©Journal of Sports Science and Medicine (2020) **19**, 84-94
http://www.jssm.org

Research article

A Technical Report on the Development of a Real-Time Visual Biofeedback System to Optimize Motor Learning and Movement Deficit Correction

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Abstract

This technical report describes the design and implementation of a novel biofeedback system to reduce biomechanical risk factors associated with anterior cruciate ligament (ACL) injuries. The system provided objective real-time biofeedback driven by biomechanical variables associated with increased ACL injury risk without the need of a present expert. Eleven adolescent female athletes (age = 16.7 ± 1.34 yrs; height = 1.70 ± 0.05 m; weight = 62.20 ± 5.63 kg) from the same varsity high school volleyball team were enrolled in the experiment. Participants first completed 10 bodyweight squats in the absence of the biofeedback (pretest), 40 bodyweight squats while interacting with the biofeedback, and a final 10 bodyweight squats in the absence of the biofeedback (posttest). Participants also completed three pretest drop vertical jumps and three posttest drop vertical jumps. Results revealed significant improvements in squat performance, as quantified by a novel heat map analysis, from the pretest to the posttest. Additionally, participants displayed improvements in landing mechanics during the drop vertical jump. This study demonstrates that participants were able to interact effectively with the real-time biofeedback and that biomechanical improvements observed during squatting translated to a separate task.

Key words: ACL injury, injury prevention, neuromuscular training.

Introduction

Due to increased participation in athletics over the last few decades, the associated cost of anterior cruciate ligament (ACL) injuries has grown to exceed 2 billion dollars a year in the United States (Kim et al., 2011; Myer et al., 2004), with female athletes incurring knee injuries four to six times more frequently than males (Arendt and Dick, 1995; Malone et al., 1993; Mandelbaum et al., 2005). Beyond the acute debilitation and prolonged recovery, there are long term complications following the ACL injury. For instance, there is a strong link between ACL injuries and post-traumatic knee osteoarthritis (Lohmander et al., 2007; Myklebust and Bahr, 2005), reduced athletic identity (Brewer and Cornelius, 2010), and depression (Garcia et al., 2016) in young individuals. Because of the associated costs and these debilitating sequelae, the National Public Health Agenda for Osteoarthritis and the National Athletic Trainers' Association advocate the need for the development of preventative programs to stem the tide of rising injury rates and the negative complications associated with ACL injury (Padua et al., 2018; Waynes and Klippel, 2010).

Neuromuscular training programs have become popular tools for ACL injury prevention in female athletes. Recent meta-analyses have revealed that the majority of these programs have at least some success in preventing ACL injuries (i.e., participants' ACL injury risk were reduced) (Myer et al., 2013; Yoo et al., 2010), but in practice they still suffer from several limitations that hold back these interventions from reaching their full potential for injury risk reduction (Gagnier et al., 2013; Myer et al., 2013; Pappas et al., 2015; Sugimoto et al., 2012a; Sugimoto et al., 2012b; Webster and Hewett, 2018). Briefly, these problems include: (a) The questionable or limited ability of training to successfully bring about the desired changes in motor behavior (Sugimoto et al., 2012b), (b) The general susceptibility of training programs to participant noncompliance (Sugimoto et al., 2012a), (c) The limited capability of training—and the difficulty in assessing improvements from training—to transfer to behavior outside of the training program (DiCesare et al., 2019), and (d) The resources associated with the need for trained specialists to supervise training (Hewett et al., 2006). Future efforts to optimize injury prevention strategies should aim to mitigate limiting factors in order to enhance the efficacy of current approaches. The current experiment targets these limitations through the development and deployment of an innovative, real-time, interactive biofeedback system that targets high-risk movement biomechanics associated with ACL injury in females. The authors have chosen to use the term biofeedback instead of feedback because biofeedback is commonly defined as a technique to induce physiological changes by utilizing technological devices to provide information to a person about a targeted physiological variable (Giggins et al., 2013). In the case of the current experiment, kinematic and kinetic information related to ACL injury risk is visually provided to a participant so that they can self-guide themselves to modify such variables in real time by interacting with the biofeedback.

The design and use of real-time biofeedback is motivated by the possibility that it can reduce the

Received: 10 May 2019 / Accepted: 08 November 2019 / Published (online): 01 March 2020

previously described barriers to implementing an effective ACL injury prevention program (Giggins et al., 2013). Specifically, it attempts to overcome previous problems by designing real-time biofeedback that: (A) can be provided largely independent of an expert's (e.g., a physical therapist) presence and involvement with individual athletes, (B) is interactive and personalized, which may enhance athlete motivation and compliance (Kiefer et al., 2015), (C) may improve learning and performance by directing athletes' attentional focus to an external source (e.g., (Mechsner et al., 2001; Wulf, 2013; Wulf and Prinz, 2001)), and (D) engages implicit motor learning strategies that may result in faster learning and improved transfer (e.g., (Swinnen et al., 1997; Varoqui et al., 2011)).

The use of real-time biofeedback has been successful in modifying risk factors related to ACL injuries (Ericksen et al., 2016; Ericksen et al., 2015; Ford et al., 2015). The biofeedback however is often inefficiently localized to a single risk factor or training component when it is well documented that multicomponent training programs reduce ACL injury risk most effectively (Lang et al., 2017; Nessler et al., 2017; Padua et al., 2018). For example, Ford et al. (2015) demonstrated great efficacy in improving an ACL injury risk factor using a biofeedback system that responded in real-time to participants' knee abduction and adduction. However, other biomechanical variables, such as trunk control and vertical ground reaction force symmetry, are also risk factors for ACL injury (Hewett and Myer, 2011; Hewett et al., 2005b; Myer et al., 2009). The integration of multiple variables—each contributing complementary training effects—into a biofeedback system may demonstrate additive benefits (Lang et al., 2017; Nessler et al., 2017; Padua et al., 2018). For example, postural control is an important factor related to ACL injury risk (Paterno et al., 2010; Tsai et al., 2019) and it may be improved by targeting multiple postural control outcome variables. Vertical ground reaction force symmetry is one such variable and if biofeedback about it is combined with another variable related to postural control, such as trunk control (e.g., lateral trunk flexion angle), the biofeedback may improve postural control beyond a single-variable training outcome.

In the present study, participants interacted with a real-time visual biofeedback system, tied to multiple ACL-injury risk variables, during the performance of double-leg bodyweight squats. The squat was chosen as the task for several reasons. First, the squat has close proximity to many everyday tasks and is one of the most utilized exercises in strength, conditioning, and performance enhancement programs (Escamilla et al., 2012; Schoenfeld, 2010), is excellent for improving lower body strength and requires the coordinated activation of nearly 200 muscles (Solomonow et al., 1987). Likewise, the squat is a common prescriptive exercise following ACL reconstruction (Dedinsky et al., 2017; Escamilla et al., 2012; Palmitier et al., 1991; Potach et al., 2018; Sanford et al., 2016; Wilk et al., 2012), and the squat has the ability to target and improve certain biomechanical variables that have previously been linked to ACL injury risk through other injury assessments (i.e., drop vertical jump; DVJ). For example, it is possible to calculate and compare performance of the trunk lean, knee abduction, knee adduction, and vGRF symmetry biomechanical variables during both the DVJ and squat exercise (Hewett and Myer, 2011; Hewett et al., 2005b; Myer et al., 2014). The DVJ is a commonly utilized task to quantify an athlete's ACL injury risk (Hewett et al., 2005b; Redler et al., 2016) and if the current biofeedback system is to effectively reduce injury rates, it must successfully transfer biomechanical improvements from the squat to other activities and environments.

The specific aims of this study were to 1) describe the specific aspects of our prototype real-time biofeedback including hardware, software, and integration of real-time biomechanical data and 2) provide preliminary evidence of our prototype system's effectiveness for altering biomechanics associated with reduced risk of ACL injury. Rather than provide the participants with verbal guidance relative to desired technical performance or an explicit assessment of their performance (which would require trained professionals like physical therapists, athletic trainers, or certified strength and conditioning specialists to administer), the real-time, interactive visual biofeedback system was designed to guide participants' movements to achieve correct form.

Motivation for this type of biofeedback is twofold. First, while verbal feedback is one of the most commonly implemented and influential forms of instruction (Benz et al., 2016; Hodges and Franks, 2002; Sigrist et al., 2013; Storberget et al., 2017; Wulf et al., 2010), it is not without its methodological limitations. Specifically, verbal feedback that is complex and addresses several different targets simultaneously is not as effective as when a single, concise verbal cue is used (Landin, 1994; Raisbeck and Diekfuss, 2017; Rink, 2014; Singer, 1988). Verbal feedback is also typically given after the participant has performed the task, which makes it difficult or impossible for participants to effect immediate biomechanical adjusts in real-time (Ericksen et al., 2016; Ericksen et al., 2015). While verbal feedback has been shown to be highly effective in altering and transferring biomechanical behavior related to ACL injury risk (Benjaminse et al., 2018; Welling et al., 2016; Welling et al., 2017), it was not utilized in the current design because of the inherent methodological constraints imposed by verbal feedback.

Secondly, a series of experiments have shown that biofeedback systems designed to map or transform participant movement into real-time visual feedback are effective at training complex and difficult to achieve movements (Mechsner et al., 2001; Varoqui et al., 2011). For example, participants can learn to turn two hand cranks in a very difficult to achieve 4:3 frequency ratio—one hand turns a crank 4 times for every 3 hand turns of the other crank—when their hand movements are mapped onto a simple visual display. The visual biofeedback achieves this by transforming the two hands' 4:3 movement frequency ratio into a 1:1 frequency ratio in the visual biofeedback. By transforming and simplifying the visual feedback such that participants were focusing on the end effect of the visual biofeedback and not the corresponding hand movements that were causing the biofeedback stimulus to move, the complex motor task became easily achievable (Mechsner et al., 2001; Swinnen et al., 1997; Varoqui et al., 2011). A similar study utilized a similar visual biofeedback design to improve the postural coordination patterns in post-stroke patients by mapping their posture movements to a simple visual biofeedback display (Varoqui et al., 2011).

Based on these past studies demonstrating the efficiency of visual biofeedback in promoting the acquisition and performance of difficult biomechanical behaviors (Mechsner et al., 2001; Swinnen et al., 1997; Varoqui et al., 2011), it was theorized that, as a result of the simplified visual biofeedback, participants would learn to better perform a relatively complex whole-body movement. Specifically, they would perform a squat in a manner associated with lower ACL injury risk, and they would achieve this by focusing on the "control" of simple changes in the real-time visual biofeedback display. In order to quantify participant control of the biofeedback, heat maps of the participants' interaction with the biofeedback were calculated. Heat map scores provide a composite index of how effectively participants controlled the biofeedback (and, thus, how the participant moved), where a higher score indicates better performance. Specifically, we hypothesized (1) a significant progressive improvement in heat map scores while participants interacted with the biofeedback during training sets (group of 10 squats), (2) a significant improvement in heat map scores from the pretest to posttest in the absence of the biofeedback, and (3) that these biomechanical improvements observed during the squat would transfer to a secondary drop landing task known to relate to ACL injury risk.

Methods

Experimental design

The present study utilized a single-group pre-to-post-test study design to investigate the efficacy of our real-time biofeedback system on heat map scores and drop landing biomechanics. Participants completed a set of 10 double-leg squats without the biofeedback present (pretest), four sets of 10 double-leg squats with the biofeedback present, and a final set of 10 double-leg squats without the biofeedback present (posttest). Participants also completed three drop vertical jumps immediately prior to the pretest and three immediately after the posttest to assess the transfer of biofeedback driven improvements to a secondary motor skill. The DVJ analysis consisted of the calculation of biomechanical variables found to relate to ACL injury risk. To limit the scope of this project, we did not include a control group given the aims of this preliminary investigation to provide a technical description and demonstrate prototype functionality. Our single group pre-to-post-test design allowed us to satisfy those aims.

Participants

Eleven healthy, adolescent female athletes from the same varsity high school volleyball team in the Cincinnati, OH metropolitan area participated in the study (age = 16.7 ± 1.34 yrs; height = 1.70 ± 0.05 m; weight = 62.20 ± 5.63 kg). The participants had never interacted with the biofeedback before and none self-reported that they had previously participated in a neuromuscular training program. No participants reported any past history of knee injury, any other neuromuscular deficit, or uncorrected visual impairment. The study was IRB-approved, and all participants and legal guardians gave written informed consent prior to participation.

Materials, apparatus, and biofeedback stimulus design

Participants viewed a dynamically changing shape (i.e., the biofeedback) that was tied to their movement biomechanics, in real time. They were instructed that their goal was to squat in such a way as to maintain the shape as close to a perfect rectangle—a goal indicating that several targeted biomechanical variables (four specifically) tied to ACL injury risk were within a desired range (see Table 1 "Optimum Value" column). Participants were not aware of how their movements mapped to the biofeedback displaynor were they informed of the biomechanical variables that were being calculated to drive the biofeedback.

Table 1. Justification, optimum value, and the effect on the stimulus for the included biomechanical variables.

Variable	Stimulus Effect	Abbreviation	Justification	Optimum Value	References
Trunk lean	Figure 1B	-	Lateral trunk displacement predicted ACL injuries with high sensitivity and specificity in females.	0°	(Hewett et al., 2009; Paterno, 2017; Zazulak et al., 2007)
Knee-to-hip joint extensor moment of force ratio	Figure 1C	KHMr	Quadriceps-dominant recruitment during dynamic movement is a risk factor for lower extremity injuries.	≤ 1	(Ford et al., 2008; Myer et al., 2009)
Knee abduction moment of force	Figure 1D	KAM	Valgus knee collapse and subsequent increased knee abduction moment occurs more frequently in ACL injury risk prone athletes.	≤ 0 Nm	(Hewett et al., 2005a; Schoenfeld, 2010)
Vertical ground reaction force ratio	Figure 1E	vGRF	Asymmetry in ground reaction force indicates preference for and the potential for abnormal joint loading on one limb.	1	(Hewett et al., 2005a)

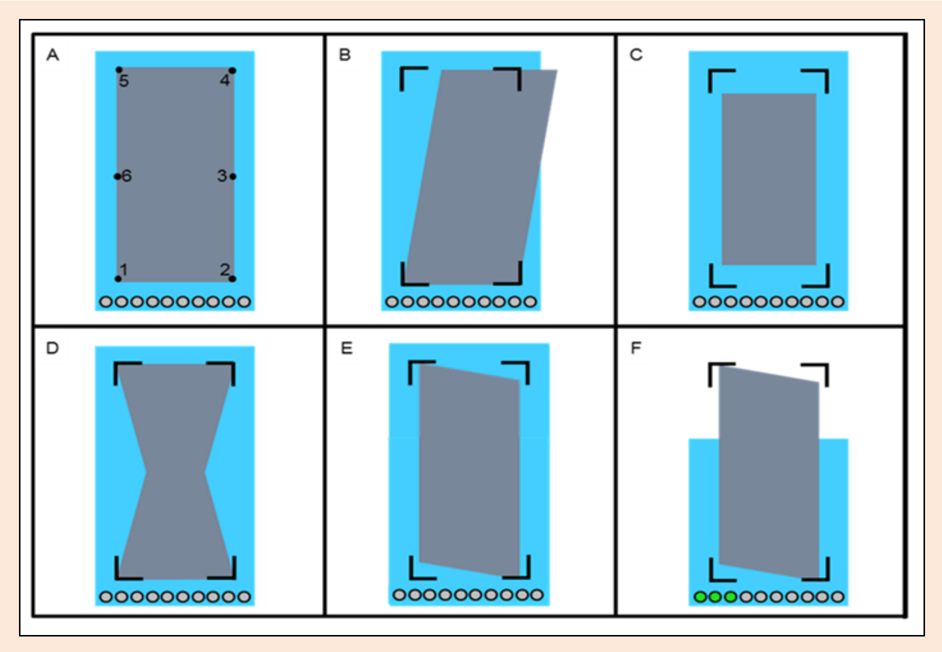

Figure 1. The stimulus used in the experiment. During the trials, the stimulus' shape started as a rectangle. This shape is depicted in Panel A and was defined by points one through six. An outline of the shape's corners (points one, two, four, and five) remained while participants were performing the squat exercise and are shown in Panels B-F. Also displayed are ten grey circles towards the bottom of each display. These were used for counting the number of squats within a block. As participants performed squats, the circles would change from grey to green. Depicted in Panels B-E are the effects of the trunk lean, KHMr, KAM, and vGRF variables, respectively. As participants deviated from the optimum value (see Table 1) the biofeedback display would react as shown in each panel; however, as the participants performed closer to the optimum value the display would begin to return to the goal shape shown in Panel A. 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, the stimulus rose as a participant began to rise back up.

The biofeedback was designed so that objective information about multiple biomechanical variables related to ACL injury risk was displayed concurrently in real time to participants in a relatively simple, global fashion (i.e., as a holistic shape). The design of the real-time biofeedback display was a simple rectangle defined by six points (see Figure 1; Panel A). The vertical and horizontal coordinates of those points were defined as a function of the following variables: (1) trunk lean, (2) knee-to-hip recruitment ratio (KHMr), (3) knee abduction load (KAM), and (4) vertical ground reaction force symmetry (vGRF). Information about these biomechanical variables, their effects on the biofeedback, their optimum values, and justification for their inclusion are presented in Table 1. As these variables changed dynamically throughout participants' movements, the biofeedback display was updated relative to participants' movements in real time. The biofeedback used the real time values of the biomechanical variables and mapped them to the biofeedback display through a predetermined gain parameter that determined the magnitude of the influence of the biomechanical variable on the change in the rectangular shape. The gain parameters were selected pragmatically so that the transformed value preserved meaningful and equivalent biofeedback changes (i.e., changes in the two dimensional coordinates) as a function of differently scaled ranges of possible biomechanical values. Each variable (see Figure 1) had a unique effect on the biofeedback display shape.

The participants were simply instructed to maintain a biofeedback shape that was as close to a rectangle as possible by modifying their movements accordingly. Achieving the goal rectangle was accomplished by producing movement patterns yielding target values of the aforementioned risk factor variables. As the values of any or all of the four variables neared, or fell within, target ranges specific to the given variable(s), a more symmetric rectangle was obtained. In addition to the previous variables, the number of squats performed by a participant was tracked by a variable measuring knee flexion angle. A single squat trial was considered "complete" when a participant achieved a knee flexion angle below 90° during the squat and then returned to the original standing position (see Figure 1F), independent of how accurate their movement patterns were or the symmetry of the rectangle produced. Knee flexion was visually displayed to participants (separately from the biofeedback rectangle just described) through the movement of a lighter-colored rectangle behind the primary biofeedback display shape. As a participant squatted into a lower position, the height of the background rectangle decreased. Ten circles served as a display counter representing the number of completed squats performed. These circles would change colors from grey to green once the participant completed a full squat (i.e., participants were standing upright after performing the squat). All participants performed 6 sets of 10 squats. The first and last block served as pre- and posttest assessments, respectively, and during these sets no biofeedback was shown; only within the middle four training sets did participants receive visual biofeedback. Participants were permitted as much rest as they required between sets; however, participants began each new set after, on average, less than 30 seconds of rest.

The visual biofeedback was constructed and presented to participants in real time using an array of hardware and custom software algorithms. Participants' movements were recorded using a 10-camera Raptor-E motion capture system (Motion Analysis Corp., Santa Rosa, CA) with a sampling rate of 240 Hz. In conjunction with the motion capture system, two embedded BP600900 force platforms (AMTI, Watertown, MA) with a sampling rate of 1200 Hz were used to collect ground reaction force from each foot. Using a software development kit provided by Motion Analysis Corp., the synchronized data (i.e., the force platform and the motion capture marker position data) were imported into a custom software program designed to calculate the above biomechanical variables and generate the visual biofeedback display. The visual biofeedback display was created by first specifying the two-dimensional coordinates of the biofeedback display (i.e., the positions of 6 points in Panel A of Figure 1). Then the calculated biomechanical values were transformed by a gain parameter and the biofeedback shape was adjusted by these transformed values of the biomechanical variables, as they were calculated in real time during performance of the squats. The program was a custom-written C++ program designed in Microsoft Visual Studio Professional 2015 (Microsoft Corp., Redmond, WA) and incorporated an OpenGL graphics application interface (Khronos Group, Beaverton, OR).

The final visual display was transmitted wirelessly, and in real time, from a desktop computer to participants through a head mounted display (HMD; 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 HMD displayed the biofeedback in a fixed position relative to the participants' eyes and encompassed their entire field of view. Video was transmitted to the HMD via an ARIES Pro Wireless HDMI Transmitter and Receiver (Nyrius, Niagara Falls, ON, Canada). The ARIES Pro can transmit uncompressed 1080p signals up to 160 feet with a latency of < 1 ms, which allowed for maximum mobility of participants without the degradation of biofeedback quality. Both the ARIES Pro and HMD 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 backpack weighing 2.4kg (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 x width x height: 33 x 27 x 7.6 cm). The backpack did not obstruct any motion capture markers, and no participants indicated that it obstructed their range of motion. Other materials included those required for the DVJ: a plyometric exercise box (45.72 x 45.72 x 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.

Procedures

Participants were outfitted with 30 retroreflective markers and the backpack containing the wireless transmitter and battery pack. Markers were placed on the sacrum between the L5 and S1 vertebrae, the sternum, and bilaterally on the acromio-clavicular joint, anterior superior iliac spine, posterior superior iliac spine, greater trochanter, mid-thigh, medial and lateral femoral condyles, tibial tubercle, lateral and distal aspects of the shank, and medial and lateral malleoli, the heel, and central forefoot (between the second and third metatarsals). After the initial preparation, all participants received identical instructions about the squat exercise. The instructions were purposefully kept very basic to allow participants to implicitly discover how their movements related to the biofeedback shape during the squat exercise; they were told only to "maintain the goal stimulus shape and size as closely as possible" and, as a secondary instruction, to squat to sufficient depth, as indicated by the circle counter shown beneath the rectangular stimulus shape. Participants were asked to keep their arms crossed in front of their chest and to avoid covering any markers. A block of squats was considered complete once all ten circles changed from grey to green, indicating that ten successful (i.e., adequately deep) 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 biofeedback 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 biofeedback.

For the DVJ task, 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 immediately in front of the box 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. While participants were not permitted any practice trials, if they did not perform the DVJ in this manner they were informed and the trial was repeated. Three correct trials for both pretest and posttest were collected.

Statistical analyses

To quantify participants' ability to control the stimulus shape, a heat map analysis was performed on the squat data during the middle four training sets and on "reconstructed" biofeedback shapes obtained from the raw position and force data in the pre- and posttest sets. The heat maps provided a holistic assessment of squatting performance by indicating how the movement patterns of the biomechanical variables associated with ACL injury related to the target values as embodied in the target biofeedback shape. The heat maps portrayed the percentage of time a defined two dimensional spatial (x, y) coordinate was occupied by the biofeedback stimulus (or, in the case of the pre- and posttest squats, during which no biofeedback was provided, would have been occupied by the biofeedback 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 calculation of each heat map's correctly occupied space consisted of first calculating the proportion of occupied space within the goal stimulus shape and then calculating the proportion of occupied space outside of the goal stimulus shape. The proportion of occupied space outside of the goal shape was subtracted from the proportion of occupied space within the goal stimulus. The possible results of this operation ranged from -1.00 to 1.00. A score of -1.00 indicated the stimulus never occupied a correct location in the display while always occupying an incorrect location. A score of 1.00 indicated a stimulus shape that never deviated from the goal shape and size. Heat maps were only calculated for periods during which a participant was actually performing a squat and not for periods during which they were not. For example, the brief moments where a participant may have paused at the end of squat before beginning another or periods where participants were adjusting their foot placement were removed from the heat map analyses. These scores were transformed and presented as percentages in the Results section.

The DVJ analysis consisted of the calculation of seven variables found to relate to ACL injury risk: (1) hip flexion angle, (2) hip adduction angle, (3) hip extensor external moment, (4) knee flexion angle, (5) knee abduction angle, (6) knee extensor external moment, and (7) knee abduction external 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. These values were averaged across both legs and across the three DVJ trials for each participant. An alpha level for significance was set *a priori* at $p < .05$. Cohen's d was used to determine the magnitude of the effect sizes and were interpreted as follows: d < 0.50, d = 0.5-1.25, d = 1.25-2.0, and d > 2.0 correspond to trivial, small, medium, and large effects, respectively (Rhea, 2004). Post-hoc power analyses were calculated using G*Power (Faul et al., 2007) and statistical analyses were performed in MATLAB (The MathWorks, Inc.; Natick, MA) and (JASP Team, 2018). All pretest and posttest comparisons were performed by paired sample *t*-tests.

Results

Squat performance quantified by heat map analysis

Heat map analyses revealed that participants improved at achieving the target biofeedback shape (i.e., more closely resembled the optimal shape of a perfect rectangle) from a pretest average of 77.17% (SD = 3.80%) to an average of 84.87% (SD = 3.13%) in the posttest. The average pre- to posttest set improvement of 7.70% (SD = 4.95%) was significant, $t(10) = 5.16$, $p < 0.001$, $d = 1.56$, 95% CI [4.38, 11.03]. A post-hoc power analysis revealed a power level of 0.99.

Additionally, participants demonstrated a trend of increasing heat map scores over the four biofeedback training sets; however, this trend was not significant. Participants produced an average heat map score of 78.76% (SD = 3.40%), 80.91% (SD = 2.20%), 81.65% (SD = 1.57%), and 85.71% (SD = 2.11%) for biofeedback sets one through four, respectively. See Figure 2 for a representative example of a heat map analysis for a single participant and Figure 3 for group means.

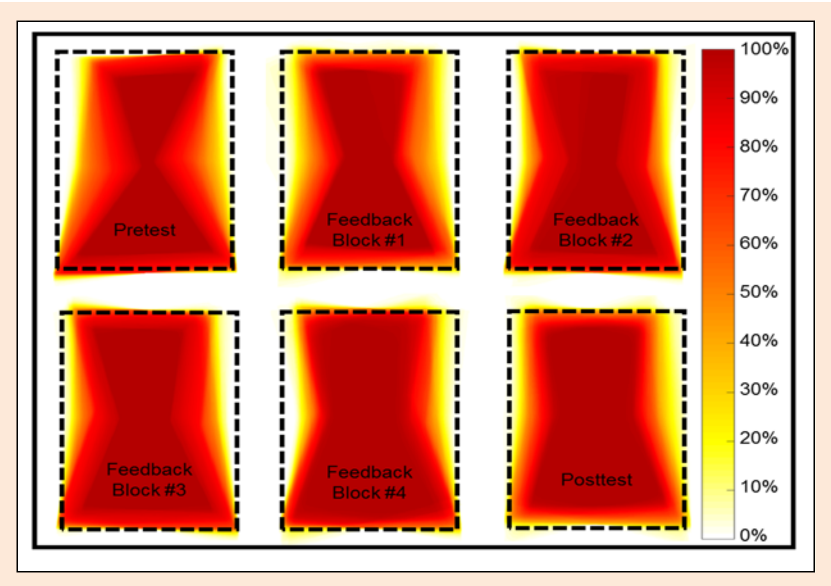

Figure 2. Participant's individual heat maps calculated for each set of squats. The heat map for each squat repetition was averaged across the entire set yielding one heat map per set of 10 squats. Also shown above is the goal biofeedback shape represented by black dotted lines. The chosen participant's heat maps were representative of average participant behavior and had the closest pre- and posttest means to the group averages. The darkest red (i.e., 100%) indicates that the stimulus occupied that space the entire period of time and white (i.e., 0%) indicates that the stimulus never occupied that space. A heat map indicating a perfect performance would fill the entire space within the goal lines (black dotted lines) with a dark red color and the space surrounding the goal lines would be entirely white.

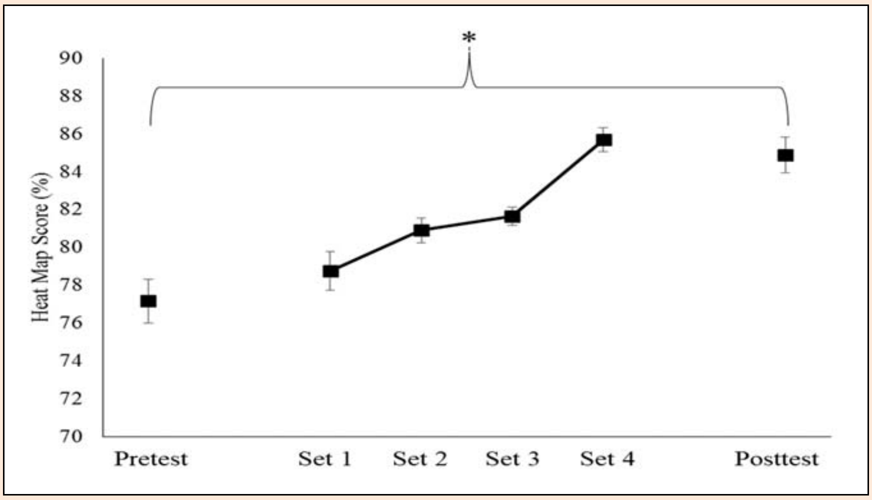

Figure 3. Heat map scores. Error bars represent the standard deviation of the mean. *Significant improvement in heat map score from the pretest to posttest.

Drop vertical jump (DVJ)

Significant improvements in the drop landing task were also found in three of the seven DVJ variables. On average, participants performed the DVJ in the posttest with greater knee and hip flexion angles combined with smaller knee extensor moments. Participants' knee flexion angle values improved from a pretest average of -79.85° (SD = 7.83°) to a posttest average of -82.48° (SD = 9.33°). The average improvement of -2.63° (SD = 3.07°) was significant, $t(10) = 2.84$, $p = 0.02$, $d = 0.86$, 95% CI [-4.69, -0.57]. A post-hoc power analysis revealed a power level of 0.73. Likewise, participants' knee extensor moment values improved from a pretest average of -120.65 Nm (SD = 23.40 Nm) to a posttest average of -110.39 Nm (SD = 23.78 Nm). The average improvement of 10.25 Nm (SD = 8.01 Nm) was significant, $t(10) = 4.25$, $p = 0.002$, $d = 1.28$, 95% CI [4.88, 15.64]. Post-hoc power analysis revealed a power level of 0.97. Participants' knee flexion angle values improved from a pretest average of 65.74° (SD = 7.88°) to a posttest average of 68.90° (SD = 10.82°).The average improvement of 3.16° (SD = 4.62°) was significant, $t(10) = 2.26$, $p = 0.047$, $d = 0.68$, 95% CI [0.05, 6.27]. A post-hoc power analysis revealed a power level of 0.53.

Due to the exploratory and technical nature of the current project, no corrections for multiple comparisons were performed; however, it must be noted that corrected p-values for the knee flexion angle ($p = 0.07$) and hip flexion angle ($p = 0.12$) variables did not remain significant following a Benjamini-Hochberg correction for false discovery rate (FDR). Knee extensor moment remained significant ($p = 0.014$). The remaining four variables (hip adduction angle $p = 0.79$, M change = -0.15, SD = 1.75; hip extensor moment $p = 0.26$, M change = 2.48, SD = 6.85; knee abduction angle $p = 0.83$, M change = -0.03, SD = 0.49; and knee abduction moment $p = 0.57$, M change = 0.52, SD = 2.89) were not significant prior to FDR corrections. It is also worth noting that the DVJ biomechanical variables were not normalized by participant weight; however, an identical pattern of results remains.

Discussion

The results of this technical report indicate significant promise for the effectiveness of this prototype biofeedback system. First, the study successfully managed the technical (hardware and software) issues associated with the biofeedback program, the display technology, and the integration of real-time biomechanical data with an interactive visual display. Second, the system promoted improved movement patterns as indicated by increases in participants' posttest heat map scores from the pretest, indicating that participants performed their posttest squats in a manner that improved biomechanical variables related to ACL injury risk and this improvement was not dependent on having the biofeedback available during the immediate posttest. Finally, we found evidence that the biomechanical improvements displayed during the squats may have transferred to a drop landing task, where three of seven variables showed post-training improvements.

While previous studies have been successful using real-time biofeedback to reduce ACL injury-risk (Ford et al., 2015), our system mapped on to *multiple* variables associated with ACL injury-risk. Our significant pretest to posttest changes in heat map scores (7.7%) and DVJ indicate that participants were able to improve multiple key biomechanical variables. This was supported by medium effect size in the improvement from pre- to posttest heat maps. Our system of real-time biofeedback also shows promise in instigating biomechanical improvements that transfer across tasks, as evidenced by consistent improvements in this group during the DVJ task. We deem the 7.7% performance improvement from pre- to posttest meaningful when considering in context of our DVJ findings. Assessing transfer of skill acquisition (repeating movements in the absence of feedback) is a robust method to differentiate performance from learning, and whether the performance changes were maintained (i.e., meaningful) (Wulf et al., 2010). As the participants in this study improved their biomechanics during the DVJ transfer test, we can tentatively attribute the 7.7% pre- to post-training improvement in achieving the target biofeedback shape as meaningful movement adaptations that contributed to the observed skill transfer.

The increased hip and knee flexion and reduced internal knee extensor moment exhibited by this group after receiving the biofeedback are indicative of a landing strategy that may reduce the risk for injury. Although the effect sizes were small-to-medium for the DVJ comparisons, the observed changes are promising due to the fact that the changes in the DVJ came following a single training session with an indirectly related task (i.e., squat). Female adolescent athletes tend to preferentially activate their quadriceps group upon landing from a jump (Ford et al., 2011), which has been associated with increased risk for anterior cruciate ligament strain and injury (Hewett et al., 2005b; Myer et al., 2009; Withrow et al., 2008). Reliance on the quadriceps without engaging the posterior chain increases the anterior shear force on the ACL, and this strategy may also make the limb less stable in the frontal plane (Lloyd and Buchanan, 2001). While no differences were exhibited in hip extensor moment in the present study, our findings indicate that participants attenuated the ground reaction force of landing more effectively through increased sagittal plane hip and knee range of motion, and—given the decreased reliance on the quadriceps group—may have relied on alternative recruitment and control strategies to eccentrically control hip and knee sagittal plane joint angular motion and the vertical momentum of the center of mass. Additionally, while no improvements were observed in the frontal plane, especially no significant decrease in knee abduction moment, it should be noted that this group of subjects had fairly low frontal plane measures during both the pre-test (i.e., 12.3 Nm, on average) and post-test (i.e., 11.7 Nm, on average). Previous literature has thresholded at-risk athletes at much higher magnitudes of knee abduction moment (e.g., >25 Nm) (Myer et al., 2007); thus, it is not unexpected that this group did not exhibit a remarkable decrease in knee abduction moment as they were low-risk initially.

Considering participants' biomechanical improvements in squat performance and the DVJ, future studies should also investigate the effects of the biofeedback over a longer training period and a longer retention period. Additionally, the biofeedback itself could be modified in several ways to further improve squat performance and DVJ biomechanics. A potential change could include individualizing the biofeedback gains. The advantage of creating individualized biofeedback gains is that participants who perform atypically (e.g., below or above an average level of performance) could interact with a biofeedback display that is tailored to her own needs. Effectively the gains could be used to increase or decrease the sensitivity of the biofeedback and, therefore, make it easier or more difficult to maintain the goal shape and size. The initial individual gains could be determined from a statistical distribution of participant pretest performances, where the location of the participant's performance relative to the distribution determines the biofeedback gains used to generate the biofeedback. 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 movement is almost negligible).

Although this experiment was successful, several limitations should be recognized. First, this study did not include a control group and therefore it cannot be definitively concluded that the real-time biofeedback drove the improvement in heat map scores. The trend of increasing scores over the four biofeedback sets signified improvements were occurring, but was limited by our small sample size. In response to this limitation, we included a transfer test consisting of the DVJ which shows good to excellent reliability for lower extremity biomechanics between separate testing sessions (Ford et al., 2007). Our results demonstrating improvements in DVJ biomechanics from the pre- to posttest following our real-time biofeedback training provide preliminary evidence that the potential to induce motor skill learning exists. However, no retention test was performed, and future studies should investigate the biofeedback's potential to induce long-term learning effects. Second, we utilized varsity athletes who showed high congruence with the real-time biofeedback from the onset of training. This potential ceiling effect could be addressed in future studies utilizing less experienced athletes or athletes recovering from injury. Future studies should also include a comparison group, determine the effects of increases in the duration of the training and retention periods, and investigate changes in the responsiveness of the biofeedback itself.

Lastly, it should be noted that the equipment (e.g., motion capture system and force plates) used to construct the real-time biofeedback system is relatively expensive which may limit public availability of the system. However, recent technological advances in computer vision and equipment (i.e., Microsoft Kinect 2; Microsoft Corp., Redmond, WA) provide cost-effective wireless and markerless body tracking. The Kinect 2, for example, includes a body tracking software development kit that provides kinematic information about a user's estimated skeletal frame. Additionally, kinematic data acquired by devices such as the Kinect 2 can be combined with kinetic data from portable force platforms such as the BODITRAK (BodiTrak Sports, Webster Groves, MO) or the loadsol (novel GmbH, Munich, Germany) systems to drive the real-time biofeedback system without the need for an expensive research grade laboratory. Future studies should incorporate and validate the accuracy and resolution of cost-effective and portable motion capture systems and force plates for providing motion data and extend the system to target other areas of injury risk

Conclusion

The current study demonstrated the feasibility and preliminary effectiveness of an interactive, real-time biofeedback system. The heat map and DVJ results revealed a positive change in participants' biomechanics from the pre- to posttest period. Overall, the real-time biofeedback system showed promise as an alternative and efficient method for reducing ACL injury risk in high-risk athlete populations.

Acknowledgements

Gregory D. Myer consults with Commercial entities to support application to the US Food and Drug Administration but has no financial interest in the commercialization of the products. Dr. Myer's institution receives current and ongoing grant funding from National Institutes of Health/NIAMS Grants U01AR067997, R01 AR070474, and industry sponsored research funding related to brain injury prevention and assessment with Q30 Innovations, LLC, and ElMinda, Ltd. Dr. Myer receives author royalties from Human Kinetics and Wolters Kluwer. Dr. Riley's institution receives current and ongoing grant funding from National Institutes of Health/NIAMS grant U01AR067997 and NIH/NIDCD grant 1R01DC017301-01. Dr. Riley receives royalties from Springer-Verlag. Drs. Myer, Kiefer and Riley are also an inventors of biofeedback technologies (2017 Non Provisional Patent Pending- Augmented and Virtual reality for Sport Performance and Injury Prevention Application filed 11/10/2016 (62/420,119), Software Copyrighted.) designed to enhance rehabilitation and prevent injuries and has potential for future licensing royalties. Scott Bonnette, Chris Dicesare, Kim Foss, Staci Thomas and Jed Diekfuss are contributors to the implementation of the biofeedback technology to which the inventors have allocated a portion of the inventor's share of potential royalties from licensing of technology. The study complied with the laws of the country of the authors' affiliation.

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Key points

- Our study demonstrated the technical feasibility for integrating real-time kinematic and kinetic data into a single, interactive visual display.
- Novel heat map analyses demonstrated that participants improved biomechanics associated with ACL injury risk over a single training session.
- Training with our real-time biofeedback system transferred to improved ACL injury-risk biomechanics during a drop landing.
- The tested real-time biofeedback system could eventually be used as an alternative and/or supplemental approach to ACL injury prevention programs.

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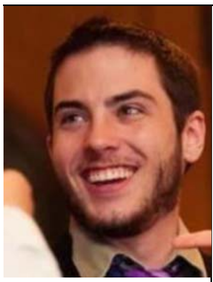

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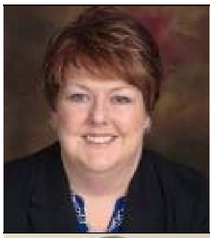

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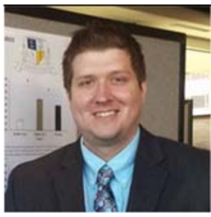

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