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A 4-Week Neuromuscular Training Program and Gait Patterns at the Ankle Joint

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Context: Previous research into the rehabilitation of ankle sprains has primarily focused on outcome measures that do not replicate functional activities, thus making it difficult to extrapolate the results relative to the weight-bearing conditions under which most ankle sprains occur.

Objective: To measure the effects of a training program on gait during walking and running in an active athletic population.

Design: Matched-pairs, controlled trial.

Setting: University motion analysis laboratory.

Patients or Other Participants: Ten subjects from an athletic population (7 healthy, 3 with functional ankle instability: age = 25.8 ± 3.9 years, height = 177.6 ± 6.1 cm, mass = 66.8 ± 7.4 kg) and 10 controls matched for age, sex, activity, and ankle instability (7 healthy, 3 with functional ankle instability: age = 27.4 ± 5.8 years, height = 178.7 ± 10.8 cm, mass = 71.6 ± 10.0 kg).

Intervention(s): A 4-week neuromuscular training program undertaken by the treatment group.

Main Outcome Measure(s): We measured ankle position and velocity in the frontal (x) and sagittal (y) planes in all subjects during treadmill walking and running for the periods 100 milliseconds before heel strike, at heel strike, and 100 milliseconds after heel strike.

Results: A 4-week neuromuscular training program resulted in no significant changes in ankle position or velocity during treadmill walking and running.

Conclusions: The mechanisms by which neuromuscular training improves function in normal subjects and those with functional ankle instability do not appear to result in measurable changes in gait kinematics. Our findings raise issues regarding methods of ankle sprain rehabilitation and the measurement of their effectiveness in improving functional activities. Further research in a larger population with functional ankle instability is necessary.

Key Words: rehabilitation, ankle sprain

Key Points

- Subjects with functional ankle instability and uninjured subjects displayed no changes in ankle position or velocity during treadmill walking and running after a 4-week neuromuscular training program.
- The mechanisms by which neuromuscular training improves ankle function do not appear to result in measurable changes in gait kinematics.

Ligamentous ankle injuries are the most common sports trauma, accounting for 10% to 30% of all sports injuries.[1] The rehabilitation of ankle sprains is complex, with as many as 70% of athletes in some sports suffering recurrent sprains and between 55% and 72% of patients complaining of residual symptoms 6 to 18 months after injury.[2,3] Freeman et al[4] coined the term functional instability (FI) to describe the phenomenon of repeated spraining or giving way of the ankle after an acute sprain. A significant amount of research has been devoted to the causes of FI in recent years, with investigators focusing on factors such as ankle strength,[5,6] proprioception,[6] postural control,[7] nerve conduction velocity,[8] and neuromuscular response times.[9] One aspect of ankle research that has not received attention in the literature is the effect of rehabilitation on dynamic movement control during a functional daily activity such as walking and running (ie, gait).

The core of ankle training research over the past decade has been directed toward the development of exercise programs aimed at the prevention and recurrence of ankle sprains. These authors have focused on proprioceptive,[9] strengthening,[5] balance,[10] and coordination exercises.[11] In a comprehensive review outlining current rehabilitation techniques for ankle sprains, Mattacola and Dwyer[12] reported that a definitive series of outcome studies documenting the number of treatments and the combination and the volume of exercises necessary to return athletes with ankle instability to full function is still lacking. Thus, optimal training methods have yet to be established as a result of an inability to identify the exact mechanisms involved in the development of FI.

When considering the effects of training for FI rehabilitation, we must address the deficits associated with FI. Monaghan et al[13] found that subjects with ankle instability were in a more inverted position during the terminal swing phase of gait and during the weight acceptance period after heel strike (HS). Biomechanical abnormalities in gait have been cited as common causes of inversion sprains, and accurate positioning of the foot at touchdown is very important in gait and sports.[14] Increased inversion of the ankle at HS places an excessive inversion load on the rear foot, and once weight bearing begins, the time taken to produce an effective recovery via the proprioception-neuromuscular complex is almost as long as

Table 1. Subject Demographic Data as Mean (SD)

	Treatment Group	Control Group	Total
Age, y	25.8 ± 3.9	27.4 ± 5.8	26.3 ± 4.9
Height, cm	177.6 ± 6.1	178.7 ± 10.8	170.6 ± 8.6
Mass, kg	66.8 ± 7.4	71.6 ± 10.0	66.8 ± 8.9
Baseline to follow-up, d	32.6 ± 2.7	31.5 ± 1.9	31.5 ± 2.3
Cumberland Ankle Instability Tool score (range 0–30)	26.3 ± 4.3	26.6 ± 5.1	26.4 ± 4.6
Sex	3 women, 7 men	3 women, 7 men	6 women, 14 men

the stance phase of running, which may predispose an individual to injury.[15] Konradsen[16] reported that compressive forces such as HS produce an inversion torque that strains the lateral constraints. Depending on the magnitude of the compressive force and the contact of the articular surfaces, this situation may cause lateral ligament and capsular injury. Proprioceptive damage from an ankle sprain may impair the feedback needed to retain function of the central motor programs responsible for controlling ankle stability during loading tasks, for example, during the stance phase of gait. Numerous authors[16–18] have linked impaired neuromuscular feedback and the resulting reduction in neuromuscular control as a potential cause of FI.

In recent years, many researchers have found discrepancies in gait patterns of patients with chronic ankle instability (CAI). Nyska et al[19] concluded that patients with recurrent ankle sprains may have modified gait patterns, which may be related to an altered connection between the central nervous system and the injured muscle or nerves (or both) surrounding the ankle. At the end of the stance phase, CAI subjects placed a greater load on the lateral forefoot, causing a lateral shift in the center of pressure. Monaghan et al[13] recently demonstrated significant kinetic and kinematic changes in the weight acceptance phase of gait in CAI subjects. These patients were in a more inverted position at the ankle from 100 milliseconds before to 200 milliseconds after HS during relaxed walking. This inability to control movement and the resulting instability may result in increased stress applied to the ankle joint during HS and loading response phases of the gait cycle, as the joint cannot absorb forces upon impact. Willems et al[14] also suggested that the effective prevention and rehabilitation of inversion sprains should include attention to gait patterns and adjustments in foot biomechanics.

Previous researchers of ankle sprain rehabilitation have primarily focused on outcome measures that do not replicate functional activities, such as open chain and low-speed isokinetic testing,[5,6] static tests,[11] and reaction times to inversion stress.[8,9] This emphasis makes it difficult to extrapolate the results relative to the weight-bearing activities during which most ankle sprains occur. Ankle sprains commonly occur during walking and running but also during lateral cutting and side-shuffle movements and when landing from a jump.[14] Thus, the medical community faces a major problem in that we have yet to identify the mechanism by which training programs affect changes in the ankle function and to measure these changes. Our purpose was to investigate the effects of a 4-week ankle training program on joint movement during walking and running in an active athletic population. We hypothesized that a dynamic training program comprising incremental levels of difficulty would result in significant changes in ankle position and velocity in the sagittal and frontal planes during gait.

METHODS

Subjects

Twenty physically active subjects (14 men, 6 women; 14 uninjured, 6 FI; mean age = 26.3 ± 4.9 years, height = 170.6 ± 8.6 cm, mass = 66.86 ± 8.9 kg) were recruited from athletic clubs and colleges in the region for the purpose of this study (Table 1). These subjects were chosen as they are generally motivated and disciplined individuals and were likely to be compliant with the exercise program. Subjects had to meet the following strict criteria in order to participate in the study: age between 18 and 40 years (inclusive), fully participating in training or activity with no current injury complaints, and negative results on the Physical Activity Readiness Questionnaire.[20] Subjects were excluded from the study if they had experienced a lower limb injury or trauma in the previous 3 months for which they had received medical advice or treatment or if they were currently taking any medication that might interfere with the neuromuscular system.

The university ethics committee approved the study, and written consent was obtained from each subject before participation. Subjects were interviewed regarding their level of participation in sport. Subjects were then randomly assigned into the treatment group (n = 10), with activity-matched, age-matched, sex-matched, height-matched, and weight-matched individuals in a control group (n = 10). One subject in the treatment group withdrew from the study as a result of illness, and another subject in the control group was excluded from data analysis as a result of incomplete data acquisition (no retest was undertaken). All subjects were given a Cumberland Ankle Instability Tool questionnaire at baseline testing. The questionnaire, developed by Hiller et al[21] as a measure of instability in subjects, is a valid and reliable method for diagnosing and measuring the severity of FI.[21] This 9-item questionnaire grades the severity of the instability between 0 and 30. Scores greater than 27.5 represent highly stable ankles, and scores less than 24 represent ankles with increasingly severe instability. Of the 20 subjects who took part in the study, 6 had a score of less than 24, which categorized them as FI subjects. The remaining 14 subjects had an average score that categorized them as having highly stable ankles (score = 28.8 ± 1.48). These subjects were equally represented in the treatment and control groups.

Subjects in the treatment group were instructed to complete 5 sessions of the training program per week (1 session per day only) for 4 weeks and to continue their normal sports training. A recording sheet, which listed the exercises to be undertaken, was provided to document the exercises and the number of sessions completed by each subject. If a subject completed fewer than 15 sessions throughout the 4 weeks, he or she was excluded from the final analysis. Subjects were not informed of this disposition before the program began. The control subjects continued their normal sports training and had no involvement with the study until the retest.

Motion Analysis Acquisition

The data acquisition for this study was undertaken in the university's motion analysis laboratory. Kinematic analysis was performed before and after the 4-week training program intervention on a group of subjects, with a nonintervention group acting as a control. A single CODA MPX 30 unit (Charnwood Dynamics Ltd, Leicestershire, UK) was used to acquire data throughout the gait cycles. The CODA MPX 30 unit is a commercially available optoelectronic motion capture system for recording and analyzing human movement. Monaghan et al[22] validated the reliability of the CODA MPX 30 for the acquisition of kinematic data during gait. Internal joint centers for the hip, knee, and ankle joints were calculated by obtaining the following anthropometric data: the pelvic width from the left anterior-superior iliac spine to the right anterior-superior iliac spine, the pelvic depth from the anterior-superior iliac spine to the posterior-superior iliac spine, the knee width, and the ankle width. Measurements were recorded in centimeters using a caliper (Lafayette Instrument Co Europe, Leicestershire, UK). The limb lengths of the thigh, shank, and foot were determined using a measuring tape. The subject's height and weight were also acquired. The CODA markers and the marker wands were applied in accordance with the manufacturer's guidelines by the same investigator for all subjects. Markers were positioned on the lateral aspect of the knee joint line, lateral malleolus, heel, and fifth metatarsal head. Wands with anterior and posterior markers were positioned on the pelvis, sacrum, thigh, and shank. The markers were fixed to the skin with double-sided adhesive tape.[22]

Subjects were familiarized with the test equipment and procedure before testing began. The CODA MPX 30 data were collected at the 200-Hz sampling rate for 20 seconds of the subject's gait at speeds of 4 km/h, 8 km/h, and 12 km/h, with the subject barefoot on a treadmill (model 945-295; Biodex Medical Systems, Inc, Shirley, NY) with no incline. Subjects were already familiar with treadmill walking and running before the study. Three trials at each speed were recorded, with a short break on the stationary treadmill between trials to save data collected from individual trials. The investigator was not blinded to the subject group assignment before the testing procedure, and the same individual demonstrated the exercises to the subjects. The initial point of acquisition occurred once the subjects were comfortable at the given speed. The subjects were not made aware of the precise period of data acquisition in order to allow the subjects to assume their normal gait patterns. A trial was terminated if a reflective marker or wand became loose; it was reapplied in the same position in accordance with markings made on the subject's skin before the test recommenced. The investigator instructed the subject when to start and stop the treadmill.

Training Program Objective

The objective of the training program was to provide a demanding, progressive collection of lower limb closed kinetic chain exercises that sufficiently challenged the neuromuscular systems of the subjects. The progressive nature of the neuromuscular training is important to achieve neuromuscular outcomes from the training.[23] Dynamic neuromuscular training has also been demonstrated to reduce sex-related differences in force absorption, active joint stabilization, muscle imbalances, and functional biomechanics while increasing the strength of structural tissues (bones, ligaments, and tendons).[24] The exercise progression was designed to ensure that subjects placed continuous changes in intensity and demand on their neuromuscular systems throughout the course of the program. Mattacola and Dwyer[12] proposed that a goal of rehabilitation is to develop strength and neuromuscular control, so that the ankle and the foot are better controlled and protected during stance and impact. Evidence is strong that neuromuscular training selectively combining several components not only decreases the potential biomechanical risk factors of lower extremity injury but also provides performance enhancement effects.[23]

Members of the medical teams for the British Olympic Team, the Irish Olympic Team, and the Irish Soccer Team outlined general strategies for their exercise rehabilitation of an athlete with a grade II ankle sprain from initial presentation to return to sporting activities. Exercises from these experts were combined with data from previous research in the literature regarding the rehabilitation of ankle sprains to design an intensive 4-week training program focusing on dynamic strength and balance exercises. Weight-bearing and closed kinetic chain exercises have gained popularity in the rehabilitation of lower extremity joint injuries[1] and formed an integral part of this program (Figure 1). The program was pilot tested on members of the University staff before the study in order to assess the correct progression of each exercise set.

Equipment Provision

Each subject was provided with a Both Sides Up (BOSU) Balance Trainer (DW Fitness, Madison, NJ), a Reebok aerobic step (model 10152; Reebok Intl Ltd, Canton, MA), and a standard gym mat. A BOSU is a balance device with a circular platform on one side and an inflated half sphere on the opposite side.[25] Subjects were also provided with a booklet detailing the components, correct technique, number of repetitions, and pictures of each exercise. They were advised to complete a warm-up session that included dynamic exercises, such as jogging on the spot, "high knees," and heel pick-ups, as well as stretching exercises for the gastrocnemius-soleus complex before beginning the exercise program. Subjects wore their normal running shoes for safety reasons, as the program contained numerous jumping and hopping activities that resulted in high-impact activity.

Progression of Exercises

The training program was divided into 4 sets of exercises (Table 2), with specific exercises from each set conducted for 1 week. Each set contained exercises with increasing levels of difficulty (levels 1 through 5). After obtaining the initial data in the gait laboratory, the investigator demonstrated exercises at level 1, indicating the desired technique to the subject. Each subject subsequently completed level 1 of the exercises while being observed by the same investigator, a physiotherapist experienced in demonstrating and performing rehabilitation exercises for athletes. The investigator assessed the ability of the subject to complete each exercise in a safe manner using the correct technique required to perform the exercise efficiently.

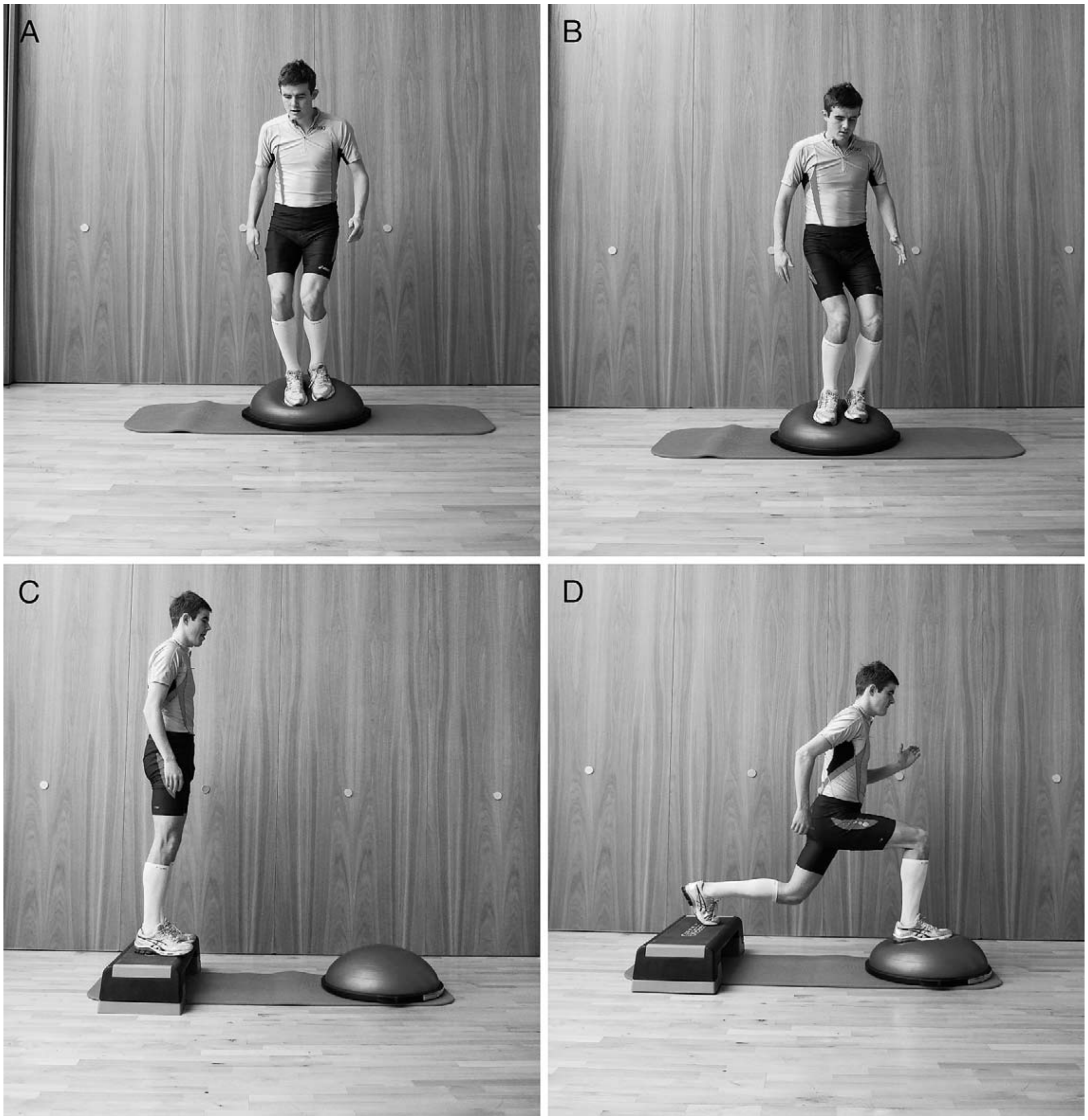

Figure 1. Examples of exercises included in the neuromuscular training program. A and B, Exercise A2: Double-leg skiing exercise on Both Sides Up Balance Trainer (BOSU). C and D, Exercise C5: Lunge from Reebok Step onto BOSU.

Once the investigator was satisfied that the subject was competent at a particular exercise and the subject reported feeling sufficiently competent, he or she was progressed to level 2 of that exercise set to initiate the program. Subjects who did not perform a particular exercise in a safe and proficient manner remained at level 1 of that exercise set and were followed for the remainder of the study on a weekly basis to assess if they could progress to the next level of difficulty in a particular exercise set. This was done to allow for any variations in the subjects' ability to complete the exercises that may have occurred at baseline level of entry to the study. The importance of maintaining correct technique throughout the course of the program was emphasized at each follow-up session by the investigator.

Program Description

Myklebust and Bahr[27] advised that early levels of neuromuscular training should emphasize sound athletic positioning to help create dynamic control of the athlete's center of gravity. Four lines were marked with white adhesive tape across the exercise mat to indicate the exact positioning of the exercise equipment during the exercises. The lines also indicated the distances the subjects were required to achieve during lunging and hopping exercises, which allowed for uniform distances during repetitions of these movements. The initial level of the program (level 1) involved bilateral stance exercises with no change in the base of support, including squats, heel raises, and toe raises, as well as an introduction to dynamic exercise on the unstable surface of the BOSU ball.

The middle phases of the program (levels 2 and 3) introduced single-leg exercises on stable surfaces aimed at developing neuromuscular control of the limb in a controlled situation. All single-leg exercises were performed bilaterally, as evidence regarding the rehabilitation of strength bilaterally is accepted clinical practice and is thought to be important for the prevention of ligamentous injuries at the ankle.[28] Improvement in single-leg stability can be obtained with a neuromuscular training program that incorporates perturbations into balance training on unstable surfaces.[26] These single-leg activities

Table 2. The Training Program*

Level	Exercise A	Exercise B	Exercise C	Exercise D
1	DLS with lumbar control 2 × 10	DLS on BOSU 2 × 10	DL compressions on BOSU 2 × 20	Forward/backward hop on BOSU 2 × 20
	Toe raises 2 × 20			
	DL heel raises 2 × 20			
2	DL skiing exercise on BOSU 2 × 10 (side to side squats)	DL box jumps onto Reebok step 2 × 15 (stabilize on landings)	SL step up on Reebok step 2 × 10	SL lunges forward 2 × 10
	SL heel raises 2 × 10		SL step down on Reebok step 2 × 10	SL lunges side to side 2 × 10
3	SLS 2 × 10	As in B2 above but increase Reebok step height	As in C2 above but increase Reebok step height	SL hopping forwards 2 × 10 (stabilize on landings)
				SL hopping sideways 2 × 10 (stabilize on landings)
4	SLS 2 × 10 and hold in squat position for 10 seconds after 10 squats	DL bunny hop onto BOSU 2 × 10 (stabilize on landings)	SL step up on BOSU 2 × 10	SL hops onto BOSU 2 × 10 (stabilize on landings)
		DL lateral bunny hop onto BOSU 2 × 10 (stabilize on landings)	SL step down on BOSU 2 × 10	Lateral SL hops onto BOSU 2 × 10 (stabilize on landings)
5	SLS on BOSU 2 × 10	High knee lifts on BOSU 2 × 20	Lunge from Reebok step onto BOSU 2 × 10	As in D4 above but increase distance of jump onto BOSU

*SL indicates single leg; DL, double leg; SLS, single-leg squat; DLS, double-leg squat; BOSU, Both Sides Up Balance Trainer.

incorporated step-ups, step-downs, squats, lunges, and hopping exercises that required more multiplane movements and, therefore, challenged the subjects' base of support by placing significant demands on postural control.

The final phases of the program (levels 4 and 5) involved more complex single-leg exercises on both stable and unstable surfaces. Exercise on an unstable surface such as the BOSU results in distorted somatosensory feedback, placing greater demands on the subject to react to an unexpected perturbation and, thus, to develop consistent motor patterns. The BOSU is more advantageous than a wobble board or ankle disk in that it allows more dynamic exercises to be performed without compromising an individual's safety. These exercises were aimed at improving dynamic joint stabilization, which is achieved by cocontraction of the muscles around the joint. During dynamic activity, muscular cocontraction, and eccentric control in particular, is necessary to minimize forces between the foot and ankle complex.[29] Excessive forces around the joint may predispose the athlete to injury.[5] Emphasis was therefore placed on stabilization at landing from hopping exercises on stable and unstable surfaces to promote muscular cocontraction and allow subjects to adapt to the forces generated through the lower limb upon impact. Subjects were instructed to stabilize, with their knees flexed upon landing, at each phase of the particular exercise for 1 second before completing the next movement in the exercise.

Statistical Analysis

We calculated kinematic data by comparing the angular orientations of the coordinate systems of the adjacent limb segments. Joint angular displacements and angular velocities were calculated for the ankle joints in the frontal (inversion [+], eversion [−]) and sagittal (dorsiflexion [+], plantar flexion [−]) planes. The point of HS was identified for 10 consecutive running cycles as the point at which the vertical acceleration of the heel marker crossed the horizontal axis of the graph for a particular gait cycle. These cycles were taken from the period between 5 and 20 seconds of the gait cycle. Kinematic data relating to the period from 500 milliseconds before HS to 500 milliseconds after HS during gait were extracted and converted to Excel (Microsoft Corp, Redmond, WA) file format for averaging and further analysis. Kinematic variables including joint angular displacement and angular velocity in the sagittal and frontal planes were averaged over time at each speed (4 km/h, 8 km/h, 12 km/h) for each subject at 100 milliseconds before HS, HS, and 100 milliseconds after HS. Further analysis was undertaken using SPSS for Windows (version 11.0; SPSS Inc, Chicago, IL). The dependent variables measured were ankle position and velocity in the frontal and sagittal planes. The independent variables measured were group (treatment versus control), treadmill velocity (4, 8, or 12 km/h), and discrete points in the gait cycle (100 milliseconds before HS, HS, and 100 milliseconds after HS). We calculated a general linear model 2-factor analysis with repeated measures to determine differences in the dependent variables before and after test group measures at different treadmill speeds and at discrete points in the gait cycle. An alpha level of $P > .05$ was set for all analyses. We performed a Bonferroni adjustment to account for multiple comparisons between the groups; our adjustment level was set at $P < .0013$. The between-subjects factor was group status (treatment versus control), and the within-subjects factor was test (before versus after). Effect sizes for group differences were calculated by taking the difference in mean values between the treatment and control groups and dividing this number by the SD of the control group. The strength of the effect sizes was interpreted using guidelines described by Cohen,[30] with values less than 0.2 interpreted as weak, values from 0.21 to 0.79 interpreted as moderate, and values greater than 0.8 interpreted as strong.

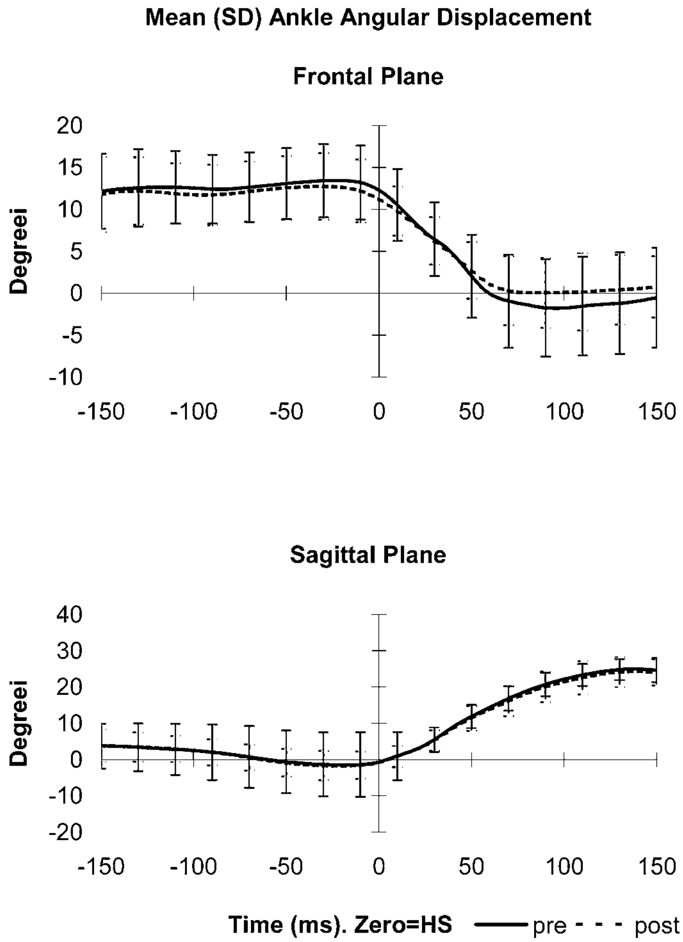

Figure 2. Ankle angular displacement over time. Time 0 indicates heel strike.

RESULTS

We observed no significant differences in ankle joint position or velocity in either group at follow-up testing compared with baseline ($P > .05$). No significant group main effects were observed between the treatment and control group pretest and posttest measures. The frontal-plane and sagittal-plane movements at the ankle in the treatment and control group are shown in Figure 2. The group mean differences in position and velocity pretest and posttest had a mainly moderate to small effect size (Tables 3 and 4), indicating that the training program had a small effect on patterns of movement. The reported compliance with the training program by the treatment group was an average of 17.9 ± 1.6 sessions of the recommended 20 sessions. No subjects were excluded from the analysis as a result of not completing the minimum of 15 training sessions. Subjects in the treatment group described the program as intensive and highly challenging. No subjects reported sustaining any injuries as a result of the exercises.

DISCUSSION

Our principal finding was that a 4-week neuromuscular training program resulted in no significant changes in ankle position or velocity during treadmill walking and running. Subjects in both the treatment and control groups demonstrated remarkable consistency in their ankle movements at differ-

Table 3. Ankle Position in the Frontal (x) and Sagittal (y) Planes, Mean ± SD*

	Period	Treatment Group, Pretest	Treatment Group, Posttest	Mean Difference	Control Group, Pretest	Control Group, Posttest	Mean Difference	*P* Value (Group Main Effect)	Effect Size
Ankle 4 km/h	100 pre	2.94 ± 3.95	5.63 ± 5.76	2.44 ± 5.17	3.92 ± 1.83	5.09 ± 5.45	1.17 ± 5.60	.897	0.23
frontal position	HS	2.35 ± 3.47	4.43 ± 4.94	1.78 ± 5.22	4.32 ± 2.02	5.65 ± 5.63	1.33 ± 6.02	.365	0.07
	100 post	−1.47 ± 3.41	0.16 ± 3.82	1.29 ± 5.29	0.09 ± 4.05	1.91 ± 6.75	1.82 ± 5.39	.564	−0.10
Ankle 4 km/h	100 pre	3.95 ± 2.28	3.95 ± 2.38	0.00 ± 2.48	3.75 ± 2.50	4.00 ± 1.80	0.25 ± 3.19	.013	−0.08
sagittal position	HS	1.92 ± 2.51	1.88 ± 2.91	−0.04 ± 2.69	1.45 ± 2.38	1.67 ± 2.21	0.22 ± 3.21	.721	−0.08
	100 post	−2.08 ± 1.83	−1.90 ± 2.67	0.18 ± 2.78	−1.87 ± 2.94	−2.11 ± 1.96	−0.24 ± 2.99	1.000	0.14
Ankle 8 km/h	100 pre	13.17 ± 2.62	11.31 ± 2.82	−1.86 ± 2.05	11.92 ± 2.82	12.19 ± 4.72	−0.27 ± 5.09	.908	−0.31
frontal position	HS	12.96 ± 3.31	11.37 ± 3.02	−1.59 ± 1.83	11.60 ± 3.02	11.05 ± 0.71	0.55 ± 4.56	.612	−0.47
	100 post	−0.54 ± 5.49	0.26 ± 4.80	−0.80 ± 6.13	−3.00 ± 4.80	−0.07 ± 5.61	−2.93 ± 7.19	.463	0.30
Ankle 8 km/h	100 pre	5.66 ± 4.98	5.03 ± 5.33	−0.58 ± 3.61	−0.71 ± 5.75	−0.07 ± 8.12	0.64 ± 7.03	.045	−0.17
sagittal position	HS	2.53 ± 6.06	2.19 ± 6.02	−0.35 ± 3.25	−3.88 ± 7.27	−3.82 ± 9.87	0.05 ± 7.80	.086	−0.05
	100 post	22.13 ± 3.34	21.26 ± 2.71	−0.87 ± 3.47	22.20 ± 4.86	21.54 ± 3.01	−0.66 ± 3.56	.874	−0.06
Ankle 12 km/h	100 pre	11.35 ± 4.09	10.99 ± 3.45	−0.36 ± 5.25	10.22 ± 3.96	11.90 ± 4.38	−1.68 ± 3.36	.938	0.39
frontal position	HS	13.99 ± 3.38	12.36 ± 3.04	−1.61 ± 2.49	11.37 ± 4.39	12.32 ± 5.24	−0.95 ± 3.69	.478	−0.18
	100 post	2.20 ± 6.17	−0.36 ± 5.01	−2.56 ± 7.31	−5.90 ± 5.43	−4.04 ± 4.51	−1.86 ± 6.07	.001	−0.12
Ankle 12 km/h	100 pre	4.95 ± 3.51	5.89 ± 0.41	1.22 ± 4.48	0.61 ± 8.17	−0.27 ± 7.74	0.88 ± 8.19	.048	0.04
sagittal position	HS	−0.49 ± 7.45	1.28 ± 7.59	1.77 ± 4.72	−3.91 ± 12.00	−4.05 ± 11.74	0.14 ± 14.88	.512	0.11
	100 post	22.26 ± 3.77	21.46 ± 2.90	−0.80 ± 6.63	24.35 ± 3.12	23.55 ± 2.91	0.80 ± 3.06	.124	−0.52

*100 pre indicates 100 milliseconds preheel strike (HS); 100 post, 100 milliseconds post-HS. Frontal: inversion, +; eversion, −; sagittal: dorsiflexion, +; plantar flexion, −.

Table 4. Ankle Velocity in the Frontal (x) and Sagittal (y) Planes, Mean ± SD*

	Period	Treatment Group, Pretest	Treatment Group, Posttest	Mean Difference	Control Group, Pretest	Control Group, Posttest	Mean Difference	*P* Value (Group Main Effect)	Effect Size
Ankle 4 km/h	100 pre	−0.14 ± 0.75	−0.34 ± 0.72	−0.20 ± 0.96	−0.26 ± 0.77	−0.52 ± 0.63	−0.26 ± 1.09	.887	0.06
frontal velocity	HS	−0.57 ± 0.37	−0.57 ± 0.25	−0.01 ± 0.41	−0.75 ± 0.71	−0.80 ± 0.34	−0.05 ± 0.89	.224	0.04
	100 post	−0.99 ± 0.48	−0.80 ± 0.42	0.18 ± 0.38	−0.86 ± 0.44	−0.86 ± 0.43	−0.01 ± 0.76	.554	0.25
Ankle 4 km/h	100 pre	−0.64 ± 0.53	−0.85 ± 0.61	−0.21 ± 0.41	−0.69 ± 0.56	−0.55 ± 0.54	0.15 ± 0.50	.607	−0.72
sagittal velocity	HS	−0.16 ± 0.27	−0.26 ± 0.39	−0.11 ± 0.27	−0.26 ± 0.37	−0.06 ± 0.24	0.20 ± 0.72	.701	−0.43
	100 post	1.23 ± 0.37	1.42 ± 0.47	0.19 ± 0.36	1.63 ± 0.26	1.43 ± 0.46	−0.21 ± 0.65	.132	0.03
Ankle 8 km/h	100 pre	−0.18 ± 0.79	−0.15 ± 0.68	−0.03 ± 6.14	−1.04 ± 3.98	0.06 ± 0.87	−1.10 ± 4.70	.578	0.23
frontal velocity	HS	−1.77 ± 0.80	−1.85 ± 0.82	0.08 ± 7.31	−2.72 ± 1.61	−2.14 ± 1.45	−0.58 ± 1.04	.247	0.63
	100 post	−0.12 ± 1.17	0.33 ± 0.74	−0.25 ± 3.27	−0.96 ± 3.34	−0.23 ± 0.64	−0.73 ± 3.57	.193	0.13
Ankle 8 km/h	100 pre	−0.60 ± 0.66	−0.70 ± 0.81	−0.11 ± 0.64	−1.03 ± 1.61	−0.66 ± 1.64	−0.37 ± 0.60	.746	0.43
sagittal velocity	HS	1.27 ± 1.73	1.54 ± 1.91	0.27 ± 1.12	2.80 ± 2.64	2.12 ± 2.70	0.68 ± 1.84	.294	−0.22
	100 post	2.32 ± 0.68	2.23 ± 0.58	−0.09 ± 0.49	2.37 ± 0.40	2.15 ± 0.67	0.22 ± 1.00	.950	−0.31
Ankle 12 km/h	100 pre	0.34 ± 1.38	0.14 ± 0.83	−0.20 ± 1.99	0.29 ± 0.62	0.49 ± 0.81	−0.21 ± 1.20	.517	0.01
frontal velocity	HS	−1.50 ± 1.08	−1.46 ± 0.88	0.04 ± 0.94	−2.04 ± 1.66	−2.19 ± 1.69	0.15 ± 1.15	.270	−0.10
	100 post	0.18 ± 1.35	0.31 ± 0.69	0.13 ± 1.55	0.35 ± 1.01	−0.29 ± 1.44	0.63 ± 1.65	.585	−0.30
Ankle 12 km/h	100 pre	−0.56 ± 0.97	−0.38 ± 0.99	0.18 ± 0.62	−0.44 ± 1.38	−0.21 ± 1.36	−0.23 ± 0.23	.349	1.78
sagittal velocity	HS	0.78 ± 1.53	0.57 ± 1.51	−0.21 ± 0.90	1.35 ± 2.33	1.23 ± 0.71	0.12 ± 1.02	.412	−0.32
	100 post	2.03 ± 1.05	2.30 ± 1.01	0.27 ± 0.97	2.28 ± 0.96	2.40 ± 0.61	−0.13 ± 0.77	.812	0.52

*100 pre indicates 100 milliseconds preheel strike (HS); 100 post, 100 milliseconds post-HS. Frontal: Inversion, +; Eversion, −; Sagittal: Dorsiflexion, +; Plantarflexion, −.

ent speeds before and after the intervention period. This was in spite of high self-reported compliance rates in a very motivated sporting population. Therefore, the mechanisms by which neuromuscular training improves function in normal and FI subjects do not appear to result in measurable changes in gait kinematics.

A number of possible reasons exist for the lack of significant changes in ankle movement after the training program. Our study population consisted of a range of individuals from recreationally active to Olympic-level athletes. It could be argued that this subject group may have had a very high level of neuromuscular control over ankle function at baseline and, therefore, would not respond to a training stimulus in a significant fashion. However, all subjects in the treatment group reported that they found the exercises to be highly challenging and intensive in nature. Furthermore, 3 subjects in the treatment group had baseline Cumberland Ankle Instability Tool scores consistent with the presence of FI. Although the FI subjects in the study had no history of an ankle sprain for the previous 3 months, they still exhibited clinically significant problems with dynamic ankle stability, reporting difficulty in completing daily activities such as running and jumping, as well as exercises in the training program, especially when stabilizing from a jump.

Another potential factor in the lack of significant changes may have been the duration and intensity of the exercise program. Our study had a training period of only 4 weeks; subjects were asked to complete 5 sessions per week, but this duration of training stimulus may not have been sufficient to result in neuromuscular adaptation to influence changes in gait patterns. Most rehabilitation studies for acute and chronic ankle instability involved a 6-week to 8-week training period.[12] Recent motor control theory indicates that learning the dynamics of a task is essential for retraining control in a motor learning task.[31] Re-educating the ankle muscles during the weight-bearing phase of gait may be required to improve subsequent motor control in the ankle.[18] In order to retrain proprioceptive feedback during dynamic movement, perhaps the program should have included some form of plyometric running drills. Changing a functional activity such as gait, with its learned, predefined motor patterns, may require more intensive training and a longer period of time, which may explain why our study resulted in no changes to the gait factors measured.

We cannot rule out the possibility that gait analysis may not be an appropriate method of measuring the effectiveness of rehabilitation programs aimed at improving neuromuscular control about the ankle. We chose to assess the effects of a training program on ankle position and velocity during gait. Owing to the lack of similar studies in the literature investigating the effects of training on gait patterns in normal and FI populations, it is difficult to compare our results with those of previous researchers. Also, in their review, Mattacola and Dwyer[12] described a number of authors whose work has shown improvements in measures such as strength,[32–34] joint position sense,[32] and postural control[35,36] using training programs and periods similar to ours. Although we did not measure these variables, our program may have positively affected some of them, even though it resulted in no difference in the gait kinematics we did measure. One previous group[37] evaluated functional tests in a self-reported FI population, including cocontraction, agility tests, and shuttle runs in FI subjects, and found no difference versus results for uninjured subjects. The authors indicated that these tests specifically targeted aspects of proprioception, such as balance, coordination, and joint control. Although it is important to assess functional capabilities such as these in FI subjects, no investigators have assessed the effects of rehabilitation on a functional daily task such as gait. We do not know whether our program had any effects on measures other than gait. However, most rehabilitation studies appear to demonstrate little or no effect on the outcome measurements used, and many of those that do show effects assess nonfunctional issues. Recent studies conducted in our laboratory have shown that CAI subjects are in a more inverted position during the terminal swing phase of gait and during the weight acceptance period after HS.[13,38] Altered foot positioning immediately before and at HS may result in a failure to adopt the optimal position to absorb force applied to the limb during the loading response and, therefore, may result in injury.[13] Thus, it is important to consider the use of gait analysis in measuring the effects of rehabilitation in subjects with altered gait mechanics in future research.

The small sample size in this study limits our interpretation of these results, as it did not allow us to differentiate between the FI and normal subjects at baseline or follow-up tests. Future authors should conduct similar and other functional tests on larger groups of FI and normal subjects. Our results might have been different had the study been completed solely on an FI population. Also, the training program was unsupervised, and, as a result, we could only assess self-reported compliance with the program from the subjects.

CONCLUSIONS

The mechanism by which a 4-week neuromuscular training program improves function in normal and FI subjects does not appear to result in measurable changes in gait kinematics. Our findings raise issues regarding methods of ankle sprain rehabilitation and the measurement of their effectiveness in improving functional activities. Further research is necessary into the effects of neuromuscular training on subjects with FI.

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