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Real-time biofeedback is more effective than sham feedback for modifying high risk biomechanics

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Abstract

Context: Existing anterior cruciate ligament (ACL) injury prevention programs have failed to reverse the high rate of ACL injuries in adolescent female athletes.

Objective: This investigation attempts to overcome factors that limit efficacy with existing injury prevention programs through the use of a novel, objective, and real-time interactive visual feedback system designed to reduce the biomechanical risk factors associated with ACL injuries.

Design: Crossover study.

Setting: Medical center laboratory.

Participants: Twenty female participants (age = 19.7 ± 1.34 y; height = 1.74 ± 0.09 m; weight = 72.16 ± 12.45 kg).

Methods: Participants performed sets of 10 bodyweight squats in each of eight training blocks (i.e., four real-time and four control blocks) and three testing blocks for a total of 110 squats. Feedback conditions were blocked and counterbalanced with half of participants randomly assigned to receive the real-time feedback block first and half receiving the control (sham) feedback first.

Results: Heat map analysis revealed that during interaction with the real-time feedback, squat performance measured in terms of key biomechanical parameters was improved compared to when participants squatted with the sham stimulus.

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Conclusion: This study demonstrates that the interactive feedback system guided participants to significantly improve movement biomechanics during performance of a body weight squat, which is a fundamental exercise for a longer-term ACL injury risk reduction intervention. A longer training and testing period is necessary to investigate the efficacy of this feedback approach to effect long-term adaptations in the biomechanical risk profile of athletes.

1. Introduction

Anterior cruciate ligament (ACL) injuries are physically and emotionally debilitating for adolescent athletes. The trauma associated with an ACL injury contributes to significant pain¹, depression², decreased athletic identity³, and lower academic performance⁴. This is in addition to the potential ending of an athletic career⁵, greatly amplified risk of a subsequent ACL injury, likelihood for long term disability⁶, and risk of early osteoarthritis and chronic pain⁷⁻⁹. Current reports conservatively estimate \$17,000-\$25,000 in costs per ACL injury with an annual economic burden in the United States between \$7.6 and \$17.7 billion dependent on treatment type (e.g., reconstruction versus rehabilitation)¹⁰. Because of these adverse consequences, the National Public Health Agenda for Osteoarthritis has strongly recommended expansion and refinement of ACL injury prevention strategies¹¹. Numerous prevention programs have been implemented to reduce ACL injury incidence¹². Some of these have shown effectiveness in reducing ACL injury risk¹³⁻¹⁷, while others have resulted in less desirable outcomes¹⁸⁻²⁰. The totality of evidence regarding the effectiveness of neuromuscular training interventions to reduce ACL injury risk unfortunately reveals that while these interventions can reduce injury risk factors in the lab their effects have not shown transfer to the actual sport environment, as injury rates have not declined despite the introduction of these programs²⁰⁻²⁴.

A common exercise, the double-leg squat, is commonly used in ACL prevention programs.^{14, 25} Despite this foundational movement's integral role within ACL prevention programs, the evidence indicating only minimal efficacy in reducing ACL injury rates¹³⁻¹⁷ warrants innovative approaches that expedite biomechanical performance improvements and increase retention and transfer. One potential avenue is through visual feedback manipulation in which the squat provides the ideal exercise for such investigation. Normally during the execution of a squat, the athlete maintains an upright posture with a forward facing gaze and focal point. This position permits athletes to easily maintain focus on the feedback without disturbing normal squatting form. The movement is relatively slow and continuous, allowing for continuous presentation of feedback in a way that allows the athlete to modify the movement as it unfolds. In contrast, training tasks such as the drop vertical jump (DVJ; drop landing) are executed quickly and ballistically and simply do not afford the opportunity for online feedback to be utilized during task execution.

In the present study, we conducted a preliminary test of a visual biofeedback system designed to guide athletes to improve double leg squat biomechanics by using a strategy of "external perceptual control"^{26, 27} of the feedback. This type of control is achieved by moving so as to achieve a desired visual biofeedback outcome. This mode of control engages automatic and implicit motor strategies that operate more efficiently and effectively than deliberate, explicitly conscious control of movement²⁸⁻³⁷, which yields fast, robust

learning, leading to high retention and transfer^{38–43}. With the advent of motion capture and mixed reality technologies, augmented feedback has become even more accessible to researchers and clinicians and provide ample opportunity for integrating visual biofeedback into areas such as sports medicine and biomechanics. Several possible applications for such technologies with a particular focus on ACL injury prevention have been outlined⁴⁴. For example, neuromuscular training can be augmented by presenting participants with an online feedback display linked to their biomechanics via 3D motion capture software⁴⁵. Such real-time biofeedback has been very effective for gait retraining^{46–48}, and many of these new technologies have already been implemented with success for non-contact ACL preventative training programs^{45, 49, 50}. However, limitations of these previous studies are that control conditions were compared with traditional feedback⁵⁰, or that biofeedback was localized to a single factor such as knee abduction/adduction⁴⁵ and did not incorporate the full biomechanical profile associated with ACL injury risk.

The innovative biofeedback approach used in the current study overcomes the aforementioned limitations by simultaneously providing feedback about a wider range of biomechanical variables (e.g., knee, trunk, hip, etc.) than previous biofeedback investigations (e.g., knee only). A potential advantage of this novel approach is its ability to simultaneously convey multiple sources of information within a single comprehensive stimulus. While presenting obvious efficiencies of concurrently training several targeted biomechanical deficiencies at once, there may be additional advantages. For instance, using a typical “one variable at a time” training approach variables may be individually trained so as to improve local performance (i.e., better performance within a single variable), while having minimal beneficial effect on overall performance. This is because the individually trained variables affect performance of other variables, and the coordination of the multiple variables as a whole must be taken into consideration. When multiple variables are trained simultaneously a user does not have to reintegrate or learn to combine individual movement variables. This inclusive nature of training multiple variables through a single stimulus may avoid the problems just described and lead to a more effective training program.

The purpose of the current study was to determine the effectiveness of a real-time biofeedback stimulus that maps to a comprehensive movement profile for reducing squatting mechanics that may contribute to ACL injury risk. To contribute to previous literature that has compared real-time biofeedback to traditional interventions, we also implemented a novel sham feedback apparatus designed to limit the amount of useful feedback information available to participants during training of squat movements. The sham feedback provided a comparable visual appearance to the real feedback stimulus; however, it provided very limited information about squat biomechanics, and as such was in principle an ineffective guide for the user to use to improve squat biomechanics. The sham thus served as a control or reference condition against which to measure the efficacy of our real-time, interactive biofeedback. We hypothesized that participants would elicit significantly better squatting performance, as indexed through a novel heat map analysis, throughout acquisition and during retention (mid and post testing) when using real-time, interactive biofeedback compared to the sham feedback stimulus.

2. Method

2.1 Participants

Twenty females participated in the study ($M_{\text{age}} = 19.7$, $SD = 1.34$ yrs; $M_{\text{height}} = 1.74$, $SD = 0.09$ m; $M_{\text{weight}} = 72.16$, $SD = 12.45$ kg). All participants were collegiate athletes recruited from three local universities. 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). Participants had no history of neurological disorders (including any neuromuscular disabilities), musculoskeletal disabilities or disorders, or balance problems. Additionally, participants were free of any recent injuries that impaired movement, the ability to stand, or perform the body-weight squats. Two participants had past knee injuries (one ACL injury and one medial collateral ligament injury); however, the dates of occurrence were not within 5 years of their participation and performance was not unusual when compared to other participants. The study was approved by the Institutional Review Board and all participants gave written informed consent prior to participation.

2.2 Materials, Apparatus, and Stimulus Design

The real-time feedback display used in the present study was designed so that objective information about multiple kinematic and kinetic variables related to ACL injury risk^{51–53} could be displayed concurrently and in real time to participants. The stimulus was designed specifically to map onto a wider range of biomechanical variables (e.g., knee, trunk, hip, etc.) than previous biofeedback investigations that were isolated to a single variable (e.g., knee only). The shape of the display was a simple, two-dimensional rectangle defined by six points (see Figure 1A). The vertical and horizontal coordinates of these points were defined as a function of five kinematic and kinetic variables previously identified as ACL-injury risk factors (for justification and references see Table 1), each having a unique effect on the feedback display (see Figure 1B-E): (1) lateral trunk flexion 21, (2) knee-to-hip joint moment of force ratio (KHM_r), (3) knee abduction moment of force (KAM) 21, (4) vertical ground reaction force ratio (vGRF), and (5) foot center of pressure (foot COP) location. The current values of the biomechanical variables were mapped via the geometric shape of the display (i.e., a rectangle), and as these variables changed dynamically throughout the participants' movements, the feedback display was updated relative to these changes and displayed to the participants in real time. The feedback shape was thus not only changing in real-time but it was also reliably tied to participants' movements.

The participants were instructed to squat so as to keep the stimulus shape as close to a perfect, symmetrical rectangle as possible. This was achieved by moving so as to produce optimum values (i.e., values associated with low ACL injury risk) of the aforementioned variables, but participants were not told that and the biomechanical variables and their optimum values were not explained to them. As the values of the variables neared or fell within optimum ranges specific to the given variable(s), a more symmetric rectangle was obtained; alternatively, the rectangle became systematically distorted by increasing amounts as the values of the variables deviated from the optimum values.

The number of squats performed by the athlete was tracked by a variable measuring knee flexion angle. A squat 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). 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 situated below the rectangle served as a counter representing the number of “completed” squats, which would change colors from grey to green once participants had completed a full squat motion (i.e., participants were standing upright after performing the squat). If participants did not complete a full squat motion, the squat was not counted.

In addition to the real-time feedback display just described, a feedback display was also developed for the sham condition. The real-time 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 2). Movements not critical to the targeted biomechanical parameters during a squat (i.e., movements occurring 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 the biomechanical variables on the stimulus shape 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). This specific type of sham feedback was utilized to facilitate similar phenomenological responses to that of the experimental stimulus without promoting movements directly associated with improvements squat biomechanics.

Participants’ movements were recorded using a 10-camera motion capture system (Raptor-E, Motion Analysis Corp., Santa Rosa, CA, USA) sampling at 240 Hz. In conjunction with the motion capture system, two embedded force platforms (BP600900, AMTI, Watertown, MA, USA) sampling at 1200 Hz were used to collect ground reaction force from each foot and were synchronized with the motion system. Using a software development kit (SDK) provided by Motion Analysis Corp., the synchronized marker trajectory and force data were accessed via a custom software program—written in C++ and designed in Microsoft Visual Studio Professional 2015 (Microsoft Corp., Redmond, WA, USA) and which also incorporated OpenGL (Khronos Group, Beaverton, OR, USA) as the graphics application interface—that was designed to calculate and map the above variables to generate the visual feedback display.

The 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 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, USA) 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, USA). The backpack provided minimal interference to natural movement as it held the equipment securely against the body and was relatively small (length $\times$ width $\times$ height: 33 $\times$ 27 $\times$ 7.6 cm).

2.3 Procedure

In order to compare the effects of the real-time and sham feedback displays, an *AB/BA* or *two-treatment crossover design* was utilized. As the name implies, half of the participants received one condition first (e.g., 'A') and another condition second (e.g., 'B'), while the other half of participants received the two identical conditions but in the opposite order. We randomly assigned participants to one of two groups: real-time biofeedback first (i.e., 'A') or sham feedback first (i.e., 'B'). First, participants completed a block of 10 squats without any feedback (pre-test). Then, participants completed four blocks of 10 squats using their assigned condition (i.e., real-time biofeedback or sham) (acquisition phase 1). Before switching to the next feedback type, a block with no feedback was administered (mid retention test) followed by four blocks of 10 squats using the opposite feedback type as used in acquisition phase 1 (acquisition phase 2). Finally, participants completed a block of 10 squats without any feedback (post retention test). In total, each participant completed 110 squats—40 training squats for each feedback type (80 total) and 10 squats during each test period (30 total; see Figure 3). Participants were permitted breaks between blocks as necessary.

Each participant was outfitted with 30 retroreflective markers, with a minimum of three tracking markers on each segment, and the backpack containing the wireless transmitter and battery pack. Markers were placed on the sacrum between the L5 and S1 vertebrae, 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 experimental preparation, all participants received identical instructions about the squat exercise and were shown an unresponsive stimulus shape that reflected the goal shape. The instructions were purposefully kept very basic as to allow for implicit discovery of how their movements related to the stimulus shape during the squat exercise; they were told only to "maintain the goal stimulus shape and size as closely as possible," as indicated by the outline of the shape's corners, and, as a secondary instruction, "to squat to sufficient depth", as indicated by the depth indicator and circle counter at the bottom of the stimulus. Participants were also asked to keep their arms crossed in front of their chest and to avoid covering any markers. A set of squats was considered complete once all ten circles' colors changed from grey to green, indicating that ten sufficiently deep squats were performed. If participants were unable to intuitively achieve the appropriate depth, they were explicitly instructed 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.

2.4 Data Reduction and Analysis

The recorded raw, three-dimensional marker positions, ground reaction forces, and center of pressure acquired from both feet were first exported from Cortex and imported into MATLAB for preprocessing. Preprocessing consisted of 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 vertical position were plotted and trimmed according to the procedure outlined in Figure 4. Only the portions of a trial 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.

In order to quantify participants' ability to control the stimulus shape, 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 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 portrayed 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 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 indicated that 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 never deviated from the goal shape and size, which meant that the relevant biomechanical parameters were achieving the desired optimal values associated with lower injury risk. These scores are transformed and presented as percentages in the following sections for ease of interpretation with higher percentages indicating better squatting performance.

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 shamfirst feedback groups were compared using an independent samples *t*-test. This step was necessary because participants required a few squat repetitions in order to explore and determine the appropriate squat depth, which may or may not have affected participants' fatigue level and subsequent squatting performance.

To assess squatting performance during the acquisition phase, each trial block's heat map scores were first averaged across each squat repetition to produce a single heat map

percentage score for each trial block. Then, to assess differences in squatting performance during training (i.e., *present* visual feedback), two separate 2 (condition; sham and real feedback) $\times$ 4 (trial block [1, 2, 3, 4]) mixed model ANOVAs with repeated measures on the last factor (i.e., trial block) were conducted for acquisition phase 1 and acquisition phase 2.

To assess learning (i.e., *absent* visual feedback), a 2 (order; sham-first and real-first feedback) $\times$ 3 (test phase; pre-test, mid-test, post-test) mixed ANOVA with repeated measure on the last factor was conducted. Bonferroni adjustments were used when appropriate and an alpha level of $p < .05$ indicating significance was selected *a priori*.

3. Results

3.1 Number of Squats Performed

There were no significant differences in the number of squats performed between the real-first feedback group ($M = 111.80$, $SD = 7.15$) and the sham-first feedback group ($M = 114.30$, $SD = 5.76$), $t(18) = 0.86$, $p = .40$, $d = 0.39$.

3.2 Acquisition Phase Squatting Performance

There were no significant differences in overall squatting performance as measured by the heat map percentage scores for condition ($F(1, 18) = 2.03$, $p = .17$, $\eta_p^2 = .10$), trial block ($F(3, 54) = 0.86$, $p = .47$, $\eta_p^2 = .05$), and a condition $\times$ trial block interaction ($F(3, 54) = 0.23$, $p = .88$, $\eta_p^2 = .01$) during acquisition phase 1. The same pattern of results held for acquisition phase 2: condition ($F(1, 18) = 1.15$, $p = .30$, $\eta_p^2 = .06$), trial block ($F(3, 54) = 1.90$, $p = .14$, $\eta_p^2 = .10$), and condition $\times$ trial block interaction ($F(3, 54) = .45$, $p = .72$, $\eta_p^2 = .02$).

Since there were no significant main effects or interactions, and in order to test if squatting performance differed while engaging with the sham and real feedback regardless of condition or block, we averaged the heat map percentage scores across the eight trial blocks (acquisition phase 1 & 2) for each condition respectively and performed a paired-samples t -test to assess differences during training per feedback type (i.e., real or sham). Performance during the real-time biofeedback trials ($M = 61.82\%$, $SD = 6.42\%$) was better than during the sham feedback trials ($M = 57.56\%$, $SD = 8.40\%$), $t(19) = 3.06$, $p = .006$, $d = 0.57$.

3.3 Learning Phase Squatting Performance

There were no significant differences in squatting performance for order, ($F(1, 18) = 0.56$, $p = .46$, $\eta_p^2 = 0.03$), test phase ($F(2, 36) = 0.19$, $p = .83$, $\eta_p^2 = .01$), or test phase $\times$ trial block interaction ($F(2, 36) = 0.43$, $p = .66$, $\eta_p^2 = .02$) during the three test phases that assessed learning. Thus, squatting performance only improved when the real feedback shape was present during acquisition and not when the real feedback was absent for learning assessment.

4. Discussion

The purpose of this study was to determine the effectiveness of a real-time biofeedback system compared to a sham feedback system for reducing squatting mechanics that may

contribute to ACL injury risk. Squatting performance, as measured through heat map analysis, was significantly better when participants interacted with the real-time biofeedback system compared to the sham. This is congruent with previous literature supporting the use of real-time biofeedback for ACL injury prevention^{45, 49, 50}. Our study makes three distinct innovations. First, we employed an interactive, real-time stimulus that implicitly guided performance while promoting external perceptual control. Second, the developed real time biofeedback system mapped multiple biomechanical variables associated with ACL injury risk onto a single stimulus. Unlike previous systems that are isolated to one factor such as knee abduction/adduction⁴⁵, our system uniquely presents athletes with a global biomechanical profile associated with ACL injury risk that includes lateral trunk flexion, knee-to-hip joint moment of force ratio, knee abduction moment of force, foot COP location, and vertical ground reaction force. Third, our inclusion of the sham feedback demonstrated that interacting with the stimulus alone was not sufficient to improve performance, but an accurate mapping from kinematics to the feedback is necessary for improved performance.

While these data provide strong initial findings for the efficacy of our real-time biofeedback system, our failure to find learning effects as measured during the mid and post retention sessions requires cautious interpretation. Motor learning is defined as relatively permanent changes in motor skill performance as a function of practice or experience⁵⁴. Non-significant differences between the groups in the absence of the stimulus during both retention tests suggests that a single session with real-time biofeedback was not effective for eliciting stable motor skill changes. There are multiple possible reasons for this finding. Most importantly, and one limitation of this study, was the brief practice period—only 40 total squat repetitions were performed in a single session lasting only about 10 minutes for each participant. Implementing our interactive feedback system over multiple training sessions (i.e., over the course of weeks or months), accompanied by a progression of greater performance criteria, increased exercise difficulty, or the inclusion of more challenging exercises, may induce more stable and permanent changes in motor skill. Relatedly, a second limitation is that the practice schedule used in the current study had minimal breaks (i.e., massed practice) which is effective for acquisition, but is typically less successful for learning than when breaks are administered (i.e., distributed practice)^{55, 56}. Third, although we used a crossover design to increase statistical power, our sample size ($n=20$) could nevertheless be considered small. Finally, our inability to determine how changes in squat mechanics transferred to more dynamic tasks, such as the drop vertical jump, require cautious interpretation in our real-time biofeedback's ability to reduce ACL injury rates.

The observed performance improvements exhibited in the presence of the stimulus do show promise for its utilization in future ACL injury prevention and rehabilitation applications. The immediate gains seen in squat performance demonstrate that the stimulus was effective and support the use of real-time biofeedback integration with kinematics and kinetics⁴⁴. Our design and implementation of the current stimuli, while overcoming the aforementioned technical difficulties, also demonstrate that it is feasible to map multiple variables associated with ACL injury risk in real-time. Modifying the amount of rest and feedback frequency are relatively simple changes that can be made to potentially improve learning and supports previous recommendations related to ACL injury risk reduction⁵⁷.

The results of this study suggest that ACL injury prevention and rehabilitation programs could be improved by integrating a real-time, interactive biofeedback stimulus. Prevention programs could use this stimulus to improve performance of prophylactic exercises, which may lead to decreased ACL injury risk. Likewise, following an ACL injury, our approach may be particularly beneficial as a rehabilitation tool for those in the recovery stages. The integration of new factors associated with ACL injury risk suggests that it may also be possible to design similar real-time biofeedback systems to target other movement dysfunction. For example, previous investigations using real-time biofeedback for gait retraining may benefit by integrating multiple factors to supplement previously seen motor skill improvements on a single variable.

5. Conclusion

In conclusion, this study demonstrates the efficacy of novel real-time, interactive biofeedback system for improving squat performance. In a single testing session we demonstrated an immediate change in biomechanics associated with ACL injury risk when participants' movements were guided by the interactive stimulus. Further, it appears that real-time biofeedback that is not properly mapped on to biomechanics (i.e., our sham condition) is less effective, highlighting the importance of accurate and appropriate mapping of key variables. Future research that utilizes longer testing sessions, more rest, and a more personalized dosing schedule may further the benefits of our real-time biofeedback system to elicit permanent biomechanical changes.

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Figure 1.

The stimulus used in the experiment. During the trials the stimulus' shape started as a rectangle (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 KHM, KAM, foot COP, 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 during the upward movement.

Figure 2.

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 3.

The crossover design used. Each rectangle represents a block that consisted of 10 squats. The darkest rectangles represent the testing time in which no visual feedback was administered. The two rows of rectangles indicate the type of feedback used for training—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.

Figure 4.

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.

Table 1:

Justification, Optimum Value, and the Effect on the Stimulus for the Included Biomechanical Variables.

Variable	Stimulus Effect	Justification	Optimum Value	References
Lateral Trunk Flexion	Figure 1B	Lateral trunk displacement predicted ACL injuries with high sensitivity and specificity in females and flexion was also present during the time of ACL injury.	0°	58–60
Knee-to-hip joint extensor moment of force ratio	Figure 1C	Quadriceps-dominant recruitment during dynamic movement is a risk factor for lower extremity injuries.	1	53, 61
Knee abduction moment of force	Figure 1D	Valgus knee collapse and subsequent increased knee abduction moment occurs more frequently in ACL injury risk prone athletes.	0 Nm	62, 63
Vertical ground reaction force ratio	Figure 1E	Asymmetry in ground reaction force indicates preference for and the potential for abnormal joint loading on one limb.	1	62
Foot center of pressure location	Figure 1F	COP should be located towards the back of the foot (heel) as shear forces are increased as the knee moves past the toes (during the downward phase of the squat). Video evidence also shows, at the time of injury, foot positions extending past the body's COM	COP within the back 70% of foot length	58, 63