I, Scott H Bonnette, hereby submit this original work as part of the requirements for the degree of Doctor of Philosophy in Psychology.

It is entitled:
On the Modification of Risk Factors for Anterior Cruciate Ligament Injuries in Female Athletes Through Visual Feedback

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On the Modification of Risk Factors for Anterior Cruciate Ligament Injuries in Female Athletes Through Visual Feedback

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Abstract

Anterior cruciate ligament (ACL) injuries are a growing public health problem in the United States, with associated healthcare costs exceeding $2 billion annually (Kim, Bosque, Meehan, Jamali, & Marder, 2011). Females are more likely to incur an ACL injury, and in recent years adolescent females (i.e., 14-17 year olds) have experienced the largest increase in ACL injury rate (Csintalan, Inacio, & Funahashi, 2008). A large amount of research has investigated and identified several potential risk factors for ACL injuries in females. Prevention of ACL injuries has emerged as a priority, but current injury prevention programs suffer from several problems, such as noncompliance (Sugimoto, Myer, Bush et al., 2012) and limited reductions in injury risk (Sugimoto, Myer, McKeon, & Hewett, 2012), and thus fail to address the rising rates of ACL injuries. The objective of this dissertation was to determine the efficacy of a real-time, visual-feedback display for ACL injury risk reduction in adolescent females. This was accomplished in two-stages. First, a pilot study tested the feedback protocol on a small group of participants to ensure the newly developed technical aspects of the feedback program and display operated successfully. The results of the pilot study were used to adjust the feedback protocol before the second stage of the project, which used the modified feedback protocol to investigate the ability of the feedback display to reduce biomechanical risk factors associated with ACL injuries. This was achieved by comparing the effects of the real feedback stimulus to those of a control stimulus—a sham display that was phenomenologically similar but did not provide informative feedback—on movement biomechanics during a body-weight squat exercise. It was hypothesized that participants would improve movement biomechanics more when they received the real feedback than when they received the sham feedback and that these enhanced, lower-risk movement biomechanics for the real-time feedback group would transfer to a separate dynamic
movement exercise (a drop vertical jump, DVJ) to a greater extent than for the control group.

The pilot experiment achieved its aims. The study successfully managed the technical issues associated with the feedback program, the display (in terms of both software and hardware), and the integration of real-time biomechanical data. Only slight modifications were made to the values of the feedback gains before the primary study began. Otherwise, the equipment and procedure for generating the feedback display remained unchanged. The pilot study also demonstrated an overall improvement in participants’ performance of the squat exercise. In the primary experiment the main difference found among comparisons was between the heat map scores during the real and sham feedback training trials. The real feedback display was beneficial to producing squats with better movement form than performing the squatting exercise with the uninformative sham stimulus. Most importantly, this finding suggests that participants were not only sensitive to the feedback stimulus but they were also able to use it to modify their movements appropriately. Participants also reported that their experience of interacting with the stimulus was generally positive, engaging, and enjoyable.

In both experiments the results revealed positive biomechanical changes. Participants’ in the pilot study improved from a pre- to post-test period, and participants’ in the primary study were better during interaction with the real than the sham feedback. The primary study also identified the need for several potential modifications to the training intervention which may improve its future effectiveness. These include changes to both the real and sham feedback stimuli, the development of a less intrusive squat depth indicator, and an increase in the duration of the training program. Of these issues the two which most likely limited the training’s effectiveness in the present study were the depth indicator and the training duration. Future changes to these aspects of the training intervention could improve participant performance and reduce ACL injury risk.
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Figure 1. Displayed above is the stimulus design used in the pilot and primary experiment. During the trials the stimulus’ shape started as rectangle. This shape is depicted in Panel A and was defined by points one through six. An outline of the shape’s corners (points one, two, four, and six) remained while participants were performing the squat exercise and are shown in Panels B-F. Also displayed are ten circles towards the bottom of each display. These were used as a visual display for counting the number of squats within a trial. As participants performed squats, the circles would change from grey to green. Depicted in Panels B-E are the effects of the trunk lean, vGRF, KHMr, and KMr variables, respectively. In Panel F the lighter background rectangle lowered from its maximum height (displayed in Panels A-E) as a participant performed the downward movement of a squat. Accordingly, it rose as a participant began to stand backup.

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Figure 3. The crossover design used. Each rectangle represents a block that consisted of 10 squats; in addition to the 10 squats, the darkest rectangles (the test periods, during which no feedback at all was presented) also included 3 DVJs. The two rows of rectangles indicate the type of feedback used—either real or sham feedback. The solid and dashed black lines respectively denote the group who received the sham feedback first and the group who received the real visual feedback first. The middle rectangle denotes the crossover point—the point that the feedback type was switched.

Figure 4. Displayed above is the technique used to derive the sham feedback. The bottom plot is a sample time series of a single squat rep performed during a sham trial. Specifically, the mid-shoulder marker is illustrated. The top plot depicts how the signal-to-noise ratio (i.e., how much of the stimulus movement was driven by participant movement or noise) corresponds to a particular movement stage of a squat.

Figure 5. Displayed above is an example time series of the virtual mid-shoulder marker. The mid-shoulder marker was used as a template to trim and parse the time series of all other markers. The orange colored sections of the time series were removed, leaving only the portions of data during which a participant was performing a squat.

Figure 6. Displayed above is an example of a time normalized time series. The red line indicates the average trunk lean value for participants in the real feedback condition. The surrounding orange area indicates the 95% CI of the red line. Similarly, the black line is the mean trunk lean value for participants in the sham feedback, and the surrounding grey area is the 95% CI of the trunk lean values.
CHAPTER 1: INTRODUCTION

Anterior cruciate ligament (ACL) injuries\(^1\) are a growing national problem in the United States, where associated healthcare costs can exceed $2 billion dollars a year (Kim, Bosque, Meehan, Jamali, & Marder, 2011; Myer, Ford, & Hewett, 2004). This problem is further amplified by sex-related differences in ACL injury rates among male and female athletes. In fact, numerous studies have found that female athletes incur knee injuries four-to-six times more frequently than their male counterparts (Chandy & Grana, 1985; Ferretti, Papandrea, Conteduca, & Mariani, 1992; Gray et al., 1985; Malone, Hardaker, Garrett, Faegi, & Bassett, 1993; Whiteside, 1980; Zelisko, Noble, & Porter, 1982). Studies comparing the rates of injury for male and female soccer players have also reported that knee injuries account for a greater proportion of all injuries in females (31.8%; Giza, Mithöfer, Farrell, Zarins, & Gill, 2005) than in males (17%; Hawkins, Hulse, Wilkinson, Hodson, & Gibson, 2001). Not only are females more likely to injure their knees than males, but in recent years, adolescent females (i.e., 14-17 year olds) have experienced the largest increase in the rate of ACL injuries (Csintalan, Inacio, & Funahashi, 2008) even after statistically controlling for a nearly 10-fold increase in female sports participation since the inception of Title IX (Agel, Arendt, & Bershadsky, 2005).

This alarming increase in the rate of ACL injuries in females causes both immediate and lasting detrimental health effects. The pain and discomfort experienced immediately following the injury and during the process of reconstructive surgery and rehabilitation is only worsened by the strong link between ACL injuries and post-traumatic knee osteoarthritis in young individuals. One longitudinal study placed the rate of developing osteoarthritis at approximately 50% within a time

\(^1\) Unless otherwise specified, an ACL injury throughout this dissertation refers to an injury not caused by contact with another object—noncontact ACL injuries account for approximately 70% of all ACL injuries (Boden, Faegi, & Garret, 2000; McNair, Marshall, & Matheson, 1990).
period of 12-20 years (Lohmander, Englund, Dahl, & Roos, 2007), with another study reporting similar results for the lifetime risk of persons with a knee injury at 56.8% (Murphy et al., 2008). Due to the increasing prevalence of ACL injuries, the health impact they cause, and the associated medical costs, the National Public Health Agenda for Osteoarthritis advocates the need for the development of preventive treatment programs (Center for Disease Control and Prevention, 2010).

**Current Injury Prevention Techniques**

Recent meta-analyses reveal that neuromuscular training programs—programs which specifically target nerves, muscles, and their interactions—have had success in preventing non-contact ACL injuries (e.g., Gagnier, Morgenstern, & Chess, 2015; Pappas et al., 2015; Hewett, Ford, & Myer, 2006; Myer, Sugimoto, Thomas & Hewett, 2012; Sugimoto, Meyer, Barber Foss, & Hewett, 2014). These programs accomplish this through the use of a particular group of exercises that promote proper movement form and dynamic ability of athletes. However, the meta-analyses and other studies have also shown that these training programs suffer from several problems and as a result they have failed to arrest the rising rates of ACL injuries. These problems include: (a) The general susceptibility of training programs to participant noncompliance, (b) the questionable or limited ability of training to successfully bring about the desired changes in motor behavior, (c) the limited capability of training to reduce actual injury risk or transfer to behavior outside of the training program, and (d) the resources associated with the need for trained specialists supervising training.

Participant noncompliance is a unique issue to consider in developing a successful injury prevention program because it is typically not directly related to the empirical motivation for how the intervention is designed (e.g., what risk factors are targeted, what methods are used to reduce these factors, and when the program is implemented). Yet, noncompliance is integrally intertwined
with the success of a program as it is crucial to reducing ACL injury rates and highly difficult to achieve at a cost-effective and widespread scale. For instance, reported compliance rates for training programs range from 10.7% to 100% (Heidt, Sweeterman, Carlonas, Traub, & Tekulve, 2000, and Steffen, Myklebust, Olsen, Holme, & Bahr, 2008, respectively). The likelihood that a participant in a low-compliance-rate study incurs an ACL injury is 4.9 times higher than a participant in a study with a high compliance rate (Sugimoto, Myer, Bush, et al., 2012). Although it is difficult to determine exact reasons for noncompliance, participant motivation seems to play a key role; Steffen et al. (2008) reported that low motivation of participants might have caused their study’s high noncompliance rate of 89.3%. Incentives for participation, although possibly not cost effective on a very large scale, do appear to increase compliance. Heidt et al. (2000) experienced 100% compliance by providing, without charge, a custom training intervention that normally cost $360.00. Additionally, it appears that training not directly related to enhancing performance (e.g., speed, endurance, and power) reduces participant compliance. In a meta-analysis by Hewett, Ford, and Myer (2006), the average compliance rate of ACL injury prevention programs was 45.3%, while they reported the average rate for performance enhancement training programs was between 80-90% compliance. Determining how to encourage participant compliance without incentives is a crucial problem that must be overcome to successfully implement a widespread and cost-effective ACL injury prevention program.

Although various studies have demonstrated that training interventions can reduce rates of ACL injury and that specific biomechanical variables associated with ACL injury risk can be successfully targeted for improvement, many discrepancies exist in the literature. The most salient differences are among the content, length, frequency, total duration, and administration of the preventative training programs (for general reviews, see Gagnier, Morgenstern, & Chess, 2013;
Hewett, Ford, & Myer, 2006; Pappas et al., 2015; Sugimoto, Myer, Barber Foss, & Hewett, 2013; Sugimoto, Myer, Bush et al., 2012; Sugimoto, Myer, McKeon, & Hewett, 2012). Specifically, the differences within each category of training type include: (a) content—targeted training of flexibility/stretching, plyometrics, strength, agility, cardiovascular, balance, core stability, and education/enforced awareness/feedback; (b) length—ranges from 10-90 minutes per training session; (c) frequency—examples include a single session in total, once a day for 15 days, and twice a week for the duration of the program; (d) total duration—ranges from a single session to 9 months; and (e) administration—self, video recordings, coaches, teammates, athletic trainers, physical therapists, and physicians. While training programs using various combinations of the above differences have shown reduction of ACL injury risk (e.g., de Marche Baldon et al., 2012; Myer, Ford, Brent, & Hewett, 2007; Hewett, Lindenfeld, Riccobene, & Noyes, 1999; Mandelbaum et al., 2005; Myklebust et al., 2003), several have not displayed an improvement (e.g., Klug, Brent, Myer, Ford, & Hewett, 2012; Pfeiffer, Shea, Roberts, Grandstrand, & Bond, 2006; Söderman, Werner, Pietilä, Engström, & Alfredson, 2000).

Successful injury prevention programs share common factors within each of the categories of training types. Most of the successful programs included more than one manner of training. For example, Hewett, Lindenfeld, Riccobene, and Noyes (1999) successfully reduced risk of ACL injury with the inclusion of stretching, plyometrics, balance, weight training, and feedback. However, most cases utilizing a single manner of intervention, such as balance training or strength training, were not successful (e.g., Söderman, Werner, Pietilä, Engström, & Alfredson, 2000, and Herman et al., 2008, respectively). The most successful programs were also some of the most intensive programs in terms of the length, frequency, and entire duration. Through meta-analysis, Sugimoto et al. (2013) determined that 70% of ACL injury risk could be alleviated with 30 minutes
of training a week over the course of a sports season, and that the optimal length of a single training session was 20 minutes. They also reported that training should be performed multiple times a week across both pre- and in-season periods, because many behavioral modifications require longer times for an effective outcome.

As for administration, the last training category, it appears that the source of training (who provides it) is less important than the reception of critical analysis (i.e., information relating to the proper execution of preventative training exercises) and feedback during the training sessions (Hewett, Ford, & Myer, 2006; Hewett, Lindenfeld, Riccobene, & Noyes, 1999; Mandelbaum et al., 2005; LaBella et al., 2011). Ensuring that the feedback received during training is correct, however, usually requires the presence of a trained professional such as an athletic trainer or physical therapist. This increases the required resources for implementing a preventative program, and current estimates place the numbers needed to treat at 120 participants to prevent one ACL injury, which may cause smaller teams hesitancy in adopting such a program (Sugimoto, Myer, McKeon, & Hewett, 2012).

In addition to the problems of current ACL injury prevention programs just mentioned, the most practical issue to overcome may be the resources required to implement these programs. For example, Hewett, Ford, and Myer (2006) estimated the cost per athlete per season of three programs (Hewett, Lindenfeld, Riccobene, & Noyes, 1999; Myklebust et al., 2003; Heidt, Sweeterman, Carlonas, Traub, & Tekulve, 2000; respectively) to be $169.53, $49.67, and $442.41. Such high costs are usually outside the possibility for many school budgets, and in addition to already low compliance rates (Sugimoto, Myer, Bush et al., 2012), it seems unlikely many schools

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are likely to administer existing prevention programs. As a result of these problems, there is further need for development and evaluation of effective and efficient techniques that reduce the risk of ACL injuries. While these challenges remain to be overcome, promising progress has been made about which biomechanical deficits place an athlete at risk for an ACL injury, which is knowledge critical to the success of an injury prevention program.

**Risk Factors Associated with ACL Injuries**

Over the past 30 years, a large amount of research has investigated and identified several potential risk factors for ACL injuries in females (for reviews, see Hewett & Myer, 2011; Hewett, Myer, & Ford, 2006). Potential risk factors include: (a) *Anatomical features* such as general joint laxity (Boguszewski, Cheung, Joshi, Markolf, & McAllister, 2015; Soderman, Alfredson, Pietila, & Werner, 2001) and small femoral notch widths (Emerson, 1993); (b) *hormones* related to female physiology, such as estrogen (Moller-Nielson & Hammar, 1991); (c) *neuromuscular properties* such as abnormal synergistic relationships between the ACL, hamstrings, and quadriceps (Solomonow et al., 1987); and (d) *biomechanical properties*. This knowledge has accumulated from a variety of methodologies; however, as it is nearly impossible (barring an accident or highly unethical practices) to study an actual *in situ* incidence of an ACL injury within a motion capture laboratory, the majority of knowledge concerning the circumstances surrounding the occurrence of ACL injuries originates from the examination of video recordings and is generally qualitative in nature.

Through the video analysis of numerous ACL injuries, it appears several mechanisms are consistently present during the time of an injury (Boden, Torg, Knowles, & Hewett, 2009; Hewett, Torg, & Boden, 2009; Koga et al., 2010; Krosshaug et al., 2007; Olsen, Myklebust, Engebretsen, & Bahr, 2004). These injuries commonly occurred during competitive athletic movements like a
player landing from a jump, producing a quick deceleration, or sharply pivoting (e.g., Bode et al., 2009; Hewett et al., 2009). Starting with the trunk, each risk factor relative to the anatomical position will be described in progressive distal order ending with the feet. First, lateral sway of the trunk seems to underlie increased valgus forces at the knee joint (Boden et al., 2009; Hewett et al., 2009; Krosshaug et al., 2007), which, combined with rotation of the tibia, may result in an ACL injury (e.g., Koga et al., 2010; Olsen et al., 2004). Additionally, commonly the knee was close to full extension at the approximate time of injury (Olsen et al., 2004) and initial ground contact was made with the plantar surface of the foot flat against the ground or with the hind foot (Boden et al., 2009; Hewett et al., 2009). The combination of a laterally displaced torso, extended knee, and flat foot suggest that the leg was unable to help absorb the forces generated during the period of injury (Boden et al., 2009), and that these forces, in addition to increased knee abduction, suggest that internal rotation of the tibia combined with axial compressive forces (inward pushing forces) put an athlete at high risk for an injury. Krosshaug et al. (2007) compared video recordings of male and female athletes at the time of injury and found that females landed with significantly more hip and knee flexion and were at a 5.3 times higher risk of sustaining a valgus collapse than males. This evidence, as revealing as it is, is highly limited in its ability to provide definitive explanations because the exact time of ACL injury is unknown, no information about existing forces can be determined from the videos, and anatomical landmarks are often difficult to find on clothed athletes (e.g., Boden et al., 2009; Krosshaug et al., 2007).

Nonetheless, a prospective investigation by Hewett and colleagues (2005) corroborates the observations from the video analysis of increased knee abduction and apparent valgus forces during the time of injury. They recorded 3-dimensional biomechanical data (kinematic and kinetic) from 205 athletes performing a jump-landing task in pre-season and tracked rates of ACL injuries
over the next 2 sports seasons. Results showed a significant difference in the biomechanics of injured athletes \((n = 9)\) and non-injured athletes \((n = 196)\) during the jump-landing task. Specifically, measures of the knee abduction moment during landing predicted future ACL injuries with 73% specificity and 78% sensitivity. Knee abduction angles, moments, and differences for these measures between the two legs showed a predictive \(r^2\) value of 0.88. The results of this study and the video analyses are further supported by Ford et al. (2006) with their finding that female college athletes displayed greater knee abduction angles than males during a single-leg box drop. Since those studies were published, several experiments have investigated sex-related differences in knee abduction during landing. The results are summarized in a meta-analysis by Carson and Ford (2011). Twenty-two of 24 studies reported effect sizes that supported females exhibiting higher levels of knee abduction angles or moments than males during landing behaviors.

Furthermore, complementary results have been observed across an array of other behaviors. For instance, female athletes are shown to have a greater knee abduction angle than males during the execution of a cutting maneuver (a movement in which a participant jumps forward with both legs simultaneously and then performs a side-step towards an indicated direction; Ford, Myer, Toms, & Hewett, 2005). Trunk displacement in the lateral direction has also been shown to be a risk factor for ACL injury. In a study by Zazulak, Hewett, Reeves, Goldberg, and Cholewicki (2007), lateral trunk displacement after a sudden force release was the strongest predictor of future ACL injuries for females in a statistical model containing proprioception, history of low back pain, and trunk displacement. The model predicted ACL injury risk with 91% accuracy. Lastly, joint stiffness may also influence the risk of injury. Using a drop-landing task, Ford, Myer, and Hewett (2010) investigated changes in joint stiffness of males and females over a one-year period during puberty. While they found that both females and males showed an increase in knee stiffness over
this period, males also demonstrated an increase in ankle and hip joint stiffness whereas females did not. This suggests that over the course of puberty males may develop a different strategy for controlling movements than their female counterparts.

In their entirety, the results of the previous studies reveal a complex interaction of many factors that may place a female at risk for an ACL injury. First, evidence suggests that increased knee abduction during dynamic high-load movements (increased valgus forces) place the knee at risk for injury (Dufek & Bates, 1991; Gerberich, Luhmann, Finke, Priest, & Beard, 1987; Hewett & Myer, 2011). This can occur through a variety of mechanical and neuromuscular mechanisms; however, it seems strongly related to several biomechanical properties of an athlete that affect the amount of valgus force at the knee joint—poor trunk control, weak lower extremity muscular strength, and poor lower extremity segment positioning. Poor trunk control in the lateral plane (i.e., lateral trunk motion that shifts the body over a single leg) causes at least two scenarios that increase knee abduction moments: (a) the ground reaction force vector may move laterally resulting in knee abduction loading and (b) reactive hip abductor forces necessary to maintain upright stance may increase knee abduction moments. Lloyd and Buchanan (2001) provided biomechanical evidence supporting this and suggested that increased knee valgus forces probably reflect insufficient neuromuscular functioning or adaptation of the adductors of the hip and flexors of the knee (see also Tibone, Antich, Fanton, Moynes, & Perry, 1986). Additionally, deficient hamstring power may play a role in increasing risk in that the co-activation of hamstrings and quadriceps works to prevent knee abduction and dynamic knee valgus (Besier, Lloyd, & Ackland, 2003). Weaker hamstrings relative to the quadriceps results in lower overall co-activation and, therefore, less knee stability. Lastly, positioning of the lower extremities (flat footedness or increased knee extension) that creates shifts in the ground reaction force vector or reduces the capacity for force absorption
by the lower extremities also place an athlete at risk for an injury.

Biofeedback has recently been successfully used to alter ACL risk factors in training programs. For example, Ford, DiCesare, Myer, and Hewett (2014) demonstrated that squat performance could be improved through the use of a real-time feedback display. The feedback display presented to participants in this study consisted of either kinetic or kinematic information and was used to promote specific variables shown to increase ACL injury risk. Performance of a transfer task (i.e., drop vertical jump) also improved after training with the kinetic information feedback, but not after the kinematic information feedback. Although the feedback used by Ford et al. (2014) successfully altered the biomechanics of participants, the exact style or design of the feedback may present problems in how it directs participants’ focus. Specifically, the feedback presented included a skeleton figure of the participant’s body alongside a goal directed time series of participant’s movement. This skeleton figure, and its salient relation to participants’ bodies, may have encouraged participants to focus internally on their own movements and not on the goal time series. As discussed by Kiefer and colleagues (2015), feedback that directs a participant’s attention inwards towards their body or their movements may reduce motor learning outcomes. The issue of attentional focus and additional work by other investigators (e.g., Wulf, 2013) is discussed in the following section.

As the previous sections illustrate, designing a practical training protocol that successfully reduces the rate of ACL injuries requires a procedure that goes beyond the simple targeting of a desired risk variable, such as knee abduction, for improvement. The difficulty lies within the complicated interaction of many factors associated with both the mechanics related to ACL injuries and with the specific designs of the programs developed to prevent injuries. For example, Sugimoto and colleagues (2012) indicated that a program may have the capability to effectively
reduce the risk of injury for an athlete but it will not be able to do so if the program suffers from a low participant compliance rate. A successful training protocol must balance the demands of the programs chosen, preventative training activities, design, and cost (in terms of both time and monetary demands). Although several programs have reduced the rate of ACL injuries, none have yet developed a protocol that effectively reduces injury rates on a wide scale.

**Specific Aim**

The specific aim of this project was to develop and test a real-time feedback method that targets and improves the movement biomechanics associated with ACL injury risk in females. As described previously, many protocols have shown success in preventing ACL injuries; however, there are still many problems to overcome in implementing a widespread prevention program. The real-time feedback system may be able to overcome the problems by utilizing objective feedback that: (1) can be provided largely independent of an expert’s (e.g., a physical therapist) presence and active involvement with individual athletes, (2) is interactive and personalized which may enhance athlete motivation and compliance (Kiefer et al., 2015), (3) may improve learning and performance by directing athletes’ attentional focus to an external source (see the following section), and (4) engages implicit motor learning strategies that may result in faster learning and improved transfer (e.g., Swinnen, Lee, Verschueren, Serrien, & Bogaerds, 1997; Varoqui, Froger, Pélissier, & Bardy, 2011).

The proposed real-time visual feedback is designed so that objective information about multiple biomechanical variables related to ACL injury risk can be displayed concurrently in real-time to participants. These biomechanical variables are an assortment of kinematic and kinetic variables (see Chapter 2), some which are determined through inverse dynamics (Winter, 2009), and are known to be related to ACL injury risk (e.g., Hewett et al., 2005). As these variables change
dynamically throughout participant movements, the feedback display is updated relative to these movements and displayed to participants in real time. The display essentially uses the current values of the biomechanical variables and maps them to the display through a predetermined influence on a geometric shape (see Figure 1A) and a set gain parameter that determines the magnitude of the influence of the biomechanical variable on the change in the shape. Participants received this real-time feedback during the performance of simple bodyweight squats, and their instruction was to perform the squat in such a way as to make the shape as rectangular as possible. Squats have previously been utilized in ACL injury prevention programs (e.g., Myer, Ford, Palumbo, & Hewett, 2005) and are a less dynamic exercise compared to other movements, which should allow participants ample opportunity to become accustomed to their movements and the corresponding effects of those movements on the feedback display. This presentation method may not only have pragmatic advantages such as removing the need for detailed feedback from an expert, but the feedback design and presentation is based on fundamental theoretical principles in perception-action that may be promising for injury prevention and rehabilitation interventions.

Perceptual Feedback, Action, and Attentional Focus

The first of the aforementioned theoretical principles originates from the work of J. J. Gibson (1966, 1986). Central to his theory of perception is that it does not require the mental activity of association, construction, or other information processing methods (e.g., Marr, 1982; Marr & Nishihara, 1978; Neisser, 1967; Pylyshyn, 1989). The most relevant part of Gibson’s theory for the current dissertation’s objective lies in the idea of specification, which claims there is a lawful, one-to-one relation between the patterns of ambient stimulus-energy arrays and the perceiver/environment systems that structure them. This structuring of ambient energy arrays provides a perceiver with information that unambiguously specifies the current state of affairs and
allows for adaptive control of behavior with regard to the ever-changing flux of information found in patterned stimulus energy arrays. In other words, it is through perception that people can control their actions and, on the other hand, a person can act so as to give rise to certain perceptual events (cf. Powers, 1973). This principle is particularly important for the current dissertation because the ability for participants to control actions through perception is essential to the ability of participants to complete the training, since participant movements determine the pattern of the feedback stimulus in real time in a one-to-one fashion, and desired movement patterns correspond to a certain state of the feedback display.

Evidence supporting this principle is available in the results of an experiment investigating bimanual coordination patterns (Mechsner, Kerzel, Knoblich, & Prinz, 2001). In this experiment, participants were simply asked to maintain the circular movement of two visible objects in either in-phase (0° relative phase angle) or anti-phase (180° relative phase angle). Each of the visible objects’ movements was determined by mapping the movement of the participant’s corresponding hand to the visual display. The crucial manipulation of the study was that in order to maintain either of the instructed synchrony patterns between the two objects, the participants had to move their hands in a 4:3 frequency ratio. Normally, this frequency ratio is nearly impossible to achieve; however, when the difficult movement pattern was mapped to a simple visual display (i.e., the two visual objects moving in a 1:1 ratio), and the task was framed in terms of trying to make the visual objects move synchronously in that fashion, participants were able to learn and perform the 4:3 frequency ratio with relative ease.

Several other studies which investigated participants’ ability to produce certain coordination patterns provides further evidence that real-time feedback enhances performance of difficult motor behaviors (Swinnen, Lee, Verschueren, Serrien, & Bogaerds, 1997; Varoqui,
Froger, Pélissier, & Bardy, 2011; Varoqui, Froger, Lagarde, Pélissier, & Bardy, 2010). For example, Swinnen et al. (1997) asked participants to produce oscillations with the two arms at a 1:1 frequency ratio; however, they were also asked to perform these oscillations with a 90° phase offset. Three groups were compared in their ability to learn and maintain this pattern across three days and in an additional transfer test: (a) enhanced visual feedback (a real-time Lissajous figure constructed from the left and right arm displacement angles), (b) normal visual feedback, and (c) no visual feedback (participants were blindfolded). Results showed that participants in the enhanced visual feedback condition performed better than the other two feedback groups in the learning and maintenance of the 90° phase offset coordination pattern, and also performed better in the transfer test.

The study by Varoqui et al. (2011) tested the effectiveness of real-time feedback for retraining in- and anti-phase postural coordination patterns in post-stroke patients. The real-time feedback used in this study was a Lissajous figure that presented the relative ankle-hip angular position of participants (i.e., an angle-angle diagram). The shape of the Lissajous figure depends on the phase relation of the two signals. If the signals are in-phase (i.e., relative phase angle of 0°), the resultant display will be a positively sloped diagonal line (45° from the x-axis). For two signals that are anti-phase (i.e., relative phase angle of 180°) the resultant display will be a negatively sloped diagonal line (135° from the x-axis). During the experiment, participants were required to produce flexion-extension movements about the hip and ankle joints so as to create either the positively sloped (in-phase movement) or negatively sloped (anti-phase) line; however, they were only instructed to produce the desired outcome of the shape. No instructions were given that indicated the specific movement pattern required to make the desired shape. Coordination patterns other than in- or anti-phase caused the feedback display to deviate from a goal shape signifying
the desired output. Two experimental groups and one control group were used in the study. The two experimental groups differed in the leg used to create the Lissajous figure—one group generated the figure with data collected from the stroke-affected leg and the other group used the non-affected leg to generate the figure. After a 4-week training period, it was found that the experimental groups improved in their ability to achieve postural coordination, and they also improved in an independent test of balance function when compared to the control group. These two studies highlight the usefulness of real-time visual feedback in the training (and retraining) of difficult motor behaviors and in the ability of these motor skills to transfer and be retained across tasks and situations.

This study also has important implications for the second perception-action principle. This principle essentially states that focusing on the external effect of a bodily movement leads to better performance than if a person were to focus on the body itself. In the bimanual coordination study by Mechsner et al. (2001), participants were focusing on the end effect—the visual feedback objects—and not the movements of their hands that were causing the dots to move. If participants were to focus on the movement of their hands, the 4:3 frequency ratio would be very difficult to perform. In other words, this principle states that an external focus of attention enhances motor performance and learning relative to an internal focus of attention. There have been numerous studies demonstrating the benefits of an external focus of attention over an internal one (for a review see Wulf, 2013).

In a study by Wulf, Höß, and Prinz (1998), participants in three different groups were given instructions that emphasized an internal focus, external focus, or neither explicit focus (control group). These instructions regarded how to complete ski-type slalom movements on a ski stimulator successfully, which required producing oscillatory body movements with as large of an
amplitude as possible. In relation to how to produce large oscillatory amplitudes, the external focus group received instructions referring to how their movements would affect the machine and therefore the amplitude, while the internal focus group received instructions told how their body movements would affect the amplitude. The control group received instructions to simply make the oscillatory movements. Not only did the external instruction group perform better (i.e., larger amplitudes) than the other groups during training (days one and two), they performed better on a retention test (day three). Other examples of experiments investigating the beneficial effects of externally-focused attention using sports activities include swimming (Freudenheim, Wulf, Madureira, Corrêa, & Corrêa 2010), running (Porter, Anton, & Wu, 2012; Porter, Nolan, Ostrowski, & Wulf, 2010; Porter, Wu, Crossley, & Knopp, 2012), and maximum vertical jump height (Wulf & Dufek, 2009; Wulf, Dufek, Lozano, & Pettigrew, 2010; Wulf, Zachry, Granados, & Dufek, 2007). Performance in all of these studies improved (i.e., faster swimming and running speeds and a higher maximum jump height) when participants adopted an external focus of attention instead of an internal focus.

**Hypotheses**

The objective of this dissertation was to determine the efficacy of a real-time feedback display in reducing risk of ACL injuries in females. This was accomplished in a two-stage process. First, a pilot study (see Chapter 2) tested the developed feedback protocol on a small group of participants in order to ensure that the technical aspects of the feedback program and display were successfully operating. These technical aspects included issues such as the adjustment of the gains used to mathematically transform participant movements into the visual stimulus, the adjustment of the responsiveness of the feedback display (i.e., frames per second), and troubleshooting
hardware issues such as display connectivity lag. The collected data and comments from participants were used to adjust the feedback protocol before the next stage of the dissertation.

The second stage (see Chapter 3) used the tested and adjusted feedback protocol to evaluate the ability of the real-time feedback display to reduce biomechanical risk factors associated with ACL injuries. This was achieved by comparing the effects of the real-time feedback stimulus and of a control stimulus. The control stimulus was a sham display (described in Chapter 3) that did not relate one-to-one to the participants’ actual movements, and therefore, did not provide informative feedback about proper movement form. Participants were randomly assigned into one of two groups: (1) a group who first received the real-time feedback or (2) a group who first received the sham feedback. Movement performance was quantified in terms of overall squat performance, individual biomechanical variables measured during performance of the squat training exercise, and those variables measured during performance of a separate dynamic movement—the drop vertical jump (DVJ; for description see Chapter 2).

Using the two theoretical principles of perception and action described in the previous section, it was proposed for the present study that participants would be able to learn complex whole-body movement dynamics—dynamics that are associated with lower ACL injury risk—by externally focusing on “controlling” relatively simple movements of a real-time feedback display. Accordingly, it was hypothesized that participants would improve more when they received the real feedback in comparison to when they received the sham feedback in terms of squat biomechanics and that these enhanced, lower-risk movement biomechanics for the real-time feedback group would transfer to the dynamic DVJ exercise to a greater extent than for the control group.
CHAPTER 2: DEVELOPMENT OF METHODOLOGY AND PILOT STUDY

In this chapter the development and testing of the real time visual feedback is described. Unless otherwise later stated, the design, procedure, and materials described hereafter were identical for the pilot and primary studies.

Stimulus Design

The design of the real-time visual feedback display took the form of a rectangle defined by six points (see Figure 1A). The coordinates of the points were defined as a function of previously identified kinematic and kinetic variables identified as ACL-injury risk factors. The biomechanical variables included were trunk lean, knee-to-hip moment ratio (KHMr), knee abduction moment (KAM), and vertical ground reaction force (vGRF) ratio. Each variable had a specific effect on the feedback display. The participant’s task was to keep the shape as close to a rectangle as possible.

Trunk lean was defined as the angle of deviation from the midline of the body. Changes in trunk lean caused the stimulus to lean to the respective side (Figure 1B). The KHMr variable was defined as the ratio of the knee inverse dynamics moment to the hip inverse dynamics moment. Ratios with values larger than 1 (i.e., knee moment > hip moment) resulted in the stimulus increasing in overall size (the desired outcome). The opposite was true for ratios smaller than 1—the stimulus decreased in overall size (see Figure 1C). The overall value of the KHMr variable was determined by averaging the KHMr value of the right and left sides of the body. The KAM variable was defined as the knee inverse dynamics moment and would cause the stimulus to pinch in the middle when there was excessive valgus and to expand in the middle when there was excessive varus (see Figure 1D); however, the stimulus displayed a greater sensitivity to the knee moments with excessive valgus, as it has been shown to be a greater risk factor than excessive varus (Hewett et al., 2005). Unlike the averaged effect of the KHMr variable, the KAM value of each knee
separately affected their corresponding side of the stimulus. The vGRF ratio variable was defined as the ratio of the amount of force measured by the left and right force platforms in the vertical directions. A greater force magnitude measured by either platform caused the respective bottom and top corners to lower while the corners on the side with a lower force magnitude rose proportionally (see Figure 1F).

In addition to the previous variables, the number of squats performed by an athlete was tracked by a variable measuring the knee flexion-extension. A squat was completed when a participant achieved a knee angle below 90° during the squat and then returned to the original standing position (see Figure 1F). This variable was visually displayed to participants (separately from the feedback rectangle just described) through the movement of a lighter-colored rectangle behind the primary feedback display shape. As a participant squatted into a lower position, the height of the background rectangle decreased. Ten circles served as a counter representing the number of squats performed and a target line for participants’ knee angles were also displayed at the bottom of the background rectangle.
Figure 1. Displayed above is the stimulus design used in the pilot and primary experiment. During the trials the stimulus’ shape started as rectangle. This shape is depicted in Panel A and was defined by points one through six. An outline of the shape’s corners (points one, two, four, and six) remained while participants were performing the squat exercise and are shown in Panels B-F. Also displayed are ten grey circles towards the bottom of each display. These were used as a visual display for counting the number of squats within a trial. As participants performed squats, the circles would change from grey to green. Depicted in Panels B-F are the effects of the trunk lean, K HMr, K AM, foot COP placement, and vGRF variables, respectively. In Panel F the lighter background rectangle lowered from its maximum height (displayed in Panels A-E) as a participant performed the downward movement of a squat. Accordingly, it rose as a participant began to stand backup.

Method

Experimental design.

All participants performed 6 sets of 10 squats. The first and last sets served as pre- and post-tests, respectively, and during these sets no feedback was shown; only within the middle four
training sets did participants receive any visual feedback. Participants also performed two sets of three DVJs as additional pre- and post-tests, prior to and after, respectively, their first and last sets of (no-feedback) squats.

**Participants.**

Eleven participants were recruited for the pilot study. All participants were from a high school in the Cincinnati, OH metropolitan area and were members of the same volleyball team. Their mean age, height, and weight were 16.7 yrs. \((SD = 1.34)\), 1.70 m \((SD = 0.05)\), and 62.20 kg \((SD = 5.63)\), respectively. No participants reported any past history of knee injury or any other neuromuscular deficit. The study was IRB-approved and all participants (or legal guardians) gave written informed consent prior to participation.

**Materials and apparatus.**

The visual feedback stimulus was constructed and presented to participants in real time using an assortment of hardware and software (see Figure 2 for additional information). Participants’ movements were recorded using a 30-marker configuration tracked by a 10-camera Raptor-E motion capture system (Motion Analysis Corp., Santa Rosa, CA). Six of the markers were removed after an initial period during which a biomechanical model of participants’ limbs and joints was constructed. This model yielded an additional 7 virtual markers—specifying the centers of the ankle, knee, and hip joints—for a total of 31 markers during a trial (see Figure 2, panel 2). The procedure for constructing the biomechanical model (for an example, see Ford, Myer, Toms, & Hewett, 2005) consisted of a static motion capture lasting approximately 1 second, during which specific landmarks on the body were identified (see Figure 2). The landmarks, when paired with markers that remained on the body during the squat movement, were used to create virtual markers through simple geometrical offsets performed in the Cortex 5.3 program (Motion Analysis
Corp., Santa Rosa, CA). The virtual markers replaced markers that were frequently occluded during participant movements. During the squat motion for example, the torsos of participants frequently occluded the two anterior superior iliac spine (ASIS) markers required for calculating the hip joint centers. Using the location of the posterior superior iliac spine (PSIS) markers (which were very rarely occluded) and the biomechanical model, the program was able to interpolate the position of the ASIS markers, and subsequently, the centers of the hip joints. This process was necessary in order to increase the quality and robustness of the real-time feedback, as this permitted the feedback to be updated at a rate of 20 Hz (every 50 ms) without any detectable problems in the responsiveness of the display relative to participant movement.

In conjunction with the motion capture system, two embedded BP600900 force platforms (AMTI, Watertown, MA) were used to collect separate ground reaction forces from each foot. The
data recorded by these pieces of hardware were integrated and synchronized via Cortex. Using a software development kit (SDK) provided by Motion Analysis Corporation, the synchronized data were relayed to an external program responsible for generating the visual feedback display. The particular program used to generate the visual feedback display was a custom-written C++ program designed in Microsoft Visual Studio Professional 2015 (Microsoft Corp., Redmond, WA) and incorporating OpenGL (Khronos Group, Beaverton, OR) as the graphics application interface. This program was responsible for importing the live data stream from the Cortex SDK and exporting the finished visual display to participants.

The finished visual display was wirelessly transmitted from a desktop computer to participants using an ARIES Pro Wireless HDMI Transmitter and Receiver (Nyrius, Niagara Falls, ON, Canada). The ARIES Pro is capable of transmitting uncompressed 1080p signals up to 160 feet with a latency of < 1 ms, which allowed for maximum mobility of participants without the degradation of feedback quality. Participants viewed the real-time feedback through a pair of video eyewear glasses (Wrap 1200 DX-VR; Vuzix Corp., Rochester, NY) which had a 60 Hz screen refresh rate (a new frame appeared approximately every 16.67 ms). The glasses presented the feedback display in a fixed position relative to the participants’ eyes and encompassed their entire field of view. Both the ARIES Pro and glasses were powered by a portable battery pack (PowerGen Mobile Juice Pack 12000; PowerGen, Kwai Chung, Hong Kong, PRC). The wireless transmitter and battery pack were stored in a modified hydration pack designed for running (CamelBak Products, LLC, Petaluma, CA). The backpack provided minimal interference to natural movement as it held the equipment securely against the body and was relatively small (length × width × height: 33 × 27 × 7.6 cm). Other materials included those required for the DVJ: a plyometric exercise box (45.72 × 45.72 × 38 cm) and a basketball, attached to the ceiling, the height of which
could be adjusted from 1.52 to 2.90 m from the floor.

**Procedure.**

Upon arrival, participants’ informed consent and demographic information were obtained. In preparation for the experiment, motion-capture markers and the backpack containing the wireless transmitter and battery pack were placed on participants’ bodies. The glasses, however, were not attached until the first trial that involved the feedback displays. This procedure was instituted in order to avoid injuring participants (by hindering vision) and damaging the glasses during the DVJs, while also limiting the possible confound of training with the backpack on and then testing the DVJ without its presence.

After the initial experimental preparation, all participants received identical instructions about the squat exercise and the DVJ. The instructions were purposefully kept very basic for the squat exercise; however, the DVJ instructions were very specific and trials were repeated when a participant’s DVJ did not the predetermined standards. The instructions to participants were to first stand with their feet apart at a set distance of 0.30 m (marked by tape) on a plyometric box; then, with both feet simultaneously drop from the box, land on the ground with both feet, and immediately jump in a vertical direction upon landing. The adjustable height basketball was used as a goal for participants’ jump height and was adjusted so that participants were just able to reach the ball when jumping. Participants were instructed to try and grab the basketball during the jump, but it was not a requirement for the successful completion of a DVJ. When participants did not perform the DVJ in this manner, they were informed, and the trial was repeated.

After performing the DVJ participants donned the glasses. The addition and removal of the glasses took approximately 30 seconds to perform at the beginning and end of each feedback condition. The instructions for the squats were only to “maintain the goal stimulus shape and size
as closely as possible.” Participants were required to discover how their movements related to the stimulus shape during the squat exercise. Participants were also asked to keep their arms crossed in front of their chest and to avoid covering any of the motion-capture markers.

An additional instruction relating to the squat depth feedback was emphasized as secondary; participants were told not to focus primarily on that information. The instruction was that participants were to perform a squat that went low or deep enough so that a circle (there is one circle for each squat repetition) at the bottom of the display would change colors (from grey to green; see Figure 1F). The circle only changed color once participants had completed a full squat motion (i.e., participants were standing upright after performing a squat). A set of squats was considered complete once all ten circles’ colors were changed from grey to green indicating ten successful squats were performed. If participants were unable to intuitively achieve the appropriate depth they were explicitly informed that they must squat lower. This happened solely during the first feedback trial that participants experienced; no participants needed to be reminded again after the first trial. No other instructions were provided regarding the squats or the stimulus, and participants were permitted breaks as required.

**Data analysis.**

Analyses on both the squat and DVJ data were performed. The DVJ analysis consisted of the calculation of seven variables previously found to predict ACL injury risk (Hewitt et al., 2005): (1) hip flexion, (2) hip adduction, (3) hip extensor moment, (4) knee flexion, (5) knee abduction, (6) knee extensor moment, and (7) knee abduction moment. The specific values of these variables that were analyzed were determined by finding their maximum value that occurred within the time that a participant initially landed on the force platform and when the participant’s center of mass was at its lowest point in the z-axis. These values were averaged across both legs and across the
Heat map analysis was performed on the squat data during the middle four training sets and on “reconstructed” feedback shapes obtained from the raw position and force data in the pre- and post-test sets. (The use of reconstructed shape data was necessarily obtained afterward data collection—using the same calculations and procedures as the originally recorded stimulus shape data—because no feedback was generated during the pre- and post-test squat trials). The heat maps provided a global assessment of squatting performance by indicating how the movement patterns of the biomechanical variables associated with ACL injury related to the target feedback shape (i.e., a rectangle). Specifically, the heat maps portray the percentage of time a defined space was occupied by the feedback stimulus.

The heat map analysis consisted of two steps: (1) the construction of the heat maps and (2) the calculation of each heat map’s correctly occupied space. Heat maps were created using the MATLAB function inpolygon (The MathWorks, Inc.; Natick, MA). The heat maps were created for each set of squats (i.e., pre- and post-tests and each training set of squats). The calculation of each heat map’s correctly occupied space consisted of first calculating the proportion of occupied space within the goal stimulus and then calculating the proportion of occupied space outside of the goal shape. The proportion of occupied space outside of the goal shape was finally subtracted from the proportion of occupied space within the goal stimulus. The possible results of this operation range from -1.00 to 1.00. A score of -1.00 indicates the stimulus never occupied a correct location in the display while always occupying an incorrect location. A score of 1.00 indicates a stimulus shape never deviated from the goal shape and size.

Results

Heat map analysis revealed that the mean improvement of all participants from the pre-
post-test sets was 0.077 or 7.70%. This improvement was significant, \( t(10) = 6.63, p < .01 \), with scores rising from an average of 77.17% \( (SD = 3.80\%) \) in the pretest to an average of 84.87% \( (SD = 3.12\%) \) in the posttest.

Significant improvements were also found in two of the seven DVJ variables. Both hip and knee flexion improved from the pre- to post-test trials, \( t(10) = 2.26, p = .05 \) and \( t(10) = 2.84, p = .02 \), respectively. Hip flexion increased from an average of 65.74° \( (SD = 7.88°) \) in the pretest to an average of 68.90° \( (SD = 10.82°) \) in the posttest, and knee flexion improved from an average of -79.85° \( (SD = 7.83°) \) in the pretest to an average of -82.48° \( (SD = 9.33°) \) in the posttest. One additional DVJ variable was found to have a significant difference between the pre- and post-test, however, the effect was not in a direction that reduced ACL injury risk. Participants’ values of the knee extensor moment variable placed them at significantly greater risk for ACL injury, \( t(10) = 4.25, p = .002 \), in the post-test \( (M = -110.39 \text{ Nm}, SD = 23.78 \text{ Nm}) \) than during the pre-test \( (M = -120.65 \text{ Nm}, SD = 23.40 \text{ Nm}) \).

**Discussion**

Overall the pilot study achieved its two aims. First, the study successfully managed the technical issues associated with the feedback program, the display (in terms of both software and hardware), and the integration of real-time biomechanical data. Only slight modifications were made to the values of the feedback gains before the primary study (Chapter 3) began. Otherwise, the equipment and the general procedure for generating the feedback display remained unchanged.

Second, the pilot study demonstrated an overall improvement in participants’ performance of the squat exercise. Specifically, the heat map analysis indicated that participants improved their ability to control the stimulus shape from the pre- to posttest. Participants also showed improvement in the DVJ exercise. A pre- to posttest comparison of hip flexion and knee flexion
values revealed a decreased risk of ACL injury; however, the decreased risk associated with hip and knee flexion was accompanied with an increased risk associated with participants’ knee extensor moments.

Given the general success of the pilot study, the stimulus’ existing feedback parameters were not altered before use in the primary experiment. However, an additional parameter was planned for integration into the primary experiment’s feedback stimulus—foot center of pressure (COP) placement. This was due to findings that link foot COP placement to other variables that place an individual at risk for ACL injury (G. D. Myer, personal communication, July, 2014). A sham stimulus was also planned for development and is discussed in Chapter 3 below.
CHAPTER 3: PRIMARY EXPERIMENT

Design

Experimental design.

In order to compare the effects of the real-time and sham feedback displays, a particular type of a repeated-measures design was utilized—a crossover design. The major advantage of a crossover design is that it may provide equivalent statistical power to traditional parallel factorial designs with fewer participants; however, this design is not without its drawbacks. Its crucial limitation and advantage both stem from the fact that participants experience all experimental conditions: Statistically, that is an advantage because participants serve as their own controls, and methodologically, it is a limitation because this type of design is highly vulnerable to carryover effects. Due to the particular nature of crossover designs, they are frequently used in medical studies where treatments do not result in the removal or cure of the condition under study. In other words, crossover designs are appropriately suited to studying phenomena that are relatively permanent yet responsive to experimental treatments (such as asthma and fast acting bronchodilator drugs; Senn, 2002). The exact type of crossover design used in the current study is known as an AB/BA or two-treatment design. As the name implies, this is a very simple design where half of the participants receive one condition first and another condition second, while the other half of participants receive two identical conditions but in the opposite order.

In the case of this dissertation’s design (see Figure 3), half of the participants received the real feedback first then the sham feedback, and the second half received the opposite presentation of feedback—the sham feedback display was presented first and the real feedback second. They

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3 In the case of strong carryover effects, it is possible to exclude the data after the “crossover” from analysis. Although this removes the advantages of a repeated-measures design, there is still potential for meaningful statistical comparisons within the first half of the dataset.
received those displays in blocks of training trials that comprised four sets of 10 squats. In order to test the effect of each feedback type, three test periods were used—a *pre-test* before the presentation of the first feedback condition, a *mid-test* just before the crossover point, and a *post-test* that took place after the presentation of the second feedback condition. In total, each participant completed at least 110 squats and 9 DVJs—40 training squats for each feedback display, 10 squats during each test period, and 3 DVJs during each test period.

![Diagram](image)

*Figure 3.* The crossover design used. Each rectangle represents a block that consisted of 10 squats; in addition to the 10 squats, the darkest rectangles (the test periods, during which no feedback at all was presented) also included 3 DVJs. The two rows of rectangles indicate the type of feedback used—either real or sham feedback. The solid and dashed black lines respectively denote the group who received the sham feedback first and the group who received the real feedback first. The middle rectangle denotes the crossover point—the point that the feedback type was switched.

**Sham stimulus design and additional feedback parameter.**

In addition to the feedback display described in Chapter 2, an additional feedback display was developed for the sham condition. The real and sham feedback displays presented identical stimulus shapes that responded, at least in part, to the same biomechanical parameters. However, the sham feedback was designed to limit the amount of useful feedback information available to participants during the squat movements. This was accomplished using a stepwise gain manipulation (see Figure 4). The movements not critical to the targeted biomechanical parameters
(i.e., those close to the start/end points of squat movements) caused the sham display to respond nearly equivalently to participant movement (and thus nearly equivalently to the real feedback condition), but the influence of movements during the important phases of the squats were progressively eliminated from the stimulus, such that at the bottom of the squat movement the sham feedback stimulus deviated from the goal shape as a function of random noise, not from the movements of participants (i.e., it provided little to no actual feedback).

Figure 4. Displayed above is the technique used to derive the sham feedback. The bottom plot is a sample time series of a single squat rep performed during a sham trial. Specifically, the mid-shoulder marker is illustrated. The top plot depicts how the signal-to-noise ratio (i.e., how much of the stimulus movement was driven by participant movement or noise) corresponds to a particular movement stage of a squat.

This specific type of sham feedback was utilized for two reasons: (1) to prevent athletes in the sham group from consistently receiving feedback that directly but unintentionally promotes variables not shown to reduce ACL injury risk and (2) to permit the phenomenological response of the sham stimulus to be similar to the experimental stimulus, so that participants in the two conditions would be unlikely to identify which stimulus they received were they to discuss
participation in the study and “compare notes” about the manipulation.

One additional parameter, foot COP placement, was added to the feedback stimulus. The variable was defined as the distance of the foot COP location from the center of the foot in the medial-lateral and anterior-posterior planes. When the distance of the foot COP from the center of the foot was greater than 20% of the foot’s length, the stimulus was wider at the base than at the top (see Figure 1E). Greater distances caused the width of the stimulus base to increase. Values within 20% (the desired variable range for good squat form) resulted in an equal width of the top and bottom of the stimulus.

Method

Participants.

Twenty participants were recruited to participate in the study. All participants were female collegiate athletes recruited from three local universities in the Cincinnati, OH, metropolitan area. Nineteen participants were members of their respective basketball teams and one participant competed in the heptathlon (a track and field event consisting of seven different sub-events). Their mean age, height, and weight were 19.7 yrs. ($SD = 1.34$), 1.74 m ($SD = 0.09$), and 72.16 kg ($SD = 12.45$), respectively. Participants had no history of neurological disorders (including any neuromuscular disabilities), skeletal disabilities or disorders, or balance problems. Additionally, participants were free of any recent injuries that impaired movement, the ability to stand, perform the DVJ or the body-weight squats. Two participants had past knee injuries (one ACL injury and one medial collateral ligament [MCL] injury); however, the dates of occurrence were not within 5 years of their participation and their performance was not unusual when compared to uninjured

4. Three independent samples $t$-tests revealed that there were no significant differences between the two groups in height, weight, or age (all $ps > .05$).
participants. The study was IRB-approved and all participants gave written informed consent prior to participation.

**Procedure.**

Upon arrival, participants’ informed consent and demographic information were obtained. Subsequently, participants were prepared for the experiment in the same manner as the pilot participants. It was also at this time that participants were randomly placed into one of two groups: (1) the experimental group who first received the real-time feedback and (2) the control group who first received the sham feedback. Participants were given the same instructions as the pilot participants, regardless of their assigned condition, for the squat trials and for the DVJs.

**Data Reduction and Analysis.**

The recorded raw marker positions in the X-, Y-, and Z-axes and the force data acquired from both feet (force COP and magnitude in the X-, Y-, and Z-axes) were first exported from Cortex and imported into MATLAB for preprocessing. Preprocessing consisted of the visual inspection of a virtual mid-shoulder marker (defined as the averaged position of the left and right shoulder markers) for each squat trial (pre-, mid-, and post-test and training trials). During the visual inspection, time series of the mid-shoulder marker’s position in the z-axis were plotted and trimmed according to the procedure outlined in Figure 5. Additionally, only the portions of a trial

![Figure 5](image-url)

*Figure 5.* Displayed above is an example time series of the virtual mid-shoulder marker. The mid-shoulder marker was used as a template to trim and parse the time series of all other markers. The orange colored sections of the time series were removed, leaving only the portions of data during which a participant was performing a squat.
where the participant was performing a squat were retained for analysis. All other marker and force data were trimmed according to the time points that were identified from the mid-shoulder marker. This procedure resulted in a time series for each squat rep across every squat set.

With regard to the DVJ analysis, errors in marker placement resulted in the loss of several participants DVJ data. These errors resulted in approximately 40% of the data being unfit for the model creation from which the seven variables (described in Chapter 2) were derived. After exclusion of these trials, data from 12 participants (five real feedback first and seven sham feedback first) were retained.

In addition to the heat map and DVJ analyses described in Chapter 2, three additional analyses were performed on the primary experiment’s data: (1) Principle component analysis (PCA), (2) bidimensional regression analysis (BDR), and (3) the analysis of the biomechanical variables used to generate and control the feedback stimulus during a squat. The first analysis, PCA, was performed on the raw position and force data. PCA is useful because it enables the investigation of coordinative modes—or movement patterns—in dataset (Daffertshofer, Lamoth, Meijer, & Beek, 2004; Kiefer, Bonneaud, Rio, & Warren, 2013; Ramenzoni, Riley, Shockley, & Baker, 2012) and, therefore, quantifies the effects of a training protocol with regard to movement system dimensionality (cf. Amazeen, Mitra, & Turvey, 1997). PCA is able to accomplish this because it allows a multi-dimensional dataset to be reduced to its primary dimensions of variation (i.e., principle components) through the identification of linearly correlated relations within the multi-dimensional space. In other words, it allows for the reorganization of an original dataset into new orthogonal, linear combinations of abstract, higher-order variables that may better represent the original data. These linear combinations, or principle components, each account for an amount of variation and these principles components may be rank-ordered from the most to least amount
of associated variance with the 1\textsuperscript{st} principle component accounting for the most variance, the 2\textsuperscript{nd} principle component accounting for the second most variance, and so on. The end result of this operation is the identification of new, important variables that best describe the original dataset. Additionally, the amount of variance that each principle component accounts for may be summed, starting with the first principle component, until a predetermined amount of variance is reached. In the case of the current analysis this value was set at 95\%, and the number of components needed to reach it results in a dependent variable referred to as PC\textsubscript{95\%}. PCA was be performed using functions (i.e., princomp) available in MATLAB (The MathWorks, Inc.; Natick, MA).

The second analysis, BDR (Friedman & Kohler, 2003), was used to quantify and compare the real-time feedback display shapes to the goal feedback shape. Similar to the familiar unidimensional regression, the bidimensional regression allows one to quantify the degree of similarity between two sets of two-dimensional points. In the case of the current dataset, each individual frame of a participant’s feedback display was compared to the goal feedback shape. Each frame yielded, among other parameters (see Friedman & Kohler, 2003), an $r^2$ value that was averaged over an entire set of squats. Other parameters returned by BDR include: (1) $\alpha_x$ and $\alpha_y$, which indicate the amount of translation in the x and y dimensions, respectively; (2) scale, which indicates the amount of shape expansion or compression; and (3) $\theta$, which indicates the degree of shape rotation. These numbers were used for comparing the degree to which the feedback displays of the control and experimental participants resembled the goal shape.

The final analysis involved the creation of time normalized time series for each of the biomechanical squat variables used to generate the feedback stimulus. As mentioned before, these variables included: vGRF ratio, foot COP placement, trunk lean, KAM for both legs, and the KHMr. The first step in creating the time normalized time series involved taking each individual
variables’ time series per squat repetition and standardizing its length to 100 samples. This resulted in a time series of 100 samples for each variable per squat rep. The time series were then averaged, 95% confidence intervals were calculated, and then plotted according to the appropriate group comparison (i.e., test-period or feedback group).

Results

Number of squats.

In order to test for varying levels of fatigue caused by differences in the number of squats performed by each participant group, the total number of squats performed by the real- and sham-first feedback groups were compared. There were no significant differences, $t(18) = 0.86, p = .40$, in the number of squats performed between the real-first feedback group ($M = 111.80, SD = 7.15$) and the sham-first feedback group ($M = 114.30, SD = 5.76$).

PCA results.

There were no significant main effects of feedback group (real- vs. sham-first feedback) or testing period (pre-, mid-, and post-test), on the number of components needed to account for 95% of the data set variance, $F(1, 18) = 0.03, p > .05$ and $F(2, 36) = 1.52, p > .05$, respectively. The main effects also did not interact, $F(2, 36) = 0.09, p > .05$. Additionally, there was no significant difference between the number of PC95% during training trials (real- vs. sham-first feedback), $t(19) = 0.19, p > .05$.

Following the same pattern of results as above, the amount of variance accounted for by the 1st principle component was not significantly affected by feedback group, $F(1, 18) = 0.26, p > .05$, testing period, $F(2, 36) = 1.23, p > .05$, or the two main effects’ interaction, $F(2, 36) = 0.09$.

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5 The same pattern of results were observed using variance accounted-for-thresholds of 85%, 90%, and 92.5%.
There was no significant difference in the 1st principle component’s variance accounted for between training trials either, \( t(19) = 0.31, p > .05 \).

**Heat map results.**

A 2 × 3 mixed-factor ANOVA comparing the two feedback groups’ pre-, mid-, and post-test heat map score values was not significant, all \( ps > .05 \). However, during the training trials there was a significant difference in the score of the heat maps between the stimulus shape during the real feedback and the recreated stimulus shape during the sham feedback trials, \( t(19) = 2.94, p < .01 \). The score for the stimulus shape during the real feedback trials (\( M = 60.73\%, SD = 6.47\% \)) was greater than the score for the recreated stimulus shape corresponding to squats produced during sham trials (\( M = 56.62\%, SD = 8.42\% \)). Thus, the availability of the feedback shape during the squat training trials was beneficial to performance compared to when only the sham stimulus was available.

**BDR results.**

None of the comparisons across all of the dependent measures returned by BDR (\( r^2, \alpha_x, \alpha_y, \) scale, and \( \theta \)) were significant. This included five 2 × 3 mixed factor ANOVAs comparing the pre-, mid-, and post-test values and five independent samples t-tests comparing the values of the real- feedback and sham trials (all \( ps > .05 \)).

**DVJ results.**

Four of seven total 2 × 3 mixed-factor ANOVAs comparing the pre-, mid-, and post-test DVJ variables were not significant, all \( ps > .05 \). These four variables included: hip flexion, hip adduction, knee flexion, and knee extensor moment. For each of the remaining three variables—hip extensor moment, knee abduction, and knee abduction moment—there was a significant main effect of test period, \( F(2, 36) = 22.66, p < .01, F(2, 36) = 11.74, p < .01 \), and \( F(2, 36) = 6.45, p \)
< .05, respectively. There were no main effects of feedback group, nor did the main effects of feedback group and testing period significantly interact, all ps >.05.

In regards to the three significant main effects of test period, Bonferroni corrected post hoc comparisons revealed that participants’ values for hip extensor moment, knee abduction, and knee abduction moment were significantly different in the pre- and mid-test periods. Specifically, participants’ mid-test values for both the knee abduction variable ($M = -8.92^\circ$, $SD = 6.66^\circ$) and the knee abduction moment variable ($M = -31.77$ Nm, $SD = 15.46$ Nm) placed them at greater risk for ACL injury than in the pre-test ($M = -7.66^\circ$, $SD = 6.35^\circ$ and $M = -27.80$ Nm, $SD = 12.84$ Nm, respectively). On the other hand, participants’ hip extensor moment values for the mid-test ($M = 135.60$ Nm, $SD = 31.32$ Nm), placed them at a lower risk for an ACL injury than the value in the pre-test ($M = 124.27$ Nm, $SD = 32.69$ Nm). There were no other significant post hoc comparisons among testing periods, all ps >.05.

Figure 6. Displayed above is an example of a time normalized time series. Similar figures were made for each biomechanical squat variable. The red line indicates the average trunk lean value for participants in the real feedback condition. The surrounding orange area indicates the 95% CI of the red line. Similarly, the black line is the mean trunk lean value for participants in the sham feedback, and the surrounding grey area is the 95% CI of the trunk lean values.

**Biomechanical squat variables.**

Mainly, the results of the time normalized time series for each of the biomechanical squat variables did not indicate effects of the real or sham feedback on either the pre-, mid-, or posttest
periods or on the sham and real feedback comparisons. The sole result that returned any interesting comparison was for the trunk lean variable across the sham and real feedback comparison. As Figure 6 indicates, while participants were interacting with the real feedback the values for trunk lean were lower and less variable than when they were interacting with the sham feedback.
CHAPTER 4: GENERAL DISCUSSION

The primary difference found among the primary study’s comparisons was between the scores of the heat maps during the real and sham feedback training trials. The real feedback display was beneficial to producing squats with better movement form than performing the squatting exercise with the uninformative sham stimulus. Most importantly, this finding suggests that participants were not only sensitive to the feedback stimulus but they were also able to modify their movements appropriately. Participants also reported that their experience of interacting with the stimulus was generally positive, engaging, and enjoyable. The results of the pilot and primary experiments seem to have achieved the first three specific aims of the dissertation. As a reminder, these three aims included providing feedback that is independent of an expert’s presence, is interactive and personalized, and improves learning and performance by directing athletes’ attentional focus to an external source. The accomplishment of fourth and final aim—to provide feedback that engages implicit motor learning strategies that may result in faster learning and improved transfer—was not substantially supported by the results.

As the results indicate, the majority of analyses did not reveal any significant change in participants’ squat behavior. The BDR and PCA analyses did not reveal any statistical differences, nor were any consistent and meaningful differences found in the analysis of the DVJ. These results were most likely a result of several issues such as dropped and improper marker placement for the DVJ model, the sensitivity of the selected dependent measures, and, perhaps most importantly, the very limited duration of the training sessions.
Study Limitations

DVJ testing issues.

Due to dropped and improper marker placement 40% of participants’ DVJ data were unusable. Ideally, the marker placement would have been checked for use in the model immediately after their initial placement; however, due to the primary focus of the experiment, the time constraints of the participants, and the limited availability of the motion capture facility, this was not a feasible option. Future experiments should include time in the procedure for ensuring the quality of marker placement and subsequent model creation. Ideally, DVJ trials with questionable data should be repeated to ensure all data are recorded and suitable for later analysis.

Limitations of PCA.

PCA’s inability to reveal any effects of the feedback stimulus (sham or real) on participants’ motor behavior reflect nonlinear variation of participants’ movement data. PCA is designed to reduce dimensions of linearly related data, and if there is nonlinearity in the dataset PCA may fail to provide meaningful principle components. A related analysis—independent component analysis (ICA; see Stone, 2004)—may be able to overcome the statistical limitations of PCA with regard to nonlinear variability.

The difference between PCA and ICA can be explained by understanding that each analysis projects the original source data onto a matrix that maximizes a chosen quantity. In the case of PCA, this quality is variance accounted for and the vectors comprising this matrix are equivalent to the eigenvectors of a data set’s covariance matrix (Wold, Esbensen, & Geladi, 1987). Alternatively, ICA attempts to develop a matrix of vectors that maximizes the nongaussianity of the source data (Hyvärinen & Oja, 2000). This is motivated by implications of the central limit theorem, specifically the idea that a distribution created from the linear addition of multiple
independent variables will be more Gaussian (i.e., more normal) than the individual distributions of the variables (for an overview see, Hyvärinen & Oja, 2000). In ICA, the independent components (i.e., vectors) are estimated by maximizing a measure of non-normality or nongaussianity, such as the absolute value of normalized kurtosis or negentropy (which, in general, is based on the idea of entropy; Hyvärinen & Oja, 2000).

One of the most widely used and intuitive examples of the application of ICA is the ability of ICA to solve what is known as the cocktail-party problem (see Hyvärinen & Oja, 2000; Stone, 2004): Imagine that there are multiple sound recordings of a crowded room, from multiple physically-distinct microphones, with many different people simultaneously speaking. How then can one differentiate the multiple physically-distinct sound sources from the recorded mix of all sources? ICA is able to solve this problem by utilizing information about the sound sources’ independence, through which the original sources can be estimated from the recorded mixtures. Other applications of ICA include the analysis of financial time series data (Back & Weigend, 1997; Kiviluoto & Oja, 1998), magnetoencephalography of cortical neurons (Makeig et al., 1996; Vigário, 1997; Vigário et al., 1998), and the identification of various physical gestures through myoelectric muscle activity (Calinon & Billard, 2005; Kato et al., 2006; Naik et al., 2006; 2007). ICA may provide further insight into the current dissertation’s data and possibly prove useful in the general analysis of human movement data.

Limitations of BDR.

Similar to PCA, the BDR analysis was originally thought to be a potentially useful tool for quantifying the stimulus shape. However, the BDR results did not reveal any significant effects. Furthermore, the effect of the $\theta$ variable (rotation) on the regression model was problematic for the current dataset. In several instances, the analysis provided a best fitting model that resulted in
a 90˚ or -90˚ rotation of the stimulus shape. This rotation was nearly always accompanied by a compression of the stimulus shape by the scale variable. As the stimulus shape variables had no rotational effects (i.e., the stimulus shape always maintained a vertically oriented position), future analyses or investigations using BDR may find it useful to fix or eliminate the \( \theta \) variable. This alteration may result in a more sensitive analysis than the original, fully parameterized model provided.

**No retention of performance improvements.**

As mentioned before, the heat map results of both the pilot and primary experiments revealed that participants were able to control the stimulus shape. Specifically, in the primary experiment when participants were able to view the real feedback, the heat map scores were higher (i.e., squatting performance was better) than when participants viewed the sham feedback. In the pilot study, pre- to posttest heat map scores improved by 7.70%. Although the ability of participants to control the feedback stimulus did improve in the pilot and primary studies, the failure of the real feedback to affect change in the mid- or post-test periods when compared to the sham feedback may be a result of several issues.

The most evident issue is that participants did not have ample time to engage or train with the real feedback stimulus. The heat map results of the primary study support this explanation, in that there were no differences found among the pre-, mid-, and post-test comparisons. Additionally, participants in both studies only performed a minimum of 40 squats during a single session with the real feedback—a duration of time far less than most intervention programs designed to prevent ACL injuries require (Sugimoto et al., 2013). Future investigations should provide enough time for training so that participants are able to attain lasting biomechanical improvements that lowers the risk of an ACL injury. This may require multiple training sessions spread over several weeks.
Implications for Feedback Design

The present study suggests three improvements to the current real and sham feedback that could be made in the future. First, the design of the sham feedback could be improved to promote more accessible and credible engagement by participants assigned to the sham group. Second, the squat-depth indicator’s effect on the feedback stimulus should be modified so that it is only present when participants’ performance requires it. The salient indicator used in the primary study may have distracted participants’ attention from the feedback stimulus, limiting the effectiveness of the training. Finally, the effects of the stimulus variables on the real feedback stimulus could be refined to promote more effective motor skill learning.

Sham feedback.

The design of the sham feedback utilized in this study was motivated by two intertwined requirements. The first requirement was to create an informationally neutral stimulus in the sense that the feedback did not provide significant information about the targeted variables of the real feedback display and that it did not unintentionally promote variables not shown to reduce ACL injury risk. The second requirement was to provide a phenomenological experience of interacting with the display that was comparable to the real feedback. That is, all participants should have felt as if they were interacting with a responsive feedback display, but only the real feedback should have guided squatting performance.

The present study suggests several modifications to the sham feedback for future iterations of the training protocol. As described earlier, the current sham feedback attempted to achieve the requirements stated above using a graduated presentation of a feedback-to-noise ratio where movements at the start and finish of a squat repetition (i.e., close to an upright stance position) caused the feedback display to respond mostly to participants’ movement (high feedback signal,
low noise). In contrast, the movements made while the participant was in the lowest point of the squat (i.e., when the torso is closest to the ground) caused the feedback display to respond in a random manner driven by a white noise signal (no signal, all noise). The relative degrees of signal and noise was graduated during the progression of the movement. This graduated presentation of feedback-to-noise can be altered so as to decrease the sham stimulus’ movement that is directly linked to participant control, or alternatively, smaller graduated steps with respect to participants’ position within a squat could be used.

**Depth indicator.**

The squat-depth indicator may have inadvertently captured participants’ attention to the exclusion of the feedback shape. Information about squat depth was available to participants in two forms—through both the rising and falling background rectangle and through the circles used for counting the number of completed squats (see Figure 1F). This could have suggested to participants that depth, rather than movement form, was the most important performance factor. As a consequence, participants may not have sufficiently directed their attention to feedback shape. Future modifications to the squat-depth variable should include a period where participants exclusively train with the squat-depth variable, and at the point they are able to consistently perform at a given depth threshold (e.g., three successful, sufficiently deep squats), the squat-depth variable would be removed from the stimulus. At this time participants would also begin interacting with the real or sham feedback stimulus, but if participants perform below the squat-depth variable’s given threshold for two consecutive squat repetitions then the feedback stimulus would disappear and the squat depth indicator would reappear until they are again able to achieve sufficient depth.
Refinements to the feedback shape.

Although the efficacy of the real feedback is supported by several results (i.e., the heat maps, a few DVJ results, and the time normalized trunk lean figure), a few changes may be made to improve real feedback display. Potential changes could include individualizing the feedback gains, modifying the acceptable ranges of biomechanical values, and including the ability of the trainers and experimenters to turn off or on desired variables in order to focus on a specific deficit. In addition, feedback displays could be created for other exercises that target complementary biomechanical variables.

The advantage of creating individualized feedback gains is that participants who perform atypically (e.g., below or above an average level of performance) could interact with a stimulus display that is tailored to her own needs. Effectively the gains can be used to increase or decrease the sensitivity of the display and, therefore, make it easier or more difficult to maintain the goal feedback shape and size. The gains could then be adjusted over the course of training to introduce a progression of exercise difficulty as appropriate to a given individual’s performance—as the participant masters exercise form at one gain setting, the exercise could be progressed to further challenge the participant to improve more. The initial individual gains could be determined from a statistical distribution of participant pre-test performances, where the location of your performance relative to the distribution determines the feedback gains used to generate the feedback display. From the same distribution it would also be possible to determine acceptable ranges for the biomechanical variables. For example, it may be counterproductive to provide feedback on trunk lean values that are within ±1.0˚ of 0.0˚ (the trunk is perfectly upright). Lastly, additional exercises could be programmed that target complementary biomechanical variables. One example of this is the single-leg Romanian deadlift. The exercise is performed on a single leg.
where the person essentially bends over (at the waist) and touches the ground with their fingers. This exercise may lead to greater trunk control, more stable hip joint dynamics, and improved balance.

**Conclusion**

In both the pilot and primary studies the heat map results revealed a positive change in participant behavior. Specifically, the heat map scores of participants in the pilot study improved from the pre- to posttest period, and the scores of participants in the primary study were better during interaction with the real feedback than with the sham feedback. The primary study also identified the need for several potential modifications to the training intervention which may improve its effectiveness. These include changes to both the real and sham feedback stimuli, the development of a less intrusive depth indicator, and an increase to the duration of the training program. Of these modifications the two which most likely limited the training’s effectiveness were the depth indicator and the training duration. Future changes to these aspects of the training intervention could improve participant performance and reduce ACL injury risk.
References


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