International Journal of Athletic Therapy and Training, 2023, 28, 89-96
https://doi.org/10.1123/ijatt.2021-0100

Human Kinetics
RESEARCH REPORT

Effects of Plyometric Training on Sonographic Characteristics of Quadriceps Muscle and Patellar Tendon, Quadriceps Strength, and Jump Height in Adolescent Female Volleyball Players

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The aim of this study was to investigate the effects of plyometric training on vastus lateralis (VL) and patellar tendon size, quadriceps isokinetic strength, and vertical jump height in adolescent female volleyball players. Thirty players (age mean ± *SD*: 15.7 ± 1.1 years) participated in a 6-week Sportsmetrics™ plyometric training program. VL thickness, echo intensity, and patellar tendon cross-sectional area were assessed by real-time ultrasound. Isokinetic quadriceps strength and vertical jump were assessed. The VL thickness, quadriceps strength, and VJ height increased and VL–echo intensity decreased after training. We recommended that 6-week Sportmetrics plyometric training program may be implemented in adolescent female volleyball programs especially before the beginning of the volleyball season.

Keywords: ultrasound, knee strength, Sportsmetrics™, neuromuscular training

Plyometric exercise is extensively used in sports that require jumping ability to increase explosive power capacity.[1,2] Plyometric exercise involves a rapid eccentric action immediately followed by rapid concentric action. This transition from the eccentric to the concentric portion of the movement is known as the stretch-shortening cycle.[2] Plyometric training programs have been shown to improve jumping and running performance, and increase bone mass, and lower-extremity strength.[1–4] Plyometric trainings can lead to adaptive changes in neuromuscular function as a result of increases in neural drive to the agonist muscles, changes in muscle size and architecture, and mechanical characteristic of the muscle–tendon complex.[2] These positive effects on neuromuscular and structural properties should have potential in sports such as volleyball, which involves extensive movements analogous to plyometric drills.

Muscle strength improvement following plyometric training has been explained by the increase in muscle activation levels, increased musculotendinous stiffness and muscle hypertrophy in adult athletes.[5–7] It was postulated that a brief high-force mechanical stimulus provides sufficient stimulus for inducing a hypertrophic response.[5] However, the effects of plyometric training on muscle hypertrophy are often referred to as relatively minor, or no hypertrophy is observed in younger athletes.[5,8] Thus, increase in muscle strength after plyometric training in younger athletes is thought to be due to neuromuscular adaptations.[6] Previous studies not only reported 4%–10% increase in tendon cross-sectional area (CSA) in response to increased mechanical loading,[9–11] also, no change was observed in tendon CSA following plyometric training.[2] The tendons have a low metabolic rate and an inadequate response to growth factors triggered by loading, depending on the muscle tissues.[12] It has been suggested that superimposed mechanical loading by sports activities can increase tendon stiffness which is related to increase in CSA; however, major changes in tendon CSA might occur later in adolescent volleyball athletes when compared with muscular development.[13]

Quadriceps muscle and the patellar tendon (PT) have crucial roles for achieving plyometric task,[2] but there is limited evidence that shows how plyometric training on sonographic characteristics of the knee extensor structures in adolescent athletes. Ultrasound is a quick, and cost-effective method to assess the morphological and structural benefits of plyometric training to determine if further training or modified training is necessary. It may provide clinicians with an alternative to simple strength assessment and to better evaluate the muscle and tendon characteristics after training.[14,15] Muscle and tendon thickness and echo intensity (EI) measurements by ultrasound are easy to perform by health professionals.[13,16,17] A decrease in EI is an indication of muscle quality, and EI is associated with the amount of intramuscular fibrous and adipose tissue in the muscle.[18] As the amount of fat and fibrous tissue in the muscle decreases, lower EI values are observed.[16,18,19]

Thus, this study aimed to investigate the effects of 6-week plyometric training on the sonographic characteristics of the VL including muscle thickness and EI, and PT–CSA, quadriceps strength, and the vertical jump performance of adolescent female volleyball athletes. It was hypothesized that plyometric exercise would increase VL thickness, PT–CSA, quadriceps strength, and vertical jump height but decrease VL–EI in adolescent female volleyball players.

Methods

Participants

Thirty adolescent female volleyball players were included in this study (Table 1). Inclusion criteria of the study were: (a) ages between 14 and 18 years, (b) no previous musculoskeletal injuries

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Table 1 Demographic Characteristics of the Participants

N = 30	Mean ± *SD*
Age (years)	15.7 ± 1.1
Height (cm)	172.4 ± 5.4
Weight (kg)	61.1 ± 6.3
Body mass index (kg/cm^2)	20.5 ± 1.6
Experience in sport (years)	4.1 ± 2.4
Time spent participating in sports (hr/week)	5.8 ± 2.7

for the last 1 year, and (c) playing volleyball for at least 2 years. All participants were selected from asymptomatic volunteers from the same sports club and playing volleyball at competitive level at least 2 years. Participants were excluded if they had any known systemic, neurological disorders or rheumatological disorders, if they failed to complete the pre- or posttesting, or failed to participate in a minimum of 80% of the training sessions.

All testing and training procedures were fully explained and written informed parental consent was obtained for each participant. The study was planned in accordance with the Declaration of Helsinki and approved by the institutional review board (approval number: 20796219-896).

Instrumentation

Quadriceps size, quadriceps isokinetic strength, and vertical jump height were assessed before and after the 6-week plyometric training program.

Procedures

Initial testing included demographics and anthropometric assessments of height, body mass, and body mass index. Demographic data were collected by face to face conversation with the participants. The dominant leg was defined as the "leg you would use for single-leg jumps to achieve maximal jump height."[20]

Plyometric Exercise Program

The players performed Sportsmetrics™ training program two times (on Monday and Thursday) per week for 6 weeks[21–23] during preseason. On the other 4 days (on Tuesday, Wednesday, Friday, and Saturday), they attended volleyball technical training. The technical training duration of the players was 8 hr (2 hr/day) and included warming up, serving, passing, setting, attacking, blocking, digging, and cooling down.

The plyometric training was designed to decrease landing forces and increase knee joint stability by improving lower-extremity neuromuscular control and increasing muscle power.[21,22,24] There were three phases in the program: Phase 1 (1–2 weeks) taught appropriate jump techniques; Phase 2 (3–4 weeks) aimed to increase strength, power, and ability using the jump techniques; and Phase 3 (5–6 weeks) aimed to maximize jump ability. Prior to plyometric training, the participants were instructed to performed dynamic warm-up for lower extremity including jogging, side shuffles, and stretching. The trainers provided the verbal and visual feedback with each exercise to the participants. The training was designed to gradually progress by increase in training duration and number of ground contacts (Table 2). Considering the stress of the plyometric training on the musculotendinous unit, the exercise intensity was progressively increased from a level classified as low to moderate, an appropriate intensity for children.[25]

Table 2 Sportsmetrics™ Training Program

Jumps	Sets	Repetitions	
Technique developments (Weeks 1 and 2)		Week 1	Week 2
Wall jumps	3	20 s	25 s
Tuck jumps	3	20 s	25 s
Squat jumps	3	10 s	15 s
Barrier jumps (S/S)	3	20 s	25 s
Barrier jumps (F/B)	3	20 s	25 s
180° jumps	3	20 s	25 s
Broad jumps	3	5 rep	10 rep
Bounding in place	3	20 s	25 s
Fundamentals (Weeks 3 and 4)		Week 3	Week 4
Wall jumps	3	25 s	30 s
Tuck jumps	3	25 s	30 s
Jump, jump, jump vertical	3	5 rep	8 rep
Squat jumps	3	15 s	20 s
Barrier jumps (S/S)	3	25 s	30 s
Barrier jumps (F/B)	3	25 s	30 s
Scissor jumps	3	25 s	30 s
Single leg hops (stick)	3	5 rep	5 rep
Bounding for distance	3	1 run	2 run
Performance (Weeks 5–6)		Week 5	Week 6
Wall jumps	3	20 s	20 s
Up down 180 vertical	3	5 rep	10 rep
Squat jumps	3	25 s	25 s
Mattress jumps (S/S)	3	30 s	30 s
Mattress jumps (F/B)	3	30 s	30 s
Hop, hop, hop stick	3	5 rep	5 rep
Jump into bounding	3	3 run	3 run

Ultrasonography (Measurement of Muscle Thickness, EI, and Tendon CSA)

The ultrasonography was performed by a senior radiologist experienced in musculoskeletal radiology using a Toshiba Applio 500 system (Toshiba, Otawara, Japan) ultrasonic device and a transducer with a frequency range of 7–18 MHz. Participants were asked not to undertake any hard exercise 72 hr before ultrasonography and they rested 30 min in long sitting position before the ultrasonography measurement. The assessments were made on both dominant and nondominant limbs. All measurements were performed when the participant's legs were relaxed.

VL Thickness and EI

For the assessment of the VL muscle size, the participants were placed in the supine position with the knee joint in full extension at rest. The transducer was placed in parallel with the muscle plane at the midpoint of the distance between the greater trochanter and the upper pole of the patella. The thickness of the middle of the VL muscle was measured three times along the long axis excluding the fascia and the average of the three values was recorded. (Figure 1).

The EI was assessed by grayscale analysis using the standard histogram function of the Image-J software (version 1.37, National

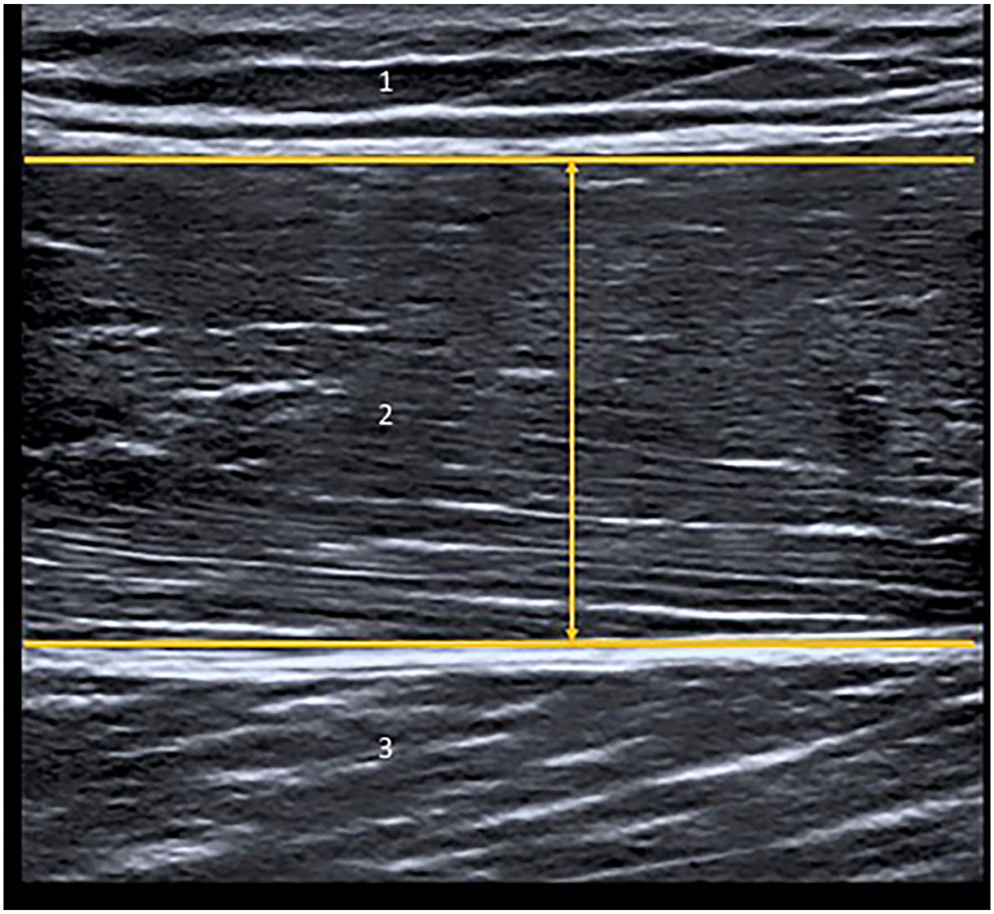

Figure 1 — Vastus lateralis thickness, (1) subcutaneous fat; (2) vastus lateralis muscle; and (3) vastus intermedius muscle.

Institutes of Health). During assessment, it was ensured that the transducer was parallel to the long axis of the muscle. Using the polygon selection tool, the hyperechoic superficial fascia of the muscle was traced to measure the mean grayscale values. It was noted that the image taken for the measurement of EI did not display any bone tissue or obvious fascia and the depth of focus was adjusted to the muscle (Figure 2). The EI of the region of interest ranged from 0 to 255 (0: Black and 255: White). The average of the three measurements was recorded.

We measured only the VL muscle, as the previous study showed that the changes in the vastus medialis and lateralis muscles were similar after plyometric training.[26] Moreover, we also wanted to compare our findings with McKinlay et al.'s[6] study where the authors examined VL muscle thickness by ultrasound in young adolescent soccer players.

Patellar Tendon Cross-Sectional Area

For PT–CSA, the examination was performed on the longitudinal and transverse axis of both knees while the patient was in a supine position with the knees supported and flexed. The examination was performed at the most appropriate degree of knee flexion (approximately 45°) at which the tendon is taut with well-defined margins and is homogenous in fibrillar echotexture.[27] The transverse CSA measurements of the PT were made 6-mm distal to the patellar attachment (proximal end).[28] Epitendon measurements were not included in the assessment of the tendon (Figure 3).

Vertical Jump Test

Countermovement jump test was used to assess the lower-extremity explosive power.[21,29] The participants were asked to stand in front of a wall where a tape measured afixed and extend their arm up above their head (standing height). They were then instructed to jump as far as possible with double leg and touch the tape during their maximum jump height. The jump height was calculated by taking the difference between maximum height and standing height. All participants completed three jumps. The distance was measured in centimeters and the average of the three jump heights was recorded.

Quadriceps Isokinetic Testing

Concentric quadriceps peak torque was measured by isokinetic dynamometer (IsoMed®2000 D&R GmbH). Participants were instructed to sit on the isokinetic dynamometer with their hips flexed at 90°. Stabilization straps were placed across the trunk, waist, and the distal femur of the limb to minimize compensatory movement. The axis of the dynamometer was aligned to the lateral femoral epicondyle while the knee was flexed at 90°, and the dynamometer force arm was secured 2 cm above the lateral malleolus. The distance from the dynamometer force arm to the axis of the dynamometer was recorded for each individual to allow the peak torque to be calculated.

Prior to muscle strength recordings, the participants were allowed three maximal concentric quadriceps tests to familiarize

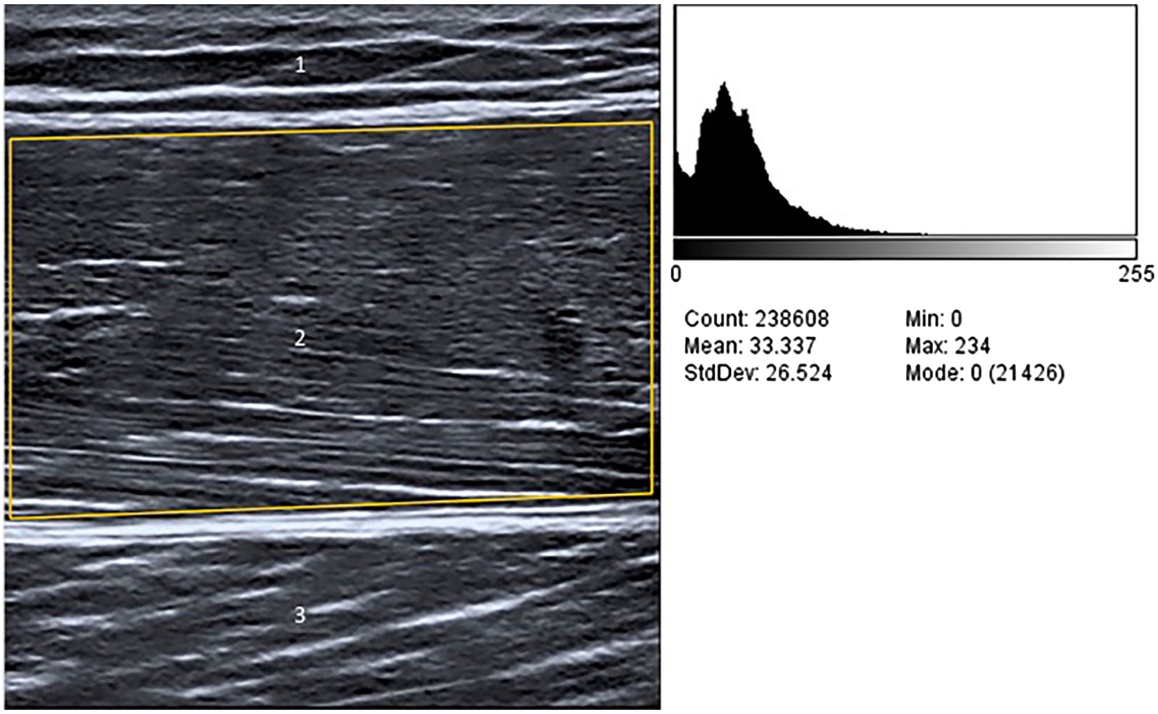

Figure 2 — Vastus lateralis histogram analysis, (1) subcutaneous fat; (2) vastus lateralis muscle; and (3) vastus intermedius muscle.

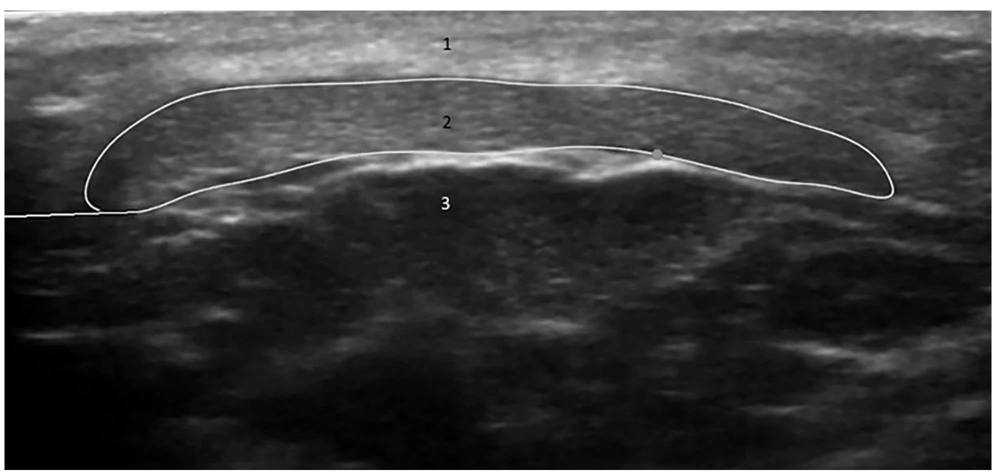

Figure 3 — Patellar tendon cross-sectional area, (1) subcutaneous fat; (2) patellar tendon; and (3) infrapatellar fat pad.

themselves with the testing procedures and to warm-up. Participants then performed maximal quadriceps contractions at angular velocities of 60°/s (five repetitions) and 180°/s (10 repetitions) with a 1-min rest interval between each set.[30] Standard verbal instructions were given regarding the procedures. Normalized quadriceps peak torque (in newton meters per kilogram) for dominant and nondominant limbs were recorded.

Statistical Analysis

Statistical analyses were performed in IBM SPSS (version 21.0). Data were expressed as means and *SD*s for descriptive data. Normality of data was tested with the Shapiro–Wilk test. Intraclass correlation coefficient and standard error of measurements were calculated for three repetitions of the ultrasound measurements. Two-way repeated measures of analysis of variance with two within factors was used to analyze time by limb interaction for sonographic characteristics of quadriceps and PT, and quadriceps strength. When significant interaction or main effect was found, pairwise comparison was performed by using Bonferroni post hoc test. Paired sample t test was performed to analyze the difference between two time points in terms of vertical jump distance.

The changes in VL thickness and EI, PT–CSA, quadriceps strength, and jump distance after plyometric training were reported with effect size. Cohen's d coefficient was used to calculate the magnitude of effect size for all variables. An effect size greater than

0.80 was considered as large; 0.5–0.79 as moderate; 0.49–0.20 as small; and 0.19–0 as negligible.[31] Significance levels were set at $p < .05$.

Results

Table 3 demonstrates intertrial reliability and standard error of measurement values of VL thickness and PT–CSA.

Sonographic Characteristics

The VL thickness in dominant and nondominant limb increased after plyometric training. However, the change for VL thickness in dominant limb did not exceed measurement error of 0.17 cm. Before the training, VL thickness was greater in dominantlimb compared with nondominant limb (limb symmetry index [LSI]: 101.4%) but after the training VL thickness did not differ between limbs ($p = .09$) (LSI: 100.7%) (Table 4).

The PT–CSA only increased in the nondominant limb but it did not change in the dominant limb after the training. However, limb difference in PT–CSA was not observed before (LSI: 103.7) and after the plyometric training (LSI: 98.1%) (Table 4).

The VL–EI decreased after plyometric training. No difference was observed between limbs in terms of VL–EI (LSI: 107.6%; Table 4).

Isokinetic Strength

Concentric quadriceps strength at 60°/s and 180°/s increased after plyometric training. After training, concentric quadriceps strength at 60°/s and 180°/s were greater in dominant limb compared with nondominant limb (LSI 60°/s: 108.6%) (LSI 180°/s: 108.5%) (Table 5).

Table 3 Intertrial Reliability and SEM Values of Each Test

	ICC	SEM (cm)
Dominant VL thickness	.97	0.17
Nondominant VL thickness	.97	0.15
Dominant PT CSA	.92	0.03
Nondominant PT CSA	.98	0.04

Note. ICC = intraclass correlation coefficient; SEM = standard error of measurement; VL = vastus lateralis; CSA = cross-sectional area; PT = patellar tendon.

Jump Performance

The vertical jump distance increased after plyometric training (Table 5).

Discussion

The results of the present study showed that VL thickness in both dominant and nondominant limbs and PT–CSA in nondominant limb increased, and VL–EI in both dominant and nondominant limbs decreased after 6-week plyometric training in adolescent female volleyball players. Quadriceps isokinetic strength at 60°/s and 180°/s of both limbs and vertical jump distance also increased with plyometric training. However, change in VL thickness in dominant limb (0.09 mm) did not exceed measurement error (0.17 mm). This finding suggested that 6-week plyometric training had minimal to no effect on VL thickness, but it led to significant improvement in quadriceps quality and isokinetic strength of the dominant limb.

In the literature, there is no study that investigated quadriceps muscle size in adolescent female volleyball players after plyometric training. Thus, it is hard to compare our findings to previous studies. McKinlay et al.[6] found 1.5 cm difference in VL thickness after 8-week plyometric training in young adolescent male soccer players. However, it is not clear if this change was related to dominant limb or nondominant limb. Previous researchers recommend that muscle size has not been shown to be significantly affected by strength training in prepubertal children.[32] Thus, the observed VL hypertrophy after plyometric training was explained by the fact that their participants were predominantly pubertal (average age: 12.5 years) in McKinlay et al.'s study.[6] In current study, we found an increase in VL thickness in dominant and nondominant limbs in adolescent female volleyball players (average age: 15.7 years old). The observed difference (0.09 mm) in dominant limb after the training did not exceed measurement error (0.17 mm) although it had moderate effect size. On the other hand, the change in VL thickness in the nondominant limb (0.19 mm) exceeded the measurement error (0.15 mm). Statistical significance level and effect size measurements may be not enough to evaluate muscle size changes, determined by ultrasonography, measurement error should be also evaluated while interpreting the results into the clinical point. The results of our study suggested that 6-week plyometric training may not have an influence in VL size of the dominant limb. We preferred to use 6-week plyometric program due to evidence that <8 weeks of plyometric training had significant effect on improving functional performance and morphological changes in muscles.[5,33] In addition, volleyball players also performed high volume jumps during their technical training sessions

Table 4 Vastus Lateralis Thickness and Echo Intensity, and Patellar Tendon Cross-sectional Area Outcomes Before and After the Plyometric Training

	Before training	After training	p	95% CI	Effect size
Dominant VL thickness (mm)	16.03 ± 0.94	16.12 ± 0.93	.002*	[−0.14, −0.04]	0.48
Nondominant VL thickness (mm)	15.81 ± 0.92	16.00 ± 0.91	<.001*	[−0.26, −0.12]	1.03
Dominant VL–EI	56.77 ± 14.0	41.10 ± 11.06	<.001*	[12.15, 19.19]	1.66
Nondominant VL–EI	53.80 ± 14.53	38.21 ± 11.22	<.001*	[11.94, 19.23]	1.59
Dominant proximal PT–CSA (mm^2)	76.94 ± 13.19	75.94 ± 11.93	.99	[−1.76, 1.76]	0.18
Nondominant proximal PT–CSA (mm^2)	74.23 ± 13.06	77.42 ± 10.69	.03*	[−4.16, −0.32]	0.60

Note. CI = confidence interval; VL = vastus lateralis; EI = echo intensity; PT = patellar tendon; CSA = cross-sectional area.
*Statistically significant (<.05).

Table 5 Quadriceps Peak Torque and Vertical Jump Height Outcomes Before and After Plyometric Training

	Before training	After training	p	95% CI	Effect size
Dominant quadriceps PT 60°/s (N·m/kg)	2.62 ± 0.68	2.92 ± 0.95	.01*	[−0.53, −0.06]	0.53
Nondominant quadriceps PT 60°/s (N·m/kg)	2.39 ± 0.62	2.69 ± 0.81	.01*	[−0.52, −0.07]	0.57
Dominant quadriceps PT 180°/s (N·m/kg)	2.51 ± 0.63	2.81 ± 0.94	.04*	[−0.59, −0.009]	0.44
Nondominant quadriceps PT 180°/s (N·m/kg)	2.27 ± 0.57	2.59 ± 0.80	.007*	[−0.55, −0.09]	0.60
Vertical jump height (cm)	20.58 ± 1.93	22.33 ± 1.93	<.001*	[−0.52, −0.17]	1.28

Note. CI = confidence interval; PT = peak torque.
*$p < .05$.

so we did not want to overload the adolescent athletes with longer-duration plyometric training.[34] Therefore, more intensive plyometric training programs may lead to greater changes in VL size in dominant limb. However, we kept plyometric training intensity low to prevent possible injury.

Consistent with the muscle thickness findings, PT–CSA in dominant limb did not change, but it increased in nondominant limb after plyometric training in present study and the change (3.19 mm^2) exceeded the measurement error (3.19 mm^2). It is suggested that the response of the tendon to mechanical loading seems to occur at a lower rate when compared with the muscle from early to mid-adolescence, which might lead to an imbalance between muscle strength and tendon stiffness.[13,32] Our results supported the previous findings that effectiveness of the plyometric training was greater in VL thickness compared with PT–CSA in the nondominant limb of the adolescent athletes. The participants in our study were mid-adolescent athletes (the average age: 15.7 years) and 6-week plyometric training seems to be efficient to stimulate the PT in the nondominant limb. As PT–CSA and the VL thickness both increased with plyometric training, there might not be an imbalance between the tendon and the muscle development after the training. PT injuries are very common in adolescent volleyball athletes.[32,35] The imbalance between the PT stiffness and the quadriceps muscle development has been shown to be related to development in patellar tendinopathy in adolescent volleyball players.[32,35] Therefore, the plyometric training programs focusing on neuromuscular training may be effective in adolescent volleyball players, especially in prevention of patellar tendinopathy. Two studies conducted with elite junior volleyball players over a long follow-up period reported conflicting results; one study reported no change in PT CSA,[14] while another study found an increase in PT–CSA after resistance training.[9] Thus, more prospective studies are needed to show the change in PT morphological characteristics following plyometric training in adolescent athletes.

The EI measurements can be used to assess muscle quality as an increase in EI represents changes in intramuscular connective and adipose tissues.[16,36] Stock et al.[17] found that VL–EI was related to functional performance such as vertical jump height, sprint speed, and agility in middle-school boys. Moreover, previous study showed that 6-week concentric and eccentric trainings reduced VL–EI of in young men and women.[19] Consistent with the findings of Cadore et al.,[36] we found a significant decrease in VL–EI for both dominant and nondominant limbs after plyometric training in adolescent female volleyball athletes and the changes exceeded the measurement errors. Larger effects sizes in EI in both limbs showed that plyometric training affected muscle quality more than size. Increase in VL muscle quality with plyometric training may be important in adolescent female volleyball athletes to prevent future quadriceps muscle injuries and to improve athletic performance. Moreover, it was suggested that muscle quality measurement via EI can have a role in health risk assessment of the athletes since the increased intramuscular fat may be associated with insulin sensitivity and the development of metabolic syndrome.[37]

Increase in muscle size is strongly correlated to increase in muscle strength in healthy adults[5] but muscle size has not been shown to be significantly affected by strength training in prepubertal children even though the muscle strength is increased.[32] Majority of the studies documented >10% muscle strength changes after plyometric training.[2] We found an increase in concentric quadriceps strength in both the dominant and the nondominant limbs of adolescent athletes after 6-week plyometric training. The increase was 11.5%–11.9% for dominant limb and 12.6%–14.1% for the nondominant limb. Although he improvements in strength is greater in nondominant limb, the quadriceps muscle strength was greater on the dominant side after the training. We can also conclude that greater change in VL quality may be more related to increase in quadriceps strength rather than small change in VL size.

The most accepted positive effect of plyometric training is to increase the VJ distance.[2,4,22,33] A recent meta-analysis showed that VJ height can increase in both male and female volleyball players with plyometric training programs of low volume and frequency (<8 weeks).[33] The studies used 6-week plyometric training reported 10%[21] and 9.2%[38] improvements in VJ height in female volleyball players, which were consistent with our findings. We found 10% improvements in vertical jump performance after 6-week plyometric training. This improvement is clinically meaningful regarding the larger effect size. The first study described and used Sports-Metric plyometric training program in female volleyball players found 7% of increase in VJ height.[22] The lower increase in VJ height was explained by due to lower intensity of the program when compared with other plyometric training program. The Sportsmetrics™ training program primarily aims to enhance lower-extremity alignment and neuromuscular control and improve jump height in adolescent female athletes to prevent lower-extremity injuries.[21,22]

Limitations

This study has some limitations. It has been demonstrated that plyometric training, which is combined with weight training, lead to greater improvement in muscle strength.[39] Therefore, performing only plyometric training program with 6-week duration may not be enough to stimulate quadriceps hypertrophy, especially in the dominant limb of adolescent female volleyball players. Second, the findings of the present study reflect the female adolescent volleyball players so they should not be generalized to similarly aged boys, or different sports types. We did not measure hamstring strength in present study since we wanted to evaluate knee extensor morphologic changes after plyometric training. Sportsmetrics™ training program has been shown to increase hamstring strength as it enhances lower-extremity neuromuscular control where the subjects can use hip and knee flexor strategy especially during landing from a jump.[22]

Clinical Implications

Six-week duration of plyometric training is an effective form of training to improve quadriceps size, quality, and strength and vertical jump height. We recommended that Sportsmetrics™ plyometric training program may be implemented in adolescent female volleyball programs especially before the beginning of the volleyball season.

Future studies are needed to document how effective the increase in size and quality of the quadriceps in the prevention of volleyball injuries after plyometric training. Moreover, evaluating hamstring muscle strength and morphology after plyometric training help better understand the effects of plyometric training in knee function in adolescent female volleyball players.

Conclusion

The results of this study showed that 6-week plyometric training increased VL thickness and PT–CSA in nondominant limb and increase the quadriceps isokinetic strength in both limbs and vertical jump height of adolescent female volleyball players. It also enhanced the quality of VL muscle based on the EI measure and the effectiveness of the plyometric training was observed more in muscle quality and vertical jump height. Moreover, limb symmetry in quadriceps size and quality could be achieved after the training.

Acknowledgments

The authors certify that there are no conflicts of interest with any financial organization regarding the material discussed in the manuscript. The authors report no involvement in the research by the sponsor that could have influenced the outcome of this work. All authors contributed equally to the manuscript and read and approved the final version of the manuscript.

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