Associations Between Single-Leg Postural Control and Drop-Landing Mechanics in Healthy Women

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Context: Impaired postural control in single-limb stance and aberrant drop-landing mechanics have been implicated separately as risk factors for noncontact anterior cruciate ligament (ACL) injury, but associations between these variables has not been reported. Objective: To determine whether there are associations between single-limb postural control and drop-landing mechanics. Setting: University motion-analysis laboratory. Design: Single-leg-landing kinematic and kinetic data were collected after participants dropped from a hang bar. Postural-control variables COP excursion and velocity were assessed during single-leg barefoot standing on a force platform. Participants: A convenience sample of 24 healthy women. Main Outcome Measures: Pearson product–moment correlation coefficients. Results: Strong associations were measured between maximal knee-abduction moment and COP excursion (r = .529, P = .003) and average COP velocity (r = .529, P = .003). Strong inverse associations were measured between minimum hip-flexion angle and COP excursion (r = −.521, P = .003) and average COP velocity (r = −.519, P = .003). Conclusions: Participants with decreased postural control had higher knee-abduction moments and a more extended hip on landing, which have been implicated separately as risk factors for ACL injury. A longitudinal prospective analysis is needed to determine whether force-platform postural-control measures can identify athletes at risk for ACL injury.

Keywords: biomechanics, postural stability, anterior cruciate ligament

Aberrations in sagittal- and frontal-plane landing or cutting mechanics have been implicated as risk factors for noncontact anterior cruciate ligament (ACL) injuries, particularly in females.1,2 Screening athletes for aberrations before they engage in sport (preparticipation screening) is crucial to identify those with a predisposition to ACL injury. Three-dimensional motion-analysis techniques have been used to identify athletes at risk for injury, but these techniques are time intensive and require specialized equipment and laboratory conditions. Thus there

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is a need to develop more portable, inexpensive, and expedient screening methods that accurately identify high-risk athletes.

One potential screening method involves the use of a force platform to identify deficits in postural control. Postural control can be assessed by measuring center-of-pressure (COP) excursion and velocity, which are computed from the ground-reaction forces as a subject stands on a force platform. Individuals with elevated COP excursion or velocity during quiet standing are thought to have impaired postural control. Past studies have shown that postural-control deficits are predictive of future ankle injuries. There is emerging evidence that impaired postural control may also be associated with an increased risk of ACL injury. Vrbanic et al reported that female handball and volleyball athletes who had postural-control deficits measured on a Sport KAT 2000 (LLC, Vista, CA) pneumatic-testing system were more likely to subsequently incur ACL injury. In a more recent prospective study, Paterno et al reported that athletes with deficits in single-leg postural control, as measured with the Biodex Balance System SD (Biodex, Shirley, NY), had a higher risk of sustaining a second ACL injury.

Given that impaired postural control and aberrant drop-landing mechanics have been implicated separately as risk factors for noncontact ACL injury, we conducted this investigation to ascertain whether there are associations between postural-control variables and single-leg drop-landing kinematic and kinetic variables. Although specific kinematic and kinetic variables have been identified in association with elevated ACL injury risk, we measured a multitude of hip, knee, and ankle kinematic variables to avoid overlooking other potentially relevant ones. In lieu of a clinical balance-testing unit such as the Sport Kat 2000 or Biodex Balance System SD, a force platform was used to assess postural control because of its potential portability. Identified associations between postural-control variables and drop-landing mechanics could aid in the development of portable, quick, and efficient preparticipation screening techniques to identify individuals at risk for ACL injury and, more important, to mitigate this risk via timely intervention.

Methods

Participants

Twenty-four healthy women (mean age 22 y, height 169.1 cm, weight 63.5 kg) were recruited from a university population to participate in this study. Students who had sustained a lower extremity injury in the past that required medical intervention were not included in this investigation. All participants reported being right-leg dominant, operationally defined as the right leg being the preferred leg for kicking a ball.

Procedures

Each participant’s height and weight were measured with a tape measure and standard balance scale, respectively. Informed written consent, in accordance with the university’s institutional review board guidelines, was obtained from all subjects before testing. Kinematic data were collected during single-leg drop landing on the right (dominant) leg with the laboratory’s 8-camera, 3-dimensional motion-analysis...
A 4-segment, rigid-link model of the lower limb was created with 15 retroreflective, 6.35-mm-diameter spherical markers in a modified Helen Hayes Marker set configuration using motion-analysis software (Innovative Sports Training, Chicago, IL). Markers were attached with adhesive tape or Velcro straps directly to the participant’s skin or footwear. The cameras, synchronized with infrared strobe lights, were used to capture the kinematic data at 240 Hz and calibrated with mean residual errors of 0.1 to 0.21 mm over a volume of $1.5 \times 1.1 \times 1.5$ m. Kinematic data were smoothed using a low-pass, fourth-order Butterworth filter with a 15-Hz cutoff frequency for marker trajectories. Participants were asked to complete a drop landing after letting go of a hang bar, to land under control, and to stop after landing (Figure 1). With the participant in the hanging position, the hang-bar height was adjusted using a windlass until the distance between the shoe heel (plantar aspect) and floor was 40 cm. Force-platform (Bertec Corp, Columbus, OH) data collected at 1200 Hz were synchronized with the cameras to measure ground-reaction forces during the drop-landing trials. These kinetic data were filtered at the same cutoff frequency as the kinematic data using the same filtering algorithm. The landing phase was defined by the first contact on the force platform at which the vertical ground-reaction force was greater than 10 N and the occurrence of peak knee flexion determined from kinematic data. Five trials were completed and data were averaged across trials. Inverse dynamics were used to calculate moments at the hip, knee, and ankle joints from the kinematic and force-platform data. Moment data were normalized to kilograms of body weight. Discrete kinematic and kinetic variables of interest were calculated from the time-history data from each landing cycle with MATLAB (The Mathworks, Natick, MA). These data were averaged across the 5 landing trials. Each participant wore New Balance 645 running shoes (New Balance Athletic Shoe, Inc, Boston, MA) to standardize any influence of footwear.

![Figure 1](image-url) — Drop-landing test: (a) hang-bar starting position and (b) landing position.
Postural control was measured during single-leg stance on the right (dominant) leg using a testing protocol described previously by Kernozek et al. A 50 × 50-cm force platform (AccuSway, AMTI Inc, Watertown, MA) interfaced with a personal computer sampling at 50 Hz was used to measure COP excursion in the anteroposterior and mediolateral directions and average velocity of the COP along its path. Participants performed 3 single-leg barefoot standing trials on the dominant leg on the force platform with 30-second rest breaks between trials. The opposite leg was maintained in a self-selected, comfortable position with the hip and knee flexed so that the foot was approximately 6 in. off the floor and not in contact with the stance leg (Figure 2). The participants’ arms were folded across their chest to minimize motion of the upper extremities. Participants were asked to look straight ahead during the test to standardize the visual influence on balance. They were instructed to remain as motionless as possible during testing without losing their balance. Data were collected for 30 seconds while participants balanced without uncrossing their arms or touching the floor with their opposite leg. If the arms uncrossed or the opposite leg came in contact with either the floor or the leg being tested, the trial was terminated. COP-data variables were sampled through a computer at 50 Hz using SwayWin software (AMTI Inc). Data for the 3 single-leg-stance trials were averaged.

Figure 2 — Postural-control test on a force plate.
Statistical Analyses

Pearson product–moment correlation coefficients were calculated to determine the strength of associations between the selected discrete landing kinematic and kinetic variables and COP excursion and average COP velocity. Using criteria established by Cohen, correlations were classified as weak if <.3, moderate if .3 to .5, and strong if >.5. Statistical analyses were conducted using the Statistical Package for the Social Sciences (version 12.0, SPSS Inc, Chicago, IL) with alpha set a priori at $P < .05$.

Results

Results of the correlation analysis are presented in Table 1. Correlations <.3 were omitted for brevity. Strong associations were measured between COP excursion and peak knee-abduction moment ($r = .529, P = .003$) and between average COP velocity and peak knee-abduction moment ($r = .529, P = .003$; Figures 3 and 4). Strong inverse associations were observed between COP excursion and minimum hip-flexion angle at initial contact ($r = -.521, P = .0003$) and between average COP velocity and minimum hip-flexion angle at initial contact ($r = -.519, P = .003$; Figures 5 and 6).

Table 1  Associations Between Drop-Landing Kinetic and Kinematic Parameters and Force-Plate (Postural-Control) Parameters

<table>
<thead>
<tr>
<th>Drop-landing kinetic or kinematic parameter</th>
<th>Force-plate (postural-sway) parameter</th>
<th>Pearson's $r$</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip-flexion angle</td>
<td>Average COP velocity</td>
<td>-.521</td>
<td>.003</td>
</tr>
<tr>
<td></td>
<td>Length of COP path</td>
<td>-.519</td>
<td>.003</td>
</tr>
<tr>
<td></td>
<td>Average $\times$ displacement of COP</td>
<td>-.424</td>
<td>.020</td>
</tr>
<tr>
<td>Hip-flexion ROM</td>
<td>Average COP velocity</td>
<td>.371</td>
<td>.043</td>
</tr>
<tr>
<td></td>
<td>Length of COP path</td>
<td>.371</td>
<td>.044</td>
</tr>
<tr>
<td>Hip-abduction angle</td>
<td>Average $\times$ displacement of COP</td>
<td>-.384</td>
<td>.036</td>
</tr>
<tr>
<td>Peak hip-abduction moment</td>
<td>Length of COP path</td>
<td>.364</td>
<td>.048</td>
</tr>
<tr>
<td></td>
<td>Average COP velocity</td>
<td>.366</td>
<td>.047</td>
</tr>
<tr>
<td>Peak knee-abduction moment</td>
<td>Average COP velocity</td>
<td>.529</td>
<td>.003</td>
</tr>
<tr>
<td></td>
<td>Length of COP path</td>
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<td>.003</td>
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<tr>
<td>Ankle-abduction angle</td>
<td>Average $\times$ displacement of COP</td>
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<td>.026</td>
</tr>
<tr>
<td>Ankle-abduction ROM</td>
<td>Average $\times$ displacement of COP</td>
<td>.469</td>
<td>.009</td>
</tr>
</tbody>
</table>

COP, center of pressure; ROM, range of motion.
Figure 3 — Peak knee-abduction moment and center-of-pressure (COP) path excursion (cm; $r = .529$, $P = .003$).

Figure 4 — Peak knee-abduction moment and average center-of-pressure (COP) velocity (cm/s; $r = .529$, $P = .003$).
Figure 5 — Hip-flexion angle and center-of-pressure (COP) path excursion (cm; $r = -0.519$, $P = .003$).

Figure 6 — Hip-flexion angle and average center-of-pressure (COP) velocity (cm/s; $r = -0.521$, $P = .003$).
Discussion

To our knowledge this is the first time that relationships have been studied between single-leg postural control and discrete single-leg drop-landing kinematic and kinetic variables. Our results showed a strong association between peak knee-abduction moment and COP variables indicative of poorer postural control. This finding suggests that larger knee frontal-plane moments may be related to poorer postural control. Past studies have shown that females tend to exhibit larger knee-abduction moments when landing from a jump or during a cutting or pivoting maneuver than males.11,12 Our findings suggest that this tendency may be related to impaired postural control, as well. One apparent consequence of large knee-abduction moments during jump landing is increased loading of the ACL.13,14 Video analyses have shown that ACL ruptures are more likely when a knee-abduction moment is combined with axial impulsive loading of the knee joint, often in conjunction with internal or external tibial rotation.15 Hewett et al1 reported that female athletes who eventually sustained a noncontact ACL injury had a 2.5 times greater knee-abduction moment than their injury-free peers. Knee-abduction moments predicted ACL-injury status in the Hewett et al study with 73% specificity and 78% sensitivity.

Our results also revealed a strong inverse association between decreased postural control and hip-flexion angle at initial contact, suggesting that the women in our study with impaired postural control landed in less hip flexion. Landing with reduced hip flexion appears to increase impact forces at the knee.16–18 Previous studies19,20 have shown that females tend to land in more hip extension than males, but our results suggest that this tendency may also be related to impaired postural control. The more hip-extended landing techniques that we observed may be similar to the “stiff” landing described by Devita and Skelly,21 although their definitions of stiff and soft landings were predicated on knee-flexion angle (<90° and >90°, respectively). According to Devita and Skelly, the adoption of a soft landing requires a greater use of the hip muscles than a stiff landing. It is possible that poor hip neuromuscular control or hip-extensor weakness contributed to the hip-extended landing postures and higher knee-abduction moments that we observed. However, we did not attempt to measure this in our study. Hewett et al22 hypothesized that reduced muscle control during landing may lead to increased reliance on the knee ligaments to decelerate the body’s center of mass. Weakness of the sagittal-plane muscles may also increase reliance on frontal-plane muscles for deceleration during impact activities, resulting in higher knee-abduction moments.23 Pollard et al23 similarly reported that individuals who used a low-hip- and -knee-flexion landing pattern during a drop-landing task demonstrated greater knee loading in both the sagittal and frontal planes.

We also observed moderate associations between decreased postural control and hip-abduction moment (Table 1). Whether this, too, is the result of increased reliance on frontal-plane muscles for stabilization and deceleration is unknown. Likewise, we cannot definitively account for the associations that we observed between hip-flexion range of motion and decreased postural control. Greater hip-flexion excursion after landing may be a result of impaired eccentric control of the hip extensors during the body’s downward progression.24 Alternatively, this may
represent an attempt to absorb kinetic energy via the hip extensors in response to landing in a more erect position.\textsuperscript{24} We did not measure associations between decreased postural control and peak ground-reaction forces or between decreased postural control and peak proximal anterior tibial shear force, although both ground-reaction forces and peak proximal anterior tibial shear force have been purported to contribute to ACL loading.\textsuperscript{13,14}

Moderate associations were measured between ankle-abduction (ie, eversion) measures and mediolateral COP excursion (Table 1), suggesting that participants with decreased postural control moved through a greater range of ankle motion in the frontal plane. The data used to calculate “ankle” motion, however, were derived from calcaneal and forefoot markers. Thus it would be more accurate to interpret these findings as suggesting that participants with decreased mediolateral postural control moved through a greater range of frontal-plane ankle and foot movement (ie, abduction/eversion). The marker placement and link-segment model precluded us from determining whether “ankle” abduction was attributable solely to foot pronation.

Two studies to date have examined the relationship between postural-control deficits and future ACL injury. Vrbanic et al\textsuperscript{8} analyzed static and dynamic balance in 52 female handball and volleyball athletes using a pneumatic Sport KAT 2000 (LLC, Vista, CA) testing system. Static- and dynamic-balance scores were combined into a balance index score. Athletes who incurred ACL knee injuries after the testing had higher balance index scores (indicative of postural-control deficits) than healthy athletes. Because Vrbanic et al combined static- and dynamic-test results into an aggregate score, it remains to be seen whether static or dynamic assessments of postural control have a greater predictive value regarding injury risk. The protocol Vrbanic et al used to measure static balance was similar to our protocol, but they also assessed dynamic balance, which we did not.

Paterno et al\textsuperscript{9} also used a clinical testing system, the Biodex Balance System SD (Biodex, Shirley, NY), to assess postural control in a group of athletes who had previously undergone ACL reconstruction. They reported that athletes with postural-control deficits of the involved limb were twice as likely to incur a second ACL injury as athletes with greater postural control. When postural-control measures were combined with transverse-plane hip kinetics and frontal-plane knee kinematics during landing and sagittal-plane knee moments at landing, a second injury was predicted with 92% sensitivity and 88% specificity. Along with decreased postural control, specific predictive parameters included an increase in total frontal-plane (valgus) motion, greater asymmetry in internal peak knee-extensor moments at initial contact, and an internal-rotation moment at the hip. We did not measure associations between any of these variables and postural control, although none of our participants had undergone ACL reconstruction.

In 2 similar studies, Zazulak et al\textsuperscript{25,26} examined relationships between neuromuscular control of the trunk and future knee and ACL injuries. They reported that impaired trunk proprioception, measured by active repositioning of the trunk, predicted knee-injury risk in female athletes.\textsuperscript{25} Likewise, increased trunk displacement after sudden force release predicted risk of ACL injury and other knee-ligament injuries with high sensitivity and moderate specificity in female athletes.\textsuperscript{26} Taken together, the findings of Vrbanic et al,\textsuperscript{8} Paterno et al,\textsuperscript{9} and Zazulak et al\textsuperscript{25,26} seem to suggest that postural-control measures may have a role in screening athletes for...
risk of future ACL injury. As with the Paterno study, combining postural-control measures and kinematic and/or kinetic factors may prove to be more effective for identifying high-risk athletes than postural-control measures alone. Regardless, the screening measures need to be simple, inexpensive, and expedient for adoption by health care professionals in a preparticipation physical examination context. As opposed to Vrbanic et al\textsuperscript{8} and Paterno et al\textsuperscript{9}, a force platform was used in the current study because force plates are relatively portable and readily available. However, a longitudinal prospective analysis is needed to determine whether standing postural-control measures using a force platform can accurately and reliably identify athletes at high risk of ACL injury.

There is some evidence that postural-stability training can alter knee mechanics, which in turn may reduce ACL-injury risk. Hurd et al\textsuperscript{27} reported that perturbation training improved quadriceps–hamstring balance and increased active knee stiffness during frontal-plane perturbations in a group of female athletes. Paterno et al\textsuperscript{28} reported that female athletes who participated in a 6-week balance- and plyometric-training program significantly improved sagittal-plane single-limb postural stability. Myer et al\textsuperscript{29,30} reported that balance training reduced knee-valgus and -varus moments during a single-limb dynamic stabilization task. In one of these studies\textsuperscript{29} they also reported that balance training was more effective than plyometric training in improving force attenuation during landing from a single-leg hop. After the training period, their balance group decreased vertical ground-reaction force by roughly 7.0%, whereas vertical ground-reaction force in the plyometric group increased approximately 8.0%. In a separate study, Myer et al\textsuperscript{30} reported that balance training affected sagittal-plane kinematics during single-leg drop landing and plyometric training affected sagittal-plane kinematics primarily during a drop vertical jump. Even more compelling, Caraffa et al\textsuperscript{31} reported a 7-fold decrease in ACL injuries in male soccer players who participated in balance-board and disk-training drills, although those authors did not measure improvement in the athletes’ postural control. Likewise, Wedderkopp et al\textsuperscript{32} reported that female handball players who underwent ankle-disc training experienced 79% fewer lower extremity injuries than the control group over the subsequent competitive season.

Thus there appears to be some precedence to support the inclusion of postural-stability training in ACL-injury-prevention programs. ACL-injury-prevention programs that focus solely on strength gains appear to be minimally effective in reducing injury risk\textsuperscript{22,33} Combining different training modalities may enhance an athlete’s ability to activate lower extremity muscles and improve stability of the knee joint under more dynamic loading conditions. Postural-control training may play a role in reducing knee-ligament loading via improved control of an individual’s center of mass.\textsuperscript{9}

Our subject sample was limited to women so we do not know whether or how these postural variables were related to drop-landing kinematic and kinetic variables in men. Future studies could shed light on this. Another limitation of our study is that participants were shod during the drop-landing tests but were barefoot during the postural-control analysis. Postural-control measures were made with subjects barefoot to eliminate any influence of footwear on standing balance.\textsuperscript{34} Participants wore the same model of athletic shoe during drop landings to standardize the influence of footwear. Nonetheless, footwear may have affected associations between the postural-control and landing measures.
Conclusions

In this study, decreased postural control in healthy women was associated with a more extended hip at initial contact and higher knee-abduction moments after a single-leg drop landing from a hang bar. Higher knee-abduction moments and the adoption of a more erect landing strategy have been identified separately as risk factors for noncontact ACL injuries. In addition, there is emerging evidence that impaired postural control is also associated with an increased risk of ACL injury. Further prospective analyses are needed, however, to determine whether measures of postural control using a force platform can accurately and reliably identify athletes with a greater risk of ACL injury.

Acknowledgments

This study was approved by the University of Wisconsin–La Crosse institutional review board for human research.

References


