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original research

# Sagittal-Plane Trunk Position, Landing Forces, and Quadriceps Electromyographic Activity

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***Context:*** Researchers have suggested that large landing forces, excessive quadriceps activity, and an erect posture during landing are risk factors for anterior cruciate ligament (ACL) injury. The influence of knee kinematics on these risk factors has been investigated extensively, but trunk positioning has received little attention.

***Objective:*** To determine the effect of trunk flexion on landing forces and quadriceps activation during landing.

***Design:*** Two (sex) × 2 (task) repeated-measures design.

***Setting:*** Research laboratory.

***Patients or Other Participants:*** Forty healthy, physically active volunteers (20 men, 20 women).

***Intervention(s):*** Participants performed 2 drop-landing tasks. The first task represented the natural, or preferred, landing strategy. The second task was identical to the first except that participants flexed the trunk during landing.

***Main Outcome Measure(s):*** We measured peak vertical and posterior ground reaction forces and mean quadriceps electromyographic amplitude during the loading phase of landing (ie, the interval from initial ground contact to peak knee flexion).

***Results:*** Trunk flexion decreased the vertical ground reaction force ($P < .001$) and quadriceps electromyographic amplitude ($P < .001$). The effect of trunk flexion did not differ across sex for landing forces or quadriceps electromyographic activity.

***Conclusions:*** We found that trunk flexion during landing reduced landing forces and quadriceps activity, thus potentially reducing the force imparted to the ACL. Research has indicated that trunk flexion during landing also increases knee and hip flexion, resulting in a less erect landing posture. In combination, these findings support emphasis on trunk flexion during landing as part of ACL injury-prevention programs.

***Key Words:*** anterior cruciate ligament, ground reaction forces, injury prevention, risk factors

**Key Points**

- Trunk flexion during landing reduced landing forces and quadriceps activity.
- The influence of trunk flexion on landing forces and quadriceps activity did not differ across sex.
- Trunk flexion potentially reduces the quadriceps force requirement and subsequent load placed on the anterior cruciate ligament immediately after ground contact during landing.
- Because of its influences on kinetic, kinematic, and neuromuscular risk factors for anterior cruciate ligament injury, active trunk flexion during landing might be an important component of injury-prevention programs.

Noncontact anterior cruciate ligament (ACL) injury commonly occurs immediately after initial ground contact during landing activities.[1,2] Upon ground contact, the knee is subjected to an external flexion moment produced by vertical and posterior ground reaction forces and downward acceleration of the mass proximal to the knee (Figure 1). These landing forces have been reported in excess of 10 times the body weight[3] and have received considerable attention for their potential influence on ACL injuries. In a prospective investigation by Hewett et al,[4] individuals who sustained ACL injuries produced landing forces that were 20% greater than those who did not incur injury. Similarly, vertical and posterior ground reaction forces have been demonstrated to be predictors of anterior tibial acceleration[5] and shear force[6] during landing tasks, which are factors indicative of ACL loading.[7,8] Based on this notion, numerous investigations and ACL injury-prevention programs have been implemented in an effort to reduce landing forces.[9–11]

After initial ground contact during landing, the quadriceps act eccentrically to counter the knee flexion imposed by ground reaction forces. Research in the cadaveric knee[12,13] and in vivo[14] has indicated that quadriceps activation introduces stress and strain to the ACL and is capable of producing ACL injury and rupture in vitro.[15] External knee flexion moment increases as a function of greater landing forces,[3] thus requiring a proportional increase in quadriceps force to provide adequate countermoment. Therefore, lower ground reaction forces are likely associated with a lower quadriceps force requirement, potentially reducing the force imparted to the ACL. Higher ground reaction forces are associated with a more erect or upright landing posture.[11,16] Females, who compose a population at heightened risk for ACL injury,[17,18] display a more erect posture during landing compared with males, as evidenced by more extended knee,[6,19–22] hip,[6,19–22] and trunk[19] positions. Not surprisingly, greater quadriceps electromyographic (EMG) activity[23] and ground reaction forces[21] have been reported in females than in males during landing. Therefore, a more erect posture may place the ACL at greater risk for injury by increasing landing forces and the quadriceps force requirement.

The closed kinematic chain nature of landing necessitates that lower extremity joint kinematics are coupled and function in concert to attenuate landing forces.[22,24] In a

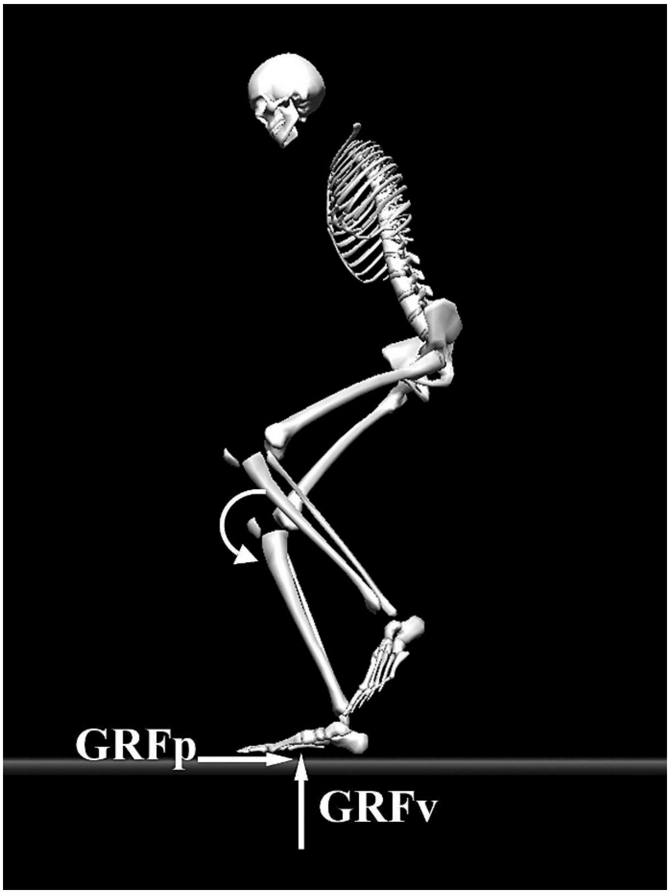


**Figure 1. Influences of landing forces on the knee joint. Both the vertical (GRFv) and posterior (GRFp) ground reaction forces have the tendency to produce knee flexion during landing. This imposed knee flexion must be countered by the quadriceps to prevent collapse of the lower extremity during landing.**

previous report on the kinematic data associated with this investigation, we demonstrated that active trunk flexion during landing produced concomitant increases in knee and hip flexion,[25] placing the lower extremity in a more flexed position, consistent with reduced ACL injury risk.[26] As such, greater trunk flexion during landing may limit ACL loading and injury risk by reducing ground reaction forces and quadriceps force requirement. Therefore, the purpose of our investigation was to determine the effect of trunk flexion on landing forces and quadriceps activity during a drop-landing task. We hypothesized that active trunk flexion during landing (flexed landing strategy) would decrease landing forces and quadriceps EMG amplitude compared with the participants' natural or preferred landing strategy. Additionally, we hypothesized that landing forces and quadriceps EMG amplitude would be greater in women than in men but that active trunk flexion would decrease these values in women so that they would be similar to those in men during the preferred landing strategy.

## METHODS

### Participants

Forty healthy individuals volunteered to participate in our investigation (20 men: age = 22.35 ± 2.25 years, height = 1.80 ± 0.08 m, mass = 86.05 ± 17.04 kg; 20 women: age = 20.70 ± 0.80 years, height = 1.66 ± 0.06 m, mass = 63.15 ± 7.73 kg). All participants were physically active and had no history of ACL injury, lower extremity surgery, neurologic disorder, chronic lower extremity injury, or acute lower extremity injury within the 6 months before data collection. We defined *physically active* as participating in physical activity for a minimum of 20 minutes, 3 times per week. Before data collection, all participants read and signed an informed consent document, and the study was approved by the Biomedical Institutional Review Board at the University of North Carolina at Chapel Hill. All data were sampled from the right lower extremity, which corresponded with the dominant limb (ie, limb used to kick a ball for maximal distance) in 37 of 40 participants (93%).

### Instrumentation

Kinematic, kinetic, and EMG data acquisition were synchronized using the MotionMonitor motion capture system (Innovative Sports Training Inc, Chicago, IL). Using doubled-sided tape, we placed 6–degrees-of-freedom electromagnetic sensors (Flock of Birds; Ascension Technologies Inc, Burlington, VT) on the right shank and thigh, sacrum, and thorax. We established world and segment axis systems via a right-hand coordinate system and designated the x-axis as positive anteriorly (forward), the y-axis as positive medially (left), and the z-axis as positive superiorly (upward). A segment linkage model of the trunk and lower extremity was generated by digitizing the joint centers of the ankle, knee, hip, T12-L1, and C7-T1. Spinal column landmarks were defined as the digitized space between the associated spinous processes, whereas the ankle and knee joint centers were defined as the midpoints between the digitized medial and lateral malleoli and medial and lateral femoral condyles, respectively. The hip joint center was defined via a least-squares method.[27] Ground reaction forces were sampled via a nonconductive force plate (model 4060-NC; Bertec Corp, Columbus, OH). We placed preamplified surface EMG electrodes (Bagnoli 8 Desktop EMG System; DelSys Inc, Boston, MA) over the vastus lateralis muscle parallel to the direction of action potential propagation to monitor quadriceps activity. The interelectrode distance was 10 mm, the amplification factor was 10 000 (20–450 Hz), the common mode rejection ratio at 60 Hz was more than 80 dB, and the input impedance was more than $10^{15}$ ohms. Proper electrode placement and minimal cross-talk were verified via manual muscle testing.[28]

### Experimental Procedures

Participants performed 2 drop-landing tasks during which trunk and lower extremity kinematics, ground reaction forces, and quadriceps EMG were sampled using a repeated-measures design. The first task (preferred landing) represented the participant's natural, or preferred, landing strategy and consisted of a vertical drop landing from a platform that was 60 cm high and positioned 10 cm from the leading edge of the force plate.[21] We instructed participants to step off the platform with the right leg extended while minimizing vertical displacement (Figure 2) and to perform a double-leg landing with only the right foot making contact with the force plate.[3] The second task

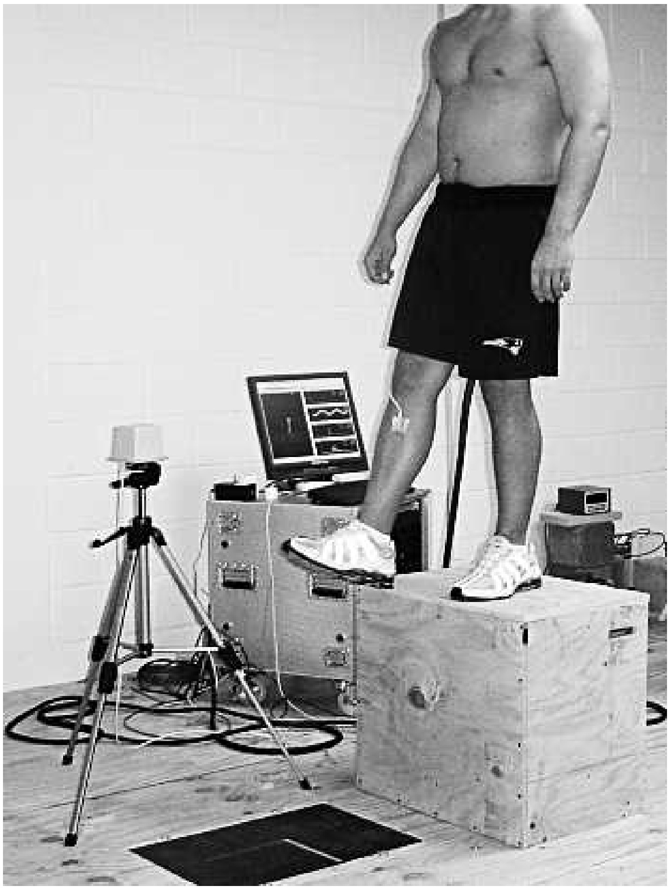

**Figure 2. Participant positioning during drop-landing tasks.**

(flexed landing) was identical to the preferred-landing task, except that we instructed participants to actively flex the trunk during landing. Five trials were conducted for each task. After completion of each trial, we assessed the maximal displacement of the electromagnetic sensor placed on the sacrum. If this displacement exceeded 10 cm, indicating jumping rather than stepping off the box, the trial was discarded and repeated. Preferred landings were always performed before flexed landings because participant knowledge of the intent of the second task (ie, trunk flexion during landing) may have biased the preferred-landing strategy.

## Data Sampling and Processing

We sampled electromagnetic sensor data at 100 Hz, whereas EMG and force plate data were sampled at 1000 Hz. Kinematic data were time synchronized to the EMG and force plate data and resampled to 1000 Hz. Kinematic data were low-pass filtered at 10 Hz with a fourth-order, zero-phase-lag Butterworth filter.[22] Kinetic data were low-pass filtered at 50 Hz with a fourth-order, zero-phase-lag Butterworth filter,[4] and ground reaction forces were standardized to body weight. The EMG data were corrected for direct current bias; band-pass filtered (20–350 Hz) and notch filtered (59.5–60.5 Hz) with a fourth-order, zero-phase-lag Butterworth filter; and smoothed using a root mean square sliding window function with a 10-millisecond time constant. We standardized EMG amplitudes for each task to maximal voluntary isometric contractions (MVICs) derived from manual muscle tests.[28] Participants were seated with the test knee flexed to 90° and contracted maximally against manual resistance. Kinematic angles were calculated as Euler angles rotated in a yxz (sagittal plane, frontal plane, transverse plane) sequence.[6] Knee angles were calculated as the shank reference frame relative to the thigh reference frame; hip angles were calculated as the thigh reference frame relative to the pelvis reference frame; and trunk angles were calculated as the trunk reference frame relative to the thigh reference frame. Although this definition of trunk flexion differs from standard kinematic conventions (ie, motion of the trunk segment relative to the pelvis), the angle between the trunk and thigh segments is more readily measured in the clinical setting and may be more easily incorporated into future injury-prevention efforts.

We calculated peak values for the vertical and posterior ground reaction forces and calculated mean quadriceps EMG amplitude over the loading phase of each landing (ie, interval from initial ground contact to peak knee flexion angle).[6] Initial ground contact was defined as the instant at which the vertical ground reaction force exceeded 10 N. We calculated mean values for each dependent variable across the 5 trials for each task. Dependent variables were compared across sex and landing tasks (preferred, flexed) using a 2 (sex) $\times$ 2 (task) analysis of variance with repeated measures. The $\alpha$ level was set a priori at .05.

## RESULTS

The kinematic data resulting from this investigation have been detailed in a previous report.[25] In brief, the flexed landing produced increases in peak trunk (mean increase = 47°), hip (mean increase = 31°), and knee (mean increase = 22°) flexion angles. Mean quadriceps EMG amplitude was less during the flexed landing than during the preferred landing ($F_{1,38} = 22.053$, $P < .001$) but did not differ across sex ($F_{1,38} = 0.150$, $P = .70$). The sex $\times$ task interaction effect was not significant ($F_{1,38} = 0.269$, $P = .993$), indicating that the decrease in quadriceps activity attributable to trunk flexion was similar across sex. The peak vertical ground reaction force was also less during the flexed landing than during the preferred landing ($F_{1,38} = 41.607$, $P < .001$) and was greater in men than in women ($F_{1,38} = 12.212$, $P = .001$). This sex difference was consistent across both landing tasks, as the sex $\times$ task interaction effect was not significant ($F_{1,38} = 0.045$, $P = .833$), indicating that the decrease in the vertical ground reaction force attributable to trunk flexion was similar in men and women. Lastly, peak posterior ground reaction force was less during the flexed landing than during the preferred landing. This difference approached but did not reach significance ($F_{1,38} = 3.914$, $P = .055$; effect size [Cohen d] = 0.26).[29] Additionally, peak posterior ground reaction force did not differ across sex ($F_{1,38} = 2.991$, $P = .092$), and the sex $\times$ task interaction effect was not significant ($F_{1,38} = 1.777$, $P = .191$). Means and SDs for each dependent variable during each drop-landing task are presented in the Table.

## DISCUSSION

The primary findings of this investigation were that trunk flexion during landing reduced vertical ground reaction forces and quadriceps activity. These findings

Table. Dependent Variable Descriptive Statistics (Mean ± SD)

| | Preferred | Flexed |
|---|---|---|
| Vertical ground reaction force (× body weight) | | |
| Men[a] | 4.37 ± 0.80 | 3.78 ± 0.68 |
| Women | 3.60 ± 0.65 | 3.05 ± 0.78 |
| Collapsed across sex[b] | 3.98 ± 0.82 | 3.42 ± 0.81 |
| Posterior ground reaction force (× body weight) | | |
| Men | 0.77 ± 0.17 | 0.70 ± 0.13 |
| Women | 0.82 ± 0.15 | 0.80 ± 0.16 |
| Collapsed across sex | 0.79 ± 0.16 | 0.75 ± 0.15 |
| Quadriceps electromyographic amplitude (%MVIC) | | |
| Men | 205 ± 172 | 145 ± 131 |
| Women | 227 ± 222 | 166 ± 163 |
| Collapsed across sex[b] | 216 ± 197 | 156 ± 146 |

Abbreviation: %MVIC, percentage of maximal voluntary isometric contraction.

[a] Men different from women (ie, sex main effect).

[b] Preferred landing different from flexed landing (ie, task main effect).

indicate that trunk flexion potentially reduces the quadriceps force requirement and subsequent load placed on the ACL immediately after ground contact, which is when ACL injury reportedly occurs.[1,2] Our previous report on the lower extremity kinematics from this investigation demonstrated that trunk flexion during landing produced greater knee and hip flexion compared with a more erect or trunk-extended landing posture,[25] placing the lower extremity in a position associated with decreased ACL injury risk.[26] As such, active trunk flexion could be an integral component of ACL injury-prevention programs by virtue of its ability to simultaneously influence kinetic, kinematic, and neuromuscular variables that have been suggested as risk factors for ACL injury.

Comparison of our data with findings in the literature is limited because we are unaware of any investigations in which the researchers evaluated the effects of sagittal-plane trunk position on kinetics and neuromuscular control during landing tasks. However, our data for the preferred landing correspond with findings in the literature for vertical ground reaction forces[21,22] during drop landings from a height of 60 cm. We expected that vertical ground reaction forces (standardized to body weight) would be larger in women, in accordance with the findings of Salci et al.[21] However, these values were greater in men. Though not significantly different, Decker et al[22] and McNair and Prapavessis[30] reported larger standardized vertical ground reaction forces in males compared with females. With regard to EMG amplitudes, Hanson et al[23] reported a mean vastus lateralis EMG amplitude (collapsed across sex) of 198% MVIC during a drop-landing task from a height of 30 cm. The greater EMG amplitude noted in our investigation is likely due to the greater drop height. However, the data that Hanson et al[23] provided validate the notion that quadriceps EMG during landing tasks commonly exceeds maximal values obtained during isometric reference contractions. We also expected quadriceps EMG amplitude to be greater in women, as previously reported.[23] However, the lack of a sex difference in quadriceps activity during landing also has been reported by Fagenbaum and Darling.[31] Finally, Saha et al[32] assessed lower extremity kinematics and kinetics during walking gait and reported increases in peak hip and knee flexion and a decrease in the vertical ground reaction force with trunk flexion. Their findings correspond with our findings during landing tasks.

Vertical and posterior ground reaction forces induce knee flexion during ground contact (Figure 1). To prevent collapse of the lower extremity during landing, these forces and the imposed external knee flexion must be countered by the internal knee extension moment that the quadriceps provide. Yu et al[6] demonstrated that peak vertical and posterior ground reaction forces were correlated with peak anterior tibial shear force and peak internal knee extension moment during a landing task, and they suggested that ground reaction forces could be used to predict ACL loading. Based on these notions, we suggest that the decreases in landing forces with trunk flexion noted in our investigation likely are indicative of a decrease in ACL loading. Although the absolute magnitudes of ground reaction forces are not representative of the load magnitude realized by the ACL, they are correlated with anterior tibial acceleration[5] and anterior tibiofemoral shear force,[6] which directly contribute to the load placed on the ACL.[7,8]

Trunk flexion during landing also resulted in a substantial decrease in quadriceps EMG amplitude of 60% MVIC (collapsed across sex). Although EMG amplitude and muscle force are not synonymous, investigators have long recognized that these phenomena are correlated in a highly linear manner during submaximal isometric contraction.[33] Researchers have demonstrated decreases in quadriceps EMG amplitude and tensile force, internal knee extension moment, and anterior tibial shear force during simulated landing tasks during which participants performed an isometric squat with the trunk in either a flexed or extended position.[34,35] This reduction in quadriceps force requirement is likely due to the fact that trunk flexion brings the trunk segment center of mass closer to the knee joint, thus decreasing its contribution to the external knee flexion moment[36] (Figure 3). Although an accurate quadriceps force estimate during drop landings is not available for our investigation, the reduced quadriceps activity combined with the decreased landing forces indicates that trunk flexion during landing effectively reduces the quadriceps force requirement. Numerous investigators have demonstrated both in vitro[12,13,15,37] and in vivo[14] that ACL stress and strain increase as a function of quadriceps or patellar tendon force. In fact, Withrow et al[37] recently indicated that 75% of the variance in ACL strain in the cadaveric knee is attributable to quadriceps force, and DeMorat et al[15] were able to induce cadaveric

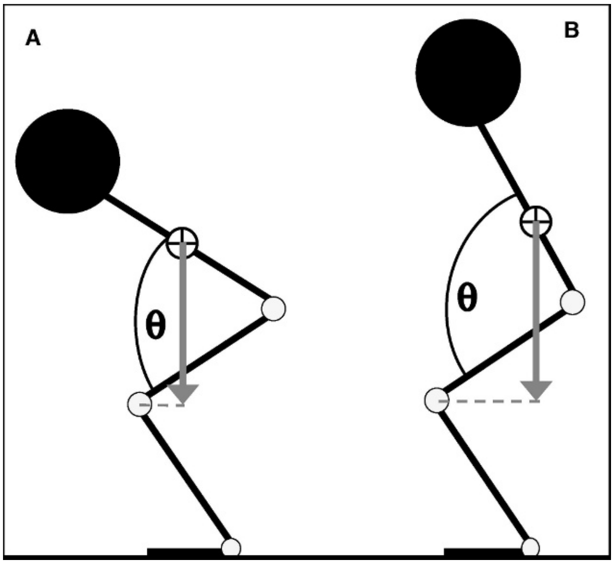


**Figure 3. Effect of trunk flexion angle (θ) on trunk center-of-mass location. Trunk flexion (A) moves the trunk center of mass (white circle) and associated weight force (solid arrow) closer to the knee joint center of rotation relative to a more extended trunk position (B). The approximation of the trunk center of mass and knee joint effectively decreases the moment arm for the trunk weight force about the knee (dashed line).**

ACL injury and rupture via isolated quadriceps loading. As such, any factor that reduces the force requirements placed on the quadriceps during landing and gait activities (eg, trunk flexion) potentially reduces ACL loading and subsequent injury risk.

A flexed landing posture improves the ability of the lower extremity to attenuate landing forces. DeVita and Skelly[16] measured landing kinetics and kinematics during stiff and soft landings. Soft landings were characterized by a more flexed posture during landing and resulted in lower peak vertical ground reaction forces. This change was achieved via an enhanced ability of the lower extremity musculature to absorb landing forces, thus reducing stress imparted to the capsuloligamentous and skeletal structures. Decker et al[22] suggested that a more erect landing posture impedes the ability of the lower extremity musculature to absorb landing forces and that the associated more-extended knee position would likely increase the anterior tibial shear force induced by the quadriceps via changes in the patellar tendon angle of insertion as demonstrated by Zheng et al.[38] Our data correspond with findings in these previous investigations, because a more flexed landing posture resulted in reduced landing forces. Our findings potentially have important implications for future ACL injury-prevention efforts, because a single, modifiable kinematic factor (ie, trunk flexion angle) simultaneously influenced landing kinetics, kinematics, and neuromuscular control in manners that are purported to pose a lower risk for ACL injury. Specifically, flexing the trunk during landing resulted in greater hip and knee flexion, lesser vertical ground reaction forces, and lesser quadriceps activity.

## Limitations

The most important limitation to this investigation is that the magnitude of the load imparted to the ACL during the landing tasks is unknown. As noted, quadriceps force increases the load placed on the ACL. Although we suggest that active trunk flexion reduces ACL loading, as evidenced by decreases in quadriceps EMG amplitude and landing forces, it is not clear to what extent these changes influence the actual stress placed on the ACL and the risk of ACL injury. In addition, although the decreases in quadriceps EMG and landing forces with trunk flexion were significant, their clinical or physiologic importance is not clear. Future research is necessary to evaluate the in vivo load placed on the ACL during these tasks and the extent to which ground reaction forces predict ACL loading and to determine if flexing the trunk during landing is an effective mechanism for reducing the risk of ACL injury.

A second limitation to our investigation is that it is unclear if the large-magnitude changes observed in trunk flexion angle (mean difference for preferred versus flexed = 47°) are feasible for implementation in ACL injury-prevention programs. Previous research on ACL injury-prevention programs indicates that success depends on compliance and that compliance is related to the participants' perceptions of performance enhancement in addition to injury prevention.[26,39] If a large change in trunk flexion angle has negative consequences for performance, the feasibility of its use in injury-prevention programs may be limited. Additionally, trunk angle was calculated as the angle between the trunk and the thigh, so it is a combination of the relative motions of both segments. As such, the observed changes in landing mechanics and neuromuscular control cannot be attributed solely to motion of the trunk segment but rather to the combined motions of the trunk and thigh. Future research is necessary to determine the minimal change in trunk position that is required to positively influence risk factors for ACL injury and to determine if other definitions of trunk motion (eg, trunk segment relative to pelvis or world vertical axis) produce similar results.

## Clinical Implications

This investigation provides an initial assessment of the potential influence that sagittal-plane trunk motion during landing has on biomechanical and neuromuscular variables that researchers have suggested are risk factors for ACL injury. Flexing the trunk during landing places the lower extremity in a more flexed, less erect posture, which decreases quadriceps activity and landing forces, indicating a decrease in ACL loading. In combination, these results support emphasis on trunk flexion during landing as part of ACL injury-prevention programs. However, application of these results to clinical practice should be approached with caution, because the direct influence of trunk flexion on ACL loading and injury risk is unclear. Future research is necessary to establish these influences and to evaluate the feasibility of including trunk flexion in ACL injury-prevention programs.

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