Immediate Effects of Real-Time Feedback on Jump-Landing Kinematics

Approximately 250,000 anterior cruciate ligament (ACL) injuries occur annually in the United States. Roughly 80% of ACL injuries occur from noncontact mechanisms, suggesting that correcting movement behavior associated with ACL injury may help prevent future injury. The high rate of noncontact ACL injuries has prompted the development of prevention programs to decrease the risk of noncontact ACL injury. Many of these prevention programs have been found to be effective and utilize varied approaches, such as strength training, plyometrics, proprioceptive training, and movement retraining.

Females participating in landing and cutting activities have demonstrated a 4-fold to 6-fold greater chance of incurring an ACL rupture compared to their male counterparts. There is evidence that females demonstrate greater knee abduction angles and decreased knee and hip flexion during various dynamic tasks, which have been theorized to increase stress on the ACL and elevate the risk of rupture. Neurromuscular training programs have been implemented to alter these movement patterns in females for the purpose of decreasing ACL injury rates. An important component of many of these neurromuscular training programs is feedback, which has been found to decrease ACL injury rates when compared to no feedback in similar neuromuscular training programs.

Feedback is commonly used to correct potentially injurious biomechanics during specific movements. For example, augmented feedback training has been shown to alter jump-landing biomechanics. A recent systematic review concluded that a combination of expert-provided and self-analysis modes of feedback may produce the greatest effects in reducing ground reaction force during a jump-landing task. However, the optimal mode or combination of modes of feedback to reduce ACL injury rates has yet to be fully established.

Real-time feedback (RTF) is a method that allows participants to observe their movements for the purpose of making immediate biomechanical adjustments. Real-time feedback has previously been used in conjunction with other feedback modes and varies from postresponse feedback (PRF), in which participants receive feedback after completing the task.
studies have demonstrated positive results in altering lower extremity biomechanics during gait using RTF. Dynamic landing tasks are commonly used to assess abnormal lower extremity biomechanics, yet there has been limited research on the effects of RTF on this kind of movement. The purpose of the current study was to determine if the addition of RTF to PRF improves jump-landing mechanics compared to PRF alone and a no-feedback control group. We hypothesized that after undergoing the feedback intervention, the participants in the RTF plus PRF group would exhibit increased hip and knee flexion angles and hip and knee extensor moments, decreased knee abduction angles, and decreased vertical ground reaction forces (VGRFs) during a jump-landing task compared to PRF alone and a no-feedback control group.

METHODS

Study Design and Participants

Thirty-six healthy, pain-free females with no previous history of fracture, surgery, or significant orthopaedic injury to the lower extremity volunteered for this study. We only recruited females because of their higher risk for ACL rupture due to noncontact mechanisms. Sample size was estimated using means and standard deviations for peak knee flexion angle from a previous study with a similar design. This analysis indicated that 11 participants per group were needed to detect statistical significance with an alpha level of .05 and 80% power.

Block randomization was used with concealed allocation to assign participants to 1 of 3 groups: RTF plus PRF, PRF, or a no-feedback control group. Biomechanical measures were evaluated at baseline and immediately following the interventions. An opaque envelope was used to conceal group assignment until after baseline testing. Participants were recruited from the general student population at the University of Toledo. The study was approved by the University of Toledo Institutional Review Board, and written consent was obtained from each participant prior to data collection.

Biomechanical Measures

Biomechanical measures for all participants were collected at baseline and postintervention. Kinematic and kinetic data were collected as participants performed 3 trials of a jump-landing task from a 30-cm box, positioned at a horizontal distance of 50% of the participant’s height from 2 force platforms. Participants were instructed to jump forward, land on the force platforms (1 foot on each), and immediately perform a maximum vertical jump, as if going up for a basketball rebound or volleyball block. Prior to baseline testing, the participants performed practice jumps until the investigator was satisfied that the participants were comfortable with the task. Participants were allowed a maximum of 3 practice jumps prior to testing. None of the participants were provided feedback during baseline and postintervention testing.

Biomechanical Analysis

Forty reflective markers (FIGURE 1) were used to obtain kinematic data, with a 12-camera motion-analysis system (Motion Analysis Corporation, Santa Rosa, CA) and associated Cortex software (Version 3.6.1; Motion Analysis Corporation) at a sampling rate of 100 Hz. A static calibration trial was conducted with the participant standing in a neutral position. The knee joint center was defined as the midpoint between the medial and lateral femoral epicondyles, and the ankle joint center was defined as the midpoint between the medial and lateral malleoli. The hip joint center was calculated with Visual3D software (C-Motion, Inc, Germantown, MD). Ground reaction forces were obtained using 2 AMTI OR6-5 force platforms (Advanced Mechanical Technology, Inc, Watertown, MA) at a sampling rate of 1000 Hz. Kinematic and kinetic data were filtered with a low-pass Butterworth filter at a cutoff frequency of 12 Hz. Visual3D software was used to calculate 3-D joint rotations and moments. Joint rotations were quantified based on the position of the distal segment relative to the proximal segment. Joint moments were calculated using inverse dynamic equations and were reported as internal moments. All joint moments were normalized to each participant’s mass and height (Nm/kg/m).

PRF Protocol

Prior to the intervention, both the RTF plus PRF and PRF feedback groups were presented with a PowerPoint presentation (Microsoft Corporation, Redmond, WA) explaining the goals of the jump-landing task (TABLE 1). After viewing the presentation, participants in both intervention groups performed 3 sets of 6 jumps from the box, as described above. Participants were instructed to “stick the landing.” During each of these jumps, a single experienced investigator with 6 years of clinical experience recorded which of the goals of jump landing the participants were unable to accomplish. Three jumps were observed from the frontal view and 3 jumps from the sagittal view. Following each set of 6 jumps, the investigator reviewed the goals that
the participant failed to accomplish in the previous jumps and showed the participant the corresponding PowerPoint slides to reinforce the correct form.

**RTF Protocol**

In addition to the PRF, participants in the RTF plus PRF group received a live, digital representation of their body segments and were able to see a reference line to assist in making biomechanical corrections in the frontal plane. A 107-cm monitor (Sony BRAVIA; Sony Corporation, Tokyo, Japan) interfaced with the motion-capture system was positioned in front and to the right of participants so that they were able to visualize a real-time representation of their kinematics as they performed the jump landing (FIGURE 2). The participants observed 2 lines. The first line represented the shank segment, which was made by connecting the patella and great toe markers using Cortex motion-analysis software. The second line was a stationary, vertical reference line that was made by connecting a reflective marker placed on the floor to another on a tripod.

Before beginning the intervention, the investigator instructed the participant to stand on the box and to align the great toe of the right foot with a tape line that was in line with the reflective marker on the floor. The investigator adjusted the screen to allow the participant to see both lines while performing the task. The RTF plus PRF group was then provided the following instructions: “You will now be able to see markers representing your knee and toe on the screen in real time; start with your toe marker in line with the reference line and then line your knee marker up with the reference line. This is the way the markers should line up when you land; we want you to watch the video monitor, focusing on keeping the shank segment in line with the reference line when you land from your jump. You can aim to land with your foot on the tape line, but your main focus should be to keep the shank segment lined up with the line when landing from the jump.”

**Control Group**

Participants in the no-feedback control group performed 3 sets of 6 jump landings as described above, except that they received no feedback or PowerPoint presentation on the major goals of jump landing.

**Data Analysis**

The peaks of the following variables were extracted within the first 25% of stance (defined as initial contact to toe-off): VGRF, hip and knee extensor moments, knee abduction angle, and knee and hip flexion angles. The first 25% of stance phase was selected for analysis because peak ACL loading has been estimated to occur within the first 60 milliseconds upon landing.15

Initial contact and toe-off were defined as the point at which the VGRF exceeded or fell below 10 N, respectively, upon landing from the jump and rebounding for maximum height. The dependent variables of interest were averaged over 3 trials, and change scores (postintervention minus preintervention) were calculated and used for statistical analysis.

**Statistical Analysis**

A 1-way analysis of variance (ANOVA) was used to assess differences between groups at baseline. Separate 1-way ANOVAs were used to assess differences in change scores between groups. Fisher’s least-significant difference post hoc testing was used in the presence of statistical significance to determine where the differences occurred. A priori alpha levels set at \( P < .05 \) indicated statistical significance. All statistical analyses were performed with SPSS Version 19.0 software (SPSS Inc, Chicago, IL).

**RESULTS**

The groups were similar in terms of age, height, and weight (TABLE 2). There was a significant difference between groups for hip flexion angle at baseline (\( F_{2,33} = 3.74, P = .03 \)). Post hoc testing revealed that the PRF group (70.9° ± 17.6°) had greater hip flexion compared to the control group (55.2° ± 14.7°, \( P = .01 \)). None of the other outcome variables were significantly different between groups at baseline (\( P > .05 \)) (TABLE 3).

**Knee Kinematics and Kinetics**

The ANOVA comparing the change score in knee flexion angle between groups was statistically significant (\( F_{2,33} = 4.836, P = .014 \)). Post hoc testing revealed that the RTF plus PRF group had a greater increase in knee flexion (10.6° ± 8.9°) compared...
compared to the no-feedback control group (–1.5° to 9.5°, \(P = .002\)) (TABLE 4). The PRF group also demonstrated a greater increase in knee flexion (7.9° to 11.5°) compared to the control group (–1.5° to 9.5°, \(P = .028\)) (TABLE 4). There were no significant differences between the PRF and RTF plus PRF groups with respect to knee flexion angle (\(P = .51\)). The ANOVAs comparing change scores for knee abduction angle and knee extensor moment were not significant (\(P = .35\) and \(P = .19\), respectively).

**Hip Kinematics and Kinetics**

The ANOVA comparing the change score in hip flexion angle between groups was statistically significant (\(F_{1,43} = 2.96\), \(P = .043\)). Post hoc testing revealed that the RTF plus PRF group had a greater increase in hip flexion (4.8° to 7.3°) compared to the control group (–1.2° to 5.6°, \(P = .041\)) (TABLE 4). There were no significant differences between the PRF group and the control group (\(P = .1\)) or between the PRF and RTF plus PRF groups (\(P = .87\)). The ANOVA comparing change scores with respect to hip extensor moment was not significant (\(P = .169\)).

**Vertical Ground Reaction Force**

The ANOVA comparing the change score in VGRF between groups was statistically significant (\(F_{1,43} = 4.363\), \(P = .009\)). Post hoc testing revealed that the RTF plus PRF group had a greater decrease in VGRF (–0.2 ± 0.3 N/kg) compared to the no-feedback control group (0.0 ± 0.2 N/kg, \(P = .034\)) following the intervention (TABLE 4). The PRF group also demonstrated a greater decrease in VGRF (–0.2 ± 0.2 N/kg) compared to the no-feedback control group (0.0 ± 0.2 N/kg, \(P = .012\)) following the intervention (TABLE 4). There was no significant difference between the PRF and RTF plus PRF groups with respect to the change in VGRF (\(P = .70\)).

**DISCUSSION**

Overall, there were no significant differences between the RTF plus PRF and PRF groups for any of the biomechanical variables of interest. Participants in both groups increased their hip and knee flexion angles and decreased VGRFs following the respective interventions, suggesting that RTF plus PRF may not enhance immediate improvements in lower extremity kinematics beyond those of PRF alone. It is
important to note that changes in the RTF plus PRF group cannot be solely attributed to the RTF intervention. Participants in the RTF group also received PRF; therefore, we are unable to decipher exactly which aspect of the intervention produced the change in jump-landing kinematics. Further research should examine each aspect of various feedback interventions to determine which are producing biomechanical changes that could reduce ACL injury risk.

The PRF and RTF plus PRF groups immediately decreased VGRFs following the intervention period when compared to the no-feedback control group. Decreased VGRFs during jump landing have been reported previously after simple instruction to “land softly.” The results of the current investigation agree with a systematic review that reported a consistent decrease in VGRF, regardless of the type of feedback provided. More recently, Beaulieu and Palmieri-Smith reported a decrease in VGRF following an RTF intervention in which participants were instructed to minimize their knee abduction moment as visualized on a real-time graph. A previously reported positive moderate correlation between increased VGRF and increased anterior tibial acceleration when landing from a jump supports the hypothesis that individuals who land with greater impact loads could have a heightened risk of ACL injury.

The RTF plus PRF and PRF groups also demonstrated a significant increase in knee flexion following the intervention compared to the no-feedback control group. Previous studies have demonstrated similar increases in knee flexion angles using similar instructions to those used in the current investigation. In a prospective study, females who experienced an ACL tear exhibited decreased knee flexion during jump landing. Thus, the immediate increase in knee flexion observed with both the PRF and RTF plus PRF interventions may decrease ACL loading and reduce the risk of injury while landing from a jump. The hip flexion angle also increased in the RTF plus PRF group compared to the control group. Although the PRF group did exhibit an increase in hip flexion angle following the intervention, this difference was not significantly different compared to the control group. This can be ex-

### TABLE 3

<table>
<thead>
<tr>
<th>Group/Variable</th>
<th>Preintervention</th>
<th>Postintervention</th>
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<tbody>
<tr>
<td><strong>RTF plus PRF group</strong></td>
<td></td>
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<tr>
<td>Knee flexion angle, deg</td>
<td>92.4 ± 14.2</td>
<td>103.0 ± 11.0</td>
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<tr>
<td>Knee abduction/adduction angle, deg</td>
<td>-19 ± 4.8</td>
<td>-2.4 ± 3.7</td>
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<tr>
<td>Knee extensor moment, Nm/kg·m</td>
<td>1.7 ± 0.5</td>
<td>1.6 ± 0.5</td>
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<tr>
<td>Hip flexion angle, deg</td>
<td>64.5 ± 8.3</td>
<td>69.3 ± 5.3</td>
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<tr>
<td>Hip extensor moment, Nm/kg·m</td>
<td>1.3 ± 0.4</td>
<td>0.9 ± 0.5</td>
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<tr>
<td>Vertical ground reaction force, N/kg</td>
<td>1.9 ± 0.5</td>
<td>1.7 ± 0.5</td>
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<tr>
<td><strong>PRF group</strong></td>
<td></td>
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<tr>
<td>Knee flexion angle, deg</td>
<td>95.9 ± 10.0</td>
<td>103.8 ± 16.3</td>
</tr>
<tr>
<td>Knee abduction/adduction angle, deg</td>
<td>0.1 ± 8.8</td>
<td>1.1 ± 6.6</td>
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<tr>
<td>Knee extensor moment, Nm/kg·m</td>
<td>1.9 ± 0.7</td>
<td>1.6 ± 0.6</td>
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<tr>
<td>Hip flexion angle, deg</td>
<td>70.9 ± 12.6</td>
<td>75.1 ± 12.2</td>
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<tr>
<td>Hip extensor moment, Nm/kg·m</td>
<td>1.6 ± 0.7</td>
<td>1.0 ± 0.6</td>
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<tr>
<td>Vertical ground reaction force, N/kg</td>
<td>1.8 ± 0.3</td>
<td>1.6 ± 0.3</td>
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<tr>
<td><strong>Control group</strong></td>
<td></td>
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<tr>
<td>Knee flexion angle, deg</td>
<td>85.0 ± 21.4</td>
<td>83.5 ± 20.5</td>
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<tr>
<td>Knee abduction/adduction angle, deg</td>
<td>-0.2 ± 5.3</td>
<td>-2.4 ± 5.2</td>
</tr>
<tr>
<td>Knee extensor moment, Nm/kg·m</td>
<td>1.8 ± 0.3</td>
<td>1.8 ± 0.4</td>
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<tr>
<td>Hip flexion angle, deg</td>
<td>55.2 ± 14.7</td>
<td>54.0 ± 15.4</td>
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<tr>
<td>Hip extensor moment, Nm/kg·m</td>
<td>1.5 ± 0.6</td>
<td>1.2 ± 0.6</td>
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<tr>
<td>Vertical ground reaction force, N/kg</td>
<td>2.0 ± 0.4</td>
<td>2.0 ± 0.4</td>
</tr>
</tbody>
</table>

**Abbreviations:** PRF, postresponse feedback; RTF, real-time feedback.

*Values are mean ± SD.

<table>
<thead>
<tr>
<th>Variable</th>
<th>RTF plus PRF Group</th>
<th>PRF Group</th>
<th>Control Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee flexion angle, deg</td>
<td>10.6 ± 8.9†</td>
<td>79 ± 11.5</td>
<td>-15 ± 9.5</td>
</tr>
<tr>
<td>Knee abduction angle, deg</td>
<td>-0.5 ± 2.3</td>
<td>1.0 ± 5.2</td>
<td>-2.2 ± 3.0</td>
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<tr>
<td>Knee extensor moment, Nm/kg·m</td>
<td>-0.1 ± 0.3</td>
<td>-0.3 ± 0.4</td>
<td>0.0 ± 0.4</td>
</tr>
<tr>
<td>Hip flexion angle, deg</td>
<td>4.8 ± 7.3‡</td>
<td>4.2 ± 10.0</td>
<td>-1.2 ± 5.6</td>
</tr>
<tr>
<td>Hip extensor moment, Nm/kg·m</td>
<td>0.4 ± 0.5</td>
<td>0.6 ± 0.4</td>
<td>0.3 ± 0.5</td>
</tr>
<tr>
<td>Vertical ground reaction force, N/kg**</td>
<td>-0.2 ± 0.3</td>
<td>-0.2 ± 0.2</td>
<td>0.0 ± 0.2</td>
</tr>
</tbody>
</table>

**Abbreviations:** PRF, postresponse feedback; RTF, real-time feedback.

*Values are mean ± SD.

†A positive change score indicates an increase in knee flexion angle.
‡Statistically different from control group (P<.05).
§A negative change score indicates an increase in knee abduction angle.
‖A negative change score indicates a decrease in knee extensor moment.
¶A positive change score indicates an increase in hip flexion angle.
‖A positive change score indicates a decrease in hip extensor moment.
*A negative change score indicates a reduction in vertical ground reaction force.
plained by the fact that the variability in the PRF group’s hip kinematic data was relatively large. We also recognize that the PRF group began with significantly more hip flexion than the control group at baseline; this might have also contributed to the lack of change in hip flexion following the intervention.

Contrary to our hypothesis, the RTF plus PRF and PRF groups did not demonstrate a significant change in the knee extensor moment or hip extensor moment. One would expect to see an increase in knee and hip extensor moments with increased knee flexion and hip flexion angles. A potential explanation for no change in knee and hip extensor moments may be related to trunk position during the jump-landing task. It has been shown that trunk posture can influence knee and hip moments during a jump-landing task. Given that we did not standardize trunk posture in the current investigation, variable trunk postures could have contributed to between-subject differences in hip and knee extensor moments.

No significant differences were noted between groups for the knee abduction angle. Video analysis of basketball ACL injuries identified a dynamic knee valgus collapse during many of the injuries evaluated, indicating that valgus loading was likely present before ACL rupture. A prospective study also demonstrated greater knee abduction angles in females who went on to incur an ACL rupture. One intention of the RTF plus PRF intervention was to decrease frontal plane motion at the knee. The primary reason for no difference observed between groups in knee abduction angle was that there was little to no motion in the frontal plane for the participants to correct. Also, the room for improvement in frontal plane knee kinematics was not very large, making it difficult to identify a statistical difference. This was supported by our data, in which the RTF plus PRF group changed by 0.51°, whereas the PRF group changed by only 1°. Participants were not prescreened for excessive knee abduction prior to inclusion in this study. Screening for abduction may be important in future studies investigating RTF for the correction of frontal plane knee kinematics.

Multiple sessions with RTF plus PRF may also be necessary to realize the full benefits of this combined intervention. It also may be more beneficial to provide RTF in a cyclic manner or with slower movements to allow for better processing and implementation. Providing RTF in a cyclic manner, with an inertial-based sensor system along with feedback instructions, has been previously demonstrated to decrease knee abduction moment following a 1-time intervention. It has also been noted that combination feedback may be most effective at improving jump-landing biomechanics. Perhaps a combination of videotape feedback and RTF may produce the most effective results in altering jump-landing biomechanics and reducing ACL injury risk. Future research investigating modes of feedback should aim to discern which modes are most effective at changing specific lower extremity jump-landing mechanics. This knowledge would allow for intervention programs to be tailored to target specific deficits and potentially further reduce injury risk.

The present study is not without limitations. We only investigated the immediate effect of the addition of RTF to PRF compared to PRF alone and a no-feedback control group. As previously mentioned, future research should investigate the effects of a longer feedback intervention, with testing for retention over time. Another limitation is that there was no prescreening (specifically for dynamic knee valgus during jump landing) as part of the inclusion criteria. As previously mentioned, if participants do not present with a dynamic knee valgus prior to the start of the feedback intervention, there may be little need to alter kinematics in this plane. Real-time feedback was only administered to the right limb. In future studies, it may be appropriate to assess symmetry during administration of RTF to ensure that symmetry is balanced during application of the feedback. Real-time feedback as an intervention is heavily dependent on instrumentation, which makes it difficult to test multiple participants and reduces clinical applicability. Finally, we recognize that our small sample size might have limited statistical power, which may explain the lack of significant findings for several of the variables examined.

Participants may respond favorably to an intervention in which they are exposed to the major components of jump landing more frequently. The optimal dosage and frequency of feedback needed to produce lasting changes in landing biomechanics remain unclear. It is unknown if feedback interventions are capable of producing lasting biomechanical changes and if those changes can be transferred to other dynamic tasks. Future research should investigate this premise by testing participants on a task other than the task for which feedback is provided.

**CONCLUSION**

The RTF plus PRF and PRF groups demonstrated similar increases in peak knee flexion and decreased peak VGRF following the immediate intervention compared to a no-feedback control group. The RTF plus PRF group also demonstrated an increase in hip flexion angle compared to the control group. No changes between groups were observed in knee abduction angle. The addition of RTF to PRF, compared to the PRF intervention alone, did not result in changes in jump-landing biomechanics.

**KEY POINTS**

**FINDINGS:** The RTF plus PRF and PRF groups demonstrated similar changes in lower extremity sagittal plane kinematics and VGRFs following the intervention period; however, no changes in frontal plane kinematics were observed between groups.

**IMPLICATIONS:** The addition of RTF to PRF did not result in significant changes in jump-landing kinematics.
compared to PRF alone. Therefore, RTF and/or PRF may be beneficial in immediately changing lower extremity jump-landing kinematics.

**CAUTION:** Retention and transfer of learned feedback should be investigated to determine the full clinical applicability of these interventions.

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