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Single leg jumping neuromuscular control is improved following whole body, long-axis rotational training

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ABSTRACT

Improved lower extremity neuromuscular control during sports may decrease injury risk. This prospective study evaluated progressive resistance, whole body, long-axis rotational training on the Ground Force 360 device. Our hypothesis was that device training would improve lower extremity neuromuscular control based on previous reports of kinematic, ground reaction force (GRF) or electromyographic (EMG) evidence of safer or more efficient dynamic knee stability during jumping. Thirty-six healthy subjects were randomly assigned to either training (Group 1) or control (Group 2) groups. Using a pre-test, post-test study design data were collected from three SLVJ trials. Unpaired *t*-tests with adjustments for multiple comparisons were used to evaluate group mean change differences ($P \leqslant 0.05/25 \leqslant 0.002$). During propulsion Group 1 standardized EMG amplitude mean change differences for gluteus maximus (−21.8% vs. +17.4%), gluteus medius (−28.6% vs. +15.0%), rectus femoris (−27.1% vs. +11.2%), vastus medialis (−20.2% vs. +9.1%), and medial hamstrings (−38.3% vs. +30.3%) differed from Group 2. During landing Group 1 standardized EMG amplitude mean change differences for gluteus maximus (−32.9% vs. +11.1%) and rectus femoris (−33.3% vs. +29.0%) also differed from Group 2. Group 1 peak propulsion vertical GRF (+0.24 N/kg vs. −0.46 N/kg) and landing GRF stabilization timing (−0.68 vs. +0.05 s) mean change differences differed from Group 2. Group 1 mean hip (−16.3 vs. +7.8°/s) and knee (−21.4 vs. +18.5°/s) flexion velocity mean change differences also differed from Group 2. Improved lower extremity neuromuscular efficiency, increased peak propulsive vertical GRF, decreased mean hip and knee flexion velocities during landing, and earlier landing stabilization timing in the training group suggests improved lower extremity neuromuscular control.

1. Introduction

Lower extremity injuries sustained during sports can lead to long-term, and/or permanent physical health impairments (Hootman et al., 2007). Potentially injurious alignment and excessive joint forces associated with poor lower extremity neuromuscular control may increase injury risk (Pollard et al., 2010). Anterior cruciate ligament (ACL) injuries in particular often occur from non-contact injury mechanisms, such as jump landings (Yu et al., 2002).

The single leg vertical jump (SLVJ) is a sports movement that requires lower extremity neuromuscular control to be performed safely (Williams et al., 2001; Yu et al., 2002). The loading response that occurs as the foot impacts the ground during single leg jump landings creates a chain reaction through multiple lower extremity joint linkages (Powers, 2003; Pollard et al., 2010; Yu et al., 2002). Lower extremity neuromuscular control represents unconscious efferent responses to afferent signals that help dampen or mitigate lower extremity joint loads facilitating dynamic joint stability (Lephart et al., 2000; Williams et al., 2001). Improving trunk-lower extremity neuromuscular control using exercises that closely simulate sport movements is an essential component of many lower extremity injury prevention training programs (Imwalle et al., 2009; Myer et al., 2008).

Evidence supporting improved lower extremity neuromuscular efficiency using conventional progressive resistance exercises that do not closely replicate specific sport movements has been previously reported (Bruhn et al., 2004; LaStayo et al., 2008). Following 8 weeks of submaximal effort eccentric cycling ergometry in healthy subjects, LaStayo et al. (2008) identified decreased vastus lateralis EMG amplitudes suggesting a reduced neural drive requirement to withstand higher knee loads. In having healthy subjects perform twice weekly maximum effort leg presses over 4 weeks, Bruhn et al. (2004) observed decreased gastrocnemius, peroneus longus, and tibialis anterior EMG amplitudes in association with improved single leg postural stabilization times, and decreased sway displacement during single leg stance on a swinging platform. During unfatigued conditions EMG signal amplitude is generally proportional to muscle force (de Vries, 1968). Therefore,

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more efficient muscle activation requires a lesser amount of a given muscle's total activation capacity to perform the same task with the same level of neuromuscular control, as a weaker, or less efficient muscle (Hof, 2003).

Previous studies have revealed efficient lower extremity neuromuscular control during countermovement jump performance in healthy men through muscle activation efficiency, lower extremity angular displacement, and lower extremity angular velocity regulation (Bosco et al., 2000, 1982; Bosco and Viitasalo, 1982). Reduced lower extremity neuromuscular control has been observed among patients following unilateral ACL reconstruction through decreased propulsive SLVJ vertical ground reaction forces (Myer et al., 2006; Paterno et al., 2007). Reduced lower extremity neuromuscular control has also been observed among healthy athletes considered to be at risk for ACL injury (Alentorn-Geli et al., 2009) and among individuals following unilateral ACL reconstruction (Paterno et al., 2007) through increased jump landing vertical ground reaction forces. In a study of 13 subjects at a mean 3.3 years following unilateral ACL reconstruction reduced lower extremity neuromuscular control was indicated by a significantly greater time needed at the surgical lower extremity compared to the non-surgical lower extremity to achieve postural stabilization during a single leg step down task from a 19 cm tall step (Colby et al., 1999). Increased knee injury risk when jumping has been related to decreased hip and knee flexion angles at initial landing (Hewett et al., 2006; Pollard et al., 2010). Increased peak hip and knee flexion angular displacement among subjects with long-term ACL deficiency has also been reported as kinematic compensations to increase lower extremity neuromuscular control during one-leg hop for distance performance (Gauffin and Tropp, 1992). The ability to reduce hip and knee flexion velocity during jump landings has also been related to improved lower extremity neuromuscular control and decreased knee injury risk among athletically active individuals (Hewett et al., 2006).

Through the application of progressive concentric and eccentric resistance, and range of motion during whole body, long-axis rotation, the Ground Force 360 Device (Center of Rotational Exercise, Inc., Clearwater, FL) was designed to improve trunk-lower extremity neuromuscular control during simulated sport movements (Fig. 1). During upright, weightbearing function, trunk and lower extremity movements, load transfer, and muscle power are directly coupled (Gracovetsky, 1997; Gracovetsky and Iacono, 1987; van Wingerden et al., 1993; Vleeming et al., 1995). Therefore long-axis trunk rotation occurs in synchrony with lower extremity movements. Through tendon insertions and fascial connections, gluteus maximus and hamstring neuromuscular activation in particular is highly integrated with axial trunk rotation (van Wingerden et al., 1993; Vleeming et al., 1995). Knee injury prevention studies have identified direct relationships between neuromuscular trunk control deficits and increased knee injury risk (Zazulak et al., 2007a,b). As movement patterns become more automatic through effective practice they become more neuromuscularly and biomechanically efficient (Wu et al., 2008). Enhanced neuromuscular connectivity is considered to be the primary reason for improved efficiency (Green and Wilson, 2000; Wu et al., 2008). The close association between trunk and lower extremity movements, load transfer, and muscle power during the whole body, long axis rotation that occurs with Ground Force 360 Device training may simulate the coordinated trunk and lower extremity function that occurs during jump landings. The concentric-to-eccentric exercise mode in particular was considered a potentially useful setting for simulating the concentric-to-eccentric muscle activation of SLVJ propulsion and landing. Foot position was adjusted between exercise sets from standard athletic ready position placement (at or slightly greater than shoulder-width apart) to diagonal placement (stride position with the left foot forward for concentric left rotation and with the right foot forward for concentric right rotation) to modify frontal and transverse plane lower extremity alignment and better facilitate hip abductor-adductor and internal-external rotator neuromuscular contributions (Neumann, 2010). Training with this device may provide a useful, non-impact method for increasing the lower extremity neuromuscular control needed to improve dynamic knee stability during single leg jumping.

The purpose of this study, which represents part of a larger project, was to evaluate the efficacy of using progressive resistance, whole body, long-axis rotational training to improve the lower extremity neuromuscular control that enhances the dynamic knee stability of healthy subjects during SLVJ propulsion and landing. The study hypothesis was that the training group would display significantly greater mean change differences identifying improved lower extremity neuromuscular control and enhanced dynamic knee stability compared to the control group.

2. Methods

2.1. Experimental design

This was a prospective, randomized controlled study using a pre-test, post-test design with statistical comparison of mean change differences between data collection sessions. The time period between pre-test and post-test measurements was 4.0 ± 0.5 weeks (range = 3.5–5 weeks) for both groups.

2.2. Subject recruitment and group assignment

The Institutional Review Boards of the University of Louisville and Norton Healthcare, Louisville, KY approved this study. An a priori sample size calculation based on pilot test data was performed. Using the "unit-less" method of EMG standardization described in the methods section, a mean change difference of 10 with a standard deviation of 5 in the device training group and a mean change difference of 3 with a standard deviation of 5 in the control group produced an effect size of 1.4. Based on this estimate a minimum of 17 subjects were needed in each group with a directional hypothesis at a beta error level of 0.80 and an alpha error level of $P = 0.002$. To be considered for study inclusion subjects had to be between 18 and 50 years of age, be regularly participating in an exercise program or sports activity at least twice weekly, be without low back injury history or current low back pain, be without current lower extremity injury, and have no history of lower extremity surgery other than partial menisectomy (and be at least 2 years post-surgery).

Written informed consent was obtained from each subject. Forty-six potential subjects responded to campus flyer advertisements. Ten potential subjects were rejected from study participation because of previous knee ligament reconstruction, low back injury history, the desire to increase existing exercise program or sports activity volume during the study period, or because of an inability to comply with the study time commitment. Using a random numbers table with block randomization for gender, subjects were assigned to the device training group (Group 1) or to a control group (Group 2). Subject perceived activity level was determined using the International Knee Documentation Committee (IKDC) Activity Scale (1 = highly competitive sports person, 2 = well-trained and frequently sporting, 3 = sporting sometimes, 4 = non-sporting) (Table 1). Subjects continued regular exercise program or sport activities during the study period without increasing intensity, frequency, or volume. Female subjects were required to provide a negative pregnancy test at study initiation. Based on allocated time requirements, training group subjects were reimbursed

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Fig. 1. Training in the Ground Force 360 device (Center of Rotational Exercise, Inc., Clearwater, FL, USA).

Table 1
Subject demographics and SLVJ heights (mean ± standard deviation).

	Group 1 (9 women, 9 men) $n = 18$	Group 2 (9 women, 9 men) $n = 18$
Age (years)	22.3 ± 2.3	25.4 ± 6.9
Height (cm)	173.6 ± 10.5	177.7 ± 8.5
Pre-test subject weight (kg)	70.0 ± 9.4	75.7 ± 12.1
Post-test subject weight (kg)	70.8 ± 10	74.2 ± 10
IKDC physical activity scale level (median)	3 (range = 2–4)	3 (range = 2–4)
Exercise program or sports activity participation	9 of 18 (50%) subjects regularly participated in recreational running or weight training, 9 of 18 (50%) regularly participated in soccer, basketball, volleyball, tennis, flag football, or swimming	16 of 18 (88.9%) subjects regularly participated in recreational running, 10 of 18 (55.6%) regularly participated in weight training, 6 of 18 (33.3%) regularly participated in basketball, soccer, flag football or tennis, and 5 of 18 (27.8%) regularly participated in recreational cycling
SLVJ height during pre-test (cm)	11.8 ± 2.9	11.7 ± 3.2
SLVJ height during post-test (cm)	12.2 ± 2.5	12.1 ± 2.9

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$120 for study participation, and control group subjects were reimbursed $20.

2.3. Experimental group (Group 1)

Group 1 subjects performed nine, approximately 20-min exercise sessions using the training device (approximately two sessions/week). The computerized training device used compressed air to provide concentric (positive work) or concentric (positive work)-to-eccentric (negative work) progressive resistance. The device harness enabled up to 15.2 cm of side-to-side excursion, and 280° one-way, long-axis rotation. The open training device frame provided an unobstructed view for monitoring user performance. The training device mirror positioned in front of the user provided visual performance feedback.

Each training and data collection session was preceded by 10-min of stationary cycling at a self-selected pace and 5-min of static stretching performing stretches that each subject routinely performed prior to exercise program or recreational sports activity. Stretching was not standardized to enable subjects to adhere to their existing routines. Subjects in each group displayed similar static stretching practices. Group 1 subjects performed seven exercise sets/session. During exercise performance subjects were instructed to assume an athletic ready position of slight trunk, hip, and knee flexion, and ankle dorsiflexion. Long-axis device rotation was set at 60 ± 10° one-way rotation (120 ± 20° total rotation) based on subject comfort. The primary investigator used the Borg Rating of Perceived Exertion Scale to monitor and control for subject perceived exercise intensity (Borg et al., 1987). Exercise session information is provided in Table 2. The primary investigator timed exercise set duration and subjects received between set rest periods based on a 3:1 rest-to-work ratio.

2.4. Control group (Group 2)

Group 2 (control) subjects did not participate in experimental device training.

2.5. Data collection

Prior to data collection subjects were instructed in SLVJ technique using their preferred stance lower extremity. The preferred stance lower extremity was operationally defined as the lower extremity that subjects preferred to use for stance when kicking a ball. Upon cue, subjects flexed their right knee approximately 45° to raise the right foot off the force platform, assuming a single leg stance position with the preferred stance lower extremity. Following this they were instructed to perform a maximal effort counter-movement SLVJ. Subjects were instructed to jump as powerfully and high as possible during propulsion and then perform a soft, controlled single leg landing with a flexed left knee, attempting to achieve and maintain stability as quickly as possible. Based on previous reports, kinematic (Gauffin and Tropp, 1992; Hewett et al., 2006; Pollard et al., 2010), ground reaction force (Alentorn-Geli et al., 2009; Colby et al., 1999; Myer et al., 2006; Paterno et al., 2007), or EMG (Bosco et al., 2000, 1982; Bosco and Viitasalo, 1982) evidence of safer or more efficient dynamic knee stability during jumping was operationally defined as improved lower extremity neuromuscular control. Subjects performed 3–4 practice trials prior to data collection. Subjects were encouraged to use natural arm swing during both SLVJ phases (Hara et al., 2006). Each data collection session consisted of three trials.

2.6. Surface electromyography

Surface electrode sites were cleansed with isopropyl alcohol and shaved. Figure eight shaped Ag/AgCl bipolar adhesive electrodes (4 cm × 2.2 cm) with two circular conductive areas (each 1 cm diameter) and a 2 cm inter-electrode distance (dual electrode #272, Noraxon, Scottsdale, AZ) were applied to the skin in parallel to the mid-muscle belly of gluteus maximus, gluteus medius, vastus medialis, rectus femoris, vastus lateralis, medial hamstrings, biceps femoris, and the medial head of gastrocnemius (SENIAM Sensor Location Recommendations, 2010). A reference electrode was applied over the anterior superior iliac spine of the test lower extremity. Electrode sites were demarcated with an oil-based skin marker to enable consistent pre-test, post-test placement.

Electromyographic (EMG) data were collected using an eight channel cable system (MyoSystem 1200, Noraxon, Scottsdale, AZ) with a 10–500 Hz bandwidth, >10 Mohm differential input impedance, a common mode rejection ratio of 100 db @ 50/60 Hz, and a 1000 Hz data sampling rate. After warm-up and stretching, surface EMG electrodes were applied and subjects were instructed in manual muscle testing (Kendall and McCreary, 2005) ramp contractions for each muscle or muscle group with an approximately 2 s time to peak activation, 6 s peak activation hold time, and 2 s gradual relaxation time. Mean maximal volitional isometric contraction (MVIC) EMG amplitudes (μV) from the 6 s peak activation period were used to standardize the EMG amplitudes measured during SLVJ trials.

2.7. EMG signal analysis

Following data collection, EMG signals were full wave rectified, a 60 Hz notch filter was applied, and 50 ms root mean square smoothing was performed. Propulsion and landing were partitioned into separate SLVJ phases for analysis so that each mean EMG amplitude value represented 100% of the respective phase. Subject bodyweight during relaxed single leg stance was determined following SLVJ practice and prior to data collection as

Table 2
Group 1 Ground Force 360 device training regimen. Rating of perceived exertion scale range (6 = no exertion to 20 = maximal exertion) (Borg et al., 1987). 13 = somewhat hard, 15 = hard (heavy) (mean ± standard deviation).

Session #	Set #	Mode	Subjective intensity	Rating of perceived exertion	Resistance (kg/cm^2)	Repetitions	Foot placement
1–5	1	Two-way concentric rotation	Low	13.1 ± 1.8	2.64 ± 0.84	20	Standard
	2	Two-way concentric rotation	Moderate	13.9 ± 2	3.24 ± 0.84	10	Standard
	3	Concentric left rotation–eccentric right rotation	Moderate-to-high	14.2 ± 1.7	4.27 ± 1.27	10	Standard
	4	Concentric right rotation–eccentric left rotation	Moderate-to-high	14.2 ± 1.8	4.27 ± 1.27	10	Standard
	5	Concentric left rotation–eccentric right rotation	Moderate	13.6 ± 1.7	3.61 ± 1.05	10	Diagonal
	6	Concentric right rotation–eccentric left rotation	Moderate	13.8 ± 2	3.60 ± 1.05	10	Diagonal
	7	Two-way concentric rotation	Moderate-to-low	13.4 ± 2	2.38 ± 0.63	20	Standard
6–9	The same subjective intensity, resistance progressions, and foot placements were used. The exercise mode for the fifth and sixth exercise sets changed to one-way concentric left and right rotation, respectively. The repetition goal changed to Set 1. = 15 repetitions, Sets 2–6 = 8 repetitions, and Set 7. = 15 repetitions. This was a planned study modification to maintain subject cognitive focus.						

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subjects stood motionless on in single leg stance on a force platform. During data collection the time period between vertical ground reaction force production greater than pre-determined single leg stance bodyweight and force cessation represented the SLVJ propulsion phase, and the time period between landing vertical ground reaction force production and return to pre-determined single leg stance bodyweight represented the SLVJ landing phase. Mean EMG signal amplitudes were determined for each jump trial phase. These values were divided by previously determined MVIC values. Following this, standardized EMG signal amplitudes determined during SLVJ propulsion and landing phases were divided by the peak vertical ground reaction force (standardized to subject bodyweight in N) determined during SLVJ propulsion and landing, respectively. Standardized EMG signal amplitude divided by vertical ground reaction force production provides a valid and reliable lower extremity neuromuscular efficiency measurement (Bosco et al., 2000, 1982; Bosco and Viitasalo, 1982; Cannon et al., 2001). The mean of these "unit-less" trial values was then determined for the pre-test and post-test conditions. Differences between conditions were expressed as mean percent change. All EMG signal smoothing and analysis was performed using MyoResearch software version 2.10 (Noraxon, Scottsdale, AZ).

2.8. Kinematics

Two cm diameter retro-reflective markers were applied via adhesive discs to the skin overlying the third lumbar spinous process, the greater trochanter (over cycling type gym shorts), the lateral femoral epicondyle, and over an athletic shoe approximately 2 cm distal to the lateral malleolus protuberance of the preferred stance lower extremity. Markers enabled two-dimensional sagittal plane kinematic data collection with a 60 Hz sampling rate, using a video camera (Sony DCR-HC30, Tokyo, Japan) positioned perpendicular to a sagittal plane calibration space (0.9 m wide by 1.4 m tall). Kinematic and ground reaction force data collection was time-synchronized (Simi Motion 2D, Unterschleissheim, Germany).

Hip angle was defined as the angle formed by the markers positioned over the third lumbar spinous process (low back), greater trochanter (hip), and lateral femoral epicondyle (knee). The angle that was operationally defined as hip angle has also been referred to as the trunk flexion angle as it represents composite or "non-partitioned" movement between the hip joint and trunk segments (Blackburn and Padua, 2009). Knee angle was defined as the angle formed by markers positioned over the greater trochanter (hip), lateral femoral epicondyle (knee) and immediately distal to the lateral malleolus (ankle).

2.9. Ground reaction forces

The force platform (Model 9286AA, Kistler, Winterthur, Switzerland) sampling rate was 1000 Hz. Peak vertical ground reaction forces during SLVJ propulsion and landing phases were also determined. Composite vertical-anteroposterior-mediolateral ground reaction force stabilization timing represented the sum of the time between initial SLVJ landing and the onset of when single leg stance bodyweight values were consistently re-established for vertical (±20 N), anteroposterior (±5 N) and mediolateral (±5 N) ground reaction forces divided by three.

2.10. Data analysis

Unpaired *t*-tests were used to compare pre-test, post-test mean change differences between groups (Dimitrov and Rumrill, 2003). The independent variable was subject group. The dependent variables included SLVJ propulsive and landing phase lower extremity neuromuscular efficiency, peak vertical ground reaction forces, composite ground reaction force stabilization timing following SLVJ landing, hip and knee position at SLVJ landing and peak displacement, and mean hip and knee flexion velocity during SLVJ landing. A pilot study of four subjects (2 men, 2 women) that met study inclusion criteria was performed to determine preliminary measurement reliability. Intraclass correlation coefficients (ICC) and 95% confidence intervals (95% CI) were calculated to describe the mean pre-test, post-test measurement reliability obtained without intervention and with four weeks between sessions. The ICC (3,1) formula was selected, since only one tester evaluated the subject population and compared mean measurements (Shrout and Fleiss, 1979). Moderate to high reliability was observed for gluteus maximus (0.93, 95% CI = 0.75–0.99; 0.90, 95% CI = 0.73–0.97), gluteus medius (0.91, 95% CI = 0.70–0.98; 0.94, 95% CI = 0.71–0.97), vastus medialis (0.95, 95% CI = 0.75–0.99; 0.81, 95% CI = 0.70–0.98), rectus femoris (0.95, 95% CI = 0.79–0.98; 0.95, 95% CI = 0.77–0.99), vastus lateralis (0.90, 95% CI = 0.75–0.99; 0.80, 95% CI = 0.67–0.98), medial hamstrings (0.91, 95% CI = 0.73–0.98; 0.98, 95% CI = 0.72–0.99), biceps femoris (0.94, 95% CI = 0.74–0.99; 0.91, 95% CI = 0.72–0.97), and medial gastrocnemius (0.87, 95% CI = 0.70–0.99; 0.92, 95% CI = 0.74–0.99) standardized EMG measurements during SLVJ propulsion and landing phases, respectively. Moderate to high reliability was observed for hip (0.91, 95% CI = 0.83–0.95; 0.93, 95% CI = 0.84–0.96) and knee (0.90, 95% CI = 0.85–0.95; 0.92, 95% CI = 0.84–0.98) initial and peak angular displacement magnitudes during SLVJ landing, and for mean hip (0.96, 95% CI = 0.74–0.99) and knee (0.86, 95% CI = 0.73–0.98) velocities during SLVJ landing. Moderate to high reliability was observed for peak vertical ground reaction force magnitude during SLVJ propulsion (0.94, 95% CI = 0.84–0.98) and SLVJ landing (0.98, 95% CI = 0.83–0.99), and for composite vertical, mediolateral, and anteroposterior ground reaction force stabilization timing (0.96, 95% CI = 0.79–0.99). An alpha level of $P \leqslant 0.05$ with Bonferroni corrections for multiple comparisons ($0.05/25 \leqslant 0.002$) was selected to indicate statistical significance. All statistical analysis was performed using SPSS version 11.0 software (SPSS, Chicago, IL).

Table 3
Standardized mean EMG amplitude/peak vertical ground reaction force during SLVJ propulsion (mean ± standard deviation).

	Group 1			Group 2			
	Pre-test	Post-test	Mean % change	Pre-test	Post-test	Mean % change	
Gluteus maximus	1.19 ± 0.46	0.93 ± 0.36	−21.8	0.92 ± 0.38	1.08 ± 0.46	+17.4	$t = -3.5$, $P = 0.001$*
Gluteus medius	1.33 ± 0.68	0.95 ± 0.44	−28.6	1.07 ± 0.41	1.23 ± 0.53	+15.0	$t = -3.4$, $P = 0.002$*
Vastus lateralis	1.81 ± 1.23	1.44 ± 0.61	−20.4	1.70 ± 0.93	1.70 ± 1.04	0	$t = -0.90$, $P = 0.38$
Rectus femoris	1.44 ± 0.59	1.05 ± 0.29	−27.1	1.16 ± 0.42	1.29 ± 0.59	+11.2	$t = -3.4$, $P = 0.002$*
Vastus medialis	1.83 ± 0.64	1.46 ± 0.49	−20.2	1.65 ± 0.41	1.80 ± 0.55	+9.1	$t = -3.7$, $P = 0.001$*
Medial hamstrings	0.94 ± 0.70	0.58 ± 0.21	−38.3	0.66 ± 0.35	0.86 ± 0.89	+30.3	$t = -4.3$, $P < 0.0001$*
Biceps femoris	0.82 ± 0.32	0.64 ± 0.34	−22.0	0.52 ± 0.25	0.43 ± 0.18	−17.3	$t = 0.95$, $P = 0.36$
Gastrocnemius	1.18 ± 0.59	1.23 ± 0.50	+4.2	1.12 ± 0.55	1.06 ± 0.40	−5.4	$t = -0.21$, $P = 0.83$

* $P \leqslant 0.002$.

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3. Results

3.1. Surface electromyography

For SLVJ propulsion, Group 1 standardized EMG amplitude mean change differences for gluteus maximus, gluteus medius, rectus femoris, vastus medialis, and medial hamstrings displayed greater reductions than Group 2. Training group subjects required less lower extremity neuromuscular activation to achieve the same level of lower extremity neuromuscular control as control group subjects suggesting improved neuromuscular efficiency for those muscles (Bosco et al., 2000, 1982; Bosco and Viitasalo, 1982; Green and Wilson, 2000; Wu et al., 2008) (Table 3). For SLVJ landing, Group 1 standardized EMG amplitude mean change differences for gluteus maximus and rectus femoris also displayed greater reductions than Group 2, suggesting a similar training effect (Table 4).

3.2. Ground reaction forces

For SLVJ propulsion, Group 1 standardized peak vertical ground reaction force mean change differences (+0.24 N/kg vs. −0.46 N/kg) differed from Group 2, suggesting that the training group generated greater SLVJ propulsive force. During SLVJ landing Group 1 subjects displayed a mean composite vertical-anteroposterior-mediolateral ground reaction force stabilization timing mean change difference that was quicker than Group 2 (−0.68 vs. +0.05 s) (Table 5). Greater SLVJ propulsive forces and earlier ground reaction force stabilization timing improvements suggest improved lower extremity neuromuscular control in the training group (Colby et al., 1999; Myer et al., 2006; Wikstrom et al., 2005).

3.3. Kinematics

For SLVJ landing, Group 1 mean hip flexion velocity (−16.3 vs. +7.8°/s) and mean knee flexion velocity (−21.4 vs. +18.5°/s) mean change differences displayed significant velocity reductions compared to Group 2 (Table 6). Decreased hip and knee velocity during SLVJ landing indicates improved lower extremity neuromuscular control (Hewett et al., 2006).

4. Discussion

Non-contact lower extremity injuries are more likely to occur during sport maneuvers like the SLVJ when trunk and lower extremity neuromuscular control is poor (Imwalle et al., 2009; McLean, 2008; Shimokochi and Shultz, 2008; Zazulak et al., 2007a,b). The goal of the lower extremity neuromuscular control system during single leg jump landings is to provide shock absorption (Coventry et al., 2006; Shimokochi and Shultz, 2008). Therefore, neuromuscular training programs that more effectively develop trunk-lower extremity neuromuscular control may be superior for maintaining safe lower extremity alignment and knee joint loads during dynamic tasks (Blackburn and Padua, 2009; Myer et al., 2008).

The increased peak vertical ground reaction force, and improved gluteus maximus, gluteus medius, rectus femoris, vastus medialis, and medial hamstrings neuromuscular efficiency observed during SLVJ propulsion suggests improved lower extremity neuromuscular control. Reduced mean hip and knee flexion velocity, earlier composite ground reaction force stabilization timing and improved gluteus maximus and rectus femoris muscle neuromuscular efficiency during SLVJ landing suggests a similar training effect.

This study provides evidence that short duration, progressive resistance, whole body, long-axis rotational training improved the lower extremity neuromuscular control of healthy subjects during SLVJ performance. Study limitations include a lack of synchronized three-dimensional kinematic, and inverse dynamic lower extremity internal moment analyses. These additions would have better delineated specific hip, knee, and ankle segment contributions to SLVJ performance. Also, given the relatively short training period, study results represent primarily neurogenic training adaptations. Subject responses to progressive resistance exercise are mediated by both neurogenic and myogenic factors,

Table 4
Standardized mean EMG/peak vertical ground reaction force during SLVJ landing (mean ± standard deviation).

	Group 1			Group 2			
	Pre-test	Post-test	Mean % change	Pre-test	Post-test	Mean % change	
Gluteus maximus	0.79 ± 0.33	0.53 ± 0.19	−32.9	0.72 ± 0.32	0.80 ± 0.46	+11.1	$t = -3.3$, $P = 0.002$*
Gluteus medius	0.87 ± 0.39	0.93 ± 0.75	+6.9	1.03 ± 0.99	0.92 ± 0.45	−10.7	$t = -0.27$, $P = 0.79$
Vastus lateralis	0.86 ± 0.52	0.67 ± 0.33	−22.1	0.74 ± 0.36	0.62 ± 0.20	−16.2	$t = -0.36$, $P = 0.72$
Rectus femoris	1.02 ± 0.80	0.68 ± 0.43	−33.3	0.69 ± 0.34	0.89 ± 0.49	+29.0	$t = -3.3$, $P = 0.002$*
Vastus medialis	1.04 ± 0.43	1.04 ± 0.55	0	1.04 ± 0.40	0.84 ± 0.21	−19.2	$t = 0.77$, $P = 0.45$
Medial hamstrings	0.65 ± 0.48	0.58 ± 0.74	−10.8	0.58 ± 0.41	0.66 ± 1.04	+13.8	$t = -.84$, $P = 0.41$
Biceps femoris	0.50 ± 0.16	0.38 ± 0.25	−24.0	0.31 ± 0.17	0.28 ± 0.13	−9.7	$t = -1.27$, $P = 0.21$
Gastrocnemius	0.63 ± 0.27	0.60 ± 0.27	−4.8	0.65 ± 0.25	0.51 ± 0.13	−21.5	$t = 0.64$, $P = 0.53$

* $P \leqslant 0.002$.

Table 5
Mean peak vertical ground reaction force during SLVJ propulsion and landing standardized to subject bodyweight, and composite vertical-anteroposterior-mediolateral ground reaction force stabilization timing results (mean ± standard deviation).

Variables	Group 1			Group 2			P
	Pre-test	Post-test	Mean % change	Pre-test	Post-test	Mean % change	
Peak vertical ground reaction force during Propulsion (N/kg)	7.63 ± 1.7	7.87 ± 1.5	+0.24	8.18 ± 1.9	7.72 ± 1.5	−0.46	$t = 3.3$, $P = 0.002$*
Peak vertical ground reaction force at landing (N/kg)	14.6 ± 2.7	15.1 ± 2.0	+0.50	14.0 ± 2.9	14.3 ± 1.8	+0.30	$t = 0.42$, $P = 0.68$
Stabilization time (s)	1.83 ± 0.83	1.15 ± 0.57	−0.68	1.65 ± 0.54	1.70 ± 0.79	+0.05	$t = -3.7$, $P = 0.001$*

* $P \leqslant 0.002$.

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Table 6
Left hip and knee kinematic results during SLVJ landing (mean ± standard deviation).

Variables	Group 1			Group 2			P
	Pre-test	Post-test	Mean % change	Pre-test	Post-test	Mean % change	
Hip flexion at landing (°)	21.1 ± 11	22.8 ± 9	+1.7	26.0 ± 9	25.7 ± 9	−0.3	$t = -0.25$, $P = 0.81$
Knee flexion at landing (°)	22.9 ± 6	23.9 ± 6	+1	25.7 ± 4	24.4 ± 6	−1.3	$t = 2.0$, $P = 0.05$
Peak hip flexion (°)	51.2 ± 17	52.2 ± 17	+1	50.1 ± 14	54.3 ± 15	+4.2	$t = 1.1$, $P = 0.27$
Peak knee flexion (°)	59.7 ± 9	64.2 ± 13	+4.5	55.6 ± 12	59.1 ± 11	+3.5	$t = 1.0$, $P = 0.31$
Mean hip flexion velocity (°/s)	−76.0 ± 16.2	−59.7 ± 20.5	−16.3	−58.8 ± 17.7	−66.6 ± 34.7	+7.8	$t = 3.3$, $P = 0.002$*
Mean knee flexion velocity (°/s)	142.8 ± 45.4	121.4 ± 50.9	−21.4	108.1 ± 37.9	126.6 ± 31.3	+18.5	$t = -4.1$, $P < 0.0001$*

* $P \leqslant 0.002$.

however neural system effects of improved recruitment responsiveness and efficiency are more common over the initial 3 weeks of a new training program (Moritani and de Vries, 1979). Study findings do not provide information regarding possible long-term benefits associated with progressive resistance, whole body, long-axis rotational training. Additionally, in this study the primary investigator oversaw all aspects of device range of motion, resistance, exercise mode adjustments and settings, subject positioning, technique, rest period monitoring, and total exercise volume control. Differences may exist when subjects independently adjust settings, select different movement patterns, resistance or training modes, or use differing postures and foot positions. Lastly, all subjects were healthy and athletically active. Further study is needed with other populations that might benefit from having improved lower extremity neuromuscular control during sport movements such as athletically active adolescents (Hewett et al., 2004; Myer et al., 2008) and patients that seek to safely return to sports with jumping components after undergoing lower extremity surgery such as ACL reconstruction (Gerber et al., 2009).

In conclusion, this study found that short duration, progressive resistance, whole body, long-axis rotational training improved the lower extremity neuromuscular control of healthy subjects during SLVJ performance. These findings are encouraging because no training session involved any actual jumping or jump landing tasks or their associated lower extremity impact loads and increased injury risks. For these reasons this type of training may also be a useful, low impact rehabilitation supplement following hip, knee or ankle surgery when jumping activities cannot be safely performed because of increased injury risk to healing and remodeling tissues. Further studies with other populations are indicated.

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