Barber-Westin et al., J Athl Enhancement 2015, 4:1
http://dx.doi.org/10.4172/2324-9080.1000185

Journal of Athletic Enhancement

Research Article

A SCITECHNOL JOURNAL

A Six-Week Neuromuscular and Performance Training Program Improves Speed, Agility, Dynamic Balance, and Core Endurance in Junior Tennis Players

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Abstract

Objective: Tennis requires speed, agility, and explosive power. Few studies have assessed the effects of a training program in junior players who are not on an elite or national level. We evaluated the impact of a program that combined components of a knee ligament injury prevention program with other exercises to improve athletic performance indicators. We hypothesized that this program would significantly improve dynamic single-leg balance and function, correct lower limb asymmetry, enhance speed and agility, and improve core endurance.

Methods: Forty-two players (31 females, 11 males; mean age, 14 ± 2 years) participated in the 6-week program conducted by a tennis professional and certified trainers. Each training session included a dynamic warm-up, jump training, strength training, and tennis-specific agility and hitting drills. Two single-leg hop tests, baseline and service box speed and agility tests, a 1-court suicide run, and an abdominal endurance test were conducted at baseline and 3 days after the last session. Fifteen athletes participated in more than one training program a mean of 9 months apart.

Results: In all 42 players, statistically significant improvements and large-moderate effect sizes were measured for speed, agility, dynamic single-leg balance, and abdominal endurance. Players who participated in multiple programs continued to improve, although the magnitude of the improvements was smaller than those obtained from the first training program. There were no differences in the percent of improvement in any of the tests between genders.

Conclusions: The program improved neuromuscular and athletic performance indicators in junior tennis players. Repeated training for continued improvements is justified as required or desired by the player. The program is appropriate for pre-season training for high school players or before the initiation of seasonal tournament play.

Keywords: Plyometrics; Physical testing; Racquet sport

Introduction

Over 75 million people worldwide play tennis [1] and 200 nations are associated with the International Tennis Federation [2]. The health benefits of this sport are well recognized; tennis players have a higher level of aerobic fitness, a decreased risk of cardiovascular disease, a lower body fat percentage, and improved bone health compared with less active individuals [3]. Unfortunately, tennis is associated with several common traumatic injuries and overuse syndromes. The lower extremity is affected most frequently with injuries such as muscle strains, meniscus tears, ligament tears, and patellofemoral pain that account for 39-59% of the total incidence of injuries sustained by tennis players [2,4,5]. The effort to reduce lower extremity injuries and overuse syndromes should involve a reduction in loads or stresses on the lower extremity and improvement in technique, strength, dynamic balance, agility, and aerobic fitness. In young junior players who are not on an elite level, the large biomechanical demands of competitive tennis can be problematic, especially in athletes who have not developed adequate strength, aerobic fitness, and neuromuscular control to avoid common lower extremity injuries.

We designed a tennis-specific training program based on prior work in other sports in which neuromuscular retraining techniques were incorporated along with athletic performance enhancement drills in a program known as Sportsmetrics. Sportsmetrics has been reported to reduce the risk of anterior cruciate ligament (ACL) tears in female athletes [6,7] and has improved lower limb alignment (from excessive valgus to neutral) on a drop-jump test [8,9], increased hamstrings isokinetic strength [6,8,10], increased knee flexion [6,11] and reduced deleterious abduction/adduction moments and ground reaction forces on landing after training [6]. The training program we devised for competitive junior tennis players implemented the essential components of Sportsmetrics in regard to reducing high impact forces and improving lower limb alignment during athletic maneuvers. It is unique because the teaching elements of neuromuscular retraining during jumping, landing, cutting, and pivoting [6,8,12-14] are combined with other exercises to improve dynamic balance, agility, speed, and strength specifically related to tennis.

Few studies [15] have assessed the effects of a neuromuscular and performance enhancement training program in adolescent tennis players, especially those who participate in school or local tournaments, but are not on an elite or national level. The majority of investigations related to tennis either assessed physiological profiles, analyzed the results of one training session [16-24], or focused on male professional or national-level players [25,26]. Another unique aspect of our investigation is that male and female athletes who were not elite or national level players were the focus of the study.

The consequences of a lower extremity injury to junior tennis players such as those who participated in this study may include decreased interest in resuming the sport or in resuming play on a competitive basis. A large epidemiologic study [27] of 17,397 athletes of all skill levels and ages reported 300 knee injuries related to tennis; 11% of which were confirmed ACL injuries. Another report [5] found that any prior injury sustained during tennis significantly increased the risk of a subsequent injury to the same location (odds ratio, 8.8, p=0.003), with the majority of injuries (51%) sustained to the lower extremity. In 55 players (12-18 years of age) who played at least twice a week, 39 sustained a total of 100 injuries over a two-year period, of which approximately one third were recurrent.

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Received: November 14, 2014 **Accepted:** December 15, 2014 **Published:** December 15, 2014

doi:http://dx.doi.org/10.4172/2324-9080.1000185

Our study analyzed the effects of our tennis-specific training program on neuromuscular and athletic performance indices in junior tennis players. In addition, the effects of multiple training programs were studied in a subgroup of players who completed the program more than one time. We hypothesized that this 6-week program would significantly improve dynamic single-leg balance and function, correct lower limb asymmetry, enhance speed and agility as related to tennis-specific movement patterns, and improve core endurance. Second, that improvement would be obtained in athletes who participated in more than one training program, although the magnitude of the improvements would be smaller than those obtained from the first training program.

Methods

Participants

Forty-two junior tennis players (31 females, 11 males; mean age, 14 ± 2 years) voluntarily participated in the training program. No athlete had a history of knee injury, pain, patella instability, or visible joint effusion. The players had participated in competitive tennis (high school team or United States Tennis Association levels 6-7) for at least 2 years before entering into the training program. Before data collection, all athletes and their parents provided their informed consent in accordance with the Internal Review Board of the Jewish Hospital of Cincinnati, Ohio for use of human subjects. Three days before the first training day and 3 to 5 days after the last training day, the athletes underwent a series of tests on the court under close supervision by one certified instructor and one tennis professional. The tests have been previously used to determine speed, agility, dynamic balance, and abdominal endurance in junior tennis players [15]. The tests were recorded and the video sequences used for player education regarding knee flexion, lower limb alignment, landing patterns, footwork, and stroke mechanics.

Single-leg hop and single-leg triple crossover hop for distance

Dynamic balance was assessed with single-leg hop and single-leg triple crossover hop tests that have been described in detail elsewhere [15]. The athletes had to hold the landing of the hops for a few seconds for the test to be considered valid, and were allowed to use their arms for balance as required. Several practice trials were first performed for each hop to familiarize the subjects with the tasks. Then, each player completed two single-leg hops on the right leg, followed by 2 on the left leg. The same sequence was completed for the single-leg crossover hops. Limb symmetry was calculated by dividing the mean distance hopped of the right leg by the mean distance of the left leg and then multiplying the result by 100. A normal limb symmetry index was considered to be ≥ 85% [28]. These tests have acceptable reliability, with intraclass correlation coefficients (ICC)>0.85 [28-30].

Baseline speed and agility forehand/backhand tests

The players began in the center of the baseline, behind a cone that was positioned directly on the line. Upon command, they ran to the singles sideline of their forehand and completed a forehand swing with the racquet over a cone that was placed 0.9 meters inside the court. They cut back to the starting position and continued the pattern back and forth for 30 seconds. No instruction was provided regarding footwork or movement patterns. However, the players were allowed to slowly practice the test to become familiar with the pattern. One repetition equaled one full run from the center of the baseline to the swing cone and back to center cone. If a subject reached the swing cone at the end of the 30 seconds, half of a repetition was added to the total count. After 2 minutes of rest, the test was done with the swing cone placed on the singles sideline of the player's backhand [15,31].

Service box speed and agility test

The players began in the middle of the service box. Upon command, they ran and touched the center service box line and then the singles sideline with their racquet, back and forth, as many times as possible within 30 seconds. No instruction was provided regarding footwork or movement patterns. However, the players were allowed to slowly practice the test to become familiar with the pattern. Each time the subject touched a line counted as 1 repetition. The distance between the 2 lines was approximately 4.1 meters. Each player performed this test twice, with a 2-minute rest between tests. The mean number of repetitions was recorded and converted to the total distance covered. This test has acceptable reliability, with an ICC of 0.85 [15,31].

1-Court suicide

Beginning on the doubles sideline, the players ran forward and touched the singles sideline with their racquet, ran backward and touched the doubles sideline, ran forward and touched the center of the service line, ran backward and touched the doubles sideline, and so on until all lines on the court were touched for a total of approximately 46.6 meters. The time to complete the test was recorded with a digital stopwatch by a single examiner. Two subjects performed the test at the same time to encourage maximal effort. The subjects completed one practice trial at one-half speed to ensure they understood the test method.

Abdominal endurance

The players were positioned on their back on a mat with their arms by their side while sitting on their hands. Upon command, both legs were lifted together approximately 15 cm off the ground and the players were instructed to maintain this position for as long as possible. The amount of time that the athletes were able to maintain this position (keeping both legs off of the ground) was recorded with a digital stopwatch by a single examiner.

Neuromuscular and performance training program

The program consisted of 18 supervised training sessions over a 6-week period. Training was conducted 3 times a week (Monday, Wednesday, Friday) by one or two certified trainers and a tennis professional certified by the United States Professional Tennis Association (elite level). All testing and training was held outdoors in the afternoon. Training was conducted before the start of the school tennis season or when none of the players were peaking for important tournaments. The players participated in routine tennis practice on 2 off-days a week. None of the athletes played other sports or were involved in other training programs while participating in our program. Over the course of the study collection period, 15 athletes voluntarily participated in more than one training program.

The training sessions consisted of a dynamic warm-up (Table 1), plyometric and jump training (Table 2), strength training (Table 3), and agility/speed/tennis drills (Table 4). A gradual progression of the components was employed to avoid overuse problems and injuries. The instructors kept written records of all exercises performed by each athlete for each training session. This program has been described in detail previously [32].

Table 1: Dynamic Warm-up for all Testing and Training Sessions*

Exercise	Length
1 lap around 2 courts/side-step/arm circles (half speed)	2 courts
1 lap around 2 courts carioca (half speed)	2 courts
Straight leg march	Baseline-net-baseline
Forward lunge	Baseline-net-baseline
Lateral lunge	Baseline-net-baseline
Gluteal kicks/jog	Baseline-net-baseline
Hip rotator walk	Baseline-net-baseline

Note: *These exercises have been described in detail elsewhere [12,32].

Table 2: Jump Training*

Session No.	Jump	Duration/Repetitions
1-18	Wall jump	20-25 secs
1-18	Tuck jump	20-25 secs
1-18	Squat jump	10-20 sec
1-3	Barrier jump (side-to-side)	20 sec
1-3	Barrier jump (forward-backward)	20 sec
1-6	180° jump	20-25 sec
1-6	Broad jump	5-10 reps
7-12	Triple broad jump, vertical jump	5-8 reps
7-12	Single-leg triple hop	3 reps on each leg
13-15	Scissors jump	20 sec
13-18	Backward broad jump	5 reps
16-18	180-degree scissors jump	20 sec
4-18	4-Square, various patterns (linear, diagonal)	25 sec

Note: *These exercises have been described in detail elsewhere [12,32].

Proper stroke instruction and footwork were emphasized throughout all agility and hitting drills. The teaching components of the neuromuscular program [33] were used during jumping, landing, and cutting drills. Instructors reinforced that the knees and ankles should be kept hip-distance apart, and deep knee and hip flexion used when landing and decelerating. During cutting and pivoting, the athletes were instructed to avoid a valgus lower limb position, use short steps during deceleration, keep the pivot/cut planted leg close to the body's center of gravity, and to maintain knee flexion of at least 30°. Instructional cues such as "land softly," "we don't want to hear you land" and "bend your knees more" were repeated frequently. These technique instructions are believed by many investigators to reduce the risk of knee ligament rupture [6,8,12-14].

Statistical analyses

All data were normally distributed (Kolmogorov-Smirnov test). A 2-tailed paired t-test was used to detect differences for each test between the pretrain and posttrain periods. Effect sizes were calculated and interpreted according to Cohen's standards, where small effects were defined as ≤ 0.2; moderate effects, as 0.05; and large effects, as 0.8 and above[34]. Unpaired t tests were used to detect differences between genders before training and then after training in the absolute values and percent improvement on all tests. Statistical significance was considered for $P \leq 0.05$.

Results

Effect of the training program in all 42 athletes

No injuries or overuse syndromes occurred during testing or training. Minor patellofemoral complaints were experienced by 5 athletes, all of which were resolved by modifying the squat jump and lunges to avoid extremely deep knee flexion. All 42 athletes participated in at least 14 of the 18 training sessions.

Table 3: Strength Training*

Session No.	Exercise	Duration/Repetitions
1-6, 10-12	Medicine ball forehand, backhand, overhead	2 sets of 6-12 reps
4-6	Medicine ball backwards, between legs	2 sets of 6-12 reps
7-9	Etchswing forehand, backhand, serve^	2 sets of 15 reps each
13-18	Twisting forward lunge with medicine ball	2 sets of 8-10 reps
1-18	Backward lunge, add hand weight, add 3-second count each lunge	2-3 reps, baseline-net-baseline
1-18	Single-leg toe raise, add hand weight	3 sets of 10-20 reps
1-18	Toe walking (may substitute for toe raise)	1-4 reps, baseline-baseline
1-18	Theraband hip crab walking, add medicine ball chest pass with partner & increase to side-shuffle	1-3 reps, baseline-net-baseline
1-18	Wall push-ups (girls) or regular push-ups (boys)	3 sets of 10-20 reps
1-18	Biceps, triceps, arm curls with free weights	3 sets of 10 reps
1-18	Mini-arm circles, tennis ball against wall	30-60 reps. each direction
1-18	Wall sits	2-3 sets, 45-60 sec
1-18	Wall sits, ball pressed between legs	2-3 sets, 45-60 sec
1-18	Medicine ball sideways core toss against wall, forehand & backhand	2 sets of 10-15 reps each side
1-18	Medicine ball overhead dribble against wall	1-2 sets 10-30 reps
1-18	Abdominals: crunches, bicycle, twisting crunches, plank, alternate leg raise, sit-up and pause	Progress as tolerated

Note: *These exercises have been described in detail elsewhere [12,32]. The medicine balls used were 4 pounds for girls and 6 pounds for boys.
^Etchswing

Upon completion of the program, statistically significant improvements were found for all tests (Table 5). Large effect sizes were found for the 1-court suicide, abdominal endurance, baseline backhand, and service line tests. Moderate effect sizes were noted for the remaining tests. The percent of the players that improved test scores ranged from 98% in the 1-court suicide to 59% in the single-leg triple crossover hop on the left leg (Table 6). Before training, the only significant difference between genders was the distance hopped on the single-leg hop test, with males hopping further compared with females on both the right (148 ± 24 cm and 120 ± 26 cm, respectively, p=0.004) leg and left leg (147 ± 35 cm and 122 ± 19 cm, respectively, p=0.009). After training, there were no differences between genders regarding the absolute or percent improvement in any of the tests.

There were 10 players who had abnormal lower limb symmetry (<85%) in the single-leg hop in the pretrain test; all but 2 were corrected to normal values after training. Four players had abnormal symmetry in the single-leg crossover hop pretrain test, and 3 of these were corrected to normal values after training.

Effect of repeated training in 15 athletes

A subgroup of 15 players voluntarily participated in more than 1 training program. The numbers of training programs completed in this subgroup were: 2 programs, 15 players; 3 programs, 7 players; 4 programs, 4 players; 5 programs, 2 players; and 6 programs, 1 player. The amount of time between programs averaged 9 ± 5 months. These players were motivated to participate in order to prepare for either high school or summer tournament competition.

The percent of players that demonstrated improvements on the tests after the first, second, and third training programs are shown in Table 7. The data indicate improvements between the pretrain test and posttrain test for each program individually. We did not calculate cumulative improvements (i.e., difference between the pretrain test of the first training program to the posttrain test of the third training program) due to the small number of players and the range of time between training programs (3-24 months).

Table 4: Agility, speed, tennis drills*

Exercise	Duration/Repetitions
Cross-shadow, singles sideline-sideline	2 sets of 8 reps
Net zigzag, baseline-net-baseline	2-4 sets of 9 cones
Shadow swing baseline	2 sets, 10 sec
Forehand with resistance belt	2 sets, 20 sec
Backhand with resistance belt	2 sets, 20 sec
Forehand/backhand baseline reaction	30 sec, 30 sec rest, 2 mins.
Short/deep ball reaction: forehand	2 sets of 8 reps
Short/deep ball reaction: backhand	2 sets of 8 reps
Forehand/backhand alternating reaction	2 sets of 8 reps
Sprints: net-baseline	10 reps
Ladder: various patterns	2 reps
1-court suicide	2-4 reps
2-court suicide	1 rep
Return of serve continuous feeds: forehand/ backhand	2 sets of 8 reps each side

Note: *5-6 drills performed during each session. These exercises have been described in detail elsewhere [32,12].

Statistically significant improvements and large or moderate effect sizes were found for the speed and agility and abdominal endurance tests after the first, second, and third training programs (Table 8). Greater improvements were found in the repeated training programs in the abdominal endurance test than those measured after the first training program. For the other tests, smaller mean improvements were noted; however, these were still statistically significant. An example is shown in Figure 1, where 7 players who underwent at least 3 training programs all continued to improve in the 1-court suicide run.

There were no significant improvements in this subgroup of players in the distance hopped in the 2 single-leg hop tests for any of the training programs.

Discussion

Tennis requires speed, agility, explosive power, aerobic conditioning, and reaction time, as well as the ability to cope with fatigue and pressure throughout a match [35,36]. Our program blends neuromuscular retraining and sport-specific athletic tasks to improve dynamic balance, agility, speed, and core endurance. We were unable to find a program designed for junior female and male players to compare our results with because most studies either assess physiological profiles, analyze the results of one training session [16-24], or focus on male professional or national-level players [25,26]. Other sport-specific training programs (for basketball, volleyball, and soccer) that combine knee ligament injury prevention with athletic performance enhancement exercises and drills have reported significant improvements in core endurance [37], vertical jump height [37,38], and speed [38].

Table 5: Results of the First Training Program*

Test	Pretrain	Posttrain	Difference	*P*	Effect Size
1-court suicide (s)	18.55 ± 1.68 (14.60-23.60) CI: 18.0-19.1	16.04 ± 1.23 (13.40-19.06) CI: 15.7-16.4	-2.51 ± 1.18 (-4.54 - 0.30)	<0.0001	1.70
Abdominal endurance (s)	87 ± 56 (12-246) CI: 69.5-104.4	162 ± 98 (45-510) CI: 131.5-192.5	74 ± 75 (-14-396)	<0.0001	0.94
Baseline backhand (# reps)	8.5 ± 0.9 (7.0-10.5) CI: 8.2-8.8	9.2 ± 0.7 (8.0- 10.5) CI: 8.9-9.4	0.7 ± 0.7 (-1.0-2.0)	<0.0001	0.88
Baseline backhand distance (m)	42.8 ± 4.6 (41.4-44.2) CI: 40.5-43.2	46.3 ± 3.6 (40.1-52.7) CI: 45.2-47.4	3.5 ± 3.8 (-5.0-10.0)	<0.0001	0.85
Service line (# reps)	22.4 ± 2.9 (17.0-29.5) CI: 21.5-23.3	24.5 ± 2.2 (18.0-30.5) CI: 23.8-25.2	2.1 ± 2.6 (-2.0-11.0)	<0.0001	0.82
Service line distance (m)	89.4 ± 11.8 (67.7-121.1) CI: 85.7-93.1	97.8 ± 8.9 (71.8-123.1) CI: 95.0-100.6	8.4 ± 10.9 (-14.4-45.1)	<0.0001	0.80
Baseline forehand (# reps)	8.6 ± 1.0 (6.5-10.5) CI: 8.2-8.9	9.3 ± 0.8 (8.0-11.0 CI: 9.1-9.5	0.7 ± 0.9 (-1.0-3.0)	<0.0001	0.77
Baseline forehand distance (m)	43.2 ± 5.1 (32.6-52.7) CI: 41.6-44.8	46.8 ± 4.2 (40.1-55.2) CI: 45.5-48.1	3.6 ± 4.7 (-5.0-15.1)	<0.0001	0.77
Single-leg hop, right leg (cm)	128.2 ± 28.5 (55.9-195.6) CI: 119.3-137.1	141.8 ± 22.8 (109.7-201.9) CI: 134.7-148.9	13.7 ± 21.3 (-27.4-61.0)	0.0004	0.53
Single-leg hop, left leg (cm)	129.5 ± 27.1 (72.4-196.9) CI: 121.1-137.9	138.3 ± 26.0 (78.7-208.3) CI: 130.2-146.4	8.9 ± 14.6 (-15.2-40.6)	0.0007	0.33
Single-leg triple crossover hop, right leg (cm)	340.7 ± 71.9 (193.0-482.6) CI: 318.3-363.1	373.6 ± 70.1 (275.6-588.0) CI: 351.7-395.4	32.8 ± 68.9 (-71.1-228.6)	0.006	0.46
Single-leg triple crossover hop, left leg (cm)	340.5 ± 77.6 (152.4-483.9) CI: 316.3-364.7	374.3 ± 78.4 (236.2-607.1) CI: 349.9-398.7	33.8 ± 67.2 (-61.5-232.4)	0.004	0.43

Note: *Mean ± *SD*, range, 95% confidence intervals. Positive values indicate improvements, except for the 1-court suicide where the negative mean difference represents improved speed.

doi:http://dx.doi.org/10.4172/2324-9080.1000185

Table 6: Percent of players who improved each test

Test	% Improved
1-court suicide	98%
Abdominal endurance	90%
Service line	76%
Single-leg hop, right leg	76%
Baseline backhand	74%
Single-leg hop, left leg	70%
Baseline forehand	69%
Single-leg triple crossover hop, right leg	65%
Single-leg triple crossover hop, left leg	59%

Table 7: Percent of players who improved after first, second, and third training programs*

Test	1st Training Session	2nd Training Session	3rd Training Session
1-court suicide run	100%	86%	100%
Baseline forehand	87%	80%	71%
Baseline backhand	87%	64%	71%
Service line	93%	67%	100%
Abdominal endurance	93%	79%	100%
Single-leg triple crossover hop, distance hopped, left leg	73%	45%	57%
Single-leg triple crossover hop, distance hopped, right leg	64%	55%	57%
Single-leg hop, distance hopped, right leg	55%	45%	29%
Single-leg hop, distance hopped, left leg	55%	55%	86%

Note: Data shown represent difference between tests conducted before and upon completion of each training program.

The physical requirements of competitive tennis may lead to traumatic injuries or overuse syndromes [39], especially in players who participate more than 3 hours per week [2]. Acute injuries occur most often, but overuse syndromes are also problematic [2]. During training, we constantly reminded players to land softly during the jumps, to decelerate using small quiet steps, and to stop during sprinting drills with as little impact as possible. In addition, exaggerated knee flexion was stressed in order to avoid an extended or hyperextended position. Although not measured in our study, many investigators have noted decreased ground-reaction forces and improved lower extremity alignment on landing and during cutting when these techniques are used that may decrease the risk of lower extremity injury [6,8,40-43].

The improvements obtained in the tests were similar to those previously reported in a smaller group of players [15] and compliance with training was excellent. With 42 players, the maximum number of individual training sessions that could have been completed (if players attended all 18 sessions) was 756. The athletes participated in a total of 652 sessions (86%). Other neuromuscular training programs have reported problems with compliance [44-46]. Speculated reasons include boredom (especially when there is no drill variation or progression), little or no supervision, poor understanding of the rationale of injury prevention training, and lack of time. We found that a supervised program in which progression of exercises occurs weekly helped solve these issues. Kovacs et al. [47] reported that a 5-week unsupervised but structured program in a nationally ranked men's collegiate tennis program resulted in significant reductions in speed, power, and aerobic capacity. The authors speculated that compliance was most likely the reason and warned of problems from detraining effects, including decreased performance and an increased risk of injury.

The tests used in our program were designed to be feasible in terms of cost and time. We realize the potential problems of using digital stopwatches to record times compared with electronic photo cells and that the exact distances covered in the baseline and service line tests could not be computed. However, the tests may be conducted at any tennis facility without advanced medical personnel. The results provide a valid profile of lower limb power and symmetry, agility and speed, and abdominal endurance. At the conclusion of the training program, each player was given a report that described their pretrain and posttrain test results and was advised of any deficiencies or problems that required further training. In addition, the videotape recordings of the agility and hop tests shown to the athletes assisted in the learning process of proper body mechanics. Subjectively, we found that approximately one third of the players were able to perform the single-leg hops with good knee flexion and control before training. The others had poor mechanics and experienced difficulty holding the landing for even a few seconds. After training, noteworthy subjective improvements were found in all but seven players who were advised to continue training.

It was of interest that fifteen players elected to participate in more than one training program in order to prepare for their school or summer tournament competition. Although acknowledging the program was difficult, the players expressed satisfaction with the overall results in terms of increased speed, agility, dynamic balance, and body control. All of these players participated in routine tennis practices throughout or during a good portion of the year. Although the results of repeated training programs were usually not as dramatic as those experienced during the initial training program, gains were still made in the majority of players in speed, agility, and abdominal endurance. We acknowledge that these players were highly motivated and that repeated training may not be as effective in less motivated athletes or in those who do not voluntarily participate in a rigorous program. We were not able to determine if gender played a role in the magnitude of continued improvements in this subgroup due to the small number of athletes (10 girls and 5 boys).

Core strength and stability is crucial for the trunk rotation that occurs during the serve and open-stance forehand [48,49]. Ellenbecker and Roetert [50] recommended that core-stabilization training focus on both directions of trunk rotation to promote symmetrical strength between the forehand and backhand. Our program incorporated many exercises for core stabilization and strengthening and all but 4 players improved in the posttrain abdominal endurance test.

The agility and hitting drills encompassed linear, lateral, and multidirectional directions, as recommended by Kovacs [51], with many simulating the time requirements experienced during match play that range from 5 to 20 seconds. Players were required to perform both preplanned and reactive tasks, with the dominant and nondominant sides receiving equal attention. For instance, the net zig-zag and ladder drills were reversed during the sessions to ensure that the drills were initiated with either the right or left foot and with either the forehand or backhand volley motion.

One limitation of our study is the lack of a control group.

Table 8: Improvements in speed, agility, and abdominal endurance tests in players who completed more than one training program*

Training Session	1-Court Suicide (sec)			Baseline Forehand (m)			Baseline Backhand (m)			Service Line (m)			Abdominal Endurance (sec)		
	Mean± SD	*P*	ES	Mean± SD	*P*	ES	Mean± SD	*P*	ES	Mean± SD	*P*	ES	Mean± SD	*P*	ES
1st	2.56 ± 1.17 (0.26-4.54)	<0.0001	1.63	4.6 ± 3.9 (0-15.1)	0.0004	1.01	4.8 ± 3.2 (-1.2 -10.0)	<0.001	1.07	12.3 ± 11.3 (-4.1 -45.1)	<0.001	1.30	84 ± 98 (-6 -396)	0.005	1.02
2nd	1.11 ± 1.07 (-1.00-3.10)	0.0003	1.36	2.6 ± 3.5 (-2.5-7.5)	0.01	0.73	1.6 ± 4.2 (-7.5-8.9)	NS	0.46	3.2 ± 9.9 (-16.4-26.7)	NS	0.32	70 ± 89 (-10-301)	0.01	1.20
3rd	0.96 ± .032 (0.51-1.37)	0.004	0.73	3.8 ± 2.9 (0-7.5)	0.02	1.33	2.7 ± 2.3 (0-5.0)	0.02	0.89	11.6 ± 10.8 (3.9-32.9)	0.03	0.73	111 ± 86 (41-262)	0.02	0.95

Note: *Data shown are mean ± SD (range) and effect size (ES) for the difference between tests conducted before and upon completion of each training program. Positive values indicate improvements, except for the 1-court suicide where the negative mean difference represents improved speed.
NS: Not significant

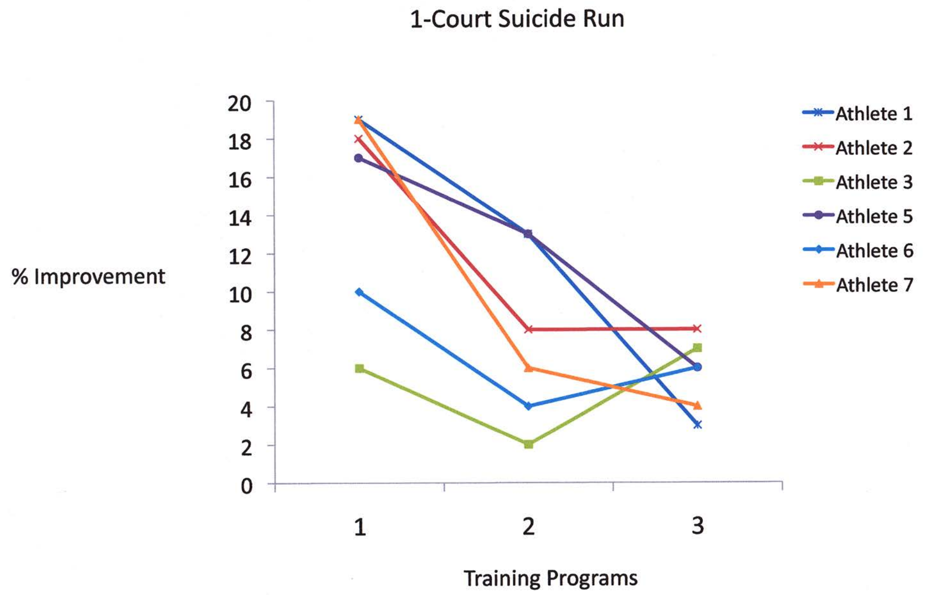

Figure 1: Improvements in the suicide run were found after each training program in the 7 athletes who participated in at least 3 training programs.

However, we believe that the use of each athlete as their own control (by comparison of pretrain and posttrain test data) provides a more sensitive analysis of the effect of our program. To obtain results similar as those reported here, the program should be supervised by an experienced tennis professional who understands the intricacies required for proper footwork, body positioning, preparation, and stroke mechanics. The neuromuscular training concepts should also be understood by the professional or trainer, who can demonstrate appropriate form and make required corrections. Due to the time allotment required for the program, the player's normal practice time will be limited on days training is conducted. We encourage our players to hit for 20-30 minutes after training is finished, but would not recommend intensive hitting or match play on those days due to possible deleterious fatigue effects.

In our experience, two courts were used for training. All players completed the warm-up and jumps together. Then, the tennis professional took the players through hitting and footwork drills on one court, while the trainer supervised running, agility, and strength training exercises on the other court. If this facility set-up is not available, the program may be done on one court. Many of the strength exercises can be done off the court if space is an issue. The program may be shortened to 60 minutes by eliminating many strengthening exercises (except the core component). However, the results presented here are based on the 90-minute program and a reduction in time may not have the same beneficial effects. Upon completion of the program, a 30-minute warm-up routine that continues to apply the concepts of correct body alignment, knee flexion, and movement patterns may be done before practices (Table 9). The warm-up routine the authors recommend is similar to programs that have been described for neuromuscular injury prevention for soccer and basketball players [52-54]. It would be anticipated that players who complete the formal training program and then continue with the warm-up routine at least 2-3 days a week may continue to maintain the beneficial results in speed, agility, dynamic balance, and abdominal endurance.

Conclusion

The 6-week training program significantly improved speed, agility, dynamic balance, and abdominal endurance in competitive junior tennis players. The program and assessment tests may be conducted at any tennis facility and are feasible in terms of cost and equipment required. Training gradually increases in intensity and varies in order to maintain player compliance and motivation. An experienced tennis professional or coach may supervise the program,

doi:http://dx.doi.org/10.4172/2324-9080.1000185

Table 9: Tennis Warm-up Program

Exercise/Drill	Duration
1 lap around 2 courts/side-step/arm circles	2 courts
Straight leg march	Baseline-net-baseline
Hip rotator walk	Baseline-net-baseline
Gluteal kicks/jog	Baseline-net-baseline
Quick feet	20 sec × 3
Tuck jump	25 sec
Squat jump	25 sec
Triple broad jump, vertical jump	3 reps
180-degree scissors jump	25 sec
Twisting forward lunge with medicine ball*	15 reps
Theraband side-shuffle, medicine ball chest pass with partner	2 reps, baseline-net-baseline
Net zig-zag, baseline-net-baseline (9 cones)	2 reps
Ladder (typewriter pattern) behind baseline, run to cone at net, backpedal to baseline	2 reps
1-court suicide	2 reps

*Note: Medicine ball: 4 pounds for girls, 6 pounds for boys.

but they should have an understanding of the neuromuscular retraining concepts for correct posture and body alignment for jump-landing and cutting techniques. Motivated athletes will continue to benefit from repeated training programs in terms of improved speed, agility, and core endurance.

Acknowledgements

Funded by the Noyes Knee Institute, Cincinnati, OH, USA. Study conducted at Gateway Golf and Country Club, Fort Myers, FL, USA. The authors thank Michael Stamps and Debbie Conley for their assistance with training and data collection.

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