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Original Research

Safety and Effectiveness of a Perturbation-based Neuromuscular Training Program on Dynamic Balance in Adolescent Females: A Randomized Controlled Trial

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Background

Adolescent females are at much greater risk for ACL injury than their male counterparts when participating in the same sports. Preventative and pre-operative rehabilitation neuromuscular (NM) exercise programs are often recommended to improve knee function and reduce injury rates. The effectiveness of perturbation-based NM training program has been established in an adult population but has yet to be investigated in the at-risk adolescent female population.

Purpose

To determine the effectiveness of a perturbation-based NM exercise program in a group of physically active adolescent females.

Study Design

Prospective randomized trial.

Methods

Twenty-four healthy and an exploratory group of 10 ACL-injured females (ages 12-18) were equally randomized into a perturbation-based NM training or control group and evaluated before and after a five-week intervention period. The primary outcome of dynamic balance was measured using the Y-Balance test (YBT); secondary outcome measures included lower limb strength, proprioception, and flexibility.

Results

The perturbation-based NM training intervention was safely completed by all participants but had no significant effect on YBT scoring, lower limb strength, proprioception or flexibility in either the healthy or ACL-injured groups.

Conclusions

Perturbation-based NM training is safe, but may offer little preventative benefit for healthy or pre-operative rehabilitation benefit for ACL-injured adolescent females. Future research should examine whether the effectiveness of perturbation-based NM training is influenced by the length of the training intervention, training intensity, or when it is combined with other forms of prophylactic or pre-surgical rehabilitation frequently used with at-risk adolescent females who regularly participate in sport.

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Level of Evidence

Level 3.

INTRODUCTION

Rupture of the anterior cruciate ligament (ACL) is one of the most common knee injuries, with an estimated 250,000 ACL ruptures documented per year in North America.[1] It is also the most commonly injured knee ligament in a pediatric population,[2,3] with its incidence growing fastest in physically active adolescents (14 – 18 years old) participating in high school sports.[4] While an ACL injury is a significant risk for both sexes, adolescent females have a 1.6-fold greater rate of ACL injury per athletic exposure than adolescent males participating in the same sports.[4,5]

In North America, the standard of care for young patients following ACL rupture is surgical reconstruction.[6,7] Early surgical repair is especially favored for adolescent patients because it helps to restore joint stability, reduces the incidence of secondary joint injury, and promotes return to pre-injury levels of physical activity.[8] However, skeletal immaturity[7,9] and long surgical wait times[10] can result in significant delays in the injury-to-surgery time line. The average injury-to-surgery wait time following ACL injury within a local Canadian regional health authority has been documented to be as high as 438 days.[10] As a result, pre-operative exercise programs are frequently prescribed for patients awaiting ACL reconstructive surgery,[11,12] as they are thought to help re-establish the normal kinetic and kinematic function of the affected joint. Superior functional outcomes and higher return-to-sport rates have been reported for adult patients who participated in rehabilitation programs that included perturbation-based neuromuscular training as part of a pre-operative treatment regimen.[13]

Neuromuscular (NM) training is designed to improve dynamic joint stability, generate fast and optimal muscle activation, and decrease joint forces. It forms a critical aspect of injury prevention exercise programs that are designed to reduce the costs and morbidity associated with ACL injury in young athletes.[14] In addition to reducing the rate of ACL ruptures in female adolescents by approximately 50%,[15–18] research suggests that NM training during early adolescence can improve lower extremity performance[19,20] and dynamic balance.[21–24] While the specific exercises included in an NM training regime can vary greatly, NM programs typically include some form of plyometric single-leg hopping, jumping, pivoting, or cutting maneuvers that are considered unsafe or impractical for use with an ACL-injured individual.[15–20,25–29]

Perturbation-based NM training regimens are designed to be safe and effective for ACL-injured patients as part of a pre-operative exercise program.[30] They typically include exercises that require the patient to maintain their balance on a support surface while a clinician deliberately perturbs (i.e., manipulates) the support system.[31] Research targeting an ACL-injured adult population indicates that perturbation-based NM training is effective for improving knee joint kinematics, gait patterns, subjective functional outcomes and return-to-sport rates.[13,31–38] Unfortunately, the safety and effectiveness of a perturbation-based NM training regime in an at-risk adolescent female population is unreported in the literature.

The purpose of this investigation was to determine the effectiveness of a perturbation-based NM exercise program in a group of physically active adolescent females. The primary outcome measure was dynamic balance, while lower limb strength, proprioception, and flexibility were outcome measures of secondary interest. Program safety was assessed by evaluating the number and severity of injuries sustained by subjects. The authors hypothesized that completion of a perturbation-based NM exercise program would improve 1) dynamic balance and 2) lower extremity strength, proprioception and flexibility in physically active adolescent females.

METHODS

PARTICIPANTS

Following institutional ethics approval (H2014:302), healthy and ACL-injured physically active adolescent females were recruited from the community. Inclusion criteria stated that healthy volunteers were required to be female, 12-18 years of age, with no history of any lower limb injury or concussions in the past 6 months. A group of subjects awaiting ACL surgical repair were recruited from a community-based orthopaedic clinic to participate in this clinical study following the same inclusion criteria (Figure 1). Subjects were evaluated clinically by an orthopaedic surgeon and the diagnosis of an isolated ACL rupture (without secondary injury to menisci or chondral surfaces) was confirmed via magnetic resonance imaging. Participants were excluded if they were unable to attend either the testing or training sessions or if they failed an established standardized screening protocol[30] at the beginning of the study. A participant was scored as a "failure" and excluded from study participation if they presented with knee joint effusion, were unable to fully flex and extend the knee joint though a full range of motion, had quadriceps lag with an active straight-leg raise, had isometric quadriceps strength less than 75% of the unaffected leg measured via manual muscle testing or were unable to perform 10 consecutive single-legged hops pain free.[30]

TESTING PROTOCOL

Prior to participation, informed consent was obtained from all girls and their parents. Anthropometric data including height, weight, and body mass index (BMI) were recorded. Bilateral knee joint laxity was evaluated using the KT-1000 (MEDmetric Corp.; San Diego, CA).[39] Demographic information, including age, maturation status determined by using the self-reported pubertal maturation observational scale (PMOS),[40] leg dominance (determined by leg preference for kicking a ball), and type of sport participation were collected. Participants were then equally randomized into 2 groups (perturbation-based NM training or control) using pre-coded envelopes that were assigned to each participant. Baseline measurements for dynamic balance, lower limb strength, proprioception, and flexibility were completed on all participants. Participants randomized to the intervention group completed a 5-week perturbation-based NM training regime while the participants randomized into the control group were instructed to continue with their normal activities. All participants returned for follow-up evaluation.

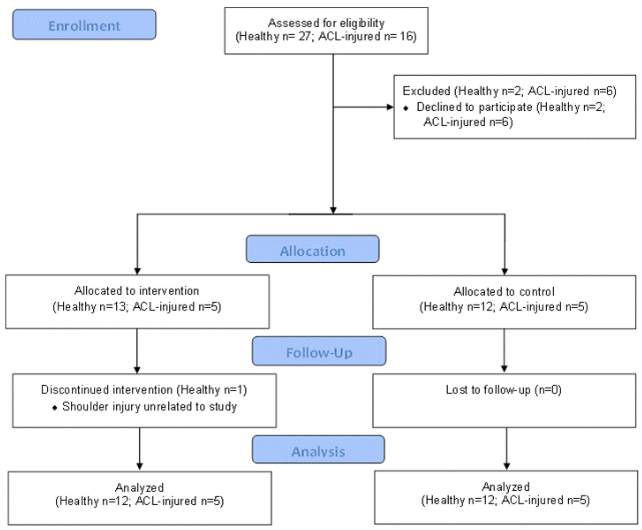

Figure 1. CONSORT study flow diagram.

DYNAMIC BALANCE MEASUREMENT

To measure dynamic balance, the Y-Balance Test (YBT) (Move2Perform; Evansville, IL) was completed according to previously described protocols.[41,42] The distance from the YBT apex of the most proximal edge of the reach indicator was recorded while participants performed movement in three directions: anterior (ANT), posteromedial (PM) and posterolateral (PL). The average of 3 successful trails for each reach direction was used for analysis. All reach distances were normalized as a percentage of each participant's stance-limb length (%LL), measured from the anterior superior iliac spine to the most distal aspect of the ipsilateral medial malleolus in a supine, lying position.[43]

LOWER LIMB STRENGTH EVALUATION

Hand-held dynamometry (HHD) is a valid, reliable measure of isometric muscle strength in adolescents[44] and an ideal test method for use when evaluating lower extremity strength in a clinical setting.[44,45] The "make-test" method was used because it is preferred for use with adolescents: the examiner held the dynamometric instrument (Chatillon DFX II Series; Largo, FL) in a stationary position while the subject gradually built resistance for a 5-second push against the dynamometer.[44] Standardized positions were used to assess strength during knee flexion, knee extension, hip external rotation, hip abduction, and ankle plantar flexion movements.[46] Strength scores for each movement were determined by calculating the average of three HHD measurements for each movement. Strength scores for each subject were then expressed as HHD force (N) relative to body weight (kg).

KNEE PROPRIOCEPTION EVALUATION

Joint-position sense (JPS) - the awareness of limb position in three dimensions - is a common proprioceptive test routinely used during weight bearing (WB) activity to provide a functional evaluation[47] with greater clinical relevance[48] for conditions such as ACL instability.[49] Using previously described methodologies,[47,48] the WB-JPS for each participant was assessed. Briefly, with eyes closed and while maintaining a unilateral stance, each subject was instructed to slowly flex the knee of the WB limb and to stop at approximately 30 degrees of flexion - the test angle (TA). An electro-goniometer (Acumar Dual Inclinometer ACU0002, Lafayette Instrument Company; Lafayette, IN) was then used to confirm the exact knee-joint angle. The TA was held for approximately 5 seconds, after which the subject was directed to return to a position of full knee extension and bilateral stance. The subject was then asked to reproduce the same amount of unilateral knee flexion - response angle (RA). Absolute angular error (AAE) is the absolute arithmetic difference between the TA and RA scores. All subjects repeated the WB-JPS test three times, with the average AAE for each limb being used for analysis.

LOWER EXTREMITY FLEXIBILITY EVALUATION

Hamstring and calf muscle flexibility were evaluated using joint-specific tests executed according to previously established protocols.[50–52] A standing toe-touch test was used to assess hamstring flexibility.[51] Briefly, subjects stood on a step-stool with their feet hip-width apart and were instructed to keep their knees, arms and fingers straight while they bent forward as far as possible. The maximum reach position (held for a minimum of 6 seconds) was measured to the nearest 0.5 cm. The average of three trials was used for analysis.[51] Calf muscle flexibility was determined using the weight-bearing lunge test (WBLT).[50] Briefly, while in a standing position facing a wall, subjects were instructed to keep their test heel on the floor while flexing their knee to touch the wall in front of them. The maximum reach position was determined by measuring the distance from the great toe to the wall (measured to the nearest 0.5 cm) while maintaining heel and knee contact. After three practice trials, subjects completed three test trials, the average of which was used for analysis.[50]

PERTURBATION-BASED NM EXERCISE REGIME

Participants randomized to the perturbation-based NM training group completed two supervised training sessions per week for five consecutive weeks (for a total of 10 sessions). This validated training program[11,31–34,53–57] was administered according to a previously established procedure (Appendix).[30] In brief, a series of destabilizing perturbations were applied during either unilateral or bilateral stance on each of three unstable surfaces (rockerboard, rollerboard and rollerboard/platform).[30] Over the five-week training regime, application of the destabilizing force progressed in a standardized manner from an informed unilateral direction (slow and low in magnitude), to an unexpected, rapid application of destabilizing forces in random directions with sport-related distractions (catching and throwing a ball at the same time performing balance activity).

STATISTICAL ANALYSIS

A power analysis based on scoring from previous investigations that examined dynamic balance in a healthy group of recreationally active adults indicated that a total of 11 subjects per group would be required for the current investigation.[58,59] Following the recommendation of a previous report,[60] the dominant limb of all healthy participants and the affected limb of the ACL-injured participants was used for analysis. SPSS for Windows 24.0 (SPSS Inc.; Chicago, IL) was used for analysis. One-way analysis of variance (ANOVA) was used to test the differences in baseline demographic and anthropometric data between perturbation and control groups for each of healthy and ACL-injured groups. Two-way ANOVAs were used to compare baseline and follow-up scoring on dynamic balance, proprioception, flexibility, and strength. A *post hoc* Bonferroni correction of $p \leqslant 0.008$ was set to determine statistical significance. A Fisher's exact test was used to examine the relationship between the group (control or perturbation training) and clinically significant improvements in each YBT reach direction. The level of statistical significance was set at $p \leqslant 0.05$ while a clinically significant improvement was classified as greater than 8.54%, 13.50% and 13.70% for the ANT, PM and PL reach directions, respectively.[61]

RESULTS

Table 1 provides descriptive data for participant demographics and anthropometry. Baseline data indicated that there were no significant differences between control and perturbation groups on the demographic and anthropometric data between groups. However, the ACL-injured control group was significantly older than both healthy-perturbation and healthy-control groups. Knee joint laxity for both the ACL-injured control and perturbation groups was also significantly greater than both of the healthy groups – as would be expected. For ACL-injured participants, the mean time from injury to the baseline examination was 143 days (range: 24-365). Over the duration of the study, there were no significant changes in weight, or BMI for any of the groups. Results suggested that participants in each group were predominantly post-pubertal adolescents who were right leg dominant and participated in a variety of sporting activities.

All participants completed both testing sessions and the mean time from the initial assessment to follow-up assessment was 41 days (range: 30-47). All subjects (healthy and ACL-injured) randomized to the perturbation group safely completed the training program without any incidence of pain, swelling or knee instability. The training program included 10 sessions; the mean number of completed sessions was nine (range: 7-10). On average, each training session was completed in approximately 30 minutes and the 10 training sessions took place over an average of 31 days (range: 21-35). No subjects randomized to the training group reported any incidence of knee joint pain, swelling or instability while participating in the training program exercises or at the follow-up assessment.

Comparisons of baseline and follow-up test scores for the YBT are presented in Figures 2 through 4. For the ANT

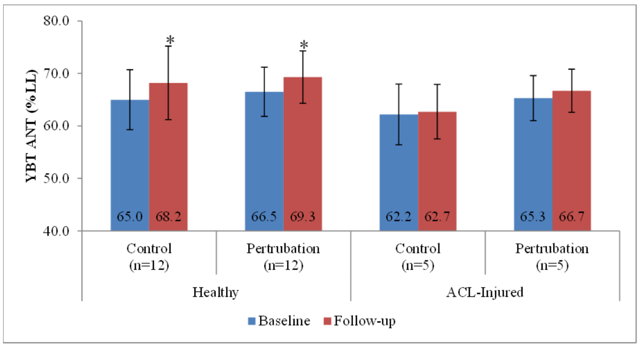

Figure 2. Performance changes on the YBT Anterior (ANT) reach direction for healthy and ACL-injured subjects (mean ± SD).

Time effect:*$p \leqslant 0.008$ (Bonferroni correction).

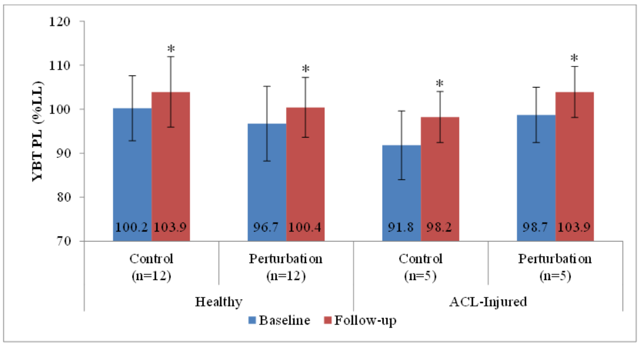

Figure 3. Performance changes on the YBT Posterolateral (PL) reach direction for healthy and ACL-injured subjects (mean ± SD).

Time effect:*$p \leqslant 0.008$ (Bonferroni correction).

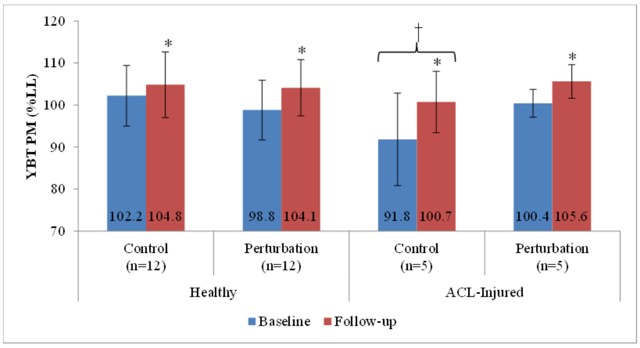

Figure 4. Performance changes on the YBT Posteromedial (PM) reach direction for healthy and ACL-injured subjects (mean ± SD).

Time effect: *$p \leqslant 0.008$; Training effect: †$p \leqslant 0.008$ (Bonferroni correction).

Table 1. Demographic and anthropometric information for all subjects, reported as mean ± SD, (95% confidence interval).

	Healthy (n=24)		ACL-injured (n=10)	
	Control (n=12)	Perturbation (n=12)	Control (n=5)	Perturbation (n=5)
Age (years)	13.9 ± 1.1 (13.2, 14.6)	14.3 ± 1.5 (13.3, 15.2)	16.9 ± 0.9* (15.8, 18.0)	15.7 ± 2.0 (13.2, 18.2)
Height (cm)	161.8 ± 6.2 (157.9, 165.7)	164.5 ± 5.5 (161.0, 168.0)	166.4 ± 6.1 (158.8, 174.0)	164.5 ± 6.8 (156.1, 172.9)
Weight (kg)	54.3 ± 10.8 (47.4, 61.2)	63.3 ± 17.7 (52.0, 74.5)	63.1 ± 16.9 (42.1, 84.1)	72.9 ± 10.3 (60.1, 85.7)
BMI (kg/m^2)	20.6 ± 3.2 (18.6, 22.6)	23.3 ± 5.4 (19.9, 26.7)	22.6 ± 4.9 (16.5, 28.7)	26.9 ± 3.4 (22.7, 31.1)
Knee Laxity Difference (mm)	1.5 ± 1.1 (0.8, 2.2)	1.5 ± 1.0 (0.8, 2.1)	5.1 ± 3.7† (0.5, 9.7)	5.0 ± 2.6‡ (1.8, 8.2)
Time since injury (months)	-	-	3.6 ± 2.1 (1.0, 6.2)	5.9 ± 3.7 (1.3, 10.5)
Leg Dominance – Right, n	11	10	4	5
Developmental status, n				
Pre-pubertal	2	1	0	0
Mid-pubertal	3	2	2	1
Post-pubertal	7	9	3	4
Sport (n)				
Basketball	-	1	1	2
Badminton	1	-	-	-
Baton	1	2	1	-
Dance	2	2	-	-
Cross country running	-	1	-	-
Gymnastics	1	1	-	-
Hockey/Ringette	4	1	1	-
Rugby	-	-	1	-
Soccer	1	1	-	1
Softball	1	-	-	-
Tennis	-	1	-	-
Volleyball	1	2	1	2

*Significantly different than the healthy control (p<0.001) and healthy perturbation (p=0.002)
†Significantly different than the healthy control (p=0.006) and healthy perturbation (p=0.005)
‡Significantly different than the healthy control (p=0.001) and healthy perturbation (p=0.001)

reach direction, follow-up test scores of the healthy participants were significantly larger for both the control and perturbation training groups (time effect: $p \leqslant 0.008$), while there were no significant differences between baseline and follow-up scores for either of the ACL-injured groups (Figure 2). The YBT data for PL & PM reach directions indicated that regardless of group allocation (control or perturbation), follow-up test scores of both the healthy and ACL-injured groups were significantly larger than scoring from baseline testing (time effect: $p \leqslant 0.008$) (Figures 3 and 4).

The results of the Fisher's exact test for the YBT are presented in Table 2. For both the healthy and ACL-injured subjects, no clinically significant differences (p>0.05) were found between the control and perturbation training groups for any of the reach directions.

Strength measurements for the healthy participants indicated a statistically significant improvement in hip abduction strength following completion of the perturbation-based NM training regime; however, the improvement was not clinically significant.[44] All other changes for both groups were not statistically significant, and data suggested that participation in the perturbation-based NM exercise program had no significant effect on strength scores for both the healthy and ACL-injured participants (Tables 3 and 4).

Finally, proprioception and flexibility measurements indicated that there were no significant differences in scoring when comparing both the control or perturbation groups at baseline or follow-up, or when examining the effect of the perturbation-based NM exercise regime on either the healthy or ACL-injured participants (Tables 5 and 6).

Table 2. Numbers of healthy participants having reached clinically significant* improvements in each Y-balance test (YBT) reach direction.

	Healthy (n = 24)			ACL-injured (n=10)		
	Control (yes/no)	Perturbation (yes/no)	*p* value	Control (yes/no)	Perturbation (yes/no)	*p* value
ANT	1/11	1/11	1.0	0/5	1/4	1.00
PL	0/12	0/12	-	1/4	0/5	1.00
PM	0/12	2/10	0.48	0/5	0/5	-

*Clinically significant improvement was classified as ANT >8.54%, PM >13.50% and PL >13.70%; * $p \leq 0.05$

Table 3. Strength measurements for the healthy subjects, reported as mean ± SD, (95% confidence interval).

	Control (n=12)		**Perturbation (n=12)**		**p-value[a]**	
	Initial	**Follow-up**	**Initial**	**Follow-up**	**Time**	**Time x Group**
Knee Flexion (N/kg)	3.7 ± 0.6 (3.3, 4.1)	3.8 ± 0.6 (3.4, 4.2)	2.9 ± 0.6* (2.5, 3.3)	3.3 ± 0.7 (2.9, 3.7)	0.02†	0.11
Knee Extension (N/kg)	5.4 ± 1.3 (5.6, 6.2)	5.8 ± 1.2 (5.0, 6.6)	4.8 ± 1.1 (4.1, 5.5)	5.5 ± 1.3 (4.7, 6.3)	0.02†	0.52
Hip External Rotation (N/kg)	2.1 ± 0.5 (1.8, 2.4)	2.3 ± 0.4 (2.0, 2.5)	1.9 ± 0.3 (1.7, 2.1)	2.0 ± 0.4 (1.7, 2.2)	0.01†	0.48
Hip Abduction (N/kg)	2.0 ± 0.4 (1.7, 2.2)	1.8 ± 0.3 (1.6, 2.0)	1.7 ± 0.3 (1.5, 1.9)	1.9 ± 0.4 (1.6, 2.1)	0.86	<0.01‡
Ankle Plantarflexion (N/kg)	5.9 ± 1.3 (5.1, 6.7)	5.7 ± 1.2 (4.9, 6.5)	5.7 ± 1.3 (4.9, 6.5)	5.4 ± 1.3 (4.6, 6.2)	0.43	0.82

[a] Findings from multivariate analysis of variance
* Lower than the Control initial (p=0.003) and follow-up (p=0.002) groups.
† Increased from initial to follow-up for all groups
‡ Control group decreased and perturbation group increased

Table 4. Strength measurements for the ACL-injured subjects, reported as mean ± SD, (95% confidence interval).

	Control (n=5)		**Perturbation (n=5)**		***p*-value[a]**	
	Initial	**Follow-up**	**Initial**	**Follow-up**	**Time**	**Time x Group**
Knee Flexion (N/kg)	3.1 ± 1.1 (1.7, 4.5)	3.6 ± 1.1 (2.2, 5.0)	2.7 ± 0.3 (2.3, 3.0)	3.0 ± 0.3 (2.6, 3.4)	<0.01*	0.55
Knee Extension (N/kg)	5.0 ± 1.8 (2.8, 7.2)	5.6 ± 1.4 (3.9, 7.3)	4.5 ± 0.5 (3.9, 5.1)	4.9 ± 0.8 (3.9, 5.9)	0.09	0.77
Hip External Rotation (N/kg)	1.9 ± 0.7 (1.0, 2.8)	2.1 ± 0.7 (1.2, 3.0)	1.6 ± 0.2 (1.3, 1.8)	1.8 ± 0.3 (1.4, 2.2)	0.02[b]	0.91
Hip Abduction (N/kg)	1.5 ± 0.3 (1.1, 1.9)	1.5 ± 0.3 (1.1, 1.9)	1.5 ± 0.2 (1.2, 1.7)	1.6 ± 0.3 (1.2, 2.0)	0.37	0.44
Ankle Plantarflexion (N/kg)	5.4 ± 1.4 (3.7, 7.1)	5.6 ± 1.1 (4.2, 7.0)	4.8 ± 1.0 (3.6, 6.0)	4.9 ± 0.6 (4.1, 5.6)	0.51	0.82

[a] Findings from multivariate analysis of variance
* Increased from initial to follow-up for all groups

DISCUSSION

This is the first investigation to examine the safety and effectiveness of a perturbation-based neuromuscular training program on dynamic balance in physically active adolescent females at risk of ACL injury. These results suggest that participation in the perturbation-based NM training program was safe but had no significant effect on YBT performance in either healthy or ACL-injured adolescent females. In healthy participants, a significant improvement in hip abduction strength was noted following completion of the perturbation-based NM training program; however, the improvement was not clinically significant. All other

Table 5. Proprioception and flexibility measurements for the healthy subjects, reported as mean ± SD, (95% confidence interval).

	Control (n=12)		Perturbation (n=12)		*p*-value[a]	
	Initial	Follow-up	Initial	Follow-up	Time	Time x Group
Knee Proprioception (Δ^0)	2.8 ± 1.2 (2.0, 3.6)	3.3 ± 2.3 (1.8, 4.8)	2.8 ± 1.7 (1.7, 3.9)	3.3 ± 3.2 (1.3, 5.3)	0.54	0.98
Hip Flexibility (cm)	5.6 ± 15.6 (-4.3, 15.5)	7.1 ± 15.5 (-2.7, 16.9)	8.2 ± 7.1 (3.7, 12.7)	7.6 ± 9.1 (1.8, 13.4)	0.61	0.25
Ankle Flexibility (cm)	11.3 ± 3.5 (9.1, 13.5)	11.0 ± 3.5 (8.8, 13.2)	11.8 ± 3.2 (9.8, 13.8)	12.3 ± 3.2 (10.3, 14.3)	0.85	0.43

[a] Findings from multivariate analysis of variance

Table 6. Proprioception and flexibility measurements for the ACL-injured subjects, reported as mean ± SD, (95% confidence interval).

	Control (n=5)		Perturbation (n=5)		*p*-value[a]	
	Initial	Follow-up	Initial	Follow-up	Time	Time x Group
Knee Proprioception (Δ^0)	3.6 ± 2.1 (1.0, 6.2)	2.1 ± 1.5 (0.2, 4.0)	1.9 ± 1.8 (-0.3, 4.1)	3.3 ± 4.8 (-2.7, 9.3)	0.95	0.23
Hip Flexibility (cm)	1.1 ± 9.8 (-11.1, 13.3)	4.1 ± 7.6 (-5.3, 13.5)	9.5 ± 9.4 (-2.2, 21.2)	10.0 ± 6.6 (1.8, 18.2)	0.31	0.44
Ankle Flexibility (cm)	13.4 ± 3.3 (5.2, 21.6)	13.3 ± 4.1 (8.2, 18.4)	9.4 ± 1.8 (7.2, 11.6)	9.8 ± 1.8 (7.6, 12.0)	0.51	0.33

[a] Findings from multivariate analysis of variance

measures of lower extremity strength, proprioception and flexibility were unaffected by completion of the training regime. The hypothesis that completion of a perturbation-based NM exercise program would improve YBT scoring, as well as lower extremity physical measures such as strength, proprioception and flexibility was not supported. While results suggest that the perturbation-based NM regime can be safely completed by both healthy and ACL-injured adolescent females, the results call into question the ability of the exercise program to successfully improve dynamic balance or other physical attributes believed to influence ACL-injury rates in this at-risk adolescent population.

The results of the current investigation address a gap in the current literature regarding the safety and effectiveness of perturbation-based NM training in at-risk adolescent females who regularly participate in recreational sporting activities. Previous research has established that YBT performance scores are significantly influenced by the sample population's age,[59,62,63] sex,[58,64–67] sport involvement,[64,65] and level of competitiveness.[68–70] Beyond this, published studies on perturbation-based NM training have focused on a physically active adult population.[31–38] The demographic and anthropometric data showed that the study sample was comprised of physically active females who participated in a variety of recreational sporting activities, have normal body weight and physical stature, and had reached or were approaching physical maturity. The participants were representative of an athletic adolescent female population at-risk for sustaining an ACL injury.[1,4,5] As such, the authors' believe the results are generalizable to a representative population.

Previous investigations targeting physically active adult populations have demonstrated the effectiveness of perturbation-based NM training programs.[31–38] A quadriceps-dominant muscular activation pattern (demonstrated in physically active healthy adult females) has been suggested as one variable that may contribute to a higher risk of ACL injury in female athletes.[35] Perturbation training has been used to eliminate an imbalance between quadriceps and hamstring performance in adult females and thus may be beneficial as an ACL injury prevention program for this demographic.[35,36] Females with ACL-deficient knee also demonstrate improved gait and coordination after participating in a perturbation-based NM training program.[31–34,37,38] Although these results are encouraging for ACL injury prevention and rehabilitation in an adult population, differences in lower extremity biomechanics observed during adolescence may place teenage females at greater risk of ACL injury. A recent meta-analysis reported an age-related association between the outcomes of neuromuscular training and the risk of ACL injury, and highlighted the value of neuromuscular training in female athletes under 18 years of age.[18] This investigation was necessary to determine if the positive effects of perturbation-based NM training demonstrated in an adult population would also be observed in adolescent females at risk of ACL injury.[1,4,5,71]

As all subjects randomized to the training group were able to complete the program without any incidence of knee joint pain, swelling or instability the current data suggest that the perturbation-based training was safe. However, the data indicated that completion of the training program had no significant effect on the YBT reach distances of this adolescent female population. Previous studies reported improvements in YBT scores after healthy youth athletes completed NM training.[21–23] Vitale et al. evaluated an eight-week program focused on core stability, plyometric and body-weight strengthening exercises[21]; two other studies assessed a four-week[22] or 10-week[23] FIFA 11+ Kids program which included seven activities: a running game, two jumping exercises, a balance/coordination task, two exercises targeting body stability and an exercise to improve falling technique. Recent meta-analyses suggest that combining plyometric and balance exercises may maximize effectiveness of preventive NM programs for healthy adolescent females.[26,29,72] The present study used a perturbation-based NM program in isolation so both the preventive effects in healthy subjects and the rehabilitative effects in ACL-injured subjects could be assessed. The current results suggest that perturbation training alone did not affect dynamic balance. Notably, plyometric exercises used in other NM programs may not be safe or practical for ACL-injured subjects.[73] Failla et al. found that the addition of a preoperative rehabilitation program that combined perturbation and strength training resulted in greater functional outcomes and return-to-sport rates two years after ACL reconstruction in an active adult population.[13] Additionally, an investigation by Capin et al. concluded that there were no added benefits to including perturbation-based exercises to a post-operative RTS training program that incorporated strengthening, agility and plyometrics among young female athletes after ACL reconstruction.[74] Thus, further investigations of perturbation-based training regimes with various parameters (such as longer duration or increased training intensity) and alternative forms of NM training that combine perturbation training with other exercises that are safe for ACL-injured adolescent females (such as resistance training, cardiovascular conditioning, core strengthening and gait re-education), are still necessary to improve prevention and rehabilitation programs for those at-risk.

LIMITATIONS

It is important to acknowledge that the current study had several limitations. First, this study utilized a YBT testing protocol that was established for use in an adult population. The typical YBT protocol in adults involves four training trials and three test trials to report a reach distance as the average of the three test trials.[41] The few studies that have investigated YBT in an adolescent population have reported significant variations in the testing protocol.[21–23,43] A recent study of the YBT in an adolescent male population noted a diminished reliability in adolescent athletes compared to adults and recommended that six practice trials and three test trials should be performed to increase the reliability of adolescent YBT assessments.[61] Dynamic body changes that occur during the process of puberty may affect results and should to be accounted for to create a standardized YBT protocol specifically for the adolescent population. A second limitation is that the *a priori* analysis indicated that 22 subjects would provide adequate power to assess dynamic balance.[58,59] Time and funding limits for study completion, as well as the strict age, gender, and activity-level inclusion criteria for participants in the ACL-injured group meant that recruitment was limited to only an exploratory group of 10 subjects. Having said this, the authors believe it was important to include this limited data set because pre-surgical data that is specific to an ACL-injured adolescent female population is lacking in the literature. Finally, the data collection methods focussed exclusively on quantitative outcome measures; however, many subjects commented on how participation in the perturbation-based NM training regime lead to subjective improvements in confidence levels when performing the follow-up testing and enhanced their ability to complete activities of daily living such as riding a bike or participating in physical education classes. The inclusion of subjective or psychological assessment tools would have expanded the analysis and allowed examination of how participation in the perturbation-based NM training program may have influenced participant's confidence, self-esteem, and overall quality of life.

CONCLUSION

The goal of this study was to investigate the safety and effectiveness of a perturbation-based NM training program for improving dynamic balance in healthy and ACL-injured adolescent females. The results suggest that the perturbation training program is safe but has no significant effect on YBT performance in either the healthy or ACL-injured adolescent female participants. All measures of lower extremity strength, knee proprioception and flexibility of the hip and ankle joints were unaffected by the training program. Future research should examine whether perturbation-based NM training has a positive effect when combined with other forms of training currently used for ACL injury prevention or pre-operative rehabilitation in an at-risk population of adolescent female who regularly participate in sport.

CONFLICTS OF INTEREST

The Authors declare that there is no conflict of interest

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APPENDIX

Perturbation Training Program Protocol
Early Phase (Sessions 1-4)

Treatment Goals:

- Expose athlete to perturbations in all directions
- Elicit an appropriate muscular response to applied perturbations (no rigid co-contraction)
- Minimize verbal cues

Movement Application:

- ***Inform patient*** of direction & timing
- Slow force; Low magnitude
- Each set 1 min

Session	Rocker Board	Roller Board/Platform	Roller Board
1	• Bilateral stance • 2 sets anterior/posterior • 2 sets medial/lateral	• 2 sets with injured limb on roller board, anterior/posterior • 2 sets with uninjured limb on roller board, anterior/posterior • 2 sets with injured limb on roller board, medial/lateral • 2 sets with uninjured limb on roller board, medial/lateral	• Bilateral stance • 2 sets anterior/posterior • 2 sets medial/lateral
2	• Unilateral stance • 2 sets anterior/posterior • 2 sets medial/lateral	• 2 sets with injured limb on roller board, anterior/posterior • 2 sets with uninjured limb on roller board, anterior/posterior • 2 sets with injured limb on roller board, medial/lateral • 2 sets with uninjured limb on roller board, medial/lateral	• Unilateral stance • 2 sets anterior/posterior • 2 sets medial/lateral
3	• Unilateral stance • 3 sets anterior/posterior • 3 sets medial/lateral	• 3 sets with injured limb on roller board, anterior/posterior • 3 sets with uninjured limb on roller board, anterior/posterior • 3 sets with injured limb on roller board, medial/lateral • 3 sets with uninjured limb on roller board, medial/lateral	• Unilateral stance • 3 sets anterior/posterior • 3 sets medial/lateral
4	• Unilateral stance • 3 sets anterior/posterior • 3 sets medial/lateral	• 3 sets with injured limb on roller board, anterior/posterior • 3 sets with uninjured limb on roller board, anterior/posterior • 3 sets with injured limb on roller board, medial/lateral • 3 sets with uninjured limb on roller board, medial/lateral	• Unilateral stance • 3 sets anterior/posterior • 3 sets medial/lateral

Mid Phase (Sessions 5-7)

Treatment Goals:

- Add light sport-specific activity during perturbation techniques
- Improve athlete accuracy in matching muscle responses to perturbation intensity, direction and speed

Movement Application:

- ***Unexpected forces***
- ***Rapid, increasing magnitude*** force application
- ***Short delay*** between subsequent force applications
- Begin ***combining directional movement*** of roller board
- ***Distraction*** via ball toss (Beginning at sessions 6)

Session	Rocker Board	Roller Board/Platform	Roller Board
5	• Unilateral stance • 2 sets anterior/posterior • 2 sets medial/lateral	• 1 set with injured limb on roller board, anterior/posterior • 1 set with uninjured limb on roller board, anterior/posterior • 1 set with injured limb on roller board, medial/lateral • 1 set with uninjured limb on roller board, medial/lateral • 2 sets with injured limb on roller board, combination movement • 2 sets with uninjured limb on roller board, combination movement	• Unilateral stance • 1 set anterior/posterior • 1 set medial/lateral • 2 sets combination movements
6	• Unilateral stance • 2 sets anterior/posterior • 2 sets medial/lateral	• 1 set with injured limb on roller board, anterior/posterior • 1 set with uninjured limb on roller board, anterior/posterior • 1 set with injured limb on roller board, medial/lateral • 1 set with uninjured limb on roller board, medial/lateral • 2 sets with injured limb on roller board, combination movement • 2 sets with uninjured limb on roller board, combination movement	• Unilateral stance • 1 set anterior/posterior • 1 set medial/lateral • 2 sets combination movements
7	• Unilateral stance • 2 sets anterior/posterior • 2 sets medial/lateral	• 1 set with injured limb on roller board, anterior/posterior • 1 set with uninjured limb on roller board, anterior/posterior • 1 set with injured limb on roller board, medial/lateral • 1 set with uninjured limb on roller board, medial/lateral • 3 sets with injured limb on roller board, combination movement • 3 sets with uninjured limb on roller board, combination movement	• Unilateral stance • 1 set anterior/posterior • 1 set medial/lateral • 3 sets combination movements

Late Phase (Sessions 8-10)			
Treatment Goals: • Increase difficulty of perturbation by using sport-specific stances • Obtain accurate, selective muscular responses to perturbations in any direction & any intensity, magnitude or speed **Movement Application:** • ***Increased magnitude*** force application • ***Random direction*** movements • ***Little to no delay*** between applications • ***Distraction*** via ball toss			
Session	**Rocker Board**	**Roller Board/Platform**	**Roller Board**
8	• Unilateral stance • 1 set random (linear foot) • 2 sets random (diagonal foot)	• 2 sets with injured limb on roller board, combination movement • 2 sets with uninjured limb on roller board, combination movement • 1 set with injured limb on roller board, combination movement (no delay) • 1 set with uninjured limb on roller board, combination movement (no delay)	• Unilateral stance • 2 sets combination movements • 1 set combination movements (no delay)
9	• Unilateral stance • 1 set random (linear foot) • 2 sets random (diagonal foot)	• 3 sets with injured limb on roller board, combination movement (no delay) • 3 sets with uninjured limb on roller board, combination movement (no delay)	• Unilateral stance • 3 sets combination movements (no delay)
10	• Unilateral stance • 1 set random (linear foot) • 2 sets random (diagonal foot)	• 3 sets with injured limb on roller board, combination movement (no delay) • 3 sets with uninjured limb on roller board, combination movement (no delay)	• Unilateral stance • 3 sets combination movements (no delay)