Traumatic and debilitating anterior cruciate ligament (ACL) injuries occur at a 2- to 10-fold greater rate in female compared with male athletes. Prospective measures of knee abduction load during landing predict ACL injury risk in young female athletes.1 Females exhibit increased lower-extremity valgus alignment and load compared with males during landing and pivoting movements.2–14 Similar lower-extremity valgus alignments are often demonstrated by females at the time of injury.15–17 Therefore, based on the previous literature, knee abduction posture and load are often addressed during injury prevention interventions.

Neuromuscular training in females increases active knee stabilization in the laboratory and decreases the incidence of ACL injury on the field and court of play in athletic female populations.14,18–20 Neuromuscular training facilitates neuromuscular adaptations that focus on joint stabilization and safe movement patterns. This training allows female athletes to adopt muscular recruitment strategies that decrease joint motion and protect the ACL from the high impulse loading.19,21,22 However, poor implementation, combined with low athlete compliance, has resulted in a lack of widespread reduction in ACL incidence.18,23 In addition, a clearer identification of the putative modifiable mechanisms would increase the potential for both screening for high-risk athletes and for targeting interventions to address the specific mechanisms that increase ACL injury risk in female athletes.

Intervention studies that have successfully reduced ACL injuries used analysis of the movement biomechanics and feedback to the athlete regarding proper body position and technique.18,20,24 Education and enforced awareness of dangerous positions and mechanisms of ACL injury have also been shown to decrease ACL injuries.25 Hewett et al20 used a trainer to provide feedback and awareness to an athlete during training. Verbal and visualization cues such as “on your toes,” “straight as an arrow,” “light as a feather,” “shock absorber,” and “recoil like a spring” were used by the trainer for each phase of the jump.20 Multiple studies support the importance of feedback within a training program.18,24,26,27 Recent studies with real-time gait retraining reinforce the concept of providing critical feedback but with more detailed
real-time motion analysis data. Barrios et al and Noehren et al used 3D motion analysis technologies to provide real-time feedback aimed at modifying a risk factor related to different types of knee pathology. Biofeedback training is a method that enables an athlete to learn how to alter biomechanical and physiological function via biomechanical and physiological data presentation during real-time or immediately after a task. The goal of this form of training is to facilitate motor learning of improved and safe movement patterns without the need for continued use of biofeedback. Specifically, kinematic or kinetic biomechanical data with a skeletal representation of the athlete is displayed in real-time on a large computer screen. The kinematic data provides the athlete with a spatial perspective of how their joints are moving. The kinetic feedback utilizes inverse dynamics calculations to provide the athlete with real-time frontal plane knee joint loading and is typically used to help explain how the movement occurs. Incorporating this novel technology may supplement and potentially improve the outcomes of injury prevention programs. The purpose of this study was to examine and compare the effects of kinetic- or kinematic-based real-time biofeedback during repetitive double-leg squats on reducing risk factors related to ACL injury.

Methods

A crossover study design was used to test the effects of 2 methods of real-time biofeedback during repetitive double-leg squats. Baseline and postraining drop vertical jumps (DVJs) were collected to determine if either training method transferred to another activity. Dependent variables consisted of knee abduction angle and moment. Female high school soccer players (age 14.8 ± 1.0 y; height 162.6 ± 6.8 cm; mass 55.9 ± 7.0 kg; n = 4) participated in this pilot study at Cincinnati Children’s Hospital. Informed written consent was obtained from each parent or guardian and assent obtained from each subject in accordance with the protocol approved by the Cincinnati Children’s Hospital institutional review board.

Each subject was instrumented with 43 markers attached with double-sided tape with a minimum of 3 tracking markers placed on each right and left lower-extremity segment (foot, shank, thigh) and trunk (pelvis, thorax). Motion and force data were collected at 240 Hz and 1200 Hz, respectively, using a 10-camera motion capture system (RaptorE, Motion Analysis Corp, Santa Rosa, CA) and multiple force platforms (AMTI, Watertown, MA). A standing static trial for each subject was collected to define the neutral kinematic posture. Kinematic analysis and real-time biofeedback was performed in Visual 3D (C-Motion, Inc, Germantown, MD). Three-dimensional marker trajectories and ground reaction force from each trial were filtered at a cutoff frequency of 12 Hz (low-pass fourth-order Butterworth filter). Kinematic data were combined with force data to calculate knee joint moments using inverse dynamics.

Each participant was randomly allocated to receive kinetic biofeedback and kinematic biofeedback. During the feedback conditions, a monitor displaying a real-time animation of the subject and a data curve with a highlighted goal region was positioned in front of the subject. Subjects were instructed to keep the curve within the highlighted region. Three trials of 10 double-leg squat repetitions were collected and displayed in real time. Knee abduction/adduction angle was displayed for the kinetic biofeedback condition. Knee abduction/adduction moment was displayed for the kinetic biofeedback condition. Three DVJ trials were collected before and following each feedback condition and averaged for further analysis (Figure 1). Paired t tests were used to determine differences from baseline to postfeedback in average knee abduction moment and angle when performing the DVJ.

Results

Maximum knee abduction moment during DVJ landing was significantly decreased after kinetic biofeedback (P = .04). Subjects exhibited a 32.8% improvement in knee abduction moment from baseline (−12.5 Nm) to postkinetic biofeedback (−9.8 Nm). However, the 5.7% reduced knee abduction moment during the DVJ following kinetic biofeedback (−10.8 Nm) was not statistically different (P = .2). Maximum knee abduction angle was significantly decreased following kinetic biofeedback (P < .01) but only showed a trend toward reduction following kinematic biofeedback (P = .08). Subjects exhibited a 31.5% improvement in knee abduction angle from baseline to postkinetic biofeedback compared with a 16.3% change postkinematic biofeedback.

Knee abduction moment averaged over all subjects during squat biofeedback is presented in Figure 2. During the eccentric and concentric phases of the squat, subjects were able to maintain feedback torque within the goal region for 80.8% of the trials during kinetic biofeedback compared with only 29.3% of the trials during kinematic biofeedback (Figure 2).

Discussion

Intervention studies that have successfully reduced ACL injuries have used analysis of movement biomechanics and feedback regarding proper body position and technique. Education and enforced awareness of dangerous positions and mechanisms of ACL injury decreases ACL injuries. The results from this pilot study indicate that kinetic biofeedback technique modifications during squat biofeedback may rapidly transfer to dynamic drop landings.

Our results support previous research that reported the use of augmented feedback as part of a neuromuscular training program as effective for improvement of athletic performance, movement biomechanics, and ACL injury risk in young athletes. Frequent use of verbal feedback on the technical performance of plyometric and dynamic
Figure 1 — Examples of initial setup and double-leg squat with real-time biofeedback.

Figure 2 — Average knee adduction (positive) curve during eccentric (left) and concentric (right) phases of the squat. The shaded region was the target goal during each kinetic feedback squat.
stabilization exercises produced significant reductions in dynamic lower-extremity abduction during a DVJ task in female high school volleyball players. Feedback regarding position and technique during sport-related movements may increase an athlete’s awareness and allow them to make adjustments during training. In the current study, the reductions in knee abduction angle and moment during the landing trials after biofeedback indicate that subjects were able to adjust lower-extremity frontal plan positioning and torque as a result of the training. This method of training is useful for the enhancement of the user’s awareness and visual understanding of important kinematic and kinetic factors that may be related to injury. A particularly salient finding is that the feedback provided during a squat task transferred to the more dynamic mechanics of a plyometric DVJ.

Previous work in athletes who were characterized as high risk for ACL injury significantly reduced their knee abduction torque through neuromuscular training and feedback. However, this reduction did not decrease sufficiently enough to recategorize the athletes as low risk; therefore, it is likely that high-risk athletes could benefit from additional feedback techniques. Using real-time biofeedback such as kinetic or kinematic biofeedback provides an intriguing option for delivering augmented feedback and can maximize the effectiveness of traditional neuromuscular intervention programs. Recent studies with real-time gait retraining have reinforced the concept of providing critical feedback with detailed real-time motion analysis data. Multiple studies support that providing real-time feedback modifies potential risk factors related to different knee pathologies. Both immediate and longer-term improvements have been identified.

Individuals that received real-time feedback can exhibit immediate improvements in injury-related movement mechanics. The results of the current study indicate that subjects were able to make adjustments after only a single training session that reduced their knee abduction angle and moment during landing. The potential for active real-time feedback systems to rapidly induce improvements in factors that predispose individuals to ACL injury indicates that the use of such systems may be an effective addition to traditional neuromuscular intervention programs, particularly by enhancement of athlete self-awareness and understanding of dangerous body positions and lower-extremity biomechanics. While the implementation of the current technique required the use of a dedicated motion laboratory and skilled research staff, there is potential for biofeedback modalities to be more user-intuitive and generally applicable. In a recent study, subjects performed DVJ trials and received immediate feedback from inertial sensors on knee flexion angle, trunk lean, and coronal plane thigh angular velocity. The subjects were able to quickly and effectively improve these kinematic variables in a single training session, with the implication being that subjects were able to assess and respond to feedback without the assistance of a skilled trainer. Future work to determine the potential effects of the proposed real-time biofeedback techniques is warranted to determine the potential to reduce injury risk with these techniques.

The novel and innovative biofeedback employed in the current study reduced knee abduction load and posture from baseline to posttraining during landing. A limitation in our technical note was the low number of subjects (N = 4). However, significant differences were identified that indicate that this form of intervention may have a large effect size. Another limitation is that we focused our analyses on the change in peak knee abduction moment, which may not explicitly relate to the timing of an ACL injury. Future work should identify the changes in lower-extremity biomechanical measures early during landing (eg, first 100 ms). In addition, while the immediate improvements are important, long-term retention of adapted motor performance is critical for overall success of an intervention. Retention of biofeedback training should be further investigated to determine both the change in mechanics and injury reduction effects. Incorporation of biofeedback aspects may improve outcomes from injury prevention programs.

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References


4. Ford KR, Myer GD, Smith RL, Vianello RM, Seiwert SL, Hewett TE. A comparison of dynamic coronal plane excursion between matched male and female athletes when...


31. Myer GD, Ford KR, Brent JL, Hewett TE. The effects of plyometric vs. dynamic stabilization and balance training
