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Visual-Motor Control of Drop Landing After Anterior Cruciate Ligament Reconstruction

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Context: Visual feedback is crucial in the control of human movement. When vision is obstructed, alterations in landing neuromuscular control may increase movements that place individuals at risk for injury. Anterior cruciate ligament (ACL) injury may further alter the motor-control response to alterations in visual feedback. The development of stroboscopic glasses that disrupt visual feedback without fully obscuring it has enabled researchers to assess visual-motor control during movements that simulate the dynamic demands of athletic activity.

Objective: To investigate the effect of stroboscopic visual-feedback disruption (SVFD) on drop vertical-jump landing mechanics and to determine whether injury history influenced the effect.

Design: Cohort study.

Setting: Movement-analysis laboratory.

Patients or Other Participants: A total of 15 participants with ACL reconstruction (ACLR; 7 men, 8 women; age = 21.41 ± 2.60 years, height = 1.72 ± 0.09 m, mass = 69.24 ± 15.24 kg, Tegner Activity Scale score = 7.30 ± 1.30, time since surgery = 36.18 ± 26.50 months, hamstrings grafts = 13, patellar tendon grafts = 2) and 15 matched healthy control participants (7 men, 8 women; age = 23.15 ± 3.48 years, height = 1.73 ± 0.09 m, mass = 69.98 ± 14.83 kg, Tegner Activity Scale score = 6.77 ± 1.48).

Intervention(s): Drop vertical-jump landings under normal and SVFD conditions.

Main Outcome Measure(s): The SVFD effect for knee sagittal- and frontal-plane excursions, peak moments, and vertical ground reaction force were calculated during landing and compared with previously established measurement error and between groups.

Results: The SVFD altered knee sagittal-plane excursion (4.04° ± 2.20°, $P = .048$) and frontal-plane excursion (1.98° ± 1.53°, $P = .001$) during landing above within-session measurement error. Joint-moment difference scores from full vision to the SVFD condition were not greater than within-session error. We observed an effect of ACLR history only for knee flexion (ACLR group = 3.12° ± 3.76°, control group = –0.84° ± 4.45°; $P = .001$). We did not observe an effect of side or sex.

Conclusions: The SVFD altered sagittal- and frontal-plane landing knee kinematics but did not alter moments. Anterior cruciate ligament reconstruction may induce alterations in sagittal-plane visual-motor control of the knee. The group SVFD effect was on a level similar to that of an in-flight perturbation, motor-learning intervention, or plyometric-training program, indicating that visual-motor ability may contribute to knee neuromuscular control on a clinically important level. The individual effects of the SVFD indicated possible unique sensorimotor versus visual-motor movement strategies during landing.

Key Words: neurodynamics, biomechanics, lower extremity, kinesiology

Key Points

- Stroboscopic visual-feedback disruption via stroboscopic glasses altered bilateral landing kinematics.
- Stroboscopic visual-feedback disruption altered sagittal-plane but not frontal-plane kinematics in those with a history of anterior cruciate ligament reconstruction relative to matched controls.
- Recognizing the visual-motor implications of maintaining neuromuscular control may help clinicians mitigate patients' injury risk beyond traditional measures.
- Using a visual-disruption technology, such as stroboscopic glasses, supplements traditional interventions and may more closely mimic the cognitive stress of sport in the clinic.

Anterior cruciate ligament (ACL) rupture is a common activity-related knee injury that usually requires reconstruction to restore knee stability and function.[1] The lifetime burden of ACL injury ranges from \$7.6 to \$17.7 billion per year in the United States.[2] Despite surgical reconstruction and physical rehabilitation, ACL injury dramatically increases the risk for costly and long-term disabling osteoarthritis, associated decreased lifelong physical activity, and decreased work productivity.[2–5] Moreover, ACL reconstruction (ACLR) and rehabilitation that rely primarily on traditional neuromuscular interventions result in rates of second ACL injury after return to sport participation as high as 25%.[6–9] This high failure rate is further compounded because most individuals do not return to preinjury levels of activity.[10]

Whereas neuromuscular training effectively reduces injury risk, conventional approaches primarily target biomechanical factors, such as muscle strength, balance, and plyometric function, with less consideration of cognitive or neurologic components.[11–14] Rectifying the biomechanical profile via standard neuromuscular training is a vital component of the rehabilitation process, but it may be possible to further improve neuromuscular function and decrease the reinjury risk by examining sensory and neural variables that contribute to postinjury disability.[15,16] For example, researchers[17–21] have demonstrated unresolved neurologic alterations after injury, reconstruction, and rehabilitation that may limit function and delay the return to sport participation. By targeting neurologic factors during neuromuscular rehabilitation progressions, clinicians may be able to improve the transfer of sensorimotor adaptations from the clinic to activity and ultimately improve patient outcomes.[22–24]

Investigators[24–27] studying neuroplasticity after ACLR have suggested a possible visual-motor control alteration after injury that remains unresolved after conventional therapy. Corroborating the neurologic data, authors of biomechanical studies[28,29] have demonstrated that participants with ACLR experienced a greater degradation in postural control when vision was reduced relative to matched controls. However, given the method of limiting vision, these studies lacked generalizability and sport specificity because the tasks were single movements without environmental interaction.[30] The development of stroboscopic glasses that disrupt vision without completely obscuring it allows for visual-motor assessment during dynamic movements and target-acquisition tasks.[31] The additional environmental interaction and only limited visual disruption allow more of the neurocognitive demands of sport function to be reproduced in the laboratory.[16,32] To our knowledge, no researchers have considered the effect of dynamic stroboscopic visual-feedback disruption (SVFD) on lower extremity drop-landing mechanics after ACLR. Therefore, the purpose of our study was to investigate the effects of SVFD on drop vertical-jump (DVJ) landing mechanics and determine the influence of ACLR history on the effect of SVFD on neuromuscular control. We hypothesized that SVFD would decrease landing knee flexion and increase landing knee abduction, ground reaction force, knee-flexion moment, and knee-abduction moment, with a more pronounced effect on patients with a history of ACLR.

METHODS

Participants

We recruited participants from the university community and used an online survey to determine whether volunteers met the inclusion criteria: a minimum score of 5 on the Tegner Activity Scale and engagement at least once a week in a running or cutting/change-of-direction activity on the Marx Activity Scale. The participants with ACLR were individually matched to participants serving as healthy controls by age; sex; height; mass; upper and lower extremity dominance; history of and current physical activity level, including sport participation; and education level. Of the 502 individuals screened, 30 (15 with ACLR, 15 controls) fit the criteria and satisfied the matching requirements. We excluded volunteers with a history of other lower extremity injuries. The participants with ACLR (7 men, 8 women; age = 21.41 ± 2.60 years, height = 1.72 ± 0.09 m, mass = 69.24 ± 15.24 kg, Tegner Activity Scale score = 7.30 ± 1.30, time since surgery = 36.18 ± 26.50 months, hamstrings grafts = 13, patellar tendon grafts = 2) had undergone reconstruction 6 months to 5 years before the study, had been cleared for full return to activity by their physicians, and were engaged in regular physical activity. Control participants (7 men, 8 women; age = 23.15 ± 3.48 years, height = 1.73 ± 0.09 m, mass = 69.98 ± 14.83 kg, Tegner Activity Scale score = 6.77 ± 1.48) had no history of lower extremity injury. We observed no demographic differences between groups. All participants provided written informed consent, and the study was approved by The Ohio State University Institutional Review Board.

Data Collection

A 3-dimensional passive motion-capture system (model MX-F40; Vicon, Los Angeles, CA) with 10 cameras and the point-cluster marker technique[33–35] and two 40- × 60-cm force plates (Bertec Corp, Columbus, OH) were used to capture the kinematics and kinetics of all participants. For the DVJ assessment, participants fell forward from a 30-cm box, immediately performed a vertical jump, raised both upper extremities, and hit a target (Vertec Power Systems, Knoxville, TN) set at 90% of their maximal jump height.[36] The primary biomechanical outcomes collected were sagittal- and frontal-plane knee excursions and peak moments from initial contact to peak stance (peak knee flexion) during landing. These outcomes are highly reliable and constitute commonly used standard analyses for knee control and predictors for primary and secondary ACL injury risks.[36–41] We selected joint-angle excursion rather than focusing on initial contact or peak angle because researchers[31,42,43] have reported that knee mechanics at initial contact were stable but the landing movement pattern from contact to peak stance was altered when visual feedback was modified.

The DVJ was completed under 3 conditions: full vision, low SVFD, and high SVFD. Three trials under each condition were completed and averaged for each participant. Before the SVFD conditions, individuals completed an accommodation protocol consisting of a 5-minute ball toss during which the rate of SVFD increased after each set of 5 successful catches to allow accommodation to the SVFD and to limit effects due to novelty.[44,45] A minimum of 2 practice DVJs were completed before each condition.

The SPARQ Vapor Strobe goggles (Nike, Inc, Beaverton, OR) imposed the SVFD condition. These goggles, which are similar to sunglasses, have a wraparound strap for a secure fit and lenses constructed with battery-powered liquid crystal displays. They do not block vision continuously but strobe to block vision for milliseconds at a time. The length and frequency of these periods of "lost" and "intact" vision can be customized to 8 levels, with constant 100-millisecond transparent and 50- to 900-millisecond opaque periods. We used 2 levels of disruption: low (100-millisecond opaque, 100-millisecond transparent) and high (250-millisecond opaque, 100-millisecond transparent). In

Table 1. Stroboscopic Visual-Feedback Disruption Effects, Within-Session Errors, Test Statistics, and Effect Sizes Across Variables of Interest[a]

Variable	Stroboscopic Visual-Feedback Disruption Effect Overall[b] (Mean ± SD)	Within-Session Error[c]	Stroboscopic Visual-Feedback Disruption Effect Relative to Error[d]		Effect Size Relative to Within-Session Error
			t Value	*P* Value	
Knee-flexion excursion,[e] °	4.04 ± 2.20	3.20	2.09	.048[f]	0.38 (Small)
Knee-adduction excursion,[e] °	1.98 ± 1.53	0.90	3.87	.001[f]	0.70 (Moderate)
Peak vertical ground reaction force, % body mass	38.72 ± 26.63	0.003	7.96	<.001[f]	1.45 (Large)
Peak external knee-flexion moment (mass normalized), Nm/kg	0.19 ± 0.13	0.15	1.65	.14	0.27 (Small)
Peak external knee-abduction moment (mass normalized), Nm/kg	0.04 ± 0.04	0.12	12.05	<.001[g]	2.20 (Large)

[a] *Stroboscopic visual-feedback disruption effect* indicates the difference between the baseline condition and the peak stroboscopic condition.
[b] Indicates the absolute effect for the entire cohort regardless of group.
[c] The within-session error was from previously reported literature values.[40,47]
[d] Values are from a 1-sample *t* test to determine the stroboscopic visual-feedback disruption effect greater than error.
[e] Indicates the relative displacement from initial contact to peak stance.
[f] Indicates stroboscopic visual-feedback disruption effect was higher than error.
[g] Indicates stroboscopic visual-feedback disruption effect was lower than error.

our pilot testing, visual-disruption levels greater than 250 milliseconds resulted in complete loss of vision during the DVJ and great difficulty in hitting the in-air target. These glasses have been used to improve reaction time, visual processing, and anticipatory ability, but they have not been assessed for their influence on lower extremity neuromuscular control.[44,45]

Data Analysis

Data analysis was performed in Visual3D (version 5.0; C-Motion Inc, Germantown, MD) and MATLAB (version R2013B; The MathWorks Inc, Natick, MA). *Initial contact* of each limb was defined as the point when the vertical ground reaction force first exceeded 20 N. The *landing phase* was defined as the period from initial contact to peak knee flexion. The mean of 3 trials for each condition was used for statistical analysis.

We used a low-pass Butterworth filter with a cutoff frequency of 15 Hz to filter marker trajectories. Using a previously described method,[46] we estimated hip-joint centers to improve joint-center approximation. The midpoint between the medial and lateral knee- and ankle-joint markers defined the *joint centers* for the knee and ankle, respectively. Knee flexion and adduction were described as positive values. The changes in adduction and flexion angle from initial contact to peak knee flexion were extracted for analysis. We used a low-pass Butterworth filter at a matched cutoff frequency of 15 Hz to filter force data. External (force acting on the body) knee-flexion and knee-abduction moments were described as positive values. Given that we observed no difference between SVFD conditions, an SVFD difference score was calculated by subtracting the peak mean of the 2 SVFD conditions from the mean of the full-vision trials. This SVFD effect was used for the following statistical analysis, Tables 1 and 2, and Figures 1 through 5.

Statistical Analysis

Power analysis with pilot data from our laboratory and previous reports[47,48] in which similar methods were used to detect movement differences showed that a sample size of 14 per group was required to detect differences in our primary outcome variable of interest: knee excursion (2.4 ± 3.7).[38] To determine whether the SVFD condition altered knee mechanics beyond previously established within-session error, a 1-sample *t* test was used for the absolute SVFD effect (full-vision condition minus SVFD condition, as described) versus the previously established measurement error.[41,49] This 1-sample *t* test for joint excursion and moment was calculated relative to the previously established error threshold to determine whether the SVFD effects were beyond the error of the measure and typical variations in human performance.

A paired-samples *t* test between groups (ACLR, matched control) was conducted on the SVFD effect (full-vision condition minus SVFD condition, as described). A paired analysis was selected because the groups varied by sex, height, mass, sport, activity level, and limb dominance but were pairwise matched; therefore, for example, a collegiate-level soccer player was compared with a collegiate soccer player of the same level and position to limit between-subjects variability beyond the history of ACLR. In this way, we ensured that the comparison was between each matched pair (ACLR versus matched control), whereas the typical group analysis would compare the ACLR and control group means, which would be a major limitation for our design (heterogeneous groups but homogeneous pairs). This participant-level paired design was planned a priori because this investigation was completed in parallel with a neuroimaging study[20]; given the large variations in participants' brain activity due to various experiential factors (eg, sport, activity, education), we completed a participant-level pairwise matched design and carried this design strength forward to this analysis. The *P* values are reported without correction because we were analyzing a novel intervention. A Pearson product moment correlation was completed on each variable of interest and time from surgery for the ACLR cohort to determine whether time since surgery influenced the data (Table 2). We used the guidelines of Cohen[50] to determine the strength of effect

Table 2. Stroboscopic Visual-Feedback Disruption Effects Between Groups and Relationships With Months Since Surgery in the Anterior Cruciate Ligament Reconstruction Group[a]

	Stroboscopic Visual-Feedback Disruption Effect						
	Group (Mean ± SD)		Pairwise Difference			Relationship With Months Since Surgery in the Anterior Cruciate Ligament Reconstruction Group	
Variable	Anterior Cruciate Ligament Reconstruction	Control	*t* Value[b]	*P* Value	Effect Size	*r*	*P* Value
Knee-flexion excursion,[c] °	3.12 ± 3.76	−0.84 ± 4.45	2.63	.001	0.96 (Large)	0.173	.51
Knee-adduction excursion,[c] °	−1.57 ± 2.72	−1.05 ± 1.42	0.66	.43	0.23 (Small)	0.181	.49
Peak vertical ground reaction force, % body mass	2.00 ± 50.00	−14.00 ± 45.00	0.92	.40	0.34 (Small)	−0.116	.66
Peak external knee-flexion moment (mass normalized), Nm/kg	11.66 ± 12.78	12.18 ± 15.27	0.10	.88	0.04 (Small)	0.015	.95
Peak external knee-abduction moment (mass normalized), Nm/kg	3.17 ± 3.78	1.95 ± 2.10	1.09	.31	0.40 (Small)	0.260	.33

[a] *Stroboscopic visual-feedback disruption effects* indicates the difference between the baseline condition and the peak stroboscopic visual-feedback disruption condition.
[b] Values are from the paired *t* test to determine the stroboscopic visual-feedback disruption effect between the pairwise matched anterior cruciate ligament reconstruction and control participants.
[c] Indicates the relative displacement from initial contact to peak stance.

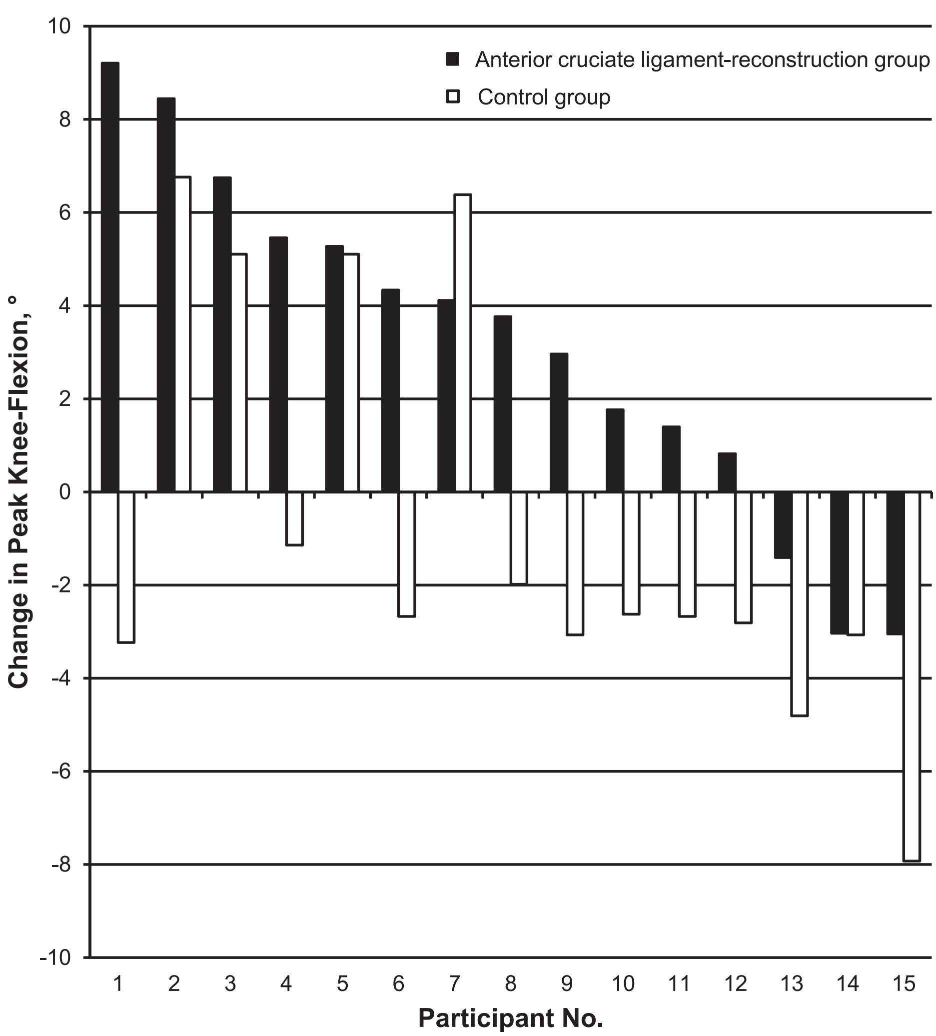

Figure 1. Effect of stroboscopic visual-feedback disruption (SVFD) on knee sagittal-plane excursion. A value >0 indicates increased sagittal-plane knee excursion under the SVFD condition; <0 indicates decreased sagittal-plane knee excursion under the SVFD condition.

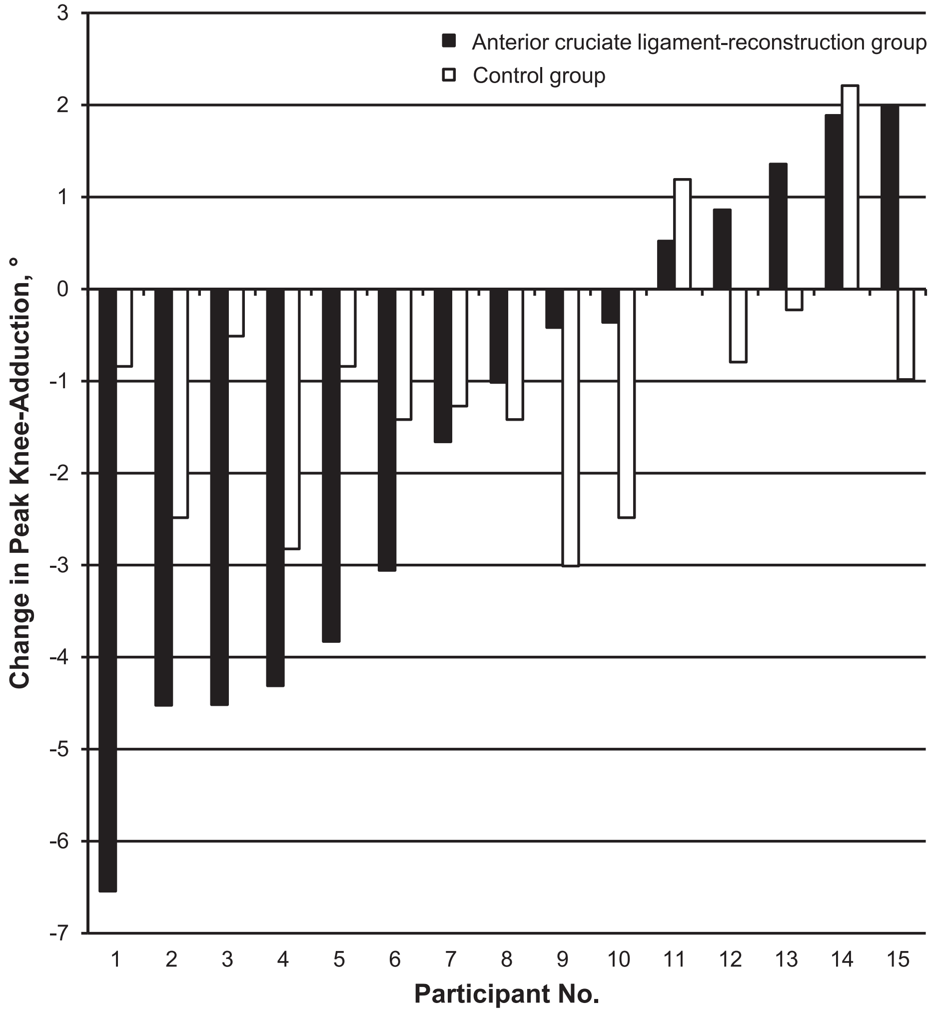

Figure 2. Effect of stroboscopic visual-feedback disruption on knee frontal-plane excursion. Under the stroboscopic visual-feedback disruption condition, a value >0 indicates increased frontal-plane knee excursion toward adduction, and a value <0 indicates increased frontal-plane knee excursion toward abduction.

sizes: *weak* (<0.02), *small* (0.21–0.5), *moderate* (0.51–0.8), or *large* (>0.8). All statistical analyses were conducted using SPSS (version 24.0; IBM Corp, Armonk, NY). The α level was set a priori at $P \leq .05$.

RESULTS

We observed no differences in any dependent variable between sides; therefore, we focused our analysis on the ACLR (always left in this case) and matched control knees. The mean and standard deviation for each variable of interest under each visual condition are presented in Table 3. The SVFD condition induced effects beyond within-session error for knee-flexion and knee-adduction excursion and ground reaction force but not for knee-flexion or knee-abduction moment (Table 1). Knee-flexion excursion increased more under the SVFD condition in participants with ACLR than in controls, but we observed no other kinematic or kinetic differences between groups (Table 2). Figures 1 through 5 display the SVFD effect for each participant with ACLR next to the matched control for each variable of interest.

DISCUSSION

The purpose of our study was to evaluate the effects of SVFD on landing mechanics. Our results suggest that this disruption to visual-motor processing can influence landing motor control.

Sagittal Plane

The primary effect of SVFD was in the sagittal plane, where it induced altered knee excursion during landing. Our finding of increased knee flexion with visual disruption was contrary to reports[42,43] of decreased knee flexion when vision was fully removed in healthy participants. This is likely due to methodologic differences, including no vertical-jump component after landing[42] (our study involved a jump to an in-air target to better simulate sport), increased drop height (our study was set at 30.5 cm, whereas other researchers have used 50 cm[42,43] or variable heights, ranging from 20 to 80 cm[51]), and comparison of only full- and blind-vision conditions with no component of decreased visual input via stroboscopic glasses.[42,43] The limited effect of SVFD, as opposed to fully obscuring vision via a blindfold, may have allowed some of our

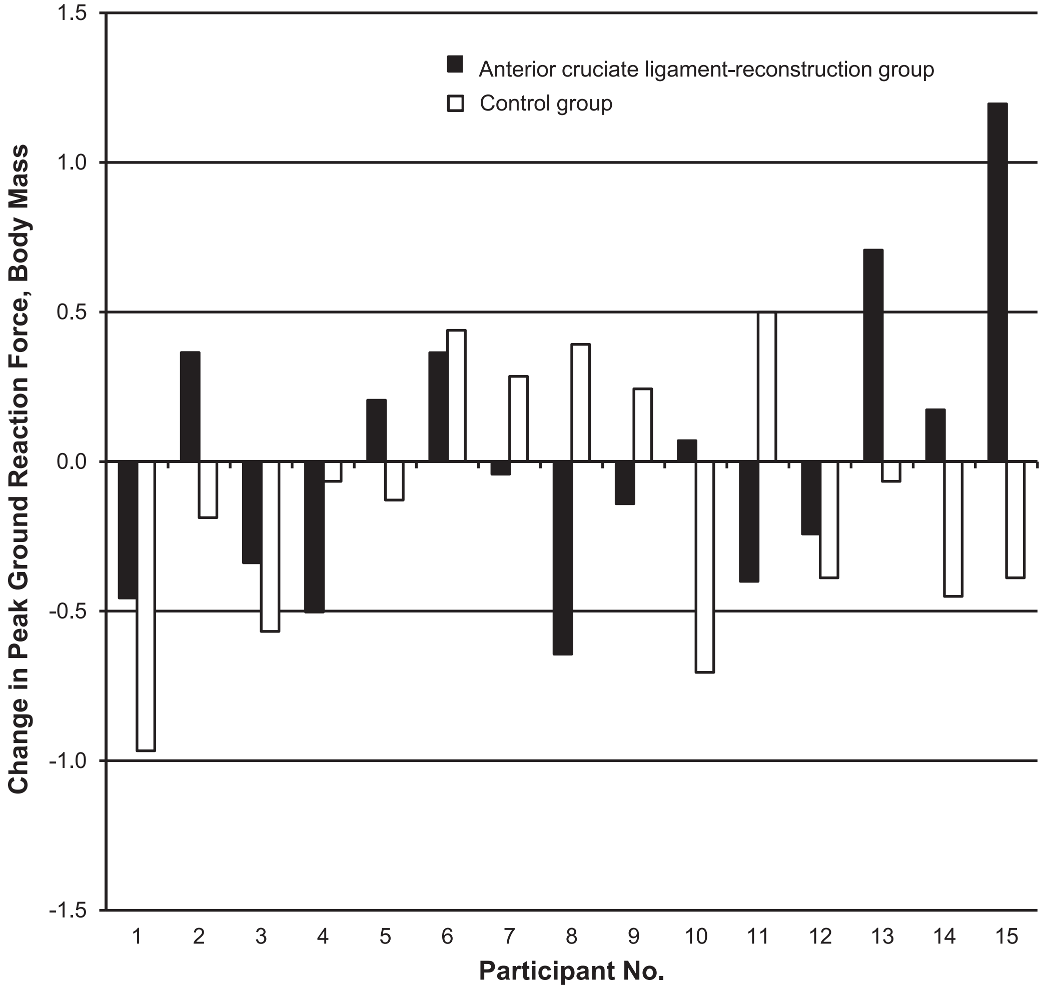

Figure 3. Effect of stroboscopic visual-feedback disruption on peak vertical ground reaction force.

participants to alter motor planning to accommodate the depressed visual feedback and not execute a stiffening strategy as previously reported.

The ACLR pairwise increase in knee-flexion excursion may indicate a specific visual-motor adaption associated with the injury or recovery process. However, some individuals in the control group demonstrated an ACLR-like adaptation in motor control by also increasing knee flexion. Eight participants with ACLR increased knee flexion above the typical error of 3.2°, whereas only 4 control participants experienced a similar change (Figure 1). Although such a small change in knee flexion (absolute mean change of 4°) may seem clinically unimportant, it is on a level similar to an in-flight perturbation, with a 3.1° change in knee flexion due to a 15% body mass lateral perturbation during the drop phase before ground contact.[52] It is also in line with the effects of an in-season neuromuscular injury-prevention training program, with changes in knee flexion of 3.1°,[53] a plyometric–jump-training program effect with a change of 3.0°,[54] and the immediate effects of a landing feedback intervention of 3.5°.[55] Altering knee flexion with SVFD on levels similar to the given examples and a large effect size (Table 2) indicate that visual-motor control may influence knee neuromuscular control on a clinically important level.

Frontal Plane

Knee frontal-plane excursion changed with the visual condition but was not influenced by injury history. The SVFD effect on knee-adduction angle was more consistent regardless of group, with most participants going into more abduction (knee-valgus) excursion during landing due to SVFD. Seven participants with ACLR increased knee-abduction excursion beyond the minimal detectable threshold of 0.9°, whereas only 4 matched control participants experienced a similar increase (Figure 2). The 1.98° absolute change in knee frontal-plane excursion due to disrupted visual feedback is also consistent with previous reports on the effect of a multiweek neuromuscular-training program (1.7° change),[53] a self-feedback intervention (0.96° change),[55] and an in-flight perturbation (2.31° change)[52] and, combined with a moderate effect size, indicates that SVFD may influence frontal-plane knee control generally, with no particular effect for ACLR (Table 2).

Kinetics

The absolute SVFD effect for peak vertical ground reaction force was 38.72% of body mass (large effect size) with no effect of ACLR history (Table 1). This is similar in magnitude to the effects of ACL injury-prevention programs that decrease vertical ground reaction force by

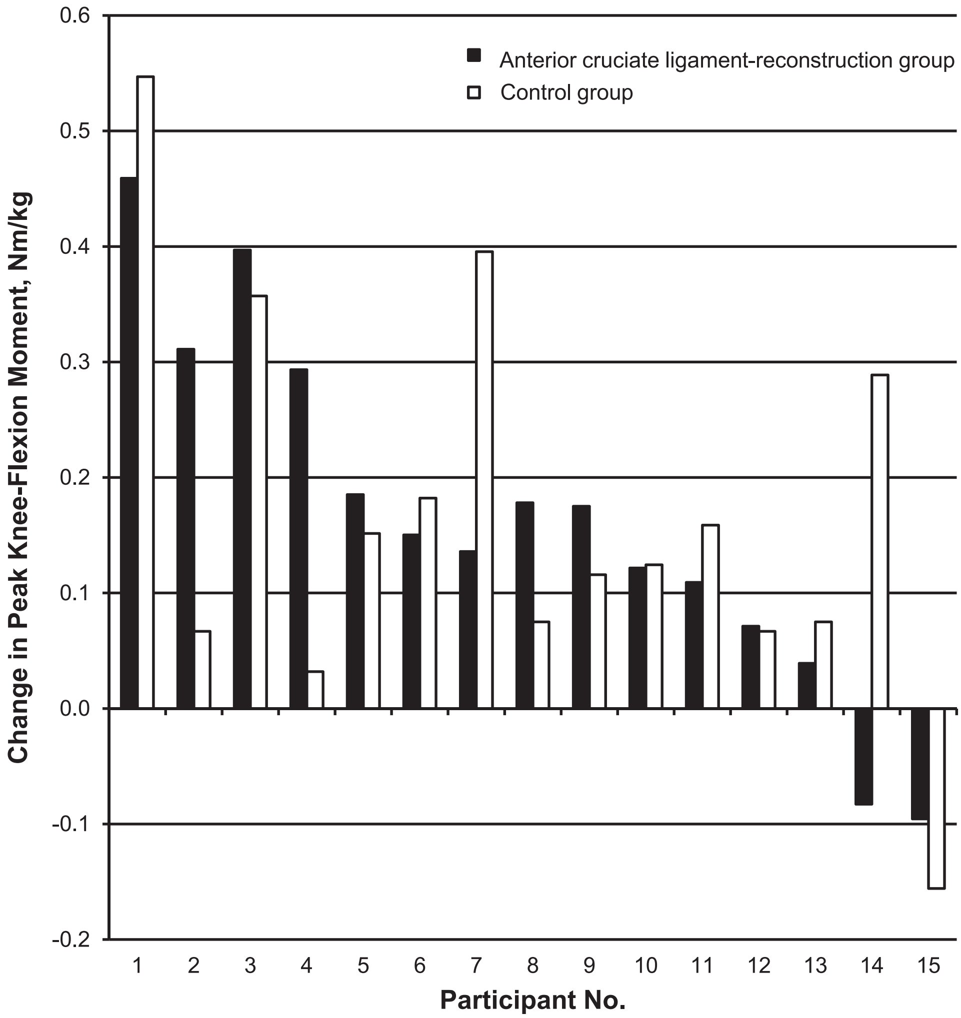

Figure 4. Effect of stroboscopic visual-feedback disruption on peak knee-flexion moment (mass normalized).

18% to 38%.[56] However, the responses to SVFD were more varied, with 18 individuals decreasing and 12 increasing peak vertical ground reaction forces (Figure 3). The SVFD effect on knee sagittal- and frontal-plane peak moments was not greater than the previously reported measurement error, and we observed no difference between the ACLR and control cohorts. We found it interesting that whereas overall, we observed no change in knee-flexion moment in the 1-sample *t* test for the absolute SVFD effect, 16 individuals experienced a change in knee-flexion moment greater than the typical error, with an almost even split between those with ACLR (n = 8) and controls (n = 7; Figure 4). This may warrant further investigation to discover the neuromuscular factors that caused these individuals to respond to the SVFD. The SVFD altered the knee-abduction moment beyond the typical error in only 1 participant with ACLR and no control participants, indicating that SVFD had little effect on knee-abduction moment (Figure 5).

Physical activity and athletic participation place high demands on the visual-motor system to maintain environmental interaction as well as neuromuscular control.[57,58] The alterations in knee mechanics under SVFD indicate that lower extremity landing movement control may be influenced by the amount of visual feedback. Our data further supported the role of visual-motor function on landing motor control; specifically, visual feedback may provide a larger input to sustain sagittal-plane neuromuscular control after ACL injury. It interested us that some individuals demonstrated a movement pattern more dependent on visual feedback for motor control, with larger changes during the SVFD condition, and others experienced little effect. Using SVFD may allow clinicians to replicate the visual-motor demands of the complex athletic environment before return to play.[59–61]

LIMITATIONS

The ACLR cohort was heterogeneous relative to sport and time from surgery. However, despite the cohort's demographic variability, the response to visual disruption was still unique in some ways in the ACLR group. The group heterogeneity was mitigated by the matched-pair design and analysis, and we controlled for any sex, sport, activity-level, or limb-dominance differences between groups in the paired analysis because participants were matched on these key variables that may influence landing mechanics. We selected the study design a priori to scale the visual disruption from none to low and then to high to limit any effects of task novelty from the SVFD. By having participants always perform practice and full-

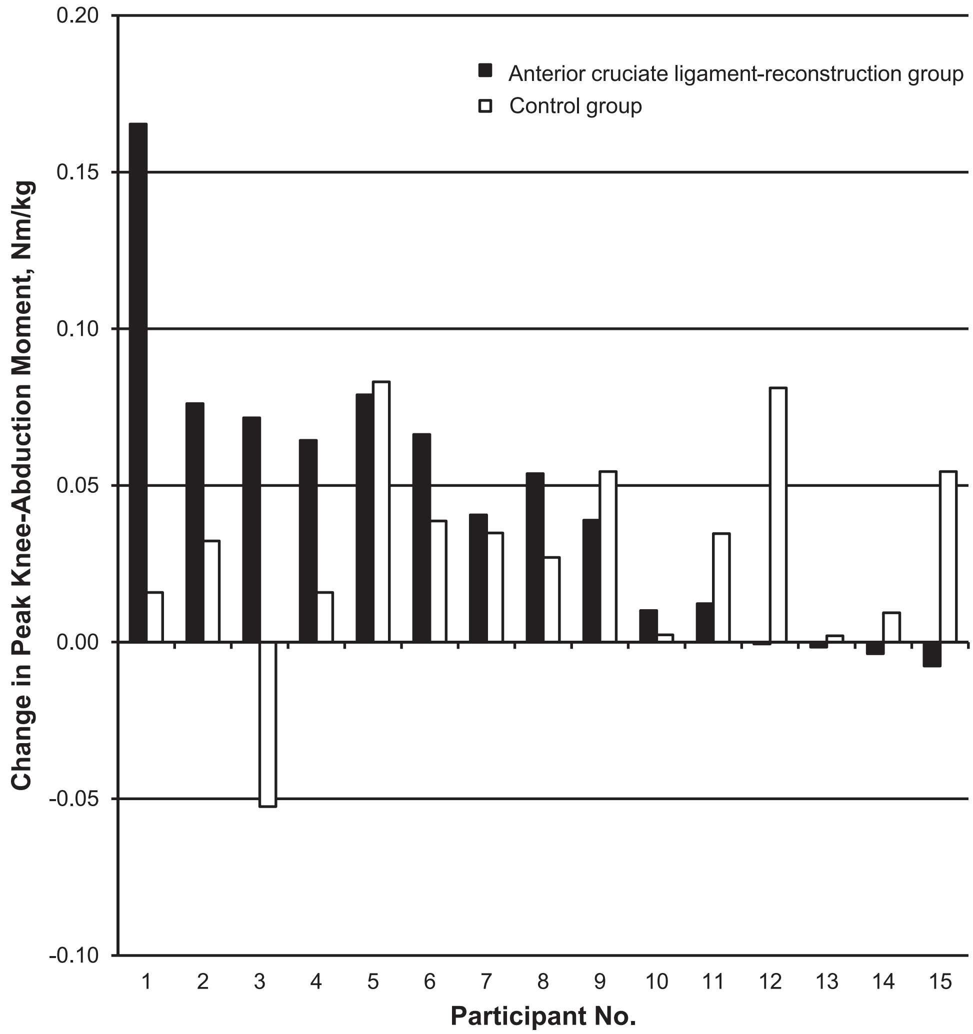

Figure 5. Effect of stroboscopic visual-feedback disruption on peak knee-abduction moment (mass normalized).

Table 3. Drop Vertical-Jump Landing Mechanics by Visual Condition (Mean ± SD)

	Visual Condition		
		Stroboscopic Visual-Feedback Disruption	
Variable	Full Vision	Low	High
Knee-flexion excursion,[a] °			
Right limb	58.46 ± 12.53	59.47 ± 14.09	58.96 ± 14.72
Left limb	54.87 ± 13.78	55.84 ± 15.06	55.62 ± 15.38
Knee-adduction excursion,[a] °			
Right limb	−3.01 ± 5.06	−3.82 ± 4.81	−3.38 ± 5.36
Left limb	−3.28 ± 5.85	−4.29 ± 5.82	−3.89 ± 5.60
Peak external knee-flexion moment, Nm			
Right limb	117.23 ± 41.06	125.51 ± 47.78	123.86 ± 45.15
Left limb	96.97 ± 39.59	108.23 ± 45.25	104.44 ± 40.73
Peak external knee-abduction moment, Nm			
Right limb	11.3 ± 11.26	12.51 ± 11.18	12.99 ± 13.03
Left limb	13.17 ± 9.47	3.78 ± 10.97	114.61 ± 10.58
Peak ground reaction force, body mass			
Right limb	1.95 ± 0.46	2.11 ± 0.58	2.01 ± 0.48
Left limb	1.91 ± 0.35	1.94 ± 0.56	1.77 ± 0.46

[a] Indicates the relative displacement from initial contact to peak stance.

vision test trials first, we ensured they had as much familiarity with the task as possible before their vision was disrupted to limit the effect of task novelty on performance. Simply wearing the stroboscopic glasses can be a sufficient challenge to the neuromuscular control system, and we wanted to avoid the combined challenge of a new task and visual disruption. Conducting the combined practice trials and full-vision trials first ensured a motor pattern that was as stable as possible before inducing visual disruption. In addition, we selected the progressive difficulty to mimic how this technology may be used clinically.

The lack of longitudinal data limited our ability to determine whether any alteration in visual-motor control was present before injury or partially induced by the trauma, surgery, and rehabilitation. Researchers[62–66] have noted altered knee neuromuscular control during visual-motor interactions in healthy active participants. Swanik et al[67] prospectively reported that decreased visual-processing ability increased the risk of experiencing a noncontact ACL injury. The role of visual-motor processing to facilitate preparation of the neuromuscular control system is imperative to sport function, whereby visual feedback must be handled with minimal preparation time.[58,68,69] The

ACLR likely induces increased use of visual feedback to program motion, but such a motor-control strategy may also be present to a degree in healthy individuals and may be accentuated after injury.

FUTURE RESEARCH

The variability in the individual responses indicated that some participants may have had a relative visual-motor processing bias for landing motor control. Capturing other metrics of function, such as proprioception, strength, and psychological factors, may help answer why some participants responded to a greater degree to SVFD. Given that the DVJ is a bilateral task and brain visual processing is not lateralized, we did not detect an SVFD effect for side. More complex or unilateral tasks may be better able to detect variations in visual-motor control after ACL injury. Intervention studies with traditional neuromuscular-control training and visual-motor–focused neuromuscular training may provide a mechanistic understanding of how altering visual-motor processing ability influences landing mechanics.

CONCLUSIONS

Visual-feedback disruption via stroboscopic glasses altered bilateral landing kinematics. Recognizing the visual-motor implications of maintaining neuromuscular control may help clinicians mitigate injury risk beyond traditional measures.[68,69] Using a visual-disruption technology, such as stroboscopic glasses, provides an opportunity to supplement traditional interventions and may more closely mimic the cognitive stress of sport in the clinic.[59–61]

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REFERENCES

1. Spindler KP, Wright RW. Clinical practice: anterior cruciate ligament tear. *N Engl J Med*. 2008;359(20):2135–2142.
2. Mather RC III, Koenig L, Kocher MS, et al. Societal and economic impact of anterior cruciate ligament tears. *J Bone Joint Surg Am*. 2013;95(19):1751–1759.
3. Barenius B, Ponzer S, Shalabi A, Bujak R, Norlén L, Eriksson K. Increased risk of osteoarthritis after anterior cruciate ligament reconstruction: a 14-year follow-up study of a randomized controlled trial. *Am J Sports Med*. 2014;42(5):1049–1057.
4. Lohmander LS, Englund PM, Dahl LL, Roos EM. The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. *Am J Sports Med*. 2007;35(10):1756–1769.
5. Ajuied A, Wong F, Smith C, et al. Anterior cruciate ligament injury and radiologic progression of knee osteoarthritis: a systematic review and meta-analysis. *Am J Sports Med*. 2014;42(9):2242–2252.
6. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clin J Sport Med*. 2012;22(2):116–121.
7. Wright RW, Dunn WR, Amendola A, et al. Risk of tearing the intact anterior cruciate ligament in the contralateral knee and rupturing the anterior cruciate ligament graft during the first 2 years after anterior cruciate ligament reconstruction: a prospective MOON cohort study. *Am J Sports Med*. 2007;35(7):1131–1134.
8. Hui C, Salmon LJ, Kok A, Maeno S, Linklater J, Pinczewski LA. Fifteen-year outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft for "isolated" anterior cruciate ligament tear. *Am J Sports Med*. 2011;39(1):89–98.
9. Paterno MV, Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med*. 2010;38(10):1968–1978.
10. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to the preinjury level of competitive sport after anterior cruciate ligament reconstruction surgery: two-thirds of patients have not returned by 12 months after surgery. *Am J Sports Med*. 2011;39(3):538–543.
11. Grindstaff TL, Hammill RR, Tuzson AE, Hertel J. Neuromuscular control training programs and noncontact anterior cruciate ligament injury rates in female athletes: a numbers-needed-to-treat analysis. *J Athl Train*. 2006;41(4):450–456.
12. Yoo JH, Lim BO, Ha M, et al. A meta-analysis of the effect of neuromuscular training on the prevention of the anterior cruciate ligament injury in female athletes. *Knee Surg Sports Traumatol Arthrosc*. 2010;18(6):824–830.
13. Myer GD, Paterno MV, Ford KR, Hewett TE. Neuromuscular training techniques to target deficits before return to sport after anterior cruciate ligament reconstruction. *J Strength Cond Res*. 2008;22(3):987–1014.
14. Myer GD, Ford KR, Brent JL, Hewett TE. An integrated approach to change the outcome part II: targeted neuromuscular training techniques to reduce identified ACL injury risk factors. *J Strength Cond Res*. 2012;26(8):2272–2292.
15. Gokeler A, Benjaminse A, Hewett TE, et al. Feedback techniques to target functional deficits following anterior cruciate ligament reconstruction: implications for motor control and reduction of second injury risk. *Sports Med*. 2013;43(11):1065–1074.
16. McLean SG. The ACL injury enigma: we can't prevent what we don't understand. *J Athl Train*. 2008;43(5):538–540.
17. Baumeister J, Reinecke K, Schubert M, Weiss M. Altered electrocortical brain activity after ACL reconstruction during force control. *J Orthop Res*. 2011;29(9):1383–1389.
18. Konishi YU. ACL repair might induce further abnormality of gamma loop in the intact side of the quadriceps femoris. *Int J Sports Med*. 2011;32(4):292–296.
19. Madhavan S, Shields RK. Neuromuscular responses in individuals with anterior cruciate ligament repair. *Clin Neurophysiol*. 2011;122(5):997–1004.
20. Grooms DR, Page SJ, Nichols-Larsen DS, Chaudhari AM, White SE, Onate JA. Neuroplasticity associated with anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 2017;47(3):180–189.
21. Lepley AS, Gribble PA, Thomas AC, Tevald MA, Sohn DH, Pietrosimone BG. Quadriceps neural alterations in anterior cruciate ligament reconstructed patients: a 6-month longitudinal investigation. *Scand J Med Sci Sports*. 2015;25(6):828–839.
22. Hall KG, Magill RA. Variability of practice and contextual interference in motor skill learning. *J Mot Behav*. 1995;27(4):299–309.
23. Baumeister J, Reinecke K, Liesen H, Weiss M. Cortical activity of skilled performance in a complex sports related motor task. *Eur J Appl Physiol*. 2008;104(4):625–631.
24. Grooms D, Appelbaum G, Onate J. Neuroplasticity following anterior cruciate ligament injury: a framework for visual-motor

training approaches in rehabilitation. *J Orthop Sports Phys Ther*. 2015;45(5):381–393.
25. Friden T, Roberts D, Movin T, Wredmark T. Function after anterior cruciate ligament injuries: influence of visual control and proprioception. *Acta Orthop Scand*. 1998;69(6):590–594.
26. Kapreli E, Athanasopoulos S, Gliatis J, et al. Anterior cruciate ligament deficiency causes brain plasticity: a functional MRI study. *Am J Sports Med*. 2009;37(12):2419–2426.
27. Grooms DR, Page S, Onate JA. Brain activation for knee movement measured days before second anterior cruciate ligament injury: neuroimaging in musculoskeletal medicine. *J Athl Train*. 2015; 50(10):1005–1010.
28. Bonfim TR, Jansen Paccola CA, Barela JA. Proprioceptive and behavior impairments in individuals with anterior cruciate ligament reconstructed knees. *Arch Phys Med Rehabil*. 2003;84(8):1217–1223.
29. Dingenen B, Janssens L, Claes S, Bellemans J, Staes FF. Postural stability deficits during the transition from double-leg stance to single-leg stance in anterior cruciate ligament reconstructed subjects. *Hum Mov Sci*. 2015;41:46–58.
30. Swanik K, Swanik C, Huxel K, Hamstra K, Tierney R, Hillerstrom H. Gender differences in drop jumps from unknown heights: an EMG and kinematic analysis. *J Athl Train*. 2004;39(suppl 2):S14–S15.
31. Bjornaraa J, Di Fabio RP. Knee kinematics following ACL reconstruction in females: the effect of vision on performance during a cutting task. *Int J Sports Phys Ther*. 2011;6(4):271–284.
32. Magill RA. *Motor Learning and Control: Concepts and Applications*. 8th ed. Boston, MA: McGraw-Hill; 2007.
33. Jamison ST, Pan X, Chaudhari AM. Knee moments during run-to-cut maneuvers are associated with lateral trunk positioning. *J Biomech*. 2012;45(11):1881–1885.
34. Chaudhari AMW, Jamison ST. Trunk control influences run-to-cut but not drop-jump maneuvers: implications for studies on ACL injury mechanics [poster]. *Med Sci Sport Exerc*. 2010;42(5):170.
35. Jamison ST, McNeilan RJ, Young GS, Givens DL, Best TM, Chaudhari AM. Randomized controlled trial of the effects of a trunk stabilization program on trunk control and knee loading. *Med Sci Sports Exerc*. 2012;44(10):1924–1934.
36. 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(4):492–501.
37. Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes: a prospective study. *Am J Sports Med*. 1999;27(6):699–706.
38. Pollard CD, Sigward SM, Powers CM. Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. *Clin Biomech (Bristol, Avon)*. 2010;25(2):142–146.
39. Myer GD, Ford KR, Brent JL, Hewett TE. Differential neuromuscular training effects on ACL injury risk factors in "high-risk" versus "low-risk" athletes. *BMC Musculoskelet Disord*. 2007;8:39.
40. Hewett T, Snyder-Mackler L, Spindler KP. The drop-jump screening test: difference in lower limb control by gender and effect of neuromuscular training in female athletes. *Am J Sports Med*. 2007; 35(1):145–147.
41. Ford KR, Myer GD, Hewett TE. Reliability of landing 3D motion analysis: implications for longitudinal analyses. *Med Sci Sports Exerc*. 2007;39(11):2021–2028.
42. Santello M, McDonagh MJ, Challis JH. Visual and non-visual control of landing movements in humans. *J Physiol*. 2001;537(pt 1): 313–327.
43. Chu Y, Sell TC, Abt JP, et al. Air assault soldiers demonstrate more dangerous landing biomechanics when visual input is removed. *Mil Med*. 2012;177(1):41–47.
44. Appelbaum LG, Schroeder JE, Cain MS, Mitroff SR. Improved visual cognition through stroboscopic training. *Front Psychol*. 2011; 2:276.
45. Appelbaum LG, Cain MS, Schroeder JE, Darling EF, Mitroff SR. Stroboscopic visual training improves information encoding in short-term memory. *Atten Percept Psychophys*. 2012;74(8):1681–1691.
46. Camomilla V, Cereatti A, Vannozzi G, Cappozzo A. An optimized protocol for hip joint centre determination using the functional method. *J Biomech*. 2006;39(6):1096–1106.
47. Cortes N, Blount E, Ringleb S, Onate JA. Soccer-specific video simulation for improving movement assessment. *Sports Biomech*. 2011;10(1):22–34.
48. Wikstrom EA, Tillman MD, Schenker S, Borsa PA. Failed jump landing trials: deficits in neuromuscular control. *Scand J Med Sci Sports*. 2008;18(1):55–61.
49. Cordova ML, Armstrong CW. Reliability of ground reaction forces during a vertical jump: implications for functional strength assessment. *J Athl Train*. 1996;31(4):342–345.
50. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed. Hillsdale, NJ: Lawrence Erlbaum Associates; 1998.
51. Thompson HW, McKinley PA. Landing from a jump: the role of vision when landing from known and unknown heights. *Neuroreport*. 1995;6(3):581–584.
52. Yom JP, Simpson KJ, Arnett SW, Brown CN. The effects of a lateral in-flight perturbation on lower extremity biomechanics during drop landings. *J Appl Biomech*. 2014;30(5):655–662.
53. 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(3):223–227.
54. Hewett TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes: decreased impact forces and increased hamstring torques. *Am J Sports Med*. 1996;24(6):765–773.
55. 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(2):161–171.
56. Padua DA, Distefano LJ. Sagittal plane knee biomechanics and vertical ground reaction forces are modified following ACL injury prevention programs: a systematic review. *Sports Health*. 2009;1(2): 165–173.
57. Wilkerson GB. Neurocognitive reaction time predicts lower extremity sprains and strains. *Int J Athl Ther Train*. 2012;17(6):4–9.
58. 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(3):359–367.
59. Di Stasi S, Myer GD, Hewett TE. Neuromuscular training to target deficits associated with second anterior cruciate ligament injury. *J Orthop Sports Phys Ther*. 2013;43(11):777–792, A1–A11.
60. Smith TQ, Mitroff SR. Stroboscopic training enhances anticipatory timing. *Int J Exerc Sci*. 2012;5(4):344–353.
61. Mitroff S, Friesen P, Bennett D, Yoo H, Reichow A. Enhancing ice hockey skills through stroboscopic visual training: a pilot study. *Athl Train Sports Health Care*. 2013;5(6):261–264.
62. Pollard CD, Davis IM, Hamill J. Influence of gender on hip and knee mechanics during a randomly cued cutting maneuver. *Clin Biomech (Bristol, Avon)*. 2004;19(10):1022–1031.
63. Borotikar BS, Newcomer R, Koppes R, McLean SG. Combined effects of fatigue and decision making on female lower limb landing postures: central and peripheral contributions to ACL injury risk. *Clin Biomech (Bristol, Avon)*. 2008;23(1):81–92.
64. McLean SG, Lipfert SW, van den Bogert AJ. Effect of gender and defensive opponent on the biomechanics of sidestep cutting. *Med Sci Sports Exerc*. 2004;36(6):1008–1016.
65. Brown TN, Palmieri-Smith RM, McLean SG. Sex and limb differences in hip and knee kinematics and kinetics during anticipated and unanticipated jump landings: implications for anterior cruciate ligament injury. *Br J Sports Med*. 2009;43(13): 1049–1056.

66. Ford KR, Myer GD, Smith RL, Byrnes RN, Dopirak SE, Hewett TE. Use of an overhead goal alters vertical jump performance and biomechanics. *J Strength Cond Res*. 2005;19(2):394–399.
67. Swanik CB, Covassin T, Stearne DJ, Schatz P. The relationship between neurocognitive function and noncontact anterior cruciate ligament injuries. *Am J Sports Med*. 2007;35(6):943–948.
68. Harpham JA, Mihalik JP, Littleton AC, Frank BS, Guskiewicz KM. The effect of visual and sensory performance on head impact biomechanics in college football players. *Ann Biomed Eng*. 2014; 42(1):1–10.
69. Mihalik JP, Blackburn JT, Greenwald RM, Cantu RC, Marshall SW, Guskiewicz KM. Collision type and player anticipation affect head impact severity among youth ice hockey players. *Pediatrics*. 2010; 125(6):E1394–E1401.

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