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Effects of Plyometric Training on Lower Extremity Force Production and Reactive Strength in Adolescent Female Basketball Players

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Abstract:

Purpose: The purpose of this investigation was to determine the effects of a 6-week, standardized, group-based plyometric training program on force generating potential of knee extensors, hip abductors, and hip extensors and reactive strength as measured by the reactive strength index in a sample of adolescent female basketball players.

Methods: Seventeen female basketball players completed the study, 13 to 16 years of age (average of 14 years). Isometric force production of knee extensors, hip abductors, and hip extensors was measured with the hand-held MicroFet3 dynamometer. Reactive strength index was measured with the MuscleLab Ergotest infrared contact grid using depth jumps. The intervention consisted of 6 exercises performed prior to normal basketball practice twice per week for 6 weeks. **Results:** statistically significant improvements were observed between pre-test and post-test for all force measurements with the exception of right leg hip abduction. Reactive strength index did not significantly change. **Conclusions:** findings suggest the proposed plyometric training program offers sufficient stimulus to improve lower extremity force production, but not reactive strength in adolescent female athletes. More research is needed comparing the intervention to a control group and to determine an exercise dose necessary to produce changes in reactive strength index.

Keywords: Plyometrics, Reactive Strength, Adolescent Female, Basketball, Force Production

1. Background

Organized high school sports provide opportunities for adolescents to participate in regular physical activity. The National Federation of State High School Associations notes that athletic participation is associated with higher GPAs, increased math and science test scores, a greater sense of belonging and engagement, development of life skills, healthier behaviors, and greater success in post high school settings (Ritchie, 2018). Participation rates remain near all-time highs, with nearly 8 million high school student athletes registering in the 2018-2019 season (National Federation of State High School Associations, 2019). While these numbers are encouraging, high rates also come with increased opportunities for injury.

The National High School Sports-Related Injury Surveillance Study reports 1.36 million injuries with Girls' basketball registering a 4.12 incidence rate per 1000 athlete exposures (AE) (Comstock; Currie; & Pierpoint, 2013). This is significantly higher than the incidence rate of their male peers, at 2.74 per 1000 AE (Comstock; Currie; Pierpoint, 2013). Female athletes are at a particularly high risk for overuse type injuries of the lower extremity such as apophysitis and patellofemoral pain syndrome (Caine et al., 2008; Patel et al., 2017; Stracciolini et al., 2014).Overuse type injuries are also more commonly observed in adolescent athletes when compared with younger players participating in a similar sport (Stracciolini et al., 2013; Schroeder et al., 2015). Although statistically rare in comparison, traumatic injuries of the anterior cruciate ligament (ACL) disproportionately affect

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female adolescent athletes, with some researchers identifying an up to 8 times greater incidence rate when compared to their sport-matched male counterparts (Stracciolini, et al., 2014; Gornitzky et al., 2016; Herzog et al., 2017; Hewett et al., 2006; Hewett et al., 2016; Joseph et al., 2013). Short- and long-term consequences of these injuries include significant time missed from school, psychological changes, lengthy rehabilitation, increased risk of re-injury, and increased likelihood of developing early onset knee osteoarthritis (Caine, Maffulli, & Caine, 2008; Patel et al., 2017; Caine & Golightly, 2011; Filbay et al., 2015; Friel & Chu, 2013; Frisch et al. 2009; Blond & Hansen, 1998; Smith et al., 1990).Risk factors for injury are multi-factorial and include various intrinsic variables, some of which are amenable to modification through training (Caine, Maffulli & Caine, 2008; Patel et al., 2017; Schroeder et al., 2015; Joseph et al., 2013; Frisch et al., 2009). Standardized group exercise programs may offer a workable solution to reduce injury risk and improve performance.

1.1 Female Adolescent Athletes

Divergent sex-related injury incidence rates emerge in post-pubertal female athletes (Stanitski, 1995; Gallagher et al., 1984). The incidence of patellofemoral pain peaks during early adolescence (Myer et al., 2010). Significant gender-based differences in motor control and neuromuscular characteristics appear to correspond with the rapid changes in height and weight adolescents experience during puberty (Ford et al., 2010; Quatman-Yates et al., 2013). Some adolescents experience delays or regressions in aspects of sensorimotor function such as postural control and limb coordination (Quatman-Yates et al., 2012).

While these athletes are particularly susceptible to injury due to rapid physiologic change, they also respond well to training and prevention programs (Abernethy & Bleakley, 2007). Adolescence presents itself as a critical transitional period for intervention.

1.2 Lower Extremity Force Production

The ability of an athlete to produce force is important for both sport performance and injury risk reduction (Abernethy & Bleakley, 2007; Suchomel, Nimphius & Stone, 2016; Huang et al., 2020; Augustsson & Ageberg, 2017). Specifically, the quadriceps and hamstring muscle groups act as active, dynamic stabilizers of the knee during jumping, landing, and cutting tasks(Solomonow et al., 1987; Baratta et al., 1988; Colby et al., 2000; Ciccotti et al., 1994). Neuromuscular control and strength qualities of these muscles significantly affect hip and knee joint kinematics during athletic movements (Ward et al., 2018; Ebben et al., 2010; Thomas, McLean & Palmieri-Smith, 2010). Lower extremity fatigue also alters jumping and landing mechanics (Thomas, McLean, & Palmieri-Smith, 2010; McLean et al., 2007). Strengthening the lower extremity may delay fatigue and mitigate these biomechanical changes (Aagaard& Andersen, 2010; Beattie et al., 2014).

Female adolescent athletes display landing strategies and muscle force characteristics which may increase their injury risk (Patel et al., 2017; Stracciolini et al., 2014; Schroeder et al., 2015; Gornitzky et al., 2016; Hewett et al., 2016; Myer et al., 2010; Augustsson & Ageberg, 2017; Ebben et al., 2010; Hewett et al., 2005; Hewett, Torg & Boden, 2009; Pollard et al., 2005). In a sample of female soccer and basketball players, Rozzi et al. (1999) found that female athletes inherently possessed greater knee joint laxity and diminished proprioception when compared with their male counterparts. The researchers suggest healthy athletes compensate for these differences with increased hamstring activity, noting the importance of maintaining a large force generating potential in this muscle group. Augustsson and colleagues (2017) sampled 225 high school athletes and found lower extremity strength to be a predictor of traumatic knee injury in female, but not male, athletes. An inability to perform a barbell back squat at 105% bodyweight placed athletes at a 9.5 times higher risk for injury (Augustsson & Ageberg, 2017). Therefore, specific training to improve lower extremity strength is a high priority for professionals working in primary prevention, performance enhancement, and rehabilitation.

1.3 Reactive Strength

Sport specific movements often require an athlete to produce a maximum amount of force over the shortest amount of time. Reactive strength is a representation of an athlete's ability to change quickly from the eccentric to concentric phase of a movement and can be pragmatically defined as "explosiveness" (Kipp, Kiely & Geiser, 2016). The reactive strength index (RSI) is a valid and reliable measure of plyometric performance calculated by dividing jump height over ground contact time prior to take off (Kipp, Kiely & Geiser, 2016; Chmielewski et al, 2006; Ebben & Petushek, 2010; Byrne et al., 2017). This measure can be used to determine optimal training strategies, track progress, and provide external feedback to the athlete (Flanagan & Comyns, 2008).

Young athletes with patellofemoral pain may lose explosive strength capacity and their ability to absorb force during deceleration and landing tasks. In a 2-year prospective study of 282 student athletes age 17-21, Witvrouw et al. (2000) found participants who developed anterior knee pain possessed significantly less lower extremity explosive strength capacity compared to healthy controls.

Interestingly, despite decreased quadriceps and hamstring strength being frequently cited as etiologic factors contributing to the development of patellofemoral pain, they found no between group differences for isokinetic strength parameters (Witvrouw et al., 2000; Thomeé et al., 1995). This led authors to hypothesize that functional explosive strength capacity is a more valid assessment tool for this population as it represents an athlete's ability to absorb high patellofemoral forces during fast eccentric sports activities (Witvrouw et al., 2000). Similar findings were reported by Thomeé et al. (1995) in which researchers observed significant differences in eccentric strength and vertical jump height in women with patellofemoral pain but no differences in isometric or concentric conditions. Exercise interventions to improve explosive strength capacity may be useful prevention and treatment options in a high risk population such as female adolescent athletes.

Training to improve reactive strength may improve or lessen the deficits in rate of force development often seen in ACL reconstructed athletes (Birchmeier et al., 2019; Flanagan & Harrison, 2006). In a sample of 35 female athletes with a history of unilateral ACL reconstruction, Birchmeier and colleagues (2019) showed that RSI explained 61.8% of the affected limb variance in normalized triple hop distance, and that triple hop distance exhibited a strong, positive correlation with single-limb jump height. Reactive strength index may be an accurate assessment of the neuromuscular properties necessary for improved jumping ability and predict performance on jump tests (Birchmeier et al., 2019). Training to improve reactive strength is likely to carryover to improvements in triple hop and single-limb jump height. Further, Beattie et al. (2017) found that reactive strength during a drop jump is related to maximal strength measured by an isometric mid-thigh pull. Given these associations and their role in sporting performance, physical preparation programs should attempt to train all of these movement qualities. However, it is especially important to enhance the reactive strength ability of athletes participating in sports with high eccentric demands such as basketball.

1.4 Plyometric Training

Strength and conditioning plays an important role in both performance enhancement and injury risk reduction in youth athletics (Caine, Maffulli & Caine, 2008; Frisch et al., 2009; Quatman-Yates et al., 2012; Faigenbaum et al., 2009; Arundale et al., 2018). Plyometric training is safe and effective for female adolescent athletes and demonstrates many benefits including injury risk reduction, improved sprint times, and power and agility enhancement (Booth & Orr, 2016; Davies, Riemann & Manske, 2015; Stojanović et al., 2017; Peitz, Behringer & Granacher, 2018). Performance benefits of plyometric training have been primarily attributed to neuromuscular adaptations such as changes in neural drive, enhanced muscle activation strategies, and changes in the muscle-tendon complex (Markovic & Mikulic, 2010; McKinlay et al., 2018; Tillin, Pain & Folland, 2012). Plyometric exercises utilize the stretch shortening cycle, whereby a lengthening, or eccentric, movement is followed by a shortening, or concentric, movement. The movements are separated by an amortization, or loading, phase (Davies, Riemann & Manske, 2015).

Hop tests are commonly used to quantify athletic performance, determine return to sport readiness for injured players, and are predictors of dynamic knee stability (Tillin, Pain & Folland, 2012).Brumitt and colleagues (2013) discovered that female athletes with a greater than 10% side-to-side asymmetry in their single leg hop distance had a 4-fold increase in foot or ankle injury. Athletes with lower scores on the 6 meter timed hop test are at a higher risk for lower extremity muscle strain (Iguchi, Yamada & Ando, 2010). Further, female high school athletes exhibit significantly lower normative values on hop tests than males (Myers et al., 2014). Plyometric exercises offer specificity unique to other training modes as they incorporate various forms of jumping and landing which mirror these functional tests as well as the physical demands of many sporting activities. Additionally, they have the potential to improve performance metrics such as lower extremity force production and reactive strength as well as reduce injury risk (Booth & Orr, 2016; Stojanović et al., 2017; Peitz, Behringer & Granacher, 2018; Ramírez-Campillo et al., 2015).

1.5 Purpose

Pre-collegiate athletes face accessibility barriers to advanced testing, assessment, and coaching (Somerset & Hoare, 2018). Consequently, these athletes may experience lower fitness levels, poor sport performance, and a higher risk for injury (Caine, Maffulli & Caine, 2008; Schroeder et al., 2015; Schulz et al., 2004). There are several standardized exercise programs described in the literature which make use of plyometric training to reduce injury risk (Huang et al., 2020; Arundale et al., 2018; Monajati et al., 2016).While there is substantial evidence that this type of training can decrease injury risk and improve athletic performance, the mechanism of action, ideal dosing strategies, and most effective exercises continue to be the subject of much professional debate (Pfile et al., 2013; Lephart et al., 2005; Stojanović et al., 2017; Booth & Orr, 2016). Limited evidence exists determining whether a standardized group plyometric training program can improve lower extremity force production and reactive strength in adolescent female athletes. This poses a potential problem for coaches and clinicians looking to optimize pre/in-season conditioning and goal-driven exercise prescription. Our research proposes a standardized preseason 6-exercise, by 6-week (6X6), plyometric training intervention for the purpose of improving sport-specific performance measures correlated with high injury risk in female adolescent basketball players. We hypothesize the 6X6 program will result in significant improvement in lower extremity force production and RSI.

2. Methods

2.1 Participants

Twenty-two participants were recruited on a volunteer basis from a women's basketball team located in Fresno, California. Written consent was obtained from participants and their legal guardians prior to participation in the study. Mean age of participants was 14 years ± 1. Descriptive statistics for the participants are listed below in Table 1.

Table 1. Descriptive Statistics of Participants

Characteristic	Mean (SD)
Age (years)	14.4 ± 0.7
Height (cm)	163.6 ± 6.9
Weight (kg)	72.7 ± 18
BMI (kg/m^2)	27.0 ± 6

Participants were excluded if they 1) had experienced an acute lower extremity injury within the past three months 2) had a history of reconstructive surgery of the ankle or knee within the past 24 months, or 3) possessed any neurologic or musculoskeletal disorder prohibiting participation in sporting activity. Participants completed a medical screening questionnaire prior to testing which was reviewed by the lead researchers prior to inclusion.

2.2 Testing Procedures

All testing took place at a thecampus gym which served as the teams' practice facility. Researchers obtained height and weight measurements for each participant before and after the intervention period. Participants were tested in random order.

The maximal voluntary force of knee extensors, hip abductors, and hip extensors in isometric conditions was measured by a single researcher with a MicroFET 3 hand-held dynamometer (Salt Lake City, Utah), a device found to be valid and reliable (Clarke et al., 2011; Kelln et al. 2008). Intrarater reliability of 0.93 was established prior to testing. Testing positions were adapted from Mentiplay et al (2015). The best effort of three attempts was recorded for each targeted movement.

Reactive strength index was measured using the MuscleLab Ergotest infrared contact grid (Stathelle, Norway) (Figure 2), which demonstrates excellent reliability (r = .99) when compared to other validated instruments (Bosquet, Berryman & Dupuy, 2009; Glatthorn et al., 2011).

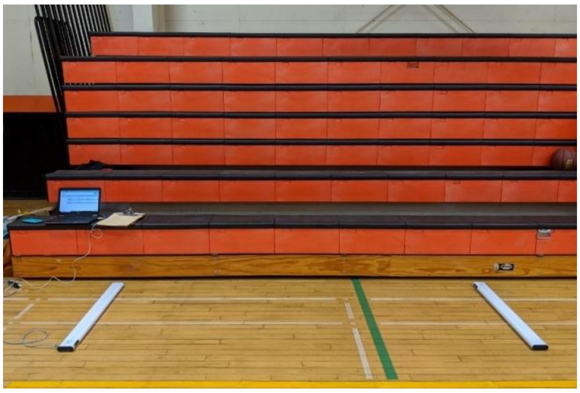

Figure 2. Set-up for testing reactive strength index using the MuscleLab Ergotest infrared contact grid. Data was gathered and synthesized using the included software according to manufacturer recommendations. Depth jumps are the preferred exercise for measuring lower extremity explosiveness and reactive strength (Flanagan & Comyns, 2008; Markovic et al, 2004). Participants were provided a visual example of a depth jump performed by one researcher and a verbal cue of "step off the platform with your dominant leg and land with both feet shoulder-width apart. Then jump as quick and as high as you can." After being afforded one practice attempt, participants performed three depth jumps from a 42cm high platform and the best effort was recorded.

2.3 Intervention

Participants first completed a 2-3 minute active warm-up consisting of jogging, butt kicks, side shuffles, walking lunges with overhead side reaches, high knees, and alternating straight leg kicks performed over 2 widths of the basketball court.

Researchers developed a standardized group plyometric training program consisting of 6 exercises based upon dosage recommendations from Chmielewski (2006) and colleagues using foot contacts as a measure of volume.Researchers trained participants and coaches at the start of the intervention period and again at the progression period. Prior to the beginning of the intervention period, participants and coaches were allowed one 30-minute session for familiarization training to practice proper technique and ensure correct form. Subsequent routines were led by team captains, with coaches supervising, and researchers observing once per week. Researchers provided simple instructions such as "jump as high and as fast as you can", "stick the landing", and "keep your shoulders, hips, knees, and toes stacked." The training program was performed twice per week over a period of 6 weeks with at least 48 hours between sessions. This training frequency has been shown to improve explosive performance with greater efficiency when compared to higher frequencies (de Villarreal et al., 2008).After the first 3 weeks, the program was progressed to increase the intensity and volume. Specifically, participants began depth jumps at the progression period, double-limb jumps were progressed to single-limb jumps, and total foot contacts per session were increased from a beginner volume of 90, to an advanced volume of 135. The 6 exercises were completed in 12-15 minutes prior to the teams' normal basketball training. Specific exercises with sets and repetitions are listed below in Table 2.

Table 2. Volume of Exercises in Phase 1 and Phase 2 of Intervention by Sets, Repetitions, and Foot Contacts Per Limb

Exercise	Weeks 1-3	Weeks 4-6
CMJ with arm swim	2 x 5	
Tuck jumps	2 x 10	3 x 10
Lateral bounding	2 x 10	3 x 10
Split squat jumps	2 x 10	3 x 10
Double leg ankle hops	2 x 10	
Drop freeze	2 x 5	
Single leg vertical jumps		2 x 5
Single leg ankle hops		2 x 10
Depth jumps		2 x 5
Total foot contacts	90	135

3. Results

Seventeen of the original 22 participants were included in post-intervention analysis of lower extremity force production and 16 were included for RSI. Five participants were unavailable due to dismissal from the team. One participant was excluded from RSI analysis due to a measurement error. No adverse events were reported.

3.1 Statistical Analysis

Statistical tests were conducted using SPSS software (Version 26, SPSS, Inc Chicago, IL). Means, standard deviations, and paired sample T-tests (alpha .05) were used to determine statistically significant change in force measurements and RSI following the intervention period.

3.2 Lower Extremity Force Production

All measurements of knee extension, hip abduction, and hip extension showed statistically significant improvements with the exception of right limb hip abduction (1.9 ± 6.3 p=.228). Left knee extension (14.8 ± 10.5 p=.000) and right knee extension (11.63 ± 15 p=.006) showed the greatest improvement. Complete descriptive statistics for lower extremity force production are available in Tables 3 and 4.

Table 3. Results of Lower Extremity Force Production in Pounds

Muscle Group	Mean	SD	SEM
RKE pre	81.4765	18.42480	4.46467
RKE post	93.1059	19.46469	4.72088
LKE pre	77.2412	19.45399	4.71828
LKE post	92.0882	18.24787	4.42576
RHABD pre	36.0588	7.28707	1.76737
RHABD post	37.9882	8.28695	2.00988
LHABD pre	35.6059	7.25495	1.75958
LHABD post	38.3471	8.56250	2.07671
RHE pre	38.8824	7.77707	1.88622
RHE post	42.7941	7.09256	1.72020
LHE pre	37.1176	6.95919	1.68785
LHE post	42.8000	6.96769	1.68911

SD = standard deviation; SEM = standard error mean; RKE = right knee extensors; LKE = left knee extensors; RHABD = right hip abductors; LHABD = left hip abductors; RHE = right hip extensors; LHE = left hip extensors.

Table 4. Lower Extremity Force Production Paired Sample t Test

Muscle Group	95% UCL	t	df	p
RKE	-3.80346	-3.150	16	.006*
LKE	-9.44239	-5.822	16	.000*
RHABD	1.33332	-1.254	16	.228
LHABD	-.27050	-2.352	16	.032*
RHE	-.65266	-2.560	16	.021*
LHE	-2.29800	-3.559	16	.003*

UCL = upper confidence limit; df = degrees of freedom; RKE = right knee extensors; LKE = left knee extensors; RHABD = right hip abductors; LHABD = left hip abductors; RHE = right hip extensors; LHE = left hip extensors. * = statistical significance.

3.3 Reactive Strength Index

Reactive strength index did not significantly change following the 6-week intervention (1.6 ± 24.8 p=.797). Complete descriptive statistics for RSI are available in Tables 5.

Table 5. Results of Reactive Strength Index

	Mean	SD	SEM
RSI pre	72.8125	27.90034	6.97509
RSI post	74.4375	22.12681	5.53170

SD = standard deviation; SEM = standard error mean.

4. Discussion

The purpose of this study was to examine the effects of a 6X6 plyometric training program on lower extremity force production and RSI in adolescent female basketball players. The results of this study suggest that the 6X6 program can elicit significant increases in lower extremity force production, but not reactive strength index.

Results of this study may help practitioners identify which mode of exercise has the greatest effect on specific physical performance measures in order to guide exercise prescription and augment the already promising results of standardized group-training programs.

Designing efficient and specific evidence-informed training programs is an important role of professionals working in health promotion, fitness, and rehabilitation. Young athletes should be given every opportunity to participate in these programs to improve their performance, reduce their injury risk, bolster their recovery, and better their health-related quality of life.

Recently, Huang et al. (2020) have suggested injury prevention programs can reduce ACL injuries by 53%, however the mechanisms behind these protective effects and precise dose-response relationship remains elusive. Unsurprisingly, there is an inverse relationship between compliance and injury rate, therefore a certain level of participation is required to achieve prophylactic effects (Sugimoto et al., 2012). Prior research has thoroughly investigated the effects of standardized exercise programs on injury rates, however little is known is about their effects on various measures of physical fitness (Caine, Maffulli & Caine, 2008; Abernethy & Bleakley, 2007; Huang et al., 2020; Arundale et al., 2018; Monajati et al., 2016; Stevenson et al., 2015). The lack of attention given to female adolescents is a particularly concerning shortcoming in the literature given the relatively high rate of injury in this population.While investigating injury risk reduction is certainly a worthwhile venture, understanding how various training modes improve neuromuscular function and sport performance will allow professionals to prescribe exercise with improved specificity and raise compliance rates of these programs. Vescovi and colleagues (2010) examined the effects of the popular Prevent Injury Enhance Performance (PEP) ACL injury prevention program on sprint times, countermovement jump height (CMJ), and agility performance in adolescent female soccer players. After 12 weeks of intervention they found no difference compared to a control group and concluded that prevention programs lack the necessary stimulus to improve athletic performance. We suggest that our program offers a comprehensive fitness approach with standard, specific dosing guidelines that can easily be incorporated into a team practice setting and engage athletes by limiting redundancy.

4.1 Lower Extremity Force Production

Our results offer evidence that a 6-week plyometric training program is effective for improving knee extensor, hip abductor, and hip extensor force production in adolescent female basketball players. The greatest effect was seen in knee extension, with some participants producing a 37 foot/pound increase in torque. Plyometric training has a high specificity effect, where training in a given plane of motion transfers most effectively to skills performed in the same plane (Ramírez-Campillo et al., 2015; McCormick et al., 2016). A majority of the exercises in the 6X6 occur in the sagittal plane and this may explain the disproportionate increase in knee extensor torque when compared to hip abductor and hip extensor force production.

Despite a general consensus on the effects of plyometric training on LE force production in young athletes, significant gaps in the literature remain. Prior research has primarily involved male athletes and fails to sufficiently examine the effects of gender and maturation on neuromuscular adaptation. Our findings agree with previous studies on the effects of plyometric training on LE force production in young athletes and extend them to include adolescent female basketball players (Peitz, Behringer & Granacher, 2018; De Villarreal, Requena & Newton, 2010).

Matavulj et al. (2001) demonstrated improvements in knee and hip extensor strength in young male basketball players following a 6-week plyometric training program. The authors' intervention consisted of 3 sets of 10 drop jumps from either a 50cm or 100cm platform performed 3 times per week with 3 minutes of rest between each set. Lephart and colleagues (2005) studied the effects of an 8-week training program in a sample of 27 high school female athletes randomized into plyometric or basic training groups.The plyometric program consisted of 11 exercises performed for 10 repetitions each. Similar to our results, training resulted in significant improvements in knee extensor torque. However, hip extensor and hip abductor force production did not significantly improve and there were no between group differences for any strength variables. Additionally, Hewett et al.(1996) examined the effects of a 6-week training program consisting of static stretching, warm up, 7 plyometric exercises, and a cool down performed over 2 hours 3 days per week in a sample of 11 female high school volleyball players, and found significant improvements in hamstring torque. More recently, McKinlay and colleagues (2018) examined the effects of plyometric training versus resistance training on strength, explosiveness, and jump performance in 41 male soccer players age 11-14 years.

Following an 8-week intervention period, researchers observed significant improvement in peak torque of knee extensors and squat jump performance in both experimental groups when compared to controls.

Our data corroborates prior investigations and further establishes plyometric training as a safe and effective training modality for improving LE force production in young athletes.

4.2 Reactive Strength Index

There is a paucity of research examining the effects of exercise interventions on reactive strength in adolescent female athletes. Our results show no training effect of the suggested plyometric training program in terms of RSI. This is in contrast to findings from Lloyd and colleagues (2012) who observed an increase in reactive strength following a 4-week plyometric training program in 12 year olds, but not 9 or 15 year old male athletes. However, some authors used the maximal hopping test to determine RSI as opposed to our study which used depth jumps, and selected exercises may have superior transfer to a given testing procedure (Ramírez-Campillo et al., 2015; McCormick et al., 2016). In a group of 17 runners, age 19-24 years,Ramírez-Campillo et al.(2015) discovered significant improvements in RSI, CMJ, and sprint times following a 6-week plyometric program.They detected no significant differences between the 9 men and 8 women and pooled both genders as a group. The same researchers found similar results in a larger study of 76 male soccer players between 10-16 years of age (Ramírez-Campillo et al., 2014).Following a 7-week plyometric program, participants demonstrated significant improvements in CMJ, RSI, and multiple 5 bounds distance. In both studies, RSI was calculated based upon a drop jump from a 40cm platform and exercises were dosed using a 10-point rate of perceived exertion scale to ensure high intensity; this may help explain the disparity between our results and those previously reported.

Several studies have demonstrated that an optimal drop height exists for maximizing training effect and that excessive drop heights may lead to performance detriments in adult athletes (Witvrouw et al., 2000; Andrade et al., 2020; Lesinski et al., 2018). This has primarily been attributed to the triggering of neuronal inhibitory mechanisms, due to increased ground reaction forces, leading to reduced force generation potential (Komi & Gollhofer, 1997). Prieske et al. (2019) examined the effect of drop height on RSI in adolescent female handball players and found significantly greater RSI from heights of 20-35cm when compared to 35-50cm.It is possible that our selected height of 42cm was not optimal for training or sensitive enough detect to changes in RSI.

We expect the lack of improvement in RSI is largely due to insufficient volume of test-specific exercises. In the study from Ramírez-Campillo et al.(2014) drop jumps were the sole plyometric exercise used in the experimental groups. Participants transitioned to depth jumps at week 4 of our program, giving them 3 weeks of training to positively adapt. This was likely too low of a stimulus to produce a meaningful effect on RSI as measured with a depth jump. Additionally, varying results may be due to gender and age differences of participants.

4.3 Sex-related Differences and the Effect of Maturation

Knowledge of the effectiveness of plyometric training in female adolescents is scarce. A recent meta-analysis with no date restrictions identified a mere 14 studies examining the effects of plyometric training on CMJ in females age 8-18 years (Moran et al., 2019).The authors found a small but significant improvement in CMJ compared to control (effect size = 0.57). Scarcity of studies for inclusion was attributed to lack of comparison to a control group and inadequate data reporting. A previous systematic review and meta-analysis found similar results when comparing data across 16 studies examining the effect of plyometric training on vertical jump height in amateur, collegiate, and elite female athletes (Stojanović et al., 2017).

Although changes in muscle strength and power are well-reported in young male athletes following plyometric training, the effect size appears to be smaller in females (Booth & Orr, 2016; Peitz, Behringer & Granacher, 2018; De Villarreal, Requena & Newton, 2010; Moran et al., 2019; de Villarreal et al., 2009). Female adolescent athletes appear to have similar trainability as their male counterparts in regards vertical jump height, however sex-related differences regarding the efficacy of plyometric training on various aspects of the stretch shortening cycle remain unknown.

There is a sharp increase in the disparity of muscle mass between sexes during puberty that corresponds with differences in maximal strength and may affect muscular power (Korff et al., 2009; McManus & Armstrong, 2011). In a study of 379 basketball players age 13-30 years Spiros et al. (1999) found males increased their vertical jump height in relation to chronological age while females showed a tendency toward decline. An age-related increase in muscle mass corresponding with an age-related increase in muscle power is observed in much greater magnitude in males and may be an outcome of greater muscle cross-sectional area (Kellis et al, 1999; Neu et al., 2002; Beunen & Malina, 1988).

Prior to puberty, sex-related differences in muscle mass are negligible. However, by maturity muscle mass in males reaches near 55% of total body mass, while females have between 25-45% smaller muscle cross-sectional area and 52-66% maximal strength (McManus & Armstrong, 2011; Miller et al., 1993).Buchanan et al. (2003) found the relative quadriceps strength of female basketball players age 11-13 years, compared to 15-17 years, did not differ, while male athletes increased their relative strength 66%. Furthermore, the stagnation of relative strength corresponds with peak height and weight velocity which may place this group at a disadvantage when managing impact forces during training and competition (Buchanan & Vardaxis, 2003).Tønnessen and colleagues (2015) examined results from 1373 male and 1149 female athletes age 11-14 years across various track and field events.They found male and female athletes perform almost equally up to age 12, however relative annual performance development in females gradually decreases with age while it is accelerated in males.Overall improvement rates were reported more than 50% higher in males than females, with the magnitude of improvement in jumping events twice that of running events.

It is unclear whether sex-related differences in muscle strength and power were germane to our results, as changes in muscle mass do not fully account for changes in reactive strength. Participants ranged from 13-16 years of age and their developmental stage was not assessed. This is a limitation to the current study as it does not allow subgrouping based upon factors related to pubertal development. It should be noted that despite relevant sexual di-morphisms during puberty, recent reviews consistently support plyometric training as an effective modality for improving strength and jumping ability in female athletes of all ages (Stojanović et al., 2017; Peitz et al., 2018; Moran et al., 2019). It is possible the subjects included in our study were particularly affected by the relationship between muscle mass, power, and explosiveness, however this relationship cannot be established with our current data and requires further investigation.

Musculotendinous unit stiffness (MTS) is an important architectural characteristic for the expression of explosive strength (Maffiuletti et al., 2016; Wilson, Murphy & Pryor, 1994). In a study of 20 highly trained male and female runners, Westh et al. (2008) found significantly less achilles tendon stiffness in the female participants, suggesting training adaptations may be attenuated in female runners. Although training effects appear to be similar when normalized across sexes, differences in neurophysiologic responses remain equivocal.Skurvydas et al. (2010) found similar training effects of a 2 month twice weekly plyometric program in young male and female athletes with the exception of twitch torque, showing a 323% increase in males compared to 21% females. The authors used twitch torque as a measure of excitation contraction coupling, an important physiological process in plyometric movements which measures the time from electrical impulse to max voluntary contraction.

When taken together, these studies suggest that females may respond differently to plyometric training than males in regards to certain neuromuscular characteristics and this should be taken into account when programming plyometric exercises.

4.4 Volume

Training adaptations depend largely upon the intensity and volume of an exercise relative to the chronic activity level of the individual (Booth & Orr, 2016; De Villarreal; Requena & Newton, 2010; de Villarreal et al., 2009).The heterogeneity of current dosage guidelines is a potential problem for coaches looking to optimize exercise prescription. For improving strength, training for less than 10 weeks with 3 sessions per week appears more beneficial than longer programs (De Villarreal, Requena & Newton, 2010).Further, a program of greater than 15 sessions with more than 40 repetitions seems to be the most beneficial volume (De Villarreal, Requena & Newton, 2010).

Short-term plyometric programs of 2 days a week with 840 jumps produce similar improvements as a frequency of 4 days per week with 1680 jumps, suggesting a maximal training volume beyond which further performance gains are no longer realized (de Villarreal, González-Badillo & Izquierdo, 2008; De Villarreal, Requena & Newton, 2010).

Meta-analytic findings from Stojanović and colleagues (2017) showed programs greater than 10 weeks were more effective for improving vertical jump performance in female athletes than those less than 10 weeks, with effect sizes of 1.87 and 0.58 respectively. They identified only a small training effect for 6-week interventions, however found that low-frequency interventions of 1 day per week could be beneficial. Similarly, a review by Markovic et al. (2010) found plyometric programs of 6-15 weeks can change the stiffness of the muscle-tendon complex and improve lower-extremity strength, power, and stretch shortening cycle muscle function. Slimani and colleagues (2016) concluded that plyometric programs of 4-16 weeks can improve physical fitness in team sport players.

For the purposes of increasing jump height, de Villarreal et al.(2009) recommend training for 10 weeks with more than 20 sessions and greater than 50 jumps per session. A recent meta-analysis examining plyometric training in female youth found programming characteristics such as session times greater than 30 minutes, frequencies greater than 2 day per week, programs longer than 8 weeks, and interventions with greater than 16 sessions could enhance the effectiveness of a training cycle (Moran et al., 2019). The authors postulate a positive dose response in this population and ultimately recommend training 3 days per week in an 8-week cycle.

Our results suggest a short-term (6-week), low-moderate volume (90-135 foot contacts), low frequency (2 days per week), and high intensity program improves lower extremity force production in female adolescents, but not reactive strength. Based upon the investigations of prior studies, the 6X6 program should be tested over a longer training cycle to determine its viability as a comprehensive fitness routine for young team sport athletes.

5.Limitations

The are several limitations to the current study. The lack of a control group makes it difficult to draw firm conclusions on the effect of the program. Supplementary training was not officially tracked and the improvements in lower extremity force production may have been due to concurrent exercise routines. A relatively small sample size and high recidivism lowers the power of our findings. Previous fitness level of participants was not determined. This may have led to a heterogenous population and skewed the effect of the program as trained individuals respond differently compared to untrained individuals.

6. Future Research

In order to validate the findings of this pilot study future research should add a control group and recruit a larger sample size. Further, the suggested 6X6 program may need adjustment in order to see improvements in RSI. It would also be beneficial to undertake a longitudinal study to determine if the program offers a protective effect against lower extremity injury.

7. Conclusion

Our findings suggest that the proposed 6X6 plyometric training program offers sufficient stimulus to improve lower extremity force production, but not reactive strength, in adolescent female athletes. More research is needed comparing the intervention to a control group and to determine an exercise dose necessary to produce changes in RSI.

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