Journal of Athletic Training 2004;39(1):17–23

www.journalofathletictraining.org

Neuromuscular Changes in Female Collegiate Athletes Resulting From a Plyometric Jump-Training Program

Gary B. Wilkerson*; Marisa A. Colston*; Nancy I. Short†; Kristina L. Neal‡; Paul E. Hoewischer§; Jennifer J. Pixley‖

*University of Tennessee at Chattanooga, Chattanooga, TN; †Oakwood Chiropractic, Largo, FL; ‡Boyd Buchanan High School, Chattanooga, TN; §Covenant College, Lookout Mountain, GA; ‖Emmanuel College, Boston, MA

Gary B. Wilkerson, EdD, ATC/L; Marisa A. Colston, PhD, ATC/L; Nancy I. Short, MS, ATC/L; Kristina L. Neal, MS, ATC/L; Paul E. Hoewischer, MS, ATC/L; Jennifer J. Pixley, MS, ATC/L contributed to conception and design; acquisition and analysis and interpretation of the data; and drafting, critical revision, and final approval of the article.

Address correspondence to Gary Wilkerson, EdD, ATC/L, University of Tennessee at Chattanooga, 615 McCallie Ave, Department 6606, Chattanooga, TN 37403-259. Address e-mail to gary-wilkerson@utc.edu.

Objective: To assess performance changes induced by a 6-week plyometric jump-training program.

Design and Setting: We used a quasiexperimental design to compare groups formed on the basis of team membership. Testing was conducted in an athletic training research laboratory, both before and after a 6-week period of preseason basketball conditioning.

Subjects: Nineteen female collegiate basketball players from a National Collegiate Athletic Association Division I program (8 subjects) and a National Association of Intercollegiate Athletics Division II program (11 subjects) who had no history of anterior cruciate ligament injury and who had no history of any lower extremity injury during the preceding 6 months.

Measurements: The variables of primary interest were hamstrings and quadriceps isokinetic peak torque. Of secondary interest were 5 variables derived from step-down and lunging maneuvers performed on a computerized forceplate system and 4 variables derived from tracking the position of the body core during performance of a T-pattern agility drill with a computerized infrared tracking system.

Results: A significant group x trial interaction was found for hamstrings peak torque at $60^\circ \cdot s^{-1}$ ($F_{1,17} = 9.16$, $P = .008$.), and the proportion of total variance attributable to the treatment effect produced by the jump-training program was relatively large ($\eta^2 = .35$, $\omega^2 = .30$). None of the other variables demonstrated statistically significant changes.

Conclusions: Our primary results support plyometric jump training as a strategy for improving neuromuscular attributes that are believed to reduce the risk of anterior cruciate ligament injury in female college basketball players. They also provide the basis for reasonable isokinetic strength goals.

Key Words: isokinetic testing, muscle coactivation, antagonist strength ratio

---

For more than 2 decades, the hamstrings to quadriceps isokinetic peak torque ratio (H/Q ratio) has been recognized as an indicator of the ability to dynamically stabilize the knee.[1–3] The anterior cruciate ligament (ACL) strain-shielding effect provided by the hamstring muscles has been well documented.[4–8] Because the quadriceps can generate force that exceeds the ACL failure load,[9,10] coactivation of the hamstrings is believed to be essential for maintenance of knee stability.[5,11,12] The strength relationship between the hamstrings and quadriceps has been related to hamstrings coactivation[11] and to knee proprioceptive capabilities.[13]

Hewett et al[14] observed that male athletes had a threefold greater level of hamstrings utilization and demonstrated significantly less varus and valgus displacement of the knee than female athletes during jump landings. They also reported that a 6-week plyometric jump-training program increased the H/Q ratio in female athletes to a level comparable with that of untrained male subjects, a level associated with improved jump-landing mechanics. In a subsequent study, Hewett et al[15] prospectively evaluated the effect of the plyometric jump-training program on the incidence of knee injury in female athletes. Those female athletes who did not participate in the jump-training program had an ACL injury rate 3.6 times greater than for trained female athletes and 4.8 times greater than for untrained male athletes. Heidt et al[16] reported that female soccer players whose preseason conditioning program included plyometric training had a lower extremity injury rate of 14.3% (2.4% ACL injury rate), whereas players who had not been trained with plyometric exercises had a 33.7% lower extremity injury rate (3.1% ACL injury rate).

The exact mechanisms by which plyometric jump training may decrease knee injury risk are poorly understood. For example, lowered vertical ground reaction forces (VGRFs) on jump landing are believed to represent a positive jump-training adaptation that decreases injury risk in female athletes,[14,17] but male athletes demonstrate significantly greater VGRFs, higher H/Q ratios, and lower incidence of ACL injury.[14] Thus, a jump-training–induced increase in the H/Q ratio might be expected to be associated with increased tolerance for high VGRFs under certain conditions, such as a task that demands a high-impact force for successful performance. A forward lunge onto a forceplate involves landing and reverse-thrust phases during ground contact that collectively represent the total work performed. Higher levels of performance in this task are associated with greater VGRFs and a greater force impulse.[18] Conversely, a controlled, forward step-down maneuver onto a forceplate is believed to represent greater proprioceptive motor control when the maximum VGRF is minimized by eccentric muscle tension in the lower extremity contralateral to the one contacting the forceplate.[19,20]

Although isokinetic performance of the hamstrings and quadriceps has been shown to relate to closed chain functional-performance capabilities,[21–27] plyometric jump training may produce neuromuscular adaptations that can only be identified through assessment of closed chain movement patterns. A T-pattern agility test requires repetitive changes in movement direction, which closely replicates some of the functional demands of basketball.[28] Plyometric training reduces the time required for voluntary muscle activation, which may facilitate faster changes in movement direction and thereby decrease the amount of time required to complete the test.

The pretraining and posttraining isokinetic data reported by Hewett et al[14] were acquired at a faster velocity than that typically performed in clinical practice ($360°\cdot s^{-1}$). Both clinicians and researchers have traditionally tested subjects at 2 or 3 different isokinetic velocities. The velocity typically used at the low end of the spectrum for knee-extension/flexion testing has been $60°\cdot s^{-1}$,[1–3,8,22,29–43] and the H/Q ratio cited in several recent research reports was calculated from peak-torque values observed at $60°\cdot s^{-1}$.[29,36,38,41] At the high end of the knee testing velocity spectrum, $300°\cdot s^{-1}$ has been commonly used.[3,12,22,24,31,32,38,42]

Because plyometric jump training has been demonstrated to both increase the H/Q ratio and decrease the incidence of ACL injuries in female athletes, our primary purpose was to quantify the magnitude of change in the hamstrings and quadriceps peak torque that results from the 6-week program used by Hewett et al.[15] A secondary purpose was to identify any improvements in performance of selected closed chain functional tests that might result from plyometric jump training.

METHODS

Nineteen healthy female collegiate basketball players who had no history of ACL injury and no history of any lower extremity injury during the preceding 6 months volunteered to serve as subjects for this study. The Institutional Review Board of the University of Tennessee at Chattanooga approved the study, and informed consent was obtained from each subject before participation. Group assignment was determined by team membership. The experimental group consisted of 11 members of a National Association of Intercollegiate Athletics (NAIA) Division II basketball team (age = 19 ± 1.4 years; height = 173.2 ± 5.5 cm; mass = 74.9 ± 12.4 kg) who participated in a 6-week preseason conditioning program that included plyometric jump training, stretching, and isotonic strengthening. All exercises were closely supervised by 1 of the investigators, and each was performed according to instructions provided by written materials and a videotape produced by the Cincinnati Sportsmedicine Research and Education Foundation.[44] This program consists of 3 phases of progressively increasing jump complexity and intensity, and its elements correspond to those previously reported.[14,15]

A reference group consisted of 8 members of a National Collegiate Athletic Association (NCAA) Division I basketball team (age = 19 ± 1.1 years; height = 170.2 ± 6.7 cm; mass = 69.1 ± 9.0 kg) who also participated in a preseason conditioning program directed by their coaches, which included stretching, isotonic strengthening, and periodic performance of plyometric jumping drills. The plyometric component of this program was relatively unstructured, having no systematic method for increasing the complexity or intensity of the jumps.

Pretesting of both groups was performed 1 week before the start of the plyometric jump-training program. Both teams had already completed 1 week of general preseason basketball conditioning. Data were collected for isokinetic quadriceps and hamstrings strength, impact forces produced by forward lunging and unilateral step-down tests, and displacement of the body core during performance of a T-pattern multidirectional agility drill. Posttesting was conducted 6 weeks after pretesting. During the intervening period, all subjects regularly attending basketball practices and conditioning sessions, and the only substantial difference in the nature of the training regimens of the 2 groups was the degree of emphasis on plyometric jump training. Any difference that might have existed would have favored the reference group, which had a designated strength coach, a much larger coaching staff, and greater performance expectations associated with NCAA Division I competition.

Isokinetic Testing

Reciprocal-motion, concentric isokinetic peak-torque data were obtained for the knee extensors and flexors from 5 maximum-effort repetitions at $60°\cdot s^{-1}$ and 15 maximum-effort repetitions at $300°\cdot s^{-1}$ (System 3 Dynamometer and version 3.27 software; Biodex Medical Systems, Inc, Shirley, NY). Leg dominance was defined as the leg identified by subjects as the one that would be used to kick a ball. Testing was performed in a seated position, with the hip maintained at approximately 90° of flexion. Stabilization straps were used to minimize movement of the torso and the thigh segment of the tested extremity. Before testing, dynamometer position, seat position, and attachment arm length were recorded to ensure posttest replication of the pretest condition, and a gravity-correction procedure was performed. Both submaximal and maximal warm-up repetitions were performed before each testing bout. Subjects were instructed to maintain a grasp of the chest straps with both hands, and loud verbal encouragement for maximal effort was provided during each test bout.

Impact Force Testing

Subjects performed 3 trials of 2 tests on a computerized forceplate system (Balance Master System 6.0; NeuroCom International, Inc, Clackamus, OR). Both tests were performed in the barefoot condition. The forward step-down test started with the subject standing with both feet on a platform 20.3 cm above the forceplate. Subjects were instructed to step down with the designated leg ‘‘as slowly as possible’’ and to descend with the contralateral leg after forceplate contact had been made by the leading extremity. Impact index, expressed as a percentage of body weight, represents the maximum VGRF generated by the contact of the leading extremity on the forceplate. The recorded impact index value was the average of 3 trials. A 0.91 impact index reliability coefficient has been reported, which was calculated by linear regression analysis of test-retest impact index values acquired on 2 separate days for 176 subjects.[45]

The forward-lunge test started from a standing position. Subjects were instructed to lunge forward on the designated leg as far as possible and to return to the starting position as fast as possible. Lunge distance, impact index, contact time, and force impulse (force × contact time) were measured, with reported separate-day test-retest reliability coefficients of 0.93, 0.87, 0.75, and 0.73, respectively.[45] Lunge distance, expressed as a percentage of height, represents the amount of forward displacement of the body core. The impact index, expressed as a percentage of body weight, represents the maximum VGRF generated during landing by the lunging extremity. Contact time represents the interval between contact of the lunging foot with the forceplate and removal of the lunging foot from the forceplate when returning to the starting position. Force impulse, expressed as a percentage of body weight per second, represents the total work performed by the lunging extremity during both the landing and reverse-thrust phases of the test. Each recorded value was the average of 3 trials.

Agility Testing

An infrared motion-analysis system (TRAZER; Arena, Inc, Westlake, OH) was used to track the position of the body core during performance of a T-pattern agility drill. An infrared signal transmitter was attached to the subject by means of a belt that positioned the transmitter near the umbilicus, and the system's optical sensing electronics and software provided the subject with visual feedback of motion in the form of an animated figure that moves within a virtual space displayed on a large monitor. Changes in the position of the animated figure within the virtual space correspond with changes in the position of the subject's body core, without any perceived visual lag. During testing, the subject's movements were guided by the appearance of targets within the virtual environment display that disappeared when the body core had been moved the proper direction and distance. The minimum distance of body-core movement for completion of each segment of the T-pattern was 60.94 cm of forward movement from the starting position to the first central target, 26.80 cm of lateral movement to a lateral target, 53.60 cm of lateral movement in the opposite direction to another lateral target, 26.80 cm of lateral movement back to a central target, and 60.94 cm of backward movement to the starting position. This sequence of T-pattern movement was repeated 12 times for each test bout, and the first direction of lateral movement was alternated between right and left on each successive repetition of the pattern.

Each subject performed 3 sets of the T-pattern agility drill. The first set was used to familiarize the subject with the motion-analysis system and the requirements of the task, which was followed by 2 test sets. During the familiarization set, subjects were encouraged to move progressively faster and to make abrupt changes in movement direction. During a 1-minute rest period that preceded the first test set, subjects were instructed to complete the 12 T-pattern movement sequences as rapidly as possible. One minute of rest preceded the second test set. Variables measured included test duration(s), average speed (m/s), average power (W/kg), and average vertical position of the body core (cm; ± upright standing position). The performance values recorded for each subject were an average of the results for the 2 test sets. Previous testing of 30 college-aged subjects in our laboratory for assessment of test-retest reliability on 3 separate days yielded intraclass correlation coefficients of 0.74 for test duration (SEM = 9.33 seconds), 0.74 for average speed (SEM = 0.10 m/s), 0.75 for average power (SEM = 0.57 W/kg), and 0.56 for average vertical position of the body core (SEM = 1.96 cm) (M.A. Colston, unpublished data, 2002).

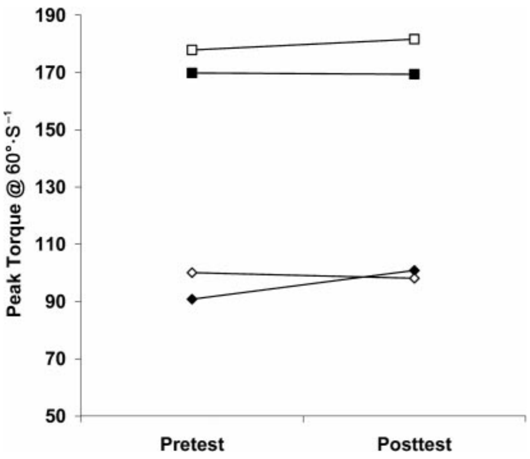

Figure 1. Pretest and posttest means for the quadriceps (□ reference group, ■ experimental group) and the hamstrings (◇ reference group, ◆ experimental group) at $60^\circ \cdot s^{-1}$ peak torque (N·m).

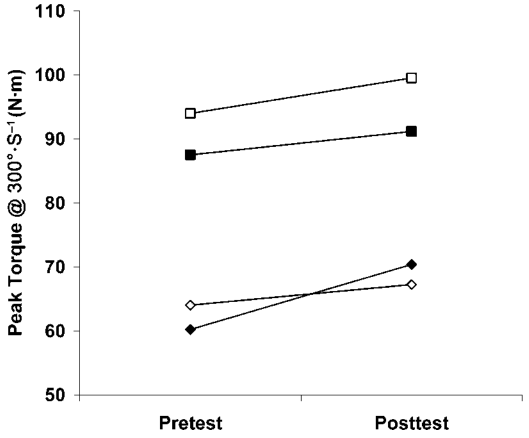

Figure 2. Pretest and posttest means for the quadriceps (□ reference group, ■ experimental group) and the hamstrings (◇ reference group, ◆ experimental group) at $300^\circ \cdot s^{-1}$ peak torque (N·m).

Statistical Analysis

Separate 2 × 2 mixed analyses of variance, with group membership as the between-subjects factor and trials as the within-subjects factor, were performed for each of the following test variables: (1) quadriceps peak torque at $60^\circ \cdot s^{-1}$; (2) quadriceps peak torque at $300^\circ \cdot s^{-1}$; (3) hamstrings peak torque at $60^\circ \cdot s^{-1}$; (4) hamstrings peak torque at $300^\circ \cdot s^{-1}$; (5) forward step-down impact index; (6) forward-lunge distance; (7) forward-lunge impact index; (8) forward-lunge contact time; (9) forward-lunge force impulse; (10) agility-test duration; (11) agility-test average speed; (12) agility-test average power; and (13) agility-test average body-core vertical position. Data derived from the isokinetic and the impact force tests were analyzed for the dominant extremity only. The interaction of group membership and trials was tested at the $P < .05$ level using the Statistical Package for Social Sciences (version 10.0

Table 1. Isokinetic Peak-Torque Values (Mean ± SD)

	Pretest		Posttest	
Performance Variable	REF	EXP	EXP	REF
$60^\circ\cdot s^{-1}$ Hamstrings peak torque (N·m)*	100.07 ± 26.24	90.81 ± 17.91	98.12 ± 20.91	100.81 ± 21.85
$60^\circ\cdot s^{-1}$ Quadriceps peak torque (N·m)	177.81 ± 18.99	169.82 ± 26.78	181.64 ± 29.10	169.38 ± 27.30
$300^\circ\cdot s^{-1}$ Hamstrings peak torque (N·m)	64.02 ± 17.47	60.21 ± 14.87	67.24 ± 10.23	70.38 ± 21.71
$300^\circ\cdot s^{-1}$ Quadriceps peak torque (N·m)	93.97 ± 19.58	87.51 ± 15.17	99.53 ± 21.19	91.17 ± 17.94

*Group × trial interaction significant at .05 level with Bonferroni correction ($\alpha = .0125$). REF indicates reference group; EXP, experimental group.

Table 2. Isokinetic Peak-Torque Ratios (Mean ± SD)

	Pretest		Posttest	
Variable	REF	EXP	EXP	REF
$60^\circ\cdot s^{-1}$ Quadriceps/body weight	86.79 ± 7.08	76.61 ± 9.95	88.28 ± 9.41	76.47 ± 10.83
$60^\circ\cdot s^{-1}$ Hamstrings/body weight	48.14 ± 8.84	40.70 ± 4.84	47.51 ± 6.79	45.10 ± 5.64
$60^\circ\cdot s^{-1}$ Hamstrings/quadriceps	55.73 ± 10.49	53.61 ± 7.10	54.12 ± 8.34	59.90 ± 10.69
$300^\circ\cdot s^{-1}$ Quadriceps/body weight	45.30 ± 4.67	39.45 ± 5.66	48.10 ± 6.15	41.01 ± 6.87
$300^\circ\cdot s^{-1}$ Hamstrings/body weight	30.75 ± 6.02	27.05 ± 5.68	32.73 ± 3.16	31.25 ± 6.87
$300^\circ\cdot s^{-1}$ Hamstrings/quadriceps	67.61 ± 9.33	69.14 ± 14.52	68.89 ± 9.80	77.55 ± 20.77

for Windows; SPSS Inc, Chicago, IL). The 3 categories of testing were treated as separate experiments, and we used the Bonferroni correction to adjust the alpha level for multiple analyses performed for each category (.05/4 = .0125 for isokinetic testing and agility testing, .05/5 = .01 for impact force testing). Follow-up 2 × 2 mixed analyses of variance were performed to identify any interaction between group membership and trials for H/Q ratios. Because the H/Q ratios were calculated from the same peak-torque values that were analyzed separately in the preceding analyses, the Bonferroni correction was not used to adjust the alpha level (.05) for the follow-up analyses.

RESULTS

The group x trial interaction for the hamstrings peak torque at $60^\circ\cdot s^{-1}$ was found to be significant ($F_{1,17} = 9.16$, $P = .008$; Tables 1 and 2). Graphic display of the data clearly demonstrates the treatment effect that was produced by the jump-training program (Figure 1). An increase in hamstrings peak torque on the posttest was observed for every subject in the experimental group, whereas only 3 of the 8 subjects in the reference group demonstrated an increase. Although the power to reject the null hypothesis of no treatment effect was somewhat limited by the small sample size ($1 - \beta = .814$), the proportion of total variance attributable to the group × trial interaction was relatively large ($\eta^2 = .35$, $\omega^2 = .30$). Effect size (ES), calculated as the difference between experimental group posttest and pretest means divided by the pretest standard deviation, and corrected for the small number of subjects was 0.50.

The $300^\circ\cdot s^{-1}$ hamstrings peak-torque data did not demonstrate a significant group x trial interaction ($F_{1,17} = 1.56$, $P = .228$) (Figure 2). Despite failure to reject the null hypothesis of no group x trial interaction, the power to reject the false null hypothesis was low ($1- \beta = .219$), and increased hamstrings peak torque on the posttest was observed in 9 of the 11 experimental-group subjects. Effect size was 0.62. Increased hamstrings peak torque in the experimental group was apparent at both velocities, but greater overall variance in relation to the size of the cell means at the faster test velocity explained the lack of statistical significance.

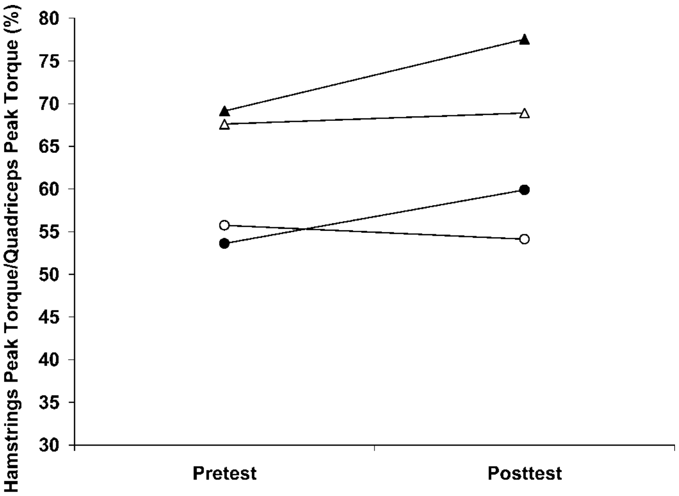

Figure 3. Antagonist peak-torque ratio (percent) pretest and posttest means at $300^\circ\cdot s^{-1}$ (△ reference group, ▲ experimental group) and $60^\circ\cdot s^{-1}$ (○ reference group, ● experimental group).

No significant group x trial interaction was evident for quadriceps peak torque at either the $60^\circ\cdot s^{-1}$ or $300^\circ\cdot s^{-1}$ isokinetic test velocities, and none of the separate analyses for the 9 closed-chain test variables of secondary interest demonstrated statistically significant improvement in the experimental group. Only 2 of the 9 closed-chain tests demonstrated the expected pattern of pretest to posttest improvement for the experimental group and minimal or no improvement in the reference group; agility-test average power (ES = 0.30) and agility-test average body-core position (ES = 0.28). The results of follow-up analyses of H/Q ratios were consistent with the results of the analyses of hamstrings and quadriceps peak torque (Figure 3). Significant group x trial interaction was evident for the H/Q ratio at $60^\circ\cdot s^{-1}$ ($F_{1,17} = 5.24$, $P = .035$) but was not evident at $300^\circ\cdot s^{-1}$ ($F_{1,17} = 1.40$, $P = .253$).

DISCUSSION

Fundamental concerns of those responsible for the welfare of female athletes include the identification of any modifiable knee-injury risk factors in individual athletes and the proper administration of any interventions that have been shown to be effective in reducing knee injury risk. Clinical utilization of isokinetic knee testing has markedly decreased over the past decade, because of widespread acceptance of the notion that isokinetic data are unrelated to closed chain function, concern about deleterious ACL graft strain induced by resisted open chain knee extension, decreased third-party reimbursement for muscle performance testing, and the failure of clinics to maintain or upgrade isokinetic equipment. Studies of the relationship between isokinetic data and performance on closed chain functional tests have produced conflicting results. The findings of those that have not demonstrated a strong correlation between isokinetic performance and closed chain test performance[30,46,47] have been interpreted by many clinicians as evidence that closed chain tests are superior to isokinetic testing for assessment of an individual's functional status. However, closed chain tests involving vertical jumping, horizontal jumping, unilateral hopping, or timed agility runs cannot identify isolated muscle-performance deficiencies that may relate to knee injury risk.[48] Our results support the findings of Hewett et al[14,15] concerning the value of jump training for improvement of hamstrings performance capability in female athletes.

An important practical consideration for interpretation of isokinetic test performance is the establishment of a threshold value for the H/Q ratio that can be used to discriminate those individuals who have a relatively greater risk of knee injury from those whose risk is lower. Factors that greatly affect the isokinetic H/Q ratio include test velocity, test posture, and gravity correction.[3,31–33,35,42,43,49,50] Hewett et al[14] cited Dunnam et al[1] in identifying .60 as the minimum H/Q ratio for avoidance of high knee injury risk, but they failed to note the discrepancy between the isokinetic test velocity of $360^\circ\cdot s^{-1}$ used in their study and the $60^\circ\cdot s^{-1}$ velocity that corresponded with the .60 H/Q ratio standard that they cited. Dunnam et al[1] cited Nosse[51] as the source of the standard for decreased knee injury risk, but Nosse actually criticized what he perceived as widespread acceptance of the .60 H/Q ratio standard for assessment of isokinetic performance. He documented that the widely accepted standard had been derived from isometric cable-tensiometer testing of collegiate football players and suggested that its application to isokinetic testing was inappropriate. Our results suggest that .60 is a reasonable goal for the isokinetic H/Q ratio at $60^\circ\cdot s^{-1}$ in female college athletes.

Mean gravity-corrected $60^\circ\cdot s^{-1}$ H/Q ratios of .54 and .56 were observed for the dominant extremity of the experimental and reference groups on the pretest, and a value of .54 was observed for the dominant extremity of the reference group on the posttest. These values are comparable with gravity-corrected $60^\circ\cdot s^{-1}$ H/Q ratios calculated from hamstrings and quadriceps torque to body-weight ratios reported by Huston and Wojtys[36] for both female collegiate athletes and female nonathletes (.53), those reported by Anderson et al[29] for female high school basketball players (.56), and the finding of Neder et al[38] for 20- to 80-year-old nonathletic female subjects (.53). The dominant extremity mean H/Q ratio of .60 that was observed for the experimental group on the posttest is comparable with that calculated from data reported by Huston and Wojtys[36] for male college athletes (.59) and that reported by Anderson et al[29] for male high school basketball players (.61). This finding is consistent with the observation of Hewett et al[14] that a 6-week jump-training program increased the $360^\circ\cdot s^{-1}$ H/Q ratio of female high school athletes to a value equivalent to that for male athletes.

Moore and Wade[3] presented recommended isokinetic strength goals (peak torque to body-weight ratios for the quadriceps and hamstrings) and H/Q ratios at $60^\circ\cdot s^{-1}$ and $300^\circ\cdot s^{-1}$ for female basketball players that were not gravity corrected. Lack of gravity correction results in an overestimation of hamstrings torque and underestimation of quadriceps torque, and the effect of gravity increases with faster isokinetic test velocity.[31,50] Figoni et al[49] reported H/Q ratios that were both corrected and uncorrected for gravity effect at $15^\circ\cdot s^{-1}$ and $90^\circ\cdot s^{-1}$. At both of these slow test velocities, there was a 16% difference. Analysis of similar corrected and uncorrected H/Q data reported by Appen and Duncan[31] yields a 16% difference at $60^\circ\cdot s^{-1}$ and a 29% difference at $300^\circ\cdot s^{-1}$. Application of corresponding corrections to the H/Q ratio goals recommended by Moore and Wade[3] for female basketball players yields values of .59 for $60^\circ\cdot s^{-1}$ (.70 uncorrected) and .70 for $300^\circ\cdot s^{-1}$ (1.0 uncorrected). The pretest mean H/Q value we observed at $300^\circ\cdot s^{-1}$ for the experimental group was .69, and it was .78 for the dominant extremity on the posttest. Our findings suggest that H/Q ratios of .60 or greater at $60^\circ\cdot s^{-1}$, and .80 or greater at $300^\circ\cdot s^{-1}$ are reasonable and attainable goals for female college athletes.

An extremely important point to consider in the interpretation of isokinetic test results is the possibility that a favorable H/Q ratio may exist in the presence of relative weakness in both the hamstrings and quadriceps.[3,40] Although quadriceps force transmitted through the patellar tendon can produce anterior tibial translation in the absence of hamstrings coactivation, quadriceps strength is important for optimal functional performance,[22,24,46,47] dampening of high VGRF,[52,53] and control of varus and valgus displacement of the knee.[54] Anderson et al[29] recently reported observations that support the hypothesis that the size of the ACL in females is proportionate to isokinetic quadriceps strength measured at $60^\circ\cdot s^{-1}$. Differences in quadriceps strength between male and female athletes may relate to the greater tolerance for high VGRFs and the lower ACL injury rate observed in male athletes.

When adjusted for the effect of gravity determined from the work of Appen and Duncan[31] and Nelson and Duncan,[50] the goal recommended by Moore and Wade[3] for the quadriceps peak torque-to-body weight ratio (QPT/BW) at $60^\circ\cdot s^{-1}$ for female basketball players is reduced 4.5% from 1.20 to 1.15. The fact that none of the college basketball players in our study demonstrated a QPT/BW ratio greater than 1.00 suggests that 1.15 may not be a realistic goal for many individuals. Gravity adjustment for the $300^\circ\cdot s^{-1}$ QPT/BW goals recommended by Moore and Wade[3] for female basketball players (centers and forwards) yields a value of approximately .50, which seems to be a reasonably attainable goal.

Despite having greater height and weight, the NAIA Division II players comprising our experimental group demonstrated quadriceps strength values at $60^\circ\cdot s^{-1}$ on the pretest that were 13% lower than those for the NCAA Division I players who comprised the reference group. Average $60^\circ\cdot s^{-1}$ QPT/BW values for the dominant extremity were .77 and .87, respectively. On the basis of our observations, a $60^\circ\cdot s^{-1}$ QPT/BW goal of 1.00 seems reasonable, which would correspond with a hamstrings peak torque-to-body weight ratio goal of at least

Table 3. Recommended Strength Goals for Female Collegiate Basketball Players*

Velocity	Hamstrings/ Quadriceps	Quadriceps/ Body Weight	Hamstrings/ Body Weight
60°/s	0.60	1.00	0.60
300°/s	0.80	0.50	0.40

*Gravity-corrected isokinetic peak-torque ratios.

.60 for maintenance of the H/Q ratio at .60 or greater. The NAIA Division II players had 15% lower QPT/BW values than the NCAA Division I players at the $300° \cdot s^{-1}$ test velocity on the pretest, with average values of .39 and .46 respectively. A $300° \cdot s^{-1}$ QPT/BW goal of .50 would require a hamstrings peak torque-to-body weight value of at least .40 for the H/Q to be .80 or greater. Table 3 presents a summary of recommended strength goals for female collegiate basketball players.

Plyometric jumps require high levels of concentric quadriceps and hamstrings force development for propulsion and high levels of eccentric force for control of knee and hip motion during landing. Our isokinetic test results clearly indicate that the jump-training program increased the performance capability of the hamstrings, but no change was evident in quadriceps performance. The lack of significant changes or trends in the impact-force values for the forward-lunge and step-down tests may have been due to relatively greater use of the quadriceps than the hamstrings during performance of the tests. These tests may identify differences between ACL-deficient and uninjured extremities in individual subjects,[21] but they apparently lack sufficient sensitivity to detect neuromuscular adaptations from 6 weeks of jump training in the extremities of healthy athletes. Measurable performance changes on the closed chain tests used in this study might be detected with a longer training period.

Acknowledged limitations of this study include the relatively small sample, a relatively short training period, a lack of randomized subject selection and group assignment, and the difference in the competitive levels of the 2 basketball teams. Despite these factors, and the fact that the reference group participated in a rigorous conditioning program between the pretest and posttest, a strong treatment effect was evident in the improved hamstrings performance of the experimental group and the corresponding increase in the H/Q ratio. The findings of this quasiexperimental study clearly support those of Hewett et al[14,15] concerning the value of plyometric jump training for enhancement of dynamic knee stability in female athletes, and we believe that they also support the value of isokinetic testing for identification of functionally relevant muscle-performance deficiencies.

CONCLUSIONS

Although a direct correlation between lower extremity strength and subsequent ACL injury has not been established, considerable research evidence supports the hypothesis that ACL injury risk can be reduced by exercises designed to enhance muscle-performance capabilities. Our results demonstrate that open chain isokinetic performance values for the hamstrings are responsive to changes induced by a plyometric jump-training program, but none of the closed chain tests employed in this study identified a meaningful change in performance capabilities. Our findings suggest that H/Q ratios of .60 or greater at $60° \cdot s^{-1}$ and .80 or greater at $300° \cdot s^{-1}$ are reasonable goals for female collegiate basketball players who possess an adequate level of quadriceps strength. Furthermore, athletes who demonstrate H/Q ratios that are lower than these goal values are likely to derive significant benefit from the 6-week plyometric jump-training program evaluated by this study.

REFERENCES

1. Dunnam LO, Hunter GR, Williams BP, Dremsa CJ. Comprehensive evaluation of the University of Alabama at Birmingham women's volleyball training program. *Natl Strength Cond Assoc J.* 1988;10:43–49.
2. Grace TG, Sweetser ER, Nelson MA, Ydens LR, Skipper BJ. Isokinetic muscle imbalance in knee-joint injuries: a prospective blind study. *J Bone Joint Surg Am.* 1984;66:734–740.
3. Moore JR, Wade G. Prevention of anterior cruciate ligament injuries. *Natl Strength Cond Assoc J.* 1989;11:35–40.
4. Draganich LF, Jaeger RJ, Kralj AR. Coactivation of the hamstrings and quadriceps during extension of the knee. *J Bone Joint Surg Am.* 1989; 71:1075–1081.
5. Hagood S, Solomonow M, Baratta R, Zhou BH, D'Ambrosia R. The effect of joint velocity on the contribution of the antagonist musculature to knee stiffness and laxity. *Am J Sports Med.* 1990;18:182–187.
6. Renström P, Arms SW, Stanwyck TS, Johnson RJ, Pope MH. Strain within the anterior cruciate ligament during hamstring and quadriceps activity. *Am J Sports Med.* 1986;14:83–87.
7. Solomonow M, Baratta R, Zhou BH, Sohji H, Bose W, Beck C, D'Ambrosia R. The synergistic action of the anterior cruciate ligament and thigh muscles in maintaining joint stability. *Am J Sports Med.* 1987; 15:207–213.
8. Walla DJ, Albright JP, McAuley E, Martin RK, Eldridge V, El-Khoury G. Hamstring control and the unstable anterior cruciate ligament-deficient knee. *Am J Sports Med.* 1985;13:34–39.
9. Noyes FR, Grood ES. The strength of the anterior cruciate ligament in humans and Rhesus monkeys. *J Bone Joint Surg Am.* 1976;58:1074–1082.
10. Woo SL-Y, Hollis JM, Adams DJ, Lyon RM, Takai S. Tensile properties of the human femur-anterior cruciate ligament-tibia complex: the effects of specimen age and orientation. *Am J Sports Med.* 1991;19:217–225.
11. Baratta R, Solomonow M, Zhou BH, Letson D, Chuinard R, D'Ambrosia R. Muscular coactivation: the role of the antagonist musculature in maintaining knee stability. *Am J Sports Med.* 1988;16:113–122.
12. Osternig LR, Caster BL, James CR. Contralateral hamstring (biceps femoris) coactivation patterns and anterior cruciate ligament dysfunction. *Med Sci Sports Exerc.* 1995;27:805–808.
13. Corrigan JP, Cashman WF, Brady MP. Proprioception in the cruciate deficient knee. *J Bone Joint Surg Br.* 1992;74:247–250.
14. Hewett TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes: decreased impact forces and increased hamstring torques. *Am J Sports Med.* 1996;24:765–773.
15. Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes: a prospective study. *Am J Sports Med.* 1999;27:699–705.
16. Heidt RS Jr, Sweeterman LM, Carlonas RL, Traub JA, Tekulve FX. Avoidance of soccer injuries with preseason conditioning. *Am J Sports Med.* 2000;28:659–662.
17. Prapavessis H, McNair PJ. Effects of instruction in jumping technique and experience jumping on ground reaction forces. *J Orthop Sports Phys Ther.* 1999;29:352–356.
18. Objective Quantification of Balance and Mobility. Clackamas, OR: NeuroCom International, Inc; 2000:41.
19. Cavanaugh JT, Stump TJ. Forward step down test [abstract]. *J Orthop Sports Phys Ther.* 2000;30:A46–A47.
20. Stump TJ, Cavanaugh JT, Noonan DJ. A comparison of the sensitivity of two separate forward step down test protocols for assessing functional strength deficits in the anterior cruciate ligament insufficient knee [abstract]. *J Orthop Sports Phys Ther.* 2000;30:A39–A40.
21. Barber SD, Noyes FR, Mangine RE, McCloskey JW, Hartman W. Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. *Clin Orthop.* 1990;255:204–214.

22. Kannus P. Peak torque and total work relationship in the thigh muscles after anterior cruciate ligament injury. *J Orthop Sports Phys Ther.* 1988; 10:97–101.
23. Noyes FR, Barber SD, Mangine RE. Abnormal lower limb symmetry determined by function hop test after anterior cruciate ligament rupture. *Am J Sports Med.* 1991;19:513–518.
24. Sachs RA, Daniel DM, Stone ML, Garfein RF. Patellofemoral problems after anterior cruciate ligament reconstruction. *Am J Sports Med.* 1989; 17:760–765.
25. Tegner Y, Lysholm J, Lysholm M, Gillquist J. A performance test to monitor rehabilitation and evaluate anterior cruciate ligament injuries. *Am J Sports Med.* 1986;14:156–159.
26. Wiklander J, Lysholm J. Simple tests for surveying muscle strength and muscle stiffness in sportsmen. *Int J Sports Med.* 1987;8:50–54.
27. Wilk KE, Romaniello WT, Soscia SM, Arrigo CA, Andrews JR. The relationship between subjective knee scores, isokinetic testing, and functional testing in the ACL-reconstructed knee. *J Orthop Sports Phys Ther.* 1994;20:60–73.
28. Tippett SR, Voight ML. *Functional Progressions for Sport Rehabilitation.* Champaign, IL: Human Kinetics; 1995:43.
29. Anderson AF, Dome DC, Gautam S, Awh MH, Rennirt GW. Correlation of anthropometric measurements, strength, anterior cruciate ligament size, and intercondylar notch: characteristics to sex differences in anterior cruciate ligament tear rates. *Am J Sports Med.* 2001;29:58–66.
30. Anderson MA, Gieck JH, Perrin D, Weltman A, Rutt R, Denegar C. The relationship among isometric, isotonic, and isokinetic concentric and eccentric quadriceps and hamstring force and three components of athletic performance. *J Orthop Sports Phys Ther.* 1991;14:114–120.
31. Appen L, Duncan PW. Strength relationship of the knee musculature: effects of gravity and sport. *J Orthop Sports Phys Ther.* 1986;7:232–235.
32. Berg K, Blanke D, Miller M. Muscular fitness profile of female college basketball players. *J Orthop Sports Phys Ther.* 1985;7:59–64.
33. Bohannon RW, Gajdosik RL, LeVeau BF. Isokinetic knee flexion and extension torque in the upright sitting and semireclined sitting positions. *Phys Ther.* 1986;66:1083–1086.
34. Gür H. Concentric and eccentric isokinetic measurements in knee muscles during the menstrual cycle: a special reference to reciprocal moment ratios. *Arch Phys Med Rehabil.* 1997;78:501–505.
35. Holmes JR, Alderink GJ. Isokinetic strength characteristics of the quadriceps femoris and hamstring muscles in high school students. *Phys Ther.* 1984;64:914–918.
36. Huston LJ, Wojtys EM. Neuromuscular performance characteristics in elite female athletes. *Am J Sports Med.* 1996;24:427–436.
37. Lucca JA, Kline KK. Effects of upper and lower limb preference on torque production in the knee flexors and extensors. *J Orthop Sports Phys Ther.* 1989;11:202–207.
38. Neder JA, Nery LE, Shinzato GT, Andrade MS, Peres C, Silva AC. Reference values for concentric knee isokinetic strength and power in nonathletic men and women from 20 to 80 years old. *J Orthop Sports Phys Ther.* 1999;29:116–126.
39. Tippett SR. Lower extremity strength and active range of motion in college baseball pitchers: a comparison between stance leg and kick leg. *J Orthop Sports Phys Ther.* 1986;8:10–14.
40. St Clair Gibson A, Lambert MI, Durandt JJ, Scales N, Noakes TD. Quadriceps and hamstrings peak torque ratio changes in persons with chronic anterior cruciate ligament deficiency. *J Orthop Sports Phys Ther.* 2000; 30:418–427.
41. Wojtys EW, Huston LJ, Taylor PD, Bastian SD. Neuromuscular adaptations in isokinetic, isotonic, and agility training programs. *Am J Sports Med.* 1996;14:187–192.
42. Worrell TW, Perrin DH, Denegar CR. The influence of hip position on quadriceps and hamstring peak torque and reciprocal muscle group ratio values. *J Orthop Sports Phys Ther.* 1989;11:104–107.
43. Wyatt MP, Edwards AM. Comparison of quadriceps and hamstring torque values during isokinetic exercise. *J Orthop Sports Phys Ther.* 1981;3:48–56.
44. *Sportsmetrics: A Jump Training Program for Women Proven to Reduce the Risk of Knee Injury* [videotape]. Cincinnati, OH: Cincinnati Sportsmedicine Research and Education Foundation; 1996.
45. Assessment of balance and mobility functions: a reference population study based on the Balance Master 6.1. Clackamas OR: NeuroCom International, Inc; 1998.
46. Blackburn JR, Morrissey MC. The relationship between open and closed kinetic chain strength of the lower limb and jumping performance. *J Orthop Sports Phys Ther.* 1998;27:430–435.
47. Greenberger HB, Paterno MV. Relationship of knee extensor strength and hopping test performance in the assessment of lower extremity function. *J Orthop Sports Phys Ther.* 1995;22:202–206.
48. Davies GJ, Heiderscheit B, Clark M. Open kinetic chain assessment and rehabilitation. *Athl Train Sports Health Care Perspect.* 1995;1:347–370.
49. Figoni SF, Christ CB, Massey BH. Effects of speed, hip and knee angle, and gravity on hamstring to quadriceps torque ratios. *J Orthop Sports Phys Ther.* 1988;9:287–291.
50. Nelson SG, Duncan PW. Correction of isokinetic and isometric torque recordings for the effects of gravity: a clinical report. *Phys Ther.* 1983; 63:674–676.
51. Nosse LJ. Assessment of selected reports on the strength relationship of the knee musculature. *J Orthop Sports Phys Ther.* 1982;4:78–85.
52. Bland JH, Cooper SM. Osteoarthritis: a review of the cell biology involved and evidence for reversibility, management rationally related to known genesis and pathophysiology. *Semin Arthritis Rheum.* 1984;14: 106–133.
53. Snyder-Mackler L, DeLitto A, Bailey SL, Stralka SW. Strength of the quadriceps femoris muscle and functional recovery after reconstruction of the anterior cruciate ligament: a prospective, randomized clinical trial of electrical stimulation. *J Bone Joint Surg Am.* 1995;77:1166–1173.
54. Pope MH, Johnson RJ, Brown DW, Tighe C. The role of the musculature in injuries to the medial collateral ligament. *J Bone Joint Surg Am.* 1979; 61:398–402.