Improving the Q:H Strength Ratio in Women Using Plyometric Exercises

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Abstract

Tsang, KKW and DiPasquale, AA. Improving the Q:H strength ratio in women using plyometric exercises. *J Strength Cond Res* 25(10): 2740–2745, 2011—Plyometric training programs have been implemented in anterior cruciate ligament injury prevention programs. Plyometric exercises are designed to aid in the improvement of muscle strength and neuromuscular control. Our purpose was to examine the effects of plyometric training on lower leg strength in women. Thirty (age = 20.3 ± 1.9 years) recreationally active women were divided into control and experimental groups. The experimental group performed a plyometric training program for 6 weeks, 3 $d \cdot wk^{-1}$. All subjects attended 4 testing sessions: before the start of the training program and after weeks 2, 4, and 6. Concentric quadriceps and hamstring strength (dominant leg) was assessed using an isokinetic dynamometer at speeds of 60 and $120° \cdot s^{-1}$. Peak torque, average peak torque, and average power (AvgPower) were measured. The results revealed a significant ($p < 0.05$) interaction between time and group for flexion PkTq and AvgPower at $120° \cdot s^{-1}$. Post hoc analysis further revealed that PkTq at $120° \cdot s^{-1}$ was greater in the plyometric group than in the control group at testing session 4 and that AvgPower was greater in the plyometric group than in the control group in testing sessions 2–4. Our results indicate that the plyometric training program increased hamstring strength while maintaining quadriceps strength, thereby improving the Q:H strength ratio.

Key Words anterior cruciate ligament, injury prevention, training

Introduction

Participation in physical activity and sports by women has significantly increased since the 1970s. The sustained growth, attributed to the implementation of Title IX in 1972, encompasses participation in activities such as community soccer and basketball leagues and formal organized athletics at the high school and collegiate levels. The increase in the number of participants along with an advancement in the level of competition have brought about an increase in the incidence of injuries experienced, of particular interest is that of anterior cruciate ligament (ACL) injuries (4,10,45). The available research literature not only indicates an increase in the prevalence of ACL injures but also that women experience a higher rate of ACL injuries in comparison to their male counterparts (4,15,27,33).

In response, extensive efforts have been made in the scientific community to identify possible predisposing factors of women to ACL injuries and develop intervention and prevention strategies. A plethora of literature (7,19,25,26, 34,38,41) is available identifying the multifactorial nature of the predisposition including hormonal fluctuations, anatomical variances, and neuromuscular anomalies. Efforts to develop effective intervention and prevention strategies have focused primarily on the later factor of neuromuscular anomalies, more specifically the area of motor control. A predominant theme arising from the literature (6,9,16,21, 22,26,37,39,42) is that of strength imbalances between the quadriceps and hamstring muscles, the Q:H strength ratio (Q:H), often attributed to deficiencies or weakness of the hamstring muscles. Because these muscle groups serve as the primary functional stabilizers of the knee, an improper balance or deficient ratio predisposes the ACL to injurious forces.

In their analysis of the neuromuscular performance characteristics of elite female athletes, Huston and Wojtys (26) described the female athlete as being quadriceps dominant, possessing a lower Q:H ratio and male athletes as hamstring dominant, possessing a higher ratio. Moul (34) observed female basketball players to have a significantly decreased Q:H ratio bilaterally when compared to male counterparts. Soderman et al. (38) related a lower Q:H ratio to a higher risk of injury in women. The investigators observed a Q:H ratio of 55% or lower in the ACL injured leg in comparison to the noninvolved leg in female soccer players.

A variety of methods have been used in developing ACL injury intervention and prevention training programs, including informational videos, proprioception training, and

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functional movement training (9,16,22,39). The use of plyometric exercises or training has been demonstrated to be effective in improving physical performance. Hewett et al. (21) observed decreased impact forces at the knee and increased hamstring strength in female athletes participating in a plyometric training program. In addition, participation in the plyometric training program was associated with a reduced incidence of knee injury when compared to those who did not participate in the program. Plyometric training is reported to be a safe and effective method in increasing strength and power, promoting joint stability, and improving efficient functional motor patterns (11,40). Additionally, trochanteric bone mineral content, leg strength, and balance in adolescent girls have been shown to improve after a 9-month plyometric training program (44).

The purpose of this study was to evaluate the effects of a plyometric training program on the quadriceps:hamstring ratio in recreationally active women. We hypothesized that the plyometric training program would increase quadriceps and hamstring muscle strength, thereby improving the quadriceps:hamstring ratio. Improvements in these variables may contribute to reducing the overall number of ACL and knee injuries experienced in women and lead to development and implementation of intervention and prevention training programs.

Methods

Experimental Approach to the Problem

To assess the impact of plyometric training on leg strength, female subjects were randomly assigned to either the experimental group (plyometric training) or control group (no training). Quadriceps and hamstring strength (dominant leg) was assessed using a Biodex System 3 (Biodex Inc., Shirley, NY, USA) isokinetic dynamometer. Peak torque (PkTq), average peak torque (AvgPkTq), and average power (AvgPwr) generated by the muscle groups were measured during knee flexion and extension at speeds of 60 and $120°\cdot s^{-1}$. Dependent variables were defined as follows: (a) PkTq–highest amount of force generated through the range of motion, (b) AvgPkTq–average torque produced through the range of motion, and (c) AvgPwr–total amount of work divided by the total time of the work.

To highlight the addition of plyometric exercises to existing fitness activities or training programs, subjects were instructed to maintain their current regimens. All subjects completed a Paffenbarger Physical Activity Questionnaire before starting and after completion of their participation in the study. The questionnaire assesses the type and intensity of activities performed by the individual and produces a kilocalorie value.

Subjects

Twenty-five women (age: 20.32 ± 1.99 years; height: 167.69 ± 6.91 cm; and mass: 59.81 ± 9.37 kg) completed the study. All subjects indicated they had no history of a diagnosed knee, ankle, or foot injury in either limb or coexisting concussion or head injury. The women were required to be recreationally active, defined by participating in physical fitness activities at least 3 $d\cdot wk^{-1}$ but had not been participating in strength training for the past 2 months. Subjects were instructed not to participate in additional training or activities and to maintain a euhydration state for the duration of their participation in the study.

Of the 30 women that began the study, 5 subjects (4 from the experimental group and 1 from the control group) withdrew from the study because of extenuating circumstances not related to their participation in the study. As a result, the experimental group consisted of 11 subjects and the control group 14 subjects. Upon agreeing to participate in the study, each subject completed and signed an informed consent form approved by the University's Institutional Review Board.

Procedures

All subjects attended 4 testing sessions throughout the study: one before the start of the training program and after weeks 2, 4, and 6 of the training program. Testing sessions were conducted at the same time of the day for each subject. At each testing session, subjects participated in a 5-minute warm-up consisting of jogging and skipping before isokinetic testing.

Isokinetic Testing

Standard setup and application protocol described by the manufacturer was used for all testing sessions. Gravity correction was performed by measuring the amount of torque placed on the dynamometer with the knee in a relaxed state at 45° of flexion. The investigator provided verbal encouragement during each testing session for all subjects. Testing consisted of 8 total sets, 4 sets of knee extension and 4 sets of knee flexion. Two sets of 10 repetitions of concentric flexion and extension at 60 and $120°\cdot s^{-1}$ were performed on the dominant leg. A 1-minute rest period was given between each set. Five repetitions were performed as practice before testing at a new speed.

Plyometric Training Program

The training program consisted of 13 lower extremity plyometric exercises, varying in difficulty and intensity. During each training session, subjects completed at least 7 exercises selected from the total pool of 13. Exercises were performed for a specified time period or a number of repetitions. The duration of each set and the number of repetitions of each exercise completed during train sessions increased throughout the duration of the study. A detailed description of each exercise is provided in Table 1. Training sessions were led by the investigator and lasted approximately 45–60 minutes. Subjects attended training sessions 3 times per week (on alternating days), for 6 weeks. All training sessions were conducted at the same time each day.

The plyometric training program used in this study is adapted from a program previously established by Hewett et al. (21). At the first training session, the investigator

TABLE 1. Description of plyometric exercises.

Exercise	Time/repetitions/distance	Description
Wall jumps	20–30 s	Knees slightly bent, arms raised overhead, bounce up and down off toes
Tuck jumps	20–30 s	From standing position, jump and bring both knees up to chest as high as possible
Squat jumps	10–25 s	Standing jump raising both arms overhead, land in squatting position touching both hands to the floor
Single leg jump distance	5–10 reps	One-legged hop for distance, hold landing for 5 s
Scissors jump	30 s	Start in stride position, jump and alternate position in midair
Jump jump jump vertical jump	5–10 reps	Three broad jumps followed immediately with a vertical jump
Jump into bounding	15 m	Two-footed broad jump, land on single leg progress into jump
Hop hop stick	5 reps	Single-legged hop, hold landing for 5 s
Cone jumps (single and double leg)	30 s	Jump side to side over cones, repeat in forward–backward directions
Broad jumps stick landing	5–10 reps	Two-footed jump as far as possible holding landing for 5 s
Bounding in place	20–25 s	Jump from 1 leg to the other straight up and down
Bounding for distance	15 m	Start bounding in place, slowly increase distance with each step keeping knees high
180 Jumps	20–25 s	Two-footed jump, rotate 180 in midair, hold landing for 2 s, reverse direction

TABLE 2. Isokinetic ($120°\cdot s^{-1}$) strength test results ($p < 0.05$).*†

	Group	
Variable	Plyometric (mean ± *SD*)	Control (mean ± *SD*)
Flexion AvgPwr: baseline	30.76 ± 7.69	30.69 ± 9.41
Week 2‡	33.76 ± 9.97	29.06 ± 7.87
Week 4‡	34.40 ± 10.24	27.57 ± 7.33
Week 6‡	35.56 ± 7.92§	28.38 ± 9.94
Flexion PkTq: baseline	24.71 ± 4.85	26.22 ± 5.57
Week 2	24.83 ± 5.80	25.34 ± 4.10
Week 4	25.51 ± 6.41	24.44 ± 3.88
Week 6	27.20 ± 5.16§	24.96 ± 5.85
Extension AvgPwr: baseline	62.95 ± 11.66	61.53 ± 17.13
Week 2	68.04 ± 16.85	59.44 ± 13.97
Week 4	68.28 ± 13.68	58.30 ± 15.66
Week 6	68.47 ± 9.46	58.07 ± 12.56
Extension PkTq: baseline	46.43 ± 8.06	47.61 ± 9.63
Week 2	46.63 ± 5.16	46.58 ± 8.94
Week 4	48.15 ± 6.05	45.39 ± 7.91
Week 6	47.95 ± 4.58	44.91 ± 7.47

*AvgPwr = average power; PkTq = peak torque.
†Values are given as mean ± *SD.*
‡Difference between groups.
§Difference from baseline within the group.

explained and demonstrated each exercise. The investigator is a certified athletic trainer with 3 years of clinical experience working with strength training techniques including plyometric exercises. Emphasis was placed on proper technique, focusing on overall posture, and correct take-off and landing positions. A handout detailing the program and each exercise was provided to each subject. The contents of the handout described each jump, length of time or repetitions of each set, and how to increase performance intensity.

Subjects assigned to the control group did not participate in the plyometric training sessions.

Statistical Analyses

A separate 3-way mixed factor analysis of variance (ANOVA) (group × velocity × time) was used for each leg movement

Table 3. Isokinetic ($60° \cdot s^{-1}$) strength test results ($p > 0.05$).*†

Variable	Group	
	Plyometric (mean ± *SD*)	Control (mean ± *SD*)
Flexion AvgPwr: baseline	32.27 ± 6.22	27.73 ± 7.05
Week 2	29.58 ± 5.57	25.56 ± 5.87
Week 4	29.52 ± 5.83	23.54 ± 5.51
Week 6	31.11 ± 5.24	24.32 ± 6.22
Flexion PkTq: baseline	38.20 ± 5.44	36.76 ± 6.48
Week 2	36.60 ± 7.73	35.42 ± 5.85
Week 4	35.81 ± 6.76	33.65 ± 5.25
Week 6	37.61 ± 5.287	33.93 ± 5.63
Extension AvgPwr: baseline	86.88 ± 16.93	79.53 ± 18.12
Week 2	76.30 ± 16.61	73.03 ± 16.35
Week 4	76.16 ± 16.28	69.95 ± 14.52
Week 6	77.18 ± 12.34	69.98 ± 14.83
Extension PkTq: baseline	74.30 ± 10.83	72.22 ± 10.91
Week 2	66.86 ± 11.10	66.16 ± 11.35
Week 4	64.57 ± 9.23	63.62 ± 8.01
Week 6	63.01 ± 9.84	62.04 ± 10.19

*AvgPwr = average power; PkTq = peak torque.
†Values are given as mean ± *SD*.

(extension, flexion). In the event of significant interactions, pairwise comparisons were evaluated with a Tukey post hoc to determine which means were significantly different. An alpha level of 0.05 was established a priori for all statistical tests. Analyses were performed using SPSS version 13.0 (SPSS Inc., Chicago, IL, USA) statistical software package.

Results

A significant group by time interaction was found for knee flexion AvgPwr at $120° \cdot s^{-1}$ ($F_{3,69} = 3.487$, $p = 0.02$). Post hoc analysis revealed greater hamstring strength in the plyometric group compared to that in the control group in testing sessions 2–4. In addition, within the plyometric group, hamstring strength was greater in the last testing session in comparison to that in the first testing session (Table 2).

A significant group by time interaction was found for knee flexion PkTq at $120° \cdot s^{-1}$ ($F_{3,69} = 3.162$, $p = 0.03$). Post hoc analysis revealed greater hamstring strength within the plyometric group in the last testing session compared to in the first testing session (Table 2).

Analysis of the Paffenbarger Physical Activity Questionnaire indicated no differences in activity levels between the plyometric group and control group at the onset and conclusion of their participation in the study. This finding provides assurance that the 2 treatment groups were similar at the onset of the study and refrained from participating in extracurricular training throughout the duration of the study.

No significant interactions or main effects were found for knee extension at $60° \cdot s^{-1}$ (PkTq [$p = 0.971$, $1-\beta = 0.936$]; AvgPkTq [$p = 0.822$, $1-\beta = 0.486$]; AvgPwr [$p = 0.912$, $1-\beta = 0.919$]), knee flexion at $60° \cdot s^{-1}$ (PkTq [$p = 0.512$, $1-\beta = 0.792$]; AvgPkTq [$p = 0.527$, $1-\beta = 0.798$]; AvgPwr [$p = 0.209$, $1-\beta = 0.608$]), knee extension at $120° \cdot s^{-1}$ (PkTq [$p = 0.251$, $1-\beta = 0.645$]; AvgPkTq [$p = 0.636$, $1-\beta = 0.838$]; AvgPwr [$p = 0.052$, $1-\beta = 0.366$]), or knee flexion at $120° \cdot s^{-1}$ (AvgPkTq [$p = 0.103$, $1-\beta = 0.477$]) (Table 3).

Table 4. Q:H strength ratio (%) based on isokinetic ($120° \cdot s^{-1}$) strength.

Variable	Group	
	Plyometric	Control
Average power baseline	48.86	49.74
Week 2	49.62	48.88
Week 4	50.38	47.28
Week 6	51.93	48.87
Peak torque baseline	53.21	55.07
Week 2	53.24	54.40
Week 4	52.98	53.84
Week 6	56.72	55.57

Discussion

The findings from this study support the hypothesis that plyometric training is effective in improving hamstring strength in women. Participants in our plyometric jump training program experienced an increase in hamstring strength while maintaining quadriceps strength level, consequently improving the Q:H strength ratio (Table 4). Facilitated stability of the knee joint during dynamic function may positively contribute to the prevention and reduction of ACL and knee injuries in female athletes.

Strength imbalances, specifically the Q:H ratio, have been indicated significant risk factors for knee injuries in both male and female athletes (6,9,16,21,22,26,37,38,42). The research literature (26,34,38) clearly elucidates that female athletes are at greater risk of developing ACL injuries because of a deficient Q:H ratio lending to the descriptor of being "quadriceps dominant." Huston and Wojtys (26) observed in response to an anterior tibial translation perturbation that female athletes activate their quadriceps first in contrast to the hamstring muscles by male athletes. In a kinematic analysis of functional movements, Malinzak et al. (31) described female athletes to use an erect posture with extended knees and hips while landing from a jump. The concomitant presentation of these variables in the dynamic knee increases stress on the ACL thereby increasing the incidence of injuries in women. The plyometric training program used in this study effectively increased hamstring strength while quadriceps strength was maintained. Although not a part of the original study design, the increase in hamstring strength without a correlative increase in quadriceps strength may demonstrate a more effective means to improve the Q:H strength ratio and is worthy of further investigation.

Strength gains from plyometric training stems from the physiological concept that stretching a muscle before contraction leads to greater force production (5,11,21,44). The actions of the quadriceps muscle while performing jumping activities illustrate this concept as the quadriceps muscle is stretched during the preparatory phase of jumping (knee and hip flexion) before contraction during the execution of the jump (knee and hip extension). In contrast, subjects in our plyometric training group did not experience an increase in quadriceps strength. We believe that this is a result of the focus of our training protocol because the subjects in the plyometric training group were not encouraged to jump higher or farther, thus accounting for the sustained level of quadriceps strength seen in this study.

The emphasis during training sessions in this study was on proper technique, overall posture, and correct take-off and landing positions. This focus may have contributed to the strength increases of the hamstrings as the exercises place the hamstring muscles on stretch during the preparatory and landing mechanics involved with the exercises. When considering the actions of the hamstrings during jumping and landing, it is apparent that the hamstring muscles contribute via an eccentric manner. More specifically, the hamstrings create tension eccentrically to stabilize the tibia from the actions of the quadriceps muscle thereby providing knee joint stability.

Eccentric muscle actions can develop greater maximum forces than concentric or isometric muscle actions can (14) and therefore have been thought to be able to be more successful at increasing overall strength (20). In this study, the plyometric jumps had a positive effect on the concentric strength of the hamstring muscles, even though the jumps repeatedly used the eccentric actions of the hamstring muscle. Our results support existing literature that eccentric training has been shown to improve concentric strength through increased neural activation (23,29) and muscle hypertrophy (23), specifically type 2 fibers (24).

Results from this study indicate the plyometric exercises had a velocity specific training effect on muscle strength as statistical significance was observed at $120°\cdot s^{-1}$ and not at $60°\cdot s^{-1}$. The relationship of velocity-specific training adaptations and subsequent transfer to movement velocities has been examined in the research literature but is not clearly understood. Some investigators have indicated positive effects with training at or close to performance velocities (8,12,28), others have reported improvements with training velocities at or below those required of performance (1,32), and still others indicating an intermediate training velocity can enhance performance over a large range of contraction velocities (17,35,36).

To optimize adaptations from training, it is suggested that exercises should not only include slow and fast movements but also simulate the movement velocity of the targeted activity, for example, sprinting, jumping (18,30,36). Although the exact velocity of execution during the plyometric exercises in this study was not monitored, it is reasonable to estimate that the motions of jumping and landing occurred at speeds closer to $120°\cdot s^{-1}$ rather than $60°\cdot s^{-1}$. The velocity-specific effect demonstrated in our results support the use of training velocities that simulate the movement velocity of a specific activity, and this effect should be considered when incorporating plyometric activities in the clinical setting.

Another related topic worth mentioning but beyond the scope of this study is the use of testing protocols that are isokinetic rather than isoinertial based. Although isokinetic testing is very common in the research literature, numerous investigators suggest that isoinertial protocols are more specific to training and competitive environments and more closely relate to the coordination dynamics of movement (2,13,43). It is therefore important to consider testing protocols and research designs when attempting to assimilate testing results into exercise training programs.

Practical Applications

The use of plyometric exercises to improve strength and power is well documented in the research literature. The results of this study indicate plyometric jump training can be effectively used in a group setting, for example, athletic team, and attain positive results by improving hamstring muscle strength. In addition, the gains attained by plyometric jump training were standalone because our subjects did not participate in other training activities, thereby highlighting the time effectiveness of plyometric training.

References

1. Adeyanju, K, Crews, TR, and Meadors, WJ. Effects of two speeds of isokinetic training on muscular strength, power, and endurance. *J Sports Med* 23: 352–356.
2. Almasbakk, B and Hoff, J. Coordination the determinant of velocity specificity. *J Appl Physiol* 80: 2046–2052, 1996.
3. Arendt, E, Agel, J, and Dick, R. Anterior cruciate ligament injury patterns among collegiate men and women. *J Athl Training* 34: 86–92, 1999.

4. Arendt, E and Dick, R. Knee injury patterns among men and women in collegiate basketball and soccer: NCAA data and review of literature. *Am J Sports Med* 23: 694–701, 1995.
5. Bishop, DC, Smith, RJ, Smith, MF, and Rigby, HE. Effect of plyometric training on swimming block start performance in adolescents. *J Strength Cond Res* 23: 2137–2143, 2009.
6. Blackburn, T, Guskiewicz, K, Petschauer, M, and Prentice, W. Balance and joint stability: The relative contributions of proprioception and muscular strength. *J Sport Rehab* 9: 315–328, 2000.
7. Boden, BP, Griffin, LY, and Garrett, WEJ. Etiology and prevention of noncontact ACL injury. *Phys Sportsmed* 28: 53–60, 2000.
8. Caiozzo, VJ, Perrine, JJ, and Edgerton, VR. Training-induced alterations of the in vivo force–velocity relationship of human muscle. *J Appl Physiol* 51: 750–754, 1981.
9. Caraffa, A, Cerulli, G, Projetti, M, Aisa, G, and Rizzo, A. Prevention of anterior cruciate ligament injuries in soccer. A prospective controlled study of proprioceptive training. *Knee Surg Sports Traumatol Arthrosc* 4: 19–21, 1996.
10. Chandy, TA and Grana, WA. Secondary school athletic injury in boys and girls: A three-year comparison. *Phys Sportsmed* 12: 106–111, 1985.
11. Chu, D. *Jumping into Plyometrics.* Champaign, IL: Human Kinetics, 1995.
12. Coyle, EF, Feiring, DC, Rotkis, TC, Cote, RW, Roby, FB, Lee, W, and Wilmore, JH. Specificity of power improvements through slow and fast isokinetic training. *J Appl Physiol* 51: 1437–1442, 1981.
13. Cronin, J, McNair, PJ, and Marshall, RN. Velocity specificity, combination training and sport specific tasks. *J Sci Med Sport* 4: 168–178, 2001.
14. Doss, W and Karpovich, P. A comparison of concentric, eccentric, and isometric strength of the elbow flexors. *J Appl Physiol* 20: 351–353, 1965.
15. Engstrom, B, Johansson, C, and Tornkvist, H. Soccer injuries among elite female players. *Am J Sports Med* 19: 372–375, 1991.
16. Ettlinger, CF, Johnson, RJ, and Shealy, JE. A method to help reduce the risk of serious knee sprains incurred in alpine skiing. *Am J Sports Med* 23: 531–537, 1995.
17. Ewing, JL, Wolfe, D, Rogers, M, Amundson, M, and Stuff, G. Effects of velocity of isokinetic training on strength, power, and quadriceps muscle fibre characteristitcs. *J Appl Physiol* 61: 159–162.
18. Fleck, SJ and Kraemer, WJ. *Designing Resistance Training Programs.* Champaign, IL: Human Kinetics, 1987. pp. 81–94.
19. Griffin, L. The female athlete. In: *Orthopaedic Sports Medicine: Principle and Practice.* J. DeLee and D. Drex, eds. Philadelphia, PA: Saunders, 1994. pp. 356–373.
20. Häkkinen, K and Komi, P. Effect of different combined concentric and eccentric muscle work regimens on maximal strength development. *J Hum Mov Stud* 7: 33–44, 1981.
21. Hewett, T, Stroupe, A, Nance, T, and Noyes, F. Plyometric training in female athletes. *Am J Sports Med* 24: 765–773, 1996.
22. Hewett, TE, Lindenfeld, TN, Riccobene, JV, and Noyes, FR. The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *Am J Sports Med* 27: 699–705, 1999.
23. Higbie, E, Cureton, K, Warren, G, and Prior, B. Effects of concentric and eccentric training on muscle strength, cross sectional area, and neural activation. *J Appl Physiol* 81: 2173–2181, 1996.
24. Hortobagyi, R, Hill, J, Houmard, J, Fraser, D, Lambert, N, and Israel, R. Adaptive responses to muscle lengthening and shortening in humans. *J Appl Physiol* 80: 765–772, 1996.
25. Huston, LJ, Greendield, MLVH, and Wojtys, EM. Anterior cruciate ligament injuries in the female athlete. Potential risk factors. *Clin Orthopaed Rel Res* 50–63, 2000.
26. Huston, LJ and Wojtys, EM. Neuromuscular performance characterisitics in elite female athletes. *Am J Sports Med* 24: 427–436, 1996.
27. Ireland, ML, Gaudette, M, and Crook S. ACL injuries in the female athlete. *J Sport Rehabil* 6: 97–110, 1997.
28. Kanehisa, H and Miyashita, M. Specificity of velocity in strength training. *J Appl Physiol* 52: 104–106, 1983.
29. Komi, P and Buskirk, E. Effect of eccentric and concentric muscle conditioning on tension and electrical activity in human muscle. *Ergonomics* 15: 417–434, 1972.
30. Kraemer, WJ, Deschenes, MR, and Fleck, SJ. Physiological adaptations to resistance exercise. *Sports Med* 6: 246–256, 1988.
31. Malinzak, B, Colby, S, Kirkendall, D, and Garrett, W. Electromyographic and three-dimensional kinematic analysis of cutting maneuvers in men and women: Implications for anterior cruciate ligament injury at footstrike. *AOSSM Specialty Day.*
32. Mastropaolo, J and Takei, Y. Weight training pivoted the force–velocity curve. *Int J Sports Med* 12: 345, 1991.
33. Messina, DF, Farney, WC, and DeLee, JC. The incidence of injury in Texas high school basketball. A prospective study among male and female athletes. *Am J Sports Med* 27: 294–299, 1999.
34. Moul, JL. Differences in selected predictors of anterior cruciate ligament tears between male and female NCAA division I collegiate basketball players. *J Athl Training* 33: 118–121, 1998.
35. Poliquin, C. Theory and methodology of strength training: At which speed should repetitions be performed. *Sports Coach* 35–38, 1990.
36. Sale, D and MacDougall, D. Specificity in strength training: A review for the coach and athlete. *Sci Period Res Technol Sport* 1–7, 1981.
37. Schultz, S, Perrin, D, Adams, J, Arnold, B, Gansnede, B, and Granata, K. Neuromuscular response characteristics in men and women after knee perturbation in a single-leg, weight-bearing stance. *J Athl Training* 36: 37–43, 2001.
38. Soderman, K, Alfredson, H, Pietila, T, and Werner, S. Risk factors for leg injuries in female soccer players: A prospective investigation during one out-door season. *Knee Surg Sports Traumatol Arthrosc* 9: 313–321, 2001.
39. Soderman, K, Werner, S, Pietila, T, Engstrom, B, and Alfredson, H. Balance board training: Prevention of traumatic injuries of the lower extremities in female soccer players. *Knee Surg Sports Traumatol Arthrosc* 8: 356–363, 2000.
40. Swanik, C and Swanik, K. Plyometrics in rehabilitating the lower extremity. *Athl Ther Today* 4: 16–22, 2000.
41. Toth, A and Cordasco, F. Anterior cruciate ligament injuries in the female athlete. *J Gender Specific Med* 4: 25–34, 2001.
42. Wilk, K, Escamilla, R, Fleisig, G, Barrentine, S, Andrews, J, and Boyd, M. A comparison of tibiofemoral joint forces and electromyographic activity during open and closed kinetic chain exercises. *Am J Sports Med* 24: 518–527, 1996.
43. Wilson, GJ, and Lyttle, AD, Ostrowski, KJ, and Murphy, AJ. Assessing dynamic performance: A comparison of rate of force development tests. *J Strength Cond Res* 9: 176–181, 1995.
44. Witzke, KA and Snow, CM. Effects of plyometric jump training on bone mass in adolescent girls. *Med Sci Sports Exerc* 32: 1051–1057, 2000.
45. Zillmer, D, Powell, J, and Albright, J. Gender-specific injury patterns in high school varsity basketball. *J Women's Health* 1: 69–76, 1992.