

[Physical Therapy]



Unstable Surface Improves Quadriceps:Hamstring Co-contraction for Anterior Cruciate Ligament Injury Prevention Strategies

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Background: Increasing quadriceps:hamstring muscular co-contraction at the knee may reduce the risk of anterior cruciate ligament (ACL) injury. The purpose of this investigation was to examine muscle activation in the quadriceps and hamstrings and peak kinematics of the knee, hip, and trunk when performing a single-leg drop (SLD) on to a Bosu ball (unstable surface) compared with on to the floor (stable surface).

Hypotheses: (1) The SLD on an unstable surface would lower the quadriceps to hamstrings electromyographic (EMG) activation ratio (Q:H EMG activation ratio) compared with being performed on the floor. (2) Lower Q:H EMG activation ratio would be caused by a relative increase in hamstring activation, with no significant change in quadriceps activation.

Study Design: Controlled laboratory study.

Methods: Thirty-nine Division I National Collegiate Athletic Association (NCAA) female athletes performed 3 SLDs per leg onto a Bosu ball and onto the floor. Muscle activity of the vastus lateralis and lateral hamstrings were used to estimate peak quadriceps and hamstring activation, along with the Q:H EMG activation ratio. Kinematic measures at the knee, hip, and trunk were also estimated. Differences between landings were assessed using a 2-level analysis of variance (limb and surface).

Results: The maximum Q:H EMG activation ratio was significantly reduced when athletes performed an SLD onto the Bosu ball (20%, $P < 0.001$) compared with the floor. Peak hamstring activity was higher when athletes landed on a Bosu ball (18% higher, $P = 0.029$) compared with when they landed on the floor.

Conclusion: Compared with landing on the floor (a stable surface), landing on a Bosu ball (unstable surface) changed the athlete's co-contraction at the knee and increased hamstring activity. However, landing on a Bosu ball also decreased the athlete's knee flexion, which was an undesired effect.

Clinical Relevance: These findings highlight the potential utility of unstable surfaces as a training tool to reduce the risk of ACL injury in female athletes.

Keywords: anterior cruciate ligament (ACL); sports injuries; prevention; intervention; perturbation

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Noncontact anterior cruciate ligament (ACL) injuries are 70% more common than contact ACL injuries²⁰ and often occur because of a perturbation, such as landing on an unstable surface. For example, noncontact ACL injuries are thought to occur at or near maximum knee extension during deceleration or acceleration when there are imbalances in the quadriceps and hamstrings.²⁶ This is a multifactorial problem with several well-established kinematic and neuromuscular risk factors. Female athletes are at risk when they land with reduced hip and knee flexion angles and increased trunk sway compared with uninjured athletes.^{11,12} The neuromuscular imbalance that occurs at the knee when there is decreased hamstring activation relative to quadriceps activation is also an established risk factor for ACL injury.^{1,15}

During landing and cutting, hamstrings activation can provide a counterbalancing force to protect against the relatively higher quadriceps force; this activation can reduce anterior tibial translation and decrease ACL strain.¹⁵⁻¹⁷ However, the ability of the hamstrings to coordinate recruitment with the quadriceps is in question.²⁴ In one study, decreased knee flexion (ie, straighter leg at landing) increased the overall quadriceps to hamstrings co-contraction index relative to landing with a more flexed knee; quadriceps activation was reduced when landing with decreased knee flexion, whereas the lateral hamstring activation was greater with decreased knee flexion.²⁴

Quadriceps and hamstrings muscle coordination is an important component to consider when understanding injury mechanisms and developing prevention strategies.

Perturbation and balance programs have been used to reduce the risk of ACL injuries.⁶⁻⁸ These programs generally involve standing or stepping onto unstable devices. Jump training is also used to reduce the risk of ACL injuries but is commonly performed on stable surfaces.^{11,14,21} One jump-training program onto a mattress, an unstable surface, produced an overall reduction in ACL injuries¹¹ and an increase in the hamstring-quadriceps peak torque ratio during dynamic muscle strength testing¹⁴; however, quadriceps and hamstring activations were not measured during the mattress jumps. Measuring the quadriceps to hamstring (Q:H) electromyographic (EMG) activation ratio during unstable jumping tasks may improve the assessment of an athlete's ability to co-contract in a game-like environment, where surface perturbation and instability are common.

Reduced knee and hip flexion, along with increased trunk sway during landing, are associated with increased ACL injury.^{1,12,22} Maximum ACL protection is achieved between 15° and 60° of knee flexion.¹⁷ Recently, a positive correlation between increased trunk sway and the knee valgus moment has also been found.^{12,22} The trunk is the largest mass of the body, and an inability to control trunk sway can increase the knee valgus moment.⁹ This is an important component of ACL injury prevention.

The objective of this study was to examine muscle activation patterns in the quadriceps and hamstrings and peak kinematics of the knee, hip, and trunk when performing a single-leg drop

(SLD) on to a Bosu ball (unstable surface) compared with on to the floor (stable surface). We hypothesized that performing a Bosu ball SLD would lower the Q:H EMG activation ratio compared with performing an SLD on the floor. We further hypothesized that the lower Q:H EMG activation ratio would be caused by a relative increase in hamstring activation, with no significant change in quadriceps activation.

METHODS

Experimental Approach to the Problem

Using surface EMG synchronized with a motion capture system, we estimated muscle activation patterns and joint kinematics of the knee, hip, and trunk. An SLD was selected for the movement, as it mimics similar movements found in sports where athletes are at risk for ACL injuries, such as rebounding and cutting. SLDs are also often used during screening, training, and rehabilitation. We used knee and trunk kinematics and the muscular activation ratios as dependent variables, as they have been previously associated with ACL injuries.¹⁷ The landing styles (surfaces) were selected for the independent variable because they are an easy environmental factor to modify and hypothesized to solicit change to the kinematic and neuromuscular variables.

Subjects

Thirty-nine female National Collegiate Athletic Association (NCAA) Division I athletes (mean age, 19.2 ± 1.2 years; mean weight, 67.2 ± 8.7 kg; mean height, 1.73 ± 0.09 m) from field hockey (n = 13), lacrosse (n = 18), or basketball (n = 8) volunteered to participate in this study. Written informed consent was obtained for all subjects in accordance with the requirements of the Stanford University Institutional Review Board.

Procedures

Electromyography data were recorded (1200 Hz) from the vastus lateralis, shown to be an active quadriceps muscle during landing tasks,²⁷ and lateral hamstrings (Bagnoli Desktop; DelSys, Inc) using preamplified, single-differential, rectangular Ag electrodes with 10-mm interelectrode distance (DE-2.1; DelSys, Inc).

Kinematic data were collected (120 Hz) using an 8-camera optical motion analysis system (Vicon; Oxford Metrics Group) synchronized with a floor-mounted force plate, collected at 1200 Hz (Bertec Corporation). Three retroreflective tracking markers per segment were affixed to each subject's foot, shank, and thigh. Retroreflective markers were also attached to anatomical landmarks (Figure 1). A static standing trial was performed with feet hip width apart and parallel to the laboratory's coordinate system. The participant performed a star pattern with each limb, which was used to calculate the functional hip joint center for both limbs.³ The medial markers on the femur and malleoli were subsequently removed for all dynamic trials.

Dynamic testing commenced with an SLD onto the floor (6-mm rubber flooring, ie, a stable surface) followed by an SLD



Figure 1. Tasks. (a) Single-leg drop (SLD) onto a level force plate off a 46-cm step (floor SLD). (b) Single-leg drop off a 46-cm step onto a Bosu ball located 19 cm above the force plate (Bosu SLD).

on to the flat surface of a Bosu ball (ie, an unstable surface) (Bosu). The force plate was located below the surface during all landings (Figure 1). Subjects had previously trained with Bosu balls; however, they had not previously performed an SLD on to a Bosu ball. For the floor SLD, athletes dropped down from a 46-cm step on to the floor that was 6 mm above the force plate. For the Bosu SLD, the athletes dropped down from a 46-cm step on to a Bosu ball that was approximately 19 cm above the force plate after deformation. The athletes held all landings for a minimum of 2 seconds. Three successful trials per leg were collected per activity. Further description of the data analysis can be found in the appendix (available at <http://sph.sagepub.com/content/by/supplemental-data>).

Statistical Analysis

Three trials were averaged for each subject after being visually checked for consistency and compliance with the experimental protocol. A 2-level (limb and surface) analysis of variance (ANOVA) was used to test for significant differences across the surfaces. A 3-level (limb, surface, muscle) ANOVA was used to test for significant differences in the timing of peak quadriceps and hamstring activations. SPSS (IBM) was used for all analyses, with significance set at $P < 0.05$. As there were no significant differences with respect to limb dominance, the following results and discussion for both the EMG and kinematics measures are reported with pooled-limb data.

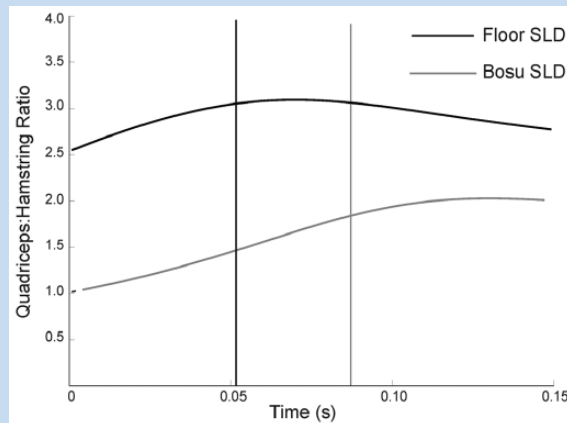


Figure 2. Quadriceps:hamstrings electromyographic (Q:H EMG) activation ratio curve during a single-leg drop (SLD). The quadriceps activation compared with the hamstring activation at each time point (Q:H EMG activation ratio) for subjects performing the floor SLD (black line) and a Bosu SLD (gray line). All peaks were calculated between the point of initial contact (time = 0 seconds) to maximum deceleration (indicated by the vertical lines; black, floor SLD; gray, Bosu SLD).

RESULTS

The Q:H EMG activation ratio was reduced by 20% from 4.22 ± 2.97 during the floor SLD to 3.36 ± 2.44 during the Bosu SLD ($P < 0.001$) (Figure 2, Table 1). Peak hamstring activation was significantly greater during the Bosu SLD (0.41 ± 0.15) compared with the floor SLD (0.38 ± 0.21 , $P = 0.029$) (Figure 3). The quadriceps activation was reduced when the athletes performed the Bosu SLD compared with when they performed the floor SLD (Bosu SLD, 0.57 ± 0.26 ; floor SLD, 0.90 ± 0.64 ; $P < 0.001$). The reduction in quadriceps activation when subjects performed the Bosu SLD had a greater effect on the maximum Q:H EMG activation ratio than the increased hamstring activation.

We observed a muscle-surface interaction for the timing of peak quadriceps and peak hamstring activation ($P < 0.001$) (Figure 4). This indicated that peak quadriceps activation occurred significantly later (69 ± 32 ms) when subjects performed the Bosu SLD compared with when they performed the floor SLD (48 ± 16 ms) and compared with the hamstring activation (Bosu SLD, 40 ± 42 ms; floor SLD, 41 ± 23 ms). The timing of peak hamstring activation was not significantly different between the single-leg drops ($P = 0.888$).

Peak knee and trunk flexion differed between activities (Figure 5, Table 1). Athletes' peak knee flexion angles were less (Bosu SLD, $30^\circ \pm 8^\circ$; floor SLD, $38^\circ \pm 7^\circ$; $P < 0.001$), as were their trunk flexion angles (Bosu SLD, $11^\circ \pm 6^\circ$; floor SLD, $12^\circ \pm 5^\circ$; $P = 0.035$) when subjects performed the Bosu SLD compared with when they performed the floor SLD. There were no significant differences in the peak hip flexion angle.

Table 1. Kinematic data and muscle activities for 39 female NCAA division I athletes (field hockey [n = 13], lacrosse [n = 18], basketball [n = 8]) who performed a single-leg drop onto a stable surface (floor) and an unstable surface (Bosu ball)^a

	Stable Surface, Mean (SD)	Unstable Surface, Mean (SD)	P Value (Surface)	P Value (Limb)
Magnitude–surface interaction				
Max knee flexion angle, deg	38 (7)	30 (8)	0.000	0.252
Max hip flexion angle, deg	38 (7)	39 (6)	0.134	0.606
Max hamstrings	0.38 (0.21)	0.41 (0.15)	0.029	0.853
Max quadriceps	0.90 (0.64)	0.57 (0.26)	0.000	0.248
Max Q:H EMG activation ratio	4.22 (2.97)	3.36 (2.44)	0.000	0.972
Max trunk flexion angle, deg	12 (5)	11 (6)	0.035	1.000
Max trunk sway angle, deg	3 (2)	4 (2)	0.040	0.842
Frontal plane displacement of the knee joint center, cm	1.5 (1.6)	2.0 (2.2)	0.019	0.128
Timing–surface and muscle interaction				
Time of peak hamstring activation, ms	41 (23)	40 (42)	0.000	0.849
Time of peak quadriceps activations, ms	48 (16)	69 (32)		

EMG, electromyography; H, hamstrings; max, maximum; NCAA, National Collegiate Athletic Association; Q, quadriceps.

^aThe hip flexion angle was the only variable that was not significantly different between the 2 surfaces.

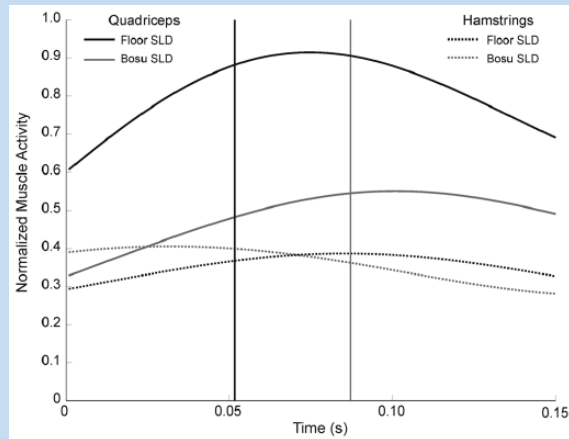


Figure 3. Quadriceps and hamstring activation during a single-leg drop (SLD). The mean curves of the peak quadriceps (solid) and hamstring activation (dotted) for subjects performing the floor SLD (black line) and a Bosu SLD (gray line). All peaks were calculated between the point of initial contact (time = 0 seconds) to maximum deceleration (indicated by the vertical lines; black, floor SLD; gray, Bosu SLD).

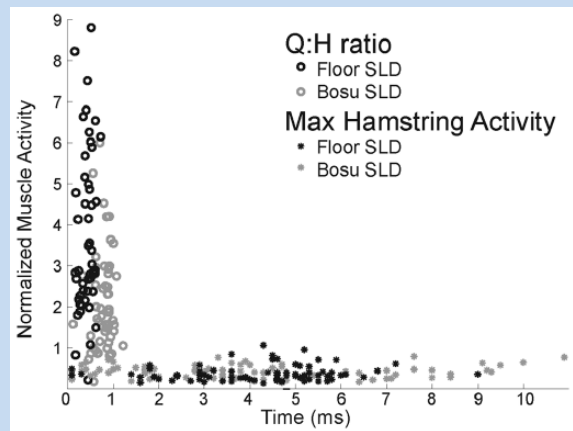


Figure 4. Peak co-contraction and hamstring activation during a single-leg drop (SLD). The peak quadriceps activation compared with the hamstring activation (Q:H ratio, open circles) and the peak hamstring activation (stars) for subjects performing the floor SLD (black) and a Bosu SLD (gray).

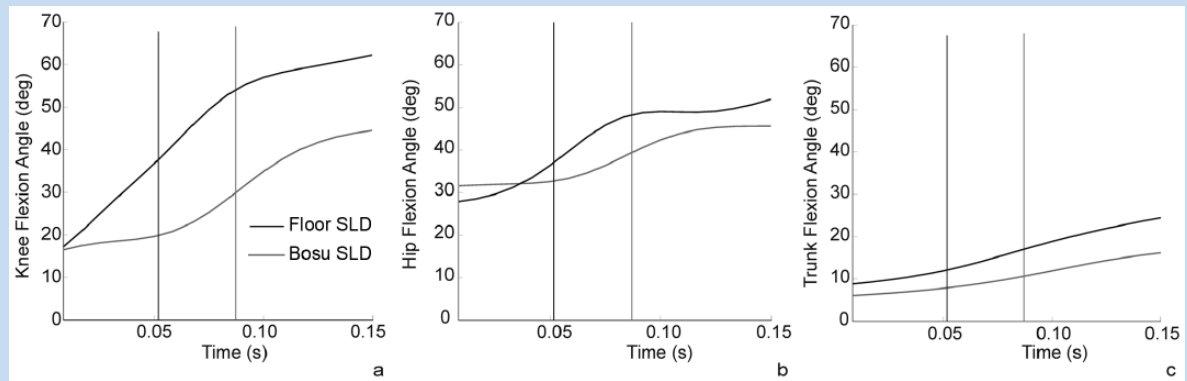


Figure 5. Flexion angles of the knee, hip, and trunk during a single-leg drop (SLD). Mean (a) knee, (b) hip, and (c) trunk flexion angles for subjects performing the floor SLD (black line) and Bosu SLD (gray line). All peaks were calculated between the point of initial contact (time = 0 seconds) to maximum deceleration (indicated by the vertical lines; black, floor SLD; gray, Bosu SLD).

Athletes also increased their trunk sway when performing the Bosu SLD compared with the floor SLD (Bosu SLD, $4^\circ \pm 2^\circ$; floor SLD, $3^\circ \pm 2^\circ$; $P = 0.040$). Medial knee movement in the frontal plane was also significantly greater ($P = 0.019$) when subjects performed the Bosu SLD (2.0 ± 2.2 cm) compared with when they performed the floor SLD (1.5 ± 1.6 cm).

DISCUSSION

As hypothesized, the maximum Q:H EMG activation ratio was significantly lower when subjects performed the Bosu SLD compared with when they performed the floor SLD (see Figure 2, Table 1). In support of our second hypothesis, the Bosu SLD increased peak hamstrings recruitment compared with the floor SLD.

A less balanced quadriceps to hamstring strength ratio may increase ACL injury risk,^{1,11,23,28} as the tibia may translate more anteriorly without the counterforce provided by the hamstrings.^{17,19} Strength is one component of this injury prevention mechanism, but if an athlete does not solicit this muscle in the proper activation sequence, the strength gain may not be translated to movement patterns that reduce the risk of injury. Quadriceps dominance in an athlete is often caused by an imbalance between the more activated quadriceps and the less activated hamstrings. Muscle strength, recruitment, and coordination all influence the degree to which co-contraction occurs.¹⁴ Our results show similarities to the results to Podraza and White,²⁴ who found that decreased knee flexion (ie, straighter leg at landing) lowered the quadriceps activation and increased the lateral hamstring activation. Although hamstrings activation increased throughout the deceleration phase when the athletes performed the floor SLD, it remained less than the activation levels obtained during the Bosu SLD. It is also possible that the decrease in peak knee flexion when athletes landed on a Bosu ball may have been due to the athlete's apprehension when performing the unstable task. Individuals tend to use higher levels of co-contraction when performing new tasks.¹⁸

Increased knee flexion may reduce the risk of ACL injuries, as the ACL is best protected at 60° of knee flexion.^{2,4} During the Bosu SLD, subjects landed with less knee flexion (Figure 5), which is an undesired effect.^{1,13} It is important to consider that apprehension from the athlete performing a new task may have created a more upright posture during the Bosu ball landing, thereby decreasing their trunk lean as well. The potential benefits of the unstable surface with respect to co-contraction may neutralize the increased risks found in the knee and trunk kinematic results. Training on an unstable surface in a safe environment, such as one that progresses an athlete from an assisted step-down to a solo step-down on to an unstable surface, may be a useful technique to prepare athletes to co-contraction during on-the-field training, where surface perturbation and instability are common.

This research has limitations. Athletes participated in a variety of Bosu ball training exercises and were given unlimited preparatory trials; however, they may have remained apprehensive about landing. We did not adjust the height of the step to compensate for the higher landing surface when the athletes landed on a Bosu ball, which could have changed the relative muscle activations and knee kinematics observed in our study. However, we suspect that any differences due to landing heights (current study floor SLD, 46 cm; Bosu SLD, 27 cm) are likely negligible, as a previous study found no significant difference in knee kinematics or muscle activations when landing from 50.8 and 25.4 cm.¹⁰

In conclusion, the athletes not only reduced their quadriceps activation relative to their hamstrings activation, but they also decreased their knee flexion when they performed a Bosu SLD compared with the floor SLD.

Practical Application

Unstable surface training when standing on quasi-static systems, such as wobble boards, has produced significant changes in

neuromuscular recruitment patterns and the athlete's ability to react to perturbations.^{6,8} An athlete can solicit similar protective neuromuscular recruitment patterns during landing on an unstable surface. Using unstable surface training during landing, which is a more sport-specific activity than standing, may better prepare the athlete for the challenges during sport.

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