Training Affects Knee Kinematics and Kinetics in Cutting Maneuvers in Sport

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ABSTRACT

COCHRANE, J. L., D. G. LLOYD, T. F. BESIER, B. C. ELLIOTT, T. L. A. DOYLE, and T. R. ACKLAND. Training Affects Knee Kinematics and Kinetics in Cutting Maneuvers in Sport. Med. Sci. Sports Exerc., Vol. 42, No. 8, pp. 1535–1544, 2010. Purpose: The current study examined how different training affects the kinematics and applied moments at the knee during sporting maneuvers and the potential to reduce loading of the anterior cruciate ligament (ACL). The training programs were 1) machine weights, 2) free weights, 3) balance training, and 4) machine weights + balance training. Methods: Fifty healthy male subjects were allocated either to a control group or to one of four 12-wk training programs. Subjects were tested before and after training, performing running and cutting maneuvers from which knee angle and applied knee moments were assessed. Data analyzed were peak applied flexion/extension, varus/valgus, and internal/external rotation moments, as well as knee flexion angles during specific phases of stance during the maneuvers. Results: The balance training group decreased their peak valgus and peak internal rotation moments during weight acceptance in all maneuvers. This group also lowered their flexion moments during the sidestep to 60°. Free weights training induced increases in the internal rotation moment and decreases in knee flexion angle in the peak push-off phase of stance. Machine weights training elicited increases in the flexion moment and reduced peak valgus moments in weight acceptance. Machine weights + balance training resulted in no changes to the variables assessed. Conclusions: Balance training produced reductions in peak valgus and internal rotation moments, which could lower ACL injury risk during sporting maneuvers. Strength training tended to increase the applied knee loading known to place strain on the ACL, with the free weights group also decreasing the amount of knee flexion. It is recommended that balance training be implemented because it may reduce the risk of ACL injury. Key Words: MOMENTS, SIDESTEPPING, BALANCE, STRENGTH, PREVENTION, ACL INJURY

The knee is one of the most commonly injured joints in sport. Clinically, the knee accounts for nearly 50% of all sporting injuries (39). Within these, rupture of the anterior cruciate ligament (ACL) is common and devastating, occurring often during noncontact cutting and landing maneuvers (8,12). Previous studies have shown that large loads are exerted on the knee during these sporting maneuvers, placing the ACL at risk of injury, especially in unanticipated circumstances (3–5).

The ACL primarily supports anterior draw of the tibia with respect to the femur, a movement produced during active leg extension, and it also acts as a major restraint to varus, valgus, and internal rotation moments (30,31). Combined loading or joint loading in this article refers to the combined externally applied moments at the knee. Combined loading from anterior draw and varus, valgus, or internal rotation moments place greater load on the ACL compared with anterior draw alone, and these loads are exacerbated when the knee is extended (30,31). These findings have been gathered from non–weight-bearing situations. However, the experiments have been replicated during static in vivo conditions (18), which also revealed the ACL strain increased when valgus and internal rotation moments were applied to the extended knee in weight bearing.

Previous laboratory-based research demonstrated that, during sidestepping tasks, large valgus and internal rotation moments were applied to the knee while the quadriceps were producing a knee extension moment (5). This work also showed that these moments were further magnified when maneuvers were performed in unanticipated conditions (4) or when a defensive player was present (35). Such knee loading scenarios are likely mechanisms for ACL rupture (3–5,26,34,35); therefore, reducing the magnitude

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of these loads may help to reduce the risk of ACL injury. Decreasing this loading has been achieved using sidestep technique training (14). In addition, more general forms of neuromuscular and physiological training, such as strength and/or balance training, may be effective (10,29,37,44); however, the mechanisms by which these work are yet to be fully determined. This information is important to assist efforts to reduce the incidence of ACL injury in sport and understand its long-term detrimental effects on knee joint health (13). Specifically, it is unknown what impact the aforementioned neuromuscular training may have on knee loading, thereby altering the risk of ACL injury.

Balance training has been implemented in sports with the objective of preventing knee ligament injuries (10,29,37,44). In addition to providing stability, the knee ligaments have an important neurosensory function (41). Mechanoreceptors within the ligaments function to detect tissue strains providing feedback to the central nervous system, which may be used to alter feed-forward muscle activation strategies and movement patterns to reduce knee loading, thereby protecting ligaments from injury (9,16,41). Training programs that load and stimulate the knee ligaments, such as balance or perturbation training, may facilitate this protective mechanism (2,26). Indeed, there is evidence to suggest that balance training can reduce the incidence of ACL injury (10,29,37,44). However, the mechanisms underlying these changes are still to be clearly defined. In particular, it is not known what effect balance training has on the knee loading and kinematics during the execution of running and cutting maneuvers in sport.

Strength training is commonly adopted by most sporting teams for improving performance. It is known that resistance training can decrease muscular cocontraction about the knee and increase coordination of synergist muscles (11). For example, studies on leg flexion and extension strength training (11,40) found that cocontraction of the hamstrings and quadriceps muscles decreased and there was greater coordination of agonist muscles. Therefore, training optimized muscle activation patterns needed to perform the movement and usually decreased cocontraction (11,17,36,40). The reduction of cocontraction may diminish the activation patterns needed to protect the ligaments of the knee (3,27), so there may be a negative outcome from strength training. However, it is not yet known if the reduced levels of cocontraction map over into performance of maneuvers that challenge knee stability. There are studies that support the notion that neuromuscular changes from strength training carry over into dynamic maneuvers (36,45). If this does occur, the effect on stabilization of the knee joint may be unfavorable with decreased cocontraction levels, providing less support for the knee during the sporting maneuvers. It has been speculated that free weights are better than machine weights for training stability because of greater balance and joint stability requirements and because of the more functional nature of free weight exercises (2,19). However, there has been no research on the effect that free weights or machine weights training may have on knee joint loading and kinematics during the performance of sporting maneuvers.

The purpose of this study was to investigate the effect of strength training and balance training on knee joint loading and lower limb kinematics during sporting maneuvers of running and cutting. An intervention study was performed to assess whether the loading at the knee joint could be altered by training. Four hypotheses were proposed: 1) balance training reduces the applied loading on the knee during sporting maneuvers, 2) strength training using machine-based resistance increases loading on the knee joint during sporting maneuvers, 3) strength training using free weights increases loading of the knee joint to the same level as machine-based resistance training, and 4) combined balance and machine-based resistance training results in no significant change in knee joint loading during sporting maneuvers because their potential effects would counter one another.

**METHODS**

Participants recruited were 50 healthy male subjects with no history of lower limb pain or injury and had limited previous exposure to endurance, strength, or balance training (age = 23.0 ± 5.5 yr, height = 1.82 ± 0.05 m, mass = 78.2 ± 9.7 kg). The study was approved by the human research ethics committee at the University of Western Australia, and informed written consent was obtained from all subjects before commencement of the study. Subjects from Australian Rules Football teams were randomly allocated either to a control group or to one of four training groups (10 players per group).

This study comprised three stages: pretesting, training, and posttesting. The pretesting and posttesting followed the same methodology as developed previously by Besier et al. (3–5). Pretesting was conducted within 1 wk before commencement of the training programs, and the posttesting was conducted within 1 wk after the 12-wk training schedule. Kinematic and kinetic variables were obtained for each subject while performing sidestepping to 30° and 60° (S30 and S60), crossover cutting to 30° (XOV), and straight line running (RUN) (3–5). All maneuvers were performed as both preplanned and unanticipated. Subjects executed these maneuvers at a speed of 4.0–4.5 m s⁻¹, stepping from their preferred leg. Subjects performed three acceptable trials of each maneuver in the preplanned condition and a further three trials in the unanticipated condition. For the unanticipated trials, individual time delays were determined before each testing session. The delay time was adjusted to suit each individual’s reactions so that the appropriate LED indicating the trial type illuminated at a point where the subject was just able to react in time to perform the maneuver successfully. The order of trials was randomized to prevent subject anticipation, and to reduce the effects of learning, subjects were given a 3-min rest between each trial.

Motion analysis of the subjects was performed using a six-camera Vicon 370 motion analysis system (Oxford...
Metrics, Oxford, UK) with a 1200 × 600-mm² force plate (AMTI, Watertown, MA) sampling at 2000 Hz. The infrared cameras sampled at 50 Hz tracking retroreflective markers were placed externally on each subject’s skin at selected landmarks. A Fourier analysis was performed on the ground reaction forces recorded during pilot testing of the maneuvers to investigate the movement frequency content, and it was found that 98% of the frequency content was below 19 Hz, with 95% below 10 Hz. These results confirmed that the motion analysis frame rate was sufficient to represent the underlying movement frequencies without aliasing. However, to ensure that there were enough points in the stance phase on which to carry out the analyses, we up-sampled the marker motion data from 50 to 200 Hz using an interpolating cubic spline. To view the effectiveness of the resulting sampling rate, typical extension/flexion, valgus/varus, and internal/external rotation moment curves are provided for the weight acceptance (WA) phase (defined below) of sidestepping (Fig. 1). Figure 4 in the study of Dempsey et al. (15) also displays typical mean ± SD curves collected in our laboratory.

Motion data were collected using the “UWA marker set” with definitions of segment and joint coordinate systems and joint axis as per the “UWA kinematic and kinetic model” (6). This lower body marker set consisted of markers placed on anatomical landmarks and clusters of three markers on each segment. Before testing, subject calibration trials were performed (6), which were used to locate anatomical landmarks and define joint coordinate systems. In this, functional hip and knee tasks were performed to locate hip joint centers by fitting a sphere to the motion of the thighs markers, with the knee joint flexion/extension axes defined using a mean helical axis-based method. The subject also stood on a foot calibration rig, which was used to establish the position of the foot markers and to measure foot abduction/adduction and rear foot inversion/eversion angles. These protocols have been shown to improve repeatability of joint kinematic and kinetic data (6).

Filtering of the marker trajectory and force plate data was performed using a low-pass fourth-order, zero-lag Butterworth filter with a cutoff frequency of 18 Hz. Applying the same filter to the motion and force plate data follows the recommendations of van den Bogert and de Koning (42) and studies by McLean et al. (33–35). Selection of the best cutoff frequency was conducted using a residual analysis and visual inspection of the final kinematic and kinetic data.

The three-dimensional kinetics were calculated using inverse dynamics (6) for the knee joint. Knee joint moments were expressed as those externally applied to the joint in the distal segment’s anatomical coordinate system. It is intuitive to express moments as those applied externally because knee injury most likely occurs when these moments exceed the limits of joint strength. The definitions of the moments were as follows: flexion moment is one that acts to flex the knee and vice versa for an extension moment, a valgus moment is one that acts to cause abstraction of the knee (i.e., places the knee into a knock-kneed position) and vice versa for a varus moment, and an internal rotation moment is one that acts to internally rotate the tibia on the femur and vice versa for an external rotation moment.

The knee flexion angle and three-dimensional knee moments were analyzed in different phases. Stance was divided into two phases; the WA and peak push-off (PPO) phases. WA was defined from heel strike to the start of the main knee power absorption during stance (which corresponded to the trough after the heel strike transient in the ground reaction force). PPO phase was the active phase, i.e., 10% of stance on either side of peak ground reaction force during stance phase (4,5). Variables were calculated in each of these gait phases to enable comparisons across testing sessions and training groups.

Knee joint moments were normalized (divided by) to height × weight to account for between-subject variation in body proportions. Visual inspection of graphs for each moment type across the maneuvers revealed particular moment peaks or areas of importance for subsequent analysis. Similar to other studies (14,15,34), the valgus peak was
identified as occurring during the WA phase of the sidestepping and XOV maneuvers. Both varus and valgus peaks were common in WA and PPO during sidestepping, so peak varus moments were also calculated for both phases. As in our previous studies (14,15,34), peak flexion moment was not found in WA, but it was present in PPO. Mean flexion moment in WA was very small and had large variance, so only the peak flexion moment in PPO was analyzed. Peak internal rotation moment was present and determined for both phases, and mean knee flexion angle was also calculated for each phase (4,5).

The results presented throughout the article refer to the percentage change in knee joint moments and knee flexion angle. Actual values are presented to demonstrate the magnitudes of moments.

Training. The training programs were as follows: 1) Machine weights strength training only—using pin-loaded isotonic resistance machines for leg curl and leg press exercises. 2) Free weights strength training only—using leg curl and squat exercises with free weights. 3) Balance training only—balance exercises using equipment such as wobble boards, tilt boards, mini trampolines, dura discs, and Swiss balls. The exercises included progressions from double-legged to single-legged static balancing, double-legged to single-legged squats, and additional stability-challenging exercises while maintaining balance on the various equipment. The athletes were progressed in exercise difficulty when they could competently complete exercises at the current level of difficulty. 4) Machine weights + balance training—using the machine-based exercises as in the machine weights group and balance exercises as in the balance training only group. All training groups exercised for 30 min, three times per week for 12 wk. Strength training groups followed a progressive overload plan starting at 80% of one-repetition maximum for the tasks. At the end of 12 wk of balance training, all subjects were able to perform full squats on the Swiss balls. The control group carried out their normal team training exercises.

Data treatment. The influence of training on knee loading during each maneuver performed under preplanned and unanticipated conditions was determined using a four-factor repeated-measures ANOVA (training group × maneuver × anticipation × before–after training). ANOVA was collapsed to a two-factor model when no interactions for anticipation or maneuvers were found. The maneuvers were combined in the collapsed model to demonstrate the overall effect of training on these tasks. LSD post hoc analysis was also performed, and the significance level was set at $P < 0.05$. A three-factor repeated-measures ANOVA (training group × maneuver × anticipation) was also conducted on the data at baseline to identify if any differences existed between the training groups before testing. The ANOVA was collapsed to a two-factor model when no significant interactions were identified between the groups at baseline. Data analyses were conducted in DataDesk statistical software Version 6.1 (Data Description, Inc., Ithaca, NY).

If significant differences were found in any measures between the groups at baseline, they were not included in the results or they have been discussed in the results where necessary. No differences at baseline would indicate that any changes after posttesting could be attributed to the training. In most cases, the values presented are those that occurred in each phase for all sporting maneuvers combined. However, if an interaction did occur among the training group, session, and trial type, the changes for each trial type are presented.

<table>
<thead>
<tr>
<th>Training Type*</th>
<th>Peak Valgus Moment</th>
<th>Peak Varus Moment</th>
<th>Peak Internal Rotation Moment</th>
<th>Peak Flexion Moment</th>
<th>Mean Knee Flexion Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>WA ↑</td>
<td>(−)</td>
<td></td>
<td>PPO ↓</td>
<td>(−)</td>
</tr>
<tr>
<td>Balance training</td>
<td>WA ↓ (+)</td>
<td>WA ↓ (+)</td>
<td>WA ↓ (+)</td>
<td>PPO ↓ (+)</td>
<td>PPO ↓ RUN</td>
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<td>PPO ↓ (+)</td>
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<td>↓ S60 (+)</td>
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<td>Free weights</td>
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<td>PPO ↑ (−)</td>
<td>PPO ↓ S60 (+)</td>
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<td>PPO ↓ (−)</td>
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<tr>
<td>Machine weights</td>
<td>WA ↓ (+)</td>
<td>WA ↓ (+)</td>
<td>PPO ↓ (+)</td>
<td>PPO ↑ (−)</td>
<td></td>
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<tr>
<td>Machine weights + balance training</td>
<td>PPO ↓ S30 (+)</td>
<td>PPO ↓ S30 (+)</td>
<td>PPO ↓ S30 (+)</td>
<td>PPO ↓ (−)</td>
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</tr>
</tbody>
</table>

* indicates an increase in load or knee flexion.
↓ indicates a decrease in load or knee flexion.
(+) indicates a possible decrease in injury risk, i.e., favorable.
(−) indicates a possible increase in injury risk, i.e., less favorable.
If the phase has no maneuver named, it indicates the change was significant across all maneuvers. However, if a maneuver is named, this indicates that significant differences were evident for that maneuver only. All changes in the table are significant ($P < 0.05$).
RESULTS

All resistance training groups significantly increased their three-repetition maximum strength after the intervention ($P < 0.001$). The free weights group increased strength by 60% on the squat exercises and by 74% on the leg curl exercises. The machine weights group increased strength by 53% on the leg press exercises and by 66% on the leg curl exercises, whereas the machine weights + balance training group increased by 58% on the leg press and by 43% on the leg curl exercises. In the performance of the maneuvers, no significant differences were found for approach velocity between the groups when compared within and between the sessions for each maneuver type. Generally, in the WA phase of all maneuvers, the knee was close to full extension, with a mean ± SD flexion angle of 11.3° ± 4.8°, whereas the knee was more flexed in PPO (45.1° ± 7.2°).

In the following sections, the changes that occurred in the two phases will be presented. Within each section, the order of changes presented is peak valgus (in WA) or peak varus (PPO), peak internal rotation (in both WA and PPO) and peak flexion moments (in both WA and PPO), and then the knee flexion angle. Further, because there were no differences between results for the preplanned and unanticipated conditions, the data were collapsed, and these results were combined. A summary of all the results is presented in Table 1.

WA phase. The balance training group decreased peak valgus moments during WA by an average of 62% reducing from 0.09 N·m·kg⁻¹ before testing to 0.03 N·m·kg⁻¹ after testing for all maneuvers ($P < 0.001$; Fig. 2). The machine weights group also experienced a reduction in the peak valgus moments (27%, $P < 0.05$) from 0.13 N·m·kg⁻¹ before testing to 0.09 N·m·kg⁻¹ after testing (Fig. 2). The control group increased their peak valgus moment by 26% (from 0.09 to 0.11 N·m·kg⁻¹, $P < 0.05$) during the 12-wk period. The peak valgus moments for the balance training group were similar to those for the control group before training but were significantly less than those for the control group after training ($P < 0.001$). None of the other training groups exhibited differences from the control group before or after training.

In the WA, peak varus moment decreased from before to after training in the balance training and the machine weights groups across all sporting maneuvers (Fig. 3). In the balance training group, this moment decreased by 24% from 0.32 N·m·kg⁻¹ before testing to 0.24 N·m·kg⁻¹ after training ($P < 0.001$), and the machine weights group experienced a 21% reduction from 0.28 to 0.22 N·m·kg⁻¹ ($P < 0.001$).

Balance training also altered the peak internal rotation moments in all maneuvers (Fig. 4). The internal rotation moment at the knee was reduced with balance training during the WA phase by 32% from 0.08 to 0.06 N·m·kg⁻¹ ($P < 0.001$).

PPO phase. In the PPO, the peak varus moment decreased from before to after training in the balance training and the machine weights groups across all sporting movements (Fig. 3). In the balance training group, this moment decreased by 24% from 0.32 N·m·kg⁻¹ before testing to 0.24 N·m·kg⁻¹ after training ($P < 0.001$), and the machine weights group experienced a 21% reduction from 0.28 to 0.22 N·m·kg⁻¹ ($P < 0.001$).

Balance training also altered the peak internal rotation moments in all maneuvers (Fig. 4). The internal rotation moment at the knee was reduced with balance training during the WA phase by 32% from 0.08 to 0.06 N·m·kg⁻¹ ($P < 0.001$).
maneuvers (Fig. 3). In the balance training group, this moment decreased by 8% from 0.55 N·m·kg⁻¹ before testing to 0.50 N·m·kg⁻¹ after training ($P = 0.018$), and the machine weights group experienced an 18% reduction from 0.65 to 0.53 N·m·kg⁻¹ ($P < 0.001$).

In the PPO phase, the peak internal rotation moment increased by 28% after free weights training, increasing from 0.13 to 0.16 N·m·kg⁻¹ after the training ($P < 0.001$; Fig. 4). The balance training group decreased the peak internal rotation moments by 15% from 0.19 to 0.16 N·m·kg⁻¹ ($P < 0.001$), and the machine weights group decreased by 11% from 0.18 to 0.16 N·m·kg⁻¹ ($P = 0.018$) after training (Fig. 4). However, the balance training and machine weights groups were significantly greater than the control group in this measure before testing and were decreased to values not significantly different to the control group after testing.

In PPO, there was a significant increase in the peak flexion moment after machine weights training, with a 13% increase from 0.86 to 0.97 N·m·kg⁻¹ after training ($P < 0.001$; Fig. 5). Balance training, machine weights + balance training, and free weights tended to decrease the peak knee flexion moment, but these changes were not significant. A deeper examination of the results revealed significant changes when considering the maneuver type. The peak flexion moment in the PPO phase increased in the RUN ($P < 0.001$), S30 ($P = 0.04$), and XOV ($P < 0.001$) after the machine weights training by 26% (from 0.67 to 0.84 N·m·kg⁻¹), 10% (from 0.94 to 1.04 N·m·kg⁻¹), and 24% (from 0.78 to 0.97 N·m·kg⁻¹), respectively. The machine weights + balance training group experienced a decreased moment during S30 of 10% from 1.25 to 1.13 N·m·kg⁻¹ ($P < 0.001$). The balance training group experienced an increased moment in the RUN of 10% from 0.95 to 1.05 N·m·kg⁻¹ ($P = 0.04$) but decreased during the S60 by 11%, from 1.27 to 1.48 N·m·kg⁻¹ ($P < 0.001$).

The free weights group also decreased the peak flexion moment in the S60 by 11%, from 0.75 to 0.65 N·m·kg⁻¹ ($P = 0.001$) after training.

The free weights group experienced a small but significant 5% ($P < 0.001$) decrease in mean knee flexion angle in the PPO phase (Fig. 6). There was also a small (3.5%, $P < 0.05$) but significant decrease in the control group knee flexion angles.

**DISCUSSION**

The objective of this study was to investigate the effect of different types of training on knee joint loading and kinematics during sporting maneuvers to highlight potential training methods that may prevent ACL injury. It was hypothesized that the balance training group would experience a reduction of applied loading at the knee during sporting maneuvers and that the machine weights and free weights groups would experience increased loading, whereas the machine weights + balance training group would experience no changes. These hypotheses were generally supported except in regard to the machine weights + balance training because this group also experienced a general decrease in knee loading. For easy reference, the results of the current study are summarized in Table 1.

In a previous research, differences were found between preplanned and unanticipated trials (4). However, in this study, no significant differences were observed, which may be because of learning in the training that occurred or because of the faster running speeds used in the current study. Therefore, the study analyzed all trials of the same type together, and significant differences were observed, which may have implications for knee joint loading and risk of ACL injury in both preplanned and unanticipated cutting maneuvers.

Several studies have shown that training can reduce the incidence rate of ACL injuries; however, few have attempted
to investigate the underlying mechanisms, and no studies have investigated changes in these mechanisms in running and cutting maneuvers. One of the initial studies was that of Caraffa et al. (10), who reported that players who underwent balance training had about 10 times fewer ACL injuries than a no-intervention, but active, control group. Holm et al. (23) demonstrated that neuromuscular training improved dynamic balance, and this effect was maintained a year after training. Hewett et al. (20) demonstrated that plyometric training reduced the incidence of ACL injuries. The research demonstrated decreased peak landing force, lowered knee adduction and abduction moments, increased hamstring-to-quadriceps muscle peak torque ratios, and increased hamstring muscle power after training (22). Although these results looked at landing after a jump, and not sidestepping, parallels can be drawn with the current study.

It is unknown when ACL rupture actually occurs during sporting maneuvers. Most research to date has shown that the applied loads are lower during the WA phase and greater in PPO (4,5,34,35). Flexion/extension moments are small during WA, which may mean less support of the varus/valgus and internal/external rotation moments by the knee flexor and extensor musculature (27,28). However, it is in this phase that peak valgus moments occur (15,34). Some evidence suggests that ACL rupture occurs immediately after contact (8,24,38), with the knee giving way in valgus and internal rotation after injury (8,12,24,38). Furthermore, in the WA phase, the knee is at more extended angles (\(\sim 10^\circ\)), when higher strains are placed on the ACL (30,31).

ACL rupture could also occur in midstance (PPO) where the loads are large, although knee flexion angle is around 45\(^\circ\). Many studies have shown that the ACL is under greatest strain when the knee is close to full extension, but the ACL can also be strained in the 20\(^\circ\)–50\(^\circ\) knee flexion range (7). Markolf et al. (30) showed that, when a valgus moment is added to anterior tibial translation force, the ACL loading is greatest around 30\(^\circ\)–40\(^\circ\) knee flexion and similar to that in 0\(^\circ\)–10\(^\circ\) of extension from anterior tibial translation force alone. This suggests that the ACL may be loaded in the PPO phases of sporting maneuvers, especially sidestepping, which can subject the knee to large flexion, valgus, and internal rotation moments (4,5). However, it remains unclear in which phase ACL rupture actually occurs, and therefore, changes in both phases were considered. Further, if the applied knee loading can be decreased in any or both phases, then the risk of strain and injury on the ACL should be lessened.

**Control group.** Except for an increase in the peak valgus moment in WA, the control group experienced no changes in the applied loading on the knee joint from before to after testing (Table 1). The increase in control group’s valgus moment may have been due to random variation or typical in-season training. Nevertheless, the general lack of changes in the controls indicates that any changes experienced in the other groups were probably because of their specific training programs. Significant changes were seen in the knee flexion angle in PPO for the control group, but these were very small, being only a 3.5% decrease.

**Balance training.** Previous researchers have shown a decrease in the incidence of ACL or lower limb injuries after a balance training intervention (10,29,37,43,44). The current study demonstrates the mechanisms that possibly underlie these changes. It is suggested that the 62% reduction in the peak valgus moment across all maneuvers in WA after balance training (Fig. 2 and Table 1) is a critical factor for the reduction in these injury rates. During the early stance phase of sidestepping, McLean et al. (35) observed knee moments that fluctuate between varus and valgus with a clearly obvious valgus peak, whereas others have noticed valgus moments (4,5) again with distinct valgus peaks (14,15). Valgus moments are a likely contributor to ACL injury because analysis of videos of these injuries has shown that the knee gives way in the valgus direction after ACL rupture (8,12,24,38). Hewett et al. (21) also showed that compared with uninjured athletes, those who had ACL injuries also had greater valgus knee loading during landing tasks in preseason testing. Furthermore, valgus moments combined with other anterior draw loading increases the force on the ACL, particularly at knee flexion angles between 10\(^\circ\) and 40\(^\circ\) (1,30), such as those occurring in the WA phase (11.3\(^\circ\) \(\pm\) 4.84\(^\circ\)). Taken together, these studies suggest that valgus moments contribute to ACL injuries and that the decrease in the peak valgus moments after balance training may lower the risk of ACL injury.

After balance training, there was also a general reduction in peak internal rotation moments in both WA and PPO across all maneuvers. In WA during sidestepping, the applied internal rotation moments changed to external rotation, with significant changes occurring in the S30. These changes have the potential to reduce ACL injury risk because an external rotation moment applied to the knee places less force on the ACL compared with a similar internal rotation moment magnitude (30,31). Moreover, Markolf et al. (30) demonstrated that internal rotation moments cause the greatest loading of the ACL between full extension and 20\(^\circ\) flexion and that ACL strain further increased when valgus or varus loading was added to internal rotation moments. Hence, this reduction to peak internal rotation moments in WA, along with the decrease in the peak valgus moment after balance training, should result in a decreased risk of ACL injury. Although not explicitly examined, it could be speculated that the balance training group had better control of their upper body than the other groups. Intuitively, the decreased moments around the knee may have been because of good control of the very large mass of the upper body. Indeed, our previous work has shown that changes to the upper body posture can increase knee valgus and internal rotation moments in sidestepping (14,15), and Zazulak et al. (46) have demonstrated that deficits in trunk stability are predictive of ACL injury.

Although there was a general reduction, no significant decrease in the applied flexion moment occurred after balance training when all maneuvers were considered. However, a
significant 10% decrease did occur in the more challenging S60 in PPO, where the greatest applied flexion moments occur (4,5). These applied flexion moments can also be viewed as internally generated extension moments by the quadriceps. The quadriceps cause anterior tibial translation (7,32) with the ACL being the main restraint in knee postures from 30° flexion to full extension (25,30,31). As a consequence, these decreased knee flexion moments may lower the risk of ACL injury, again possibly because of improved control of the upper body.

**Free weights training.** Free weights training elicited mixed results with respect to risk of ACL injury. After the free weights training, the peak internal rotation moments significantly increased in PPO (Table 1). However, in PPO, there were significant decreases in the applied peak flexion moment. As already stated, the higher external rotation moments would place the ACL under high strain (1,30,31). However, in PPO, this may be moderated by the lower flexion moment and knee flexion angles of around 45°, although flexion angle decreased slightly (4%) after training. This is because, at these knee postures, the internal rotation moments do not transfer to high ACL loading (1,30,31), and therefore, free weights training may not increase the risk of ACL injury.

**Machine weights training.** As with the free weights, machine weights training elicited changes to the knee loading, which may both increase and decrease risk of ACL injury, although most changes would act to decrease injury risk. Nevertheless, the most striking change after machine weights training was an increase in the applied flexion moment in PPO (Table 1): more than 20% in the RUN and XOV and approximately 10% in the S30 trials. These increased flexion moments can potentially increase anterior tibial translation. However, given the large knee flexion angle in PPO, this increase may not be that important for risk of ACL injury. Importantly, the machine weights training reduced the peak valgus and peak varus moments in WA, although not as large as that seen in balance training group. These changes have the potential to lower ACL loading and risk of injury during WA.

**Machine + balance training.** The balance training group tended to have numerous favorable changes that may decrease the potential risk of ACL injury, whereas the machine weights group experienced a mixture of changes. The machine weights + balance training group, however, tended to be neutral with only a few changes that may reduce the risk of injury (Table 1). These results support the research of Wedderkopp et al. (43), who showed that, compared with strength training alone, a combination of strength and balance training had significantly fewer traumatic lower limb injuries. The current results show the possible reasons for this difference, that is, machine weights + balance training seems better in preventing ACL injury than machine weights alone. However, on the basis of results from the current research, machine weights + balance training may not be as beneficial as balance training alone.

In reading these results, there are several limitations that are important to note. First, the testing and training took place in a laboratory, and results in the real world may differ from what are found in the current study. Future research should look to evaluate a balance-based intervention in the field to assess its efficacy with respect to decreasing ACL injuries. Second, the weight training programs consisted of only two exercises, and it may not represent a complete weight training program as part of an athlete’s complete physical preparation. The balance training was matched for training time but not volume on the basis of repetitions. In addition, the strength training was limited to sagittal plane exercise, whereas the balance training exercises involved coordination in all three planes. It is not known if similar results would have been found if the strength training was performed in all planes.

An additional limitation is that this study investigated the peak loadings on the knee joint, and although these were analyzed in phases, it did not distinguish the exact temporal aligning of the peak valgus and peak internal rotation moments. If the peak moments occurred at the same time, it is likely that the ACL loading would increase. For example, in WA, typically the peak valgus moment occurred slightly before peak internal rotation moments, although there was variability (Fig. 1). In the instance that the peak valgus moment occurs at a similar time as the peak internal rotation moment, as demonstrated in Figure 4 in the study of Dempsey et al. (15), ACL load would be raised. Furthermore, the subjects in the resistance training groups experienced increases in strength, and it is unknown if the ligaments are being strained to a greater degree with the increase in applied loading after these strength increases. EMG-driven knee models such as that developed by Lloyd et al. (28) could be used with the data from this study to estimate ligament and soft tissue loading at the knee and to monitor how this loading changes after the various training programs. Finally, reported in this article are the moments that at the knee; although high knee moments will certainly put a person at an increased risk of ACL injury, these knee moments are likely not the risk factor per se because these moments are a measure of the outcome of many other actions before initiating and performing a sidestep. Further research is required to elucidate what other measurable indicators may be risk factors for ACL injury, for example, poor upper body stability or one-legged balance.

**CONCLUSIONS**

The results indicate that balance training tended to induce positive changes in joint loading that serve to reduce the risk of ACL injury, whereas strength training elicited changes that could reduce or increase injury potential, depending on the variable and phase of stance evaluated. The balance training group reduced the loading at the knee with decreases in the applied varus/valgus, flexion, and internal rotation moments.
The take home message for athletes and coaches is that balance training may reduce the risk of ACL injury. Strength training, needed to maximize other aspects of performance, is recommended to be done in combination with balance training because it may reduce the potential for ACL injury.

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