The Use of Augmented Information for Reducing Anterior Cruciate Ligament Injury Risk During Jump Landings: A Systematic Review

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Context: A comprehensive systematic review of the literature on the use of augmented information in anterior cruciate ligament (ACL) injury-prevention programs to improve jump-landing technique was conducted. The use of motor-learning concepts could provide more robust means of preventing ACL injuries.

Objective: To systematically summarize the effectiveness of augmented information in improving the biomechanical factors associated with an increased risk for ACL injury.

Data Sources: Articles were retrieved using the electronic databases of PubMed, MEDLINE, CINAHL, and Google Scholar and 3 lines of truncated search words: (a) *lower extremity, knee, ACL, and anterior cruciate ligament*; (b) *prevention, injury prevention, and prehab*; and (c) *augmented information, augmented feedback, feedback, cue, and instruction*. We also performed a hand search of the reference lists of the screened articles.

Data Extraction: We independently assessed the methodologic quality using the Cochrane Group on Screening and Diagnostic Test Methods list. Articles were placed in 1 of 3 augmented-information categories: prescriptive, feedback, or transition. Articles were also categorized based on whether the information likely encouraged an internal or external focus of attention.

Data Synthesis: The searches identified a total of 353 studies, of which 18 were included. Most researchers found that augmented information could lead to technique changes to reduce the biomechanical risk factors associated with ACL injury. The average methodologic quality of the studies was 11.8 out of 17, with a range from 8 to 15. The authors of only 7 studies examined retention of the improved techniques.

Conclusions: The evidence suggests that augmented information can be used to significantly improve the biomechanical indicators associated with ACL injury and to enhance current ACL injury-prevention programs. Combined prescriptive and feedback information that encouraged both internal and external foci led to the largest retention effect sizes.

Key Words: feedback, motor learning, injury prevention, knee

Key Points

- Incorporating motor-learning concepts enhanced anterior cruciate ligament injury-prevention programs.
- Augmented information led to the retention of the improved biomechanical techniques.

In the United States, approximately 250 000 anterior cruciate ligament (ACL) injuries occur annually. An ACL injury is one of the most costly injuries to treat, often requiring surgical repair and a lengthy rehabilitative process.[1] Of these injuries, 80% occur via noncontact mechanisms, ie, no other athlete or object is directly involved.[2,3] Noncontact ACL injuries typically occur during decelerations, pivoting movements, or jump landings,[4,5] when large forces are placed on the ACL, and biomechanical factors can predispose the individual to a greater risk of injury.[5–7] Among noncontact injuries, improper jump-landing technique is one of the leading causes.[2,3,8] Specific kinematic and kinetic risk factors for ACL injury resulting from jump-landing technique include small knee-flexion,[5] hip-flexion,[1] and trunk-flexion angles[1] and large knee-abduction angles[5,9] and moments[5] and vertical ground reaction forces (GRFs).[5] These risk factors may predispose individuals to ACL injury by contributing to greater forces on the ACL.[3,5,7] Athletes receive little to no coaching on the performance of jump landings, but these motor skills may be enhanced through focused instruction. Indeed, research suggests that individuals can improve their motor skills[10,11] and that participation in ACL injury-prevention programs can reduce the relative risk of noncontact ACL injury up to 70%.[12]

Given our goal to develop the motor skills of athletes in order to reduce the presence of risk factors for ACL injury, we naturally turned to the field of motor learning, which includes the processes involved in motor-skill acquisition as well as the variables that enhance or hinder learning.[13] Some experienced athletes do not naturally perform safe movement patterns. From a motor-learning perspective, these athletes need *augmented information*, or information in addition to their inherent feedback. Augmented information consists of 3 types: prescriptive, feedback, and transition.[14,15] *Prescriptive information* describes what the

to-be-learned movement pattern or outcome should be. *Feedback information* addresses the movement the athlete is currently performing (concurrent) or has performed in the past (terminal) and the resulting outcome. In contrast with the other 2 types, *transition information* more directly guides an athlete's search for a new movement coordination and control solution during the ongoing or a future performance. For example, a visual or auditory metronome rhythm that increases in frequency can alter an individual's movement coordination. This category is a novel consideration for motor learning; to date, researchers and practitioners have focused on prescriptive or feedback information, either separately or in combination.

When providing augmented information, it is important to consider both how the information is given and how it is delivered to the athlete. In the motor-learning literature, augmented feedback has been distinguished on the basis of whether it is information about the movement pattern (knowledge of performance) or the outcome (knowledge of results).[16,17] The risk factors identified earlier focus on knowledge of performance rather than on the outcome of the task, which in a game situation is unlikely to concentrate on safe jumping, landing, or cutting. However, when the goal of the task becomes the technique, the knowledge of performance and knowledge of results coalesce. The most common way to provide augmented information is verbally, which has the benefit of matching the typical approach of coaches.[18,19] Augmented information can also be provided visually. This can be a live or video demonstration of the movement technique to be learned, the use of a mirror for augmented feedback, a video of performance, or computed kinematic or kinetic measures for terminal information feedback. Although many different kinds and forms of information can be provided to an athlete, it is important to consider the motor-learning principle of minimizing the amount of augmented information due to the limited attention and processing capacity of individuals.[17,20]

Motor-learning researchers have examined where to best focus attention during the performance and learning of a motor skill. In particular, a distinction has been drawn between internal and external foci of attention.[21] *Internal focus* involves attending to the body, whereas *external focus* involves attending to the environment. For a vertical-jump test, the knees are the internal focus, and a mark on the wall is the external focus. Generally, an external focus of attention enhances both the performance and learning of motor skills.[22] This has led to the claim that an external focus of attention is better than an internal focus for developing safer movement techniques.[10,11] However, indiscriminately applying these findings is not advisable. Previously, Russell[23] argued that an external focus of attention worked better because it more closely matched what must be controlled in relation to how the outcome was measured (eg, vertical-jump height is relative to the point on the wall to be touched); yet it does not necessarily provide a mechanism for improving errors in technique (eg, reducing knee abduction). To directly correct movement form, coaches typically emphasize an internal focus of attention on the error itself. Therefore, even though recent literature[10,11,22] on motor learning promoted an external focus of attention, it is important to assess the roles of both internal and external foci when developing safer movement techniques while maintaining performance at a high level.

The goal of training in safer movement techniques is for athletes to retain these skills and transfer them to the practice and competition environments.[24] Performance during practice does not necessarily predict how well individuals will retain a skill after a period of time.[20,25] Additionally, skills learned in the practice context do not always transfer to other situations. Therefore, it is critical to assess retention and transfer to determine the learning effects of practice conditions. To date, no authors have conducted a comprehensive review of the effectiveness of learning proper jump-landing technique through the use of augmented information to improve the biomechanical risk factors associated with ACL injury. We undertook this systematic review to (1) determine whether prescriptive, feedback, or transition information provided an effective means of improving jump-landing technique to reduce the risk of ACL injury and (2) assess the influence of the focus of attention as encouraged by augmented information.

METHODS

Literature Search

The following electronic databases were searched for relevant studies in January 2017: (a) PubMed, (b) MEDLINE, (c) CINAHL, and (d) Google Scholar. In addition to the electronic search, we performed a manual search of reference lists and authors' names to find additional eligible studies. The search strategy consisted of 3 lines of search words, truncated when possible: (a) *lower extremity, knee, ACL, and anterior cruciate ligament*; (b) *prevention, injury prevention, and prehab*; and (c) *augmented information, augmented feedback, feedback, cue, and instruction*.

Selection Criteria

Inclusion criteria for this review were studies (a) with full-text articles available, (b) in peer-reviewed journals published between 1980 and 2017, (c) in English, (d) that included healthy adults (age >18 years), (e) using augmented information as a comparison variable, and (f) in which either single- or double-limb jump-landing technique was analyzed. Although investigators have trained athletes to improve the performance of a number of tasks associated with noncontact ACL injury, we considered only jump-landing tasks in this review. Jump landing is a common cause of noncontact ACL injury[3,26] and has been the most frequently examined task in this literature. Etnoyer et al[27] found no evidence of transfer between jump-landing and cutting tasks, indicating they are not similar tasks from a motor-learning perspective. Hence, for a clearer comparison of effect sizes for the same key biomechanical risks, we studied only jump landings. Further exclusion criteria were unpublished theses or dissertations and studies published in conference proceedings. Editorials, commentaries, case studies, guidelines, and review articles were also excluded. For the initial search, the first author (C.N.A.) screened titles and abstracts for eligibility based on the inclusion and exclusion criteria.

After the initial search, the first author sought articles focusing on the use of augmented information to decrease
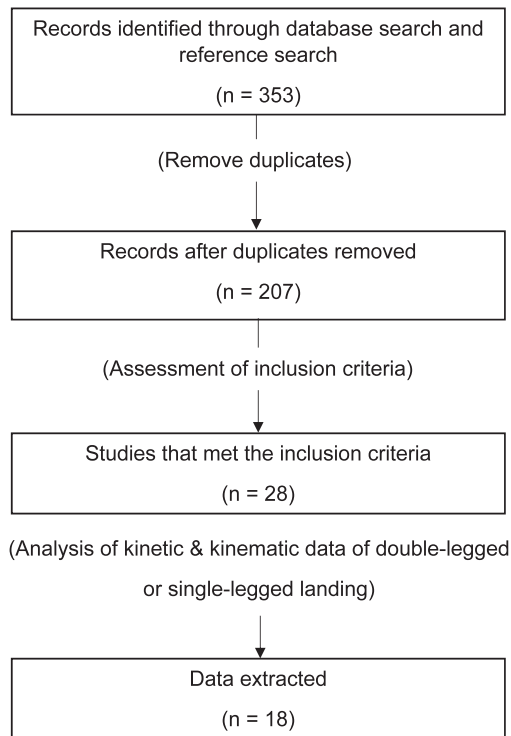
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┌─────────────────────────────────────┐
│ Records identified through database  │
│ search and reference search          │
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│              (n = 353)               │
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              or single-legged landing)
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Figure. Flow chart describing article-selection process.

the biomechanical risk factors associated with ACL injury during jump landings. Eighteen articles met all the inclusion criteria (see the Figure for the selection process). Excluded articles did not address augmented information or did not describe the use of augmented information in the intervention, did not address some form of jump-landing technique, or did not analyze jump-landing technique using kinetic or kinematic variables. For the purposes of this study, *augmented information* included verbal and visual modalities. Providing augmented information via oral instructions was defined as the use of verbal communication only; visual instructions were those provided through visual means only.[13,16,17]

Data Extraction

Demographic information was obtained from each article, including the number of participants, sex distribution, and the average age, height, weight, and body mass index of the participants (Table 1). The methodologic characteristics and major findings were extracted from each article. These characteristics were the jump-landing task, how the augmented information was provided, the tool used to capture or assess the jump-landing task, the outcomes measured (kinetic or kinematic variables or both), and the key findings (Table 2).

Methodologic Quality

A modified version of the Cochrane Group on Screening and Diagnostic Test Methods list[28] was used independently by the first and second authors (C.N.A., J.A.H.) to appraise the included studies and assess any risk of bias (Table 3). The quality of the methods was based on a list derived by Benjaminse et al[11] using the following criteria: (1) Oxford

Centre for Evidence Based Medicine levels of evidence (level 1 = 5 points, level 2 = 4 points, level 3 = 3 points, level 4 = 2 points, level 5 = 1 point)[29]; (2) the use of randomization or a counterbalanced within-subjects design (1 point); (3) the inclusion of a control group (1 point); (4) the similarity of groups at baseline (1 point); (5) clearly described inclusion and exclusion criteria (1 point); (6) a clearly described protocol that could be replicated (1 point); (7) demographics of participants provided, including age (mean and standard deviation) and sex distribution (1 point); (8) investigators, participants, and interventions blinded to experimental condition and results (1 point); (9) clearly described statistical analysis with mean, median, and standard deviation provided (1 point); (10) if appropriate, missing data or participants reported (1 point); (11) whether retention testing of the task was performed (1 point); (12) outcome variables clearly defined and clearly explained (1 point); (13) and confounding variables reported (1 point). The maximum possible score for each study was 17 points.[11]

RESULTS

Search Strategy

The initial search results identified 351 studies: 166 in MEDLINE, 124 in PubMed, and 61 in CINAHL. Two additional articles were located through reference and author searches. Once duplicate articles were removed, 207 studies remained for evaluation. A total of 179 studies were excluded because they failed to meet the inclusion criteria and 10 were excluded because they did not use or describe the augmented information, test a single- or double-limb jump-landing task, or analyze kinetic or kinematic variables. Of the articles assessed for eligibility, 18 studies met all inclusion criteria for this systematic review.[18,27,30–45]

Study Characteristics

Participant characteristics from each article included in this review are described in Table 1. Sample sizes ranged from 12 to 58 participants, and female participants predominated across studies, totaling 572 females to 130 males. The participants' ages ranged from 13 to 28 years old. The average height of the participants was 173 cm, and the average weight was 67.6 kg; the authors of 4 studies[32,41,43,44] did not report the height and weight of their participants. All participants were considered active or athletic individuals. Only 4 examinations[31,40,41,44] provided the average body mass index of participants: 23.34. Of the 18 investigations, 13 included a control group.[27,30–35,37–39,41,44,45]

The methodologic characteristics and findings of the investigations are shown in Table 2. Of the 18 studies, 14 used 3-dimensional (3-D) motion-capture systems along with force plates to collect data on kinetic and kinematic variables.[18,27,31,33,36–45] These systems can provide precise measurements of GRFs and joint kinematics, and they allow computation of joint kinetics that have been found to be valid and to provide good to excellent reliability for landing tasks.[46] Researchers in the remaining 4 studies used 2-dimensional (2-D) methods of motion analysis.[30,32,34,35] Although 2-D methods offer less precision regarding joint angles, they supply adequate consistency and validity.[47] Therefore, the measurements in the studies were likely to

Table 1. Demographics of Participants Included in the Studies

Study	Sex	Group	Mean ± SD			
			Age, y	Height, cm	Weight, kg	Body Mass Index
Beaulieu and Palmieri-Smith[37] (2014)	F	FB	21.9 ± 1.8	165.8 ± 5.5	60.9 ± 10.8	NA
		CTRL	21.2 ± 2.2	164.4 ± 5.3	62.6 ± 8.7	
Cowling et al[43] (2003)	24 F		21.8 ± 4.7	NA	NA	NA
Dowling et al[41] (2012)	10 F, 7 M		27.5 ± 2.9	NA	NA	22.8 ± 2.3
Ericksen et al[33] (2015)	F	RTF+PRF	20.3 ± 1.6	164.5 ± 5.5	65.7 ± 8.3	NA
		PRF	20.4 ± 1.9	166.2 ± 6.4	62.0 ± 6.9	NA
		CTRL	21.3 ± 3.2	163.9 ± 9.8	65.6 ± 12.8	NA
Ericksen et al[45] (2016)	F	RTF+TF	20 ± 1.63	163 ± 7	59.76 ± 8.46	NA
		TF	19.25 ± 1.39	165 ± 8	56.49 ± 7.04	NA
		CTRL	19.75 ± 1.73	164 ± 5	59.23 ± 8.83	NA
Etnoyer et al[27] (2013)	F		21.47 ± 1.55	165 ± 8	63.78 ± 12.00	NA
Favre et al[44] (2016)	18 F, 21 M		26.8 ± 4.3	NA	NA	22.9 ± 2.1
Herman et al[38] (2008)	F	ST+FB	22.5 ± 2.3	167 ± 7	64.1 ± 9.1	NA
		FB	22.5 ± 3.8	166 ± 6	62.1 ± 7.3	NA
Khuu et al[36] (2015)	10 F		20.8 ± 2.0	187 ± 7	82.5 ± 10.8	NA
	10 M		20.8 ± 1.4	176 ± 7	67.6 ± 7.1	NA
Milner et al[18] (2012)	F		25 ± 2	162 ± 5	57.33 ± 9.5	NA
Mizner et al[40] (2008)	F		19.5 ± 1.2	173 ± 9	74.6 ± 7.8	24.8 ± 1.8
Munro and Herrington[39] (2014)	12 F	AF	22.6 ± 3.8	166.9 ± 6.3	67.2 ± 10.9	NA
	8 M		24.3 ± 4.7	178.1 ± 6.8	81.1 ± 7.7	NA
	4 F	CTRL	20.0 ± 4.0	164.9 ± 2.7	57.8 ± 9.2	NA
	4 M		23.0 ± 4.2	181.3 ± 7.19	76.5 ± 12.4	NA
Myer et al[30] (2013)	F	AF	14.7 ± 1.4	160.8 ± 5.1	54.6 ± 7.8	NA
		CTRL	14.7 ± 1.7	160.9 ± 8.1	54.1 ± 6.8	NA
Oñate et al[34] (2005)		EM				
	8 F, 4 M	Kinetic	20.17 ± 1.34	169 ± 9	66.67 ± 10.05	NA
	7 F, 4 M	Kinematic	20.18 ± 1.40	171 ± 9	66.13 ± 10.05	NA
		SM				
	8 F, 4 M	Kinetic	20.25 ± 1.96	168 ± 13	70.25 ± 10.53	NA
	6 F, 2 M	Kinematic	20.50 ± 2.20	168 ± 16	69.58 ± 11.39	NA
		Combo				
	7 F, 6 M	Kinetic	20.08 ± 1.44	168 ± 12	64.87 ± 12.37	NA
	5 F, 5 M	Kinematic	19.80 ± 1.48	168 ± 12	65.51 ± 13.57	NA
		CTRL				
	9 F, 5 M	Kinetic	20.29 ± 0.91	173 ± 12	64.42 ± 14.70	NA
	7 F, 4 M	Kinematic	20.18 ± 0.75	173 ± 13	63.89 ± 16.59	NA
Oñate et al[35] (2001)	9 F, 8 M	AF	20.82 ± 2.24	174 ± 8.3	71.45 ± 12.90	NA
	11 F, 4 M	SEN	20.80 ± 1.97	166 ± 8.5	65.25 ± 11.89	NA
	12 F, 3 M	CON I	20.27 ± 1.33	167 ± 6.4	67.60 ± 22.84	NA
	10 F, 6 M	CON II	20.38 ± 2.22	174 ± 11.6	75.47 ± 15.07	NA
Parsons and Alexander[32] (2012)	F 10	AF	13.2 ± 0.4	NA	NA	NA
	F 9	CTRL	13.1 ± 0.3	NA	NA	NA
Tate et al[31] (2013)	F	AF	21.7 ± 1.9	166 ± 8	62.4 ± 7.0	22.6 ± 1.8
		CTRL	20.6 ± 2.4	167 ± 6	65.7 ± 10.9	23.6 ± 2.4
Wernli et al[42] (2016)	26 M		21.1 ± 2	179 ± 5	78.3 ± 12.2	NA

Abbreviations: AF, augmented feedback group; Combo, combination of augmented information; CON I, control condition 1; CON II, control condition 2; CTRL, control group; EM, expert model; F, female; FB, feedback only; M, male; NA, not included in the study; PRF, postresponse feedback group; RTF+PRF, real-time feedback and postresponse feedback group; RTF+TF, real-time feedback and traditional feedback; SEN, sensory feedback; SM, self model; ST+FB, strength training and feedback; TF, traditional feedback.

be valid and reliable even though the process of determining feedback information was not necessarily as precise. Among the 18 studies, the authors of 4 indicated which assessment criteria were being used to evaluate jump-landing technique.[34,38,39,45] Examiners in 2 studies[34,45] used the Landing Error Scoring System as the assessment tool, whereas investigators in the remaining 2 studies[38,39] used the primary author's expert opinion to evaluate jump-landing technique.

Augmented information was conveyed verbally or visually or via both methods. In some studies,[27,30–35,37,40,44,45] instructions or cues were provided verbally through written or oral (or both) formats. Many authors[27,30–35,37,40,44,45] supplied information visually, such as figures of kinetic and kinematic feedback, videotaped recordings, visual demonstrations, and PowerPoint (Microsoft Corp, Redmond, WA) presentations. The jump-landing tasks included the drop vertical jump with double-legged landing,[27,30,33,35–37,39–41] drop vertical jump with single-legged landing,[42] running-jump double-legged landing,[27,32,34,37,38,44,45] running-jump single-legged landing,[43] and countermovement double-legged landing jump.[18,31,37]

Table 2. Methodologic Characteristics and Findings Continued on Next Page

Study	Jump-Landing Task	Feedback	Augmented Information	Focus of Attention	Results
Beaulieu and Palmieri-Smith[37] (2014)	Drop vertical jump	Visual and verbal	Prescriptive and feedback	Internal	No effect of real-time feedback during the training program on double- or single-legged landings. Peak GRFs decreased from pretraining to posttraining for all groups.
Cowling et al[43] (2003)	Single-legged drop landing	Verbal	Prescriptive	Internal	Participants landed with greater knee flexion and less vertical GRFs with the knee instructions. The muscle instructions resulted in increased knee flexion but also increased GRFs.
Dowling et al[41] (2012)	Drop vertical jump	Visual	Feedback	Internal	Posttraining, 13 participants landed with a more neutral thigh coronal angular velocity. The changes in knee-abduction moment and thigh coronal angular velocity were correlated.
Ericksen et al[33] (2015)	Drop vertical jump	Visual and verbal	Prescriptive and feedback	Internal	Increase in knee- and hip-flexion angles as well as a decrease in GRFs in augmented information groups compared with the control group. No differences between the postresponse feedback groups and the postresponse plus real-time feedback groups.
Ericksen et al[45] (2016)	Rebound landing	Visual and verbal	Prescriptive and feedback	Internal	No difference from acquisition to retention testing in the traditional feedback and real-time feedback groups.
Etnoyer et al[27] (2013)	Drop vertical jump Running jump	Visual and verbal	Prescriptive and feedback	Internal	Differences between positions of maximum flexion 4 weeks after augmented information. Maximal hip flexion was greater in the feedback group. Immediately after augmented information and 2 weeks after: right knee and hip flexion increased.
Favre et al[44] (2016)	Block jump	Verbal	Prescriptive	Both	Differences found from pretesting to posttesting of the jump: changes in knee-flexion and knee-adduction angles and in flexion and adduction moments at the knee. Additionally, GRFs decreased.
Herman et al[38] (2009)	Running-jump double-legged landing	Visual	Prescriptive and feedback	Internal	Strength gains from 37%–50% in the strength group. Main effects for peak vertical GRF, decreased knee-abduction moment, increased hip-abduction moment, increased knee-flexion angle, increased hip-flexion angle, increased hip-abduction angle (all P values < .05).
Khuu et al[36] (2015)	Drop vertical jump	Verbal	Prescriptive	Both	The CT participants decreased sagittal-plane hip, knee, ankle joint range of motion; reduced ground contact time, and displayed a shorter reactive strength index than the EX and HT conditions. Peak GRF, power, and stiffness were greater in the CT condition than in the EX and HT conditions.
Milner et al[18] (2012)	Countermovement jump	Verbal	Prescriptive	Both	Peak GRFs were lower in "soft landing" than in other conditions ($P < .05$). Greater knee-flexion angle for soft landing and knees over toes compared with all other conditions ($P < .05$). Symmetry index was lower in equal weight compared with all other conditions ($P < .05$).
Mizner et al[40] (2008)	Drop vertical jump	Visual and verbal	Prescriptive and feedback	Internal	Postfeedback had longer landing times, lower vertical GRF, increased peak knee-flexion angles, decreased knee-abduction angles, and decreased external knee-abduction moments. Regression models were not significant.
Munro and Herrington[39] (2014)	Drop vertical jump	Visual	Prescriptive and feedback	Internal	Decreases in frontal-plane projection angle (−23.9°) and jump height (−0.03 m) and increase in contact time (0.13 s) for feedback.
Myer et al[30] (2013)	Tuck jump and drop jump	Visual and verbal	Feedback	Internal	Main effect for feedback group, reducing their average FPKA by 37.9%, control only reduced by 26.7% (not significant). Feedback group reduced FPKA by 6.9° in the right leg and 6.5° in the left leg.
Oñate et al[34] (2005)	Running-jump double-legged landing	Visual	Feedback	Internal	All feedback groups increased knee angular-displacement flexion angles and decreased peak GRFs for performance and retention tests ($P < .05$). No changes in knee-flexion angle at initial contact or peak proximal anterior tibial shear forces ($P > .05$) for both testing sessions and each group.

Table 2. Continued From Previous Page

Study	Jump-Landing Task	Feedback	Augmented Information	Focus of Attention	Results
Oñate et al[35] (2001)	Maximal vertical jumps	Visual and verbal	Prescriptive and feedback	Both	Augmented feedback group reduced peak vertical GRFs immediately after and at 1 week posttesting compared with the 2 control groups and the sensory group.
Parsons and Alexander[32] (2012)	Spike jump with double-legged landing	Visual and verbal	Prescriptive and feedback	Both	Peak frontal-plane knee angles were different between conditions (right: $F = 16.6$, $P < .05$; left: $F = 10.3$, $P < .05$); less frontal-plane knee motion in contact group versus other 2 ($P < .05$). Peak GRFs and frontal-plane knee angles were different between conditions (right: $F = 17.3$, $P < .05$; left: $F = 16.0$, $P < .05$).
Tate et al[31] (2013)	Countermovement jump	Visual	Prescriptive and feedback	Internal	Significant test-by-group interaction; peak GRFs for performance and retention tests were reduced. Each feedback group reduced peak GRFs and increased knee-flexion angles for both performance and retention tests. Feedback groups had greater knee-flexion angles than control group.
Wernli et al[42] (2016)	Run-jump single-legged landing	Verbal	Prescriptive	External	The instructions "land quieter" resulted in quieter landings with increased knee flexion, whereas the instructions "land louder" increased landing sound and knee flexion.

Abbreviations: CT, reduce contact time; EX, triple extend; FPKA, frontal-plane knee angle; GRF, ground reaction force; HT, jump as high as you can.

Methodologic Quality

The methodologic quality of the included studies is shown in Table 3. The average score for methodologic quality was 11.8 points out of 17 (69.4%), and the range was 8 to 15 points.

Data Synthesis

Prescriptive Information. Eight studies addressed a total of 17 conditions in which participants received prescriptive information alone, ie, information on how to perform the task; no feedback was given about how the participant was performing.[18,34–37,42–44] Prescriptive information was provided primarily via verbal instructions that encouraged both internal and external foci of attention. In 1 investigation, an external cue ("land softly") was provided along with an internal cue ("increase knee-flexion angle during landing after the block jump").[44] Combining these cues led to significant decreases in both vertical GRFs and knee-flexion angle (Tables 4 and 5) with large effect sizes, as well as smaller improvements in knee-flexion and knee-abduction moments. Providing the instruction "land softly" or "land as softly as possible" alone, which likely encouraged an external focus of attention, reduced maximum vertical GRFs (mean $g = 0.53$) and increased peak knee flexion (mean $g = 0.39$).[18,35,42] Only Milner et al[18] noted that "land softly" led to significant improvements in landing technique compared with the control group. When compared with instructions to "maximize jump height" (external focus) and "triple extend the hips, knees, and ankles when jumping" (internal focus), "reduce contact time" (external focus) led to lower jump heights, as well as increases in the injury risk factors of increased peak vertical GRFs, as well as reduced peak hip- and knee-flexion angle during ground contact.[36] The ACL injury risk could also be increased by the internal-focus cue "turn the muscles at the back of your thigh on earlier and more before landing," which significantly increased GRFs.[43] In another study,[18] the instructions to land with "knees over toes," "equal weight," and a "soft landing" were compared with each other and a control condition. "Soft landing" led to the smallest peak vertical GRFs, whereas "knees over toes" led to the largest peak knee-flexion angle ($g = 3.77$), which was different from the control group, and "equal weight" resulted in the greatest symmetry between legs.[18] Therefore, verbal prescriptive information can acutely alter the risk factors for ACL injuries.

Prescriptive information was also supplied visually through a live or video demonstration. No authors assessed the effect of a demonstration alone, but 1 group[34] combined the use of demonstration with verbal instructions to assess acute performance effects. Oñate et al[34] offered verbal instructions along with a video of an "expert" performer to 1 group of participants. This training led to reduced vertical GRFs ($g = 0.82$) and increased knee flexion ($g = 3.37$) compared with baseline, but these values were not different from those of the control group (vertical GRFs $g = 1.54$, knee flexion $g = 1.61$) that received only verbal instructions. Hence, seeing an "expert" model perform did not benefit the acute performance, but it is vital to determine the long-term learning effects.

Three groups[34,35,37] found retention of improvements in jump-landing technique. Oñate et al[35] simply requested

Table 3. Methodologic Quality of Studies[11]

Study	1	2	3	4	5	6	7	8	9	10	11	12	13	Total (17)
														Item[a]
Beaulieu and Palmieri-Smith[37] (2014)	4	1	1	1	0	1	1	0	1	1	0	1	1	13
Cowling et al[43] (2003)	3	0	0	0	0	1	1	0	1	1	0	1	0	8
Dowling et al[41] (2012)	3	0	1	1	1	1	1	0	1	1	0	1	0	11
Ericksen et al[33] (2015)	4	1	1	1	1	1	1	0	1	1	0	1	0	13
Ericksen et al[45] (2016)	4	1	1	1	1	1	1	0	1	1	1	1	0	14
Etnoyer et al[27] (2013)	4	1	1	1	1	1	1	0	1	1	1	1	0	14
Favre et al[44] (2016)	3	0	0	1	1	1	1	0	1	1	0	1	0	10
Herman et al[38] (2009)	4	1	0	1	1	1	1	0	1	1	0	1	0	12
Khuu et al[36] (2015)	3	0	1	1	0	1	1	0	1	1	0	1	0	10
Milner et al[18] (2012)	3	0	1	1	1	1	1	0	1	1	0	1	1	12
Mizner et al[40] (2008)	3	0	0	0	1	1	1	0	1	1	0	1	0	9
Munro and Herrington[39] (2014)	4	0	1	1	1	1	1	0	1	1	0	1	0	12
Myer et al[30] (2013)	4	1	1	1	1	1	1	1	1	1	0	1	1	15
Oñate et al[34] (2005)	4	1	1	1	1	1	1	0	1	1	1	1	0	14
Oñate et al[35] (2001)	4	1	1	1	0	1	1	0	1	1	0	1	0	12
Parsons and Alexander[32] (2012)	4	0	1	1	1	1	1	0	1	1	1	1	0	13
Tate et al[31] (2013)	4	1	1	1	0	1	1	0	1	1	1	1	0	13
Wernli et al[42] (2016)	3	0	0	0	1	1	1	0	1	1	0	1	0	9

[a] 1, Oxford Centre for Evidence Based Medicine levels of evidence (level 1 = 5 points, level 2 = 4 points, level 3 = 3 points, level 4 = 2 points, level 5 = 1 point); 2, use of randomization or a counterbalanced within-subject design (1 point); 3, the use of a control group (1 point); 4, similarity of groups at baseline (1 point); 5, inclusion and exclusion criteria clearly described (1 point); 6, protocol described clearly and replicable (1 point); 7, demographics of participants including sex and age with mean and standard deviation reported (1 point); 8, investigator, participants, and interventions blinded to experimental condition and results (1 point); 9, statistical analysis clearly described (1 point); 10, if appropriate, missing data or participants reported (1 point); 11, retention testing performed (1 point); 12, outcome variables clearly defined and clearly explained (1 point); 13, confounding variables reported (1 point).

Table 4. Prescriptive Verbal Cues and Their Immediate Effect on Jump-Landing Technique[a]

Study	Cue	Focus of Attention	Result
Cowling et al[43] (2003)	"Land with your knee bending"	Internal	Reduced peak GRFs compared with baseline and other condition
	"Turn the muscles at the back of your thigh on earlier and more before landing"	Internal	Increased peak GRF compared with baseline and other condition
Favre et al[44] (2016)	"Land softly" and "increase knee flexion angle during landing after the block jump"	External and internal	Increased knee-flexion and -adduction angles Reduced knee-flexion and -adduction moments Reduced vertical GRFs
Khuu et al[36] (2015)	"Reduce contact time"	External	Decreased sagittal-plane hip, knee, and ankle range of motion throughout ground contact time compared with other conditions Decreased frontal-plane knee motion compared with other conditions Increased vertical GRFs, vertical stiffness compared with other conditions Decreased knee-abduction angle compared with other conditions
	"Maximize jump height"	External	No difference between triple-extend cue
	"Triple-extend the hips, knees, and ankles when jumping"	Internal	No difference between cues
Milner et al[18] (2012)	"Land softly"	External	Decreased vertical GRFs[b] Increased peak knee-flexion angle[c]
	"Knees over toes"	Internal	Increased peak knee-flexion angle
	"Equal weight distribution on both your feet"	Internal	Decreased vertical GRFs Increased peak knee-flexion angle[c]
Wernli et al[42] (2016)	"Land quieter"	External	Increased ankle and knee excursion compared with baseline
	"Land louder"	External	Decreased ankle excursion and increased hip excursion

Abbreviation: GRF, ground reaction force.

[a] Includes those studies that only used prescriptive verbal information.

[b] Greater than "knees over toes" and "equal weight distribution on both your feet."

[c] Greater than "knees over toes."

Table 5.   Effect Sizes (Hedges _g_) of Kinematic and Kinetic Risk Factors Associated With Anterior Cruciate Ligament Injury Due to Jump-Landing Technique[a]

Study	Group	Focus	Performance or Retention	Knee-Abduction Angle	Knee-Abduction Moment	Knee-Flexion Angle	Vertical Ground Reaction Forces	Hip-Flexion Angle	Trunk-Flexion Angle
Prescriptive information									
Cowling et al[43] (2003)	KI	Internal	Performance			0.76[b]	0.36[b]		
	MI	Internal	Performance			0.45[b]	−0.32[b]		
Milner et al[18] (2012)	EW	Internal	Performance	0.05		0.21	0.1		
	KT	Internal	Performance	0.02		**3.77[c]**	0.27		
Milner et al[18] (2012)	SL	External	Performance	0.14		0.39[c]	**0.81[c]**		
Oñate et al[35] (2001)	SF	External	Performance				0.27		
	Control I	External	Performance				0.24		
Wernli et al[42] (2016)	QL	External	Performance			**1.07[b]**		0.44	
	LL	External	Performance			0.21		0.11	
Favre et al[44] (2016)		Both	Performance	0.24[b]	0.21[b]		**0.85[b]**		
Oñate et al[34] (2005)	EM	Both	Performance			**3.37[b]**	**0.82[b]**		
	Control	Both	Performance			**1.61**	**1.54**		
Khuu et al[36] (2015)		Both	Performance						
Beaulieu and Palmieri-Smith[37] (2014)	Control	Internal	Retention	−0.23	0.09[b]		0.54[b]		
Oñate et al[35] (2001)	SF	External	Retention				0.59		
Oñate et al[34] (2005)	EM	Both	Retention			**2.78[b]**	**0.90[b]**		
	Control	Both	Retention			**1.15**	**1.31**		
Feedback information									
Dowling et al[41] (2012)		Both	Performance		0.63	**2.29[b]**			**2.71[b]**
Myer et al[30] (2013)		Both	Performance	0.61[FPKAc]					
Combined prescriptive and feedback information									
Etnoyer et al[27] (2013)	Box SM	Internal	Performance	0.25		0.51		0.57	
	Box Combo	Internal	Performance	0.71		0.51		0.49	
Tate et al[31] (2013)	SP1	Internal	Performance	0.26	0.44	0.61[b]	0.23		
	SP2	Internal	Performance	0.38	0.41	0.60[b]	0.33		
Herman et al[38] (2009)	ST-FB	Internal	Performance	0.10	0.77[b]	0.16	0.65[b]	0.57	
	FB	Internal	Performance	0.13	**0.90[b]**	0.4	0.59[b]	**0.84**	
Ericksen et al[33] (2015)	RTF-PRF	Both	Performance	0.11		**0.81[c]**	0.39[c]	0.67[c]	
	PRF	Both	Performance	−0.12		0.56[c]	0.64[c]	0.23	
Ericksen et al[45] (2016)	RTF-TF	Both	Performance	0.43	**0.97**	**2.14[c]**	**1.71[c]**	**1.78[c]**	
	TF	Both	Performance	0.53	0.39	**3.05[c]**	**3.02[c]**	**1.79[c]**	
Mizner et al[40] (2008)		Both	Performance	0.26[b]	0.50[b]	**1.46[b]**	**1.35[b]**	0.71[b]	
Munro and Herrington[39] (2014)	FB	Both	Performance	**1.53[b]**			0.51		
Oñate et al[35] (2001)	AF	Both	Performance				**1.34[b,c]**		
Oñate et al[34] (2005)	SM	Both	Performance			**5.68[b]**	**1.35[b,c]**		
	Combo	Both	Performance			**4.91[b,c]**	**1.48[b,c]**		
Parsons and Alexander[32] (2012)		Both	Performance			**1.62[b]**		**1.05**	**0.82**
Beaulieu and Palmieri-Smith[37] (2014)	Feedback	Internal	Retention	0.21	0.51[b]		0.32[b]		
Etnoyer et al[27] (2013)	Box SM	Internal	Retention	0.21		0.28		0.61	
	Box Combo	Internal	Retention	0.21		0.12		0.2	
Tate et al[31] (2013)	HP1	Internal	Retention	0.25	0.15	0.23[b]	0.35[b]		
	HP2	Internal	Retention	0.65	0.16	0.33[b]	0.73		
Ericksen et al[45] (2016)	RTF-TF	Both	Retention	0.29	**0.97**	**1.75**	**1.60**	**1.46**	
	TF	Both	Retention	0.70	0.39	**2.36**	**2.67**	**1.76**	
Oñate et al[34] (2005)	SM	Both	Retention			**6.20[b,c]**	**1.79[b,c]**		
	Combo	Both	Retention			**4.39[b,c]**	**1.72[b,c]**		
Parsons and Alexander[32] (2012)		Both	Retention			**0.92[b]**		**1.06[b]**	**1.36[b]**

Abbreviations: AF, augmented-feedback group; Combo, combination of augmented information; Control, control group with prescriptive information; EM, expert model; EW, equal weight; FB, feedback only group; FPKA, 2-dimensional measure of frontal plane knee angle; HP, home-based practice; KI, knee instruction; KT, knees over toes; LL, loud landing; MI, muscle instruction; PRF, postresponse feedback group; QL, quiet landing; RTF-PRF, real-time feedback and postresponse feedback group; RTF-TF, real-time feedback and traditional feedback; SF, sensory information; SL, soft landing; SM, self model; SP, supervised practice; ST-FB, strength training and feedback; TF, traditional feedback.

[a] Effect sizes ≥0.80 are indicated in bold.
[b] Difference from baseline measures ($P < .05$).
[c] Difference from control group ($P < .05$).

participants to reflect for 2 minutes on how to "land softer." This resulted in reduced peak vertical GRFs 1 week after training ($g = 0.59$). The other 2 studies combined verbal instructions with visual demonstration. In a later study, Oñate et al[34] observed that participants who had trained with verbal instructions and a video of an expert model produced smaller vertical GRFs ($g = 0.90$) and greater knee flexion ($g = 2.78$) 1 week posttraining compared with baseline. Beaulieu and Palmieri-Smith[37] gave their control group a live "expert" demonstration and verbal instructions that emphasized keeping knees "over your feet." Two to 3 days after the second practice session, this group displayed changes from baseline, with a medium reduction in peak vertical GRFs ($g = 0.54$) and a small decrease in peak abduction moment ($g = 0.09$). These results suggest that improvements in landing technique from augmented prescriptive information can be retained after training. Not examined in any study was whether prescriptive information led to transfer of learning from the specific training to the practice or sports field.

Feedback Information. Two groups[30,41] focused on providing augmented feedback about the participant's jump-landing technique. Feedback in 1 investigation[30] involved showing a video of the participant's jump-landing technique along with verbal instructions about key errors based on a checklist. The majority of checklist errors could be described as encouraging an internal focus of attention, although 1 or 2 errors could encourage an external focus of attention (eg, "excessive landing contact noise"). In the other study,[41] participants were provided with quantitative feedback on 3 movement factors that emphasized an internal focus of attention. Immediate improvements in ACL injury risk factors at the knee and hip due to augmented feedback were evident. Participants increased their knee-flexion angle ($g = 2.29$) and trunk flexion ($g = 2.71$) compared with baseline.[41] In the frontal plane, knee-abduction angle decreased compared with a control group ($g = 0.61$),[30] whereas knee-abduction moment decreased ($g = 0.63$) but failed to reach the level of significance (see Table 5).[41] These findings suggest that augmented feedback provided via video or kinematic measurements could be used to improve landing technique. Only Myer et al[30] considered the actual feedback that was provided to participants; overall, most feedback appeared to have encouraged an internal focus of attention when participants attempted to remedy their errors. Taken together, these findings indicate that augmented feedback using an internal focus can help to reduce the ACL injury risk. However, neither study employed a retention or transfer test, so the learning effects of augmented feedback alone are unknown.

Transition Information. No researchers identified where the augmented information could be considered transition information. This is partially due to a lack of attention to coordination of body parts and how it might have changed with information.

Prescriptive and Feedback Information Combined. Eleven studies[27,31–35,37–40,45] included a total of 17 groups that were provided a combination of augmented prescriptive and feedback information in an effort to improve the safety of jump-landing technique. The augmented information mostly addressed body kinematics, which likely engaged an internal focus of attention, although some investigators also encouraged a "soft" or "quiet" landing, which may promote an external focus of attention. No authors isolated an external focus of attention while using a combination of prescriptive and feedback information. Combined augmented information resulted in acute reductions in ACL injury risk factors at the knee, hip, and trunk (Table 5). At the knee, participants increased knee-flexion angles moderately with an internal focus alone (mean $g = 0.67$) with 1 study[31] revealing significant effects.[27,38] Using both foci of attention, the effect size for knee-flexion angle was large (mean $g = 2.50$) as well as being different from baseline measures[31,32,34,40] and from the control groups.[33,34,45] Knee-abduction angles were reduced, but not significantly, using internally focused information (mean $g = 0.31$),[27,31,38] whereas combined internally and externally focused information resulted in significant reductions in 2 studies[39,40] (mean $g = 0.46$).[33,45] Importantly, knee-abduction moment decreased significantly in some studies, whether augmented information was internally focused ($g = 0.54$)[31,38] or both internally and externally focused ($g = 0.62$).[40,45] At the hip, an internal focus of attention increased hip flexion but not significantly (mean $g = 0.62$),[27,31,38] whereas both types of attention together led to, on average, large and significant effect sizes (mean $g = 1.04$).[32,33,40,45] At the trunk, 1 study[32] that combined internal and external foci demonstrated a large effect size for trunk lean, although it did not reach the level of significance ($g = 0.82$). Evidence[27,38] indicated a reduction in vertical GRFs in 9 studies.[31–35,37–40] An internal focus led to effect sizes ranging from small ($g = 0.23$) to medium (0.65), with an average of $g = 0.45$ that was significant only for 2 groups in 1 study.[31] Providing an additional attentional focus on landing softly or quietly led to a larger overall mean effect size ($g = 1.31$) with significant changes from baseline[34,35,40] and from a control group.[33–35,45] Even with reductions in vertical GRFs and an overall safer landing technique, jump-height performance was maintained.[35,40] Overall, acute improvements in the safety of jump-landing technique can be achieved through combined augmented prescriptive and feedback information. The largest increases in knee flexion and decreases in vertical GRF tended to occur when instructions and feedback also included an externally focused cue.

Six studies[27,31,32,34,37,45] that assessed a total of 10 conditions examined the effect of combined prescriptive and feedback information on the retention of motor-skill techniques. The retention interval after practice varied from 2 to 3 days (1 study) to 1 week (4 studies) and 4 weeks (2 studies). Some of the improvements in jump-landing technique were retained, but differences were noted between foci of attention (Table 5). At retention testing, internally focused information had a small effect on knee-flexion angle that was significant in 2 groups in 1 study (mean $g = 0.24$),[27,31] but both internally and externally focused information led to very large effect sizes that were significantly different from baseline and a control group (mean $g = 3.12$).[32,34,45] For the internal-focus conditions, the effect sizes for knee abduction were small (mean $g = 0.33$)[27,31,37]; 1 study[45] that included both internal- and external-focus conditions revealed a moderate effect (mean $g = 0.50$). However, the effects on knee-abduction angle were not significant in any of these investigations. The effect size for the reduction in knee-abduction moment was small but significant for internal-focus

conditions (mean $g = 0.27$),[31,37] whereas for conditions with both internally and externally focused information, the effect was moderate but not significant (mean $g = 0.68$).[45] Combined prescriptive and feedback information led to increased hip flexion that was retained during testing. With an internal focus only, the effect size was small and nonsignificant (mean $g = 0.41$),[27] but this increased to a significant large effect size (mean $g = 1.43$)[32,45] when internal and external foci were encouraged. Increased trunk flexion was also retained over a 4-week period with a large significant effect size under combined internal-and external-focus conditions ($g = 1.36$).[32] Finally, reduced vertical GRFs during retention testing represented an almost moderate effect size for the internal-focus conditions (mean $g = 0.47$) that was significant in 2 studies[31,37] and a large significant effect size when externally focused cues were also included (mean $g = 1.80$).

Some authors failed to note significant improvements in retention compared with a control group. Beaulieu and Palmieri-Smith[37] found improvements in knee-abduction moments and peak vertical GRFs from baseline to retention testing by providing real-time feedback of knee-abduction moment; however, these changes were not different from the control group.[37] Tate et al[31] did not observe retention benefits of a home-based training program involving the use of a mirror compared with a control group. Ericksen et al[45] also did not detect benefits relative to a control group, yet these findings are likely due to statistically assessing the change score between retention and acquisition rather than between retention and baseline. Overall, the evidence indicates that reductions in movement risk factors for ACL injury can be retained for up to 4 weeks after athletes have been provided with augmented prescriptive and feedback information and that combining external with internal attention leads to larger effect sizes.

DISCUSSION

The purpose of our research was to systematically review the literature on providing athletes with augmented information in an effort to reduce the risk factors for ACL injury associated with jump-landing technique. A number of outcomes emerged. First, our findings offer a guide for providing augmented prescriptive and feedback information to enhance the safety of techniques used by athletes. Second, the methods and methodologic quality indicators raise areas of concern and supply guidelines for future work in this area.

Certain jump-landing mechanics have been identified as potential risk factors for noncontact ACL injuries.[1,48,49] These include small knee-flexion angles, small hip-flexion angles, small trunk-flexion angles, large knee-abduction angles, large knee-abduction moments, and large vertical GRFs.[5] Even highly experienced athletes display movement techniques that are high risk for ACL injury, indicating that they need specific training to learn safer movement mechanics.[11,12] According to the field of motor learning, augmented information is likely necessary when athletes do not readily discover safer movement patterns on their own. This review provides substantial evidence to support the use of augmented information to improve jump-landing mechanics known to be associated with the risk of ACL

injury.[18,27,30–41] More importantly, this review provides evidence that improvements in jump-landing technique using augmented information can be successfully retained[27,30,32] and potentially transferred to sports.[32]

Augmented information can be categorized in 3 ways: prescriptive, feedback, and transition. We assessed all 3 categories in each of the articles reviewed.[14,15] Of the 18 studies that met the inclusion criteria, 7 included conditions that provided prescriptive augmented information alone, without any feedback.[18,34–36,42–44] Prescriptive information was given through verbal instructions or video of safer jump-landing techniques. Only 2 studies included conditions that provided augmented feedback information exclusively,[30,41] whereas the remainder used a combination of prescriptive and feedback information.[27,31–35,37–40,45] Feedback information was given through verbal cues, video of the performance, graphs of particular kinematic or kinetic variables, or use of a mirror. Transition information is a novel category of augmented information that drives changes in movements without directly specifying the changes to be achieved. No researchers employed transition information. We also considered whether augmented information was likely to encourage an internal or external focus of attention, which refers to attention paid to the body or outside of the body, respectively.[21] Using these augmented-information and focus-of-attention concepts from the motor-learning literature, we evaluated which forms of information led to movement techniques believed to reduce the risk of ACL injury. An important consideration from this literature is the distinction between short-term transient performance changes and long-term, more stable learning changes. Many authors examined only the current performance effects of the training. Fewer studies assessed whether athletes retained enhanced movement skills over a period without specific training (retention) or could transfer the movement skills to different tasks or contexts.

Performance Effects

Augmented prescriptive information alone led to changes in jump-landing technique that could reduce the risk for ACL injury. Encouraging an internal focus of attention with the cue "knees over toes" resulted in large knee-flexion increases during landing, whereas the cue "land softly," which likely encourages more of an external focus of attention, produced smaller peak vertical GRFs.[18] Cues can also have negative effects on jump technique: "land louder" increased landing noise, "turn the muscles at the back of your thigh on earlier and more before landing" increased vertical GRFs, and "reduce contact time" decreased knee flexion and increased vertical GRFs.[36,42,43] Together these findings indicate that cues can have specific effects on movement techniques. Combining the cues "increase knee flexion" and "land softly" resulted in both a larger range of motion at the knees and reduced GRFs.[44] These instructions also had a small but significant effect on knee-abduction angle and moment but only for individuals who tended to adduct the knee. This study highlights 2 important points for future research. First, the influence of cues is likely to depend on the individual's original technique, and second, it is important to measure multiple risk factors for ACL injury to determine the effect of cues on different

components of the landing. What this previous work showed is that verbal prescriptive instructions with an internal or external focus of attention can positively (or negatively) affect knee-flexion angle or vertical GRFs (or both), but the effect on knee frontal-plane kinematics and kinetics needs further research.

The investigations we reviewed failed to show any additional benefit to observing a demonstration of the appropriate movement form, in spite of this common approach in coaching. Oñate et al[34] compared a control group that received instructions with an expert group that also observed a video of an "expert" safely performing a jump landing. No differences between groups were observed in any dependent variable. Beaulieu and Palmieri-Smith[37] provided verbal instructions as well as a live demonstration of a safe technique, but their effect sizes were smaller than for other studies that gave only verbal prescriptive feedback. These findings did not indicate that the visual demonstration of the appropriate movement form was not beneficial but that it did not provide significant benefit to the athletes beyond verbal instructions. Future authors should compare a visual demonstration with verbal cues to possibly identify differences between these modes of providing prescriptive information.

Supplying augmented feedback alone also led to improvements in kinematic and kinetic factors that have been associated with an increased risk of ACL injury.[30,41] Myer et al[30] played video of an athlete's performance back to him or her and gave instruction about the specific error(s) made. This resulted in a moderate effect on reduced frontal-plane knee angle (a 2-D approximation of knee-abduction angle) and produced greater improvement than in the control group. Unfortunately, no other measures were reported, so the effects of the feedback on other risk factors are unknown. In contrast, Dowling et al[41] visually displayed 3 quantitative measurements to participants after each training jump. These measures were maximum knee flexion, maximum trunk lean, and maximum thigh coronal angular velocity during the landing.[41] Participants were also informed, if necessary, about how each measure could be modified. This feedback resulted in increased knee flexion and trunk lean as well as a moderate effect for decreased knee-abduction moment. In both studies, most of the feedback appeared to be related to body kinematics and was likely to encourage an internal focus of attention, although the feedback included "land softly" or reduce "excessive landing contact noise," which may encourage a more external focus of attention. We cannot identify the effects of specific information due to multiple potential feedback cues being provided to the participants. Although only 2 groups examined augmented feedback alone, their findings support the claim that athletes can acutely adapt their movement techniques based on augmented feedback that primarily focuses on internal cues.

Some similarities and differences were apparent in the effect sizes between studies that provided prescriptive versus feedback information. Feedback led to large effect sizes that were significantly greater from baseline for both knee angle and trunk lean. The value for knee angle was similar to that in studies that provided only prescriptive information,[18,34,44] but trunk angle was not assessed in any of those studies. Feedback did appear to provide an advantage in improving knee-abduction angle and moment, which showed moderate effects ($g = 0.61$ and 0.63, respectively) compared with negligible effects for prescriptive information ($g = -0.23$–0.24 and 0.05–0.09, respectively).[18,37,44] These findings may stem from feedback that emphasized knee abduction. Dowling et al[41] displayed thigh coronal angular velocity for each trial and gave cues on how to minimize it (eg, "push knees outward at the beginning of landing"), whereas feedback about knee valgus during landing was provided to participants in about one-third of the trials Myer et al[30] conducted. Rather than demonstrating the benefit of augmented feedback over prescriptive information, these results may simply indicate that information tends to have a specific influence and that to reduce knee-abduction angle and moment, more relevant cues should be used. Future research is needed to determine if more direct prescriptive cues can better influence knee abduction or if related feedback is necessary.

Most experimental conditions to date offered a combination of augmented prescriptive and feedback information and typically led to reductions in risk factors for ACL injury. Some authors[27,31,38] supplied information about movement kinematics that encouraged athletes to focus internally on their body during jump landings. Two groups[27,38] provided verbal instructions and usually showed a video recording to the participant of his or her prior performance. On average, the effect sizes were small to moderate and nonsignificant for knee-abduction angle, knee-flexion angle, and hip-flexion angle, whereas moderately significant effects were observed for knee-abduction moment and vertical GRFs. In contrast, Tate et al[31] used a mirror to provide concurrent feedback about jump-landing technique. We categorized this as encouraging an internal focus of attention because the participants likely focused on the body, even though this was an indirect image from a mirror rather than a direct look at their body. Although this categorization may be debated, 3 nonsignificant small effect sizes and only 1 significant moderate effect size for knee-flexion angle were present. Overall, studies that encouraged an internal focus with a combination of augmented prescriptive and feedback information showed a mixture of low to moderate effects, only some of which reached statistical significance.

The largest average effect sizes were observed for combined prescriptive and feedback information, which encouraged both internal and external cues.[32–35,39,40,45] The average effect sizes for knee-, hip- and trunk-flexion angle and vertical GRFs were all large, whereas the effect size for knee-abduction moment was moderate. In addition, several researchers demonstrated changes that were significantly improved from baseline measures[32,34,35,39,40] as well as from a control group.[33–35,45] These changes were primarily achieved by giving participants verbal instructions and showing them video of their previous performances. Some forms of augmented information did not seem to have any significant influence on improving landing outcomes. Similar to the prescriptive information studies, showing video of expert performances failed to improve outcomes.[34] Also, providing concurrent feedback on the body segments in the frontal plane did not offer any additional benefit for producing a safer jump-landing technique compared with terminal feedback alone.[33,45] Together, these results suggest that this additional prescriptive or feedback information was redundant. Overall, however, combining prescriptive and feedback information and including both

internal- and external-focus cues led to the largest performance improvements in factors related to ACL injury risk. These findings are promising, but it is important to consider whether these improved movements are retained.

Retention Effects

Augmented prescriptive or feedback information (or both) can improve the safety of jump-landing technique; however, gains in short-term performance did not necessarily predict long-term learning effects.[20,25] Rothstein[50] determined that, in order for augmented information to be effective as a learning tool, it needed to be implemented over several weeks. Unfortunately, only 2 groups[31,37] examined more than a single training session, and surprisingly, neither demonstrated more than a moderate effect size, suggesting their particular forms of training were not optimal. Motor-learning researchers[20,25] have discovered that some training conditions that improve immediate performance can be detrimental to longer-term learning, whereas other conditions that lead to poorer immediate performance can be beneficial for learning. This has led to the ubiquitous requirement in the motor-learning literature of a retention test with some delay after training (often 24 hours) or transfer tests to assess learning effects.[20,24] This guideline was not met by the majority of studies reviewed here, so they can only provide an indication of the performance effects. However, 7 investigations did evaluate retention and therefore can inform us about whether individuals retained changes in movement kinematics and kinetics after training.

Augmented prescriptive information led to changes in jump-landing technique that were retained. The combination of internal and external foci of attention cues was associated with the greatest effects on improved jump-landing technique. Encouraging an internal focus through live demonstration and instructions had a moderate but significant effect on GRF[37] that could also be achieved by simply asking an athlete to think for 2 minutes about how to land more softly.[35] Combining internal- and external-focus prescriptive cues led to large effect sizes, even though participants performed only a quarter of the trials conducted in the Beaulieu and Palmieri-Smith[37] study. However, there is reason to be cautious about these findings. Oñate et al[34] asked participants to "land as softly as possible" during practice and retention trials, but the goal for baseline testing was to "land in your normal manner." Hence, in that study, the effect size was partially a measure of landing under different instructions and differed from typical retention tests that did not provide added information compared with pretest trials.[24] The goal of improving the safety of jump-landing technique is retention during practices and competitions, when the athlete is unlikely to be reminded to land softly. Although the effect sizes for this study are in question, overall, the results indicate that augmented prescriptive information can improve jump-landing technique. Unfortunately, the influence of augmented feedback information alone on retention of safe jump-landing technique is unknown, as no applicable studies included a retention test.

Combining prescriptive and feedback information led to the retention of significant changes in jump-landing techniques associated with reducing the ACL injury risk.

Augmented information that emphasized an internal focus of attention led to small average effect sizes for 5 factors associated with ACL injury risk, of which only 3 reached the level of significance. The effect of externally focused information alone was not assessed, yet providing information that likely encouraged external and internal foci of attention produced moderate to large average effect sizes for 6 factors linked to ACL injury risk, of which 4 reached the level of significance. Across all risk factors, the average effect sizes were considerably greater for combined externally and internally focused information conditions than for an internal focus alone, indicating that athletes learn safer jump-landing techniques more effectively using information that encourages external and internal foci of attention. This conclusion is in agreement with the findings for prescriptive information alone: larger effect sizes were observed when the information included both external and internal cues rather than internal cues alone. Presumably, providing an overall goal (external) as well as information about how to achieve that goal (internal) promoted the greatest degree of retained improvement in body kinematics and kinetics.

When comparing the different types of augmented information tested in studies, the combination of prescriptive and feedback information led to the most effective learning. Unfortunately, as noted earlier, the influence of augmented feedback information alone on retention of jump-landing technique is unknown, as no applicable studies included a retention test. However, the combination of prescriptive and feedback information resulted in larger overall mean effect sizes than prescriptive information alone. Two investigations[34,35] also directly looked at these conditions. In both studies, groups that observed video playback of recent performances and discussed errors showed better retention than groups that received only prescriptive information. It seems that athletes do not simply need to know what to do (prescription) but they also need to know whether they are achieving it or not (feedback). Little evidence has supported the benefits of augmenting concurrent (real-time) feedback. Ericksen et al[33] compared terminal feedback with both terminal and concurrent feedback. Providing concurrent feedback via a computer model of the body did not offer any additional retention benefit over terminal feedback after each trial.[45] Tate et al[31] had participants watch their jump-landing performances in a mirror. Although GRFs were reduced after 1 week in this group versus a control group, no difference was apparent after 2 weeks. Together, these 2 studies suggest that it is difficult for athletes to use concurrent augmented feedback to learn changes in a rapid movement, such as a jump landing. Based on the studies of retention, combined prescriptive and terminal feedback information during training resulted in the greatest retained improvements in technique safety.

Transfer Effects

The end goal of training to improve the safety of jump landings is for athletes to apply the same safer techniques during regular practices and competitions to ultimately reduce their risk of injury. Applying what is learned in 1 task or situation to a different task or situation is known as *transfer*. Three studies provided information about trans-

ferred learning of a safer jump-landing technique. Most investigators examined a jump-landing task that only resembled a sport skill, but 2 researchers[32] trained volleyball players in a spike jump. Parsons and Alexander[32] found that prescriptive and feedback information improved the technique of a commonly practiced sport-specific skill. However, the technique was not examined in a separate practice or game situation. Transfer was directly measured by Myer et al,[30] who had participants practice a tuck jump, but they were examined before and after training on a drop vertical-jump task. The group that received prescriptive information on tuck-jump performance showed greater improvement in the drop vertical jump than did a control group, indicating positive transfer from the tuck jump to the drop vertical jump. Etnoyer et al[27] examined the limits of transfer by assessing participants performing a running-stop-jump task and a side-step cutting maneuver after practicing a box drop-jump task.[27] A group that received combined prescriptive and feedback information showed similar changes in knee flexion between the 2 jump tasks, suggesting that transfer had occurred to the new running-stop-jump task. In contrast, no transfer was evident for the side-step cutting maneuver. In agreement with earlier research, these studies suggest that transfer of learning can occur for similar tasks.[51] What none of these authors tested, however, was whether athletes transferred their safer movement techniques from the specific training circumstances to regular practices and competitions and whether the actual risk of injury was reduced.

Quality Assessment and Considerations for Future Work

Although the work we reviewed provides new data about the use of augmented information in altering the biomechanical risk factors associated with ACL injury, the quality of these studies is of concern. Using the Cochrane Screening and Diagnostic Test Methodology, the overall mean quality was 69.4%. Of the 18 studies, only 1 blinded the investigator, participants, and interventions to the experimental condition and results.[30] Additionally, only 2 groups[18,37] reported confounding variables and how they were addressed. Future researchers should consider the weaknesses in the current studies in an effort to design higher-quality investigations. In the following section, we outline additional concerns and make recommendations for future studies.

Identifying changes in movement technique requires accurate measurement and calculation of kinetic and kinematic variables. The use of force platforms with 3-D motion-analysis systems is considered the current criterion standard for analyzing kinetic and kinematic variables.[52] Yet several groups of investigators analyzed kinetic and kinematic variables through other means, such as 2-D video capture[30,32,39] or force transducers.[35,39,42,43] Two-dimensional video capture is not as accurate as 3-D capture because it is limited to the plane in which the camera is positioned; therefore, knee-abduction angle or moment may not be accurately determined. It is important to note that 3-D motion analysis also has its approximations and limitations when used to estimate kinetic and kinematic variables, which can be of particular concern when collecting data over multiple days. Some researchers tried to minimize this concern by indicating the locations of markers on the skin and assessed the reliability of measurements over time.

Technology enables the measurement and calculation of movement-technique variables, which can be shared directly with athletes; however, larger effect sizes occurred from providing verbal feedback, which requires jump-landing technique to be assessed by researchers. Only a few authors[27,37,38] described how this was done. One group[27] used the Landing Error Scoring System, an assessment tool deemed valid and reliable, to analyze jump-landing technique.[53] The additional 2 groups[27,37] did not use any assessment tool; instead, jump-landing technique was analyzed based solely on the judgment of the investigator. A concern about studies that did not use a valid and reliable assessment tool is that the feedback provided was likely to be more subjective and therefore could have confounded the results.

It is also important to recognize that a change in 1 joint motion is likely to involve concomitant changes in motion of other body parts. Nicholai Bernstein, a Soviet scientist, demonstrated that humans do not independently prescribe each degree of freedom, such as each plane of possible motion in a joint, but rather degrees of freedom are coordinated to act together.[54] In an effort to explain this fundamental finding, researchers have taken a dynamic-systems approach, which seeks to understand the constraints within and on the body that lead to degrees of freedom being coordinated to act as functional units, referred to as *synergies* or *coordinative structures*.[55] For example, in a jump landing, greater flexion of the knees occurs with increased flexion of the hip and trunk.[32] Although many of the studies we reviewed described more than 1 joint kinematic or kinetic variable, each was considered separately. Future researchers need to not only measure several variables but also assess how they are coordinated and change together. Information can be considered a constraint on the movement.[56] Knowledge of how informational constraints alter coordination promises to provide a guide for coaches to promote safer movement techniques in their athletes. This would also allow the determination of whether certain information has a transitional effect on task performance.[14,15]

As we have highlighted in this review, assessing changes in movement technique is not enough to show that athletes have learned; ie, that they have retained the skill and transferred it to other situations. Improvements in short-term performance do not necessarily predict long-term learning,[20,25] which has led researchers in the motor-learning field to emphasize delaying testing of retention until some time after the last training session. Retention testing is not a traditional item of the Cochrane Screening, yet we included it in our quality assessment because of its critical importance in determining learning. Most investigators (56%) did not include a retention test and therefore can only provide an indication of the performance effects of augmented information. It is critical that future research includes retention tests to identify if performance changes are being retained. Learning how to jump properly in a laboratory setting is a moot point if the technique cannot be performed in an actual practice or game situation. Future authors must also examine skill transfer to determine if skills learned during training are applied to practices and competitions to potentially reduce the risk of ACL injury.

For the most part, participants were provided with so much information that it is impossible to identify the specific links between augmented information and changes in movement technique. In many studies that provided prescriptive information, participants were informed about 5 or 6 factors related to reducing their injury risk during performance of a jump landing. When participants were provided with feedback, experimenters had to identify the main errors to determine the feedback to give. Although the feedback provided tended to be systematic, unfortunately, changes in the dependent variables were not linked to the specific feedback provided to each participant. To compound this concern, many study conditions included both prescriptive and feedback information, so it is difficult to determine the specific information that guided each individual. Two exceptions were researchers[18,36] who provided specific prescriptive cues and assessed concomitant changes in movement kinetics and kinematics. Both studies demonstrated that different verbal cues could have different effects on movement. However, all studies suffered from the reporting of average results, which can mask individual learning changes.[57] Future work needs to address the particular errors in technique made by individuals and the influence specific information has on their jump-landing performance.

We also must improve the safety of jump landings by building on the foundation of the motor-learning literature. This has been done to varying degrees, with some examiners clearly using concepts and terms from the field and referencing prior relevant research, whereas others have paid little attention to this literature. Use of the motor-learning literature will encourage application of appropriate terminology and concepts and lead to experiments to identify specific augmented information and its effects rather than the approach of giving multiple items of information with the goal of finding something that will help. Terminology has varied across these studies. From the motor-learning perspective, augmented information is information provided in addition to inherent feedback; it is the use of an external source to enhance inherent feedback.[16,17] By this definition, augmented information includes verbal instruction, biofeedback, videotaped feedback, and checklists. Because recent investigators have looked toward motor learning to enhance injury-prevention programs, it is imperative that we use the terms and concepts well documented in the motor-learning literature to develop the most effective ways to enhance injury-prevention programs. Our suggestion would be to define augmented information as the use of any additional information to enhance inherent feedback. This can then be separated into the type of augmented information being provided, whether it is prescriptive, feedback, or transition. Once categorized, the information can then be assessed for an internal or external focus of attention, although examination of what individual athletes are attending to will enhance this determination. Injury-prevention programs can become more robust if we assess concepts already validated in the motor-learning literature, and these studies will in turn contribute to the motor-learning literature.

Limitations

The design of this systematic review was based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines,[58] and therefore, limitations need to be addressed. We conducted the electronic searches in databases that would be most relevant to the use of augmented information for improving double-limb jump-landing technique for injury-prevention programs and followed these searches with a hand search of the references and relevant authors. However, more evidence may be available. In addition, we excluded studies that examined skill performance as a variable but did not examine either kinetic or kinematic variables; yet we believe kinetic and kinematic variables are the most effective ways of determining the effect on biomechanical risk factors as well as reducing potential bias. Probably the most significant limitation of the research reviewed here is that changes in jump-landing technique did not necessarily inform whether injury risk was concomitantly reduced. It is possible that training improves risk factors associated with the technique but does not reduce the injury risk or that training reduces the injury risk by other factors that are not detected by the kinematic or kinetic variables measured here.

CONCLUSIONS

A systematic review of the literature revealed 18 studies in which the authors used augmented information to reduce the biomechanical risk factors of jump-landing technique associated with ACL injury. The data suggested that the use of augmented information was effective for immediate motor-skill changes as well as for retention of the learned motor skill. The most effective means of providing augmented information to elicit changes to jump-landing technique is a combination of both prescriptive and feedback information that encourages both internal and external foci of attention. Retention tests also indicated that this combination of augmented information with internal- and external-focus cues led to technique changes that were better retained over time. Practicing 1 jump-landing task with augmented information may transfer to another jump-landing task, but transfer of skills during specific training to practices and competitions has not been assessed. Future researchers will need to demonstrate that athletes learning safer landing mechanics in the laboratory can apply those mechanics to injury-risk situations. Even more importantly, it is necessary to determine whether the injury risk itself is reduced through the training, irrespective of changes in movements. So far, most investigations have supplied participants with an abundance of information, which makes it difficult to determine what effect the augmented information had on movement. To provide a scientific basis for how augmented information constrains movement, future authors need to assess individual needs and responses to specific information. Consistent terminology and systematic manipulation of augmented information will be pertinent in future research. This review demonstrates how the cohesion of injury prevention and the motor-learning literature can help to determine the most beneficial injury-prevention approaches. By investigating the effect of augmented information on improving jump-landing technique, we may further enhance and continue to develop more effective ways to reduce the risk of noncontact ACL injury.

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