0363-5465/99/2727-0699$02.00/0
The American Journal of Sports Medicine, Vol. 27, No. 6

The Effect of Neuromuscular Training on the Incidence of Knee Injury in Female Athletes

A Prospective Study

Timothy E. Hewett,* PhD, Thomas N. Lindenfeld, MD, Jennifer V. Riccobene, and Frank R. Noyes, MD

From the Cincinnati Sportsmedicine Research and Education Foundation and Deaconess Hospital, Cincinnati, Ohio

ABSTRACT

To prospectively evaluate the effect of neuromuscular training on the incidence of knee injury in female athletes, we monitored two groups of female athletes, one trained before sports participation and the other not trained, and a group of untrained male athletes throughout the high school soccer, volleyball, and basketball seasons. Weekly reports included the number of practice and competition exposures and mechanism of injury. There were 14 serious knee injuries in the 1263 athletes tracked through the study. Ten of 463 untrained female athletes sustained serious knee injuries (8 noncontact), 2 of 366 trained female athletes sustained serious knee injuries (0 noncontact), and 2 of 434 male athletes sustained serious knee injuries (1 noncontact). The knee injury incidence per 1000 athlete-exposures was 0.43 in untrained female athletes, 0.12 in trained female athletes, and 0.09 in male athletes ($P = 0.02$, chi-square analysis). Untrained female athletes had a 3.6 times higher incidence of knee injury than trained female athletes ($P = 0.05$) and 4.8 times higher than male athletes ($P = 0.03$). The incidence of knee injury in trained female athletes was not significantly different from that in untrained male athletes ($P = 0.86$). The difference in the incidence of noncontact injuries between the female groups was also significant ($P = 0.01$). This prospective study demonstrated a decreased incidence of knee injury in female athletes after a specific plyometric training program.

* Address correspondence and reprint requests to Timothy E. Hewett, PhD, Cincinnati Sportsmedicine Research and Education Foundation, 311 Straight Street, Cincinnati, OH 45219.

No author or related institution has received any financial benefit from research in this study. See "Acknowledgments" for funding information.

It is well documented that female athletes participating in jumping and cutting sports demonstrate a four- to sixfold higher incidence of knee injury than do male athletes participating in the same sports.[1,4,10,12,13,19,30,32] The National Collegiate Athletic Association (NCAA) reports that more than 100,000 women participate in collegiate sports each year. A 1990 to 1993 injury survey of approximately 15% of NCAA member institutions reported an average knee injury rate of approximately 1 per 1000 athlete-exposures (1 athlete-exposure meaning participation in either a game or practice), or greater than 1 injury for every 10 female athletes.[1,17] Therefore, more than 10,000 knee injuries are expected to occur in female athletes at the collegiate level alone during any given year.

Many of these knee injuries require either considerable nonoperative treatment, surgery, or both. Using the same figure (10,000 injuries), and an injury incidence of approximately 0.22 ACL injuries per 1000 athlete-exposures,[1,17] more than 2200 ACL ruptures are expected to occur in female collegiate athletes each year. The cost of treatment for these athletes is many millions of dollars annually. The cost of orthopaedic care, including ACL reconstruction and rehabilitation, for these athletes is approximately $17,000 per patient (F. R. Noyes, unpublished data, 1999), which would amount to over $37 million. These costs are in addition to the traumatic effect of these injuries on the athlete, including the potential loss of entire seasons of sports participation, loss of scholarship funding, and the ensuing effects on the athlete's mental health and academic performance.[11]

The total financial burden of serious knee injuries in female athletes may reach $100 million at the high school and collegiate levels combined. The 1994 high school athletic participation survey conducted by the National Federation of State High School Associations reported over 2 million female participants in high school sports programs (unpublished data, 1994). Therefore, even though knee injury rates among high school female athletes are only about one-tenth as high as for collegiate female athletes (1 knee injury per 100 participants[4]), the higher number of participants at the high school level is expected to account for twice as many injury occurrences (more than 20,000 knee injuries) each year as are found at the collegiate level. Chandy and Grana[4] reported that significantly more high school girls had knee surgery than did boys (nearly five times as many), and knee surgeries made up 70% of all surgeries for the girls. Prevention programs may present a cost-effective solution to this dilemma.[4]

Noyes et al.[24] reported that four-fifths of ACL injuries occur via a noncontact mechanism, and the majority of these occur at landing from a jump. In a rigorous study of the incidence of injury in soccer, Lindenfeld et al.[18] reported that the incidence of serious knee injury was approximately sixfold higher in female players than in male players when normalized per player-hour. Haycock and Gillette[14] attributed most differences in injury rates to differing levels of training and coaching, and not to anatomic or physiologic differences. Whiteside[30] reported similar overall injury rates for men and women, although significant knee injuries occurred 1 to 10 times more often in women than in men, depending on the sport played.

Some reports attribute injury rate differences to physiologic differences such as increased joint laxity among women,[4,14,16,32] while others refute this claim.[29] At least three reports have suggested that the hormone estrogen is directly involved in increased injury rates in women.[13,31,32] It has also been argued that anatomic differences in pelvic structure and lower extremity alignment (that is, the Q angle) may account for differences in injury rates for men and women.[14,32] Emerson,[9] Hutchinson and Ireland,[17] and Shelbourne et al.[26] have hypothesized that a narrow intercondylar notch and small ACL may predispose the female knee to ACL injury. Gray et al.[13] found that injury rate differences could not be attributed to anatomic differences, nor to lack of fitness or experience.

Chandy and Grana[4] reported that significantly more female than male high school athletes had knee injuries that required surgery, and they suggested that "emphasis be placed on functional evaluation and conditioning of the quadriceps and hamstring muscles to prevent these injuries." Jump training programs incorporating stretching, plyometric exercises, and weight lifting have been advocated to increase performance and decrease injury risk in competitive athletes in jumping sports. A number of high school, collegiate, and Olympic sports teams have developed such programs.[8,21,22] It is not known whether these programs alter jumping and landing biomechanics; only performance changes have been reported.

Training of the musculature that stabilizes the knee joint before sports participation may decrease the relative injury incidence in female athletes. Even if training and strength differences account for only part of the increased incidence of knee injury in female athletes, lowering these high figures by even a small percentage could have a significant effect on the number of knee injuries. Caraffa et al.[3] demonstrated in a prospective controlled study that proprioceptive training of semiprofessional male soccer players significantly decreased the incidence of ACL injury. After a progressive five-phase training program on balance boards, injury incidence decreased more than sevenfold in these male athletes. Neuromuscular training might have similar (or even greater) effects on female athletes.

Hewett et al.[15] demonstrated a marked imbalance between hamstring and quadriceps muscle strength in female athletes before training. In addition, male athletes had knee flexor moments during landing from a jump that were three times higher than those of female athletes. A plyometric, stretching, and strength training program was demonstrated to decrease peak landing forces by decreasing abduction/adduction moments at the knee.[15] The program also significantly increased hamstring muscle power and strength, increased hamstring-to-quadriceps peak torque ratios, and decreased side-to-side hamstring muscle strength imbalances. After the evaluation of this biomechanical evidence, the authors hypothesized that this program might decrease injury rates in female athletes. If this hypothesis proved valid, similar programs could be used to alter current methods for preparing female athletes for participation in high-level sports. Such training, if effectively used on a widespread basis, might help to significantly decrease the number of athletes injured each year. To test our hypothesis, we performed an intervention study based on high school female athletes using the training program previously reported.

MATERIALS AND METHODS

Subjects and Injury Survey

Forty-three sports teams from 12 area high schools participated in the study. Soccer, volleyball, and basketball were selected for monitoring because of the high level of jumping and cutting activity in these sports. Coaches and trainers were contacted and sent an instructional video and training manual demonstrating a 6-week preseason neuromuscular training program. This program, described in a previous study,[15] incorporates flexibility, plyometrics, and weight training to increase muscle strength and decrease landing forces. A certified athletic trainer and physical therapist demonstrated stretching and plyometric techniques with an emphasis on proper form. This program has been proven to decrease potentially dangerous landing forces by decreasing adduction and abduction moments at the knee and increasing hamstring muscle power.[15] Fifteen girls' teams elected to use the program and 15 elected not to use the program. Thirteen untrained boys' teams were observed as controls for the female groups.

A total of 1263 athletes participating in soccer, volleyball, and basketball were monitored for injury during each playing season (1 school year or 1 season per sport). These athletes consisted of three groups: 366 girls on 15 teams who participated in the 6-week preseason neuromuscular training program (trained group), 463 girls on 15 teams who did not participate in the 6-week training program (untrained group), and 434 untrained boys on 13 teams who served as a control population (male control group). The trained group consisted of 185 volleyball players, 97 soccer players, and 84 basketball players. The untrained group was composed of 81 volleyball players, 193 soccer players, and 189 basketball players. The male control group was made up of 209 soccer players and 225 basketball players.

All athletes were given preseason screening questionnaires that included sport-specific information with regard to prior injuries and number of years of participation. Certified athletic trainers were given weekly injury reporting forms to monitor the number of injuries occurring in a specific week along with game and practice injury risk exposures. Ninety-four percent of the athletes (1263 of 1344) were monitored throughout the entire season. Only these athletes were included in the data analysis. An injury risk exposure was defined as one athlete participating in one practice or match. Trainers were also given corresponding individual injury reporting forms to monitor more in-depth information, such as type of injury, mechanism, and treatment. A serious knee injury was defined as a knee ligament sprain or rupture that caused the player to seek care by an athletic trainer and that led to at least 5 consecutive days of lost time from practice and games. All serious knee injuries were diagnosed by an experienced athletic trainer, and the athletes were referred to an experienced sports medicine physician. All ACL ruptures were confirmed by arthroscopy. Medial collateral ligament (MCL) ruptures were diagnosed by the presence of pain along the ligament and increased valgus rotation with a valgus stress test. We excluded three minor first-degree MCL sprains in athletes who did not have abnormal medial joint opening. Only primary injuries were included in the study, reinjuries were tabulated but not reported.

Jump Training Program

Participating coaches and trainers were instructed in the implementation of the program using the video tape and manual documenting all phases of training. The trained group included 366 female athletes who were trained in jumping and landing techniques designed to increase vertical height and increase strength before sports participation. The training sessions lasted approximately 60 to 90 minutes a day, 3 days a week, on alternating days. Participants documented their repetitions in the training manual. Seventy percent of the athletes (248 of 366) in the trained group completed the entire 6-week program. All 366 athletes in the trained group were required to complete at least 4 weeks of the training program to be included in the study.

Three phases were implemented throughout the jump training program (Appendix 1). The technique phase (phase I) included the initial 2 weeks when proper jump technique was demonstrated and drilled. The fundamentals phase (phase II) concentrated on building a base of strength, power, and agility. Finally, the performance phase (phase III) focused on achieving maximum vertical jump height. Throughout each session of the first two phases, exercises were increased by duration. Each athlete was encouraged to do as many jumps as possible using proper technique. One to 2 minutes of recovery time was allotted between each exercise (exercises are defined in Appendix 2). Stretching was performed immediately before jump training. Weight training was performed after jump training with a 15-minute rest period and an abbreviated stretching regimen (Appendix 3).

Statistical Analysis

One-way chi-square tests were used to analyze the effect of training on the frequency of injury and to test for differences in injury rates among the separate groupings of athletes (that is, untrained female group versus male control group versus trained female group). Level of significance was set at $P \leq 0.05$.

RESULTS

All Serious Knee Injuries

There were 14 serious knee injuries among the 1263 athletes monitored throughout the entire soccer, volleyball, and basketball seasons (Table 1). Chi-square analysis of these data showed a significant difference in injury rates ($P = 0.02$) among the three groups. When the trained and untrained groups were compared with chi-square analysis, a significant effect of training on the incidence of serious knee injury was observed ($P = 0.05$). The untrained group demonstrated a significantly higher incidence of injury than the male control group ($P = 0.03$), but there was no significant difference between the trained group and the male control group ($P = 0.86$). Two female athletes (one trained, one untrained) suffered MCL sprains that were not included in the statistical analysis because the injury did not occur during sports participation or fewer than 5 consecutive days of sports participation were missed after the injury.

The total number of athlete-exposures were 23,138 for the untrained group, 17,222 for the trained group, and 21,390 for the male control group. The incidence of all knee injuries was 0.43 in the untrained group, 0.12 in the trained group, and 0.09 in the male control group (injuries per 1000 exposures) (Fig. 1). The untrained group demonstrated an injury rate 3.6 times higher than the trained group and 4.8 times higher than the male control group. The trained group showed an injury incidence only 1.3 times higher than the male control group.

Noncontact Injuries

Nine of the 14 injuries in the study subjects were noncontact knee injuries. The relative noncontact injury incidence was 0.35 for the untrained group, 0 for the trained group, and 0.05 for the male control group (Fig. 2). Chi-square analysis showed a significant difference between groups in noncontact knee injuries ($P = 0.005$). The

TABLE 1
Detailed Information on the 14 Serious Knee Injuries Observed in This Study

Group	Injury type	Sport	Injury mechanism	Time lost (days)
Untrained	ACL	Soccer	Noncontact, twisting	Out for season
Untrained	ACL	Basketball	Noncontact, varus landing	Out for season
Untrained	ACL	Basketball	Noncontact, valgus twisting	Out for season
Untrained	ACL	Soccer	Noncontact, twisting	Out for season
Untrained	ACL	Basketball	Noncontact, hyperextension/twisting	Out for season
Untrained	MCL	Basketball	Contact, lateral side at landing	7
Untrained	MCL	Soccer	Noncontact, hyperextension	5
Untrained	MCL	Soccer	Contact, valgus blow to tibia	5
Untrained	MCL	Soccer	Noncontact, twisting	20
Untrained	MCL	Basketball	Noncontact, repeated valgus stress	Out for season
Trained	ACL	Basketball	Contact, lateral blow	Out for season
Trained	ACL/MCL	Basketball	Contact, valgus blow	Out for season
Male control	ACL	Soccer	Noncontact, twisting	Out for season
Male control	MCL	Basketball	Contact, valgus blow	10

trained group had a significantly lower rate of noncontact injuries than the untrained group ($P = 0.01$).

Five untrained female athletes and one male athlete sustained noncontact ACL injuries. Chi-square analysis demonstrated a significant difference between these groups ($P = 0.05$). The trained group had significantly fewer noncontact ACL injuries than the untrained group ($P = 0.05$).

Injuries by Sport

All serious knee injuries occurred in soccer and basketball players. No serious knee injuries occurred in volleyball players. Therefore, we examined injury prevalence and incidence in soccer and basketball alone. Figure 3 shows the incidence of injury in soccer and basketball players per 1000 athlete-exposures. The number of player-exposures were 19,387 for the untrained group, 9284 for the trained group, and 21,552 for the male control group. The relative incidence of injury in the untrained group was 2.4 times higher than that in the trained group, and 5.8 times higher than the incidence in the male control group. The trained group had an incidence of serious knee injuries 2.4 times that of the male control group when only soccer and basketball were examined. There were significant differences in injury rate between the untrained group and the other two groups ($P = 0.03$). The untrained group demonstrated a significantly higher injury incidence than the male control group ($P = 0.01$). The trained group had an incidence similar to that of the male control group ($P = 0.83$). The difference between the trained and untrained groups was not significant ($P = 0.25$). However, when only noncontact injuries were considered, there was a significant difference between the trained and untrained groups ($P = 0.05$) (Fig. 4).

We also examined injury incidence in soccer and basketball separately. In girls' soccer, 290 athletes from 10 teams were monitored, 4 teams trained and 6 teams did not train. Six boys' soccer teams (209 athletes) were monitored. All five serious knee injuries among the female soccer athletes occurred in members of the untrained teams. One male soccer player suffered a knee injury. The number of soccer player-exposures were 9017 for the untrained group, 4517 for the trained group, and 8513 for the male control group. When injury incidence in soccer players alone was compared, the relative incidence of injury was 0.56 in untrained female athletes, 0 in trained female athletes, and 0.12 in male athletes. Chi-square analysis

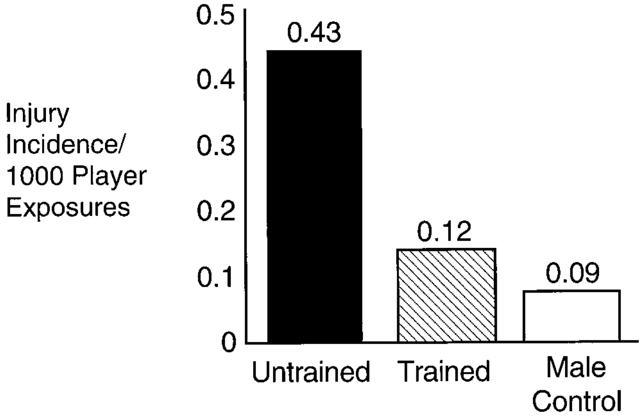

Figure 1. Serious knee injuries per 1000 athlete-exposures in each of the study groups.

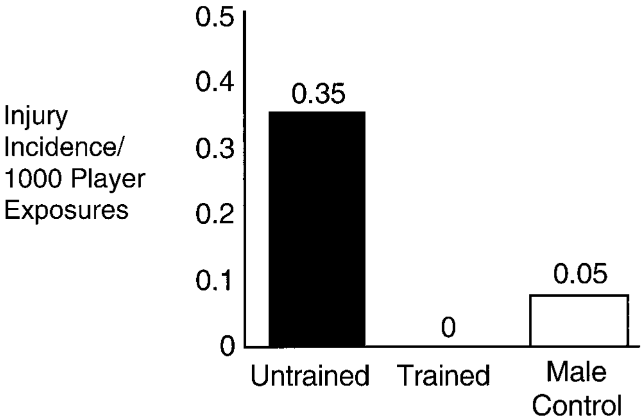

Figure 2. Noncontact injuries per 1000 athlete-exposures in each of the study groups.

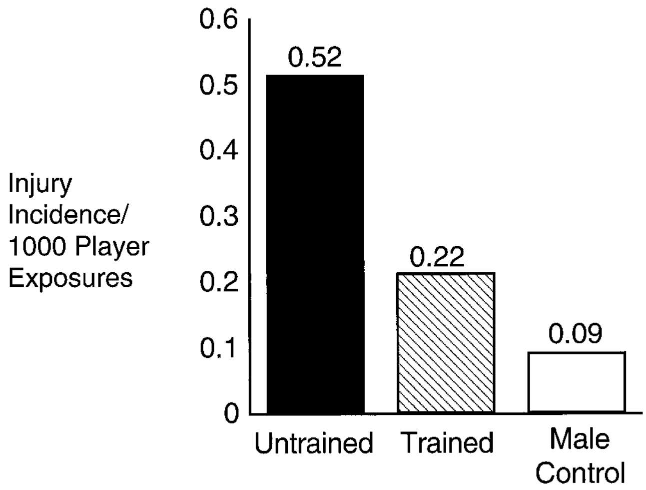

Figure 3. Serious knee injuries per 1000 athlete-exposures in soccer and basketball players.

indicated a trend for a difference in injury rates between all groups in the soccer population ($P = 0.07$). There was also a trend toward a higher incidence of serious knee injury in untrained female players versus trained female players ($P = 0.11$). Untrained female athletes had a higher incidence of serious knee injury than male athletes, although the difference was not significant ($P = 0.08$), while trained female soccer players and male soccer players had statistically similar incidences of serious knee injury ($P = 0.46$). Similar trends were observed for noncontact injuries.

Eight girls' basketball teams (273 athletes) participated in the study: three teams trained with the program and five did not. Seven boys' basketball teams were included in the study. Five knee injuries occurred on the untrained girls' teams, two knee injuries occurred on the three trained girls' teams, and one knee injury occurred in a male basketball player. The number of basketball player-exposures was 10,370 for the untrained group, 4767 for the trained group, and 13,039 for the male control group.

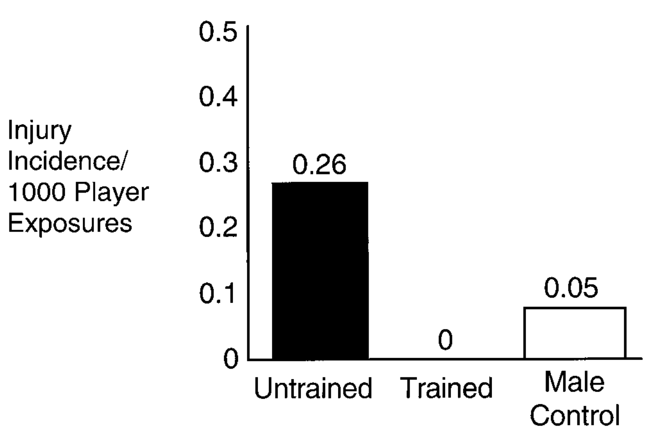

Figure 4. Noncontact injuries per 1000 athlete-exposures in soccer and basketball players.

The incidence of injury was 0.48 for untrained female athletes, 0.42 for trained female athletes, and 0.08 for male basketball players. The difference in basketball injury rates was not significant between groups ($P = 0.17$) or between trained and untrained female athletes ($P = 0.89$). Both untrained ($P = 0.06$) and trained ($P = 0.12$) groups showed strong trends toward a higher incidence of serious knee injury than the male athletes, but neither was statistically significant. However, when noncontact injuries in basketball were examined (four in the untrained group, zero in the trained group, and zero in the male group), there was a trend ($P = 0.019$) toward a lower incidence of injury to the trained basketball players relative to the untrained players. Untrained female athletes had significantly more noncontact knee injuries than did the male athletes ($P = 0.03$), while the number of noncontact injuries in trained female athletes was similar to that in male athletes.

DISCUSSION

This is the first prospective study to report the effects of neuromuscular training on knee injury in female athletes involved in high-risk sports. The incidence of serious knee injury was 2.4 to 3.6 times higher in the untrained group than in the trained group, depending on whether the sport of volleyball was included. Untrained female athletes were 4.8 to 5.8 times more likely than male athletes to suffer a knee injury, and trained female athletes were 1.3 to 2.4 times more likely than male athletes to suffer a knee injury. These results indicate that neuromuscular training may decrease injury risk in female athletes. The decreased injury incidence in trained athletes might be due to increased dynamic stability of the knee joint after training.

Nontrained female athletes are predisposed to knee ligament injuries.[1,4,10,12,13,19,30,32] High landing forces and imbalances in hamstring and quadriceps muscle strength and firing patterns may be the reasons for the predisposition.[15,16] Preventive measures, such as neuromuscular training, should be undertaken with the female athlete to decrease the incidence of serious knee injury in this high-risk population.

The increased incidence of female knee injuries could be multifactorial (that is, hormones, anatomy, length of sports participation); however, training may be able to override the effects of a number of these factors. Although we do not know the effects of this specific training program on estrogen fluctuations, other training programs have been shown to affect estrogen levels,[6] in addition to enhancing muscular stabilization of a more valgus (or varus) knee. Neuromuscular training is an intervention that can have a biomechanical effect, such as decreased landing forces and adduction and abduction moments, as well as a physiological effect, such as decreased estrogen levels and increased hamstring-to-quadriceps ratios.

More than than 90% of the female subjects in our prior study (10 of 11) effectively decreased their peak landing forces.[15] The decrease in landing forces observed is important in that it directly translates to forces in the joints of the lower extremity. Dufek and Bates[7] examined the importance of decreasing landing forces and pointed out the relation between these forces and knee injury. They argued that the high percentage of injuries that occur in jumping sports during landing (approximately 60% of the total injuries), and the high concentration of lower extremity injuries in these sports, strongly suggests that a relationship exists between landing forces and lower extremity injury.

In our prior study,[15] both knee adduction and abduction moments decreased an average of 50% at landing after training. Landing in either a varus or valgus stance is a less stable position for the knee.[25] Therefore, a decrease in adduction and abduction moments at landing may stabilize the joint and prevent serious knee injury. Thus, athletes should avoid excessive adduction or abduction forces at the knee.[20] The decrease in the adduction and abduction moments may be related to increased hamstring and gastrocnemius muscle function in stabilizing the joint in the coronal plane.

An important observation from our earlier study was the threefold-greater knee extension moment (reflective of increased knee flexor activity) demonstrated by the male athletes compared with the female athletes. Male athletes demonstrate relatively high use of the knee flexor musculature at landing compared with female athletes. This may be a protective mechanism involving the hamstring or gastrocnemius muscles to counteract the high peak landing forces that male athletes demonstrate.

Huston and Wojtys[16] demonstrated differences in muscle recruitment patterns between elite female and male athletes. In a high percentage of trials, female athletes contracted their quadriceps muscles in response to an anterior tibial translation, whereas male and female control subjects responded to an anterior tibial translation by first contracting their hamstring muscles. The hamstring muscles are an ACL agonist, resisting forces that strain the ACL, whereas the quadriceps muscle contraction at low knee flexion angles acts as an ACL antagonist, significantly increasing strain on the ACL. In addition, these authors showed that female athletes have more anterior knee laxity and significantly less lower extremity strength than their male counterparts.

The hamstring muscles are important to the stabilization of the knee joint. They function as a joint compressor and restrain anterior motion of the tibia.[27] These two functions decrease anterior shear forces and greatly reduce load on the primary restraint to anterior tibial motion, the ACL.[2,23,28] Female athletes demonstrate a marked imbalance between hamstring and quadriceps muscle strength before training.[15,16] The training program used in this study has been shown to correct this imbalance and bring the ratio of hamstring to quadriceps isokinetic strength in female athletes to the same level as that in male athletes.[15] Baratta et al.[2] noted the increased risk of ligament damage in athletes with quadriceps-to-hamstring strength imbalances and reduced hamstring-quadriceps coactivation patterns. They observed increased coactivation of the hamstring muscles in athletes with quadriceps-to-hamstring strength imbalances after hamstring muscle training exercises.

The increase in hamstring muscle peak torque and power observed in the trained subjects in our prior study[15] brought the lower hamstring-to-quadriceps ratio of female athletes (near 50%) up to values equivalent to that of male athletes (approximately 65%). Hamstring-to-quadriceps ratios at or below 50% may indicate a pathologic condition.[5] It has been hypothesized that hamstring-to-quadriceps ratios lower than 60% can predispose an athlete to ACL injury.[8] Female athletes, even to a greater extent than nonathletes, tend to be "quadriceps dominant" in both strength and muscle firing patterns.[15,16]

Study Limitations

The present study has a few important limitations. First, this was not a randomized, double-blinded study. There were not equal numbers of each type of sports participant in each group. Subjects were not randomly striated into trained and untrained groups, rather each coach decided whether his or her team would undergo training. There were more volleyball players in the trained group and this may have biased this group toward lower injury rates. Other studies have demonstrated lower rates of knee injury in women's volleyball compared with women's soccer and basketball at the collegiate level.[17] The relative levels of serious injury among these three sports in the high school athlete are not well defined. Neither the subjects nor the investigators were masked as to who was and was not trained. This also introduces possible bias into the study. A final important limitation is the low number of observed injuries. In this high school setting, with approximately 1 in 100 female athletes and 1 in 500 male athletes sustaining a serious knee injury, recruiting a sufficient number of subjects for obtaining high statistical power was problematic.

Conclusions and Future Directions

The jump training program outlined in this report decreased the overall incidence of serious knee injury. These effects undoubtedly arise from a combination of improvements in technique and strength. Much of the benefit of the program appears to be through decreases in the magnitude of the adduction and abduction moments at the knee and improvement of the hamstring-to-quadriceps strength ratio.[15] Our recommendation is that young female athletes in sports that entail jumping, pivoting, and cutting, such as basketball, volleyball, and soccer, be trained before participation with a proven effective jump training program that includes progressive resistance weight training for the lower extremity.

There remain a number of unanswered questions needing further research. We have tracked young female athletes, both trained and untrained, to determine whether injury rates are lowered with training. Two factors that should be further investigated are adduction and abduction moments at the knee and imbalances between hamstring and quadriceps muscle strength or dominant versus nondominant leg musculature, as they may serve as indicators of a predisposition to injury in specific athletes and a need for preparticipation training.

ACKNOWLEDGMENTS

We thank the trainers at the following high schools in the greater Cincinnati area for their invaluable expert assistance in collecting the injury data: Shannon Bowling, ATC, of Northwest High School, Jay Johnston, ATC, of Campbell County High School, Tony Horton, ATC, and Debbie Eisele, ATC, of Princeton High School, Diana Ivkovich, ATC, of Fairfield High School, Bill Maurer, ATC, of Colerain High School, Mike McCormack, PT, ATC, of Ross High School, Kelli Veidt, ATC, of St. Ursula Academy, Mary Winterhalter, ATC, of Milford High School, Brian Weiss, ATC, of Dixie Heights High School, Deanna Womack, ATC, of Mason High School, and Amy Zeinner, ATC, of McAuley High School. We also thank the coaches and administration at each of the aforementioned schools for allowing us to study their athletes. We express our gratitude to John McClosky, PhD, for his expert assistance with the statistical analysis of the data. The work was supported by a grant from the Bethesda Foundation and the Cincinnati Sportsmedicine Research and Education Foundation.

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 23:* 694–701, 1995
2. Baratta R, Solomonow M, Zhou BH, et al: Muscular coactivation. The role of the antagonist musculature in maintaining knee stability. *Am J Sports Med 16:* 113–122, 1988
3. Caraffa A, Cerulli G, Projetti M, et al: Prevention of anterior cruciate ligament injuries in soccer. A prospective controlled study of proprioceptive training. *Knee Surg Sports Traumatol Arthrosc 4(1):* 19–21, 1996
4. Chandy TA, Grana WA: Secondary school athletic injury in boys and girls: A three-year comparison. *Physician Sportsmed 13(3):* 106–111, 1985
5. Davies G: *Compendium of Isokinetics in Clinical Usage.* LaCrosse, WI, S & S Publishers, 1984
6. De Cree C, Ball P, Seidlitz B, et al: Responses of catecholestrogen metabolism to acute and graded exercise in normal menstruating women before and after training. *J Clin Endocrinol Metab 82:* 3342–3348, 1997
7. Dufek JS, Bates BT: Biomechanical factors associated with injury during landing in jumping sports. *Sports Med 12:* 326–337, 1991
8. Dunnam LO, Hunter GR, Williams BP, et al: Comprehensive evaluation of the University of Alabama at Birmingham women's volleyball training program. *Nat Strength Conditioning Assoc J 10(1):* 50–52, 1988
9. Emerson RJ: Basketball knee injuries and the anterior cruciate ligament. *Clin Sports Med 12:* 317–328, 1993
10. Ferretti A, Papandrea P, Conteduca F, et al: Knee ligament injuries in volleyball players. *Am J Sports Med 20:* 203–207, 1992
11. Freedman KB, Glasgow MT, Glasgow SG, et al: Anterior cruciate ligament injury and reconstruction among university students. *Clin Orthop 356:* 208–212, 1998
12. Gerberich SG, Luhmann S, Finke C, et al: Analysis of severe injuries associated with volleyball activities. *Physician Sportsmed 15(8):* 75–79, 1987
13. Gray J, Taunton JE, McKenzie DC, et al: A survey of injuries to the anterior cruciate ligament of the knee in female basketball players. *Int J Sports Med 6:* 314–316, 1985
14. Haycock CE, Gillette JV: Susceptibility of women athletes to injury: Myth vs. reality. *JAMA 236:* 163–165, 1976
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 24:* 765–773, 1996
16. Huston LJ, Wojtys EM: Neuromuscular performance characteristics in elite female athletes. *Am J Sports Med 24:* 427–436, 1996
17. Hutchinson MR, Ireland ML: Knee injuries in female athletes. *Sports Med 19:* 288–302, 1995
18. Lindenfeld TN, Schmitt DJ, Hendy MP, et al: Incidence of injury in indoor soccer. *Am J Sports Med 22:* 364–371, 1994
19. Malone TR, Hardaker WT, Garrett WE, et al: Relationship of gender to anterior cruciate ligament injuries in intercollegiate basketball players. *J Southern Orthop Assoc 2(1):* 36–39, 1993
20. Markolf KL, Graff-Radford A, Amstutz HC: In vivo knee stability: A quantitative assessment using an instrumented clinical testing apparatus. *J Bone Joint Surg 60A:* 664–674, 1978
21. Marsit JL, Kraemer WJ: Beginning off-season workout for high school volleyball. *Nat Strength Conditioning Assoc J 14(3):* 62–66, 1992
22. McGown CM, Conlee RK, Sucec AA, et al: Gold medal volleyball: The training program and physiological profile of the 1984 Olympic champions. *Res Q Exerc Sport 61(2):* 196–200, 1990
23. More RC, Karras BT, Neiman R, et al: Hamstrings—an anterior cruciate ligament protagonist: An in vitro study. *Am J Sports Med 21:* 231–237, 1993
24. Noyes FR, Mooar PA, Matthews DS, et al: The symptomatic anterior cruciate-deficient knee. Part I: The long-term functional disability in athletically active individuals. *J Bone Joint Surg 65A:* 154–162, 1983
25. Noyes FR, Schipplein OD, Andriacchi TP, et al: The anterior cruciate ligament-deficient knee with varus alignment. An analysis of gait adaptations and dynamic joint loadings. *Am J Sports Med 20:* 707–716, 1992
26. Shelbourne KD, Davis TJ, Klootwyk TE: The relationship between intercondylar notch width of the femur and the incidence of anterior cruciate ligament tears. A prospective study. *Am J Sports Med 26:* 402–408, 1998
27. Skelly WA, DeVita P: Compressive and shear forces on the tibia and knee during landing, in *Proceedings of the 6th Biennial Conference of the Canadian Society for Biomechanics.* Montreal, Quebec, Canada, Canadian Society for Biomechanics, 1990, pp 59–60
28. Tibone JE, Antich TJ, Fanton GS, et al: Functional analysis of anterior cruciate ligament instability. *Am J Sports Med 14:* 276–284, 1986
29. Weesner CL, Albohm MJ, Ritter MA: A comparison of anterior and posterior cruciate ligament laxity between female and male basketball players. *Physician Sportsmed 14(5):* 149–154, 1986
30. Whiteside PA: Men's and women's injuries in comparable sports. *Physician Sportsmed 8(3):* 130–140, 1980
31. Wojtys EM, Huston LJ, Lindenfeld TN, et al: Association between the menstrual cycle and anterior cruciate ligament injuries in female athletes. *Am J Sports Med 26:* 614–619, 1998
32. Zelisko JA, Noble HB, Porter M: A comparison of men's and women's professional basketball injuries. *Am J Sports Med 10:* 297–299, 1982

Appendix 1. Jump Training Program

Exercise	Duration or Repetitions by Week	
Phase I: Technique	**Week 1**	**Week 2**
1. Wall jumps	20 sec	25 sec
2. Tuck jumps*	20 sec	25 sec
3. Broad jumps stick (hold) landing	5 reps	10 reps
4. Squat jumps*	10 sec	15 sec
5. Double-legged cone jumps*	30 sec/30 sec	30 sec/30 sec (side-to-side and back-to-front)
6. 180° jumps	20 sec	25 sec
7. Bounding in place	20 sec	25 sec
Phase II: Fundamentals	**Week 3**	**Week 4**
1. Wall jumps	30 sec	30 sec
2. Tuck jumps*	30 sec	30 sec
4. Jump, jump, jump, vertical jump	5 reps	8 reps
5. Squat jumps*	20 sec	20 sec
6. Bounding for distance	1 run	2 runs
7. Double-legged cone jumps*	30 sec/30 sec	30 sec/30 sec (side-to-side and back-to-front)
8. Scissors jump	30 sec	30 sec
9. Hop, hop, stick landing*	5 reps/leg	5 reps/leg
Phase III: Performance	**Week 5**	**Week 6**
1. Wall jumps	30 sec	30 sec
2. Step, jump up, down, vertical	5 reps	10 reps
3. Mattress jumps	30 sec/30 sec	30 sec/30 sec (side-to-side and back-to-front)
4. Single-legged jumps distance*	5 reps/leg	5 reps/leg
5. Squat jumps*	25 sec	25 sec
6. Jump into bounding*	3 runs	4 runs
7. Hop, hop, stick landing	5 reps/leg	5 reps/leg

Before jumping exercises: Stretching (15-20 minutes), skipping (2 laps), side shuffle (2 laps).
Posttraining: Cool-down walk (2 minutes), stretching (5 minutes).
*These jumps performed on mats.
Note: Each jump exercise is followed by a 30-second rest period.

Appendix 2. Glossary of Jump Training Exercises

1. **180° Jumps:** Two-footed jump. Rotate 180° in mid-air. Hold landing for 2 seconds and then repeat in reverse direction.
2. **Bounding for Distance:** Start bounding in place and slowly increase distance with each step, keeping knees high.
3. **Bounding in Place:** Jump from one leg to the other straight up and down, progressively increasing rhythm and height.
4. **Broad Jumps-Stick (hold) Landing:** Two-footed jump as far as possible. Hold landing for 5 seconds.
5. **Cone Jumps:** Double-legged jump with feet together. Jump side-to-side over cones quickly. Repeat forward and backward.
6. **Hop, Hop Stick:** Single-legged hop. Stick second landing for 5 seconds. Increase distance of hop as technique improves.
7. **Jump into Bounding:** Two-footed broad jump. Land on single leg, then progress into bounding for distance.
8. **Jump, Jump, Jump, Vertical:** Three broad jumps with vertical jump immediately after landing the third broad jump.
9. **Mattress Jumps:** Two-footed jump on mattress, tramp, or other easily compressed device. Perform side-to-side and back-to front.
10. **Scissors Jump:** Start in stride position with one foot well in front of other.
    Jump up, alternating foot positions in mid-air.
11. **Single-Legged Jumps, Distance:** Single-legged hop for distance. Hold landing (knees bent) for 5 seconds.
12. **Squat Jumps:** Standing jump raising both arms overhead, land in squatting position touching both hands to floor.
13. **Step, Jump Up, Down, Vertical:** Two-footed jump onto 6- to 8-inch step. Jump off step with two feet, then vertical jump.
14. **Tuck Jumps:** From standing position jump, and bring both knees up to chest as high as possible. Repeat quickly.
15. **Wall Jumps (Ankle Bounces):** With knees slightly bent and arms raised overhead, bounce up and down off toes.

Appendix 3. Stretching and Weight Training Program

Stretches[a]	Weight-training exercises[b]
1. Calf stretch 1	1. Abdominal curl
2. Calf stretch 2: soleus	2. Back hyperextension
3. Quadriceps	3. Leg press
4. Hamstring	4. Calf raise
5. Hip flexors	5. Pullover
6. Iliotibial band/lower back	6. Bench press
7. Posterior deltoids	7. Latissimus dorsi pulldown
8. Latissimus dorsi	8. Forearm curl
9. Pectorals/biceps	9. Warm-down/short stretch

[a] Stretching consists of 3 sets of 30 seconds each.
[b] Weight training consists of 1 set of each exercise, generally 12 repetitions for upper body exercises and 15 repetitions for the trunk and lower body exercise.