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Winner of the 1995 Excellence in Research Award

Plyometric Training in Female Athletes

Decreased Impact Forces and Increased Hamstring Torques*

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ABSTRACT

The purpose of this study was to test the effect of a jump-training program on landing mechanics and lower extremity strength in female athletes involved in jumping sports. These parameters were compared before and after training with those of male athletes. The program was designed to decrease landing forces by teaching neuromuscular control of the lower limb during landing and to increase vertical jump height. After training, peak landing forces from a volleyball block jump decreased 22%, and knee adduction and abduction moments (medially and laterally directed torques) decreased approximately 50%. Multiple regression analysis revealed that these moments were significant predictors of peak landing forces. Female athletes demonstrated lower landing forces than male athletes and lower adduction and abduction moments after training. External knee extension moments (hamstring muscle-dominant) of male athletes were threefold higher than those of female athletes. Hamstring-to-quadriceps muscle peak torque ratios increased 26% on the nondominant side and 13% on the dominant side, correcting side-to-side imbalances. Hamstring muscle power increased 44% with training on the dominant side and 21% on the nondominant. Peak torque ratios of male athletes were significantly greater than those of untrained female athletes, but similar to those of trained females. Mean vertical jump height increased approximately 10%. This training may have a significant effect on knee stabilization and prevention of serious knee injury among female athletes.

At our center, we have noted a large number of adolescent female athletes with serious knee injuries caused by jumping and cutting sports such as soccer, volleyball, and basketball. In a recent study on the incidence of injury in indoor soccer players, researchers at our center reported that the incidence of serious knee injury was approximately sixfold higher in female than in male players.[18] A number of studies have corroborated the higher incidence of serious knee injury in female participants in jumping sports compared with male participants.[5,10,11,13,17,19,31,32]

Chandy and Grana,[5] in a 3-year study of 24,485 male and 18,289 female high school students participating in paired sports, reported that the incidence of season-ending knee injuries in female athletes was 4.6 times that of male athletes. Female athletes in jumping sports had significantly more injuries and more severe injuries. The National Athletic Trainers of America Symposium[9] reported that 18% of girls' injuries were knee-related in a population of 333,149 high school girls, compared with 10% of injuries in 380,783 high school boys. They also report that 89% of surgeries performed on female basketball players were for knee injuries. Ferretti et al.[10] reported a fourfold higher incidence of serious knee ligament injuries in female versus male National Championship level volleyball players. Zelisko et al.[32] reported in a 2-year study that the incidence of knee injuries in professional female basketball players was 2.2 times higher than that in professional male basketball players. It was suggested that even though these women were as well trained as their male counterparts, differences in knee injury frequency remained.

Haycock and Gillette[14] reported similar total injury rates for male and female collegiate athletes, although they did indicate that female athletes had higher rates of injury involving the patella and joints. They attributed any differences to differing levels of training and coaching and not to anatomic or physiologic differences. Whiteside[31] also reported similar overall injury rates for men and women, although the rate of significant knee injuries

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among women ranged from 1 to 10 times higher than that for men, depending on the sport played. Albohm[1] stated that differences she found in injury rates were due to differences in sports activities and not to physiologic or structural differences.

Some reports attribute injury rate differences to structural differences such as increased joint laxity among women,[5,14,16,32] but others refute this claim.[30] Two reports suggested that estrogen is directly involved in increased injury rates in female athletes.[13,32] It has also been argued that differences in pelvic structure and lower extremity alignment (i.e., Q angle) may account for differences in injury rates between men and women.[14,32] Chandy and Grana[5] 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 alterations in performance have been reported.

The purpose of this study was to test the effect of a jump-training program on the mechanics of landing and on the strength of the lower extremity musculature in female athletes involved in jumping sports. These parameters were compared before and after training with those of male athletes. The program we employed in this study was designed to decrease landing forces by teaching neuromuscular control of the lower limb during landing and to increase joint stability by increasing the strength of the knee joint musculature. To our knowledge, this is the first report to examine jumping and landing mechanics of the lower extremity both before and after a plyometric training program and to compare the results of untrained and trained female athletes with those of male athletes.

MATERIALS AND METHODS

General History and Examination

Eleven female high school volleyball players served as the test group. The average height of the 11 female subjects was 168 ± 5 cm (66.1 ± 2.0 inches) (mean ± SD) and the average weight was 621 ± 59 N (139 ± 13 pounds). The mean age was 15 ± 0.6 years. The average years of organized volleyball playing experience was 2 ± 1. All female subjects were right-hand dominant. The nine male subjects tested were matched by height (171 ± 3 cm), weight (614 ± 80 N), and age (15 ± 0.3 years) to the female subjects, and none of the these parameters showed statistically significant differences between the groups. A knee

TABLE 1
Jump-Training Program[a]

Exercise	Repetitions or time	
Phase I: Technique	Week 1	Week 2
1. Wall jumps	20 sec	25 sec
2. Tuck jumps[b]	20 sec	25 sec
3. Broad jumps stick land	5 reps	10 reps
4. Squat jumps[b]	10 sec	15 sec
5. Double leg cone jumps[b]	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[b]	30 sec	30 sec
3. Jump, jump, jump, vert. jump	5 reps	8 reps
4. Squat jumps[b]	20 sec	20 sec
5. Bounding for distance	1 run	2 runs
6. Double leg cone jumps[b]	30 sec/30 sec	30 sec/30 sec (side-to-side and back-to-front)
7. Scissor jump	30 sec	30 sec
8. Hop, hop, stick[b]	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[b]	5 reps/leg	5 reps/leg
5. Squat jumps[b]	25 sec	25 sec
6. Jump into bounding[b]	3 runs	4 runs
7. Single-legged hop, hop stick	5 reps/leg	5 reps/leg

[a] Before jumping exercises subjects did stretching (15–20 minutes), skipping (2 laps), and side shuffle (2 laps). After training subjects did a cool down walk (2 minutes) and stretching (5 minutes). Each jump exercise was followed by 30-second rest period.

[b] These jumps performed on mats.

examination was conducted on each participant before and after the training program to ensure that the program did not cause injury or aggravate pre-existing conditions. Flexibility was tested for all subjects, before and after training.[8]

Vertical Jump Height Testing

Maximal jump height testing was completed on the female subjects before and after the training program using a Vertec machine (Questek Corp., Northridge, California). Each subject's standing reach was recorded before each test. The highest jump of three trials was recorded. Subjects were instructed to stand directly below the Vertec machine and perform three standing, maximal-effort vertical jumps.[8] Arm swing was allowed, but an approach step was not. Subjects were tested a total of six times, just before the initiation of the program, at the beginning of each subsequent week of training, and 1 week after the end of the training program.

Muscle Strength Testing

Before muscle strength testing, subjects underwent a warm-up period consisting of 10 jump tests and 5 minutes of quadriceps and hamstring muscle stretching. Subjects were seated on the dynamometer (Biodex, Medical Systems, Inc., Shirley, New York) with the trunk perpendicular to the floor, the hips flexed to 90°, and the knees flexed to 90°. Immobilization consisted of a thoracic strap, a waist strap, bilateral thigh straps, and a shin strap.

A test session consisted of four test sets. There were two test modes for the right leg and two test modes for the left leg. The two test modes were isometric contraction at 60° of flexion and high-speed isokinetic (360 deg/sec). The range of motion defined by the manufacturer of the dynamometer was 100° with 0° representing the full extension. Three isometric contractions of 10-seconds duration separated by 10 seconds of rest and 15 isokinetic contractions (concentric) were performed with each leg.

Jump-Training Program

The training was conducted at Milford High School in Cincinnati, Ohio. Players were trained for 6 weeks in jumping and landing techniques, jumping for increased vertical height, and increased strength. The training sessions lasted approximately 2 hours a day, 3 days a week, on alternating days (i.e., Monday, Wednesday, and Friday). The program was developed based on a thorough review of the literature and the authors' athletic training experience.[4,8,21,22,25]

Three phases were implemented throughout the jump-training program (Table 1). The technique phase (Phase I) included the initial 2 weeks when proper jump technique was demonstrated and drilled. Four basic techniques were stressed: 1) correct posture (i.e., spine erect, shoulders back) and body alignment (e.g., chest over knees) throughout the jump; 2) jumping straight up with no excessive side-to-side or forward-backward movement; 3) soft landings including toe-to-heel rocking and bent knees; and 4) instant recoil preparation for the next jump. Phrases such as "on your toes," "straight as an arrow," "light as a feather," "shock absorber," and "recoil like a spring" were used as verbal and visualization queues for each phase of the jump. The fundamentals phase (Phase II) concentrated on the use of proper technique to build a base of strength, power, and ability. Finally, the performance phase (Phase III) focused on achieving maximal 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 the proper technique. As the athletes became fatigued, they were encouraged to stop if they could not execute each jump correctly. During Phase III, athletes concentrated on the height achieved in each jump and the quality of each jump. Thirty seconds of recovery time was allotted between each exercise. Definitions of each exercise employed in the program are detailed in Table 2.

Stretching was performed immediately before jump

TABLE 2
Glossary of Jump Training Exercises

1. 180° Jumps: Two-footed jump. Rotate 180° in midair. Hold landing 2 seconds, 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 leg 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[a]: 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/back-to-front.
10. Scissors jump: Start in stride position with one foot well in front of other. Jump up, alternating foot positions in midair.
11. Single-legged jumps distance[a]: One-legged hop for distance. Hold landing (knees bent) for 5 seconds.
12. Squat jumps[a]: 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.

[a] These jumps performed on mats.

TABLE 3
Stretching and Weight-Training Program

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

training. Weight training was performed next, after a 15-minute rest and an abbreviated stretching regimen. Stretching consisted of three sets of 30 seconds each (Table 3). Weight training consisted of one set of each exercise, with a set goal of generally 12 repetitions for upper body, 15 repetitions for the lower body, and a range of 15 to 45 repetitions for trunk exercises using a Universal weight training apparatus (Universal Gym Equipment, Inc., Columbus, Ohio) (Table 3).

Force Testing

Equipment: The force analysis tests were performed at the Cincinnati Sportsmedicine and Deaconess Hospital Gait Laboratory using the GaitLink System (Computerized Functional Testing Corp., Chicago, Illinois). The equipment included a two-camera, video-based, opto-electronic digitizer for measuring motion and a multicomponent force plate (Bertec, Columbus, Ohio) for measuring ground-reaction force. Measurements were obtained by a microcomputer-based acquisition system and processed at the Computerized Functional Testing Corp. laboratory using techniques previously described.[2]

Subject Preparation: The testing protocol involved placing passive, reflective markers at the superolateral most aspect of the iliac wing, the lateral most aspect of the greater trochanter, the lateral most aspect of the joint line of the knee, the lateral malleolus, and the lateral head of the fifth metatarsal. Only the left side was marked and tested (Fig. 1). Limb movement was calculated by computer software based on information from the three-dimensional position of these markers.

Testing Protocol: Subjects were instructed to make 10 jumps. Two types of jumps were completed and for each there were two practice jumps and three test repetitions. The first type of jump involved subjects performing a maximal-effort, simulated volleyball block jump over a standard height net with both feet landing within the force plate (Fig. 1). These jumps were analyzed for peak forces at landing. Data on the peak force jumps were collected at a 480-Hz force plate sampling frequency. The second type of jump differed from the first only in that subjects were instructed to land with one foot on the force plate and one foot off. These jumps were analyzed for jump height, joint angles, and joint moments.[24] Data from these jumps were collected at a 120-Hz force plate sampling frequency. Measurement started just before the foot left the force plate and continued after the foot returned to the force plate to obtain a complete jump cycle. The data acquisition time was set at 2 seconds.

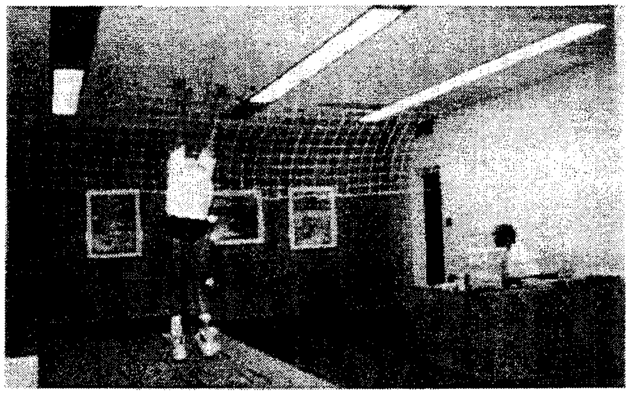

Figure 1. Subject performing volleyball block jump maneuver and landing on the force plate.

Data Analysis: Each subject completed two analyses: a pretraining jump force analysis and a posttraining jump force analysis. Data were routinely generated in graphic form to correlate events with the jump cycle. Kinematic data in the sagittal plane and kinetic data in the sagittal, coronal, and transverse planes of the hip, knee, and ankle were available for evaluation. Peak values during takeoff and landing were identified and recorded for each subject. The 11 female subjects were analyzed both before and after the training program, 9 untrained athletic male subjects were analyzed for comparative purposes.

The statistical means and standard deviations for all 11 subjects were calculated, and comparison of peak values before and after training were made using a paired, two-tailed Student's *t*-test. The nine male subjects, who matched study subjects in age and height, were used for comparison. An analysis of variance test was used to compare values from female subjects before and after training with those of the male subjects. Multiple regression analyses were performed using data from all 20 subjects. All moments were expressed as external moments and normalized to body weight and height (hence the use of units of %BW × Ht) to allow comparison between subjects of different sizes. All data are reported as mean ± SD, unless otherwise noted as mean ± SEM.

RESULTS

Ten of 11 subjects decreased their landing forces after training (Fig. 2). The mean decrease seen in landing forces after training is shown in Figure 3. These forces decreased after training an average of 456 N (103 pounds), or 80% of mean body weight from 2538 ± 525 N for untrained female subjects to 2082 ± 333 N for trained subjects, a

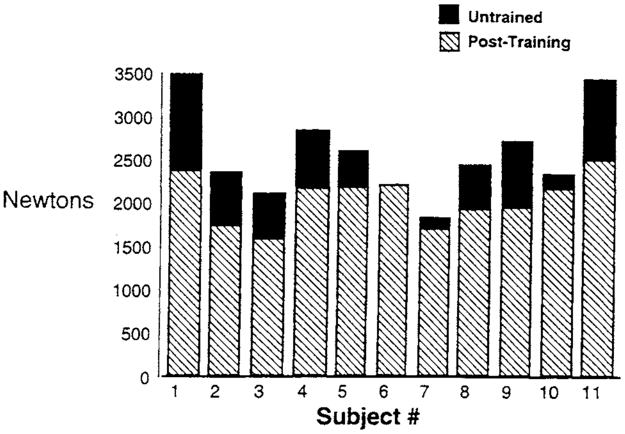

Figure 2. Distribution of peak landing forces for the 11 subjects before and after the training program.

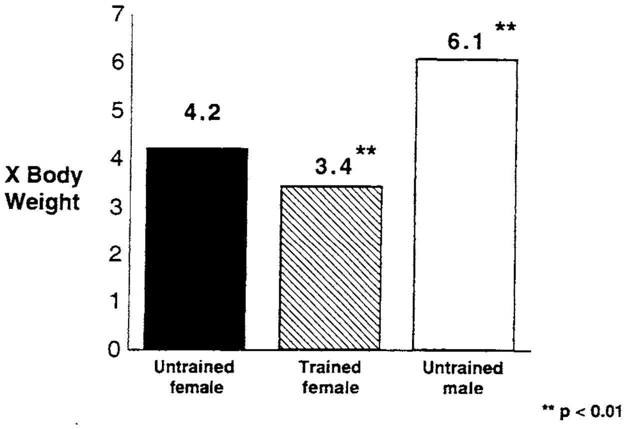

Figure 3. Bar graph of decrease in peak landing forces with training in female subjects before and after training and relative to age and weight-matched athletic male subjects.

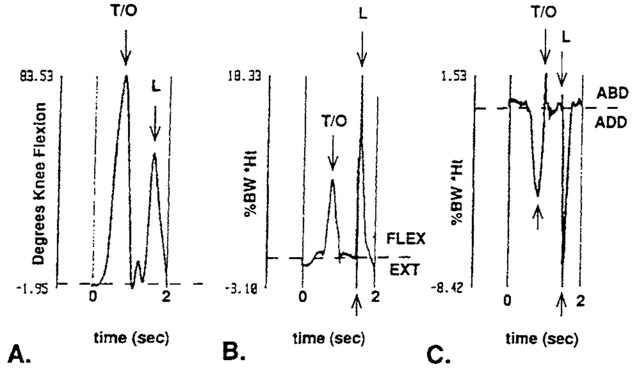

Figure 4. Representative knee flexion motion (A), flexion and extension moment (B), and abduction and adduction moment (C) graphs. Peak angles and moments at takeoff (T/0) and landing (L) are noted.

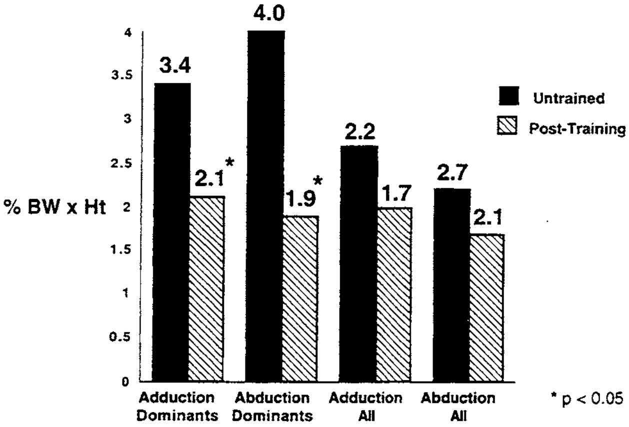

Figure 5. Bar graph of peak knee adduction and abduction moment data at landing before and after training. The female subjects were grouped according to the dominant moment (adduction or abduction) and all the female subjects grouped together (all).

TABLE 4
Multiple Regression Analysis of Independent Variable Effects on Peak Force at Landing

Variable	Coefficient	SE	*t*-value	*P*-value
Intercept	2177	1003	2.2	0.04
Peak knee landing extension moment	58	46	1.3	0.22
Peak knee landing flexion moment	26	56	0.5	0.65
Peak knee landing adduction moment	325	106	2.2	0.006[a]
Peak knee landing abduction moment	364	120	3.0	0.006[a]
Peak knee landing flexion	1.5	15.8	0.09	0.93
Peak hip landing extension moment	6	26	0.02	0.98
Peak hip landing flexion moment	9	21	0.41	0.60
Peak hip landing flexion	6	17	0.34	0.74
Peak ankle landing dorsiflexion moment	58	64	0.9	0.38
Peak ankle landing dorsiflexion	0.4	21	0.02	0.98

[a] Statistically significant.

TABLE 5
Results of Isokinetic Dynamometer Testing of Hamstring Muscle Strength in the Study Subjects[a]

Parameter	Before training	After training	Percentage increase	Untrained male
Dominant leg				
Peak torque (N-m)	41 ± 7	46 ± 7	13	61 ± 13
Average power (Watts)	94 ± 25	135 ± 17	44[b]	197 ± 73
Hamstring-quadriceps peak torque ratio	55 ± 9	62 ± 7	13[c]	62 ± 8
Nondominant leg				
Peak torque (N-m)	37 ± 7	46 ± 8	26[d]	66 ± 16
Average power (Watts)	94 ± 22	115 ± 27	21[c]	192 ± 48
Hamstring-quadriceps peak torque ratio	47 ± 8	59 ± 9	26[d]	67 ± 7

[a] Values are mean ± SD.
[b] Significant at $P < 0.001$ level.
[c] Significant at $P < 0.05$ level.
[d] Significant at $P < 0.01$ level.

decrease of 22% in the peak force ($P = 0.006$). Subjects leaped to the same mean vertical height (36 cm) both before and after training during the volleyball block jump in the laboratory. Both before and after training, the female subjects showed significantly lower ($P < 0.001$) peak landing forces than the untrained male subjects, whose mean forces were 3702 ± 800 N. The male subjects jumped to a greater mean vertical height during the block maneuver, averaging 47 cm.

Adduction and abduction moments at the knee (Fig. 4) are the moments that tend to induce a lateral or medial torque to the knee joint. Seven of the female subjects had higher peak adduction than abduction moments at landing (adduction-dominant), and four subjects demonstrated higher abduction moments at landing (abduction-dominant). In adduction-dominant subjects, the adduction force decreased with training from 3.4 ± 1.6 to 2.1 ± 1.0 %BW × Ht (Fig. 5). Abduction-dominant subjects showed a similar decrease in abduction moment with training, from 4.0 ± 1.8 to 1.9 ± 1.1 %BW × Ht ($P < 0.01$). Peak adduction and abduction moments in the male subjects were significantly greater than those in the trained female subjects (4.9 ± 3.0 and 3.7 ± 2.5, respectively) but not those in the untrained female subjects. A multiple regression analysis incorporating flexion angles, flexion and extension moments, and adduction and abduction moments at the knee, hip, and ankle demonstrated that adduction and abduction moments at the knee were the sole significant predictors of peak landing forces ($P = 0.006$) (Table 4).

The external extension moment at the knee, which is balanced by an internal flexion (hamstring muscle) moment, did not change with training (Fig. 6). Untrained male subjects demonstrated an extension moment at the knee threefold the value of the female subjects. The flexion moment at the knee (quadriceps muscle dominant) was not significantly different either before or after training in the female subjects or between male and female subjects, nor were significant differences observed in ankle or hip flexion-extension or adduction-abduction moments.

Measured knee flexion angles at takeoff and landing showed no significant differences between the before-training and the after-training measurements. Maximal knee flexion at landing increased from 69° ± 14° to 72° ± 9° in the female subjects, but this trend was not significant ($P = 0.27$). Maximal knee flexion angles at landing in the male subjects were 63° ± 19°, although the male subjects tended toward higher maximal knee flexion angles at takeoff (90° ± 11° for male subjects versus 84° ± 6° [$P = 0.10$] and 83° ± 6° [$P = 0.06$] for female subjects before and after training, respectively). No significant differences were observed in ankle or hip flexion and extension angles.

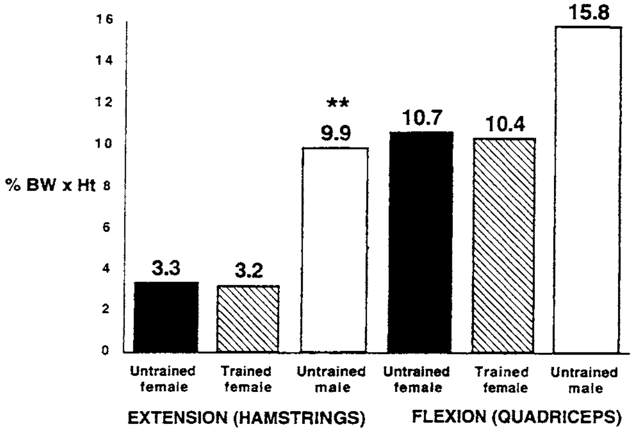

Figure 6. Bar graphs of peak external knee extension and flexion moment data at landing before and after training in the female subjects and for the male subjects.

Isokinetic dynamometer measurements of hamstring muscle strength revealed significant differences before and after training (Table 5). Isokinetic peak torque increased 26% in the nondominant leg ($P = 0.012$) and 13% in the dominant leg ($P = 0.094$). Isokinetic average power of the hamstring muscles also increased; the dominant leg increased 44% and the nondominant increased a lesser 21% (both were significant increases, $P = 0.0001$ and $P = 0.024$, respectively). In addition, the hamstring-to-quadriceps muscle peak torque ratio increased 13% on the dominant side ($P < 0.05$) and 26% on the nondominant side ($P < 0.01$). After training, the female subjects were at a

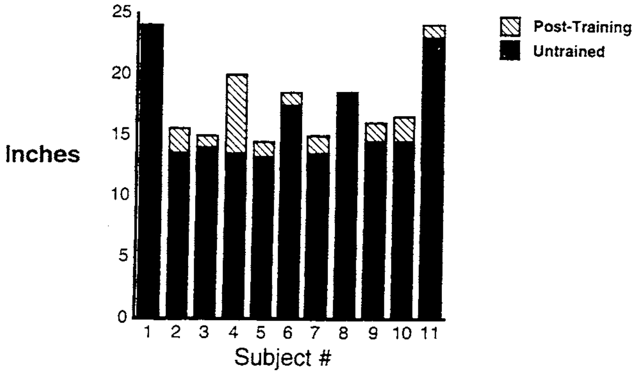

Figure 7. Distribution of changes in peak vertical jump height for the 11 female subjects.

level equivalent to that of untrained male subjects. No significant differences were demonstrated between groups for isometric measurements.

The female subjects demonstrated a 1.5 ± 0.5 inch (mean ± SEM) average increase in vertical jumping height after training. This represents a 9.2% increase during the 6-week period. The difference was statistically significant ($P = 0.016$). The range in vertical jump height increases was from 0 to 6 inches. Nine of 11 subjects demonstrated increases with training (Fig. 7). There were no differences in flexibility or knee examination scores before and after training.

DISCUSSION

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

Male subjects had peak landing forces an average of two body weights higher than female subjects. Peak landing forces are influenced by landing technique, angular momentum, and vertical height, although the relationship between these parameters is not clearly established. Multiple regression analysis showed that peak forces were significantly influenced by adduction and abduction moments but not by vertical jump height. Male athletes apparently employ different mechanical mechanisms to compensate for high landing forces than those used by female athletes, especially with respect to the effective balance of opposing joint torques.

Adduction and abduction moments at the knee decreased significantly at landing after training. The female subjects decreased these moments from values similar to those of the male subjects to significantly below that level. The observed decreases in adduction and abduction moments suggest altered muscular control of the lower extremity in the coronal plane. This likely reflects changes in contraction patterns of the adductors and abductors of the knee. Markolf et al.[20] have shown that muscular contraction can decrease both the varus and valgus laxity of the knee threefold.

Peak landing flexion and extension moments at the knee did not change with training. The peak external extension moment reflects net hamstring muscle activity, and the peak external flexion moment reflects net quadriceps muscle activity. Apparently, alteration in hamstring and quadriceps muscle contraction at landing occurred to a greater extent in the coronal plane (medial-lateral differences) than in the sagittal plane. The male subjects demonstrated threefold greater knee extension moments than the female subjects. This may be explained by the male subjects' relatively high use of the hamstring musculature as a knee flexor at landing. The high hamstring muscle use may counteract the high peak landing forces that male athletes experience.

As with knee flexion and extension moments, knee flexion angles did not increase with training, nor did the male subjects have an increased knee flexion angle at landing compared with the female subjects. One of our original hypotheses was that a decreased knee flexion angle was an important contributor to landing forces in female athletes. It is well documented that landing forces can be decreased with increased knee flexion.[4,6,7] However, our data indicate that knee flexion angle may not be the most important factor underlying decreases in peak landing force after training. Ankle dorsiflexion and hip flexion also did not change significantly with training, even after training of toe-to-heel landing and other soft landing techniques. It was surprising that none of these parameters was strongly related to the decrease in peak forces that were observed.

Abduction and adduction moments at the knee were the sole significant predictors of peak landing forces. Although these moments were of a lesser magnitude than knee flexion moments at landing in the study group, they showed a significant relationship with peak forces, and flexion moments did not. A decreased adduction or abduction moment would decrease the risk of femoral condylar liftoff from the tibial plateau. Biomechanical studies have established the relationship between varus-valgus stress and injury risk. Pope et al.[26] demonstrated that a valgus moment greater than 35 N-m elicits pain in female athletes. Markolf et al.[20] reported that stresses greater than 29 N-m put the collateral ligaments in the high-slope segment of the stress curve. The abduction and adduction moments were 42 and 36 N-m (4.0 and 3.4 %BW × Ht) in the female subjects before training, and these moments dropped to 20 and 22 N-m, respectively, after training. The decreases in these moments may reduce the risk of medial or lateral joint liftoff and associated ligamentous injury.

The increase in hamstring muscle peak torque and power observed in the subjects after training is considerable for a 6-week training period. The jump-training program brought the female athletes from a hamstring-to-quadriceps muscle ratio that was significantly lower than the male subjects (51% versus 65%, respectively) up to an equivalent value. We questioned whether this hamstring-to-quadriceps muscle imbalance was characteristic of young, relatively untrained female athletes. Gilliam et al.[12] and Highgenboten et al.[15] showed no significant differences between male and female subjects; however, these measurements were made at slower speeds than those used in this study. Stafford and Grana[28] observed that differences can occur at high speeds (360 deg/sec) that do not occur at slow speeds. For example, they showed that differences occur in the dominant versus the nondominant leg at high speeds that do not occur at low speeds or in isometric tests. It has been hypothesized that hamstring-to-quadriceps muscle ratios lower than 60% can predispose an athlete to serious knee injury.[8]

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.[3,23,29] The female subjects in this study demonstrated a marked imbalance between hamstring and quadriceps muscle strength before training. The training program corrected this imbalance and brought the ratio of hamstring-to-quadriceps muscle isokinetic strength to the level of the male subjects. Baratta et al.[3] noted the increased risk of ligamentous damage in athletes with quadriceps-to-hamstring muscle strength imbalances and reduced hamstring-quadriceps muscle coactivation patterns. They observed an increased coactivation of the hamstring muscles in athletes with quadriceps-to-hamstring muscle strength imbalances after hamstring muscle training exercises.

A statistically significant, 1.5-inch (approximately 10%), average jump increase over a 6-week training period is a considerable performance increase. The jump-training program of the 1984 U.S. Olympic Gold Medal Volleyball Team resulted in an exceptional 4-inch increase in vertical jump; however, this increase occurred over a 2-year period.[22] The increase we observed was achieved in only 6 weeks, which is a limited time for attaining a measurable increase in athletic performance. Dunnam et al.[8] reported a 1.25-inch increase in the vertical jump in female collegiate volleyball players after 11 months of training. Pestolesi[25] reported a 0.63-inch increase in a weight-training group, and a 0.45-inch increase in a jump-training group of male and female high school athletes over a similar 6-week period (both increases were not statistically significant).

There remain a number of unanswered questions needing further research. Epidemiology studies are needed to track young female athletes whose landing mechanics and muscle strength have been tested before sports participation to determine if serious knee injuries correlate with predisposing factors and if injury rates are lowered with training. Two factors that should be further investigated are increased adduction and abduction moments at the knee and imbalances between hamstring and quadriceps muscle strength or dominant and nondominant side hamstring muscle strength, as they may serve as indicators of a predisposition to injury in these athletes.

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