Published in final edited form as:

Br J Sports Med. 2008 July ; 42(7): 614–619. doi:10.1136/bjsm.2007.046086.

A pilot study to determine the effect of trunk and hip focused neuromuscular training on hip and knee isokinetic strength

G D Myer^{1,2}, J L Brent¹, K R Ford^{1,3}, and T E Hewett^{1,4}

¹Sports Medicine Biodynamics Center and Human Performance Laboratory, Cincinnati Children's Hospital Medical Center, Cincinnati, Ohio, USA

²Graduate Program in Athletic Training, Rocky Mountain University of Health Professions, Provo, Utah, USA

³Department of Kinesiology and Health Promotion, University of Kentucky, Lexington, Kentucky, USA

⁴Departments of Pediatrics and Orthopaedic Surgery, College of Medicine and the Departments of Biomedical Engineering and Rehabilitation Sciences, University of Cincinnati, Cincinnati, Ohio, USA

Abstract

Objective—The objective was to determine the effect of trunk focused neuromuscular training (TNMT) on hip and knee strength. The hypothesis was that TNMT would increase standing isokinetic hip abduction, but not knee flexion/extension, strength.

Methods—21 high-school female volleyball players (14 TNMT, mean age 15.4 (1.4) years, weight 170.5 (5.0) cm, height 64.1 (8.5) kg and 7 controls, mean age 16.0 (1.7) years, height 173.4 (10.0) cm, weight 63.9 (5.3) kg; $p>0.05$) were recruited to participate in this study. The 14 TNMT subjects participated in a TNMT protocol (twice weekly) over a 10 week period in addition to their standard once-weekly off-season strength training. Standing isokinetic hip abduction strength and seated knee flexion/extension strength were measured before and after TNMT.

Results—A significant interaction of group and time was observed. The TNMT group increased isokinetic hip abduction strength approximately 15% (13.5% in the dominant leg: mean (SD) 46.6 (10.1) to 52.9 (11.4) foot-pounds and 17.1% in the non-dominant leg: 46.1 (10.4) to 54.0 (10.7) foot-pounds; $p=0.01$). There was no difference in the control group in pre-test versus post-test measures. Post-test results also indicated no effect of TNMT on isokinetic knee extension ($p=0.57$) or knee flexion ($p=0.57$) strength.

Conclusions—Ten weeks of TNMT increased standing hip abduction strength in female athletes. Increased hip abduction strength and recruitment may improve the ability of female athletes to increase control of lower limb alignment and decrease knee loads resulting from increased trunk displacement during sports activities.

Correspondence to: Dr G D Myer, Cincinnati Children's Hospital, 3333 Burnet Avenue, MLC 10001, Cincinnati, OH 45229; greg.myer@cchmc.org.

Competing interests: None.

Female athletes are currently reported to be 4–6 times more likely to sustain a sport-related non-contact anterior cruciate ligament (ACL) injury than are male athletes.^{1–3} Altered neuromuscular trunk and hip control strategies during the execution of sports movements may result in lower limb joint mechanics (motions and loads) that increase the risk of ACL injury in female athletes. Hip abduction strength and control may be the critical modulator between altered trunk control and ultimate lower limb knee loads responsible for ACL rupture.

During peak growth velocity of both height and mass, the tibia and femur grow at rapid rates in pubertal athletes of both sexes.⁴ Rapid growth of the two longest levers in the human body initiates height increases and increased height of the centre of mass, making muscular control of trunk more challenging. In addition, increased body mass and longer joint levers leads to the development of greater joint forces and moments that are more difficult to balance and dampen at the lower limb joints during high-velocity manoeuvres.^{5–7} Brent *et al* used a longitudinal study approach to determine that in a population of 11–22-year-old athletes, male athletes increased their relative hip abduction strength at a significantly greater rate than did female athletes.⁸ Female athletes also showed decreased power and increased valgus knee motion during jumping and landing as they matured.⁵⁶ Mature female athletes who showed decreased hip abduction control were also more likely to show increased knee valgus angle during a dynamic cutting task.⁹ Based on these data, it can be hypothesised that after the onset of puberty and the initiation of peak height velocity, the increased tibia and femur lever length, with increased body mass and height of the centre of mass, lead to decreased “core stability” or control of trunk motion during dynamic tasks in the absence of increases in strength and recruitment of the musculature at the hip.⁷¹⁰ As female athletes reach maturity, decreased “core stability” may underlie their tendency to increased dynamic lower limb valgus load (hip adduction and knee abduction) during dynamic tasks.^{5–711–13}

The aim of the current study was to determine the effect of trunk and hip focused neuromuscular training (TNMT) on lower limb hip and knee strength. The hypothesis tested was that TNMT would change standing isokinetic hip abduction strength with no similar changes in knee flexion/extension or in the strength measures for control subjects.

METHODS

Subjects

Parents or guardians signed informed consent approved by the institutional review board and assent from the child participants were obtained before study participation.

In total, 21 high-school female volleyball players (14 TMNT, mean age 15.4 (1.4) years, weight 170.5 (5.0) cm, height 64.1 (8.5) kg and 7 controls, mean age 16.0 (1.7) years, height 173.4 (10.0) cm, weight 63.9 (5.3) kg; $p > 0.05$) were recruited to participate in this study. The 14 TNMT subjects participated in a TNMT protocol (twice weekly) over a 10 week period in addition to their standard once-weekly off-season strength training. Pre-testing occurred 1 week before the first day of training, and post-test measures were recorded approximately 11 weeks after the pretest on all subjects (4 days after the final training

session). The pre-established compliance criterion required that each subject participate in at least two-thirds (14 of 20) of the training sessions to be included in the study analyses.

Dynamic strength

Isokinetic knee extension/flexion strength was collected with subjects seated on a dynamometer with the trunk perpendicular to the floor, and with hip and knee flexed to 90°. Before each data-collection set, a warm-up set consisting of five knee flexion/extensions for each leg at 300°/second was performed (fig 1). The test session consisted of 10 knee flexion/extension repetitions for each leg at 300°/second. Peak flexion and extension torques were recorded. Hip abduction strength was measured with the subjects standing erect, fully supported with a stabilisation strap around the pelvis and their hands gripping a stable hand rest. The test leg was positioned lateral to the opposite leg at zero degrees of hip and knee flexion. The axis of abduction/adduction of the hip was aligned with the axis of rotation of the dynamometer. The resistance pad was affixed to the subject's leg, just proximal to the knee joint. Before data collection, subjects were familiarised with how to perform the test and were allowed to perform 5–10 submaximum repetitions until they became comfortable with the testing technique and the tester confirmed appropriate technique. The athletes were then asked to perform five repetitions with maximum exertion at 120°/second (fig 2). The initial test leg was alternated between subjects to control for a side-learning effect. Peak hip abduction torques were recorded and analysed by a single investigator. The intrarater reliability (ICC_{3,1}) for the presented hip abduction test methods showed good to excellent reliability on the left (ICC=0.857; 95% CI 0.577 to 0.971) and right (ICC=.916; 95% CI 0.727 to 0.984) sides.⁸

Training protocol

Table 1 shows the trunk and hip focused neuromuscular training protocol that was used with female athletes to target deficits in trunk control and improve hip strength and power. Five phases were used for each exercise to facilitate progression in difficulty. These exercises were designed to improve the athletes' ability control the trunk and improve "core stability" during dynamic activities. Each exercise within the individual phases progressively increased in intensity to challenge the performance of the exercise techniques continually. End-stage progressions incorporated lateral trunk perturbations that forced the athlete to decelerate and control the trunk in the coronal plane in order to execute the prescribed technique successfully (fig 3,4). All of the exercises selected for the initial phase, before progression, were adapted from previous epidemiological studies that reported reductions in ACL injury risk (table 1).^{14–17} The protocol progressions were developed from previous biomechanical investigations that reported reductions in knee abduction load in female athletes after their training protocols.^{18–21} The novelty of this training approach is that the protocol incorporated exercises that perturb the trunk to improve control of trunk musculature, in attempt to improve hip abduction strength and "core stability." Our hypothesis was that improved hip and trunk control would decrease the magnitude of peak kinematics and kinetics that induce high knee abduction loading in female athletes.

Statistics

A mixed-design, repeated-measures ANOVA (2×2×2) was used to test for the main effect and interactions of the measures of time (pre-test vs. post-test), group (trained vs. untrained control) and limb (dominant vs non-dominant) on the dependent isokinetic strength variables of (1) hip abduction, (2) knee flexion and (3) knee extension.

RESULTS

A significant interaction of group and time was observed with statistical analysis. The TNMT group increased bilateral isokinetic hip abduction strength approximately 15% (13.5% in the dominant limb, mean (SD) 46.6 (10.1) to 52.9 (11.4) foot-pounds and 17.1% in the non-dominant limb 46.1 (10.4) to 54.0 (10.7) foot-pounds; $p<0.01$). However, there were no observed effects of TNMT on isokinetic knee extension ($p=0.57$) or knee flexion ($p=0.57$) strength. There was no change in the control group with time between pre-test and post-test measures.

DISCUSSION

The aim of this study was to determine the effect of a training program on lower limb hip and knee strength. Hip abduction strength was increased in a group of female athletes after TNMT. Recent investigations indicate an association of hip abduction strength with dynamic valgus alignments that increase ACL injury risk.^{922–25} Padua *et al* examined the relationship between hip strength quantified with a hand-held dynamometer and joint kinematics during a drop-jump task in males and female athletes.²⁴ They reported that decreased hip strength (gluteus medius and gluteus maximus) was related to greater knee valgus at initial contact and greater peak knee valgus.²⁴ In addition, hip abduction strength (gluteus medius) was the only significant predictor of initial and peak valgus angles during the drop vertical jump.²⁴ Claiborne *et al* reported a significant relationship between increased concentric hip abduction strength and reduced frontal plane knee abduction motion during a single-leg squatting task.²⁵ Similarly, female athletes who showed increased eccentric isokinetic hip strength showed decreased knee valgus angles when landing from a jump.²⁶ In a follow-up investigation, Jacobs *et al* evaluated isometric hip abduction peak torque and found that female athletes showed a relationship between decreased hip strength and increased knee valgus displacement and hip adduction during landing.²⁷ Interestingly, these relationships were not evident in the male athletes in this population study, who also showed increased hip abduction strength and decreased knee valgus displacement relative to the female athletes in the study.²⁷

The theory that hip strength and control may dictate knee motion and loads underlines the importance of the improved hip abduction strength that was obtained from TNMT in the current project. As female athletes reach maturity, there appears to be an absence of adaptation in hip and “core” strength, concomitant with increased risk of high-risk biomechanics and increased risk of ACL injury.^{56828–30} Hip abduction strength measurement may be advantageous to identify and target high-risk female athletes with neuromuscular training.¹⁸ Secondly, if this association between maturation and decreased adaptive changes in hip abduction strength and recruitment is present in this population,

TNMT may be effective intervention in pubertal and pre-pubertal female athletes to induce a “neuromuscular spurt” (defined as the natural adaptation of increased power, strength and coordination that occur with increasing chronological age and maturational stage in adolescent boys) in female athletes.⁸³¹ Cumulatively these techniques may increase the effectiveness of ACL injury prevention programmes in young female athletes.

Limitations

The limitations in interpretation of the current results and establishment of links to positive adaptations towards the reduction of and ACL injury risk in female athletes are two-fold. First, the measurements of hip abduction strength quantified in the current investigation were performed in an open-chain position with concentric muscle actions. Actual ACL injury mechanisms most likely occur in closed-chain situations, with predominating eccentric muscle action at the hip. Second, there are no direct links between improved hip abduction strength and actual changes in neuromuscular strategies linked to ACL injury in female athletes. Thus, the relationships between the current findings and the potential to reduce ACL injury risk can only be inferred from these pilot data. Another potential limitation of this study is that only female volleyball players were included in the sample population. As there is a sex difference in the relative rate of ACL rupture, it is possible that inclusion of male subjects into our study design would have delineated gender differences in hip abduction strength and how these measures change with training. In addition, including athletes from different sports into the current study could have helped to show sports-specific associations for the potential to alter hip strength and been more generalisable to the overall female athletic population. Another potential limitation of this study is the lack of joint moment (torque) and electromyo-graphic data to examine the relationship between relative torques during dynamic tasks, muscle recruitment of the prime movers at the hip, and changes in isokinetic hip abduction strength. These studies are ongoing in our laboratory and may be useful to further delineate the effectiveness of the proposed protocol. Although the aforementioned limitations may exist, there appears to be a positive relationship between increased hip abduction strength and the reduction of biomechanics linked to increased ACL injury risk, which may indicate that the reported changes are positive adaptations to tested trunk and hip focused neuromuscular training.²⁵

CONCLUSION

Hip abduction strength and control may be the critical modulator between altered trunk control and ultimate knee loads responsible for ACL rupture. Schmitz *et al* reported increased gluteus medius activation in response to trunk displacement.³² The results of the current study indicate that 10 weeks of TNMT increases standing hip abduction strength in female athletes. Hip abduction strength and recruitment may improve the ability of female athletes to increase control of lower limb alignment and decrease motion and loads resulting from increased trunk displacement during sports activities.¹⁰²⁵ Further investigations are needed to determine if improved hip strength after TNMT translates into reduced knee abduction load in female athletes at high risk of ACL injury. If this association is observed, then parallel investigations should be undertaken to determine if TNMT is effective in

pubertal and pre-pubertal athletes to determine its effectiveness to increase relative hip strength and control, which is often reduced as young female athletes mature.⁸³¹

Acknowledgments

This study was supported by grant R01-AR049735 from the National Institutes of Health/National Institute of Arthritis and Musculoskeletal and Skin Diseases. We thank the Mason School Volleyball Program, especially head coach T Keesling, Mason School athletic director S Stemple, principal Dr D Allen and superintendent K Bright for their participation in this study. We also thank athletic trainer M Moore and Middletown Regional Atrium Medical Center for their support with this investigation, and the Cincinnati Children's Sports Medicine Biodynamics Center Team, particularly D Chandler, T Evans, K Foss, T Henderson, J Kirwan, S Meyer, C Quatman and B Scherer for their contributions during training and testing for this project.

REFERENCES

1. Arendt E, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. *Am J Sports Med.* 1995; 23:694–701. [PubMed: 8600737]
2. Malone TR, Hardaker WT, Garrett WE, et al. Relationship of gender to anterior cruciate ligament injuries in intercollegiate basketball players. *J South Orthop Assoc.* 1993; 2:36–39.
3. Myklebust G, Maehlum S, Holm I, et al. A prospective cohort study of anterior cruciate ligament injuries in elite Norwegian team handball. *Scand J Med Sci Sports.* 1998; 8:149–153. [PubMed: 9659675]
4. Tanner JM, Davies PS. Clinical longitudinal standards for height and height velocity for North American children. *J Pediatr.* 1985; 107:317–329. [PubMed: 3875704]
5. Hewett TE, Myer GD, Ford KR, et al. Preparticipation physical exam using a box drop vertical jump test in young athletes: the effects of puberty and sex. *Clin J Sport Med.* 2006; 16:298–304. [PubMed: 16858212]
6. Hewett TE, Myer GD, Ford KR. Decrease in neuromuscular control about the knee with maturation in female athletes. *J Bone Joint Surg Am.* 2004; 86-A:1601–1608. [PubMed: 15292405]
7. Hewett, TE.; Biro, FM.; McLean, SG., et al. Identifying female athletes at high risk for ACL injury. Cincinnati Children's Hospital: National Institutes of Health; 2003.
8. Brent, JL.; Myer, GD.; Ford, KR., et al. A longitudinal examination of hip abduction strength in adolescent males and females. Submitted to American College of Sports Medicine National Meeting; Indianapolis, IN. 2008.
9. Myer GD, Imwalle LE, Ford KR, et al. Hip adduction, not hip internal rotation, dictates knee motion related to ACL injury during cutting maneuvers. *Med Sci Sports Exerc.* 2006; 38(Suppl):S40.
10. Ford KR, Myer GD, Hewett TE. Increased trunk motion in female athletes compared to males during single leg landing. *Med Sci Sports Exerc.* 2007; 39(Suppl):S70.
11. Wilson JD, Dougherty CP, Ireland ML, et al. Core stability and its relationship to lower extremity function and injury. *J Am Acad Orthop Surg.* 2005; 13:316–325. [PubMed: 16148357]
12. Hodges PW, Richardson CA. Contraction of the abdominal muscles associated with movement of the lower limb. *Phys Ther.* 1997; 77:132–142. discussion 142–4. [PubMed: 9037214]
13. Hodges PW, Richardson CA. Feedforward contraction of transversus abdominis is not influenced by the direction of arm movement. *Exp Brain Res.* 1997; 114:362–370. [PubMed: 9166925]
14. Mandelbaum BR, Silvers HJ, Watanabe D, et al. Effectiveness of a neuromuscular and proprioceptive training program in preventing the incidence of ACL injuries in female athletes: two-year follow up. *Am J Sport Med.* 2005; 33:1003–1010.
15. Hewett TE, Stroupe AL, Nance TA, et al. Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. *Am J Sports Med.* 1996; 24:765–773. [PubMed: 8947398]
16. Petersen W, Braun C, Bock W, et al. A controlled prospective case control study of a prevention training program in female team handball players: the German experience. *Arch Orthop Trauma Surg.* 2005; 125:614–621. [PubMed: 15703919]

17. Myklebust G, Engebretsen L, Braekken IH, et al. Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. *Clin J Sport Med.* 2003; 13:71–78. [PubMed: 12629423]
18. Myer GD, Ford KR, Brent JL, et al. Differential neuromuscular training effects on ACL injury risk factors in “high-risk” versus “low-risk” athletes. *BMC Musculoskelet Disord.* 2007; 8:1–7. [PubMed: 17204151]
19. Myer GD, Ford KR, Palumbo JP, et al. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J Strength Cond Res.* 2005; 19:51–60. [PubMed: 15705045]
20. Myer GD, Ford KR, Brent JL, et al. The effects of plyometric versus dynamic balance training on power, balance and landing force in female athletes. *J Strength Cond Res.* 2006; 20:345–353. [PubMed: 16686562]
21. Myer GD, Ford KR, McLean SG, et al. The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. *Am J Sports Med.* 2006; 34:490–498. [PubMed: 16382007]
22. Nyland J, Kuzemchek S, Parks M, et al. Femoral anteversion influences vastus medialis and gluteus medius EMG amplitude: composite hip abductor EMG amplitude ratios during isometric combined hip abduction-external rotation. *J Electromyogr Kinesiol.* 2004; 14:255–261. [PubMed: 14962778]
23. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective Study. *Am J Sports Med.* 2005; 33:492–501. [PubMed: 15722287]
24. Padua DA, Marshall SW, Beutler AI, et al. Predictors of knee valgus angle during a jump-landing task. *Med Sci Sports Exerc.* 2005; 37:S398.
25. Claiborne TL, Armstrong CW, Gandhi V, et al. Relationship between hip and knee strength and knee valgus during a single leg squat. *J Appl Biomech.* 2006; 22:41–50. [PubMed: 16760566]
26. Jacobs C, Mattacola C. Sex Differences in eccentric hip-abductor strength and knee-joint kinematics when landing from a jump. *Sport Rehabil.* 2005; 14:346–355.
27. Jacobs CA, Uhl TL, Mattacola CG, et al. Hip abductor function and lower extremity landing kinematics: sex differences. *J Athl Train.* 2007; 42:76–83. [PubMed: 17597947]
28. Shea KG, Pfeiffer R, Wang JH, et al. Anterior cruciate ligament injury in pediatric and adolescent soccer players: an analysis of insurance data. *J Pediatr Orthop.* 2004; 24:623–628. [PubMed: 15502559]
29. Quatman CE, Ford KR, Myer GD, et al. Maturation leads to gender differences in landing force and vertical jump performance: a longitudinal study. *Am J Sports Med.* 2006; 34:806–813. [PubMed: 16382009]
30. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc.* 2003; 35:1745–1750. [PubMed: 14523314]
31. Myer GD, Ford KR, Hewett TE. Rationale and clinical techniques for anterior cruciate ligament injury prevention among female athletes. *J Athl Train.* 2004; 39:352–364. [PubMed: 15592608]
32. Schmitz RJ, Riemann BL, Thompson T. Gluteus medius activity during isometric closed-chain hip rotation. *J of Sport Rehabil.* 2002; 11:179–188.

What is already known on this topic

- ▶ ACL injury in female athletes probably has a multi-factorial aetiology, with several potential elements that determine injury outcome.
- ▶ Previous epidemiological data show that many physical and psychological parameters may contribute to ACL injury rates in female athletes.
- ▶ Hip abduction strength and recruitment may be a critical modulator to between the trunk control and excessive knee

What this study adds

- ▶ Ten weeks of TNMT increased standing hip abduction strength in female athletes.
- ▶ Increased hip abduction strength and recruitment may improve the ability of female athletes to increase control of lower limb alignment and decrease loads resulting from increased trunk displacement during sports activities.

Figure 1.
Example of the isokinetic knee flexion/extension testing.

Figure 2.
Example of the isokinetic standing hip-abduction testing.

Figure 3.

Example progression of training exercises targeting hip control during each phase (see table 2 for explanation).

Figure 4.

Example progression of training exercises targeting trunk control during each phase (see table 2 for explanation).

Table 1

Example trunk and hip focused neuromuscular training protocol

Phase I	Phase II	Phase III	Phase IV	Phase V	Exercise adapted from:
Lateral jump and hold	Lateral jumps	Lateral hop and hold	Lateral hops	X-hops	Hewett 1996 ¹⁵ Mandelbaum 2005 ¹⁵
Step-hold	Jump-single-leg hold	Hop-hold	Hop-hop-hold	Crossover hop-hop-hold	Hewett 1996 ¹⁵
BOSU* (round) toe-touch swimmers	BOSU (round) swimmers with partner perturbations	Prone bridge (elbows and knees) hip extension opposed shoulder flexion	Prone bridge (elbows and toes) hip extension	Prone bridge (elbows and toes) hip extension opposite shoulder flexion	Myer 2007 ¹⁸
BOSU (round) double-knee hold	BOSU (round) single-knee hold	Swiss ball bilateral knee	Swiss ball bilateral knee with partner perturbations	Swiss ball bilateral knee with lateral ball catch	Myer 2007 ¹⁸
Single-leg lateral airex hop-hold	Single-leg lateral BOSU (round) hop-hold	Single leg lateral BOSU (round) hop-hold with ball catch	Single leg 4 way BOSU (round) hop-hold	Single leg 4 way BOSU (round) hop-hold with ball catch	Myklebust 2003, ¹⁷ Petersen 2005 ¹⁶
Single tuck jump, soft landing	Double tuck jump	Repeated tuck jump	Side to side barrier tuck jumps	Side to side reaction barrier tuck jumps	Hewett 1996 ¹⁵
Front lunges	Walking lunges	Walking lunges unilaterally weighted	Walking lunges with plate cross-over	Walking lunges with unilateral shoulder press	Mandelbaum 2005 ¹⁵
Lunge jumps	Scissor jumps	Lunge jumps unilaterally weighted	Scissor jumps unilaterally weighted	Scissor jumps with ball swivel	Hewett 1996 ¹⁵
BOSU (flat) double-leg pelvic bridges	BOSU (flat) single-leg pelvic bridges	BOSU (round) single-leg pelvic bridges with weight	Supine Qwiss ball hamstring curl	Russian hamstring curl with lateral touch	Mandelbaum 2005 ¹⁵
Single leg 90° hop-hold	Single leg 90° airex hop-hold	Single leg 90° airex hop-hold reaction ball catch	Single leg 180° airex hop-hold	Single leg 180° airex hop-hold reaction ball catch	Myklebust 2003, ¹⁷ Petersen 2005 ¹⁶
BOSU (round) lateral crunch	Box lateral crunch	BOSU (round) lateral crunch with ball catch	Swiss ball lateral crunch	Swiss ball lateral crunch with ball catch	Myer 2007 ¹⁸
Box double crunch	Box swivel double crunch	BOSU (round) swivel ball touches (feet up)	BOSU (round) double crunch	BOSU (round) swivel double crunch	Myklebust 2003, ¹⁷ Petersen 2005 ¹⁶
Swiss ball back hyperextensions	Swiss ball back hyperextensions with ball reach	Swiss ball hyperextensions with back fly	Swiss ball hyperextensions with ball reach lateral	Swiss ball hyperextensions with lateral ball catch	Myer 2007 ¹⁸

* Domed balance trainer (TEAM BOSU, Canton, Ohio, USA)

Table 2

Explanation of exercises targeting hip and trunk control.

Phase	Hip		Trunk	
	Exercise	Explanation	Exercise	Explanation
I	BOSU (round) double-knee hold	The athlete begins this exercise by balancing in a kneeling position with her knees on each side of the round side of the BOSU. The athlete will maintain this balanced position with the hips slightly flexed for the duration of the exercise	BOSU (round) lateral crunch	The athlete starts lying on her side with her hip located in the center of the round side of the BOSU. The athlete's feet and legs must be anchored during this exercise by the trainer or a stationary object. The athlete will proceed to bend laterally at the waist back and forth for the prescribed repetitions.
II	BOSU (round) single-knee hold	The athlete begins this exercise by balancing in a kneeling position with one knee directly in the middle of the round side of the BOSU and the other knee extended out to the side. The athlete will maintain this balanced position with the hip slightly flexed for the duration of the exercise	Box lateral crunch	Athlete starts lying on side with hip located top of a plyometric box. The athlete's feet and legs must be anchored during this exercise by the trainer or a stationary object. The athlete will proceed to bend laterally at the waist back and forth for the prescribed repetitions
III	Swiss ball bilateral kneel	The athlete kneels and balances on Swiss ball with feet off the ground. A spotter should be available at all times in front of the athlete.	BOSU (round) lateral crunch with ball catch	Athlete starts lying on side with hip located top of the round side of a BOSU. The athlete's feet and legs must be anchored during this exercise by the trainer or a stationary object. The athlete will proceed to bend laterally at the waist back and forth for the prescribed repetitions. A ball should be tossed back and forth with a partner to increase the difficulty of this exercise
IV	Swiss ball bilateral kneel with partner perturbations	The athlete kneels and balances on Swiss ball with her feet off of the ground. Once the athlete is stabilised the a partner can perturb the ball by kicking in unanticipated directions. A spotter should be available at all times in front of the athlete	Swiss ball lateral crunch	Athlete starts lying on side with hip located top of a Swiss ball. The athlete's feet and legs must be anchored during this exercise by the trainer or a stationary object. The athlete will proceed to bend laterally at the waist back and forth for the prescribed repetition
V	Swiss ball bilateral kneel with lateral ball catch	The athlete kneels and balances on Swiss ball with feet off the ground. A ball should be tossed back and forth with a partner to increase the difficulty of this exercise	Swiss ball lateral crunch with ball catch	Athlete starts lying on side with hip located top of a Swiss ball. The athlete's feet and legs must be anchored during this exercise by the trainer or a stationary object. The athlete will proceed to bend laterally at the waist back and forth for the prescribed repetitions. A ball should be tossed back and forth with a partner to increase the difficulty of this exercise.