.

5.4: Results:

Left leg muscle thickness demonstrated moderate and significant correlations (r = 0.441-0.534, $p < 0.05$) with left leg knee extension peak torque at 60°·s^{-1} and 300°·s^{-1} (Figures 5.4.1a and 5.4.1b).



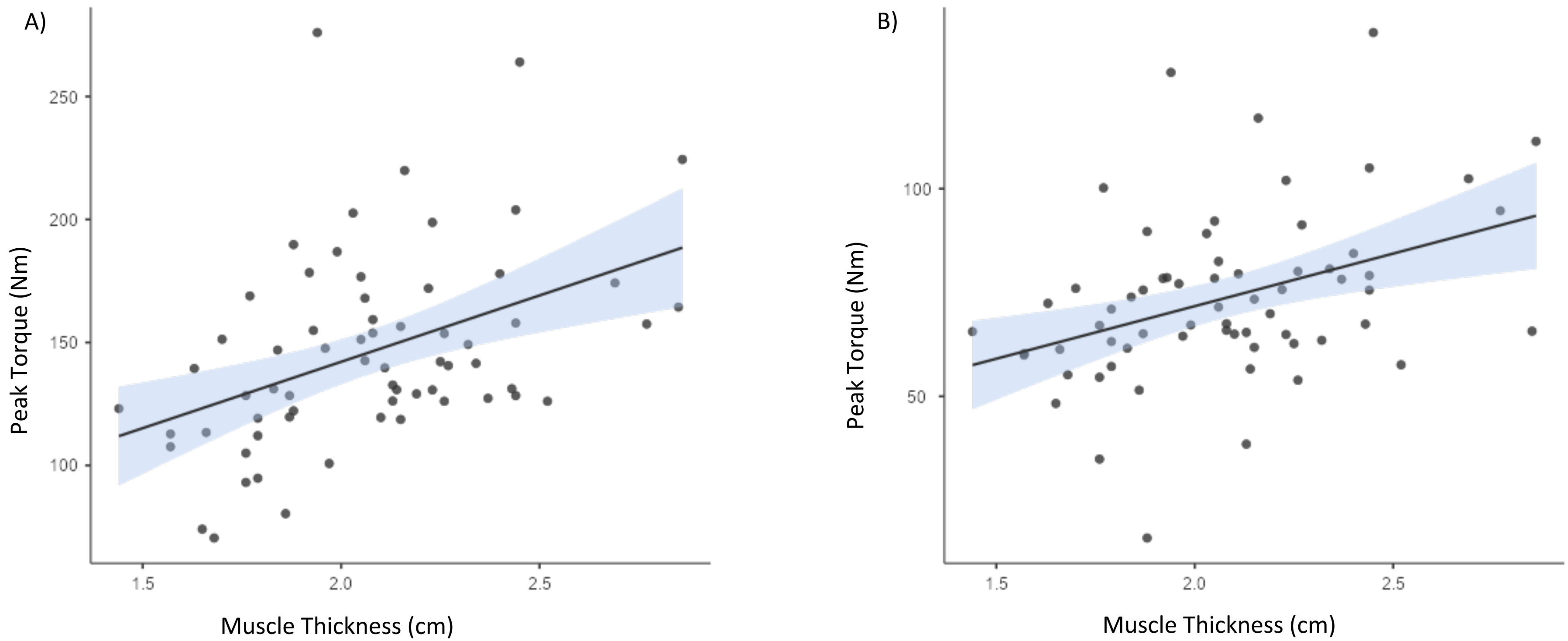
r = 0.534 (0.228 - 0.623)
p < 0.001



r = 0.414 (0.138 - 0.562)
p = 0.009

Figure 5.4.1: Correlations (Spearman's Rho) between Left Leg Vastus Lateralis Muscle Thickness and Isokinetic Peak Torque at A) 60°·s^{-1} and B) 300°·s^{-1}.

Right leg muscle thickness demonstrated moderate and significant correlations (r = 0.394-0.478, $p < 0.05$) with right leg knee extension peak torque at 60°·s^{-1} extension and 300°·s^{-1} extension (Figures 5.4.2a and 5.4.2b).



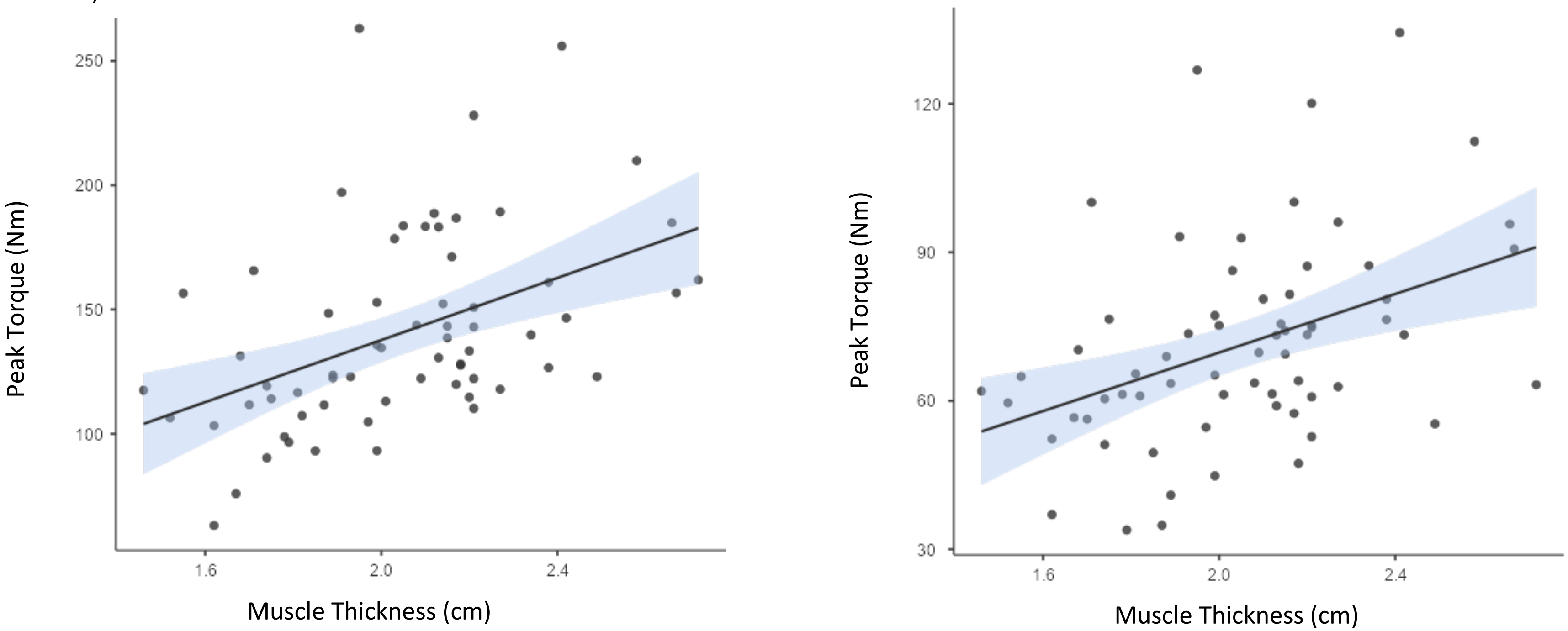
r = 0.478 (0.209 - 0.611)
$p < 0.001$

r = 0.411 (0.161 - 0.578)
p = 0.009

Figures 5.4.2: Correlations (Spearman's Rho) between Right Leg Vastus Lateralis Muscle Thickness and Isokinetic Peak Torque at A) 60°·s-1 and B) 300°·s-1.

Mean leg muscle thickness demonstrated moderate and significant correlations (r = 0.432 – 0.505, $p < 0.05$) with mean leg knee extension peak torque at 60º·s^{-1} extension and 300º·s^{-1} extension (Figures 5.4.3a and 5.4.3b).

A) B)



r = 0.505 (0.233 - 0.626)
$p < 0.001$

r = 0.432 (0.185 - 0.595)
p = 0.003

Figures 5.4.3: Correlations (Spearman's Rho) between Mean Leg Vastus Lateralis Muscle Thickness and Mean Leg Isokinetic Peak Torque at A)60°·s^{-1} and B) 300°·s^{-1}.

Countermovement jump variables demonstrated moderate to large and significant correlations (r = 0.496 - 0.794, $p < 0.05$) with muscle thickness and knee extension peak torque (Table 5.4.1); however, jump height and take-off velocity was not significantly or meaningfully correlated with mean vastus lateralis muscle thickness.

Table 5.4.1: Correlations (Spearman's Rho) between CMJ and the Average Limb Isokinetic and Average Vastus Lateralis Muscle Thickness Variable.

Variable	**Jump Height *r*-value (95% CI)**	**Take-off Velocity *r*- value (95% CI)**	**Mean Prop Power *r*- value (95% CI)**	**Peak Prop Power *r*- value (95% CI)**	**Prop Impulse *r*- value (95% CI)**	**Mean Prop Force *r*- value (95% CI)**	**Peak Prop Force *r*- value (95% CI)**	**Mean Brake Force *r*- value (95% CI)**	**Peak Brake Force *r*- value (95% CI)**
Vastus Lateralis Muscle Thickness	0.339 (0.150 – 0.571) p = 0.18	0.331 (0.134 – 0.560) p = 0.21	0.549 (0.339 – 0.692) *	0.514 (0.319 – 0.679) *	0.536 (0.382 - 0.717) *	0.507 (0.320 – 0.680) *	0.496 (0.256 – 0.641) *	0.549 (0.291 – 0.663) *	0.601 (0.358 – 0. 703) *
Peak Torque 60°·s^{-1}	0.516 (0.373 – 0.711) *	0.519 (0.382 – 0.716) *	0.756 (0.747 – 0.898) *	0.794 (0.746 – 0.898) *	0.784 (0.716 – 0.885) *	0.679 (0.645 – 0.852) *	0.662 (0.617 – 0.839) *	0.649 (0.636 – 0.848) *	0.681 (0.654 – 0.857) *
Peak Torque 300°·s^{-1}	0.592 (0.441 – 0.749) *	0.592 (0.456 – 0.757) *	0.671 (0.667 – 0.862) *	0.721 (0.668 – 0.863) *	0.726 (0.621 – 0.841) *	0.524 (0.489 – 0.775) *	0.519 (0.458 – 0.759) *	0.558 (0.513 – 0.788) *	0.581 (0.532 – 0.797) *
*$p < 0.001$ unless otherwise specified; YELLOW = moderate correlation; GREEN = strong correlation; Red = Correlation Not Significant									

Table 5.4.2: Pearson or Spearman's Rho Correlations (Pearson or Spearman's Rho) between Relative (Rel.) CMJ and the Relative Isokinetic Variables.

Variable	**Mean Prop Power *r*- value (95% CI)**	**Peak Prop Power *r*- value (95% CI)**	**Prop Impulse *r*- value (95% CI)**	**Mean Prop Force *r*- value (95% CI)**	**Peak Prop Force *r*- value (95% CI)**	**Mean Brake Force *r*- value (95% CI)**	**Peak Brake Force *r*- value (95% CI)**
Peak Torque 60°·s^{-1} Ext	0.599 (0.559 – 0.811) *	0.635 (0.540 – 0.801) *	0.627 (0.490 – 0.775) *	0.420 (0.335 – 0.689) p = 0.018	0.402 (0.252 – 0.639) p = 0.018	0.412 (0.332 – 0.687) p = 0.018	0.574 (0.383 – 0.717) p = 0.003
Peak Torque 300°·s^{-1} Ext	0.560 (0.465 – 0.762) *	0.599 (0.490 – 0.775) *	0.646 (0.476 – 0.768) *	0.320 (0.220 – 0.618) p = 0.162	0.283 (0.157 – 0.576) p = 0.396	0.430 (0.267 – 0.648) p = 0.005	0.492 (0.281 – 0.657) p = 0.007

*p < 0.001 unless otherwise specified

Blue = Pearson Correlations; Black = Spearman Rho Correlation

Yellow = moderate correlation

Red = Correlation Not Significant or Meaningful

Relative body mass countermovement jump variables demonstrated moderate and significant correlations (r = 0.402 - 0.646, p <0.05) with relative knee extension peak torque (Table 5.4.2); however, relative mean and peak propulsive force was not significantly or meaningfully correlated with relative mean peak torque at 300°·s^{-1}.

5.5: Discussion:

The aim of this study was to examine the correlations between muscle architecture, isokinetic knee extensor torque and CMJ variables within an adolescent population. The results showed a moderate correlation between the left VL MT and left extension PT at $60°\cdot s^{-1}$ and $300°\cdot s^{-1}$. Right VL MT moderately correlated with right extension PT at $60°\cdot s^{-1}$ and $300°\cdot s^{-1}$. Mean VL MT moderately correlated with mean extension PT at $60°\cdot s^{-1}$ and $300°\cdot s^{-1}$. The mean VL MT also had moderate correlations with the mean propulsion power, peak propulsion power, propulsion impulse, mean propulsion force, peak propulsion force, mean braking force and peak braking force. Mean PT at $60°\cdot s^{-1}$ and $300°\cdot s^{-1}$ had moderate to strong correlations with jump height, take-off velocity, mean propulsion power, peak propulsion power, propulsion impulse, mean propulsion force, peak propulsion force, mean braking force and peak braking force. Lastly, relative PT at $60°\cdot s^{-1}$ and $300°\cdot s^{-1}$ had moderate correlations with relative mean propulsion power, peak propulsion power, propulsion impulse, mean propulsion force, peak propulsion force, mean braking force and peak braking force. With these correlations being found this studies hypothesis stating that there would be comparable correlations among an adolescent population in relationship to previous correlations found within adult populations can be confirmed (Alegre et al., 2014; De Ruiter et al., 2006; Earp et al., 2010; Schons et al., 2018; Wickiewicz et al., 1984; Zaras et al., 2020).

Previous researchers have stated that muscle architecture of the VL and BF have had correlations with isokinetic and countermovement jump testing variables (Alegre et al., 2014; Earp et al., 2010; Wickiewicz et al., 1984; Zaras et al., 2020). The current study only had the VL correlate with the CMJ and isokinetic PT testing variables since other muscles were not found to have reliable data (Chapter 4).

The results of this study reveal moderate correlations (*r*- value between 0.36 and 0.67 and $p < 0.05$) between the left VL MT, right VL MT and mean VL MT with the two knee extension isokinetic tests at $60°\cdot s^{-1}$ and $300°\cdot s^{-1}$. Previous researchers have stated that the VL MT as well as VI, VM, RF and BF MT, PA and FL all had correlations with isokinetic and within a population of subjects aged 19-38 (Alegre et al., 2014; Wickiewicz et al., 1984). For isokinetic comparisons to muscle architecture the previous researchers did not state specific correlation values, but it did say the correlations were significant (Alegre et al., 2014 and Wickiewicz et al., 1984). These previous results from Alegre et al. (2014) and Wickiewicz et al. (1984) show that the current studies results are in concurrence with correlations being found between the VL MT and isokinetic from $0°·s^{-1}$ (isometric movement) to $300°·s^{-1}$. In the current study we only tested $60°·s^{-1}$ and $300°·s^{-1}$ but showed that VL MT was moderately correlated. These correlations can be better explained by the muscle engagement within and isometric movement. Since this study only examined the VL muscle withing the quadriceps muscle group. Therefore, only part of the concentric contraction is explained by the VL which would result in a moderate correlation instead of a strong correlation. Due to the results of this current study, it can be stated that there are similar correlations between muscle architecture and isokinetic testing within the adolescent population in relation to the correlations found in older populations in previous studies (Alegre et al., 2014; Wickiewicz et al., 1984).

This study also resulted in moderate correlations (*r*- value between 0.36 and 0.67 and $p < 0.05$) between the mean VL MT and seven of the nine CMJ variables (mean propulsion power, peak propulsion power, propulsion impulse, mean propulsion force, peak propulsion force, mean braking force and peak braking force). The two CMJ variables that did not have a meaningful or significant correlation with VL MT in this study were jump height and take-off velocity. Previous studies by Earp et al. (2010) and Zaras et al. (2020) also tested the VL along with the LG, VI, VM and RF. Earp et al. (2010) concluded a weak but significant correlation between the LG and jump height ($r^2 = 0.186$, $p = 0.018$) within a subject group with an average age of 23. Earp et al. (2010) did not find any significant correlations between the VL and the jump height, peak power and relative power of the CMJ. However, Zaras et al. (2020) did find moderate correlations with the VL MT ($r = 0.540$, $p < 0.05$), PA ($r = 0.470$, $p < 0.05$) and FL ($r = 0.658$, $p < 0.05$) and CMJ power. These researchers also conclude moderate correlations with VL ($r = 0.618$, $p < 0.05$), VI ($r = 0.797$, $p < 0.05$) and VM cross sectional area ($r = 0.506$, $p < 0.05$) with CMJ power. Since a CMJ results in a triple extension movement; meaning the hip, knee and ankle are all extending during the movement, the role of the knee extensor muscles only plays a small part in the full movement and propulsive forces of the jump. Therefore, the results of this study as well as past study results only having outcomes in the moderate correlation range is explained by the fact that more than one muscle group and more than one muscle joint playing a role in the CMJ movement. The results from the Zaras et al. study was on a range of 15-32 year old subjects with an average age of 23.5 years are in conjunction with the results of moderate correlations with mean propulsion power ($r = 0.549$, $p < 0.001$)

and peak propulsion power (r = 0.514, p < 0.001) within the current studies adolescent population. The current research has a more detailed breakdown of the time during the jump in which the variables are taken. For example, the CMJ braking, and propulsion phases were separated and there were also peak and mean power calculations obtained within the jump. The previous research just stated that the CMJ power was recorded and therefore it is not specifically known if the calculation is a mean or peak calculation or whether it is during the braking or propulsion phase (Earp et al., 2010; Zaras et al., 2020). However, as stated above the correlations are similar between the past studies and the current study and therefore it can be determined that the current study with adolescent athletes can be used in future research.

The current research also showed moderate to high correlation (r-values between 0.516 and 0.794, p < 0.05) between CMJ variables and mean isokinetic peak torque extension at $60°·s^{-1}$ and $300°·s^{-1}$. This research study also examines the relative bodyweight variable calculations between mean isokinetic peak torque and CMJ variables except for jump height and take-off velocity. These relative variables were calculated by taking the variables and dividing them by the subject's body weight to eliminate the influence of a person's size during these tests. The current study resulted in moderate correlations between the relative peak torque extension at both $60°·s^{-1}$ and $300°·s^{-1}$ and the relative CMJ variables (r-values between 0.402 and 0.646, p < 0.05). Relative mean propulsion force and relative peak propulsion force did not result in meaningful or significant difference with the relative peak torque at $300°·s^{-1}$. Previous research by De Ruiter et al. (2006) evaluated the correlation between isometric peak torque at 120° knee extension to a 90° and 120° knee flexion CMJ jump height. The results showed strong correlations between the isometric contraction and CMJ jump height (r = .76 and .86 for 90° and 120° CMJ jump height respectively, p < 0.05) (De Ruiter et al., 2006). Schons et al. (2018) tested subjects at $180°·s^{-1}$ with CMJ power and jump height. These researchers only found moderate correlations between knee extensor peak torque and CMJ power (r = 0.610, p < 0.05) (Schons et al, 2018). These two studies were conducted on subject aged 21-32 and resulted in similar correlations to the current study that tested adolescents aged 13-18 (De Ruiter et al., 2006; Schons et al., 2018). The main difference between the current study and past research is that the current study evaluated the mean values of the peak torque for leg extension during the isokinetic movements to create a bi-lateral comparison to the bilateral leg jump. The previous studies only correlated the peak torques created by the subject's dominant leg (De Ruiter et al., 2006; Schons et al., 2018). This is a difference between studies that researchers should be cognizant of when comparing studies. However, the current study did coincide with previous correlations found between isokinetic and CMJ power and jump height correlations. The current study did result in more variables calculated during a CMJ that showed correlations with isokinetic peak torque. Within the adolescent population, relative take-off velocity did not have a significant correlation with $60°·s^{-1}$ extension peak torque and relative mean propulsion force and relative peak propulsion force was found to not have a significant correlation with $300°·s^{-1}$ extension peak torque. However, the study did result peak propulsion power and propulsion impulse having strong correlations with both $60°·s^{-1}$ and $300°·s^{-1}$ extension peak torque (r between 0.721 and 0.794, $p < 0.001$). These correlations being strong is what one would expect based on the movements involved in both testing scenarios. During the propulsion phase of a CMJ the knee joint is extending which is the peak torque contraction that is being analyzed in this study. These correlations have been hypothesized to have correlations because the quadriceps muscle group and extension contraction are being used in both testing methods. Therefore, it can be concluded that the propulsion phase of a CMJ and extension phase of an isokinetic movement have moderate to strong correlations.

5.5.1: Limitations and Areas of Future Research:

The limitations of this study are due to the number of subjects tested. Even though the subject number was an appropriate sample size for the adolescent population the number of correlations run and the corrected p-value due to the smaller sample size could have caused some correlations to be not significant or meaningful. If the number of correlations run were less or there were more subjects these correlations might have been found to be significant. Other limitations of the study are the reliable variables that were found within this subject pool. Muscle architecture has been applied to strength and power output based on muscle thickness, pennation angle and fascicle length (Aagaard et al., 2001; Blazevich et al., 2003; Blazevich et al., 2007; Potier et al., 2009; Secomb et al., 2015 & Seynnes et al., 2006). Since many of these variables were not found to be reliable, they were not used in the current study of correlation. The ability to correlate muscle architecture to CMJ performance could be beneficial for the trainers and athletes to analyze how the physical performance of a jump is impacted by the muscle architecture of the athlete and what manipulations need to be made to help improve the architecture to then improve the physical performance of an athlete (Earp et al., 2011).

Future research should evaluate specific variable correlations instead of all the reliable measurements found in a previous study. Also, if continued research can be conducted on a larger population more accurate correlations could potentially be found within the adolescent population. With the correlations being found between isokinetic dynamometry, muscle architecture and CMJ variables practitioners, coaches and trainers could use CMJ performance, which is an easier test to access, and help them see if an athlete is having a performance decline. If an athlete is not performing their CMJ as well as they typically do and based on the correlations with muscle power, force and structure it may indicate that an athlete has an underlying issue that may lead to future injury. This diagnosis could help get an athlete help prior to there being a major issue and loss of participation time.

5.5.2: Conclusion:

This study concludes that vastus lateralis muscle thickness can be correlated with peak torque during extension contractions of an isokinetic test at $60°\cdot s^{-1}$ and $300°\cdot s^{-1}$ as well as mean propulsion power, peak propulsion power, propulsion impulse, mean propulsion force, peak propulsion force, mean braking force and peak braking force during a CMJ. Also $60°\cdot s^{-1}$ and $300°\cdot s^{-1}$ peak torque extension is correlated with jump height, take-off velocity, mean propulsion power, peak propulsion power, propulsion impulse, mean propulsion force, peak propulsion force, mean braking force and peak braking force during a CMJ. These correlations can be used in conjunction in future research to show that a subject that has greater CMJ variables and eccentric peak torque will be subjects that typically have greater vastus lateralis muscle thickness.

Transition from Chapter 5 to Chapter 6

Chapter 4 and chapter 5 of this thesis were completed to examine the reliability and correlations between muscle architecture, countermovement jump variables, and peak isokinetic torques of knee extensor and flexor within a population of youth athletes. Once these tests were completed, and the reliable variables were determined it was necessary to examine the best approach to determine the peak height velocity of the subjects involved in this study. There are several options that were viable; however, most research involved use of the Mirwald and Moore equations. It was not until later in the research that Khamis and Roche had started to be used more. Since Khamis and Roach was more prevalent after the subjects had been tested and involved the height measurements of both the mother and father some subjects did not respond to follow up emails and therefore this equation was considered to not be a viable option for use in the upcoming chapters. Since Mirwald is the most used equation in past research it was chosen as the equation of use for this study in order to be able to compare the past research with the current research.

Chapter 6: Comparing Peak Height Velocity Somatic Measurement Methods Within a Group of Adolescent Subjects

6.1: Abstract:

The objective of this study was to compare commonly used equations to calculate an adolescent's peak height velocity (PHV). Sixty-five subjects (38 females [age: 15.08 ± 1.48 years, height: 166 ± 5.17 cm, sitting height: 86.8 ± 4.19 cm body mass: 59.96 ± 8.65 kg] 27 males [age: 15.15 ± 1.81 years, height: 171.3 ± 10.37 cm, sitting height: 86.68 ± 5.59 cm, body mass: 60.37 ± 10.88 kg]) had their stature, sitting height, mass and age at day of testing recorded to determine maturity offset via various methods. The Mirwald and Moore equations for males and females were used to find ages at PHV for the subjects which were then categorized into pre, during and post PHV age as well as early, average and late maturers. The Khamis and Roche equation was also used to categorize pre, during and post PHV for the subjects. The results showed no significant difference between Mirwald (12.73 ± 0.77 years) and Moore (12.35 ± 0.56 years) methods for the females. For males, no significant differences were observed between the Moore 1 Revised (14.42 ± 0.55 years) and Mirwald (14.41 ± 0.70 years) methods. However, for the males the Moore 1 Revised equation (14.42 ± 0.55 years) resulted in significantly higher ($p < 0.001$) age at PHV compared to the Moore 1 (14.17 ± 0.57 years) and Moore 2 (13.90 ± 0.65 years) equations. Estimates via Mirwald (14.41 ± 0.70 years) were also significantly higher ($p < 0.001$) than the Moore 1 (14.17 ± 0.57 years) and 2 (13.90 ± 0.65 years) equations but not significantly different from the Moore 1 Revised (14.42 ± 0.55 years) equation. The results of this study show that the equation's for PHV estimates in males cannot be used interchangeably, whilst for estimates in females even though no statistically significant differences were observed, a mean difference of 4.5 months may limit practical application. Practitioners should use consistent methods to approximate PHV in adolescents and can only make meaningful comparisons to literature that use their chosen method for monitoring purposes with adolescent athletes.

6.2: Introduction:

Peak height velocity (PHV) is the time in which an adolescent has their growth spurt and is growing at the fastest rate (Beunen & Malina, 1988). For average maturers males typically reach PHV ~14 years of age and females ~12 years (Sherar et al., 2005). However, not all adolescents mature at the same rate, with some reaching their PHV earlier or later in comparison to average maturers age. Early maturers would be classified as adolescents that reach PHV ≤ 1 year before the average maturer for their sex, whereas a late maturer would reach PHV ≥ 1 year after the average for their sex (Sherar et al., 2005). Based on this information PHV has become a focus of interest among sport trainers, coaches and researchers because the youth athletes they work with can all be at different phases of maturation, therefore resulting in the potential need for different training foci, even if they are all grouped under the same chronological age (Lloyd et al., 2014).

As an adolescent progresses through their growth spurt there is an increase in their limb length, that enables the adolescent to create greater torque around the specific joint due to the increased moment arm, therefore having the ability to produce a lower countermovement depth and more forceful movements which in turn would cause a higher jump. After PHV is reached the adolescent body starts to have an increase in body weight velocity. This increase in weight causes a plateau in the individuals jump height because the extra momentum and force created by the increased potential from the countermovement depth is now being used to offset the additional weight of the body (Philippaerts et al., 2006). This increase in an individual's weight could also potentially result in reduced performance (e.g., a lower jump height, reduced linear sprint acceleration, slower change of direction performance) because the individual is no longer able to produce as much relative force to overcome the additional weight. Not only can the increase in momentum have an impact on jump height but in turn has an impact on landing forces. This increase in landing force impacts the deceleration of an individual when landing from the jump. In order to land from a jump or change direction an individual must be able to decelerate and control the forces created during the braking phase of these tasks. If an individual can decelerate in an effective and efficient way they are more likely to avoid injury. Adolescents going through their growth spurt and PHV may be susceptible to 'athletic awkwardness' whereby coordination of athletic movements such as jumping, sprinting and change of direction may be impaired to sudden increase in limb lengths. These examples of changes throughout maturation show the importance of determining PHV and devising training accordingly to prepare the adolescents body for the increase in body weight prior to the actual increase in weight. The training implications of this timing are imperative to healthy and safe developments for adolescents through their maturation phases.

In the medical and sports medicine fields methods to determine skeletal and sexual age have been used to define biological age and maturation in an individual (Lloyd et al., 2014). However, these methods are expensive and require qualified medical personnel to perform the examinations. For these reasons' researchers have focused on creating easy, fast and efficient assessments of adolescents to help approximate PHV in order to plan physical training and sports specific practice for individuals (Lloyd et al., 2014). PHV somatic assessments that have been developed include the Mirwald (Mirwald et al., 2002), Moore (Moore et al., 2015), and Khamis-Roche adult height prediction (Khamis & Roche, 1994) equations.

To initially address the need for PHV calculations for adolescents, Khamis and Roche (1994) created a method to determine what phase of maturation an individual is in. Using the current height and mass of the subject along with the subject's parents' height. Khamis and Roche (1994) were able to determine if an individual was pre, during or post their PHV. The ability to place an individual in a maturation phase enables trainers and coaches to individualize training based on maturation phase and monitor the potential impact on motor skill or sports performance. However, this method may lack inclusivity, as some individuals might not know their birth parents or may only know one of their parents and thus, presents a major issue in this method of analysis. Due to this potential complication in data collection, other methods have since been developed that rely on collecting data from variables that are only obtained from the subject. Furthermore, the Khamis and Roche (1994) method also only categorizes the phase of an adolescent and does not provide an actual age at which an individual will or did reach their PHV. Mirwald et al. (2002) developed an equation that excluded parental stature, for both males and females, to calculate an individual's age at PHV (maturity offset) and has subsequently been used in many research articles (Koziel and Malina, 2017; Lloyd et al., 2014; Malina et al., 2015; Moore et al., 2014; Read et al., 2018; Sherar et al., 2002). However, given that the Mirwald equation is based on data collected from only a specific geographic area (Saskatchewan youth), the data may be subject to overfitting (Moore et al., 2015). For example, 'Overfitting' of data suggests that the collected data is only applicable to that specific data set and if applied to the broader scale of adolescents the equations would not be as accurate. The Mirwald equation is also considered complex as additional measures of sitting height is required from standard practice of height and mass and calculates interactions between leg length and sitting height, age and leg length, age and sitting height, age and mass, and the leg to height ratio. These interactions and ratios then need to be inserted into the final equation (Moore et al., 2015). Therefore, with the numerous variables to be determined and calculations needed there is an increased potential for error.

Due to these criticisms, Moore et al. (2015) have created a simplified equation to estimate PHV for both males and females where the researcher, practitioner or coach/trainer would only need age and height from the subject providing a more simplistic and faster estimate of PHV. Moore et al. (2015) also accounted for overfitting and therefore their equations can be applied to the overall population. However, for the males they created three equations. The second equation was a recalibration of the first equation and these two used sitting heights, whereas the third equation used standing height (Moore et al., 2015). There has been limited research using these new equations and therefore it is hard to compare across different studies. Mirwald et al. (2002) have been cited over 1500 times, whereas Moore et al. (2015) have only been cited 175 times. The number of cited articles is a glaring difference between the two PHV calculation strategies which makes the Moore equations less likely to be used. Also, with the original Moore et al. (2015) research providing three different equations it is sometimes not stated in an article which equation is used and therefore, in such circumstances, data cannot be properly used for comparisons.

Limited research has been completed comparing the Mirwald and Moore PHV equations. Also, the classification of maturity phase based on the calculated PHV equations and what phase the individual is currently in versus the classification given by the Khamis Roche (1994) method also has limited or no research. Koziel and Malina (2017) performed a study using a different cohort of subjects to compare the Mirwald and Moore equations. This research concluded that the different equations were more accurate for average maturing adolescents but showed a larger inaccuracy when analyzing early or late maturing individuals. This research also shows that the closer the individual male is to PHV the more accurate the predicted PHV is for the individual. This was not the case for the female subjects whose overall accuracy over the years was always between ± 1 year of accuracy which means the Moore equations could be used with similar PHV prediction accuracy as the Mirwald equations (Koziel & Malina, 2017). More research is needed to determine which method is best to use or how the equations relate to one another to see if comparisons can be made between them.

Therefore, the aim of this study is to compare the most used estimates of PHV (Mirwald Equation, Moore Equation and Khamis and Roche analysis). This comparison will identify the magnitude of differences (if any) in estimating PHV and whether this impacts classification of individuals (pre, mid, post or early, average, late) to recognize whether methods can be compared interchangeably in literature. This analysis will help researchers, coaches and trainers better understand how the PHV equations they are using may differ from the other equations that are available. It was hypothesized that there would be no significant differences between the subjects predicted PHV maturation phase between the different equations.

6.3: Methods:

6.3.1: Experimental Approach:

This study was designed to investigate and compare the differences between PHV equations that have been used in past research studies. A within subject observational study was adopted to collect the anthropometric of adolescent athletes. Based on the information needed for the Mirwald and Moore equations, stature, sitting height, mass and age at time of the testing session were recorded. At a date following the subjects testing session the individuals were asked to provide their parents heights to calculate PHV phase using the Khamis and Roche equation.

6.3.2: Subjects:

The sample for this research was composed of male (n = 27, age 15.15 ± 1.81 years, height 171.3 ± 10.37 cm, body mass 60.40 ± 10.88 kg) and female (n = 38, age 15.08 ± 1.48 years, height 166 ± 5.17 cm, body mass 59.96 ± 8.65 kg) adolescent athletes. These adolescent athletes participated in sixteen different sports which included soccer (38), track and field/cross country (26), basketball (23), softball (13), baseball (11), volleyball (11), lacrosse (9), football (8), horseback riding (3), swimming and diving (3), dance (2), golf (2), tennis (2), wrestling (2), gymnastics (1) and hockey (1). Written informed consent was obtained from the subjects and assent from their parents/guardians was attained prior to testing. The study was approved by the University of Salford and State University of New York Upstate Medical University ethics committee.

6.3.3: Procedures:

Each subject attended a single laboratory testing session where they had their height measured by the researcher using a measuring tape on a wall in the laboratory. The subjects were instructed to remove their shoes and stand with their backs against the wall. They were then instructed to have 4 points of contact (heels, buttocks, shoulders and head) against the wall to ensure proper posture. Then the subjects were instructed to sit on the floor and with bent or straight legs (whichever way ensured their buttocks could be pressed against the wall) and maintain 3 points of contact (buttocks, shoulders, head) for the researcher to measure the subject's sitting height. The subjects were then instructed to stand still on a force plate for at least one second. Three different data trials were performed to collect the subject's mass. The data from each of the second-long trials was averaged and then the three different trial masses were averaged to determine the subject's mass on the day of testing. The subjects' age was determined by calculating the year plus month age of the subject at the time of testing. For example, if a subject was 14 years and 8 months their day of testing age would be 14 + (8/12) for an age of 14.67 years old. After the subjects were tested an email was sent post-test to both the subject and their parents to obtain the heights of both parents of the subject to evaluate the Khamis-Roche PHV calculation for this research (Khamis & Roche, 1994). Khamis and Roche (1994) determine whether a subject was pre, during or post PHV based on the percentage of predicted adult height of the subject. If the subject height at testing was less than 89% of their predicted adult height, then the subject was pre PHV. A subject would be classified as during PHV if their height percentage was between 89% and 95% and post PHV if their height at testing is more than 95% of their adult height predictions. Subjects were also classified as early, average or late maturers based on then their predicted PHV occurred (Sherar et al., 2005). The average age of an adolescent to hit PHV for girls is age 12 and for boys is age 14. Therefore, if the predicted PHV age calculation falls within ±1 year of these ages a subject would be considered an average maturer. If the subjects predicted PHV falls before age 11 for girls and 13 for boys, they would be considered early maturers and if predicted PHV fall after age 13 for girls and 15 for boys they would be considered late maturers. With the collection of subject age, standing height and sitting height the researcher then proceeded to calculate predictive PHV age using the Mirwald equation and the Moore equations (Mirwald et al., 2002; Moore et al., 2015). The following equations were the calculations used:

Mirwald Girl: Maturity Offset = -16.364 + 0.0002309·Leg Length and Sitting Height interaction + 0.006277·Age and Sitting Height interaction + 0.179·Leg by Height ratio + 0.0009428·Age and Weight interaction

Mirwald Boy: Maturity Offset = -29.769 + 0.0003007·Leg Length and Sitting Height interaction – 0.01177·Age and Leg Length interaction + 0.01639·Age and Sitting Height interaction + 0.445·Leg by Height ratio

Moore Girl: Maturity Offset = -7.709133 + [0.0042232 · (age · height)]

Moore Boy Original: Maturity Offset = -8.128741 + [0.0070346 · (age · sitting height)]

Moore Boy Original Revised: Maturity Offset = (-8.128741 – 0.2683693) + [0.0070346 · (age · sitting height)]

Moore Boy 2: Maturity Offset = -7.999994 + [0.0036124 · (age · height)]

Khamis and Roche Girl: [(father's height · 12/13) + mother's height] / 2

Khamis and Roche Boy: [father's height + (mother's height · 12/13)] /2

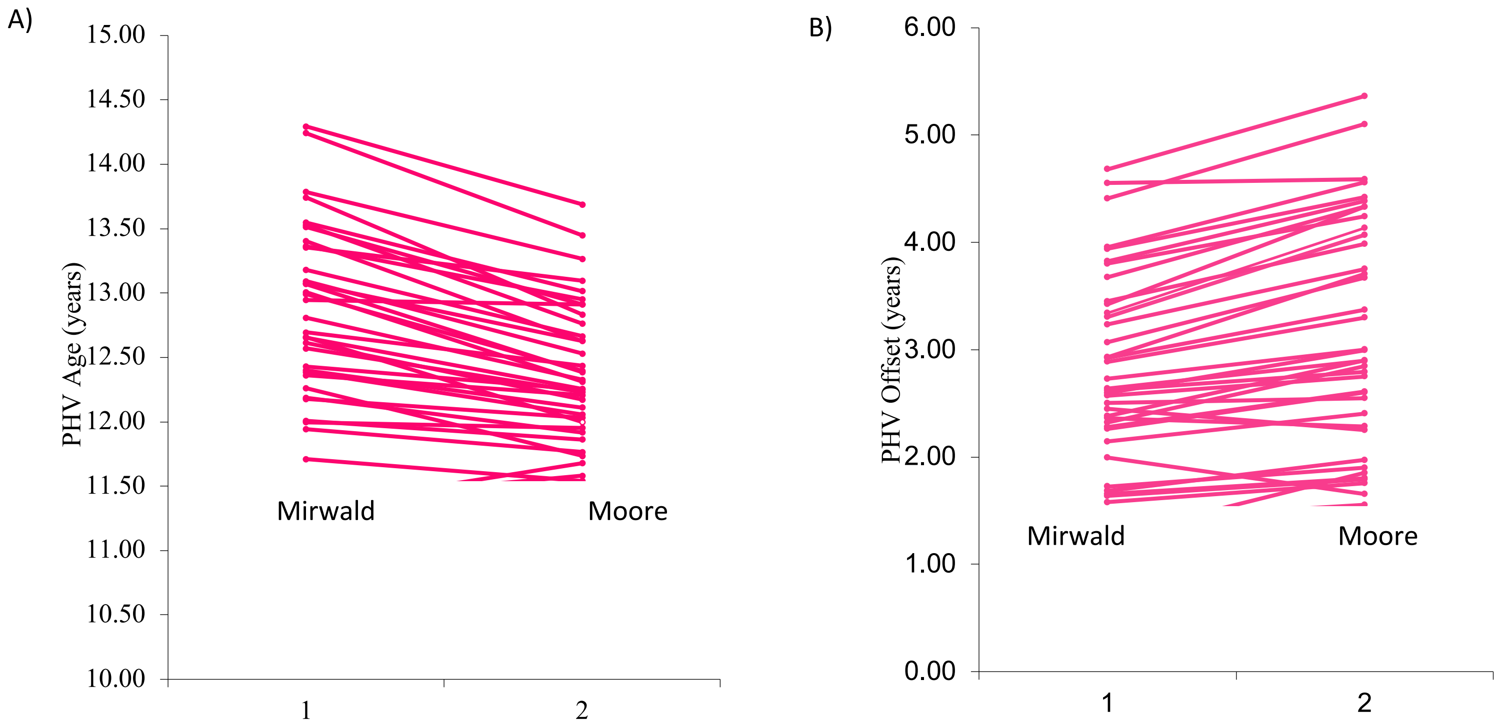
Based on these equations the subjects were categorized as pre, during or post PHV. A subject would be classified as pre PHV if their age at the testing date was more than a year less than their estimated age of PHV. During PHV subjects would be subjects who had an estimated PHV was between ± 1 year of their testing date age and post PHV subjects would have a testing date age greater than one year from their estimated PHV age.

6.3.4: Statistical Analyses:

Normality of data was determined using Shapiro-Wilk's test of normality. The results of the two female PHV equations were compared using a t-test, while a repeated measures ANOVA including pairwise comparison with Bonferroni post-hoc analysis was used to compare the results of the four male PHV equations. In addition, Cohen's d effect sizes were calculated to determine the magnitude of any differences and interpreted based on the following thresholds: trivial (< 0.19), small (0.20 – 0.59), moderate (0.60 – 1.19), large (1.20 – 1.99), and very large (2.0 – 4.0) (Hopkins, 2002). All data is expressed as mean ± *SD,* and all statistical analyses were performed using the IBM SPSS Statistics 25 software (Statistical Package for Social Sciences, Chicago, IL, USA). An *a priori* alpha level of <0.05 was used to determine statistical significance.

6.4: Results:

The female data was normally distributed (p > 0.05). The results of the paired t-test demonstrated that there were no significant or meaningful differences ($p < 0.05$, $d = 0.56$) between the Mirwald female PHV equation (12.73 ± 0.77 years) and the Moore female PHV equation (12.35 ± 0.56 years). The differences in age at PHV and years from PHV are represented in Figure 6.4.1a (years at PHV) and Figure 6.4.1b (years from PHV).



6.4.1: Comparison of age at peak height velocity based on the Mirwald and Moore equations, in A) Females age at PHV and B) Females years past PHV

The male data was determined to be normally distributed for skewness and kurtosis; however, sphericity could not be assumed and therefore the Greenhouse-Geisser adjustment was used. Results of the repeated measures ANOVA indicate that there was a significant difference between the four PHV equations, ($F_{[1.7, 44.21]}$ = 58.55, $p < 0.001$, power = 1.00). The results of the post-hoc analysis shows that the revised Moore 1 equation resulted in the highest predicted PHV which was significantly and meaningfully (small-moderate) greater than the Moore 1 and Moore 2 equations, although not significantly or meaningfully greater than the Mirwald equation. Mirwald was significantly and meaningfully greater than the Moore 1 and Moore 2 equations (Table 6.4.1). The Moore 2 equation was significantly and meaningfully lower than all other equations (Table 6.4.1).

Table 6.4.1: Statistical Analysis for the four male PHV equations.

			Pairwise Comparisons (p and *d*)			
Equation	**Mean ± SD (years)**	**95% CI**	**Vs. Moore 1 R***	**Vs. Mirwald**	**Vs. Moore 1**	**Vs. Moore 2**
Moore 1 R*	14.42 ± 0.55	14.21-14.64	~	$p = 1.00$ *d* = 0.02	$p < 0.001$ *d* = 0.45	$p < 0.001$ *d* = 0.86
Mirwald	14.41 ± 0.70	14.14-14.69	$p = 1.00$ *d* = -0.02	~	$p < 0.001$ *d* = 0.38	$p < 0.001$ *d* = 0.76
Moore 1	14.17 ± 0.57	13.95-14.40	$p < 0.001$ *d* = -0.45	$p < 0.001$ *d* = -0.38	~	$p < 0.001$ *d* = 0.44
Moore 2	13.90 ± 0.65	13.64-14.15	$p < 0.001$ *d* = -0.86	$p < 0.001$ *d* = -0.76	$p < 0.001$ *d* = -0.44	~
R* = Revised; CI = confidence intervals; p = significance level; *d* = Cohen's d effect size						

Based on these calculations the ages at PHV determined by each equation Table 6.4.2 displays the effect of the different equations on the categorization of the subjects into pre, during and post maturation during testing as well as if the subjects are early, average or late maturers (Sherar et al, 2005). Even though the Khamis and Roche data had less subjects involved it can be observed in Table 6.4.2 that the use of their data to find maturation phase of an adolescent follows the trends of phase placement using the PHV equation calculations. Table 6.4.2 also highlights that the Moore equations result in a trend of grouping more of the subjects into the average maturation timing phase than the Mirwald equation does.

Table 6.4.2: Number of Subjects in Maturation Phase or Maturation Timing Base on PHV Equation

		Maturation Phase			**Maturation Timing**		
Sex	**Equation**	**Pre**	**During**	**Post**	**Early**	**Average**	**Late**
Female	Mirwald	0	0	38 (19) **	0	23	15
	Moore	0	0	38 (19) **	0	31	7
	Khamis & Roche **	0	0	19	N/A	N/A	N/A
Male	Moore 1R*	2 (1) **	10 (5) **	15 (7) **	0	23	4
	Mirwald	3 (2) **	9 (4) **	15 (7) **	1	21	5
	Moore 1	2 (1) **	9 (4) **	16 (8) **	0	24	3
	Moore 2	0 (0) **	11 (5) **	16 (8) **	1	24	2
	Khamis & Roche **	1	4	8	N/A	N/A	N/A

R* = Revised

**Khamis & Roche equation had data collected after the testing session and therefore data was only collected for 19 Females and 13 Males subjects. The other equations are based on 38 Females and 27 Males. The Mirwald and Moore subjects that have Khamis and Roche comparison were evaluated and placed in parentheses to compare that equation to the others based on the same number of subjects.

6.5: Discussion:

The purpose of this study was to compare the differences in PHV based on commonly used equations. The results show that there were no significant differences between the female Mirwald and Moore equations, although there was an ~ 3-month difference in the prediction age with Mirwald being later in age than Moore. For the male equations it is shown that the Moore revised equation results in the oldest age of predicted PHV for the males with Mirwald slightly (6 weeks, but not significantly younger). These two equations are both significantly higher than the other two Moore equations, with Moore 1 being significantly higher than the Moore 2 equation.

For this study not all mother and father heights were able collected for all subjects. Therefore, it is shown in Table 6.4.2 where the subjects that did have their data collected were characterized based on the Khamis and Roche equation. The subject's categorization for the Khamis and Roche equations were almost identical to those found for the Mirwald and Moore equations in respect to pre, circa and post-PHV groups. Since all subjects did not have a Khamis and Roche variable the rest of the discussion focuses on the comparisons between the Mirwald and Moore equations.

Previously researchers have shown that the female equations have been validated as a way of predicting PHV (Koziel & Malina, 2018). While the research shows that the equations tend to be more accurate for average maturers around the age of their PHV the research shows that both equations are reliable in predicting the PHV age within ± 1 year 90% of the time (Mirwald et al., 2002; Moore et al., 2015; Koziel & Malina, 2018). The results also support the notion that the equations tend to group the subjects closer to average maturation age for the female sex as stated in Koziel & Malina (2018). This indicates that for early maturers their predicted PHV is later than their observed age and for late maturers it is earlier than the observed age. The female Moore equation shows greater probability of this issue based on the groupings of the subject ages shown in Figure 6.4.1 as well as in Table 6.4.2 where it is shown that the number of late maturers defined by predicted PHV was half of the Mirwald equations.

For the male cohort previous studies examining these equations show that they are all able to predict an average PHV for an individual within ± 1 year 95% of the time for Mirwald (Malina & Koziel, 2014) and 90% of the time for the Moore equations (Moore et al., 2015).

This again does not indicate which equation is best to use and based on the variation of the ages and percent accuracy variations there is no clear answer. The equations for the boys also tend to have the higher probability of grouping towards average maturers, which is also demonstrated in Table 6.4.2. These results indicate that the Mirwald equation does have less subjects in the average maturing category and therefore might reflect better on a population of adolescents. There is limited research about how many youths fall within the early, average or late maturation phases. However, Malina (2003) provided a rough estimate based on youth soccer subjects. Most of the subjects fell within the average maturing range and accounted for around 50% of the subject population, with early maturers accounting for 39% and late maturers for 11%. Since Mirwald has less subjects within the average maturing ages the percentages of subjects within the different maturation timing stages fall closer to the suggestions of Malina's previously collected data.

When observing Table 6.4.2 however, it is apparent that the phases of maturation (pre, circa and post) and timing of maturation (early, average and late), aside from the late maturing females, are quite similar as far as categorizing the athletes, which was the initial intent of Mirwald et al. (2002). Prior to the Mirwald et al. (2002) study the common maturation calculation was based on the Khamis & Roche (1994) equation that predicted maturation status based on percentage of predicted adult height. Mirwald et al. (2002) believed that this equation did not address the tempo of growth during maturation and wanted to create an equation in order to specify where in the maturation process an individual might be. Mirwald et al. (2002) believed this would be able to create maturation classification ranges (pre, during, and post) to better train and strengthen adolescents during their growth phases. It has also been stated that adolescents have a higher risk of injury while they are in their growth spurt and more susceptible to overuse injuries after their growth spurt (van der Sluis et al., 2013). This information supports the need for age calculations to help guide adolescents through their maturation phases safely. Therefore, it is important to have an age and not just a percentage of height to evaluate an adolescent. This supports Mirwald et al. (2002) in their creation for the need of a predictive PHV equation. Another reason Khamis & Roche (1994) may pose a problem for research is that in order to calculate percentage of adult stature the individual's parents' heights are needed. Not all subjects are privy to this information as they may be adopted, not have contact with a parent, or even have parents not willing to participate in the collection of the data. These potential issues are removed using the PHV equations because the only data needed is from the subjects themselves, therefore guaranteeing that PHV can be calculated based on information gained during a testing session.

When further examining the Mirwald and Moore equations it is important to understand the original studies of both. Mirwald et al. (2002) has been criticized for overfitting the data and having an overly complex equation with more parameters than can be justified by the given data (Moore et al., 2015). Therefore, in the creation of their own equations Moore et al. (2015) wanted to simplify the equation by only having one parameter that needed collection to be able to complete the analysis and provide a PHV as well as eliminate the issue of overfitting the data. Moore et al. (2015) also proposed the importance of eliminating the need to collect sitting height by stating that the measurement could be done improperly and therefore make the data output less reliable. Mirwald et al. (2002) however, believed sitting height was the key to PHV because it considers the differential timing of the adolescent spurt in body dimensions and its interaction with chronological age. This interaction allows relationships between full stature and sitting height to be examined throughout the phases of PHV and the impact it might have on other testing parameters such as strength, flexibility, and agility. However, even though Moore et al. (2015) expressed their concern over the use of sitting height they in turn use it in their equation 1 and equation 1 revised. The data Moore et al. (2015) collected supported that the sitting height × age interaction demonstrated the most appropriate measurement to create the male equation. For females, Moore et al. (2015) concluded the age × stature was the most appropriate interaction to use. However, due to their concerns over researchers not collecting or inaccurately collecting sitting height Moore et al. (2015) created a second equation using just the age × height interaction.

The Mirwald et al. (2002) equations are the more frequently used equations for studies involving estimates of PHV because they were the original equations for predicting maturity offset and age at PHV. This enables researchers to make comparisons between research articles. Neither equation gives a precise PHV age however, they can create maturation categories in which an adolescent is in. This ability to categorize these individuals allows for more productive and appropriate training methods for developing adolescents. However, the

Mirwald equation is more robust and considers sitting height which allows for a more comprehensive analysis of how a subject is growing. The equations all categorize the pre, circa and post PHV groups similarly but showed greater differences between early, average and late categorizations. It is important to know the limitations of the equations and use them along with supporting data to then create a suitable plan of development. The purpose of these equations is to be aware of the development of an adolescent to create the safest environment possible as they mature. Therefore, using the PHV equations should be completed 3-4 times a year to enable more accurate analysis of the subjects. If this cannot be done the Mirwald equation is an acceptable PHV analysis with practitioners and coaches understanding the limitations of the equations and realizing that the output is not giving you an exact date of a growth spurt but is allowing for an idea of when a subject will be experiencing their growth spurt and when training should be adapted and changed based on that timing.

6.5.1: Limitations and Areas of Future Research

The limitations of this study include the subjects only being monitored during one training session and therefore actual timing of PHV is unknown. Therefore, the analysis of the data can only compare means of the equations and not validity and reliability with the current data. The subject for this study were all mostly post-PHV subjects. When the consent and IRB (International Review Board) were created for this thesis the ages of subjects to test were selected based on ages when subjects may be more apt to transition from multiple sport to single sport athletes. Therefore, middle school to high school (13-18 years) aged subjects were selected for the study. The PHV analysis came into the research after the IRB had been created and the global covid-19 pandemic did not allow for younger subjects to come in to be tested. Therefore, since many of the subjects were post-PHV the accuracy of the equations for predicting pre and circa subject may not be as accurate. Also, the parental heights were also not taken by a practitioner and were collected post- lab test. Therefore, not all subjects were able to be analyzed using the Khamis and Roche equation. This should be addressed in the future by measuring the adults as well as the subjects, if possible, when they report for their testing session.

Further research needs to be conducted using these PHV equations and analysis to be able to create a uniform approach to evaluating adolescents in the best way. This future research should include determining PHV through mass and height measurements over several years to determine the reliability and validity of the equations to determine actual PHV age. Also, future research should compare skeletal age and stage of puberty to determine further understanding of the PHV occurrence during these other tests. The PHV research needs to incorporate further comparison between the methods that have been used to determine PHV to evaluate and study the integration between the different testing methods.

6.5.2: Conclusion:

The results of this study show that PHV age calculated by Mirwald (2002), and Moore (2015) can be used to obtain an approximate age for an individual adolescent's growth spurt. This approximate PHV age should be used along with observations of the subject's physical performances and how their performance in physical testing changes whilst they mature. Using the PHV calculated age and other growth observations should be used to apply appropriate modifications to training programs. These training adaptations should be in accordance with the long-term athletic development position statement of the National Strength and Conditioning Association (Lloyd et al., 2016) in order to ensure the best practices are being applied for the development of the adolescent athletes who are transitioning though their growth phase.

Transition from Chapter 6 to Chapter 7

Based on the results and findings from Chapters 4, 5, and 6 the subjects were separated into maturation groups using the Mirwald peak height velocity equation. This separation was made to determine whether differences exited between the variables found to be reliable in chapter 4 (jump height, mean propulsion power, peak propulsion power, propulsion impulse, mean propulsion force, peak propulsion force, mean braking force, peak braking force, right and left knee extension, and flexion peak torques at $60°\cdot s^{-1}$, and right and left knee extension peak torques at $300°\cdot s^{-1}$) and the subjects that were determined to be in pre, circa or peak PHV. For this chapter only male subjects were used, since no females in the cohort of subjects were categorized as either pre or circa in their PHV. Females tend to have their growth spurt at an average age of 12 years and boys are commonly two years later at 14 years (Sherar et al., 2005). Due to this discrepancy in ages of PHV between males and females and that the subject parameters for this study were subjects over 13 years of age is why only male subjects fell into pre, circa and post-PHV categories where the females were only post- PHV. The results of this study help show how an adolescent's performance might change based on whether they are pre, circa or post-PHV and how that may impact their needs in training.

Chapter 7: A Comparison of Isokinetic Torque and Countermovement Jump Variables Between Athletes of Different Peak Height Velocity Stages – Part A: Consideration for Pre, Circa and Post PHV.

7.1: Abstract: The aims of this study were to determine if there were differences in countermovement jump (CMJ) and isokinetic knee flexion and extension performance in adolescent athletes between pre-, circa- and post peak height velocity (PHV) groups. *Methods:* Subjects (n = 27, mean ± SD: age: 15.1 ± 1.8 years, height: 171.3 ± 10.4 cm, mass: 60.4 ± 10.9 kg) performed 3 CMJs and concentric isokinetic knee flexion and extension at $60°·s^{-1}$ and $300°·s^{-1}$. *Results:* There were no significant differences ($p > 0.05$) between pre and circa-PHV for any variable, with trivial to moderate effects (0.030 < g < 0.651). Post-PHV group did not significantly ($p > 0.05$) outperform pre and circa-PHV groups in the following variables: relative peak propulsion force, relative mean braking force, relative peak braking force, and relative right, left and average knee extension peak torque at $300°·s^{-1}$. The post-PHV group demonstrated significantly ($p < 0.05$) and meaningfully greater (g > 1.15) jump height, relative peak propulsion power, relative propulsive impulse, relative left knee extension peak torque at $60°·s^{-1}$, and relative average knee extension peak torque at $60°·s^{-1}$ compared to the circa and pre-PHV groups. Relative mean propulsion power, relative mean propulsion force and relative right knee extension peak torque at $60°·s^{-1}$ were significantly ($p < 0.05$) and meaningfully (g > 0.796) greater in the post-PHV group compared to the circa-PHV group. Even though these variables were not significantly difference between post-PHV and pre-PHV there were moderate to large meaningful differences (0.823 < g < 1.23). Relative right knee flexion peak torque at $60°·s^{-1}$ resulted in post-PHV having a significantly ($p < 0.05$) greater and large meaningful (g = 1.60) difference from pre-PHV individuals. Relative right knee flexion peak torque at $60°·s^{-1}$ was also moderately (g = 0.967) but not significantly (p>0.05) greater in the post-PHV group compared to the circa-PHV groups. *Conclusion:* The results indicate that post-PHV athletes can generate greater relative forces, power and impulse while performing a CMJ than the pre and circa-PHV athletes.

7.2: Introduction:

When evaluating adolescent athletes, it is important to understand their physical development and maturation phase, as muscular development, and the associated force production characteristics, can be influenced by maturation (Philippaerts et al., 2006). As an adolescent progresses through their growth spurt, known as the period of peak height velocity (PVH), their height increases with an associated increase in limb length. PHV has been associated with a term known as adolescent awkwardness where an adolescent may have delays or regressions in sensorimotor functions (Quatman-Yates et al., 2012). This increase in limb length associated with PHV causes a longer moment arm and will have an impact on the individuals torque production (Philippaerts et al., 2006). Based on how an individual's muscles develop during their PHV may have an impact on their physical performance due to the quick increase in limb length (Bult et al., 2018). Therefore, laboratory testing, such as the countermovement jump (CMJ) and isokinetic dynamometry to determine an individuals' force and torque production abilities throughout PHV, would be evaluations that can help determine the impacts on physical performance during that subjects PHV.

Researchers have stated that the gold standard of predicting biological age would be to determine skeletal age by way of radiograph image analysis (Lloyd et al., 2014 & Mills et al., 2017); however, cost, accessibility, and qualified clinicians to evaluate the scans make this method difficult to apply to youth athletics. Therefore, assessments such as growth rate, peak height velocity predictions, and adult stature predictions, can be measured and have become a commonly used assessment to determine biological age of adolescents (Lloyd et al., 2014; Malina et al., 2015; & Mills et al., 2017).

Mirwald et al. (2002) created equations to help predict the age at which an individual would achieve their PHV. The equations have been used in various studies to determine whether a subject is pre-, circa, or post-PHV. If an individual is more than a year less than their predicted PHV age that individual would be pre-PHV. Those individuals more than a year greater than the predicted PHV would be considered post-PHV and the individuals within a year plus or minus of their predicted PHV could be categorized a circa-PHV. Based on this information PHV has become a focus of interest among sport trainers, coaches, and researchers because the youth athletes they work with can all be at different phases of maturation, therefore resulting in the potential need for different training foci, even if they are all grouped under the same chronological age (Lloyd et al., 2014).

Bult et al. (2018) evaluated the impact PHV has on injury rates in a group of adolescent male soccer players, identifying that the subjects had a greater risk of injury as they transitioned out of circa PHV and into post PHV (Bult et al., 2018). These results in turn solidify the importance of determining the growth phase of an adolescent as they are maturing. Researchers in the past have evaluated PHV timing and used it to create long-term athlete development models to help address what adolescents should be focusing on during their growth development phases to help prevent injuries to the growing athletes (Beunen & Malina, 1988; Mirwald et el., 2002; Philippaerts et al., 2006; Rumpf et al., 2012; Lloyd & Oliver, 2012; Lloyd et al., 2014; Lloyd et al., 2015; & Mills et al., 2017).

Previous research has been conducted evaluating the performances of adolescent athletes using CMJ and isokinetic dynamometry (Christou et al., 2006; Marginson & Eaton, 2001; Marius et al., 2006; Morris et al., 2020; Myer et al., 2009; Pääsuke et al., 2001; Secomb et al., 2015). Even though these studies were using athletes categorized as adolescents they were not separated into maturation status. Most of the past research using adolescents also examines training interventions on CMJ and isokinetic dynamometry performances. The rest of the research typically compares youth subjects to adult subjects but does not specify what maturation phases the subjects are in.

The examples of physical changes as well as strength and force production fluctuations based on the growth spurt timing of adolescents throughout maturation highlight the importance of determining PHV. The determination of PHV timing can then help devise training accordingly to prepare the adolescents body for the changes in height and weight prior to the actual increase. The training implications of this timing are imperative to healthy and safe developments for adolescents through their maturation phases. Therefore, using the PHV somatic assessments created by Mirwald et al. (2002), which was evaluated and deemed to be an acceptable formula for PHV measurement in a previous research study (Chapter 6), was used in the current research to evaluate maturation phase effect on testing performance. Using the Mirwald et al. (2002) equation for PHV the aim of this research was to determine if there are any differences in isokinetic knee flexion and extension torques and CMJ performance in adolescent athletes between pre-PHV, circa-PHV and post-PHV may have on. It was hypothesized that the post-PHV athletes will perform better during the CMJ and isokinetic dynamometry testing than the pre- and circa-PHV.

7.3: Methods:

7.3.1: Experimental Approach: A cross-sectional single session research study was completed using adolescent athletes. Based on a previous reliability study (Chapter 4) the following variables were found to be reliable in adolescent athletes (based on ICC and %CV values); jump height, mean propulsion power, peak propulsion power, propulsion impulse, mean propulsion force, peak propulsion force, mean braking force, peak braking force, right and left knee extension (Ext.) and flexion (Flex.) peak torques (PT) at $60°\cdot s^{-1}$, right and left knee extension peak torques at $300°\cdot s^{-1}$. Another 16 variables were calculated based on average and relative values. Relative variables were determined by dividing the above variables by the subject's body weight. Average variables were created for $60°\cdot s^{-1}$ knee extension peak torques for extension and flexion and $300°\cdot s^{-1}$ knee extension peak torques by taking the left and right limb variables and averaging them. Appropriate variables including peak torque, CMJ peak and mean power, impulse and force variables were ratio scaled (absolute value / body mass) to create relative values, to normalize these variables and eliminate the potential increase in strength due to higher body mass. Due to the age differences and therefore weight difference between the subjects of this study of the individuals were only evaluated based on the relative values (ratio scaled) unless it was not appropriate to ratio scale the variable (e.g., jump height).

7.3.2: Subjects: Healthy youth athletes ranging from 13 to 18 years (n = 27, mean ± SD: age: 15.1 ± 1.8 years, height: 171.3 ± 10.4 cm, mass: 60.4 ± 10.9 kg) volunteered to participate in this study. Initially 64 subjects were recruited, but only the males were selected from the original cohort because none of the females tested fell into either pre-PHV or circa-PHV categories. The boys tested included 18 multi-sport athletes and 9 single sport athletes participating in 10 different sports (soccer, volleyball, athletics, lacrosse, basketball, baseball, football, tennis, swimming/diving, hockey and wrestling). The 3 pre-PHV subjects (mean ± SD: age: 13.3 ± 0.6 years, maturity offset: -1.2 years ± 0.2, height: 155.1 ± 3.5 cm, mass: 48.7 ± 9.4 kg) were all multi-sport athletes participating in soccer, basketball, baseball, football and swimming/diving. The 9 circa-PHV subjects (mean ± SD: age: 13.4 ± 0.7 years, maturity offset: -0.08 ± 0.7 years, height: 166.5 ± 8.4 cm, mass: 52.3 ± 7.8 kg) were all multi-sport athletes participating in soccer, volleyball, athletics, basketball, baseball, football, tennis, swimming/diving and wrestling. The 15 post-PHV subjects (mean ± SD: age: 16.6 ± 0.8 years, maturity offset: 2.3 years ± 0.5, height: 176.8 ± 7.7 cm, mass: 66.5 ± 8.1 kg) had 6 multi-sport athletes and 9 single sport athletes participating in soccer, volleyball, athletics, lacrosse, basketball, baseball, football, tennis, and hockey. All subjects and their guardians signed the informed consent and parental assent forms as appropriate, and the study received ethical approval from both the University of Salford and the State University of New York at Upstate Medical University research ethics committees. All subjects were instructed to maintain their regular training practices during the experiment but asked to not participate in any vigorous physical activity 24 hours prior to their testing session.

7.3.3: Procedures: Subjects were tested in one 45-minutes testing session.

7.3.3.1: Anthropometric: Height, sitting height, mass and PHV were all collected for this study. Refer to Chapter 3: Section 3.1 for more details on how these measurements were acquired.

7.3.3.2: Countermovement Jumps: After a 3-minute warm up on a cycle ergometer and 5-minute lower limb dynamic stretching the subjects completed 3 CMJ. The subjects were instructed to place their hands on the hips and not use them in their jumping movement. The subjects were also instructed that the squat depth was at their discretion, and they were told to jump as high as possible. Once the subjects stepped on the force plate, they stood still for one second to record weight and then were then instructed to jump. The subject then repeated the jump two more times with 30 second rest between each jump. Briefly, data was analyzed using a forward dynamics approach with jump height calculated from velocity of center of mass at take-off (See Chapter 3, Section 3.3 for more detail).

7.3.3.3: Isokinetic Dynamometry: The subjects then completed the isokinetic testing. The subjects performed 3 warmup repetitions at 50% effort prior to each of the different angular velocities on each leg. The subjects then completed one set of 5 repetitions at $60°\cdot s^{-1}$. The subject was then given a minute-long rest and then completed 5 repetitions at $300°\cdot s^{-1}$ test after their warm-up repetitions. Then the machine was reconfigured, and the subject completed the same testing sequence for their left leg. While performing the testing the subjects were given encouragement by the researchers. For more in depth methodology refer to Chapter 3: Section 3.4.

7.3.4: Statistical Analyses: All statistical analyses were performed using IBM SPSS Statistics version 26 and Estimation Stats (www.estimationstats.com). The male subjects were separated into their PHV category (pre, circa or post). All variables and groups were first analyzed for normality to determine the distribution of the data. If the variable for pre, circa and post PHV were found to be normally distributed a one-way ANOVA was performed with a Bonferroni post hoc analysis ($p < 0.05$), with Hedges *g* effect size calculations used to determine the magnitude of any differences between groups. Hedges *g* were considered trivial (< 0.19), small (0.20 – 0.59), moderate (0.60 – 1.19), large (1.20 – 1.99), and very large (2.0 – 4.0) in line with previous recommendations (Hopkins, 2002). The effect sizes and the associated 95% confidence intervals were considered the most appropriate way to interpret the differences, based on the low sample size in the pre-PHV group and the unequal group sizes (Cumming et al., 2007; Lakens, 2013). A conservative post-hoc was used (Bonferroni) to minimize the chances of a Type 1 error, effect sizes were used to determine whether differences between the pre-, circa-, and post-PHV subjects were meaningful if not significant, especially where the sample sizes were low. If the variable was not normally distributed the Kruskal-Wallis H test was performed ($p < 0.05$). If there was a significant difference between PHV phases during testing (Pre, Circa or Post) then Mann-Whitney tests were performed for the non-normalized data to determine what groups showed the significant difference based on PHV timing.

7.4: Results:

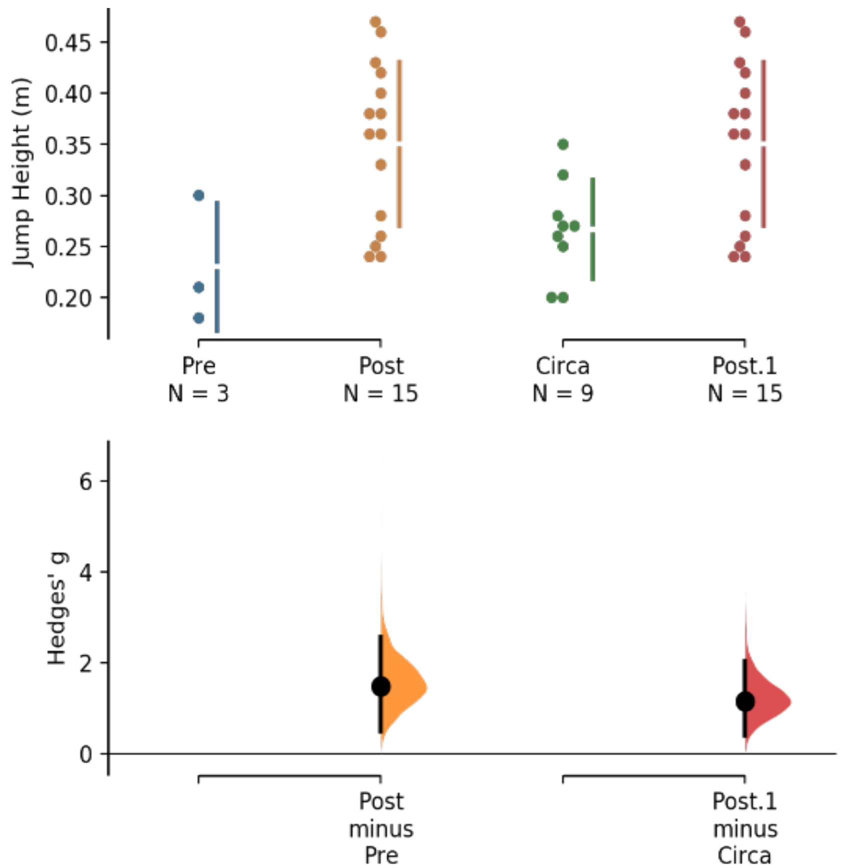
Once divided based on maturation there were 3 pre-PHV (age: 13.3 ± 0.6 years; maturity offset: -1.2 years; height: 155.1 ± 3.5 cm; mass: 48.7 ± 9.4 kg), 9 circa-PHV (age: 13.3 ± 0.7 years; maturity offset: -0.08 years; height: 167.5 ± 8.5 cm; mass: 54.0 ± 8.9 kg) and 15 post-PHV (age: 16.6 ± 0.8 years; maturity offset: 2.3 years; height: 176.8 ± 7.7 cm; mass: 66.5 ± 8.1 kg) subjects. For the countermovement jump analysis three (relative peak propulsion force, relative mean braking force, relative peak braking force) of the eight variables were not significantly different ($p > 0.05$) between the groups (Table 7.4.1). Most of the variables between pre-PHV and circa-PHV were found to show no significant ($p > 0.05$) or meaningful ($g < 0.6$) differences. Jump height and relative propulsive impulse were not significant ($p > 0.05$) but did show a moderate effect size ($g = 0.603$-0.651) (Table 7.4.1) with circa-PHV outperforming pre-PHV. Post-PHV were significantly ($p < 0.05$) and meaningfully ($g > 1.15$) greater than pre-PHV and circa-PHV for jump height (Table 7.4.1, Figure 7.4.1a), relative peak propulsion power (Table 7.4.1, Figure 7.4.1c) and relative propulsion impulse (Table 7.4.1,

Figure 7.4.1d). Post-PHV were significantly ($p < 0.05$) and meaningfully (g > 0.796) greater than only the circa-PHV group for relative mean propulsion power (Table 7.4.1, Figure 7.4.1b) and relative mean propulsion force (Table 7.4.1, Figure 7.4.1e) variables. These two variables (mean propulsion power and relative mean propulsion force) showed that post-PHV were meaningfully (g > 0.823) but not significantly ($p > 0.05$) greater than the pre-PHV group (Table 7.4.1).

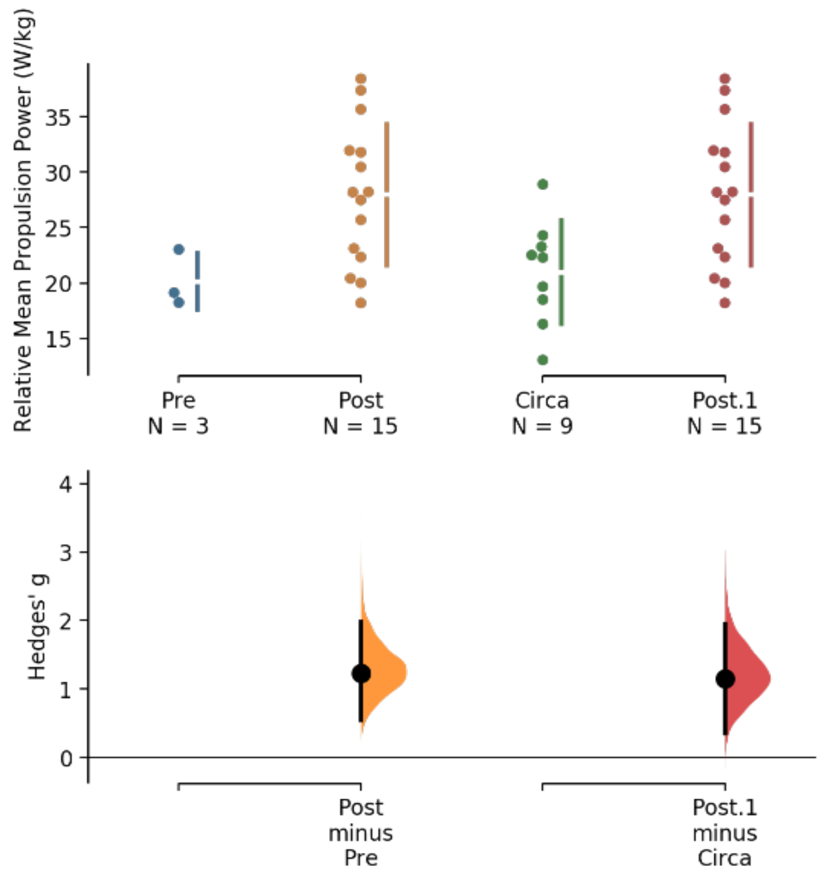
Table 7.4.1: Comparisons in countermovement jump performance between pre-, circa- and post-peak height velocity

					Pairwise Comparisons		
Variable	**Pre (mean ± SD)**	**Circa (mean ± SD)**	**Post (mean ± SD)**	***ANOVA p - value***	***Pre vs. Circa***	***Circa vs. Post***	***Pre vs. Post***
Jump Height (m)	0.23 ± 0.06	0.27 ± 0.05	0.35 ± 0.08	0.007	*p* = 1.000; g = 0.651	*p* = 0.026; g = 1.15	*p* = 0.035; g = 1.47
Relative Mean Propulsion Power (W·kg^{-1})	20.13 ± 2.55	20.98 ± 4.68	27.96 ± 6.38	0.011	*p* = 1.000; g = 0.180	*p* = 0.021; g = 1.16	*p* = 0.113; g = 1.23
Relative Peak Propulsion Power (W·kg^{-1})	38.92 ± 6.76	42.94 ± 6.58	53.01 ± 8.98	0.005	*p* = 1.000; g = 0.561	*p* = 0.021; g = 1.19	*p* = 0.033; g = 1.54
Relative Propulsive Impulse (Ns·kg^{-1})	2.12 ± 0.28	2.27 ± 0.22	2.61 ± 0.30	0.006	*p* = 1.000; g = 0.603	*p* = 0.026; g = 1.16	*p* = 0.031; g = 1.54
Relative Mean Propulsion Force* (N·kg^{-1})	17.14 ± 0.87	17.07 ± 2.48	19.40 ± 2.87	0.030*	*p* = 0.482; g = -0.030	*p* = 0.021; g = 0.796	*p* = 0.076; g = 0.823
Relative Peak Propulsion Force* (N·kg^{-1})	20.43 ± 1.34	21.77 ± 3.89	23.66 ± 3.65	0.084*	N/A	N/A	N/A
Relative Mean Braking Force* (N·kg^{-1})	14.15 ± 0.16	13.91 ± 1.94	15.33 ± 2.60	0.579*	N/A	N/A	N/A
Relative Peak Braking Force (N·kg^{-1})	18.21 ± 0.35	17.85 ± 2.87	21.22 ± 4.17	0.081	N/A	N/A	N/A
*Represents Kruskal - Wallis Non-Parametric Analysis							
Green = Significant AND Meaningful; Yellow = Meaningful but NOT Significant; Red = Not Significant OR Meaningful							

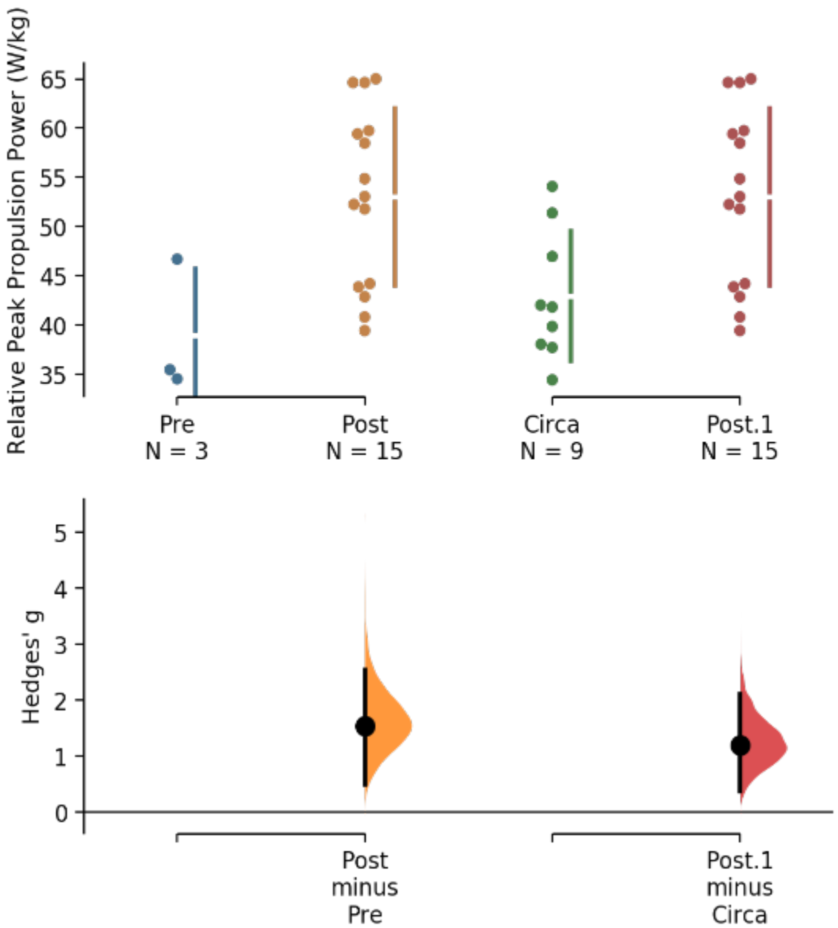
a)


Jump Height (m)
0.45
0.40
0.35
0.30
0.25
0.20
Pre
N = 3
Post
N = 15
Circa
N = 9
Post.1
N = 15
Hedges' g
6
4
2
0
Post
minus
Pre
Post.1
minus
Circa

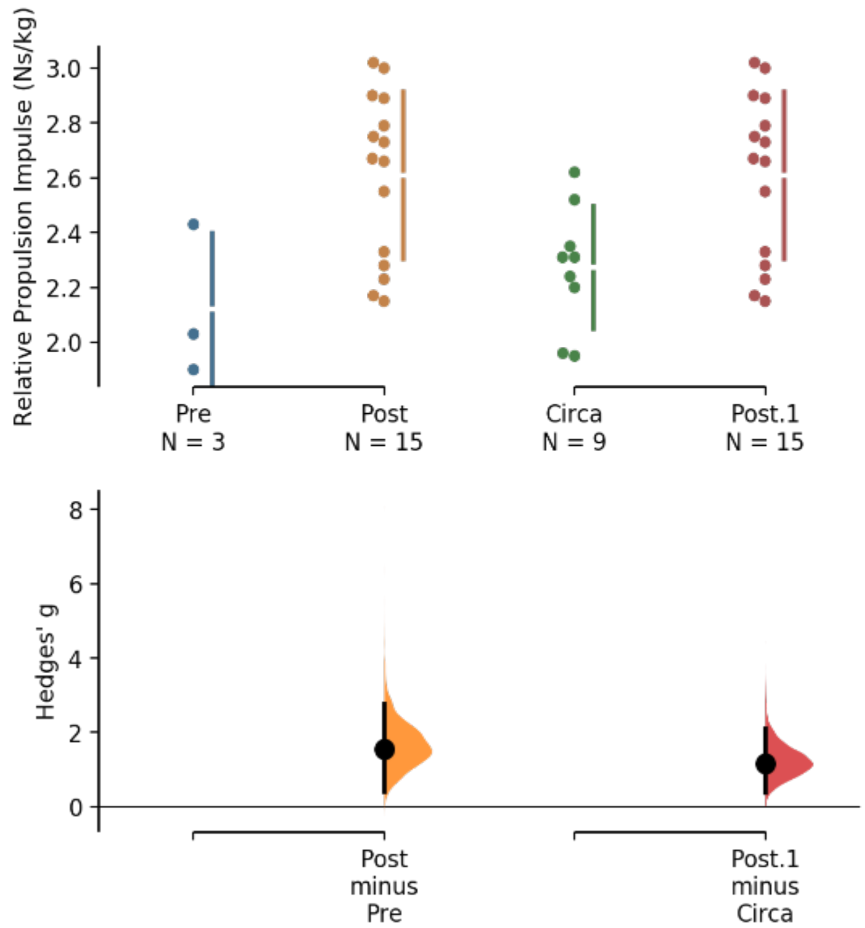
b)


Relative Mean Propulsion Power (W/kg)
35
30
25
20
15
Pre
N = 3
Post
N = 15
Circa
N = 9
Post.1
N = 15
Hedges' g
4
3
2
1
0
Post
minus
Pre
Post.1
minus
Circa

c)


Relative Peak Propulsion Power (W/kg)
65
60
55
50
45
40
35
Pre
N = 3
Post
N = 15
Circa
N = 9
Post.1
N = 15
Hedges' g
5
4
3
2
1
0
Post
minus
Pre
Post.1
minus
Circa

d)


Relative Propulsion Impulse (Ns/kg)
3.0
2.8
2.6
2.4
2.2
2.0
Pre
N = 3
Post
N = 15
Circa
N = 9
Post.1
N = 15
Hedges' g
8
6
4
2
0
Post
minus
Pre
Post.1
minus
Circa

e)

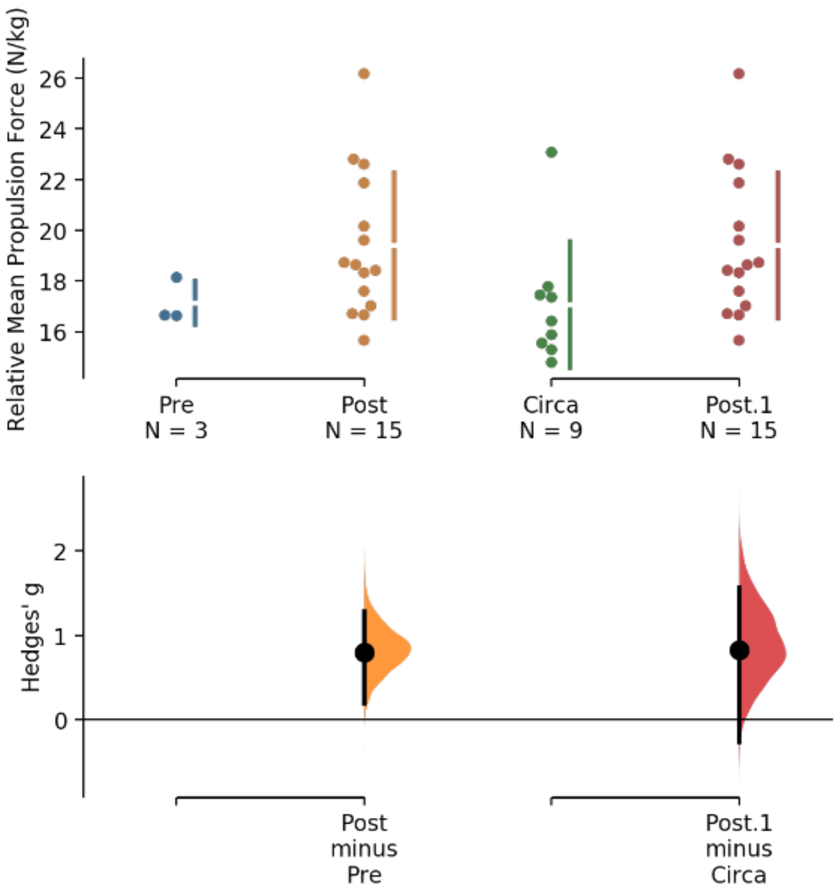


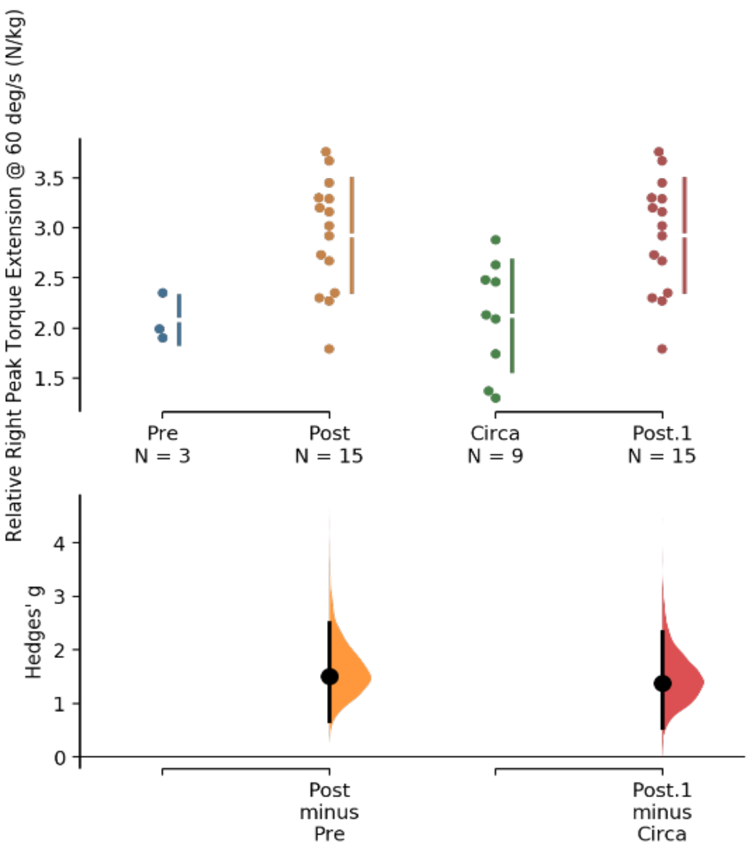
Figure 7.4.1: Comparisons in Countermovement Jump Variables between Groups – a) Jump Height, b) Relative Mean Propulsion Power, c) Relative Peak Propulsion Power, d) Relative Propulsion Impulse and e) Relative Mean Propulsion Force

The isokinetic peak torque analysis resulted in three (right and left leg relative knee extension peak torques, and relative average knee extension peak torques at $300°\cdot s^{-1}$) of the nine variables were not significantly different ($p > 0.05$) between groups (Table 7.4.2). Significant differences ($p < 0.05$) were only observed between pre-PHV and post-PHV as well as circa-PHV and post-PHV. No significant ($p > 0.05$) or meaningful ($g < 0.6$) differences were found between pre-PHV and circa-PHV except for relative right knee flexion peak torque at $60°\cdot s^{-1}$ which resulted in moderate ($g = 0.606$) but not significant ($p > 0.05$) differences with circa-PHV subjects performing better than the pre-PHV subjects. With this one variable the circa-PHV group meaningfully outperformed the pre-PHV group. Post-PHV was significantly ($p < 0.05$) greater and had moderate to very large effect sizes than pre-PHV and circa-PHV groups for relative right and left knee extension peak torque at $60°\cdot s^{-1}$ (Table 7.4.2, Figures 7.4.2a & 7.4.2b), relative right and left knee flexion peak torque at $60°\cdot s^{-1}$ (Table 7.4.2, Figures 7.4.2c & 7.4.2d) and relative average knee extension and flexion peak torque at $60°\cdot s^{-1}$ (Table 7.4.2, Figures 7.4.2e & 7.4.2f).

Table 7.4.2: Comparisons of isokinetic performance between pre-, circa- and post-peak height velocity

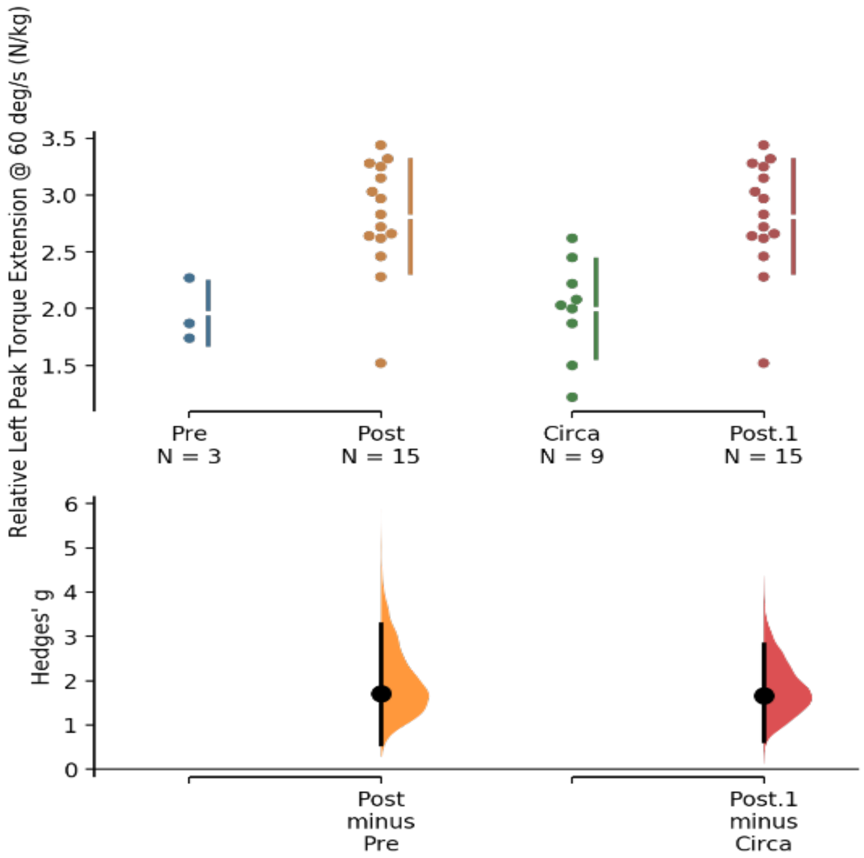
					Pairwise Comparisons		
Variable	**Pre (mean ± SD)**	**Circa (mean ± SD)**	**Post (mean ± SD)**	***ANOVA p* - value**	***Pre vs. Circa***	***Circa vs. Post***	***Pre vs. Post***
Relative Right Knee Extension Peak Torque at 60°·s^{-1} (N·kg^{-1})	2.08 ± 0.24	2.12 ± 0.55	2.93 ± 0.57	0.003	*p* =1.000; g = 0.073	*p* = 0.005; g = 1.38	*p* = 0.064; g = 1.50
Relative Left Knee Extension Peak Torque at 60°·s^{-1} (N·kg^{-1})	1.96 ± 0.28	2.00 ± 0.44	2.81 ± 0.49	0.000	*p* = 1.000; g = 0.088	*p* = 0.001; g = 1.65	*p* = 0.022; g = 1.71
Relative Right Knee Flexion Peak Torque at 60°·s^{-1} (N·kg^{-1})	1.22 ± 0.20	1.39 ± 0.28	1.67 ± 0.28	0.014	*p* = 1.000; g = 0.606	*p* = 0.069; g = 0.967	*p* = 0.044; g = 1.60
Relative Left Knee Flexion Peak Torque at 60°·s^{-1} (N·kg^{-1})	1.25 ± 0.26	1.37 ± 0.25	1.64 ± 0.29	0.026	*p* = 1.000; g = 0.455	*p* = 0.084; g = 0.946	*p* = 0.098; g = 1.31
Relative Right Knee Extension Peak Torque at 300°·s^{-1} (N·kg^{-1})	1.22 ± 0.18	1.25 ± 0.22	1.47 ± 0.29	0.102	N/A	N/A	N/A
Relative Left Knee Extension Peak Torque at 300°·s^{-1} (N·kg^{-1})	1.02 ± 0.02	1.23 ± 0.30	1.36 ± 0.41	0.306	N/A	N/A	N/A
Relative Average Knee Extension Peak Torque at 60°·s^{-1} (N·kg^{-1})	2.02 ± 0.26	2.06 ± 0.46	2.87 ± 0.51	0.001	*p* = 1.000; g = 0.086	*p* = 0.002; g = 1.58	*p* = 0.029; g = 1.67
Relative Average Knee Flexion Peak Torque at 60°·s^{-1} (N·kg^{-1})	1.23 ± 0.22	1.38 ± 0.26	1.66 ± 0.28	0.016	*p* = 1.000; g = 0.548	*p* = 0.065; g = 0.984	*p* = 0.056; g = 1.50
Relative Average Knee Extension Peak Torque at 300°·s^{-1} (N·kg^{-1})	1.12 ± 0.10	1.24 ± 0.22	1.42 ± 0.34	0.177	N/A	N/A	N/A
Green = Significant AND Meaningful; Yellow = Meaningful but NOT Significant; Red = Not Significant OR Meaningful							

a)



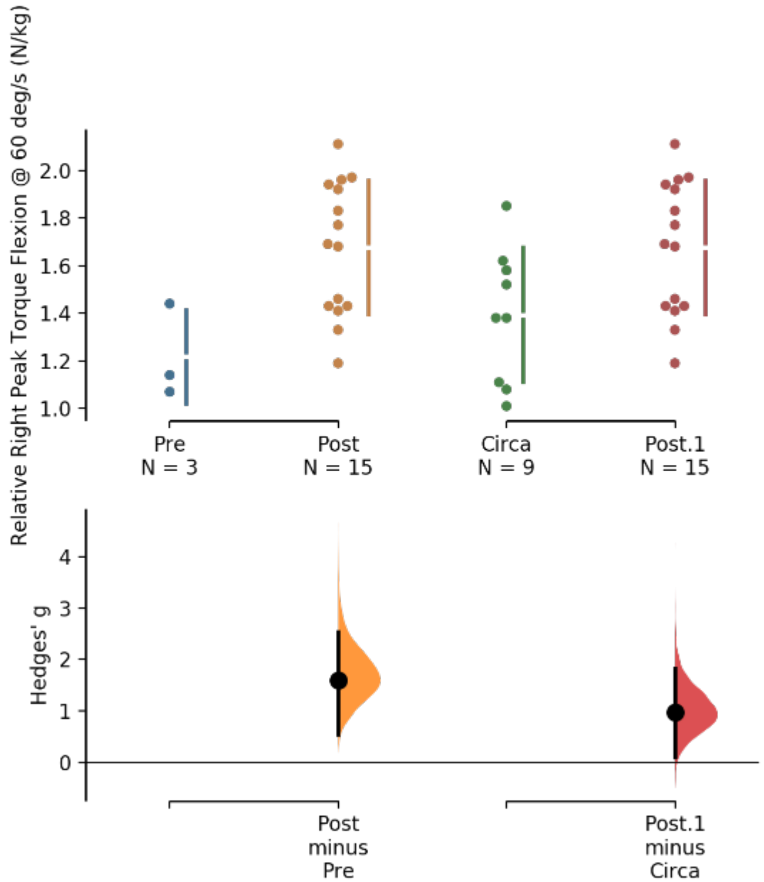
Relative Right Peak Torque Extension @ 60 deg/s (N/kg)
3.5
3.0
2.5
2.0
1.5
Pre
N = 3
Post
N = 15
Circa
N = 9
Post.1
N = 15
Hedges' g
4
3
2
1
0
Post
minus
Pre
Post.1
minus
Circa

b)

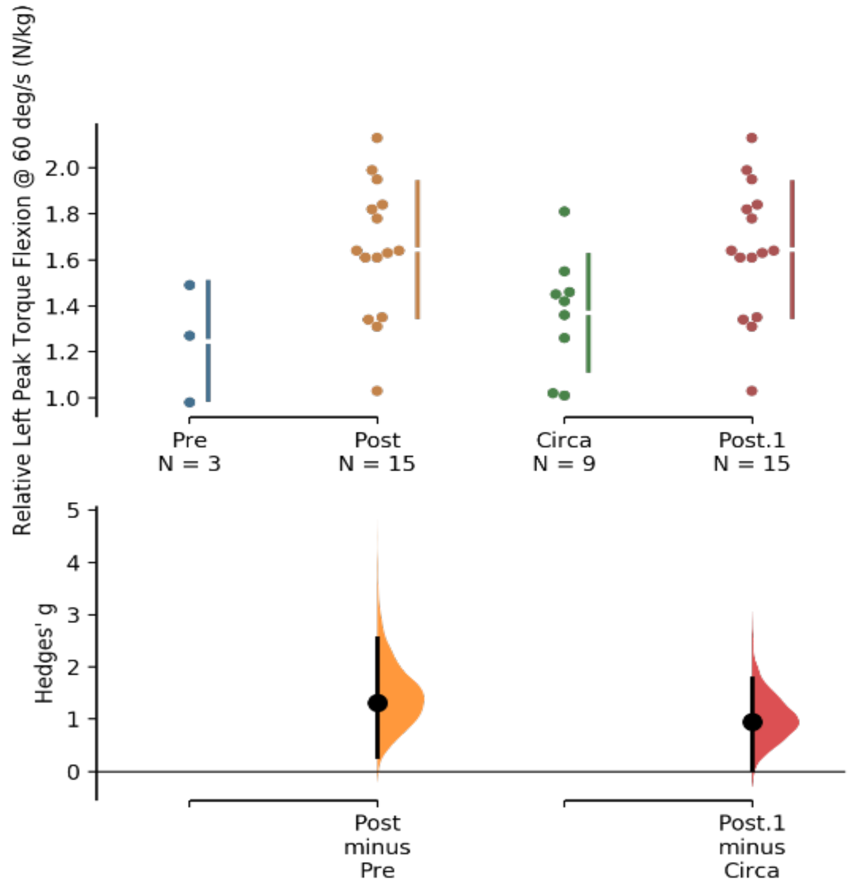


Relative Left Peak Torque Extension @ 60 deg/s (N/kg)
3.5
3.0
2.5
2.0
1.5
Pre
N = 3
Post
N = 15
Circa
N = 9
Post.1
N = 15
Hedges' g
6
5
4
3
2
1
0
Post
minus
Pre
Post.1
minus
Circa

c)


Relative Right Peak Torque Flexion @ 60 deg/s (N/kg)
Pre
N = 3
Post
N = 15
Circa
N = 9
Post.1
N = 15
Hedges' g
Post
minus
Pre
Post.1
minus
Circa

d)


Relative Left Peak Torque Flexion @ 60 deg/s (N/kg)
Pre
N = 3
Post
N = 15
Circa
N = 9
Post.1
N = 15
Hedges' g
Post
minus
Pre
Post.1
minus
Circa

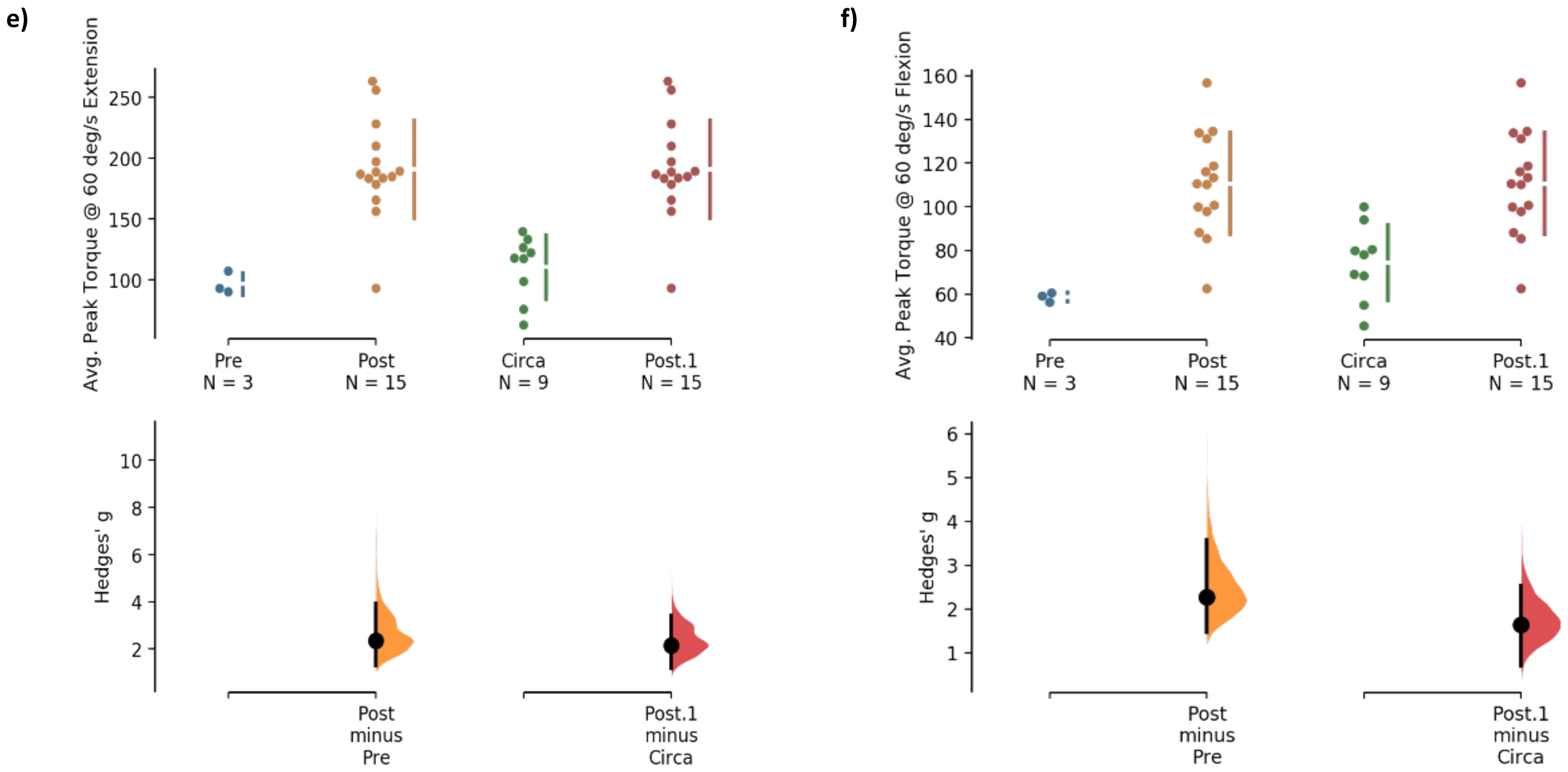


Figure 7.4.2: Comparisons in Countermovement Jump Variables between Groups – a) Relative Right Knee Extension Peak Torque at $60°\cdot s^{-1}$, b) Relative Left Knee Extension Peak Torque at $60°\cdot s^{-1}$, c) Relative Right Knee Flexion Peak Torque at $60°\cdot s^{-1}$, d) Relative Left Knee Flexion Peak Torque at $60°\cdot s^{-1}$, e) Relative Average Knee Extension Peak Torque at $60°\cdot s^{-1}$ and f) Relative Average Knee Flexion Peak Torque at $60°\cdot s^{-}$

7.5: Discussion:

Force production characteristics progressively increase with maturation, based on the greater performances of the post-PHV group compared to pre- and circa-PHV and the higher performances in the circa-PHV group compared to the pre-PHV group. The majority of CMJ and isokinetic knee flexion and extension peak torque variables showed significantly and meaningfully greater performance in post-PHV compared to pre- and circa-PHV groups, in line with the hypotheses. There were no significant ($p > 0.05$) differences between pre-PHV and circa-PHV groups. However, jump height, relative propulsive impulse, and relative right knee flexion peak torque at $60°{\cdot}s^{-1}$ did show circa-PHV outperform the pre-PHV group with a moderately meaningful difference. The circa-PHV group demonstrated moderately greater jump height, relative peak propulsion power and relative right knee flexion peak torque at $60°{\cdot}s^{1}$ compared to the pre-PHV group.

Results from previous studies have shown that there is an increase in force and power production during adolescent growth phases (Beunen & Malina, 1988; Malina et al., 2003; Philippaerts et al., 2005; Towlson et al., 2020). These studies have all evaluated absolute value increases. The consensus of these studies is that when a subject has reached post-PHV their musculoskeletal makeup is similar to those of an adult and therefore the power, force and sport performances of these athletes reflect more similarly to those of an adult athlete (Beunen & Malina, 1988; Malina et al., 2003; Philippaerts et al., 2005; Towlson et al., 2020). However, these researchers evaluated the absolute values of variable measurement, therefore, the results of these increases in strength and power could simply be due to the increase in height, limb length and mass and the impacts those increases have on the biomechanics of producing and rate of producing force. In the current study relative (ratio scaled) data was used to examine the variables without the impact of the subject's mass. This procedure is in line with McMahon et al. (2017) and Morris et al. (2020) whose studies evaluated both absolute and relative values. The results of these two studies showed that there were significant and meaningful differences between the tested groups when absolute values were used. However, when relative values (variables divided by body mass) were calculated and assessed there were less or no significant differences found between the tested groups (McMahon et al., 2017 & Morris et al., 2020). Using relative data McMahon et al. (2017) was also able to narrow down where the senior players were truly able to outperform the academy players during a countermovement jump by using relative data. Their results showed that the senior players had a significantly higher jump height. However, when evaluating the absolute values almost all the measured variables were found to be significantly different. When ratio scaled, only concentric impulse was found to be significantly greater in the senior players compared in the academy players (McMahon et al., 2017). Take-off velocity is determined by taking concentric (propulsive) net impulse divided by body mass. Take-off velocity is used to determine jump height and is why the concentric impulse generation is the main reason why the senior players were able to jump higher than the academy players. Based on the results of this study it is important to use these evaluations on athletes going forward. A coach or trainer would observe that improvement need to be made based on how the player is able to apply force over time and then manipulate and adapt their training to try and improve their performance. Therefore, observing relative data points is an important part of the evaluation of adolescents transitioning in and out of PHV.

Lloyd et al. (2014) observed that the subjects in their study that were categorized in the under 16 age group were all post-PHV and were found to perform significantly better in all the physical performance and functional movement tests than the under 11 and under 13 age groups who were all pre-PHV. This study showed that the post-PHV group of athletes had a significantly greater squat jump height than the pre-PHV athletes. Cummings et al. (2017) also examined the impact of adolescent subject performance testing based on maturation stage. Cumming et al. (2017) evaluated CMJ testing found that a subject could perform above average in comparison with other subjects of the same chronological age but when that same subject is placed and evaluated among athletes of the same maturation stage their performance was at an average or below average rate. Lloyd et al. (2014) suggests that this time period post-PHV is a natural occurring time for accelerated development and could be used as an opportune moment to improve an individual's performances. Even though the results of this study were based on absolute values and not ratio scaled variables; the results were still in line with the results of the current study. Based on the studies by Cummings et al. (2017), Lloyd et al. (2014) and the current research study it can be stated that there are significant and meaningful differences in performance based on the stage in which an adolescent is in their maturation timing. If a subject is pre- or circa- PHV then they are more likely to have lower force, power and torque outputs while performing CMJ and isokinetic dynamometer testing. Therefore, coaches, trainers and athletes should all be aware of the timing of the specific athletes PHV to ensure the best training practices are being met to help the athlete succeed.

Jump height, relative mean propulsion power, relative peak propulsion power, relative propulsion impulse and relative mean propulsion force were significantly and meaningfully greater in post-PHV individuals compared to pre- and circa-PHV. Based on the biomechanics of a CMJ when an individual has an increase in mass they must produce greater impulse (force × time) to achieve the same jump height as a lighter individual. Therefore, when an adolescent grows and has a greater mass they need to produce a greater propulsion force in order to generate a similar or greater propulsion impulse, without the propulsion duration increasing. The results of this study show that the post-PHV subjects were able to generate greater relative mean propulsion force even though they weighed more than the pre- and circa- PHV subjects. This greater relative mean propulsion force would result in a greater relative propulsion impulse and therefore a greater take-off velocity. Due to the greater jump height, caused by greater take-off velocity, and a greater mean propulsion force the subject can generate greater power during their CMJ of there are no substantial changes to the amount of time the jump takes. The current study evaluated the relative variables of the CMJ to observe the differences in performance without the impact of the mass of an individual. This breakdown enables the researchers to observe the changes in force and power between different individuals during different stages of development and growth by taking out the influences of body mass (McMahon et al., 2017; Morris et al., 2020). The results of the CMJ showed a greater mean force generation via triple extension (hip, knee and ankle joints), with a similarly greater force production was also observed in the isokinetic testing with the observation of significant increases in relative right and left knee extension peak torque at $60º·s^{-1}$, relative right and left knee flexion peak torque at $60º·s^{-1}$ and relative average knee extension and flexion peak torque at $60º·s^{-1}$.These variables showed moderate to strong correlations in Chapter 5 of this research and therefore, reiterate the relationships that are found between CMJ and isokinetic dynamometer testing outputs.

The results of this study indicate that the post-PHV individuals can generate higher relative forces and therefore impulse and power during the propulsion phase of their CMJ than the pre- and circa-PHV groups. They are also shown to produce greater peak torque about the knee joint during their isokinetic testing. Therefore, it is important for coaches, trainers and athletes to understand that the transition phase through and out of PHV can have an impact on performance and that the subjects should be trained through this phase of maturation.

7.5.1: Limitations and Areas of Future Research

Sample size is the greatest limitation of this study. For the males only three subjects were pre-PHV, while the female data was excluded from the study as no female subjects were classified as pre or circa-PHV. Based on the sample sizes of the groups Hedges' g was calculated to account for this limitation. The use of Hedges' g allowed for the evaluation of meaningfulness as an addition to null hypotheses significance testing to create a stronger result (Cumming et al., 2007; Lakens, 2013). Therefore, even though 3 subjects is a small sample, the calculation of effect sizes and the associated 95%CI removes the issues associated with null hypothesis significance testing with low sample sizes and therefore allows for it to be included. Younger subjects were encouraged to participate in the study, but recruitment was difficult, and the younger subjects needed to have a parent willing to transport them to the tasting facility since they were not able to drive themselves. Moreover, due to the COVID-19 pandemic, it was not possible to continue additional data collection. A greater number of subjects in each of the PHV groups would however present stronger evidence moving forward. Therefore, future research should be done to solidify the findings found in this study with a sample size of subjects that are more evenly distributed throughout the PHV timing for both male and female adolescent athletes.

7.5.2: Conclusion

In conclusion, the results indicate that as an adolescent athlete that is post-PHV can generate greater relative forces, power and impulse while performing a CMJ, which explains the higher jump heights, as well as greater relative peak torque about their knee joint while performing isokinetic testing. The current results and that of previous studies highlight the need for coaches, trainers and athletes to be aware of their maturation stages as they transition from one stage of PHV to the next (Beunen & Malina, 1988; Malina et al., 2003; Philippaerts et al., 2005; Towlson et al., 2020), but more importantly, the need to increase relative force production to assist with continued increases in performance irrespective of increases in body mass.

Transition from Chapter 7 to Chapter 8

The results of Chapter 7 illustrate that post-PHV subjects performed better while testing for force, power and torque production compared to the subjects identified as pre, circa-PHV. Since there were output differences found between the subjects that were pre, circa and post-PHV it was decided that further comparisons should be made to determine if they are differences when subjects are categorized as average or late maturers as well. For this study there were no subjects categorized as early maturers because it would most likely occur in a male subject around 12-13 years of age which was younger than the age of the subjects tested for this thesis. It is important to determine whether late maturing subjects who may reach PHV as much as a year or two after other individuals to see if these subjects eventually “catch up” to the average maturers in relationship to performance output. Since current sport categorizations typically are based on age late maturers may be left behind or drop out simply because they have not reached their PHV and are physically weaker than subjects of the same age who have transitioned through PHV earlier than they have. This was an important question because you could have three 13-year old boys and one could be pre, one could be circa, and one could be post PHV and chapter 7 showed that these three boys would be performing at different levels. Therefore, a late maturer may be left behind because they are not doing as well as others that are farther along in the PHV journey. However, the purpose of this chapter is to see if they eventually “catch up” and perform just as well as the early and average maturers then there needs to be ways to keep them involved in sport until they can perform at the same level. Till et al. (2016) discuss that if later maturers can stick with the program and physically catch up to the early and average maturers it may be advantageous because in order to make up for physical discrepancies they have learned to have better technical, tactical and psychological skills to continue to succeed. Therefore, it is important to know if a physical catch up does occur in order to help bring those that may be physically weaker through their maturation for them to succeed once they have gone through their PHV.

Chapter 8: A Comparison of Isokinetic Peak Torque and Countermovement Jump Performance between Athletes of Different Peak Height Velocity Stages – Part B – Consideration for Average and Late Maturers

8.1: Abstract: The aims of this study were to compare performances in the countermovement jump (CMJ) and isokinetic knee flexion and extension torque between average or late maturing adolescent athletes. *Methods:* Subjects: total: n = 53, (mean ± SD) age: 15.5 ± 1.5 years, height: 169.1 ± 7.7 cm, mass: 61.8 ± 8.9 kg; average maturers: n = 38, (mean ± SD) age: 14.9 ± 1.4 years, maturity offset: 2.4 ± 0.76, height: 171.3 ± 7.7 cm, mass: 63.5 ± 9.8 kg; late maturers: n= 15, (mean ± SD) age: 16.6 ± 0.8 years, maturity offset: 3.11 ± 0.77, height: 165.0 ± 5.9 cm, mass: 58.9 ± 6.2 kg. These subjects completed a 3-minute warm up on a cycle ergometer followed by some dynamic stretching. Subjects then performed 3 CMJs and concentric isokinetic assessment of the knee flexors and extensors at $60°\cdot s^{-1}$ and $300°\cdot s^{-1}$ to determine peak torque. *Results:* There were no significant (p>0.05) or meaningful (g ≤ 0.568) differences between the average and late maturers. *Conclusion:* In conclusion the results of this study show the importance of supporting an athlete through their entire growth phase. If an athlete is a late maturer they may be left behind or lose a spot on a team that is based on age because they cannot keep up with or are physically weaker than adolescents that hit their PHV at an earlier age, however, they appear to catch up post maturation.

8.2: Introduction:

When evaluating physical performance of adolescent athletes, it is important to understand their physical development and maturation phase. Due to the muscular development, and the associated force production characteristics, can be influenced by maturation (Philippaerts et al., 2006). As an adolescent progresses through their growth spurt, known as the period of peak height velocity (PHV) their height increases with an associated increase in limb length. This period of PHV has been associated with a term known as adolescent awkwardness where an adolescent may have delays or regressions in sensorimotor functions (Quatman-Yates et al., 2012). This increase in limb length associated with PHV causes a longer moment arm and will have an impact on the individuals torque production (Philippaerts et al., 2006). Based on how an individual's muscles develop during the period of PHV may influence their physical performance due to the rapid increase in limb length (Bult et al., 2018). Therefore, laboratory testing such as countermovement jumps (CMJ) and isokinetic dynamometry that shows an individuals' force production capability and torque production abilities throughout PHV would be evaluations that can help determine the impacts on physical performance during that subjects PHV.

Mirwald et al. (2002) gave an example of two adolescent boys who at pre peak height velocity and post peak height velocity had nearly identical heights and weights to one another. These individuals, however, reach PHV two years apart from one another. This difference in maturation phase at different ages has an impact on what training and physical abilities different adolescents will have throughout the PHV journey (Mirwald et al., 2002 & Lloyd et al., 2015). Therefore, when evaluating adolescents, it is important to determine the growth phase of an individual at their specific time of testing. Using PHV researchers in the past have evaluated maturation timing and used it to create long-term athlete development models to help address what adolescents should be focusing on during their growth development phases (Beunen & Malina, 1988; Mirwald et el., 2002; Philippaerts et al., 2006; Rumpf et al., 2012; Lloyd & Oliver, 2012; Lloyd et al., 2014; Lloyd et al., 2015; Mills et al., 2017).

Based on the Mirwald et al. (2002) example above, it is observed that adolescents can reach their PHV at an earlier age, at an average age or at a later age. The period of PHV is the time in which an adolescent has their growth spurt and is growing at the fastest rate (Beunen & Malina, 1988). For average maturers, males typically reach PHV at ~14 years of age and females at ~12 years (Sherar et al., 2005). However, not all adolescents mature at the same rate, with some reaching their PHV earlier or later in comparison to average maturers age. Early maturers would be classified as adolescents that reach PHV ≤ 1 year before the average maturer for their sex, whereas a late maturer would reach PHV ≥ 1 year after the average for their sex (Sherar et al., 2005). Based on this information PHV has become a focus of interest among sport trainers, coaches, and researchers because the youth athletes they work with can all be at different phases of maturation, therefore resulting in the potential need for different training foci, even if they are all grouped under the same chronological age (Lloyd et al., 2014).

Understanding potential maturation phase impact of adolescent muscle development is imperative because in the past almost all adolescents competing in sport have been categorized by age group. Age categorization is currently a debated subject because it does not account for physical development, but it is the simplest way to separate adolescents for sport. However, researchers have started to recently consider bio-banding, which groups athletes by their maturation status and not their chronological age (Cumming et al., 2017). To be able to classify and separate children into their bio-banding group an individuals' maturation stage needs to be calculated. Researchers have stated that the gold standard of predicting biological age would be to determine skeletal age by way of radiograph image analysis (Lloyd et al., 2014 & Mills et al., 2017); however, cost, accessibility, and qualified clinicians to evaluate the scans make this method difficult to apply to youth athletics. Therefore, given the previous information somatic assessments, such as growth rate, peak height velocity predictions and adult stature predictions, can be measured and determined on any given day have become a commonly used assessment to determine biological age of adolescents (Lloyd et al., 2014; Malina et al., 2015; Mills et al., 2017). This ability to separate athletes based on maturation phase verses age could help with missing potential athletes who are later maturers and may need a little longer to fully develop but get left out due to their smaller stature when grouped by their chronological age (Carling et al., 2012).

Hägg and Taranger (1991) and Till et al. (2017) performed studies that both evaluated the impact of PVH timing and what impacts being an early, average, or late maturer has on adolescents. These studies both found that the late maturers physically catch up to their early and average counterpart in height and weight measurements once they transition into post PHV (Hägg & Taranger, 1991 and Till et al., 2017). These results express the importance of determining and observing adolescents as they transition through PHV and reiterates the importance of the potential for categorizing youth sports by bio-banding based on maturation and not chronological age like Cummings et al. (2017) has proposed.

The timing of when a child progresses through the growth spurt can greatly impact their participation in sport. Therefore, since different individuals can reach PHV at different ages of adolescents it is important to know how being an early, average, or late maturer affects the development of an individual's physical performances. Therefore, using the PHV somatic assessments created by Mirwald et al. (2002), which was evaluated and deemed to be an acceptable formula for PHV measurement in a previous research study (Chapter 6), will be used in the current research to evaluate maturation phase effect on testing performance. Using the Mirwald et al. (2002) equation for PHV, the aim of this research was to examine the differences average and late maturation timing on isokinetic knee flexion and extension torques and CMJ performance. Due to the results of Part A of this study it was concluded that all subjects should be within their post-PHV phase since there were significant and meaningful differences between pre-PHV and circa-PHV with post-PHV performances. Also, based on findings of McMahon et al. (2017) and Morris et al. (2020), that body mass impacts CMJ performance, highlighting the importance of ratio scaling, ratio scaling (absolute value/body mass) was conducted to better compare the subjects. The aim of this study was to compare CMJ performance and isokinetic strength between average maturers and late maturers who were all post-PHV subjects. Instead of examining the impacts of what phase of maturation (pre, circa or post) a subject is in, this study will address how being an average or late maturer impacts performance output. Therefore, based on these previous studies it was hypothesized that there would be no significant or meaningful differences between average and late maturers while performing isokinetic peak torque and CMJ tests.

8.3: Methods:

8.3.1: Experimental Approach: A cross-sectional single session research study was completed using adolescent athletes. Based on a previous reliability study (Chapter 4) the following variables were found to be reliable in adolescent athletes (based on ICC and % CV values); jump height, mean propulsion power, peak propulsion power, propulsion impulse, mean propulsion force, peak propulsion force, mean braking force, peak braking force, right and left knee extension (Ext.) and flexion (Flex.) peak torques (PT) at $60°\cdot s^{-1}$, right and left knee extension peak torques at $300°\cdot s^{-1}$. Another 16 variables were calculated based on average and relative values. Knee extension peak torques for extension and flexion at $60°\cdot s^{-1}$ and knee extension peak torques at $300°\cdot s^{-1}$ were averaged across left and right limbs. Peak torque, CMJ peak and mean power, impulse and force variables were ratio scaled (absolute value / body mass) to create relative values, to normalize these variables and eliminate the potential increase in strength due to higher body mass. Due to the age differences and therefore mass difference between the subjects of this study of the individuals were only evaluated based on the relative values (ratio scaled) unless it was a variable that could not be ratio scaled (jump height).

8.3.2: Subjects: Healthy male and female youth athletes ranging from 13 to 18 years (n = 53, mean ± SD: age: 15.5 ± 1.5 years, height: 169.1 ± 7.7 cm, mass: 61.8 ± 8.9 kg) volunteered to participate in this study. The average maturing athletes (n = 38, mean ± SD: age: 14.9 ± 1.4 years, maturity offset: 2.4 ± 0.76, height: 171.3 ± 7.7 cm, mass: 63.5 ± 9.8 kg) consisted of 14 multi-sport athletes and 5 single sport athletes participating in soccer, volleyball, athletics, lacrosse, basketball, baseball/softball, football, and dance. Where the late maturing athletes (n = 15 mean ± SD: age: 16.6 ± 0.8 years, maturity offset: 3.11 ± 0.77, height: 165.0 ± 5.9 cm, mass: 58.9 ± 6.2 kg) consisted of 26 multi-sport athletes and 3 single sport athletes participating in soccer, volleyball, athletics, lacrosse, basketball, baseball/softball, football tennis, horseback riding, hockey, golf, dance and gymnastics All subjects and their guardians signed the informed consent and parental assent forms as appropriate, and the study received ethical approval from both the University of Salford and the State University of New York at Upstate Medical University research ethics committees. All subjects were middle or high school athletes (equivalent to primary or junior in the UK) without any known lower limb injuries. Subjects were instructed to maintain their regular training practices during the experiment but asked to not participate in any vigorous physical activity 24 hours prior to their testing session.

8.3.3: Procedures: Subjects were tested in one 45-minutes testing session.

8.3.3.1: Anthropometric: Height, sitting height, mass and PHV were all collected for this study. Refer to Chapter 3: Section 3.1 for more details on how these measurements were acquired.

8.3.3.2: Countermovement Jumps: After a 3-minute warm up on a cycle ergometer and 5-minute lower limb dynamic stretching the subjects completed 3 CMJ. The subjects were instructed to place their hands on the hips and not use them in their jumping movement. The subjects were also instructed that the squat depth was at their discretion, and they were told to jump as high as possible. Once the subjects stepped on the force plate, they stood still for one second to record weight and then were then instructed to jump. The subject then repeated the jump two more times with 30 second rest between each jump. Briefly, data was analyzed using a forward dynamics approach with jump height calculated from velocity of center of mass at take-off (See Chapter 3, Section 3.3 for more detail).

8.3.3.3: Isokinetic Dynamometry: The subjects then completed the isokinetic testing. The subjects performed 3 warmup repetitions at 50% effort prior to each of the different angular velocities on each leg. The subjects then completed one set of 5 repetitions at $60°\cdot s^{-1}$. The subject was then given a minute-long rest and then completed 5 repetitions at $300°\cdot s^{-1}$ test after their warm-up repetitions. Then the machine was reconfigured, and the subject completed the same testing sequence for their left leg. While performing the testing the subjects were given encouragement by the researchers. For more in depth methodology refer to Chapter 3: Section 3.4.

8.3.4: Statistical Analyses: All statistical analyses were performed using IBM SPSS Statistics version 26, Estimation Stats and G*Power 3.1.9.7. A statistical power analysis was run to determine sample size using *a priori* alpha level of 0.05 and an effect size of 0.5. Both males and females were evaluated based on the categories of average and late maturers. There was only one subject that was considered an early maturer within the subject pool and therefore they were removed from this evaluation. All variables and groups were first analyzed for normality to determine the distribution of the data. If the variable for average and late PHV were found to be normally distributed an independent samples t-test was performed ($p < 0.05$) and Hedges G effect size calculated. If the Levene's F-value was > 0.05, equal variance was assumed and if the F-value was < 0.05 equal variance was not assumed, and the corresponding *p*-values were recorded. Hedges G was determined to be trivial (< 0.19), small (0.20 – 0.59), moderate (0.60 – 1.19), large (1.20 – 1.99), and very large (2.0 – 4.0) (Hopkins, 2002). If the variable was not normally distributed the Mann-Whitney non-parametric test was performed ($p < 0.05$).

8.4: Results:

Using G*Power 3.1.9.7 a statistical power analysis was run to determined that an appropriate sample size for this study. An effect size of 0.5 and an alpha level of 0.05 was used in the calculation and it was determined that 34 subjects was an appropriate sample size. Since this study had more than 34 subjects the study was continued. Once separated based on maturation timing there were 34 average maturers (Age (years): 15.59 ± 1.51; Height (cm): 171.08 ± 7.44; Mass (kg): 63.31 ± 9.42) and 19 late maturers (Age (years): 16.81 ± 0.74; Height (cm): 163.93 ± 5.83; Mass (kg): 58.04 ± 6.42). In order to account for the family-wise error rates once the *p*-value was calculated the Bonferroni correction was applied by multiplying the *p*-value by the number of variables for each test (3 for anthropometric data, 8 for CMJ and 9 for isokinetic). These were the final corrected *p*-values to be used for analysis. Age at testing resulted in the late maturers being significantly older at the time of testing ($p = 0.011$; g =

1.37), as well as the average maturers being significantly taller than the late maturers at time of testing (p = 0.002; g = 0.866). Of the seventeen variables tested none of them resulted in significant (p < 0.05) or meaningful (g < 0.60) differences between average and late maturers. These results can be viewed in Table 8.4.1 for anthropometric data, Table 8.4.3 for CMJ comparisons and Table 8.4.4 for isokinetic peak torque comparisons.

Table 8.4.1: Anthropometric data comparisons between average and late peak height velocity

Variable	**Average (mean ± SD)**	**Late (mean ± SD)**	***T-test* *p* - value**	***Hedges' g***
Mass (kg)	63.31 ± 9.42	58.04 ± 6.42	0.052	-0.519
Height (cm)	171.08 ± 7.44	163.93 ± 5.83	**0.006**	**-0.866**
Age at Testing (Years)*	15.59 ± 1.51	16.81 ± 0.74	**0.033**	**1.37**
*Represents Mann-Whitney Non-Parametric Analysis				

Table 8.4.2 Anthropometric data based on sex of the subjects.

Variable	**Males**	**Females**
Maturity Offset	2.34 ± 0.50	2.80 ± 0.90
Age at PHV	14.64 ± 0.61	12.73 ± 0.77

Table 8.4.3: Comparisons in countermovement jump performance between average and late peak height velocity

Variable	**Average (mean ± SD)**	**Late (mean ± SD)**	***p* - value**	***Hedges' g* [95% CI]**
Jump Height (m)*	0.26 ± 0.08	0.27 ± 0.08	1.000	0.173 [-0.364, 0.794]
Relative Mean Propulsion Power ($W \cdot kg^{-1}$)*	22.30 ± 4.51	24.21 ± 6.46	1.000	0.358 [-0.200, 0.979]
Relative Peak Propulsion Power ($W \cdot kg^{-1}$)*	42.56 ± 7.76	45.10 ± 10.00	1.000	0.290 [0.264, 0.920]
Relative Propulsive Impulse ($Ns \cdot kg^{-1}$)	2.23 ± 0.32	2.30 ± 0.33	1.000	0.197 [-0.348, 0.803]
Relative Mean Propulsion Force ($N \cdot kg^{-1}$)*	17.80 ± 1.82	18.84 ± 2.74	1.000	0.464 [-0.099, 1.08]
Relative Peak Propulsion Force ($N \cdot kg^{-1}$)*	21.94 ± 2.47	22.75 ± 3.75	1.000	0.267 [-0.302, 0.912]
Relative Mean Braking Force ($N \cdot kg^{-1}$)*	14.60 ± 2.03	15.24 ± 1.85	1.000	0.318 [-0.216, 0.923]
Relative Peak Braking Force ($N \cdot kg^{-1}$)*	19.38 ± 2.85	21.01 ± 3.59	1.000	0.513 [-0.035, 1.11]
*Represents Mann-Whitney Non-Parametric Analysis				

Table 8.4.4: Comparisons of isokinetic performance between average and late peak height velocity

Variable	**Average (mean ± SD)**	**Late (mean ± SD)**	***T-test* *p* - value**	***Hedges' g* [95% CI]**
Relative Right Knee Extension Peak Torque at 60°·s^{-1} (N·kg^{-1})*	2.41 ± 0.46	2.66 ± 0.46	0.486	0.531 [-0.001, 1.12]
Relative Left Knee Extension Peak Torque at 60°·s^{-1} (N·kg^{-1})	2.26 ± 0.51	2.37 ± 0.57	1.000	0.213 [-0.369, 0.802]
Relative Right Knee Flexion Peak Torque at 60°·s^{-1} (N·kg^{-1})	1.48 ± 0.28	1.53 ± 0.23	1.000	0.176 [-0.347, 0.740]
Relative Left Knee Flexion Peak Torque at 60°·s^{-1} (N·kg^{-1})	1.41 ± 0.29	1.47 ± 0.26	1.000	0.207 [-0.332, 0.795]
Relative Right Knee Extension Peak Torque at 300°·s^{-1} (N·kg^{-1})	1.18 ± 0.30	1.30 ± 0.30	1.000	0.408 [-0.153, 0.952]
Relative Left Knee Extension Peak Torque at 300°·s^{-1} (N·kg^{-1})	1.07 ± 0.31	1.25 ± 0.30	0.441	0.568 [0.030, 1.15]
Relative Average Knee Extension Peak Torque at 60°·s^{-1} (N·kg^{-1})	2.33 ± 0.47	2.51 ± 0.48	1.000	0.376 [-0.173, 0.958]
Relative Average Knee Flexion Peak Torque at 60°·s^{-1} (N·kg^{-1})	1.45 ± 0.27	1.50 ± 0.23	1.000	0.196 [-0.335, 0.783]
Relative Average Knee Extension Peak Torque at 300°·s^{-1} (N·kg^{-1})	1.13 ± 0.29	1.28 ± 0.30	0.720	0.512 [-0.040, 1.09]
*Represents Mann-Whitney Non-Parametric Analysis				

8.5: Discussion:

The aim of this study was to evaluate whether the subjects of this study performed better during a CMJ, or isokinetic peak torque evaluations based on the subject being an average or late maturer after they have reached post-PHV. The main finding of this study was that there were no significant or meaningful differences between average and late maturers - as hypothesized.

In the current study relative (ratio scaled) data was used to examine the variable without the impact of the subjects' mass and size since the subjects in line with previous procedures of McMahon et al. (2017) and Morris et al. (2020) where absolute values showed significant and meaningful differences between groups, whereas relative values (divided by body mass) did not. McMahon et al. (2017) did also evaluate sex differences between males and females, but the subject pool tested were much older and the purpose of the study was to specifically see the differences between males and females. The study conducted by Nimphius et al. (2019) also compared males and females while performing an isometric squat and isometric knee flexion and extension. The results of this study showed that when the absolute force and torque were measured the males performed significantly better than the females. However, when the data was normalized (ratio scaled) based on body mass there were no longer the significant differences between the subject's force and torque outputs (Nimphius et al., 2019). Therefore, based on results of previous studies, the current study was able to include both males and females in the group data because the variables that could be ratio scaled based on body mass (McMahon et al., 2017; Morris et al., 2020; Nimphius et al., 2019). There were both male and female subjects represented in both the average and late groups which also allows for the grouping in this manner to take place.

Since this study combined male and female subjects the age at PHV appears skewed. This is because females mature at an earlier age as shown in Table 8.4.2. When combining both sexes into average and late maturer categories the average ages are going to look like they may impact the results of the study. However, that is why it is important to consider the maturity offset. In this study it shows that the males and females are at a similar timing from when they hit their PHV. However, if a subject is an average maturer the amount of time focused on performance and not maintenance through a subject's growth spurt would be longer than those who are later maturers. So even if the later maturers are chronologically older than the average maturers, their maturity offset is similar.

Hägg and Taranger (1991) performed a longitudinal study of 183 boys and girls from birth until adulthood (age 25). The results of this study showed that the female subjects had significant differences in height as the subjects transitioned through PHV but that the final heights of the females had no significant differences based on the female subjects being early, average, or late maturers (Hägg & Taranger,1991). The male subjects were found to have significant height differences during the ages around PHV as well however post PHV the males also showed some significant differences as well. At age 17 there were no significant differences based on early, average, or late maturers however at age 18 the late maturing boys were significantly taller than the early maturing boys and after the age of 21 the late maturers were also significantly taller than the average maturing boys (Hägg & Taranger,1991). The results of this study show that adolescents and specifically adolescent athletes should not be discarded based on size at a young age simply because they are late maturers. These late maturers will most likely develop and catch-up in height to their early and average maturing counterparts based on this study (Hägg & Taranger,1991). Till et al. (2017) also expressed the importance of understanding and knowing the individual maturity statuses of adolescent's as they transition through their PHV and competing in rugby league. These researchers observed that late maturers will gain height and mass and their sport specific knowledge and performance should be more important in evaluation for higher level competition than stature while athletes transition through PHV. The current findings also support the findings of Hägg and Taranger (1991) and Till et al. (2017) by showing that subjects who are late maturers, who may not perform as well while they are transitioning through their PHV, will continue to develop and "catch" up to their early and average maturing peers. Based on the findings of Chapter 7 of this study it is shown that subjects that are pre and circa-PHV do not perform as well as those who are post-PHV. Therefore, if a subject is a late maturer and still in their pre or circa-PVH stage their early or average peers could be post-PHV and outperforming them. The current chapter shows the importance of continuing to develop these athletes as well because they will eventually perform at the same level.

Cumming et al. (2017) evaluated a 12-year-old subject and his performance in sprints, agility and CMJ's compared to others of their same age. When evaluating this subject among his chronological age group he performed significantly higher and may therefore be categorized as an early maturer. However, when this same subject was compared to subjects within his same maturation stage he performed and an average or below average rate (Cummings et al., 2017). Valente-Dos-Santos et al. (2014) support this by showing the longitudinal effect among soccer players and their dribbling speed. By the time all athletes reached post-PHV there were no significant difference between the performance based on early, average or late maturers (Valente-Dos-Santos et al., 2017). The results of these studies show the importance of evaluation of timing of PHV and should therefore be examined when coaching and/or testing a group of adolescent athletes. The current study also showed that the late maturers performed just as well as the average maturers once they were in the post-PHV stage and reiterate the importance of finding out when and the timing of a subjects PHV to ensure that they are not being overlooked due to stature when they may just in fact be late maturers.

The results showed that the timing of when an adolescent achieves PHV (average or late maturers) does not play a significant role in athletic performance in CMJ and isokinetic peak torque testing. These results show that even though the differences may not be meaningful and significant between average and late maturers overall the late subject group still outperformed the average subject group based on the variables tested in this study. Therefore, once the late maturers reached post PHV they had better results in CMJ performance and peak torque output than those individuals who reached their PHV before them. This conclusion is extremely important when coaching and training youth athletes because so many times the late maturers are left behind and not helped through their later development timing. Some adolescents may become discouraged because they cannot keep up with the earlier maturers who are post-PHV while the later maturers are pre or circa-PHV. This could force the later maturers could drop out of a sport because they are discouraged and frustrated by competing against their more physically developed peers. It is important for coaches and trainers to know that they need to stick with athletes, especially those that mature later, through their entire growth spurt instead of potentially casting them aside due to their later development and therefore, potential mismatch in size and performance. The findings of this study agree with the results of Lefevre at al. (2009) who determined that late maturers caught up with early and average maturers when completing three performance tasks for their study. These results show the importance and impact that PHV timing can have on adolescents and the need for more coaches, trainers, and athletes to be aware of the impact it can have on the growing individual.

8.5.1: Limitations and Areas of Future Research

Based on the results of previous studies it was hypothesized that no significant or meaningful difference would be found between average and late maturers. Therefore, statistical analysis for this study was based on this hypothesis. This does not mean that the values were equivalent however it shows that there is no significant or `meaningful separation of performance between the two subject groups. The study also only included average and late maturers and it does not include early maturers. Therefore, even though this study showed minimal significance and meaning between average and late it cannot be stated that those trends are the same for early maturers. Therefore, future research should be conducted to confirm the findings in this study with a sample size of subjects that are more evenly distributed throughout the PHV timing and early, average, or late maturers. It could also be important to continue evaluation of these adolescents as they enter adulthood to see how being an early, average or late maturer affects performance past the age of 18 which is typically when athletes are entering higher levels of competitive sport.

8.5.2: Conclusion

In conclusion the results of this study show the importance of supporting an athlete through their entire growth phase. If an athlete is a late maturer they may be left behind or lose a place on a team that is based on chronological age. These late maturers may not be able to keep up with or could be physically weaker than children who achieve their PHV at an earlier age. However, the results of this study conclude that timing of PHV does not result in better performing athletes after they have transitioned out of their growth spurt and are post-PHV. This concludes that athletes, trainers, and coaches should be aware of this result to ensure athletes are not falling through the cracks and quitting a sport just because they feel physically inept to compete. This study also encourages the idea of bio-banding and separating adolescents based on maturation and not chronological age. These topics should continue to be addressed so that later developing adolescents are not discouraged with their participation in sports and end up dropping out just because they grew slower than most of their peers.

Transition from Chapter 8 to Chapter 9

Since chapter 7 resulted in differences between pre, circa and post but chapter 8 showed no significant differences existed between average or late maturers chapter 9 used all subjects that were post PHV for this chapter of the thesis. This chapter involved examining the impacts of being a single sport versus a multiple sport athlete on performance tests. Previous researchers have investigated dropout rates and injury rates and determined that single sport athletes are more at risk of these outcomes and have concluded that being a multiple sport athlete may be a better option. However, the previous research does not look directly at the performance outputs of those that are single sport athletes versus multiple sport athletes. Therefore, chapter 9 will examine how subjects perform during a CMJ and isokinetic dynamometer testing based on whether they are single sport or multiple sport athletes.

Chapter 9: A Comparison of Isokinetic Torque and Countermovement Jump Variables Between Single Sport and Multiple Sport Youth Athletes.

9.1: Abstract:

The aims of this study were to determine if there were differences in countermovement jump (CMJ) and isokinetic knee flexion and extension performance in adolescent athletes participating in a single sport or participating in multiple sports. *Methods:* Subjects (n = 53, mean ± SD: age: 15.5 ± 1.5 years, height: 169.1 ± 7.7 cm, mass: 61.8 ± 8.9 kg) performed 3 CMJs and concentric isokinetic knee flexion and extension at $60°\cdot s^{-1}$ and $300°\cdot s^{-1}$. *Results:* CMJ height, relative mean propulsion power and relative propulsive impulse were significantly ($p < 0.05$) and moderately (g > 0.60) better in single sport athletes compared to multiple sport athletes. Relative peak propulsion power, relative mean braking force and relative peak braking force were not significantly different (p > 0.05) between groups, although the single sport athletes performed moderately better (0.654 < g < 1.03) compared to the multi-sport athletes. Relative mean propulsion force and relative peak propulsion force were not significant or meaningfully different between groups ($p > 0.05$; g < 0.60). Relative right knee extension peak torque at $60°\cdot s^{-1}$, relative left knee extension peak torque at $60°\cdot s^{-1}$, relative left knee extension peak torque at $300°\cdot s^{-1}$, relative average knee extension peak torque at $60°\cdot s^{-1}$ and relative average knee extension peak torque at $300°\cdot s^{-1}$ showed the single sport athletes had significantly ($p < 0.05$) and moderately (g > 0.60) better performances than the multiple sport athletes. Relative right knee flexion peak torque at $60°\cdot s^{-1}$, relative left knee flexion peak torque at $60°\cdot s^{-1}$, relative average knee flexion peak torque at $60°\cdot s^{-1}$ and relative right knee extension peak torque at $300°\cdot s^{-1}$ showed no significant (p > 0.05) differences and all showed moderately meaningful effect sizes (0.677 < g < 1.10) with single sport athletes performing better than the multi-sport athletes except for relative right knee flexion peak torque at $60°\cdot s^{-1}$ which resulted in a small effect size (g = 0.55). *Conclusion:* Single sport athletes post-PHV possess superior CMJ and isokinetic knee extensor and flexor peak torques than multi-sport athletes with the same maturity status. Therefore, based on these results multi-sport athletes need to ensure they are participating in appropriate and adequate strength and conditioning to support the demands of participating in multiple sports.

9.2: Introduction:

Since research completed by Côté et al. (2007) on their developmental model of sport specialization more research has been conducted to evaluate the impacts of specialization on youth athletes. Côté at al. (2007) defined early specialization as a high volume of deliberate practice and a low amount of deliberate play in one sport and focus on performance as early as age six or seven. Support for early specialization assumes that specialization and deliberate practice in one sport is superior and helps achieve elite performance versus deliberate play involvement in various sporting activities during childhood (Ericson et al., 1993; Kaminski et al., 1984; Sack, 1980; Monsaas, 1985 and Klinkowski, 1985). These subjects would be considered single sport athletes versus those who play more than one sport in a year who would be considered multiple sport or multi-sport athletes. Recently this theory has been questioned due to higher rates of dropout and injury reported among the athletes specializing early and has caused researchers to have start investigating whether it is necessary to specialize at such an early age (Côté et al., 2009; Lonsdale et al., 2009; Moesch et al., 2011; Fransen et al., 2012; Hall et al., 2015; and Post et al., 2017).

Research has been conducted to determine if there are any potential negative effects of early sport specialization (Fransen et al., 2012; Post et al., 2017). Results of these studies have shown that early sport specialization can lead to athlete burnout and greater risk of injury among youth athletes; however, there are an increasing number of athletes starting to specialize at an earlier age (Fransen et al., 2012; Post et al., 2017). The reason some athletes are encouraged to specialize early is to refine specific skills for the one sport they are specializing in. However, there is also a "wining at all costs" mentality that has evolved and the increasing need to create elite athletes in order to gain college scholarships in the United States or a place in an elite academy squad in the United Kingdom and Europe. However, due to the increase in the number of athletes specializing earlier in a specific sport there is an increase in the number of athletes that have dropped out of sports due to burnout and injury (Lonsdale et al., 2009).

In 2011, Moesch et al. evaluated athletes participating in cycling, kayaking, sailing, skiing, swimming, track and field, triathlon, and weightlifting to evaluate if the athletes who had reached elite status (senior national team representation) in their respective sport were athletes that had specialized early or late. The basis of their research was on the early specialization and early diversification paths of the DMSP model from Côté et al. (2007). The questionnaire focused on six categories: biographical information, practice hours in their main sport, involvement in other sports, career development, weekly training schedule and athletic success. Results showed a trend that the athletes who had become elite in their sport had specialized later in life than athletes that did not reach elite status. It also concluded that the near elite athletes spent more hours practicing at a younger age. At 18 years of age the two groups had similar practice hours but then the elite athletes started to have more sport specific training hours (Moesch et al., 2011). Therefore, the later specializing group did end up with more sport specific training hours eventually, but it was later in their adolescents that they started to train and practice more in their sport. This research supports the idea that late specialization does not delay athletic development and that less training at earlier ages and specialization later in life is more beneficial for young athletes (Moesch et al., 2011).

Fransen et al. (2012) also tested a group of boys ages 6-12 to see if any physical fitness and gross motor coordination differences existed between single sport and multi-sport youth athletes. The differences between single sport and multi-sport athletes were not seen until the 10-12 year-old age group. Differences existed in strength, speed and agility, and gross motor control, with the multi-sport athletes performing better (Fransen et al., 2012). Based on research from Côté et al. (2009) the boys participating in more than one sport were exposed to a greater number of physical, cognitive, and psycho-social environments which allow them to have a broader range of physical, personal, and mental skills. The researchers concluded that the multiple sport participants with many hours per week had a higher ability to perform the tests and were able to jump further and had better gross motor coordination than all other groups (Fransen et al., 2012).

In 2015, Hall et al. conducted a study that consisted of 546 female basketball, soccer, and volleyball players that were broken down into 357 multi-sport athletes and 189 single sport athletes to investigate whether sport specialization causes more injuries based on self-reporting by the subjects. The methods consisted of the female athletes completing the anterior knee pain scale, the international knee documentation committee form, supplying a standardized history and physician-administered physical examination, medical history information and the anthropometric data of the athletes (Hall et al., 2015). Based on the questionnaires it was concluded that single sport athletes had an increased risk and incidence for anterior knee pain compared to multi-sport athletes. Single sport athletes had a 1.5 times greater risk of patellar-moral pain and 4 times greater risk of Osgood Schlatter Disease and Sinding Larsen Johansson/ Patellar Tendinopathy (Hall et al., 2015). These findings indicate a possible link between single-sport athletes being more at risk of injury compared to multi-sport athletes. These research studies were mostly questionnaire studies and therefore future research should investigate whether there are physical reasons why single sport athletes are more susceptible to injury than multi-sport athletes (Côté et al., 2009; Lonsdale et al., 2009; Moesch et al., 2011; Fransen et al., 2012; Hall et al., 2015; and Post et al., 2017).

To address growing concern that sport specialization can increase injury risk, Post et al. (2017) completed research to assess if there is a link between sport specialization and training volume with injury. 2011 youth athletes ages 12-18 completed a questionnaire regarding their specialization status, yearly and weekly sport participation volume and injury risk (Post et al., 2017). Post et al. (2017) concluded that high levels of specialization resulted in a history of injuries and that if an athlete exceeded the volume recommendations, independent of age or sex, they were more likely to have a history of overuse injury (Post et al., 2017). These results support the claim that limiting sport specialization could help minimize injury among youth athletes which is also in agreement with the results of the studies conducted by Côté et al. (2009), Lonsdale et al. (2009), Moesch et al. (2011), Fransen et al. (2012), Hall et al. (2015) and Post et al. (2017).

Most of the current research on sport specialization has been based on questionnaires (Côté et al., 2009; Lonsdale et al., 2009; Moesch et al., 2011; Hall et al., 2015; and Post et al., 2017). This approach has shown that there are problems with specializing in a single sport and that early specialization athletes have an increased risk of injury and dropout (Côté et al., 2009; Lonsdale et al., 2009; Moesch et al., 2011; Hall et al., 2015; and Post et al., 2017). This research is also addressing the issue of early sport specialization. This is an important differentiation when examining single versus multiple sport athletes. Early sport specialization is when an athlete focuses on a single sport at a young age, sometimes as early as 5 or 6 years of age. However, at some point an athlete needs to become a single sport athlete, which for the majority would have to at least occur when a subject joins a college team or a professional club. The underlying question needs to try and address when the optimal time is to transition from a multiple sport to a single sport athlete.

No research has explored the underlying differences between single and multi-sport athletes in force and torque production with athletes later in their adolescents. This may help explain the differing injury profiles found between the two populations of young athlete. Furthermore, identifying the force and torque production differences may further explain variances in athletic performances in jumping and other explosive movements. Past research typically evaluates groups of individuals participating in the same sport to address the differences physically between a growing athlete and the impact it might have on their performance (Cummings et al., 2017; Lloyd et al., 2014; McMahon et al., 2017 & Morris et al., 2020). Therefore, evaluation of single sport and multi-sport athletes should be made to see how the development of adolescents is affected based on sport specialization and what approaches should be made to training and competition to ensure the safest and best way to develop athletes.

Current information provided by past research results show early sport specialized athletes being more susceptible to burn-out and injury (Côté et al., 2009; Lonsdale et al., 2009; Moesch et al., 2011; Fransen et al., 2012; Hall et al., 2015; Post et al., 2017). These results make it seem like it would be better to specialize later in an individual's adolescents to decrease the chances of these issues but there have been few to no studies that evaluate the physical differences between single sport and multiple sport athletes that are post-PHV. Single sport athlete performance needs to be compared to multi-sport athlete performance to show if there is a physical reason to specialize later in sport. Therefore, the aims of this study were to evaluate athletes that are past peak height velocity (PHV) stage to see if there are performance differences in CMJ and isokinetic peak torque outputs between single sport and multi-sport adolescent athletes. This will start to evaluate if there are physical advantages to being a multiple sport athlete compared to a single sport athlete based on the strength and power profile of these athletes. Based on the studies by Moesch et al. (2011) and Fransen et al. (2012) that state that adolescents that became elite in their sport were more likely to specialize later than those who only reached near-elite status and that pre-PHV multi-sport athletes outperformed their single sport athlete counterparts, it is hypothesized that the multi-sport athletes in this study will outperform the single sport athletes in the CMJ and isokinetic performances.

9.3: Methods:

9.3.1: Experimental Approach: A cross-sectional comparative research design was adopted to compare CMJ and isokinetic performance characteristics between single and multi-sport athletes. Based on a previous reliability study (Chapter 4: Test-retest reliability of isokinetic knee flexion and extension, countermovement jump performance and muscle architecture in adolescents) the following variables were found to be reliable in adolescent athletes (based on ICC and %CV values); jump height, mean propulsion power, peak propulsion power, propulsion impulse, mean propulsion force, peak propulsion force, mean braking force, peak braking force, right and left knee extension (Ext.) and flexion (Flex.) peak torques (PT) at $60°·s^{-1}$, right and left knee extension peak torques at $300°·s^{-1}$. Another 16 variables were calculated based on average and relative values. Average variables were created for $60°·s^{-1}$ knee extension peak torques for extension and flexion and $300°·s^{-1}$ knee extension peak torques by taking the left and right limb variables and averaging them. Appropriate variables including peak torque, CMJ peak and mean power, impulse and force variables were ratio scaled (absolute value / body weight) to create relative values, to normalize these variables and eliminate the potential increase in strength due to higher body mass. Due to the age differences and therefore weight difference between the subjects of this study of the individuals were only evaluated based on the relative values (ratio scaled [divided by body mass]) unless it was a variable that could not be ratio scaled (i.e., jump height).

9.3.2: Subjects: Healthy youth athletes ranging from 13 to 18 years (n = 53, mean ± SD: age: 15.5 ± 1.5 years, height: 169.1 ± 7.7 cm, mass: 61.8 ± 8.9 kg) volunteered to participate in this study. There were 13 single sport athletes who participated in either soccer (n = 2), volleyball (n = 3), running (n = 5), or lacrosse (n = 3). The 40 multi-sprot athletes participated in more than one of the following sports: soccer (n = 36), volleyball (n = 3), running (n = 21), lacrosse (n = 5), basketball (n = 23), baseball/softball (n = 24), American football (n = 8), tennis (n = 2), horseback riding (n = 3), swimming/diving (n = 3), hockey (n = 1), golf (n = 2), wrestling (n = 2), dance (n = 1), and gymnastics (n = 1). These subjects all participated as modified, junior varsity or varsity athletes as part of their school sports programs depending on age (modified 13-14 years old, junior varsity 14-16 years old, varsity 16-18 years old). In addition, some of the subjects also participated on a club team for additional sport specific training outside of their school team. All subjects and their guardians provided written informed consent and parental assent as appropriate, and the study received ethical approval from both the University of Salford and the State University of New York at Upstate Medical University research ethics committees. All subjects were middle or high school athletes without any known lower limb injuries. Subjects were instructed to maintain their regular training practices during the experiment but asked to not participate in any vigorous physical activity 24 hours prior to their testing session.

9.3.3: Procedures: Subjects were tested in one 45-minutes testing session.

9.3.3.1: Questionnaire: The subjects first completed a questionnaire (Appendix C) that enabled the categorization of subjects into single and multiple sport athletes. Subjects were also asked how many hours a week they participated in sport as well and what sports they play.

9.3.3.2: Anthropometric: Height, sitting height, mass and PHV were all collected for this study. Refer to Chapter 3: Section 3.1 for more details on how these measurements were acquired.

9.3.3.3: Countermovement Jumps: After a 3-minute warm up on a cycle ergometer and 5-minute lower limb dynamic stretching the subjects completed 3 CMJ. The subjects were instructed to place their hands on the hips and not use them in their jumping movement. The subjects were also instructed that the squat depth was at their discretion, and they were told to jump as high as possible. Once the subjects stepped on the force plate, they stood still for one second to record weight and then were then instructed to jump. The subject then repeated the jump two more times with 30 second rest between each jump. Briefly, data was analyzed using a forward dynamics approach with jump height calculated from velocity of center of mass at take-off (See Chapter 3, Section 3.3 for more detail).

9.3.3.4: Isokinetic Dynamometry: The subjects then completed the isokinetic testing. The subjects performed 3 warmup repetitions at 50% effort prior to each of the different angular velocities on each leg. The subjects then completed one set of 5 repetitions at $60°\cdot s^{-1}$. The subject was then given a minute-long rest and then completed 5 repetitions at $300°\cdot s^{-1}$ test after their warm-up repetitions. Then the machine was reconfigured, and the subject completed the same testing sequence for their left leg. While performing the testing the subjects were given encouragement by the researchers. For more in depth methodology refer to Chapter 3: Section 3.4.

9.3.4: Statistical Analyses: All statistical analyses were performed using IBM SPSS Statistics version 26 and Estimation Stats. The subjects were separated into single sport and multiple sport athletes for this study. All athletes were also considered to be in the post-PHV phase of their adolescent growth. All variables and groups were first analyzed for normality to determine the distribution of the data. If the variable for both single and multiple sport was found to be normally distributed an independent samples t-test was performed, with an a priori alpha level set at $p < 0.05$. If the Levene's F-value was >0.05, equal variance was assumed, and if the F-value was <0.05 equal variance was not assumed with the corresponding *p*-values were recorded. Hedges *g* effect size calculated to determine the magnitude of any differences and interpreted as (< 0.19), small (0.20 – 0.59), moderate (0.60 – 1.19), large (1.20 – 1.99), and very large (2.0 – 4.0) (Hopkins, 2002). If the variable was not normally distributed the Mann-Whitney non-parametric test was performed ($p < 0.05$). To account for the family-wise error rates once the *p*-value was calculated the Bonferroni correction was applied by multiplying the *p*-value by the number of variables for each test (4 for anthropometric data, 8 for CMJ and 9 for isokinetic).

9.4: Results:

Once divided based on single versus multi-sport athletes there were 13 single sport athletes and 40 multi-sport athletes participating in one or more of the following sports: soccer, volleyball, running, lacrosse, basketball, baseball/softball, American football, tennis, horseback riding, swimming/diving, hockey, golf, wrestling, dance, and gymnastics. There were no significant differences ($p > 0.05$) between the groups based on height, mass, and maturity offset, with only trivial to moderate effect sizes (Table 9.4.1). Height (g = 0.716) showed moderately meaningful differences between single sport and multi-sport athletes with the single sport athletes being taller in the subject set for this study. Age at PHV was found to be significantly different ($p = 0.002$) with moderately meaningful differences (g = 0.971) with the single sport athletes being older than the multiple sport athletes.

Table 9.4.1: Comparisons in anthropometric data between single sport and multi-sport post-PHV adolescent athletes

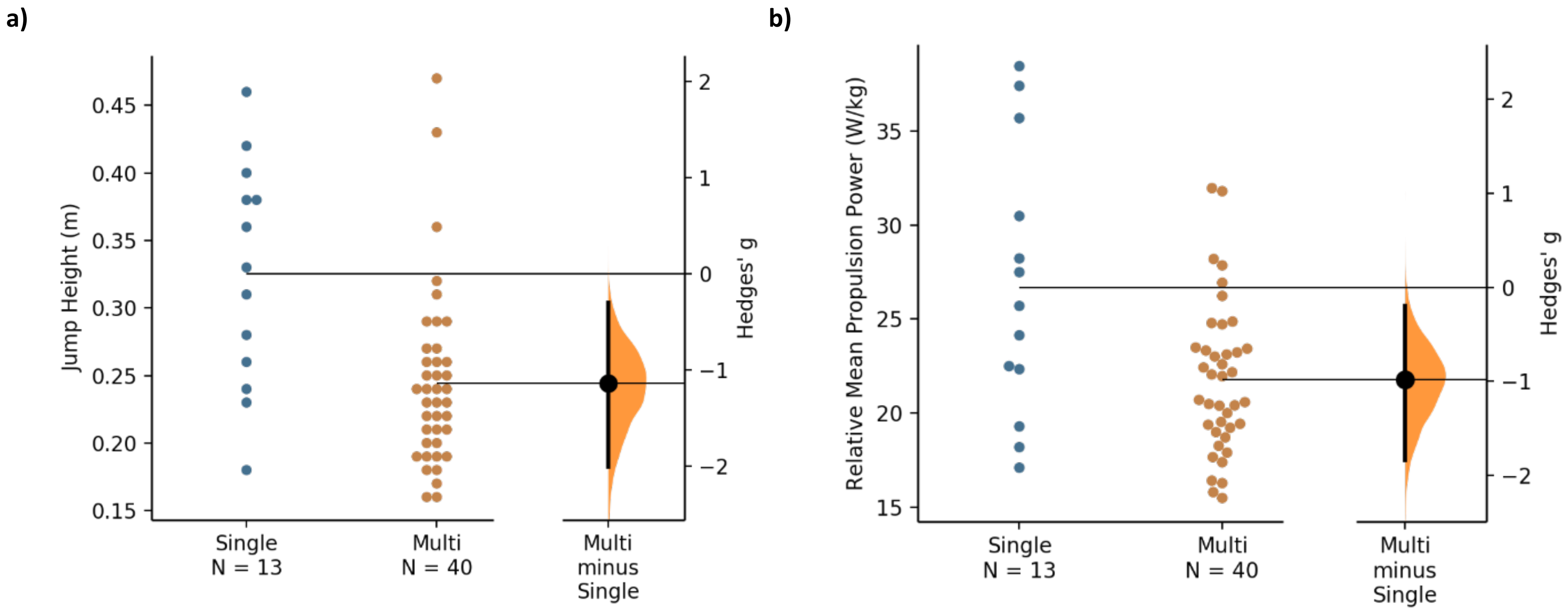
Variable	**Single Sport (mean ± SD)**	**Multi-Sport (mean ± SD)**	***p* - value**	***Hedges' g* (95% CI)**
Height (m)	173.12 ± 8.34	167.74 ± 7.08	1.000	-0.716 (-1.47, -0.04)
Mass (kg)	62.57 ± 7.11	61.58 ± 9.54	1.000	-0.109 (-0.72, 0.39)
Age at Testing *	16.43 ± 1.35	15.77 ± 1.45	0.189	0.451 (-0.15, 1.01)
Age at PHV (years)	14.05 ± 1.26	13.02 ± 0.98	0.002	-0.971 (-1.70, -0.20)
Maturity offset (years)*	2.38 ± 0.79	2.78 ± 0.83	0.328	0.457 (-0.43, 0.97)
*Mann-Whitney Non-Parametric Analysis				

Countermovement jump height, relative mean propulsion power and relative propulsive impulse, showed that the single sport athletes had significantly ($p < 0.05$) and moderately ($g > 0.60$) better performances than the multiple sport athletes (Table 9.4.2, Figure 9.4.1a-c). Relative peak propulsion power, relative mean braking force and relative peak braking force were not significantly different ($p > 0.05$) between groups, although the single sport athletes performed moderately better ($0.654 < g < 1.03$) compared to the multi-sport athletes. In contrast relative mean propulsion force and relative peak propulsion force were not significant or meaningfully different between groups.

Table 9.4.2: Comparisons of countermovement jump performance between single sport and multi-sport post-PHV adolescent athletes

Variable	**Single Sport (mean ± SD)**	**Multi-Sport (mean ± SD)**	***p* - value**	***Hedges' g* (95% CI)**
Jump Height (m)*	0.33 ± 0.08	0.24 ± 0.07	0.024	-1.14 (-2.01, -0.30)
Relative Mean Propulsion Power (W·kg^{-1})	26.69 ± 7.14	21.78 ± 3.98	0.040	-0.984 (-1.84, -0.20)
Relative Peak Propulsion Power (W·kg^{-1})*	49.70 ± 10.63	41.44 ± 6.87	0.104	-1.03 (-1.88, -0.25)
Relative Propulsive Impulse (Ns·kg^{-1})*	2.51 ± 0.34	2.17 ± 0.27	0.024	-1.14 (-1.93, -0.31)
Relative Mean Propulsion Force (N·kg^{-1})	18.97 ± 3.17	17.91 ± 1.80	0.184	-0.472 (-1.35, 0.24)
Relative Peak Propulsion Force (N·kg^{-1})*	23.20 ± 4.09	21.92 ± 2.50	1.000	-0.428 (-1.29, 0.24)
Relative Mean Braking Force (N·kg^{-1})	15.79 ± 2.46	14.52 ± 1.71	1.000	-0.654 (-1.40, -0.01)
Relative Peak Braking Force (N·kg^{-1})	21.72 ± 4.16	19.40 ± 2.64	0.608	-0.746 (-1.55, -0.02)
*Mann-Whitney Non-Parametric Analysis				
Green = Significant AND Meaningful; Yellow = Meaningful but NOT Significant; Red = Not Significant OR Meaningful				

a) b)


Jump Height (m)
0.45
0.40
0.35
0.30
0.25
0.20
0.15
Hedges' g
2
1
0
−1
−2
Single
N = 13
Multi
N = 40
Multi
minus
Single
Relative Mean Propulsion Power (W/kg)
35
30
25
20
15
Hedges' g
2
1
0
−1
−2
Single
N = 13
Multi
N = 40
Multi
minus
Single

c)

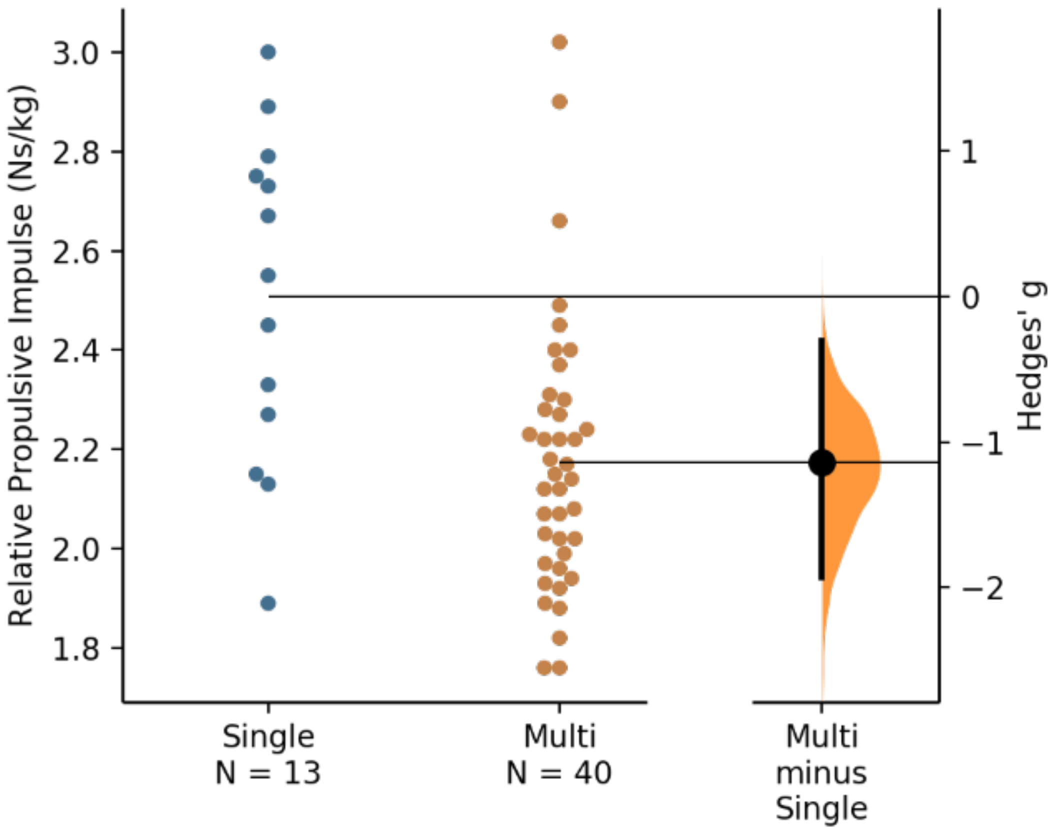


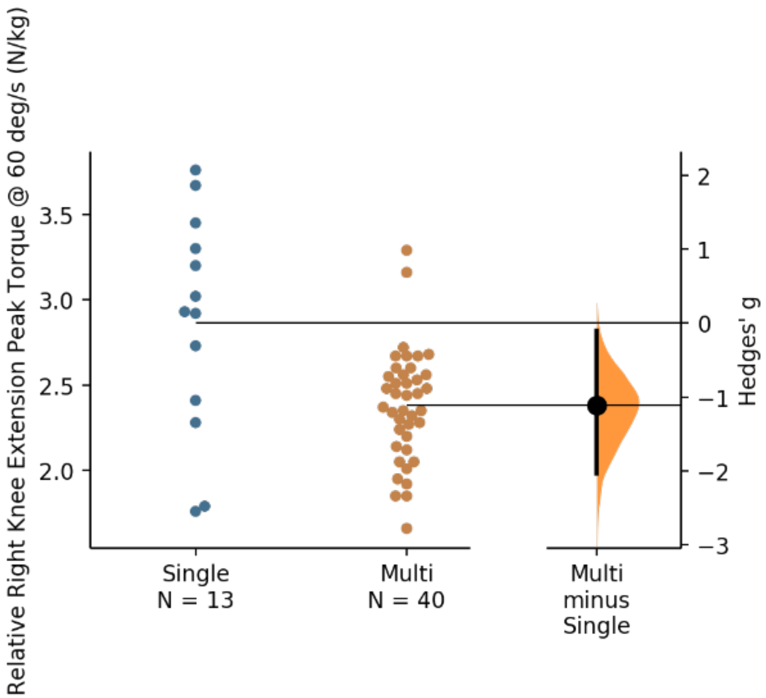
Figure 9.4.1: Comparisons of Countermovement Jump Variables between Groups – a) Jump Height, b) Relative Mean Propulsion Power, c) Relative Propulsion Impulse

Relative right knee extension peak torque at 60º·s^{-1}, relative left knee extension peak torque at 60º·s^{-1}, relative left knee extension peak torque at 300º·s^{-1}, relative average knee extension peak torque at 60º·s^{-1} and relative average knee extension peak torque at 300º·s^{-1} showed the single sport athletes had significantly ($p < 0.05$) and moderately ($g > 0.60$) better performances than the multiple sport athletes (Table 9.4.3, Figure 9.4.2a-g). Relative right knee flexion peak torque at 60º·s^{-1}, relative left knee flexion peak torque at 60º·s^{-1}, relative average knee flexion peak torque at 60º·s^{-1} and relative right knee extension peak torque at 300º·s^{-1} showed no significant ($p > 0.05$) differences and all showed moderately meaningful effect sizes ($0.677 < g < 1.10$) with single sport athletes performing better than the multi-sport athletes except for relative right knee flexion peak torque at 60º·s^{-1} which resulted in a small effect size ($g = 0.55$).

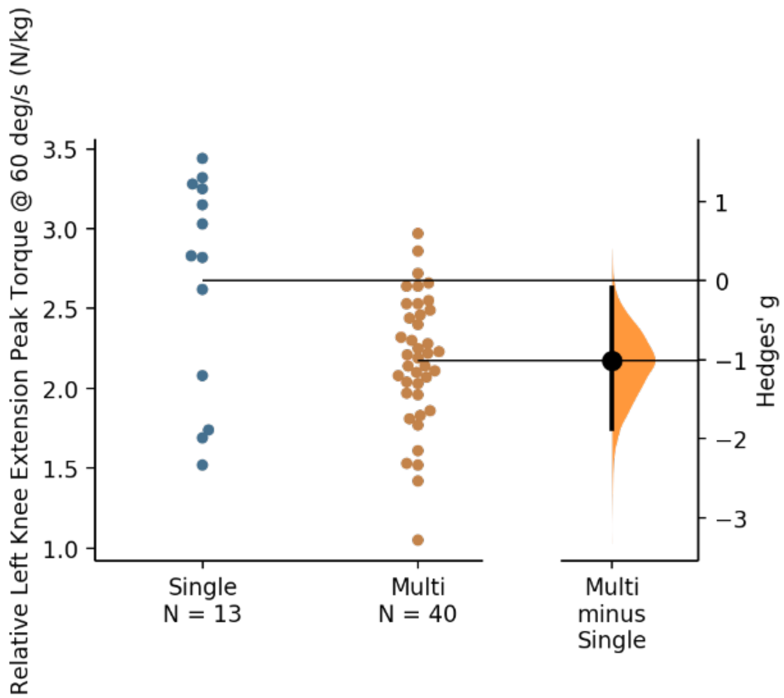
Table 9.4.3: Comparisons of isokinetic performance between single sport and multi-sport post-PHV adolescent athletes

Variable	**Single Sport (mean ± SD)**	**Multi-Sport (mean ± SD)**	***T-test* *p* - value**	***Hedges' g* (95% CI)**
Relative Right Knee Extension Peak Torque at 60°·s^{-1} (N·kg^{-1})	2.86 ± 0.65	2.38 ± 0.33	0.018	-1.12 (-2.04, -0.11)
Relative Left Knee Extension Peak Torque at 60°·s^{-1} (N·kg^{-1})	2.67 ± 0.68	2.17 ± 0.41	0.045	-1.01 (-1.88, -0.09)
Relative Right Knee Flexion Peak Torque at 60°·s^{-1} (N·kg^{-1})	1.61 ± 0.32	1.46 ± 0.23	0.828	-0.550 (-1.32, 0.23)
Relative Left Knee Flexion Peak Torque at 60°·s^{-1} (N·kg^{-1})	1.58 ± 0.37	1.38 ± 0.22	0.108	-0.737 (-1.58, 0.11)
Relative Right Knee Extension Peak Torque at 300°·s^{-1} (N·kg^{-1})*	1.46 ± 0.33	1.15 ± 0.25	0.738	-1.10 (-1.85, -0.19)
Relative Left Knee Extension Peak Torque at 300°·s^{-1} (N·kg^{-1})	1.34 ± 0.47	1.07 ± 0.22	0.004	-0.893 (-1.94, 0.17)
Relative Average Knee Extension Peak Torque at 60°·s^{-1} (N·kg^{-1})	2.77 ± 0.65	2.68 ± 0.33	0.009	-1.12 (-2.09, -0.11)
Relative Average Knee Flexion Peak Torque at 60°·s^{-1} (N·kg^{-1})	1.59 ± 0.34	1.42 ± 0.21	0.333	-0.677 (-1.51, 0.15)
Relative Average Knee Extension Peak Torque at 300°·s^{-1} (N·kg^{-1})	1.40 ± 0.39	1.11 ± 0.22	0.036	-1.05 (-1.98, -0.05)
*Represents Mann-Whitney Non-Parametric Analysis				
Green = Significant AND Meaningful; Yellow = Meaningful but NOT Significant; Red = Not Significant OR Meaningful				

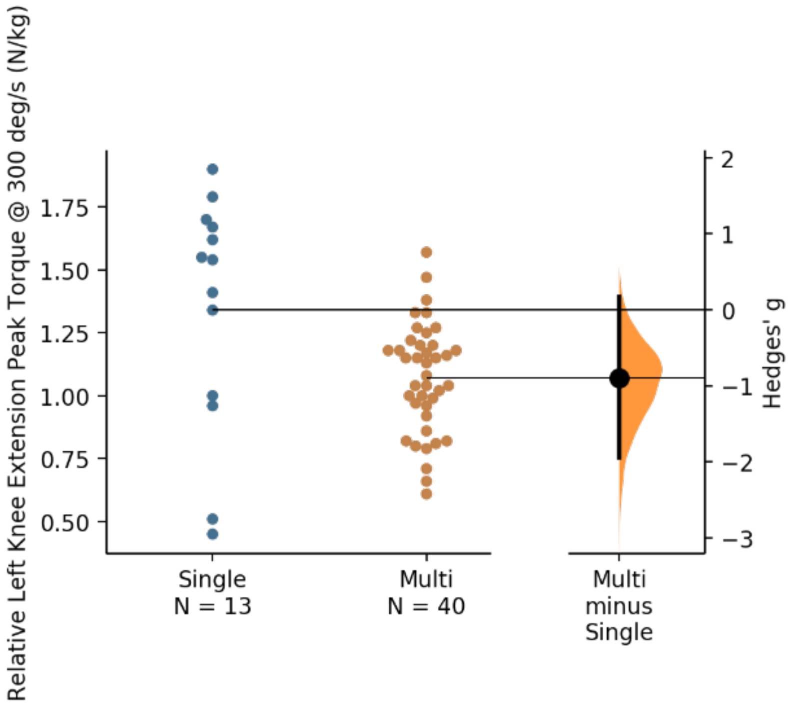
a)


Relative Right Knee Extension Peak Torque @ 60 deg/s (N/kg)
3.5
3.0
2.5
2.0
2
1
0
−1
−2
−3
Hedges' g
Single
N = 13
Multi
N = 40
Multi
minus
Single

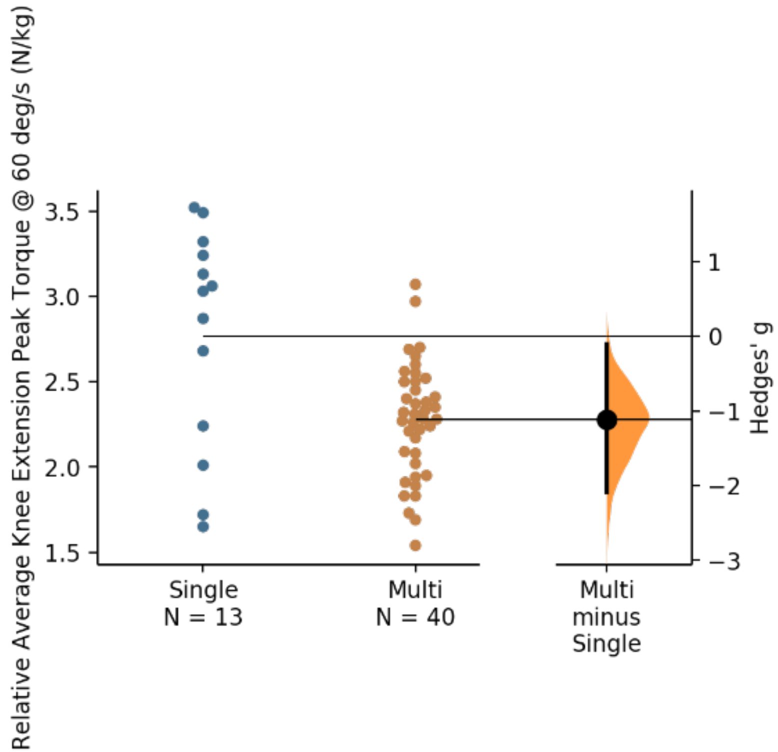
b)


Relative Left Knee Extension Peak Torque @ 60 deg/s (N/kg)
3.5
3.0
2.5
2.0
1.5
1.0
1
0
−1
−2
−3
Hedges' g
Single
N = 13
Multi
N = 40
Multi
minus
Single

c)


Relative Left Knee Extension Peak Torque @ 300 deg/s (N/kg)
1.75
1.50
1.25
1.00
0.75
0.50
Hedges' g
2
1
0
−1
−2
−3
Single
N = 13
Multi
N = 40
Multi
minus
Single

d)


Relative Average Knee Extension Peak Torque @ 60 deg/s (N/kg)
3.5
3.0
2.5
2.0
1.5
Hedges' g
1
0
−1
−2
−3
Single
N = 13
Multi
N = 40
Multi
minus
Single

e)

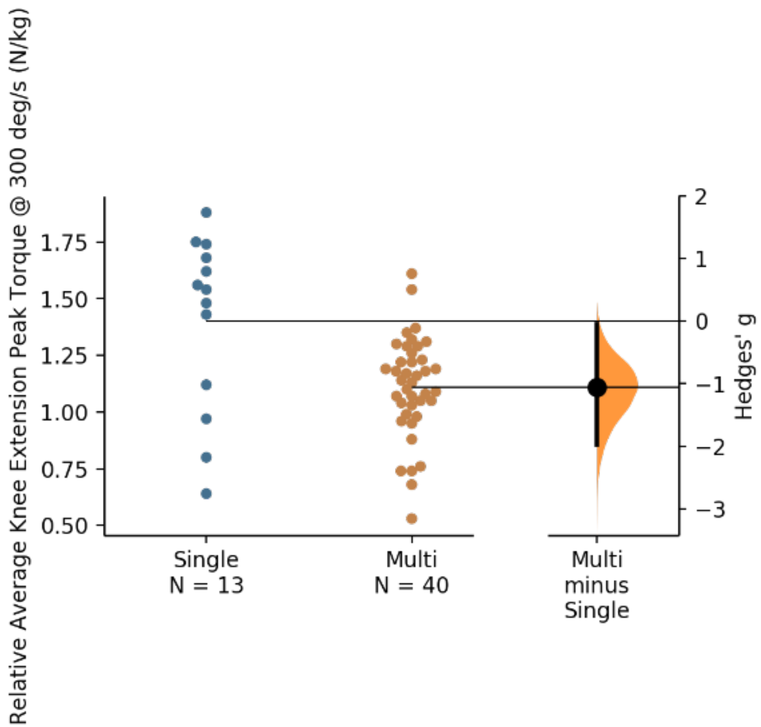


Figure 9.4.2: Comparisons of Isokinetic Variables between Groups – a) Relative Right Knee Extension Peak Torque at 60°·s^{-1}, b) Relative Left Knee Extension Peak Torque at 60°·s^{-1}, c) Relative Left Knee Extension Peak Torque at 300°·s^{-1}, d) Average Knee Extension Peak Torque at 60°·s^{-1} and e) Average Knee Extension Peak Torque at 300°·s^{-1}

9.5: Discussion:

The aims of this study were to compare CMJ and isokinetic performance between single sport and multi-sport adolescent athletes, who were post-PHV. The key findings of this study were that eight (countermovement jump height, relative mean propulsion power, relative propulsive impulse, relative right knee extension peak torque at 60º·s^{-1}, relative left knee extension peak torque at 60º·s^{-1}, relative left knee extension peak torque at 300º·s^{-1}, relative average knee extension peak torque at 60º·s^{-1} and relative average knee extension peak torque at 300º·s^{-1}) of the seventeen testing variables were superior in single sport athletes ($p < 0.05$ and $g > 0.60$) compared to multiple sport athletes, in contrast to the hypotheses. Of the nine variables that were found to no have significant differences six still exhibited moderate and therefore meaningful effect sizes (single sport > multi-sport).

Previous research has not compared single sport athletes to multiple sport athletes who are later in their adolescents (post-PHV). Therefore, in order to evaluate the current results of this study comparisons were made based on past research that was conducted performing the same tests to evaluate the mechanics of the subject's performances to past research. In the current study, results showed that countermovement jump height, relative mean propulsion power and propulsion impulse were higher in the single sport group compared to the multi-sport group. These results are in line with the research conducted by McBride et al. (2010) who reported that impulse was the best indicator of jump height and was not influenced by changes to squat depth during a CMJ and therefore would be appropriate variables for performance comparisons between single and multi-sport athletes. McBride et al. (2010) also stated that peak power was also a strong predictor of jump height and could be used in comparing performance outputs between athletes. The results of this study by McBride et al. (2010) are reiterated in the current study with mean power and impulse showing significant and meaningful differences with single sport athletes performing better than multi-sport athletes. The current study also showed that impulse as being more meaningful than power and most similar to the significance and effect size of jump height which shows impulse has a greater impact on jump height performance than power. Relative peak propulsion power, relative mean braking force and relative peak braking force were not significantly different between groups, however effect sizes revealed meaningfully greater performance in the single sport group (Figure 9.4.1). Therefore, relative peak propulsion power, relative mean braking force and relative peak braking force should be observed as having meaningful difference with single sport athletes outperforming multi-sport athletes due to the moderate to large affect sizes and the 95% confidence intervals of these variables.

Previous Dobbs et al. (2020) and Radnor et al. (2021) observed CMJ performances among single sport youth athletes that resulted in greater differences in performance being based on maturation status and not chronological age. Dobbs et al. (2020) tested elite cricket players and separated them into the categories of pre, circa and post-PHV. The post-PHV subjects had a mean jump height of 0.25 ± 0.05 meters. The jump height for the post-PHV group in the Dobbs et al. (2020) study is around 0.08 meters lower than the single sport subjects average in the current study. Whereas the Radnor et al. (2021) study evaluated elite male junior soccer players and had jump height results that were around 0.03 meters higher than the single sport athletes of this current study. Dobbs et al. (2020) used a force plate and Accupower spreadsheet to analyze their CMJ outputs and Radnor et al. (2021) performed the CMJ on a contact mat. Neither study was specific about what variable was used to calculate jump height and these differences in testing platforms and analysis software used may be the reasoning behind the different jump height outcomes in comparison to the current study. The current study was also made up of athletes specializing in a variety of sports which was unlike the two previous studies that were based solely on a single sport population. The results of these studies present a question on the differences between specific sports themselves and what impact being a single-sport athlete has in these sports may have on the development of adolescent athletes.

The findings of the current study are not in line with previous research that observed multi-sport athletes outperforming single sport athletes (Fransen et al., 2012). Fransen et al. (2012) however performed their testing on subjects between the ages of 6-12 which were all found to be categorized as pre-PHV. These subjects were classified as being members of club sports and were either participating in one sport or sampling more than one sport at these younger ages. During this time of physical development for youth it has been stated that the focus of training starts with fundamental movement skills and then transition to sport specific movement skills (Lloyd et al., 2015). The youth physical development presented by Lloyd et al. (2015) also suggest that the training structure should still have minimal structure to it when athletes are this young. These reasonings could explain why younger middle childhood subjects performing in multiple sports would perform better at physical performance tasks at a younger age than single sport athletes. The multi-sport athletes during this physical development stage are subjected to more stimuli which can help with fundamental movement skills more than those only subjected to the stimuli of a single sport. The current study however is looking at subjects who are post-PHV. Once a subject is post-PHV the athletes should have transitioned into training with higher structure and focus on sport specific movements as well as a higher focus on strength and power based on the youth physical development model by Lloyd et al. (2015). Therefore, if the subjects are following this model, it could explain the reasoning behind the single sport athletes outperforming the multi-sport athletes in the CMJ and isokinetic peak torque evaluations in this study.

Isokinetic performances resulted in five significant and meaningful differences with single sport athletes outperforming the multi-sport athletes. The peak torque variables that were significant and meaningful were relative right knee extension at $60°·s^{-1}$, relative left knee extension at $60°·s^{-1}$, relative left knee extension at $300°·s^{-1}$, relative average knee extension at $60°·s^{-1}$ and relative average knee extension at $300°·s^{-1}$. Relative right knee extension peak torque at $300°·s^{-1}$ was not found to be significant, however there were meaningful difference based on the Hedges' g effect size and 95% confidence interval with single sport athletes outperforming. Therefore, these results show that the single sport athletes were able to produce significantly greater forces with their quadriceps than the multi-sport athletes. In Study Two there were moderate to strong correlations between jump height and mean power and impulse which supports the findings in the current study and supports that these variables have direct relationships with one another.

Researchers have discussed the negative impacts of sport specialization using questionnaire-based research to examine how specialization can affect burn-out and injury rate (Côté et al., 2009; Lonsdale et al., 2009; Moesch et al., 2011; Hall et al., 2015; and Post et al., 2017). These studies concluded that athletes that specialized earlier in their adolescents had a higher risk of injury and burn-out than those that participated in multiple sports for a longer period throughout their adolescents (Côté et al., 2009; Lonsdale et al., 2009; Moesch et al., 2011; Hall et al., 2015; and Post et al., 2017). Moesch et al. (2011) concluded that athletes that achieve elite status in the designated sport were more likely to focus singularly on their sport around the age of 18. At that time the elite athletes had a drastic increase in the number of sport specific training hours and the near-elite athletes who had been participating more in the youth national teams and had more sport specific training hours at a younger age had a decrease in the number of sport specific training hours. Therefore, by the time the elite subjects were competing at the top level in their sport the total number of hours of sport specific training were comparable to those who did not reach the top level (Moesch et al., 2011). The results of this study highlight that athletes who specialize early are at a higher level competitively in the junior national team and are therefore performing better as single sport athletes compared to the multi-sport athletes. However, it seems that based on the results of Moesch et al. (2011) the individuals that specialized early and made the junior national team may have burned-out by the time they were of the age to make the senior national team. This is displayed by the fact that more multi-sport athletes made it to the senior competitive level versus those that had specialized in the sport earlier. The current research was not a longitudinal study and therefore did not determine the level of elite participation the subjects achieved as adults. However, none of these current research athletes were participating on a youth national team level but they were competitive school and club sport athletes. The results of the study by Moesch et al. (2011) could also reflect that the multi-sport athletes subjected to various movements and sports gained valuable experience and performance abilities that allowed them to excel once they specialized later in their sport. Therefore, even though the current research shows greater strength and power among single sport athletes these parameters might not create long term, successful elite athlete.

The results of the present study highlight that the CMJ and isokinetic performance of single-sport athletes is greater than the performances of multi-sport athletes, highlighting the potential strength and power performance benefits of early sport specialization. Performances of 16U elite soccer players from the Radnor et al. (2021) as well as the current study show that single sport athletes do perform better when completing a CMJ. The current study also shows that single sport athletes can produce greater extension peak torques. However, while evaluating the studies from sport Côté et al., 2009; Lonsdale et al., 2009; Moesch et al., 2011; Hall et al., 2015; and Post et al., 2017 that have concluded that early-specialization should be reconsidered based on the fact that it leads to burn-out, injury and a lower level of achievement based on elite status there needs to be further evaluation of the strength and power benefits that come from being a specialized athlete.

9.5.1: Limitations and Areas of Future Research

The limitations of this are that this group of athletes are strictly post-PHV subjects. This study was also a cross-sectional comparative study and did not follow a group of subjects throughout their transitions through adolescents. The subjects were also not all participating in the same sport or multiple sports. Therefore, there is a variety of team and individual sports between the current subject group. This enables a broader evaluation of athletes but could affect outputs depending on the breakdown of more jumping based sports like basketball and volleyball with more endurance sports like running and tennis. Categorizing subjects based on sport participation was difficult in this study because there was such a wide variety of sports played by the athletes. Ideally the best comparison would be to have a group of single sport athletes and multiple sport athletes who all participate in the same main sport with the multiple sport athletes participating in similar additional sports (either team sports or individual sports). Due to time constraints, a global pandemic and low subject participation getting subjects to fit into these parameters was not possible. This study did ensure that the single sport subjects were highly specialized according to the parameters set by Jayanthi et al. (2015). The single sport subjects in this study were participating in only one sport, had quit another sport to focus solely on their main sport and participated in their sport more than 8 months out of the year. Therefore, given the circumstances it was the most acceptable way to analyze these two groups of subjects.

Future research should incorporate a longitudinal study that can include subjects that transition from multi-sport to single sport versus those who were only single sport or continued to be multi-sport. Ideally it would be best to have early specialized athletes and athletes that transition to sport specialization at different points in their maturation. This research should also get groups of athletes all participating in the same single sport as well as the same second or third sport to eliminate questions revolving around testing performances based on the sport an individual participates in. A longitudinal study would be able to see in more detail the physical changes and implications single and multi-sport participation has on a growing adolescent body. More research should also be done to examine differences that might exist between specific single-sport athletes. There should be more information regarding normative values for this age group while performing CMJ and isokinetic testing to be able to set standards for these age groups. Within these evaluations long-term athlete development and the ability to develop life long active individuals should be observed. The goal of previous studies from sport Lloyd et al., (2005) is to start developing lifelong from birth until death but the constant need to win at all costs may be inhibiting the ability of trainers and coaches to develop this mindset of a healthy body development.

9.5.2: Conclusion

In conclusion the results of this study indicate that single-sport athletes outperform multi-sport athletes in the CMJ and isokinetic assessments after PHV has been achieved. These findings show that single sport participation may be beneficial in strength and power performance output for these athletes. However, based on previous research by Côté et al. (2009), Lonsdale et al. (2009), Moesch et al. (2011), Fransen et al. (2012), Hall et al. (2015) and Post et al. (2017) there may be more cons than pros when specializing early in sport. These past research studies have shown higher dropout rate and injury rate in those individuals who specialize early and therefore do not make it to the higher level of competition because they are no longer completing in the sport. Therefore, even though the current study shows greater performance output from the single sport athletes in the CMJ and isokinetic testing these athletes are less likely to thrive later in sports due to burn out. These results show that future focuses need to be made on using the physical benefits of being a single sprot athlete but still enabling those athletes to thrive, stay injury free and enjoy the sport they are participating in so that they continue to play their sport.

Chapter 10: Overall Thesis Discussion

The overall findings from this thesis highlight significant and meaningful differences based on where a subject was in relationship to their peak height velocity (PHV). Subjects who were post-PHV demonstrated better performances during the countermovement jump (CMJ) and isokinetic knee flexion and extension testing compared to the pre- and circa-PHV subjects; however, there were no differences in performance between the pre- and circa-PHV groups. Once an individual is post-PHV it does not appear to matter if they were an average or late maturer because there were no significant or meaningful differences in CMJ and isokinetic torques between the groups classified as early and late maturers. The findings within the thesis also illustrate that single sport athletes perform better in the CMJ and isokinetic knee flexion and extension assessments compared to the multiple sport athletes once they have reached their post-PHV phase.

These results of the current thesis show the importance of knowing what maturation phase an adolescent athlete is in based on the affect it plays on the performance abilities of these subjects completing CMJ and isokinetic knee flexion and extension assessments. Past research by McMahon et al. (2017) and Morris et al. (2020) has shown that relative values for variables such as peak eccentric force, peak concentric force, peak eccentric power, peak concentric power, impulse, eccentric impulse and rate of force development do not show significant differences between the subject groups based on age where absolute values for these variables did show differences. However, the results of these studies only occurred when the subjects were all post-PHV being compared between academy and senior teams (McMahon et al., 2017) or athletes that would most likely fall between per and circa-PHV (Morris et al., (2020). In contrast, the results of this thesis show significantly and meaningfully greater performances, based on relative data (i.e., scaled for body mass; relative force, power and torque at $60°.s^{-1}$), for the post-PHV group compared to the pre and circa-PHV group. The reasoning behind the significant differences being found in the current study (Chapter 7) and not in past studies could be the sample of subjects being used. The current research consisted of non-elite level athletes whereas the McMahon at al. (2017) and Morris et al. (2020) evaluated elite subjects at different ages. If the subjects are elite athletes, they may have developed better performance techniques at a younger age to enable better relative outputs. It is also possible that these current research subjects did not participate in appropriate training to develop a greater increase in performance output that the elite athletes might have. It is possible that the current research athletes were mainly focused on sport-specific skill training and not strength and conditioning training that would allow for better performance output in testing such as the CMJ and isokinetic dynamometer. These results pose the question of potential impacts of early specialization on performance output and how that may or may not be beneficial to the adolescent. Overall, determining an individual's PHV will help enable athletes, coaches, trainers, and researchers to better understand and prepare athletes as they are growing and enable better training techniques to develop stronger athletes in a safe and positive way.

Not only is it important to know what phase of maturation a subject is in during PHV, such as pre, circa and post, it is also important to know if a subject is an early, average, or late maturer. Research has been conducted on athletes that are post-PHV but have reached there PHV at different chronological ages (Hägg and Taranger, 1991; Till et al., 2017). This past research, as well as the current research (Chapter 8), has shown that once a subject is post-PHV there are no significant or meaningful differences based on whether the subject was an early, average, or late maturer. However, if a subject is an early maturer and they hit their growth spurt one to two years earlier than an individual of the same age, their size differences will likely positively impact their ability to perform athletic tasks simply because they are bigger and stronger than others the same age, but who may be developing later. Therefore, at certain ages athletes may be outperforming just because they grew first which could hinder their skill improvement because they are physically more dominant and that is how they achieve success. The findings in Chapter 8 supports the idea that subjects maybe better off separated by maturation timing and not chronological age until they are post-PHV. This is a difficult task because it would require PHV testing within youth sport systems which is difficult. However, within club or academy teams is may be feasible to create some training sessions based on maturation timing which would enable adolescence to develop the skills among athletes of similar maturation and hopefully not be left behind or dropped from a team simply because they are smaller. It would also benefit the early maturers because they would be competing against individuals who are physically similar so they would have to develop more skill and not rely as much on their strength and size gain success.

The results of this research within Chapter 9 illustrated that single sport athletes perform better than multi-sport athletes during the CMJ and isokinetic knee dynamometer testing. This result raises the question as to what cost being a single sport athlete has. Past researchers have shown that being a single sport athlete increases injury risk and does not necessarily create an elite athlete. The current results showed single sport athletes outperformed multi-sport athletes in the CMJ and isokinetic dynamometer peak torque for the quadriceps and hamstrings where results from other studies showed that early specialization and single sport participation are one of the reasons adolescent athletes get injured, burn out and may eventually drop out of sport (Côté et al. 2009; Fransen et al., 2012; Hall et al., 2015; Lonsdale et al., 2009; Moesch et al., 2011; Post et al., 2017). The results from Fransen et al. (2012), however, show that younger subjects, ages 10-12, who were multiple sport athletes performed better in the strength and motor coordination tests. The contrasts between the current thesis results and the Fransen et al. (2012) study questions when the transition from multiple to single sport participation would be most advantageous. Therefore, coaches, trainers, and practitioners need to be aware that there may be performance benefits to being a single sport athlete but there needs to be a way to develop them in a healthy way throughout their adolescents. Based on studies by Côté et al. (2009) and Moesch et al. (2011) the elite athletes are predominantly multi-sport athletes, which might be because the single sport athletes have dropped out prior to becoming elite. Till et al. (2018) have created a testing battery to start to analyze fitness characteristics like speed, agility and lower body power and strength among adolescents. The variables from these tests were used to create rolling averages to allow adolescent athlete comparisons based on chronological age and maturation phase (Till et al., 2018). These rolling averages assessing anthropometric data as well as speed, strength and agility will allow assessment of physical and performance impacts of single and multiple sport athletes as well as growth spurt impact. If single sport athletes can perform athletic tasks better like they did in the current thesis, Chapter 9, we may be losing some of our stronger athletes to injury and drop out because we do not have a healthy way to get them to the highest level. Therefore, the physical and mental cost of being a single sport athlete needs to be addressed to allow further development of these athletes to hopefully allow more success for the athletes that chose the path of being a single sport athlete.

Current long-term athlete development (LTAD) models presented by Côté et al. (2009) states that an individual should determine if they want to pursue an elite path of commitment to a single sport at around the age of 13 and at 16 the body is developed enough to invest the appropriate effort into highly specialized training. Lloyd et al. (2015) specified that between the ages of 11 and 12 shift a lot of training focus to sport specific skills and away from fundamental movement skills. Balyi and Hamilton (1999) accounted for sports like gymnastics and figure skating, where elite status typically occurs at a younger age, and defined them as early specialization sports. These early specialization sports require different training needs to become elite at a much younger age than the sports that a considered late specialization sports like team sports, athletics and cycling. The later specialization sports allow more time for engagement in other sports and movement training (Balyi and Hamilton, 1999). Balyi and Hamilton (1999) also believed that sport specific training should not start in the late specialization sports until the child is at least 10 years of age to prevent burn out, drop out and the inability to continue to the next phase of training. All these models approach positive ways to develop athletes but still seem to be incomplete. The results of Chapter 9 show that being a single sport athlete has a positive effect on athletic performance but is not specifically addressed in the current LTAD models. The LTAD modes need to expand to enhance the growth of single sport athletes participating in early specialization sports as well as athletes who are only interested in participating in a single sport that is considered a late specialization sport. There needs to be a way for single sport adolescents to still develop and grow into healthy active individuals who can continue sport participation if they so choose and not drop out because they are injured or burned out from the physical demands being required of them. The athletes tested between single and multi-sport were post-PHV (around 16 years or older) and therefore later in their adolescence which may start to show when transitions to single sport might be most beneficial. However, the question remains as to what cost being a single sport athlete truly has since most research supports that those athletes are at higher risk of injury and drop out which means they never reach the level of success they wanted.

The current models of LTAD initial training focuses has been determined based on where an adolescent is in their growth spurt (Lloyd et al., 2015). However, the term long term athlete development seems to only be concerned about athletes until they are around 18 years old. Balyi and Hamilton (1999) express that an individual is in sport-specific, high performance, training to win stage after the age of 18 years old for most sports. Research shows most athletes are competing at their highest level from 19-34 years of age (Petroczi and Naughton, 2008). Therefore, it remains a question as to what exactly is being achieved with the LTAD models. The idea of it being a youth development program versus a long-term athlete development program maybe more applicable. Research should be conducted to see if we can create healthy athletes for the long term. It may also be advantages to try and be able to create a model to help create elite athletes. Sports are things that some people are more gifted at than others, just like some people are artists or musicians, however, is there a not a different path to become an elite athlete or just healthy long-term athletes. It is known that being an active individual has health benefits throughout one's life. As practitioners, not only should the focus be on creating stronger, elite athletes, but also athletes who want to continue to lead active and healthy lifestyles once their competitive careers are over or to just create healthy active individuals for the entirety of their lives. It seems that it cannot be placed into one specific model and that there needs to begin to be a further breakdown of the research that exist to create more specific and concentrated model depending on what an individual's fitness goals are.

Youth athletes are the future of sport. Therefore, it is imperative that we develop them in a safe and healthy way but also help them to be better, stronger and faster athletes. Research has started to focus on the best development approaches for these subjects as they transition through maturation and how that affects their abilities to perform. The current study helped solidify the fact that performance improvements do occur while a subject is growing and that subjects that hit their spurt later in their adolescent do not show detriments in performance once they have reached post-PHV. Research should continue to evaluate athletes throughout their maturation phases and timing to enable better training practices for these individuals. Evaluation of single sport and multi-sport athletes should also continue so that subjects who choose to be single sport athletes are able to continue participation without dropout and athletes who wish to continue participation in multiple sports are able to improve their performance to the level of the single sport athletes.

10.1: Limitations

Ultrasound testing has been shown to have some limitations as a testing method because it is operator-dependent and highly manipulatable data based on probe placement, probe pressure and probe orientation (Klimstra et al., 2007; König et al., 2014). The results of Chapter 4 from the current thesis did find some reliable variables within the ultrasound scans. However, they were typically only found on one or the other of the legs or only on one of the muscles. Based on the inconsistencies of the reliable variables it was determined to not carry the ultrasound data into the proceeding studies of the current research. If the researcher had had an opportunity to retest the subjects to ensure reliable measurements it would have been done. However, the testing facility has been closed for over two years and the additional data was not able to be collected due to the global pandemic. Also, previous researchers have shown similar measurements as Chapter 4 of the current thesis and presented ICC values but did not account for 95% confidence intervals (CI) (Kwah et al., 2013). The current study would have shown all moderate to strong reliability if the lower bound 95% CI was not accounted for. Therefore, even though the current study (Chapter 4) had slightly lower ICC values the more robust evaluation of the data using the lower bound 95% CI to interpret the level of reliability may account for some of the ultrasound variables not being found reliable. Recent research by Ripley, Comfort and McMahon (2022) evaluated the impact of the probe size used while performing ultrasound testing and found that probes between 4-6 cm in length overestimate fascicle length in comparison to a longer 10 cm probe that allows for a larger field of view analysis. The current researcher only had access to a 4.5 cm probe which may account for the lower number of reliable variables from the ultrasound testing being found.

Past researchers have also shown more variables to be reliable within the CMJ and isokinetic dynamometer testing (Kannus et al., 1991; McMahon et al., 2017; Morris et al., 2020). To create a more in-depth analysis of the performance variables of athletes the past research has shown RSImod, braking impulse, propulsion time phase, braking phase time, total time to take-off and countermovement jump depth variables during a CMJ test as well as angles at peak torque and hamstring/quadriceps peak torque ratios for isokinetic dynamometer to be reliable variables (Kannus et al., 1991; McMahon et al., 2017; Morris et al., 2020). The current thesis (Chapter 4) however, found these variables to not be reliable within the subject pool for this research. The CMJ and isokinetic dynamometer peak torques of the quadriceps and hamstrings have been shown to work better if there is a familiarization period (Chan et al., 2020; Fowler et al., 1995; Kellis et al., 1999). This familiarization period enables the subject to learn the movements and perform them in a consistent and effective way. However, the current researcher had limited access to the subjects and familiarization sessions were not able to take place. This would be something to consider for future research.

The final limitation of this thesis was subject involvement. It was difficult to recruit individuals to participate in this study and the majority that did were only interested in participating in one session. The subjects also participated in a wide variety of sports and were just categorized a single or multiple sport athletes. For the analysis of these subjects based on maturation timing and phase it is not as imperative to have the consistency of sports among the subject because it enables an assessment of maturation on all youth athletes. However, when breaking down the comparisons into single versus multiple sport athlete the ideal makeup would have been all subjects participating in the same sport, whether they were single or multiple, and then the multiple sport athletes participating in their other sports. Best case scenario would be if the other sports were the same as well. This situation is quite difficult, especially with the lower participation numbers than originally hoped for. Athletes can all be evaluated based on power, strength, force production, speed, etc. but different sports can emphasize different muscle groups and movement patterns that may help athletes complete certain testing measure better than other athletes simply based on what physical demands are required in the various sports. Therefore, the single versus multiple sport analysis needs to have a more in depth and focused set of subjects to truly evaluate the effects of these two paths. This thesis was a start and showed differenced from past research and therefore presents the ability for more research to be done.

10.2: Future Research

Researchers should continue to evaluate the impacts of maturation phases on the development of youth athletes. The current thesis supports the idea that due to physical changes during an adolescent's growth spurt athletic performances during CMJ and isokinetic dynamometer tests for peak torque of the hamstring and quadricep muscles are being affected. This thesis also shows that being a late maturer does not affect the performance abilities during a CMJ or isokinetic dynamometer peak torque once an adolescent is post-PHV. Therefore, future research should evaluate the feasibility of some separation of training groups based on maturation phase and not chronological age to enable full development of all subjects no matter what phase of PHV they are in. It may not be possible to separate adolescent in competitive situations based on maturation status, but it should be possible to separate some training sessions in this way to give the more physically dominant subjects who matured earlier more physical competition to improve skills and the later developers time to improve skills because they are not being physically overpowered. The LTAD models should also be expanded to help create better approaches for the adolescents that are wishing to pursue elite athletic competition and the path that may help them achieve that. The models also have to address the individuals that may just want to stay healthy and active. The LTAD models are a great start for development throughout maturation but need to have more focused pathways depending on what an adolescent is looking to achieve throughout their athletic development.

The athletes included within this thesis participated in a wide variety of sports both as single and multi-sport athletes. This thesis did show that single sport athletes performed better then multi-sport athletes. However, future research could look into athletes that are participating as multiple sport athletes with one sport in common, for example soccer, and compare those athletes' performances to single sport athletes in the same common sport. This research would enable further examination of the performance impacts of being a single sport athlete compared to athletes in that sport that are participating in other athletic sports.

Based on previous research that involves using these testing measures to evaluate injury risk future research should be used to address this issue among the adolescent population as well. There injury rate increase and the number of children having major surgeries are reason to make injury prevention research an important topic of research going forward. Now seeing more details about athletic performance and how it is impacted by maturation and single or multiple sport participation the transition to safety while also improving performance should be made.

Therefore, the most beneficial future study would be a longitudinal study that would follow a large cohort of adolescent athletes along their athletic pathway. This study should include early specialization sport athletes like gymnasts and figure skaters, where the athletes may stop competing in their sport at a younger age because they reach peak performance at such a young age but may pick up other sports and continue to be active individuals. It would also allow evaluation of performance output when subjects change from multiple sport to single sport and how different ages at that transition may impact future performances and/or injury and dropout. The current thesis results as well as past research results are just pieces of a whole picture. Therefore, even though this would be a large undertaking and many years of commitment the longitudinal approach would allow for the most holistic and informational approach to evaluation of adolescent athletes and the true impacts on sport participation and maturation on athletic performance.

10.3: Conclusion

The findings within this thesis supported past research showing that post-PHV adolescents outperform pre- and circa-PHV subjects. The current researcher also found that subjects who are late maturers do eventually "catch up" and perform just as well as average maturers during the CMJ and isokinetic dynamometer peak torque testing once they have reached post-PHV. Also subjects that were single sport athletes post-PHV outperformed multi-sport athletes in the CMJ and isokinetic peak torque evaluations.

10.4: Practical Application

Coaches, trainers, and researchers are all interested in getting athletes to perform their best. The current thesis can help these individuals better evaluate the adolescent subjects they are working with. Adolescents need to be tracked through their PHV to ensure the safest and most effective training strategies are being used to help them grow and develop as athletes. Also, it is imperative that coaches, trainers and researchers know that adolescents that are later maturers will eventually "catch up" and perform just as well as the adolescents that mature at an early or average age. Therefore, these practitioners need to be aware of the PHV timing of an individual so that the later maturers can pursue and perform in their sports even if they are behind their peers in their growth spurt. It is also important for coaches, trainers and researchers to be aware that the single sport athletes are outperforming multi-sport athletes once they reach post-PHV based on this thesis. This analysis may show that there are more advantageous times to switch over to single sport focus that will better help athletes perform their sport specific skills and possibly lead them to elite competition if that is the path they so choose.

10.5: Thesis Reflection

The journey of this thesis was not a direct path and it consisted of a variation of peaks and valleys, twist and turns. The original focus of this thesis was to evaluate youth athletes who were at a potential higher risk of injury because they were single sport athletes. The idea for this topic began while observing isokinetic data of single sport youth athletes at IMG Academy. Based on the previous research about muscle imbalances and H/Q ratios it seemed that these athletes may be injured due to those deficiencies. However, little research existed between athletic performances of single and multiple sport athletes. The past research stated that single sport athletes were more susceptible to injury based on questionnaires but there is not any research on how they perform their sport prior to injury. Subject age 13-18 were selected for this study because they are the subject participating in their school sports as well as potentially specializing by joining a club. Therefore, the original plan of this thesis was to see what physical and performance differences could be seen between single sport and multiple sport athletes.

After analysis was completed for the test-retest reliability study there were a few variables that were not found reliable that had been used in past studies to help evaluate injury risk. With the isokinetic dynamometer the H/Q ratio for the subjects was not found to be reliable. This made it difficult to compare data with past research on injury risk since the majority of the data was based on what the athlete's H/Q ratios were. The analysis also showed that not many muscle architecture variables were found to be reliable either. Extensive ultrasound training should be completed prior to data being collected for a study. However, being a distance learner, and needing to start testing subjects it was not a feasible situation. The researcher had training in ultrasound scans and the requirements needed to perform them but consistency across multiple days is where the issue was. The remeasurement and placement of the probe in the same spot was found to be the detriment of this testing method.

Once the H/Q ratios and ultrasound variables were found to be unreliable in this study another variable was presented. Since the subjects were adolescents the need to evaluate them based on where they were in their maturation. As a coach you witness the "adolescent awkwardness" stage of maturing athletes but don't always address the physical implications that might be occurring. You accept that a kid may be smaller than another, but he will eventually grow out of it and that the kid who has not figured out his limbs will eventually gain the muscle control to not be awkward anymore. However, is there a way to see what these differences are and how to make the transition through this phase smoother. This is when the thesis changed to have a large focus on peak height velocity and how it effects the athletes who are going through this phase.

At this in the journey ideally would have been to get more subjects into the lab to have more subjects within the different stages of adolescents and to do another ultrasound reliability study in order to have this data to use. However, at this point the world was in the middle of a global pandemic and the laboratory along with the world was shut down. The research analysis continued with the subject data that had been completed and the thesis was still able to provide useful result involving the performance outputs of adolescent athletes throughout their maturation journey and also provide insight into the difference performance ability of single and multiple sport athletes using laboratory testing.

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Appendices

Appendix A: Ethical Approval from the University of Salford

Research, Innovation and Academic Engagement Ethical Approval Panel

Research Centres Support Team
G0.3 Joule House
University of Salford
M5 4WT

T +44(0)161 295 2280

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10 March 2017

Dear Candice,

RE: ETHICS APPLICATION–HSR1617-64–'Assessment of Lower Limb Muscle Structure and Performance in Youth Single-Sport and Multi-Sport Athletes.'

Based on the information you provided I am pleased to inform you that application HSR1617-64 has been approved.

If there are any changes to the project and/or its methodology, then please inform the Panel as soon as possible by contacting Health-ResearchEthics@salford.ac.uk

Yours sincerely,

Sue McAndrew
Chair of the Research Ethics Panel

Appendix B: Ethical Approval from SUNY Upstate (2017-2021)

UPSTATE
MEDICAL UNIVERSITY

Institutional Review Board for the
Protection of Human Subjects
750 East Adams Street
Syracuse, NY 13210

DATE:	October 26, 2017
TO:	Christopher Neville
FROM:	SUNY Upstate IRB
SUBMISSION TYPE:	Response/Follow-Up- NEW STUDY
PROJECT TITLE:	[1043534-2] Assessment of Lower Limb Muscle Structure and Performance in Youth Single-Sport and Multi-Sport Athletes
UPSTATE IRB #:	2017-0
ACTION:	APPROVED
APPROVAL DATE:	October 26, 2017
EXPIRATION DATE:	October 25, 2018
REVIEW TYPE:	Expedited Review
EXPEDITED REVIEW CATEGORY:	Expedited review category #4, #7.

Thank you for your submission of Response/Follow-Up materials for this project. The SUNY Upstate IRB has APPROVED your submission. All research must be conducted in accordance with this approved submission. As the Principal Investigator, you are responsible for the overall conduct of this research study.

Please note that any modifications to the project as approved must be reviewed and approved by this committee prior to initiation (unless the change is required to eliminate an immediate hazard to the subjects).

Where obtaining informed consent/permission/assent is required as a condition of approval, be sure to assess subject capacity in every case, and continue to monitor the subject's willingness to be in the study throughout his/her duration of participation. Only use current, Upstate-stamped forms in the consent process and retain a complete copy of each signed form with your study records. Consent must be obtained and documented prior to the initiation of any study procedures. Provide each participant with a complete copy of the signed consent document.

- Pediatric Risk Assessment: 45 CFR 46.404, 21 CFR 50.51- Research not involving greater than minimal risk.
- Permission of at least one parent is required
- In accordance with 45 CFR 46.408, the IRB has determined that: Assent of all children is a necessary condition for proceeding with the research. Documentation of assent on the IRB approved consent form is required for all subjects.

Report All UNANTICIPATED PROBLEMS involving risks to subjects or others and SERIOUS and UNEXPECTED adverse events promptly to this office, per the IRB policy. All FDA and sponsor reporting requirements should also be followed.

Report any COMPLAINTS regarding this project to this office.

You are reminded that you must apply for, undergo review, and be granted continued approval for this study before October 25, 2018 in order to be able to conduct your study in an uninterrupted manner. If you do not receive approval before this date, you must cease and desist all research involving human subjects, their tissue and their data until such time as approval is granted.

If you have any questions, please contact Marti Benedict at 315-464-4317 or benedicm@upstate.edu. Please include your project title and reference number in all correspondence with this committee.

Documents in this submission:

- Application Form - Application for IRB Review of Human Subject Research.doc (UPDATED: 10/19/2017)
- Consent Form - Consent Form for Adult & Minor Subjects 5.1.17 (2).doc (UPDATED: 10/23/2017)
- Other - Form-Research Billing Form 4.26.17.pdf (UPDATED: 10/23/2017)
- Other - Administrative Review Response_1043534.docx (UPDATED: 10/4/2017)
- Other - Scientific Review Questions Answers.docx (UPDATED: 06/5/2017)
- Protocol - PROTOCOL.docx (UPDATED: 10/19/2017)
- Questionnaire/Survey - Participant Questionnaire.docx (UPDATED: 06/5/2017)
- Registration Form for IRB Review - Registration Form for IRB Review (UPDATED: 10/4/2017)
- Other - Testing Brochure.docx (UPDATED: 05/5/2017)

UPSTATE
MEDICAL UNIVERSITY

CONSENT & AUTHORIZATION FORM

TITLE OF STUDY: Assessment of Lower Limb Muscle Structure and Performance in Youth Single-Sport and Multi-Sport Athletes

PRINCIPAL INVESTIGATOR: Christopher Neville, PT, PhD

ADDRESS: 3334 NAB, Upstate Medical University, Syracuse, NY 13210

PHONE NUMBER: (315) 464-6888

If you are a parent or legal guardian of a child who may take part in this study, permission from you is required and the assent (agreement) of your child may be required. When the word "you" appears in this consent form, it refers to your son or daughter.

INTRODUCTION:

Please read this form carefully. It tells you important information about a research study. A member of the research team will also talk to you about taking part in this research study. People who agree to take part in research studies are called "subjects." This term will be used throughout this consent form. Research studies include only those individuals who choose to take part. Please take your time to make your decision. Please ask the researchers to explain any words or information that you do not understand. You may also want to discuss it with family members, friends or health care providers.

BACKGROUND/PURPOSE:

The purpose of this study is to evaluate the possible muscle differences between youth athletes that participate in one sport and those athletes that participate in multiple sports. There has been some research completed in older athletes that shows multiple sport participation leads to a longer and healthier sporting career. However, little information is available for youth athletes between 13 and 18 years of age. Therefore, you have been asked to participate in this research study because you are a healthy athlete (13-18 yrs. of age) participating in either one or multiple sports.

We plan to enroll 200 subjects in this study, being conducted at Upstate Medical University. 100 subjects will be single sport athletes and 100 subjects will be multiple sport athletes. All testing will be conducted at the Institute for Human Performance on the Upstate campus.

STUDY PROCEDURES:

If you decide to participate, you will be asked to review and sign this informed consent form before any study procedures. As a participant in this study you will be asked to report to the Institute for Human Performance between two and five times. Most subjects will have 2 study visits; however, fifteen to thirty subjects will be asked to return to repeat the testing on two or three separate occasions within a 2-week period to determine the reliability of the methods. Study visits will be at least 72 hours apart and a maximum of 7 days apart. Most subjects will perform one testing session and then a 2nd testing session after three months. Three months is the typical length of a sport season and therefore we will be testing you before and after participation in a season.

Each of your visits should take approximately 1 hour. Prior to the first visit, you will be asked to complete a questionnaire. The questionnaire will ask you about the sport or sports you participate in as well as how many hours a week you spend in your sport(s). This information will be used by the researchers to categorize you into a single-sport or multi-sport youth athlete.

During the study visit you will participate in a few baseline measurements (height, weight, etc.). Then you will complete four assessments of your legs, as described below:

1. **Ultrasound:** your lower limb muscles will be scanned with an ultrasound machine to evaluate the differences between the muscles.
2. **Jumps**: you will be asked to complete a set of jumps to determine the peak power and force of your leg muscles.
3. **Lifting procedure:** you will be asked to pull up on a stationary bar as hard as you can to help determine the peak forces you create with this motion.
4. **Leg strength test:** you will be asked sit in a chair where you will push and pull a bar with your leg in order to determine peak forces and muscle balance of your leg muscles.

As a subject in this study you may have videos and/or photographs taken of you while you participate in the research assessments.

RISKS:

The research testing requires maximal effort, so there is a risk for injury. Precautions will be taken in order to reduce the possibility of injury. These include: appropriate instructions and thorough warm up procedures. Soreness and muscle fatigue may be experienced during the maximal effort testing session and a few days following the testing. This soreness will feel like a normal hard practice/game soreness that you may have experienced in the past.

Ultrasound testing can produce heat in the tissues that could produce small pockets of air. However, the ultrasound probe will not be on a location for longer than 30 seconds and all scanning of an area will be completed in less than 2 minutes. This means heat production in the tissues is unlikely. In order for you to participate you will also have no history of lower leg injury which also means ultrasound risks are minimal.

BENEFITS:

A summary of the test results will be provided to you. Hopefully this information can help you identify any imbalances and ways to potentially correct these issues. However, we cannot promise that study participation will be of any benefit to you. The information we learn from the study may help to increase our understanding of youth sport specialization and its' effects on lower limb muscles and potential associated injury risks.

VOLUNTARY PARTICIPATION / STUDY WITHDRAWAL:

Your participation in this study is entirely voluntary and you may refuse to participate or discontinue participation at any time without penalty or loss of benefits to which you would normally be entitled. Your decision about whether or not to participate in the study will not affect your relationship with or the care you receive at SUNY Upstate Medical University.

You may stop your particiaption in the study at any time. In addition, the researchers may take you out of the study at any time without your agreement. This may happen if:

- It is in your best interest to stop your participation
- You are not able to follow the study instructions
- The study is canceled

NEW INFORMATION:

You will be informed in a timely manner if new information that could affect your willingness to continue participation in this study becomes available.

COSTS/PAYMENTS:

There are no costs to you for participating in this study. The Upstate Medical University Department of Physical Therapy Education, the sponsor of this study, will pay all costs for the required study testing. You will be paid $10.00 per visit to cover your travel expenses. In the event that your participation in the study is discontinued early, you will only be paid for the visits you completed.

By accepting payment for participating in this study, identifying information about you (such as your full name and social security number) needs to be collected and may be shared with auditors and the finance office to ensure compliance with Internal Revenue Service (IRS) requirements. If you do not want to provide this information for payment reasons, you have the option to decline the payment and still participate in the study. Please note that if you earn $600 or over in a calendar year as a research subject, you may have to pay taxes on these earnings. Information provided for payment purposes will be kept confidential.

QUESTIONS:

If you have any questions about the research, or in the event of a research-related injury, please contact either Candice Hofmann at (315) 506-0799 or Chris Neville, PT, PhD at (315) 464-6888.

If you have any questions about your rights as a research subject, please contact the SUNY Upstate Medical University Institutional Review Board Office at (315) 464-4317.

IN CASE OF INJURY:

In the event of illness or physical injury resulting from taking part in this research study, medical treatment will be provided at University Hospital. You will be responsible for any costs not paid by your insurance company. No other compensation is offered by SUNY Upstate Medical University. SUNY Upstate Medical University has no plans to give you money if you are injured. You have not waived any of your legal rights by signing this form.

CONFIDENTIALITY OF RECORDS AND AUTHORIZATION TO USE/SHARE PROTECTED HEALTH INFORMATION FOR RESEARCH:

If you agree to participate in this research, identifiable health information about you will be used and shared with others involved in this research. For you to be in this research we need your permission to collect and share this information. Federal law protects your right to privacy concerning this information.

When you sign this consent form at the end, it means that you have read this section and authorize the use and/or sharing of your protected health information as explained below. Your signature also means you have received a copy of Upstate's Notice of Privacy Practices.

Individually identifiable health information under the federal privacy law is considered to be any information from your medical record, or obtained from this study, that can be associated with you, and relates to your past, present, or future physical or mental health or condition. This is referred to as protected health information.

Your protected health information will be kept confidential. Your identity will not be revealed in any publication or presentation of the results of this research.

There may be video and photographs taken of some subjects performing the testing. These will be used to demonstrate and show how the testing was performed during this study. They will be stored on a USB drive that will be kept locked with the other confidential forms from the study. Only the researchers involved with this project will have access to the files. The files will be kept once the study is completed for educational purposes and as references for future research.

Why is it necessary to use/share your protected health information with others?
The main reason to use and share your health information is to conduct the research as described in this consent form. Your information may also be shared with people and organizations that make sure the research is being done correctly, and to report unexpected or bad side effects you may have.

In addition, we may be required by law to release protected health information about you; for example, if a judge requires such release in a lawsuit, or if you tell us of your intent to harm yourself or others.

What protected health information about you will be used or shared with others as part of this research?
We may use and share the results of tests, questionnaires, and interviews. We may also use and share information from your medical and research records. We will only collect information that is needed for the research.

Who will be authorized to use and/or share your protected health information?
The researchers, their staff and the staff of Upstate Medical University participating in the research will use your protected health information for this research study. In addition, the Upstate Institutional Review Board (IRB), a committee responsible for protecting the rights of research subjects, and other Upstate Medical University or University Hospital staff who supervise the way the research is done may have access to your protected health information.

The researchers and their staff will determine if your protected health information will be used or shared with others outside of Upstate Medical University for purposes directly related to the conduct of the research.

With whom would the protected health information be shared?
Your protected health information may be shared with:

- Federal agencies that supervise the way the research is conducted, such as the Department of Health and Human Services' Office for Human Research Protections, other governmental offices in the US or other countries, as required by law.

All reasonable efforts will be used to protect the confidentiality of your protected health information. However, not all individuals or groups have to comply with the Federal privacy law. Therefore, once your protected health information is disclosed (leaves Upstate Medical University), the Federal privacy law may not protect it.

For how long will your protected health information be used or shared with others?
There is no scheduled date at which this information will be destroyed or no longer used. This is because information that is collected for research purposes continues to be used and analyzed for many years and it is not possible to determine when this will be complete.

Can you withdraw your authorization to collect/use/share your protected health information?
You always have the right to withdraw your permission (revoke authorization) for us to use and share your health information, by putting your request in writing to the investigator in charge of the study. This means that no further private health information will be collected. Once authorization is revoked, you may no longer participate in this research activity, but standard medical care and any other benefits to which you are entitled will not be affected. Revoking your authorization only affects uses and sharing of information obtained after your written request has been received, but not information obtained prior to that time.

Even after you withdraw your permission, Upstate Medical University may continue to use and share information needed for the integrity of the study; for example, information about an unexpected or bad side effect you experienced related to the study.

Can you have access to your health information?
At the end of the study, you have the right to see and copy health information about you in accordance with the SUNY Upstate Medical University policies; however, your access may be limited while the study is in progress.

CONSENT TO PARTICIPATE IN RESEARCH & AUTHORIZATION TO USE AND SHARE PERSONAL HEALTH INFORMATION:

- I have read this information and this study has been explained to me.
- It has been written in a language that I understand.
- All my questions about the study have been answered to my satisfaction.

For Subjects 18 Years of Age

I hereby give my consent to participate in this research study and agree that my personal health information can be collected, used and shared by the researchers and staff for the research study described in this form. I will receive a signed copy of this consent form.

_______________________________________ _______________
Signature of subject Date

____ _______________
Signature of Person Obtaining Consent/Authorization Date

____
Name of Person Obtaining Consent/Authorization

For Subjects less than 18 Years of Age

The nature and the purpose of the above research study have been explained to my child and me; we have agreed to have my child participate in the research study. We also agree that my child's personal health information can be collected, used and shared by the researchers and staff for the research study described in this form. We will receive a signed copy of this consent form.

___________________________________ _____________________
Signature of Parent/Guardian Date

___________________________________ _____________________
Signature of Subject Date

__________________________________ _____________________
Signature of Person Obtaining Consent/Authorization Date

____
Name of Person Obtaining Consent/Authorization

UPSTATE
MEDICAL UNIVERSITY

Institutional Review Board for the
Protection of Human Subjects
750 East Adams Street
Syracuse, NY 13210

DATE:	October 16, 2018
TO:	Christopher Neville
FROM:	SUNY Upstate IRB
SUBMISSION TYPE:	Continuing Review/Progress Report
PROJECT TITLE:	[1043534-3] Assessment of Lower Limb Muscle Structure and Performance in Youth Single-Sport and Multi-Sport Athletes
UPSTATE IRB #:	2017-1
ACTION:	APPROVED
APPROVAL DATE:	October 16, 2018
EXPIRATION DATE:	October 15, 2019
REVIEW TYPE:	Expedited Review
EXPEDITED REVIEW CATEGORY:	Expedited review category # 4, #7

Thank you for your submission of Continuing Review/Progress Report materials for this project. The SUNY Upstate IRB has APPROVED your submission. All research must be conducted in accordance with this approved submission. As the Principal Investigator, you are responsible for the overall conduct of this research study.

Please note that any modifications to the project as approved must be reviewed and approved by this committee prior to initiation (unless the change is required to eliminate an immediate hazard to the subjects).

Where obtaining informed consent/permission/assent is required as a condition of approval, be sure to assess subject capacity in every case, and continue to monitor the subject's willingness to be in the study throughout his/her duration of participation. Only use current, Upstate-stamped forms in the consent process and retain a complete copy of each signed form with your study records. Consent must be obtained and documented prior to the initiation of any study procedures. Provide each participant with a complete copy of the signed consent document.

- Pediatric Risk Assessment: 45 CFR 46.404, 21 CFR 50.51- Research not involving greater than minimal risk.
- Permission of at least one parent is required
- In accordance with 45 CFR 46.408, the IRB has determined that:

- Assent of all children is a necessary condition for proceeding with the research. Documentation of assent on the IRB approved consent form is required for all subjects.

Report All UNANTICIPATED PROBLEMS involving risks to subjects or others and SERIOUS and UNEXPECTED adverse events promptly to this office, per the IRB policy. All FDA and sponsor reporting requirements should also be followed.

Report any COMPLAINTS regarding this project to this office.

You are reminded that you must apply for, undergo review, and be granted continued approval for this study before October 15, 2019 in order to be able to conduct your study in an uninterrupted manner. If you do not receive approval before this date, you must cease and desist all research involving human subjects, their tissue and their data until such time as approval is granted.

If you have any questions, please contact Jean DeCicco at 315-464-4317 or deciccoj@upstate.edu. Please include your project title and reference number in all correspondence with this committee.

Documents in this submission:

- Consent Form - Consent Form for Adult & Minor Subjects 5.1.17 (2).doc (UPDATED: 09/24/2018)
- Continuing Review/Progress Report - Form-Continuing review report(1)(1).docx (UPDATED: 09/24/2018)

Unless otherwise stated, all documents submitted in previous packages have been approved by the SUNY Upstate IRB.

Institutional Review Board for the
Protection of Human Subjects
750 East Adams Street
Syracuse, NY 13210

DATE:	September 30, 2019
TO:	Christopher Neville
FROM:	SUNY Upstate IRB
SUBMISSION TYPE:	Continuing Review/Progress Report
PROJECT TITLE:	[1043534-4] Assessment of Lower Limb Muscle Structure and Performance in Youth Single-Sport and Multi-Sport Athletes
UPSTATE IRB #:	2017-2
ACTION:	APPROVED
APPROVAL DATE:	September 29, 2019
EXPIRATION DATE:	September 28, 2020
REVIEW TYPE:	Expedited Review
EXPEDITED REVIEW CATEGORY:	Expedited review category *#4, # 7*

Thank you for your submission of Continuing Review/Progress Report materials for this project. The SUNY Upstate IRB has APPROVED your submission. All research must be conducted in accordance with this approved submission. As the Principal Investigator, you are responsible for the overall conduct of this research study.

Please note that any modifications to the project as approved must be reviewed and approved by this committee prior to initiation (unless the change is required to eliminate an immediate hazard to the subjects).

Where obtaining informed consent/permission/assent is required as a condition of approval, be sure to assess subject capacity in every case, and continue to monitor the subject's willingness to be in the study throughout his/her duration of participation. Only use current, Upstate-stamped forms in the consent process and retain a complete copy of each signed form with your study records. Consent must be obtained and documented prior to the initiation of any study procedures. Provide each participant with a complete copy of the signed consent document.

- Pediatric Risk Assessment: 45 CFR 46.404, 21 CFR 50.51- Research not involving greater than minimal risk.
- Permission of at least one parent is required

- In accordance with 45 CFR 46.408, the IRB has determined that: Assent of all children is a necessary condition for proceeding with the research. Documentation of assent on the IRB approved consent form is required for all subjects.

Report All UNANTICIPATED PROBLEMS involving risks to subjects or others and SERIOUS and UNEXPECTED adverse events promptly to this office, per the IRB policy. All FDA and sponsor reporting requirements should also be followed.

Report any COMPLAINTS regarding this project to this office.

You are reminded that you must apply for, undergo review, and be granted continued approval for this study before September 28, 2020 in order to be able to conduct your study in an uninterrupted manner. If you do not receive approval before this date, you must cease and desist all research involving human subjects, their tissue and their data until such time as approval is granted.

If you have any questions, please contact Jean DeCicco at 315-464-4317 or deciccoj@upstate.edu. Please include your project title and reference number in all correspondence with this committee.

Documents in this submission:

- Consent Form - Consent Form for Adult & Minor Subjects 5.1.17 (UPDATED: 09/16/2019)
- Continuing Review/Progress Report - Form-Continuing review report (UPDATED: 09/16/2019)
- Other - Last signed consent form final (UPDATED: 09/19/2019)

Unless otherwise stated, all documents submitted in previous packages have been approved by the SUNY Upstate IRB.

UPSTATE
MEDICAL UNIVERSITY

Institutional Review Board for the
Protection of Human Subjects
750 East Adams Street
Syracuse, NY 13210

DATE:	September 8, 2020
TO:	Christopher Neville
FROM:	SUNY Upstate IRB
SUBMISSION TYPE:	Continuing Review/Progress Report
PROJECT TITLE:	[1043534-5] Assessment of Lower Limb Muscle Structure and Performance in Youth Single-Sport and Multi-Sport Athletes
UPSTATE IRB #:	2017-3
ACTION:	APPROVED
APPROVAL DATE:	September 6, 2020
EXPIRATION DATE:	September 5, 2021
REVIEW TYPE:	Expedited Review
EXPEDITED REVIEW CATEGORY:	Expedited review category *#4 & #7*

Thank you for your submission of Continuing Review/Progress Report materials for this project. The SUNY Upstate IRB has APPROVED your submission. All research must be conducted in accordance with this approved submission. As the Principal Investigator, you are responsible for the overall conduct of this research study.

Please note that any modifications to the project as approved must be reviewed and approved by this committee prior to initiation (unless the change is required to eliminate an immediate hazard to the subjects).

Where obtaining informed consent/permission/assent is required as a condition of approval, be sure to assess subject capacity in every case, and continue to monitor the subject's willingness to be in the study throughout his/her duration of participation. Only use current, Upstate-stamped forms in the consent process and retain a complete copy of each signed form with your study records. Consent must be obtained and documented prior to the initiation of any study procedures. Provide each participant with a complete copy of the signed consent document.

- Pediatric Risk Assessment: 45 CFR 46.404, 21 CFR 50.51- Research not involving greater than minimal risk.
- Permission of at least one parent is required
- In accordance with 45 CFR 46.408, the IRB has determined that:

- Assent of all children is a necessary condition for proceeding with research. Documentation of assent on IRB approved consent form is required for all subjects.

Report All UNANTICIPATED PROBLEMS involving risks to subjects or others and SERIOUS and UNEXPECTED adverse events promptly to this office, per the IRB policy. All FDA and sponsor reporting requirements should also be followed.

Report any COMPLAINTS regarding this project to this office.

You are reminded that you must apply for, undergo review, and be granted continued approval for this study before September 5, 2021 in order to be able to conduct your study in an uninterrupted manner. If you do not receive approval before this date, you must cease and desist all research involving human subjects, their tissue and their data until such time as approval is granted.

If you have any questions, please contact Jean DeCicco at 315-464-4317 or deciccoj@upstate.edu. Please include your project title and reference number in all correspondence with this committee.

Documents in this submission:

- Continuing Review/Progress Report - Form-Continuing review report (UPDATED: 09/3/2020)
- Other - Last signed consent form final (UPDATED: 09/3/2020)

Unless otherwise stated, all documents submitted in previous packages have been approved by the SUNY Upstate IRB.

Appendix C: Subject Questionnaire

PARTICIPANT QUESTIONNAIRE

Study: Assessment of Lower Limb Muscle Structure and Performance in Youth Single-Sport and Multi-Sport Athletes

Subject's Name: ____

Subject's Email: ____

Parent's Email: ____

Subjects DOB: _____/_____/_________

Sport/s you currently participate in:

Sport: ____________________________ Number of Years Played: ____________________

Sport: ____________________________ Number of Years Played: ____________________

Sport: ____________________________ Number of Years Played: ____________________

Sport: ____________________________ Number of Years Played: ____________________

Sport: ____________________________ Number of Years Played: ____________________

Sport: ____________________________ Number of Years Played: ____________________

Do you participate in any of these sports year-round (more than 8 months per year)?

YES / NO (circle one)

If YES, which one/s: ____

On average, how many hours per week do you spend in sports (practice + games)? __________

If you participate in only one sport, how long have you been participating in only one sport? ___

Did you give up other sports to focus on just a single sport? YES / NO (circle one)

Do you participate in a regular workout program along with your sports?   YES / NO (circle one)

If Yes, Explain in detail (lifting, cardio, fitness training etc.):

____

____

____

Have you had any previous medical issues?   YES / NO (circle one)

If YES, please explain:

____

____

____

Have you had any previous injuries to your legs, knees, ankles, hamstrings or quadriceps?

YES / NO (circle one)

If YES, please explain:

____

____

____

Subjects Participation Number: ________________________ (to be filled out by the researcher)