Motor learning in ACL injury prevention

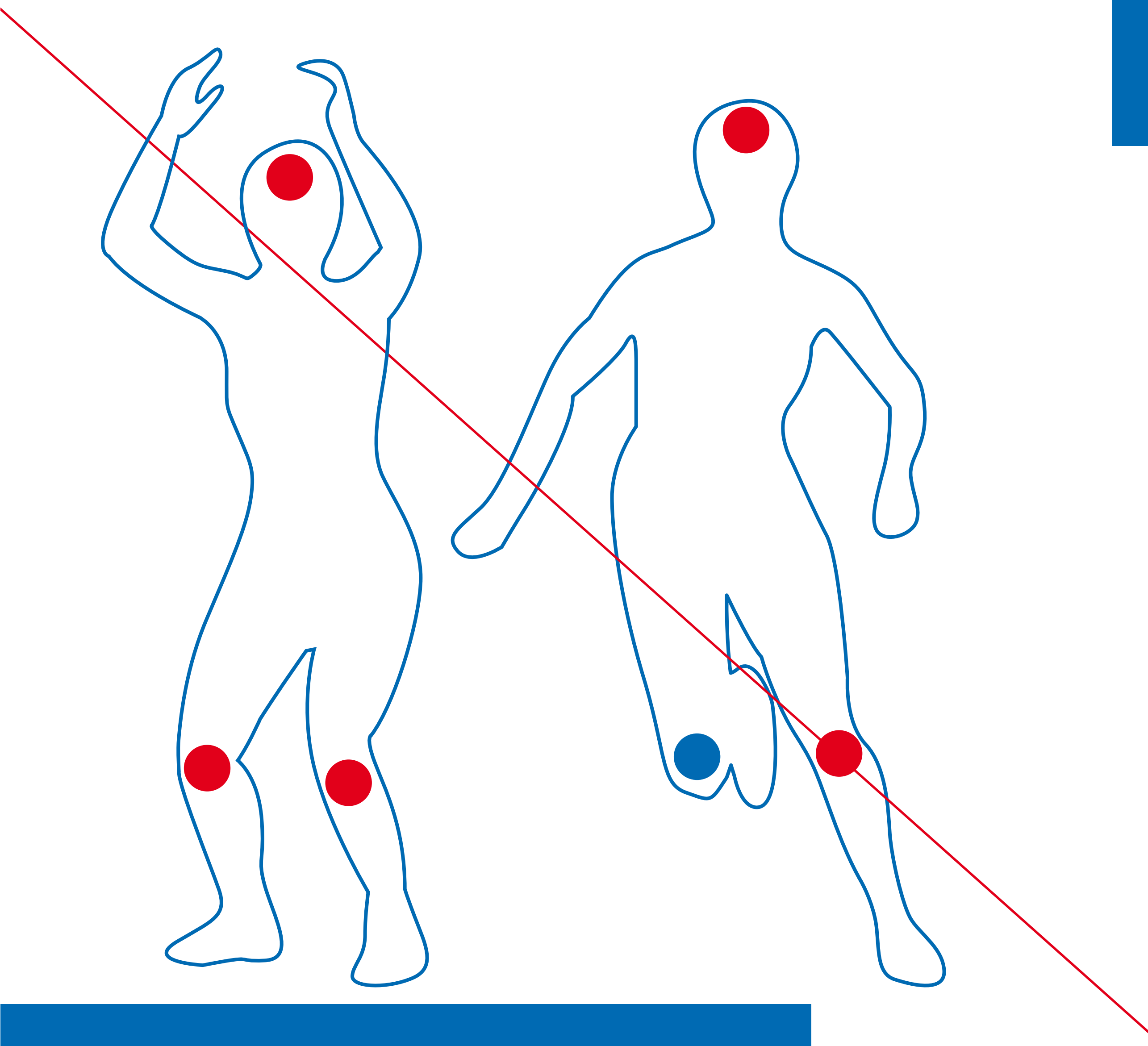
Benjaminse, Anne

CHAPTER 3

OPTIMIZATION OF THE ANTERIOR CRUCIATE LIGAMENT INJURY PREVENTION PARADIGM: NOVEL FEEDBACK TECHNIQUES TO ENHANCE MOTOR LEARNING AND REDUCE INJURY RISK

ANNE BENJAMINSE, ALLI GOKELER, ARIEL V. DOWLING, AVERY FAIGENBAUM, KEVIN R. FORD, TIMOTHY E. HEWETT, JAMES A. ONATE, BERT OTTEN, GREGORY D. MYER

J ORTHOP SPORTS PHYS THER. 2015;45(3):170-182



Abstract

Primary anterior cruciate ligament (ACL) injury prevention programs effectively reduce ACL injury risk in the short term. Despite these programs, ACL injury incidence is still high, making it imperative to continue to improve current prevention strategies. A potential limitation of current ACL injury prevention training may be a deficit in the transfer of conscious, optimal movement strategies rehearsed during training sessions to automatic movements required for athletic activities and unanticipated events on the field. Instructional strategies with an internal focus of attention have traditionally been utilized, but may not be optimal for the acquisition of the control of complex motor skills required for sports. Conversely, external-focus instructional strategies may enhance skill acquisition more efficiently and increase the transfer of improved motor skills to sports activities. The current article will present insights gained from the motor-learning domain that may enhance neuromuscular training programs via improved skill development and increased retention and transfer to sports activities, which may reduce ACL injury incidence in the long term.

Key words: ACL, focus of attention, knee

Introduction

Primary anterior cruciate ligament (ACL) injury prevention programs have been effective in the short term,[17,34,44,46,62] but lack effectiveness in the long term. One cause could be the difficulty of retention and transfer of learned motor skills, such as precise alignment of the hip, knee, and ankle emphasized in proper landing positions. Learning new or improving motor skills can be conducted with the use of an internal focus of attention (focus on the movements themselves) or with an external focus of attention (focus on the movement effect),[100] the latter being more suitable for acquisition of control of complex motor skills required for sport reintegration.[10] Gaining support from the training staff (i.e., coaches, athletic trainers, strength and conditioning specialists, and physical therapists) to implement and maintain injury prevention programs is imperative.[40,62,63,88,89] We therefore strive to develop more effective and efficient[50] training programs and present strategies to maintain the motivation of ACL injury prevention for athletes and coaches alike.[85] The purpose of this article is to present insights that may help to optimize current ACL injury prevention programs via increased retention and transfer of safe motor skills and to ultimately reduce the ACL injury incidence.

As outlined in this article, prevention training that includes instructions with an external focus of attention may increase compliance, as such training requires only periodic maintenance (is less time consuming), enhances skill acquisition more efficiently, and increases the transfer of improved motor skills to sport. A combination of more effective and efficient feedback techniques for ACL injury prevention training would be less attention demanding, improve skill retention and transfer to sport, and optimize program efficiency. The long-term outcomes of ACL injury prevention programs could be improved by incorporating instructions with an external focus or a combination of external- and internal- focus techniques.[10]

In the current article, we present insights gained from the motor-learning domain that have the potential to improve motor skill performance and may facilitate long-lasting prophylactic effects. Clinically applicable techniques that may be used to optimize adherence and training outcomes are presented, following a brief discussion of motor learning. In addition, we propose feedback training methods that enhance the ability of a coach or clinician to identify, evaluate, and target neuromuscular deficits that increase an athlete's risk of injury. Exercises presented in the tables and figures focus on technique modification to decrease biomechanical risk factors for an ACL injury. The type, frequency, and timing of feedback examples provided in the tables are all related to the advantages of an externally directed focus of attention. Training staff can vary these exercises and use sport-specific situations during the prevention program. As such, sport-specific situations will optimize the transfer to real game situations (eg., catching a ball).[22]

Motor learning

Motor learning is the relatively permanent acquisition of motor skills.[80] Though motor skills vary widely in type and complexity, the learning process that individuals utilize to acquire these skills is similar. Fitts and Posner proposed 3 stages of learning, cognitive, associative, and autonomous.[28] The cognitive stage is characterized by the learner's conscious attempt to determine what exactly needs to be done step-by-step. This requires considerable attentional capacity. The associative phase starts when one has acquired the basic movement pattern. The movement outcome is more reliable and the movements are more consistent, automatic, and economical. Once this is accomplished, more attention can be directed to other aspects of performance. After extensive practice, the performer reaches the autonomous phase, which is characterized by fluent and seemingly effortless motions. Movements are accurate, very consistent, and efficiently produced. The skill is performed largely automatically at this stage, and movement execution requires little or no attention.[28]

It is commonly believed that direction of the athlete's attention to step-by-step components of a skill is necessary during the early stages of acquisition.[9] The contention is that cognitive control (explicit knowledge) is a necessary phase that athletes must go through. It is in this stage that the athlete practices a new skill over and over to reach the autonomous stage or, in other words, automatic movement control. However, this view is not well supported in the literature.[26] Repetition of the same movement patterns may be a suboptimal method compared to utilizing pattern variations,[20] which can stimulate the brain to find optimal solutions to unanticipated events more effectively.

Focus of attention

Internal versus external

Instructions or feedback provided by practitioners during practice sessions is often directed to body movements (eg, "keep your knees over your toes", "land with your knees flexed", or "land with your feet shoulder-width apart").[60,72] In the motor learning domain this type of attentional focus is termed internal focus.[97] Conversely, an external focus of attention is induced when an athlete's attention is directed towards the outcome or effects of the movement (eg, ‘‘imagine sitting down on a chair when landing’).[97] A simple change in the wording of instructions or feedback can have dramatic effects on motor performance and learning, but can also be employed with dyad training, (real-time) visual or sensory feedback, as is outlined in the section titled “Novel techniques to enhance motor learning”.

Over the past 15 years, research in motor learning has demonstrated beneficial effects of instructions that induce an external focus of attention.[93] First, an external focus of attention accelerates the learning process – or shortens the first stages of learning – by facilitation of movement automaticity (‘constrained action hypothesis’).[101] Second, an external focus of attention enhances the production of effective and efficient movement patterns.[95,98,104] Neuroimaging studies show that the premotor cortex is active even when no movements are generated.[86] The premotor cortex is known for its role in preparation and execution of movements and conscious attention to memorized movements. Therefore, attention to memorized movements may reduce the brain resources for movement control. This means that when a skill is learned with an external focus, more resources are available to pay attention to other game factors (i.e. other athletes, field conditions, and position of the ball). Retention of newly learned motor skills may be enhanced with an external focus (eg. better balance,[43,84] reduced peak vertical ground reaction force (vGRF), and increased knee angular displacement flexion angles during landing[67]) and provides superior resilience against fatigue[48,73] and stress.[31,49,68]

A constant focus on the (same) performance during each training session may also reduce the athlete’s motivation dur- ing the course of the program.[53] Secondly, using instructions with an internal focus may hamper the transfer of new skills to more automatic performance during sports.[8] Internal-focus feedback induces conscious control of one’s movements, which may interfere with the normal, automatic motor control processes and lead to a breakdown in the natural coordination of the movement.[32,56] In addition, learning tasks with an internal focus appears to make an individual more vulnerable to “choking under pressure” due to psychological and physiological stress.[48,73]

Training schedule

To enhance the effectiveness of methods of external focus of attention in ACL injury prevention programs, it is important to consider the feedback schedule. The frequency of feedback is an important consideration. A high frequency of feedback that promotes an external focus has been shown to be superior to a low feedback frequency in guiding athletes to the correct movement-pattern technique.[94] This is in contrast to the feedback that induces an internal focus, in which a high frequency was shown to be detrimental to learning.

Self controlled learning, in terms of an athlete's choice to request feedback, is a powerful tool in motor learning.[101] There is evidence that giving the athlete some control over a practice session (i.e., an active role in deciding when to receive feedback) may enhance motor skill learning in comparison with prescribed training schedules.[3,18,20,101] Interestingly, athletes often have a relatively strong sense of how well they perform.[19] This so-called "self-controlled practice" has generally been assumed to initiate a more active involvement of the athlete, enhancing motivation and increasing the effort invested in practice.[4,16,19,39]

Clinical examples

Most of the existing ACL injury prevention programs employ several different training components, ranging from plyometrics to balance training to strength training. As such, we have a limited appreciation of how these components act individually and in concert, which may limit both the efficiency and efficacy of these interventions.[2] The clinical examples in this section are based on cumulative evidence of 2 key components that make up effective ACL injury prevention programs,[61] namely balance and plyometrics. Additional examples for review and comparison are provided in Table 1 and Figures 1 through 4. These examples illustrate how the focus of attention can be altered from internal to external by a simple change in instructions. This simple technique does not need specialized equipment and can be applied to multiple athletes at the same time. Simple instructions are best, because complex feedback can hamper motor learning.[47]

Table 1. Comparison of verbal instructions with internal and external focus

Type of exercise	Instruction with internal focus	Instruction with external focus
Single leg stance on unstable platform[43,81] (Figure 1)	Keep your balance by stabilizing your body	Keep the bar horizontal
Single leg squat (Figure 2)	Stand on 1 leg and slowly bend your knee while keeping your knee over your foot	Stand on 1 leg and reach slowly towards the cone with your knee while bending your knee
Single leg hop for distance[73] (Figure 3)	Jump as far as you can, while jumping, focus on extending your knees as rapidly as possible	Jump as far as you can, while jumping, focus on jumping as close to the cone as possible
(Walking) lunges (Figure 4)	Lunge slowly at an even pace. Bend your hips and knees until your leading knee is flexed to 90°. Keep your front knee on top of your foot and prevent buckling inward with this knee.	Lunge slowly at an even pace while pretending like you are having a plank on your back point your knee towards an imagery point in front of you / reach slowly towards the cone
Double leg squat	Bend your knees, while keeping your knees over your feet	While bending your knees, reach towards the cones with your hands and point your knees towards the cones Pretend that you are going to sit on a chair while keeping a ball between your knees
Double leg drop jump[45]	Jump down from a 30cm box, land with your feet at shoulder width and bend your knees while keeping knees over toes	Jump down from a 30cm box, land on the markers on the floor and put your toes and knees towards the cones
Vertical jump with Vertec[93,94,101]	Jump as high as you can, while concentrating on the tips of your fingers, reaching as high as possible during the jumps	Jump as high as you can, while concentrating on the rungs of the Vertec/ball, reaching as high as possible during the jumps. Jump as high as you can, push off against the ground as forcefully as possible and pretend like you have to hold a ball between your knees
Counter movement jump[45]	Jump as high as you can, reach your fingers as high as you can	Jump as high as you can, touch the hanging ball
Side-step cutting maneuver	Run 4 to 5 steps straight ahead, while changing direction and making the cut, move your trunk forward, bend your knee, and keep your knee over your toe	Run 4 to 5 steps straight ahead, while changing direction and making the cut, try to make a fluent motion and point your face and toes toward the direction you are going

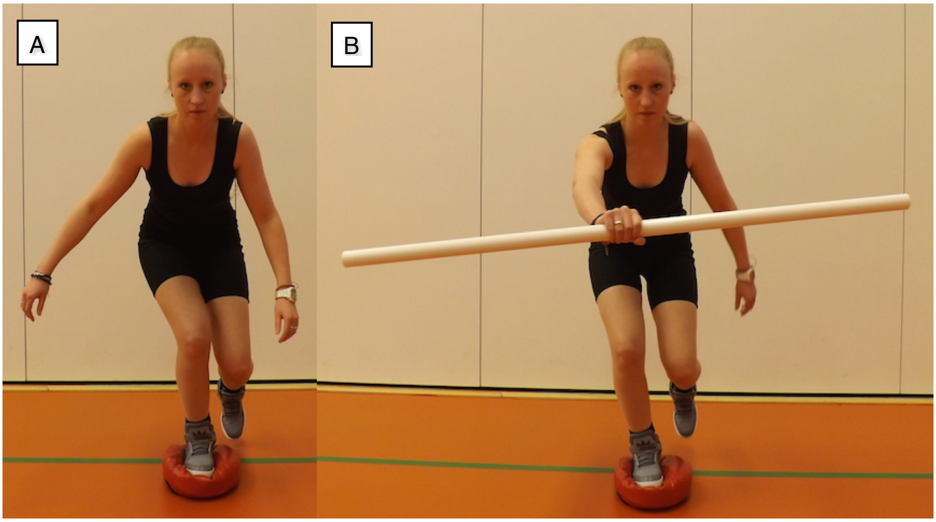


Figure 1. Comparison of instruction to reduce knee valgus motion during a balance task using (A) an internal focus (“keep your balance by stabilizing your body”) and (B) an external focus (“keep the bar horizontal”).

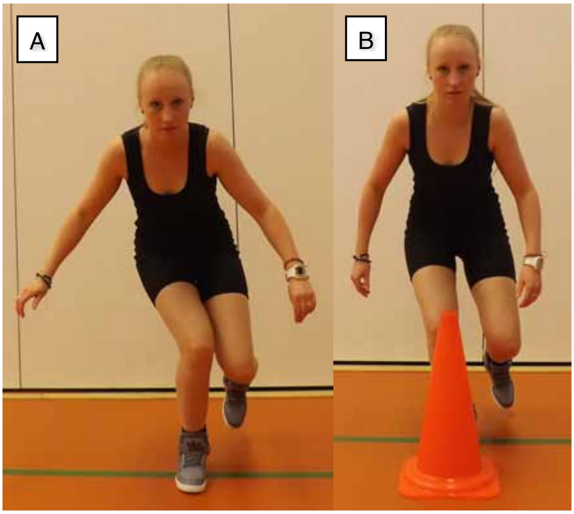


Figure 2. Comparison of instruction to reduce knee valgus motion during a single leg squat with (A) an internal focus (“keep your knee over your foot.”) and (B) an external focus (“reach towards the cone with your knee.”).

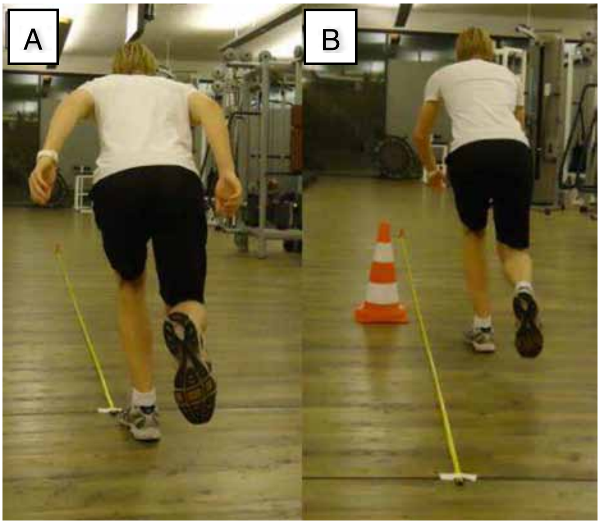


Figure 3. Comparison of instruction to reduce knee valgus and increase knee and hip flexion motion during a single leg hop for distance with (A) an internal focus ("jump as far as you can, while jumping, focus on extending your knees as rapidly as possible.") and (B) an external focus ("jump as far as you can, while jumping, focus on jumping as close to the cone as possible.").

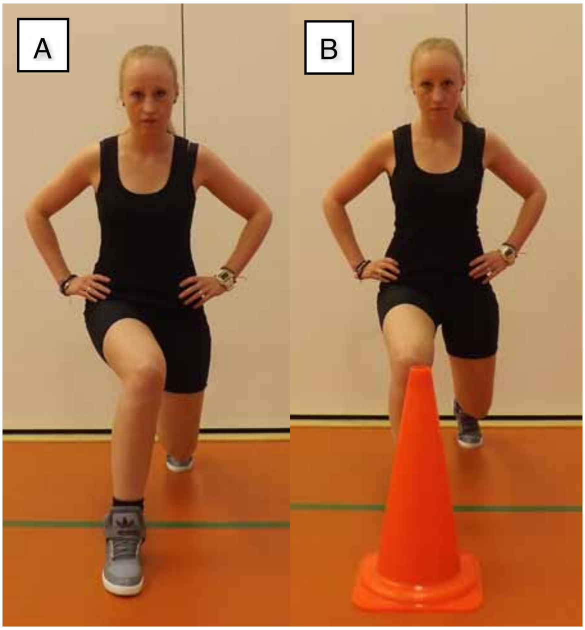


Figure 4. Comparison of instruction to reduce knee valgus motion during lunge with (A) an internal focus ("keep your knee over your foot.") and (B) an external focus ("reach towards the cone with your knee.").

Balance

Balance has an important role in ACL injury prevention. For example, increased balance is important for handling impact forces.[59] Recent evidence has shown that center of pressure control could be improved with an external focus of attention, such as instructing an athlete standing on a balance disc to keep a bar horizontal instead of keeping the disc horizontal.[99]

Plyometrics

Two recent studies found that an external focus of attention resulted in higher jump-and-reach heights, more force production, and more center-of-mass displacements (more knee flexion) compared to using an internal focus of attention.[45,95] The common element within these external instructions was to focus on an external object (a Vertec vertical jump trainer (JUMPUSA, Sunnyvale, CA) or a hanging ball) to shift the attention away from the body, whereas the internal instructions were directed to the body (concentrating on fingers reaching as high as possible).

In summary, athletes should experience feelings of success to optimize the learning process of new motor skills, which can be reinforced with positive feedback after successful trials. It is theorized that athletes have a preference to receive positive feedback, which supports the motivational influences on motor learning. Motor learning with an external focus has proven to be effective in the establishment of a certain movement goal or technique result (eg, free throw, tennis serve, or golf swing).[81,100] However, in ACL injury prevention training, learning safe movement patterns is itself the goal. Recent literature in jump and landing performance shows that movement form can be improved when using an external focus of attention, illustrated by greater knee flexion angles,[45,66] more center-of-mass displacement,[103] lower peak vGRF,[55,67,92] and improved neuromuscular coordination.[96] These findings are promising, as improved landing technique and increased jump performance yield an optimal outcome, reducing ACL injury risk without a reduction in performance.[11] Recent research in patients post–ACL reconstruction showed that an external-focus group had significantly larger knee flexion angles at initial contact, peak knee flexion, total range of motion, and time to peak knee flexion for the injured legs compared to a group using an internal focus of attention, which subsequently may help to reduce second ACL injury risk.[29] This is a research area that needs to be explored further to better define program variables, including the content, frequency, and timing of feed- back, to improve the effectiveness of ACL injury prevention protocols.

Novel techniques to enhance motor learning

In the following sections examples are given of how dyad training, video feedback and video simulation (video overlay of movement patterns), real-time visual feedback, and inertial sensor-based real-time feedback can be applied in a training situation.

Dyad training

Providing the athlete with a visual example (dyad), such as a peer athlete performing the task with desired movement patterns can enhance the effectiveness of feedback and training methods.[56] This is important, as coaches may not be willing to allocate excessive time to prevention training if direct gains in performance are not achieved or if it detracts from skill and strategy components of practice. In particular, a combination of observation and practice can result in more effective and cumulative learning than either type alone.[82,84] For example, balance on a stabilometer was measured in healthy university students by keeping the platform horizontal for as long as possible during each 90-second trial.[84] Proficiency was expressed by the root-mean-square error, with the 0° position (platform in the horizontal position) as the criterion. The results indicated that alternating between practice forms (dyad alternating group: alternating between physical, observational, and dialog practice on each trial) with a partner was more effective in retention and transfer tests than individual practice. It is intriguing to note that the benefits of dyad training transfer to situations in which participants have to perform the retention trials individually. For example, after a 7-week balance training program, healthy participants demonstrated decreased vGRF during landing from a single-leg jump.[59] Decreasing the impact forces might help in the reduction of ACL injury risk, as the magnitude and direction of the vGRF are key components to knee load associated with ACL injury.[35] Practice in dyads can have additional learning advantages due to social interaction and competition, which can enhance motivation.[30] Practicing with another person in an interactive way may encourage athletes to set goals at a higher level of difficulty, as they will "compete" with a peer.[42,91] For example, an athlete tries to match a deeper knee flexion subconsciously during a single-leg squat as performed by the other athlete. Finally, training with a partner and sharing learning strategies might increase the athlete's feeling of responsibility for involvement in the learning and treatment process.[56]

Clinical examples of dyad training

An effective way to practice dyad training with peers is to alternate roles during an exercise (Tables 2 and 3).[84] The examples given are targeted to enhance movement forms often related to ACL injury.[41,65] Changing the role of observer and performer, as indicated in Table 2, will enhance retention and transfer,[82,84] which are key elements for effective ACL injury prevention strategies.[10]

Table 2. Possible instruction and feedback methods during dyad training

Instructions and feedback			
Type of exercise	**Instruction**	**Timing**	**Feedback frequency**
Single-leg hops with 2-feet landings	In this pair-exercise, one of you is performing single-leg hopping forwards and from side to side and ending in landing on 2 feet. The other player is observing the performance of the teammate. This will be followed by changing roles.	Real time (observing) with pauses to change	After every trial
Running and plant	In this pair-exercise, one of you is performing the running and plant exercise while the other is observing the performance of the teammate. This will be followed by changing roles.	Real time (observing) with pauses to change	After every trial

Table 3. Progression of dyad training exercises

Type of Exercise	**Phase 1**		**Phase 2**		**Phase 3**		**Phase 4**		**Phase 5**	
	Sets	**Reps**	**Sets**	**Reps**	**Sets**	**Reps**	**Sets**	**Reps**	**Sets**	**Reps**
	2	**6**	**2**	**6**	**2**	**3**	**2**	**3**	**1**	**3**
Single-leg hops with 2-feet landings	4 sets of feedback		2 sets of feedback		2 sets of feedback		2 sets of feedback		1 set of feedback	
Running and plant	4 sets of feedback		2 sets of feedback		2 sets of feedback		2 sets of feedback		1 set of feedback	

Video feedback

Observational learning is an effective way to enhance motor skill learning.[52] With observational learning, as in video feedback, imitation plays an important role. Imitation, (copying body movements that are observed)[14] can activate the mirror neurons which in turn may automatically map observed movements onto a motor program.[15,38,57] Mirror neurons are visuomotor neurons that fire when an action is performed and when a similar or identical action is passively observed.[78] Therefore, an important functional aspect of mirror neurons is their potential to link visual input with motor output.

Verbal and visual instructions and feedback have been used with the goal to modify movement technique.[66,67,74] Verbal and visual feedback are used in an effort to reduce landing forces and enhance movement patterns. Both verbal and self-video feedback were tested during a jump-landing task in which participants were instructed to stand directly behind the force plates and jump as high as they could, touching a Vertec vertical jump trainer with their dominant hand.[67] The group that received both verbal and self-video feedback significantly reduced their peak vGRF compared to the sensory (instructed to self-analyze jumps using sensory (internal) experience) and control (no internal or external feedback) groups.

Clinical examples of video feedback

The use of video feedback improves lower extremity dynamics during jump-landing activities and appears to be an easy and effective tool for use in almost any clinical setting with widely available high-definition camcorders,[25,66,70] or applications for cell phones or tablets (eg, Ubersense, Dartfish, Coach's Eye, or BaM Video Delay). Video feedback can be used individually to target each individual needs or a group of athletes. For example, a video of one athlete on the team who demonstrates good performance of a drop jump after catching a basketball would be shown to all guards of the team as an example of "expert video," such that the athlete captured would see a video of himself as the target performance, and the other athletes would see a video of a model (their teammate) as the target performance. The clinical examples of video feedback are presented in Tables 4 and 5.

Table 4. Possible instruction and feedback methods for video feedback

Instructions and feedback			
Type of exercise	**Instruction**	**Timing**	**Feedback frequency**
Jump-landing task with Jump-Ball or Vertec instrument	Together we will review a checklist describing your motion and compare the expert model landings with yours. You will be allowed to discover the correct movement patterns and decide how yours relates to the one of the expert. Together we will discuss how to improve your movement pattern performance.	Post movement	After every 3 trials

Table 5. Progression of exercises with video feedback

Type of Exercise	**Phase 1**		**Phase 2**		**Phase 3**		**Phase 4**		**Phase 5**	
	Sets	**Reps**	**Sets**	**Reps**	**Sets**	**Reps**	**Sets**	**Reps**	**Sets**	**Reps**
	2	**6**	**2**	**6**	**2**	**3**	**2**	**3**	**1**	**3**
Jump-landing task with Jump-Ball or Vertec instrument	4 sets of feedback		4 sets of feedback		2 sets of feedback		2 sets of feedback		1 set of feedback	

Visual simulation-video overlay of movement pattern

Game-assisted motor-learning applications have great potential to optimize motor learning.[6] Video feedback can be used for improvement of certain sport specific exercises. When learning models are shown using a video-based tool during practice, athletes can exercise at different levels of difficulty to enhance their motor skills. Observation of an unskilled (learning) model, as well as observing oneself, can be effective.[75] For a model to be effective, the model does not have to be an expert performer; the observation of a lower-skilled athlete can have a beneficial effect on learning.[33,51] McCullagh and Meyer[51] showed that viewing either a correct model or learning model (a model with sub-optimal technique) was equally effective in learning correct form in a double legged squat. Observation of a skilled model may facilitate the development of a correct movement representation; however, observation of another athlete with the same skill level may help athletes to better identify movement deficit and to develop strategies to correct their own errors. One theoretical approach to support this contention is that learning is a problem-solving process; the more an individual is involved in visual evaluation of his or her own (or somebody else's) performance, the greater the learning value.[1,83] A software package for motor learning by comparative visualization (VizMo) has been developed (Figure 5A) and is currently being utilized as a research tool. For a given exercise, a learning model matching the body dimensions of the athlete is shown, as well as the athlete's body contour. The contour of the model (i.e., the goal pattern) works like a target for the athlete by instructing the athlete to replicate the model's movement as closely as possible. A "realistic" feeling is created and whole-body awareness is stimulated (embodied cognition). A score in terms of percentage overlap is shown to the athletes, which allows them to compare their performance with the performance of the model. The premise is that mirror neurons are crucial in imitation and observational learning.[77-79] The most important difference between VizMo and a Wii Balance Board (Nintendo Co, Ltd, Kyoto, Japan) or an Xbox Kinect (Microsoft Corporation, Redmond, WA) is the overlay method, which makes it possible for athletes to compare their performance, in real time, with that of an anthropometric matched model. The innovative feature is that athletes receive individual feedback (depending on their own overlay with the model), and, to the authors' knowledge, this is the first tool to apply this concept. Preliminary research shows promising results such as a softer landing technique in a VizMo group compared to a control group. However future research would need to further define and improve the clinical utility of this metric.

Clinical examples of visual simulation-video overlay of movement pattern

For each level of exercise, a learning model (with 3 different levels, ranging from fair to good to excellent) is shown to the athlete. Knowledge of results is presented by showing the contour of the model (goal pattern) as well as the contour of the athlete in an overlay video (Figures 5A and 6). The model as well as the athlete are shown in the same perspective (from the back). While looking at the screen, the athlete "steps into" the template of the model and is instructed to reproduce the goal movement pattern as accurately as possible to improve the percentage of overlap on subsequent trials.[13] The goal for the athlete is to achieve 100% overlap with the movements of the model. This program can be part of regular training (Figure 5B), with only a laptop and camera needed. Athletes practice for 2 weeks per level, and, based on evaluation of the learning curve (i.e., percentage overlap) athletes can move on to the next level. Examples of exercises are provided in Table 6 and 7.

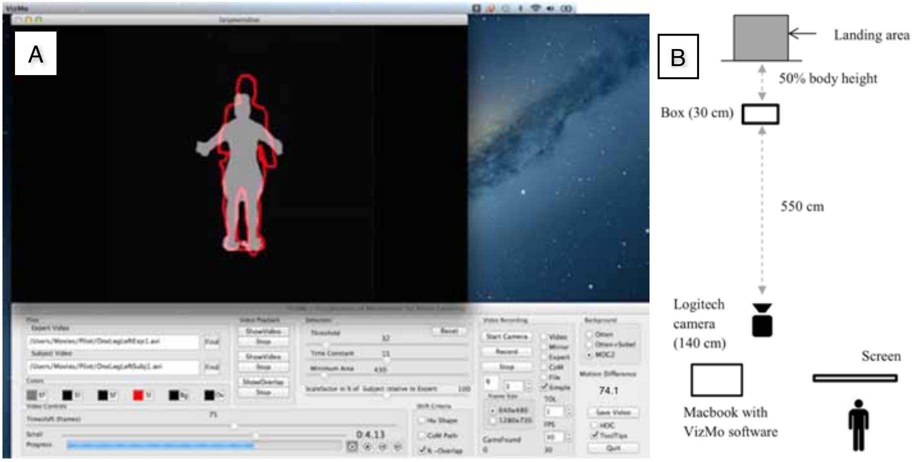


Figure 5. Custom-developed software package for the visualization of movements for motor learning (VizMo). A close-up of feedback of landing after a double legged drop vertical jump is shown in this figure. (A) The athlete views the video overlay of himself or herself and the model from the back. (B) The actual setup in the lab during a training session of the single-leg hop.

Figure 6. Screen shot from video overlay of video taken with VizMo from single leg squat (Phase 1) (A) and double legged jump landing rebound task (Phase 2) (B). White contour is the model. Gray figure is the actual performance of the athlete. Athlete sees him-/herself from posterior and is instructed to maximize the overlap with the model.

Table 6. Instruction and feedback method for visual simulation-video overlay

Instructions and feedback			
Type of exercise	**Instruction**	**Timing**	**Feedback frequency**
For all 5 exercises (Table 8)	Starting with this practice session you will see a model performing the exercise. After practicing this movement, you will see a video-overlay of the goal movement pattern performed by the model and your actual pattern of movement. Try to increase this percentage by maximizing the overlap (Figure 5).	Post movement	Minimum of 5 times per set, when athlete requests feedback[3,20,74]

Table 7. Progression of exercises with visual simulation-video overlay

Phase 1		**Phase 2**		**Phase 3**		**Phase 4**		**Phase 5**	
Sets	**Reps**	**Sets**	**Reps**	**Sets**	**Reps**	**Sets**	**Reps**	**Sets**	**Reps**
3	**10**	**3**	**10**	**3**	**10**	**3**	**10**	**3**	**10**
Lunge or single leg squat (Figure 6A)		Double leg jump landing rebound task (Figure 6B)		Single leg hop		Side-cut		Side-cut + shot + followed by landing on two legs	

Real-time visual feedback

Real-time feedback has a positive effect on task performance and influences motor memory, allowing for the successful performance of subsequent trials.[5,69] Recent studies reinforce the concept of providing real-time feedback.[7,21,64] A 3-D motion-analysis system was utilized to provide real-time feedback during gait to modify kinematic and kinetic factors related to different types of knee pathology.[7,64] As it is widely available and inexpensive, real-time visual feedback can be simply employed by the training staff through the use of a Wii Balance Board or Microsoft Xbox Kinect with customized software.[54,90] Studies show improved balance, symmetrical weight distribution, and enjoyment when using these interactive gaming tools, in both healthy athletes as well as those rehabilitating from lower-limb injuries.[54,87,90] More importantly, they can be used to heighten athletes' interest and compliance and can possibly be used as a part of a home exercise program.[12] Given these results, we assume that the display of real-time 3-D motion analysis is an effective method to improve the success of interventions aimed at prevention of ACL injuries.

Clinical examples of real time visual feedback

Real-time visual feedback techniques can be used to reduce high knee valgus moments, which have been shown to be a risk factor for ACL injury.[35] The novel training techniques (Table 8) with feedback added consist of progressive increases in the intensity of the exercises while decreasing the frequency of the external feedback (Table 9) to enhance overall motor skill learning.[5,69] The specific feedback is displayed in real time on a large display positioned in front of the athlete, using software from C-Motion, Inc (Visual3D; Germantown, MD) (Figure 7). The athletes see themselves in the same perspective (from the back) and only have to “step into” their skeleton avatar on the screen. Knee valgus moment or angle is displayed in real time for selected exercises (Figure 8). To simplify the cognitive demand to process the real-time feedback, knee valgus moment and posture are displayed in bar-chart format, with a range relative to a “safe” torque or posture. Feedback is provided in real time for the slower type of exercises, whereas feedback is provided immediately after the faster type of exercises (Table 8). The postmovement feedback of dynamic movement is presented, similar to slower movement data as described earlier; however, the focus is transitioned to review the completed performance of the entire exercise sequence over time.

Table 8. Instruction and feedback methods for real time visual feedback

Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Slower Technique				
Double leg squat	Double leg squat arms front	Double leg squat arms chest	Double leg squat arms up	Double leg squat deep
Step hold	Jump single leg hold	Hop hold	Hop hop hold	Crossover hop hop hold
Front lunge	Step lunge	Cross-over step lunge	Cross-over step lunge swivel	Cross-over step lunge double swivel
Faster Technique				
Lateral jump and hold	Lateral jumps	Lateral hop and hold	Lateral hops	X-hops
Lunge jumps	Scissor jumps	Lunge jumps swivel	Scissor jumps swivel	Scissor jumps double swivel
Single tuck jump	Double tuck jump	Repeated tuck jumps	Side to side barrier tuck jumps	Side to side reaction barrier tuck jumps

Table 9. Progression of exercises with real time visual feedback. Exercises modified from Myer et al.[58]

Feedback			
Type of exercise	**Instruction**	**Timing**	**Feedback frequency**
Slower Technique			
Double leg squat	Perform deep squat with thighs parallel to the ground (Figure 8). Observe the skeleton and bar chart feedback and keep the signal within the goal region.	Real time feedback during each trial	Progressively decreased throughout training
Step hold	Perform a single leg step and balance on the leg with deep knee flexion. Observe the skeleton and bar chart feedback and keep the signal within the goal region.	Real time feedback during each trial	Progressively decreased throughout training

Feedback			
Type of exercise	**Instruction**	**Timing**	**Feedback frequency**
Front lunge	Perform a front lunge and hold for 3 seconds. Observe the skeleton and bar chart feedback and keep the signal within the goal region.	Real time feedback during each trial	Progressively decreased throughout training
Faster Technique			
Lateral jump and hold	Perform a double leg lateral jump and hold with knee flexion. Observe the skeleton and bar chart feedback following the exercise and attempt to keep the signal within the goal region during landing.	Post exercise feedback following each trial	Progressively decreased throughout training
Lunge jumps	Perform a series of lunge jumps. Observe the skeleton and bar chart feedback following the exercise and attempt to keep the signal within the goal region during landing.	Post exercise feedback following each trial	Progressively decreased throughout training
Single tuck jump	Perform a tuck jump. Observe the skeleton and bar chart feedback following the exercise and attempt to keep the signal within the goal region during landing.	Post exercise feedback following each trial	Progressively decreased throughout training

Figure 7. Example of drop vertical jumps with real time feedback to improve knee valgus motion using Visual3D software (C-Motion, Inc, Germantown, MD). Static trial (A) is initially collected in a neutral pose and then drop vertical jumps (B) are collected prior to any feedback. Feedback exercise is described in detail (C) and then the athlete is oriented to the feedback monitor and data curves (D). Exercises are performed while athlete attempts to keep knee valgus moment or angle within the goal region (E).

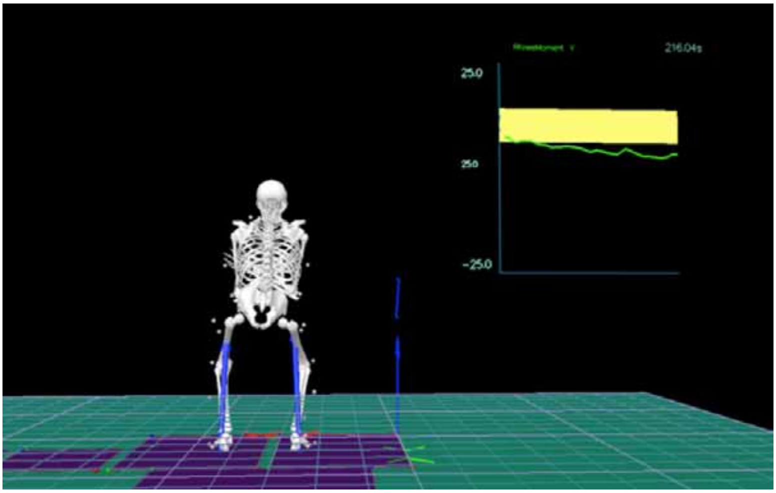


Figure 8. Close-up of feedback during a double-leg squat, with knee valgus moment or angle is displayed in real-time using Visual3D software (C-Motion, Inc, Germantown, MD).

Inertial sensor-based real-time feedback

Inertial sensor-based feedback (Physilog; Gait Up, Lausanne, Switzerland) is meant to be provided in a variety of environmental settings.[23,24,27,71,76] The feedback may consist of haptic feedback (vibratory buzzers placed near the knee such that the athlete can feel the vibration response when he or she reaches an acceptable amount of knee flexion), auditory feedback (beeping when the athlete completes an exercise properly), or visual feedback (graphs displayed on a mobile device such as a tablet or a smart- phone to indicate progression) (Figure 9).[23] In addition, the system can deliver simple instructions to athletes based on their movements, such as "land more softly".[23] This type of feedback is effective in reducing the knee abduction moment and increasing the knee and trunk flexion angles during drop-jump landing.[23] All of the feedback and instructions for the athlete are encompassed in the feedback system, which make it completely independent. In this way, the training staff can oversee multiple athletes using these systems at one time, while the athletes receive individualized instruction.

Clinical example of inertial sensor-based real time feedback

A training program using inertial sensor-based feedback is structured to fit into a team practice or training session. The training staff brings 1 to 3 measurement and feedback systems to the session, and over the course of the practice each athlete spends 10 to 15 minutes training with the system. In this way, each athlete does not need to spend extra time outside of practice to use the system, and practice does not have to be disrupted for a specific injury-prevention training program. After the initial sessions, the athletes can choose how often to receive the feedback, similar to the examples previously described. The exact timing of the feedback is dependent on the type of exercise the athlete is currently completing. For fast exercises (jumping, cutting, etc.) the feedback is given immediately after the movement has been completed (Figure 10), similar to the real-time visual feedback described earlier.[23] For slow exercises (deep squats, single-leg squats, etc), the athletes are given real-time feedback so that they can adjust their movements to properly complete the exercise (eg., continuing a squat until a specific knee flexion angle has been achieved).

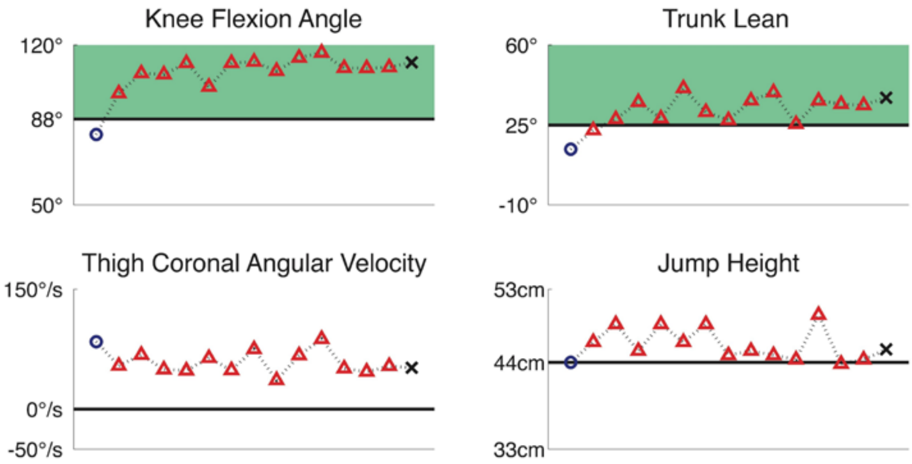


Figure 9. Example visual feedback for a training session for one athlete. For each measured parameter, blue circle indicates first measurement during training session, red triangles indicate subsequent measurements and black X indicates most recent measurement. Green shading indicates low risk range.[24] Feedback is given after double leg drop jump to improve parameters related to ACL injury risk (knee and trunk flexion angle) while maintaining performance (jump height).

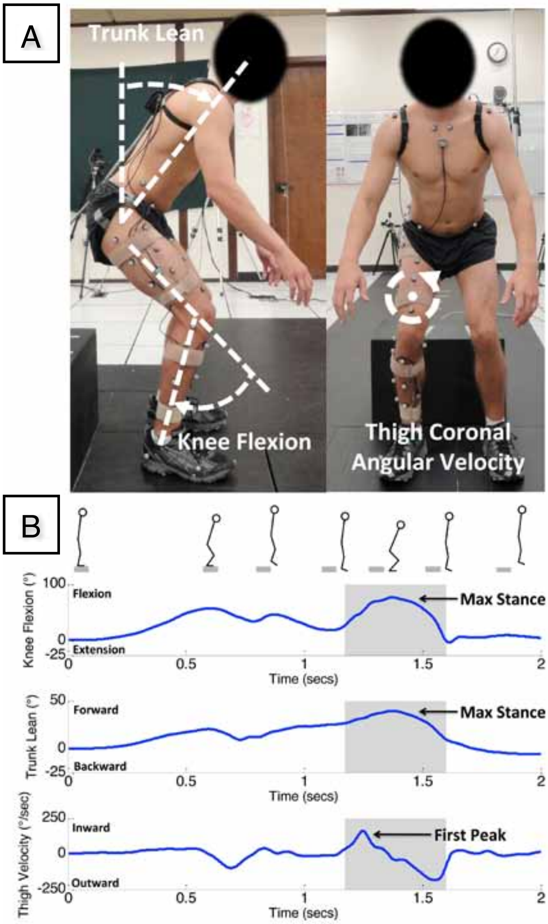


Figure 10. Feedback parameters for an athlete during a jump wearing small inertial measurement units (Physilog; BioAGM, La Tour-de Peilz, Switzerland) (A). Physical description of knee flexion angle, trunk lean, and thigh coronal angular velocity (B). Characteristic feature extracted from time series of each parameter. Figures above graph illustrate jump sequence and gray box indicates stance phase.[24] Reprinted by Permission of SAGE Publications.

Conclusion

Adoption of an external focus of attention may enhance automatic movement control and improve performance.[10] According to the "constrained action hypothesis," a focus on the movement effect (i.e., external focus) promotes the utilization of unconscious or automatic processes, whereas a focus on the movement itself (i.e., internal focus) results in a more conscious type of control that constrains the motor system and disrupts automatic control processes, as it focuses the athlete's attention on his or her own body movements.[37] For example, encouraging athletes to improve awareness and knee control during standing, cutting, jumping, and landing (an internal focus),[36] may not be optimal for the acquisition of fast and complex motor skills. Emphasizing proper alignment of the hip, knee, and ankle during landing, as ACL injury prevention programs often do, might actually have a detrimental effect on performance and learning, and disrupt the execution of automatic skills, particularly in comparison with an externally directed focus of attention.[49,102]

Adoption of instructions that induce an external focus therefore has important implications for ACL injury prevention, given the high retention and transfer rate of external focus. A better landing technique after jumping needs to occur automatically during training or a game, and therefore preprogramming with automatization for transfer from laboratory to field is most important.[10]

Motor learning with an external focus is effective in establishing safe movement technique. The development of such novel feedback techniques for ACL injury prevention therefore seems promising. This can be accomplished by using real-time video feedback or dyad training with observation of oneself or a model, while using positive, externally focused feedback to enhance jumping and landing performance. While most of our mentioned examples are relatively easy to apply, we realize that the use of video overlay or sensor technology may not be readily available for use on the field. A relatively small investment in time and money for ACL injury prevention programs benefits a team significantly in the long term.[70] Further research and development are in progress to make this technology widely available.

To increase evidence, future research should focus on which, if any, combinations of the presented novel techniques work best, create the least dependence on feedback, and yield a good transfer to the field. As such, investigations are necessary to determine how the stimulations (i.e., feedback) work, at what age they work best, and which one (or combination) results in the best retention and transfer to the field. In ACL injury prevention, the movement itself is the goal, and optimization of movement technique is part of the enhanced performance. The solution to injury prevention is grounded in the neuromechanics (i.e. the interaction of the brain and muscles to produce coordinated movements in different conditions) of the athletes. That solution needs to be stimulated by a proper intervention of motor learning that begins early in life. Because every brain and body is different, the optimal solution is also likely to be different and needs to be individually tailored to athletes.

Acknowledgements

We thank Adam Kushner for his valuable contribution to the manuscript.

References

1. Adams JA. A closedloop theory of motor learning. J Mot Behav. 1971;3:111–150.
2. Alentorn-Geli E, Mendiguchia J, Samuelsson K, et al. Prevention of non-contact anterior cruciate ligament injuries in sports. Part II: systematic review of the effectiveness of prevention programmes in male athletes. Knee Surg Sports Traumatol Arthrosc. 2014;22:16-25.
3. Andrieux M, Danna J, Thon B. Self-control of task difficulty during training enhances motor learning of a complex coincidence-anticipation task. Res Q Exerc Sport. 2012;83:27-35.
4. Badami R, VaezMousavi M, Wulf G, Namazizadeh M. Feedback after good versus poor trials affects intrinsic motivation. Res Q Exerc Sport. 2011;82:360-364.
5. Badets A, Blandin Y. The role of knowledge of results frequency in learning through observation. J Mot Behav. 2004;36:62-70.
6. Baltaci G, Harput G, Haksever B, Ulusoy B, Ozer H. Comparison between Nintendo Wii Fit and conventional rehabilitation on functional performance outcomes after hamstring anterior cruciate ligament reconstruction: prospective, randomized, controlled, double-blind clinical trial. Knee Surg Sports Traumatol Arthrosc. 2013;21:880-887.
7. Barrios JA, Crossley KM, Davis IS. Gait retraining to reduce the knee adduction moment through real-time visual feedback of dynamic knee alignment. J Biomech. 2010;43:2208-2213.
8. Beek PJ. Toward a theory of implicit learning in the perceptual-motor domain. Int J Sport Psychol. 2000;31:547–554.
9. Beilock SL, Carr TH, MacMahon C, Starkes JL. When paying attention becomes counter-productive: impact of divided versus skill-focused attention on novice and experienced performance of sensorimotor skills. J Exp Psychol Appl. 2002;8:6-16.
10. Benjaminse A, Otten E. ACL injury prevention, more effective with a different way of motor learning? Knee Surg Sports Traumatol Arthrosc. 2011;19:622-627.
11. Benjaminse A, Welling W, Otten B, Gokeler A. Novel methods of instruction in ACL injury prevention programs, a systematic review. Phys Ther Sport. 2015;16:176-186.
12. Betker AL, Szturm T, Moussavi ZK, Nett C. Video game-based exercises for balance rehabilitation: a single-subject design. Arch Phys Med Rehabil. 2006;87:1141-1149.
13. Boutin A, Badets A, Salesse RN, Fries U, Panzer S, Blandin Y. Practice makes transfer of motor skills imperfect. Psych Res. 2012;76:611-625.
14. Brass M, Heyes C. Imitation: is cognitive neuroscience solving the correspondence problem? Trends Cogn Sci. 2005;9:489-495.
15. Buccino G, Binkofski F, Riggio L. The mirror neuron system and action recognition. Brain Lang. 2004;89:370-376.
16. Chen DD, Hendrick JL, Lidor R. Enhancing self-controlled learning environments: the use of self-regulated feedback information. J Hum Mov Stud. 2002;43:69–86.
17. Chimera NJ, Swanik KA, Swanik CB, Straub SJ. Effects of Plyometric Training on Muscle-Activation Strategies and Performance in Female Athletes. J Athl Train. 2004;39:24-31.
18. Chiviacowsky S, Wulf G. Self-controlled feedback is effective if it is based on the learner's performance. Res Q Exerc Sport. 2005;76:42-48.
19. Chiviacowsky S, Wulf G. Self-controlled feedback: does it enhance learning because performers get feedback when they need it? Res Q Exerc Sport. 2002;73:408-415.
20. Chiviacowsky S, Wulf G, Lewthwaite R. Self-controlled learning: the importance of protecting perceptions of competence. Front Psychol. 2012;3:458.
21. Crowell HP, Davis IS. Gait retraining to reduce lower extremity loading in runners. Clin Biomech (Bristol, Avon). 2011;26:78-83.

22. Dempsey AR, Elliott BC, Munro BJ, Steele JR, Lloyd DG. Whole body kinematics and knee moments that occur during an overhead catch and landing task in sport. Clin Biomech (Bristol, Avon). 2012;27:466–474.
23. Dowling AV, Favre J, Andriacchi TP. Inertial sensor-based feedback can reduce key risk metrics for anterior cruciate ligament injury during jump landings. Am J Sports Med. 2012;40:1075-1083.
24. Dowling AV, Favre J, Andriacchi TP. A wearable system to assess risk for anterior cruciate ligament injury during jump landing: measurements of temporal events, jump height, and sagittal plane kinematics. J Biomech Eng. 2011;133:
25. Etnoyer J, Cortes N, Ringleb SI, Van Lunen BL, Onate JA. Instruction and jump-landing kinematics in college-aged female athletes over time. J Athl Train. 2013;48:161-171.
26. Feijen L, Hodges NJ, Beek PJ. Acquiring a novel coordination skill without practicing the correct motor commands. J Mot Behav. 2010;42:295-306.
27. Ferrari A, Cutti AG, Garofalo P, et al. First in vivo assessment of “Outwalk”: a novel protocol for clinical gait analysis based on inertial and magnetic sensors. Med Biol Eng Comput. 2010;48:1-15.
28. Fitts PM, Posner MI. Human performance. Oxford, England: Brooks and Cole; 1967.
29. Gokeler A, Benjaminse A, Welling W, Alferink M, Eppinga P, Otten B. The effects of attentional focus on jump performance and knee joint kinematics in patients after ACL reconstruction. Phys Ther Sport. 2015;16:114-120.
30. Granados C, Wulf G. Enhancing motor learning through dyad practice: contributions of observation and dialogue. Res Q Exerc Sport. 2007;78:197-203.
31. Hardy L, Mullen R, Jones G. Knowledge and conscious control of motor actions under stress. Br J Psychol. 1996;87 (Pt 4):621-636.
32. Hardy L, Mullen R, Martin N. Effect of task-relevant cues and state anxiety on motor performance. Percept Mot Skills. 2001;92:943-946.
33. Hebert EP, Landin D. Effects of a learning model and augmented feedback on tennis skill acquisition. Res Q Exerc Sport. 1994;65:250-257.
34. Heidt RS, Jr., Sweeterman LM, Carlonas RL, Traub JA, Tekulve FX. Avoidance of soccer injuries with preseason conditioning. Am J Sports Med. 2000;28:659-662.
35. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. Am J Sports Med. 2005;33:492-501.
36. Holm I, Fosdahl MA, Friis A, Risberg MA, Myklebust G, Steen H. Effect of neuromuscular training on proprioception, balance, muscle strength, and lower limb function in female team handball players. Clin J Sport Med. 2004;14:88-94.
37. Hossner EJ, Ehrlenspiel F. Time-Referenced Effects of an Internal vs. External Focus of Attention on Muscular Activity and Compensatory Variability. Front Psychol. 2010;1:230.
38. Iacoboni M. Neural mechanisms of imitation. Curr Opin Neurobiol. 2005;15:632-637.
39. Janelle CM, Barba DA, Frehlich SG, Tennant LK, Cauraugh JH. Maximizing performance feedback effectiveness through videotape replay and a self-controlled learning environment. Res Q Exerc Sport. 1997;68:269-279.
40. Joy EA, Taylor JR, Novak MA, Chen M, Fink BP, Porucznik CA. Factors influencing the implementation of anterior cruciate ligament injury prevention strategies by girls soccer coaches. J Strength Cond Res. 2013;27:2263-2269.
41. Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. Am J Sports Med. 2007;35:359-367.
42. Kyllo LB, Landers DM. Goal setting in sport and exercise: a research synthesis to resolve the controversy. J Sports Ex Psychol. 1995;17:117–137.

43. Laufer Y, Rotem-Lehrer N, Ronen Z, Khayutin G, Rozenberg I. Effect of attention focus on acquisition and retention of postural control following ankle sprain. Arch Phys Med Rehabil. 2007;88:105-108.
44. Lephart SM, Abt JP, Ferris CM, et al. Neuromuscular and biomechanical characteristic changes in high school athletes: a plyometric versus basic resistance program. Br J Sports Med. 2005;39:932-938.
45. Makaruk H, Porter JM, Czaplicki A, Sadowski J, Sacewicz T. The role of attentional focus in plyometric training. J Sports Med Phys Fitness. 2012;52:319-327.
46. Mandelbaum BR, Silvers HJ, Watanabe DS, et al. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. Am J Sports Med. 2005;33:1003-1010.
47. Marchant DC, Clough PJ, Crawshaw M. The effects of attentional focusing strategies on novice dart throwing performance and their task experiences. Int J of Sport Exerc Psych. 2007;5:291-303.
48. Masters RS, Poolton JM, Maxwell JP. Stable implicit motor processes despite aerobic locomotor fatigue. Conscious Cogn. 2008;17:335-338.
49. Masters RS, Poolton JM, Maxwell JP, Raab M. Implicit motor learning and complex decision making in time-constrained environments. J Mot Behav. 2008;40:71-79.
50. Maxwell J, Masters R, Eves F. From novice to no know-how: a longitudinal study of implicit motor learning. J Sports Sci. 2000;18:111-120.
51. McCullagh P, Meyer KN. Learning versus correct models: influence of model type on the learning of a free-weight squat lift. Res Q Exerc Sport. 1997;68:56-61.
52. McCullagh P, Weiss MR, Ross D. Modeling considerations in motor skill acquisition and performance: an integrated approach. Exerc Sport Sci Rev. 1989;17:475-513.
53. McGlashan AJ, Finch CF. The extent to which behavioural and social sciences theories and models are used in sport injury prevention research. Sports Med. 2010;40:841-858.
54. McGough R, Paterson K, Bradshaw EJ, Bryant AL, Clark RA. Improving lower limb weight distribution asymmetry during the squat using Nintendo Wii Balance Boards and real-time feedback. J Strength Cond Res. 2012;26:47-52.
55. McNair PJ, Prapavessis H, Callender K. Decreasing landing forces: effect of instruction. Br J Sports Med. 2000;34:293-296.
56. McNevin NH, Wulf G, Carlson C. Effects of attentional focus, self-control, and dyad training on motor learning: implications for physical rehabilitation. Phys Ther. 2000;80:373-385.
57. Molenberghs P, Cunnington R, Mattingley JB. Is the mirror neuron system involved in imitation? A short review and meta-analysis. Neurosci Biobehav Rev. 2009;33:975-980.
58. Myer GD, Brent JL, Ford KR, Hewett TE. A pilot study to determine the effect of trunk and hip focused neuromuscular training on hip and knee isokinetic strength. Br J Sports Med. 2008;42:614-619.
59. Myer GD, Ford KR, Brent JL, Hewett TE. The effects of plyometric vs. dynamic stabilization and balance training on power, balance, and landing force in female athletes. J Strength Cond Res. 2006;20:345-353.
60. Myer GD, Ford KR, McLean SG, Hewett TE. The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. Am J Sports Med. 2006;34:445-455.
61. Myer GD, Ford KR, Palumbo JP, Hewett TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. J Strength Cond Res. 2005;19:51-60.
62. Myklebust G, Engebretsen L, Braekken IH, Skjolberg A, Olsen OE, Bahr R. Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. Clin J Sport Med. 2003;13:71-78.

63. Myklebust G, Skjolberg A, Bahr R. ACL injury incidence in female handball 10 years after the Norwegian ACL prevention study: important lessons learned. Br J Sports Med. 2013;47:476-479.
64. Noehren B, Scholz J, Davis I. The effect of real-time gait retraining on hip kinematics, pain and function in subjects with patellofemoral pain syndrome. Br J Sports Med. 2011;45:691-696.
65. Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. Am J Sports Med. 2004;32:1002-1012.
66. Onate JA, Guskiewicz KM, Marshall SW, Giuliani C, Yu B, Garrett WE. Instruction of jump-landing technique using videotape feedback: altering lower extremity motion patterns. Am J Sports Med. 2005;33:831-842.
67. Onate JA, Guskiewicz KM, Sullivan RJ. Augmented feedback reduces jump landing forces. J Orthop Sports Phys Ther. 2001;31:511-517.
68. Ong NT, Bowcock A, Hodges NJ. Manipulations to the timing and type of instructions to examine motor skill performance under pressure. Front Psychol. 2010;1:196.
69. Park JH, Shea CH, Wright DL. Reduced-frequency concurrent and terminal feedback: a test of the guidance hypothesis. J Mot Behav. 2000;32:287-296.
70. Parsons JL, Alexander MJ. Modifying spike jump landing biomechanics in female adolescent volleyball athletes using video and verbal feedback. J Strength Cond Res. 2012;26:1076-1084.
71. Picerno P, Cereatti A, Cappozzo A. Joint kinematics estimate using wearable inertial and magnetic sensing modules. Gait Posture. 2008;28:588-595.
72. Pollard CD, Sigward SM, Ota S, Langford K, Powers CM. The influence of in-season injury prevention training on lower-extremity kinematics during landing in female soccer players. Clin J Sport Med. 2006;16:223-227.
73. Poolton JM, Masters RS, Maxwell JP. Passing thoughts on the evolutionary stability of implicit motor behaviour: performance retention under physiological fatigue. Conscious Cogn. 2007;16:456-468.
74. Prapavessis H, McNair PJ. Effects of instruction in jumping technique and experience jumping on ground reaction forces. J Orthop Sports Phys Ther. 1999;29:352-356.
75. Ram N, Riggs SM, Skaling SM, Landers DM, McCullagh P. A comparison of modelling and imagery in the acquisition and retention of motor skills. J Sport Sci. 2007;25:587–597.
76. Riskowski JL. Gait and neuromuscular adaptations after using a feedback-based gait monitoring knee brace. Gait Posture. 2010;32:242-247.
77. Rizzolatti G. The mirror neuron system and its function in humans. Anat Embryol (Berl). 2005;210:419-421.
78. Rizzolatti G, Craighero L. The mirror-neuron system. Annu Rev Neurosci. 2004;27:169-192.
79. Rizzolatti G, Fogassi L, Gallese V. Neurophysiological mechanisms underlying the understanding and imitation of action. Nat Rev Neurosci. 2001;2:661-670.
80. Schmidt RA, Wrisberg CA. Motor learning and performance. Champaign, IL: Human Kinetics; 2005.
81. Schöllhorn WI, Beckmann H, Michelbrink M, Sechelmann M, Trockel M, Davids K. Does noise provide a basis for the unification of motor learning theories? Int J Sports Psychol. 2006;37:186-206.
82. Shea CH, Wright DL, Wulf G, Whitacre C. Physical and observational practice afford unique learning opportunities. J Mot Behav. 2000;32:27-36.
83. Shea CH, Wulf G. Schema theory: a critical appraisal and reevaluation. J Mot Behav. 2005;37:85-101.

84. Shea CH, Wulf G, Whitacre C. Enhancing Training Efficiency and Effectiveness Through the Use of Dyad Training. J Mot Behav. 1999;31:119-125.
85. Shultz SJ, Schmitz RJ, Benjaminse A, Chaudhari AM, Collins M, Padua DA. ACL Research Retreat VI: An Update on ACL Injury Risk and Prevention. J Athl Train. 2012;47:591-603.
86. Simon SR, Meunier M, Piettre L, Berardi AM, Segebarth CM, Boussaoud D. Spatial attention and memory versus motor preparation: premotor cortex involvement as revealed by fMRI. J Neurophysiol. 2002;88:2047-2057.
87. Sims J, Cosby N, Saliba EN, Hertel J, Saliba SA. Exergaming and static postural control in individuals with a history of lower limb injury. J Athl Train. 2013;48:314-325.
88. Steffen K, Myklebust G, Olsen OE, Holme I, Bahr R. Preventing injuries in female youth football--a cluster-randomized controlled trial. Scand J Med Sci Sports. 2008;18:605-614.
89. Sugimoto D, Myer GD, McKeon JM, Hewett TE. Evaluation of the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes: a critical review of relative risk reduction and numbers-needed-to-treat analyses. Br J Sports Med. 2012;46:979-988.
90. Vernadakis N, Derri V, Tsitskari E, Antoniou P. The effect of Xbox Kinect intervention on balance ability for previously injured young competitive male athletes: A preliminary study. Phys Ther Sport. 2013;15:148-155.
91. Weinberg RS. Goal setting and performance in sport and exercise settings: a synthesis and critique. Med Sci Sports Exerc. 1994;26:469-477.
92. Wu WF, Porter JM, Brown LE. Effect of attentional focus strategies on peak force and performance in the standing long jump. J Strength Cond Res. 2012;26:1226-1231.
93. Wulf G. Attentional focus and motor learning: a review of 15 years. Int Rev Sport Exerc Psychol. 2013;6:77-104.
94. Wulf G, Chiviacowsky S, Schiller E, Avila LT. Frequent external-focus feedback enhances motor learning. Front Psychol. 2010;1:190.
95. Wulf G, Dufek JS. Increased jump height with an external focus due to enhanced lower extremity joint kinetics. J Mot Behav. 2009;41:401-409.
96. Wulf G, Dufek JS, Lozano L, Pettigrew C. Increased jump height and reduced EMG activity with an external focus. Hum Mov Sci. 2010;29:440-448.
97. Wulf G, Hoss M, Prinz W. Instructions for Motor Learning: Differential Effects of Internal Versus External Focus of Attention. J Mot Behav. 1998;30:169-179.
98. Wulf G, Lewthwaite R. Conceptions of ability affect motor learning. J Mot Behav. 2009;41:461-467.
99. Wulf G, Mercer J, McNevin N, Guadagnoli MA. Reciprocal influences of attentional focus on postural and suprapostural task performance. J Mot Behav. 2004;36:189-199.
100. Wulf G, Prinz W. Directing attention to movement effects enhances learning: a review. Psychon Bull Rev. 2001;8:648-660.
101. Wulf G, Shea C, Lewthwaite R. Motor skill learning and performance: a review of influential factors. Med Educ. 2010;44:75-84.
102. Wulf G, Weigelt C. Instructions about physical principles in learning a complex motor skill: to tell or not to tell. Res Q Exerc Sport. 1997;68:362-367.
103. Wulf G, Zachry T, Granados C, Dufek JS. Increases in Jump-and-Reach Height Through an External Focus of Attention. Int J Sports Sci Coach. 2007;2:275-284.
104. Zachry T, Wulf G, Mercer J, Bezodis N. Increased movement accuracy and reduced EMG activity as the result of adopting an external focus of attention. Brain Res Bull. 2005;67:304-309.