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Literature Review

Effects of augmented feedback on training jump landing tasks for ACL injury prevention: A systematic review and meta-analysis

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ABSTRACT

Objective: Determine if augmented feedback (AF) used during jump landing training can improve ACL biomechanical injury risk factors.

Methods: Articles that used AF in jump landing training were identified through database searches. Pre-identified ACL injury risk parameters were compared between AF and control groups for immediate and delayed (>24 h) post-tests. Standardised effect sizes were determined when kinematic or kinetic data were available.

Results: Fourteen articles were included; four studies using 2D kinematic data were excluded from the meta-analysis as they did not provide kinematic data that were consistent with each other or with the remaining 3D studies. During immediate post-test, peak knee and hip flexion angles (KFA, HFA) and vertical ground reaction force (vGRF) were significantly different between AF and control groups. At retention, peak KFA and vGRF remained significantly different. No significant differences between groups were observed in other parameters. High levels of heterogeneity were detected, likely caused by differences in sex, movement or AF types.

Conclusions: Jump landing training combined with AF was useful in reducing ACL injury parameters related to peak KFA, HFA and vGRF, but had little effect on frontal plane biomechanics. Future work should investigate how different types of AF may affect different participants.

1. Introduction

Anterior cruciate ligament (ACL) rupture is a common knee injury for those that practice sports involving jumping or change of direction (Acevedo, Rivera-Vega, Miranda, & Micheo, 2014). ACL injury has been associated with long-term musculoskeletal complications, including post-traumatic knee osteoarthritis (Lohmander, Englund, Dahl, & Roos, 2007), joint instability (Parikh et al., 2009), and meniscus tears (Sanders et al., 2017). Injury often occurs during jump landing, pivoting, stopping and cutting manoeuvres (Grassi et al., 2017). Potentially modifiable biomechanical injury risk factors have been identified, and include increased knee abduction with a planted foot, internal hip rotation, decreased knee and hip flexion, and high ground reaction forces during the landing phase (Acevedo et al., 2014; Hewett et al., 2005, 2016; Myer, Ford, Khoury, Succop, & Hewett, 2011; Quatman, Quatman-Yates, & Hewett, 2010). Existing injury prevention programs have included a mixture of strength, flexibility and jump training, and have been shown to be effective in reducing ACL injury risk parameters in some populations, e.g. adult women, in the short to medium term (Hewett, Ford, & Myer, 2006; Ter Stege, Dallinga, Benjaminse, & Lemmink, 2014).

The use of augmented feedback (AF) in ACL injury prevention programs has demonstrated positive outcomes on reducing injury risk in recent studies (Acevedo et al., 2014; Hewett et al., 2006a; Kiefer et al., 2014; Myer, Brent, Ford, & Hewett, 2011; Sugimoto et al., 2016; Ter Stege et al., 2014). AF is also known as extrinsic/external feedback that is given during practice, in addition to feedback that is inherent/internal to an individual (Schmidt & Lee,

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2011). Commonly used modes of AF include structured verbal instructions given by a trainer and visual feedback from displays or videos (Onate, Guskiewicz, & Sullivan, 2001). Feedback may have an internal (how to perform a movement, e.g., joint angles) or external (movement effects, e.g., landing impact) focus and provides information that is additional to the individual's own intrinsic feedback from proprioceptive or visual information (Wulf, 2013). AF may involve real-time kinematic/kinetic analysis (Beaulieu & Palmieri-Smith, 2014; Dallinga et al., 2017) or information from an expert (e.g. coach) (Prapavessis & McNair, 1999; Walsh, Waters, & Kersting, 2007). More recently, there have been calls to apply motor learning principles when using AF in ACL injury prevention training to improve learning of lower injury risk movement techniques and enhance skill retention and transfer (Benjaminse et al., 2015a).

Many individual studies have examined effects of using AF in jump landing training (Beaulieu & Palmieri-Smith, 2014; Dallinga et al., 2017; Dowling, Favre, & Andriacchi, 2012; Ericksen et al., 2015, 2016; Etnoyer, Cortes, Ringleb, Van Lunen, & Onate, 2013; Munro et al., 2014; Myer et al., 2013; Nyman et al., 2015; Onate et al., 2001, 2005; Parsons & Alexander, 2012; Prapavessis & McNair, 1999; Tate, Milner, Fairbrother, & Songning, 2013; Walsh et al., 2007). However, it is difficult to determine if AF can augment learning from these studies due to the large variation in the types of AF used, length of training sessions, and the multi-planar nature of outcome measures in these studies. The primary objective of this review was to provide a meta-analytic synthesis of the study findings to determine if the use of AF can enhance learning of safer jump landing techniques. The second objective was to determine which specific biomechanical ACL injury risk parameters could be improved using AF during jump landing training.

Given that an ACL injury is generally the result of multi-planar forces (Quatman et al., 2010), key biomechanical variables examined in this meta-analysis were the kinematic and kinetic parameters in sagittal, frontal and transverse planes and ground reaction forces (Quatman et al., 2010). Separate analyses were conducted for data obtained immediately following the last training session and those delayed (≥24 h) after the last training to assess retention. This enabled evaluation of both short and long-term effects on key injury risk parameters after training jump landing using AF.

Given the known risk factors for ACL injury, improvements in learning would be reflected as: increased knee and hip flexion angles (KFA and HFA), reduced knee and hip external flexion moments, or increased knee and hip extensor moments; reduced knee and hip abduction angles and moments; or reduced vertical ground reaction force (vGRF).

2. Methods

This systematic review was in-line with the Preferred Reporting Items for Systematic review and Meta-Analysis Protocols (PRISMA-P). (Shamseer et al., 2015).

2.1. Data source and search strategy

Five databases were searched: Scopus, MEDLINE, PubMed, Web of Sciences and SPORTDiscus. Key review papers published in recent years were identified using the “cite by” tool on Google Scholar. Three combinations of keywords, combined with the ‘OR’ operator, were used and are listed in Table 1. The search terms within each column of a combination were combined with the ‘OR’ operator; the ‘AND’ operator was used to combine the results from all columns to obtain a final yield. References from identified papers were manually evaluated to ensure all relevant papers were included for data extraction. Accepted information formats included scholarly journals, full conference papers and proceedings. Languages were restricted to English only. Literature searches ended on 31st October 2017.

2.2. Selection criteria

PICOS (Participants, Intervention, Comparators, Outcome and Setting) were defined following the Cochrane handbook (Higgins et al., 2008), and summarised in Table 2. Initial title and abstract screening following these criteria were undertaken by the first author. Full-text article eligibility assessment was conducted by the two authors independently. The selection process is shown in Fig. 1.

2.3. Data extraction and analysis

Categorical (demographic information of participants, motor task learnt, details of AF used for intervention groups and comparator groups) and quantitative data (key ACL kinematic and kinetic parameters in sagittal, frontal and transverse planes and ground reaction forces) were extracted for pre-test, immediate post-test, and at delayed post-test for control and AF groups. A delayed post-test was as at least 24 h after the last training session, to enable assessment of skill retention (Schmidt & Lee, 2011). Authors were contacted when additional numerical data were required.

Meta-analyses were conducted to investigate effects of AF using pre- and immediate post-test differences, and then effects on retention using pre- and delayed post-test differences. Pre- and post-test differences were used in case of significant between-group differences in variables at pre-test. For example, knee flexion angle in Ericksen et al. (Ericksen et al., 2015). Two studies by Ericksen et al. reported the pre- and post-test differences (Ericksen et al., 2015, 2016), while the differences for the remaining studies were calculated using data reported by the authors (Beaulieu & Palmieri-Smith, 2014; Dallinga et al., 2017; Etnoyer et al., 2013; Munro et al., 2014; Onate et al., 2001, 2005; Prapavessis & McNair, 1999; Tate et al., 2013). Means of the differences ($\Delta\mu$) were calculated using Equation (1), along with the SD by Equation (2) ($\Delta\sigma$). Equations (1) and (2) were calculations for paired, pre-post designs, recommended by Borenstein et al. (Borenstein, Hedges, Higgins, & Rothstein, 2009), where $r = 0.5$ was used to reflect the correlation

Table 1
Keywords for database searches.

Keywords	*Types of Feedback*	*Intervention*	*Motor Skills*	*General Field*	*Specific Field*
Combination 1	augmented, extrinsic, external, verbal, visual, video, auditory, haptic, tactile, robot*, multi-modal, multimodal	feedback	jump*, jump-landing, jump landing, plyometric	sport*, exercise*, training	–
Combination 2	augmented, extrinsic, external, verbal, visual, video, auditory, haptic, tactile, robot*, multi-modal, multimodal	feedback	–	sport*, exercise*, training	injur*, prevention
Combination 3	–	feedback	Anterior Cruciate Ligament, ACL	–	prevention, intervention, training

Table 2
Study eligibility - PICOS, inclusion and exclusion criteria.

PICOS	Inclusion Criteria	Exclusion Criteria
Participants	• Neurologically and physically healthy • Man and Woman • Adolescents and adults aged 12–65 years old	–
Intervention	**Augmented Feedback (AF)**: external or extrinsic feedback given during practice (e.g. visual display, sound and/or vibration) of jump landing to reduce ACL injury risk.	AF provided for multiple types of training, making it impossible to identify the effect on jump training only.
Comparator	RCTs & CCTs: changes in key landing biomechanical parameters in the AF groups compared to control groups without AF. Changes were taken from baseline to post-test and retention (if existed).	NCTs or articles without trials.
Outcome	Numerical kinematic and kinetic parameters reported	Scoring systems, e.g., Landing Error Scoring System (LESS) (Welling, Benjaminse, Gokeler, & Otten, 2016)
Setting	Laboratory, home or field	–

RCTs & CCTs: Randomised Control Trials and Clinically Controlled Trials.
NCTs: Non-Controlled Trials.

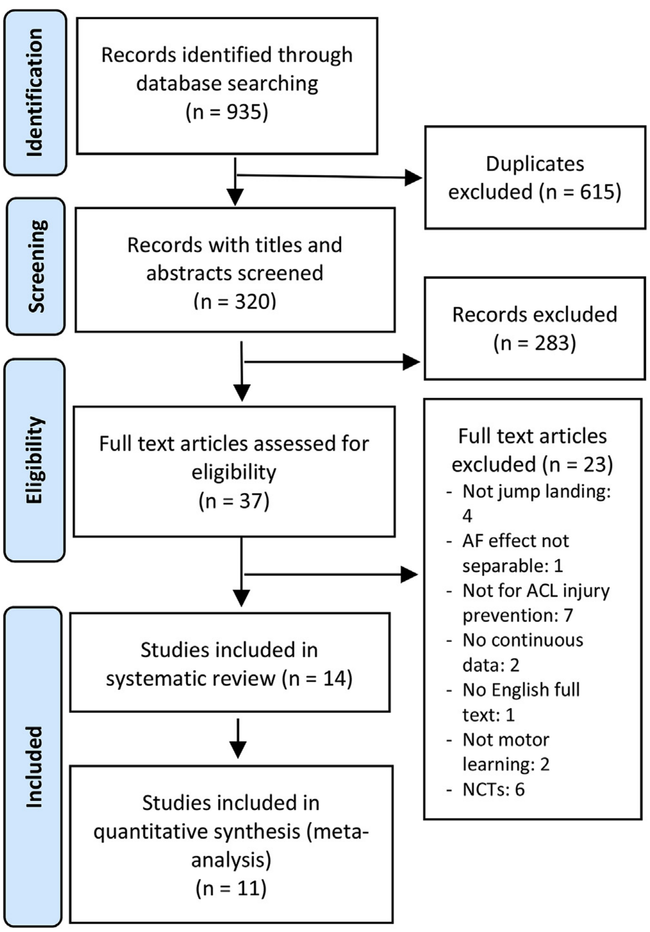

Fig. 1. Systemic Review Information Flowchart (Altered PRISMA Flow Diagram). AF, augmented feedback; NCT, non-randomised controlled trials.

between each participant's scores at pre- and post-tests.

$$\Delta\mu = \mu_{post-test} - \mu_{baseline} \quad (1)$$

$$\Delta\sigma = \sqrt{\sigma^2_{post-test} + \sigma^2_{baseline} - 2r\sigma_{post-test}\sigma_{baseline}} \quad (2)$$

Meta-analyses were undertaken for the dependent variables when data were available from at least two studies. Between-group (AF group vs control group) comparisons were made for these variables, and an overall effect test score of $P \leq 0.01$ indicated a significant between-group difference. The meta-analyses were conducted using Review Manager (RevMan, Version 5.3.) Each intervention group that used a different type of AF from the same study was entered as an individual entry in the meta-analyses. For studies that separated participants based on confounding variables, e.g. sex or limb dominance, the different groups were treated as separate entries in the meta-analyses. For studies that had multiple delayed post-test, the last post-test was used in the meta-analyses. Data were considered heterogeneous if I (Beaulieu & Palmieri-Smith, 2014)>40% and heterogeneity was explored by conducting subgroup analyses (Higgins et al., 2008).

2.4. Risk of biases and level of evidence

A modified version of the Downs and Black quality assessment was used by two reviewers independently to assess the risk of bias for included studies (Downs & Black, 1998). The modified list (Appendix A) included 22 questions from the original checklist: items 1–7, 10 from "*Reporting*"; items 11 and 12 from "*External validity*"; items 14–16, 18–20 from "*Internal validity - bias*; items 21, 23–26 from "*Internal validity - selection bias*; item 27 from "*Power*". Item 27 was changed to "Were appropriate power calculations reported?" and the score was changed from 0 to 5 to 0 or 1 (Kaur, Ribeiro, Theis, Webster, & Sole, 2016). Studies were given the score "1" if a prior power analysis was conducted. Studies with a total score over 65% were considered to have a low risk of bias, and those that scored below 65% were considered to have a high risk of bias (Kaur et al., 2016). Discrepancies between scores by the two reviewers were resolved with consensus meeting. When consensus could not be reached, a third reviewer was consulted.

The level of evidence for each reported variable is defined in Table 3 (van Tulder, Furlan, Bombardier, & Bouter, 2003).

3. Results

3.1. Search results and risk of bias assessment

Of 935 studies found from database searches, 35 were included in full-text eligibility assessment and 14 were included for data extraction. Five authors were contacted for extra data (Dallinga et al., 2017; Ericksen et al., 2015; Parsons & Alexander, 2012; Tate et al., 2013; Walsh et al., 2007). Authors from two studies did not reply and were not included in the meta-analysis (Dallinga et al., 2017; Walsh et al., 2007). Of the 14 studies, 12 were rated as low risk of bias (LR) and two were rated as high risk of bias (HR). Quality assessment results can be found in Appendix A.

Table 3
Level of evidence for each reported variable.

Evidence Level	No. Studies	Quality	Overall Effect	Heterogeneity
Strong	≥3	≥2 RCTs (LR)	–	I (Beaulieu & Palmieri-Smith, 2014) ≤ 40%
Moderate	≥2	1 RCT (LR)	$P \leq 0.01$	I (Beaulieu & Palmieri-Smith, 2014) > 40%
	≥2	≥2 RCTs/CCTs (HR)	–	I (Beaulieu & Palmieri-Smith, 2014) ≤ 40%
Limited	1	1 RCT/CCT (HR)	–	–
Conflicting	≥2	–	$P > 0.01$	I (Beaulieu & Palmieri-Smith, 2014) > 40%

No. Studies, number of studies reported the variable investigated; Quality, quality of the studies that reported this variable; LR, Low risk of bias; HR, high risk of bias; Overall Effect, statistical significance of pooled results.

3.2. Overview of included studies

Of the 14 studies, 12 included randomised controlled trials (RCTs) (Beaulieu & Palmieri-Smith, 2014; Dallinga et al., 2017; Ericksen et al., 2015, 2016; Etnoyer et al., 2013; Myer et al., 2013; Nyman et al., 2015; Onate et al., 2001, 2005; Prapavessis & McNair, 1999; Tate et al., 2013; Walsh et al., 2007) and two included non-randomised clinical controlled trials (CCTs) (Munro et al., 2014; Parsons & Alexander, 2012). Data from three studies were not synthesised due to insufficient 2D kinematic data reported in the sagittal plane, inconsistent definitions of frontal plane kinematic parameters and kinetic data being unattainable (Myer et al., 2013; Parsons & Alexander, 2012; Walsh et al., 2007). The remaining 11 studies were included in the meta-analyses (Beaulieu & Palmieri-Smith, 2014; Dallinga et al., 2017; Ericksen et al., 2015, 2016; Etnoyer et al., 2013; Munro et al., 2014; Nyman et al., 2015; Onate et al., 2001, 2005; Prapavessis & McNair, 1999; Tate et al., 2013) Basic characteristics of the included studies are in Appendix B. In total, 525 participants were included (70% women). Mean ages of participants were between 13 and 25 years. Three studies involved participants who participated in competitive volleyball (Parsons & Alexander, 2012), basketball (Walsh et al., 2007), and gymnastics (Nyman et al., 2015), while the remaining studies involved participants who were healthy and recreationally active (Beaulieu & Palmieri-Smith, 2014; Dallinga et al., 2017; Ericksen et al., 2015, 2016; Etnoyer et al., 2013; Munro et al., 2014; Myer et al., 2013; Onate et al., 2001, 2005; Prapavessis & McNair, 1999; Tate et al., 2013).

Most studies used visual (video, 2D or 3D graphical) and/or verbal feedback, while one used a combination of audio and visual feedback (Nyman et al., 2015). Five studies used concurrent feedback (Beaulieu & Palmieri-Smith, 2014; Ericksen et al., 2015, 2016; Nyman et al., 2015; Tate et al., 2013) and the remainder provided terminal feedback, i.e. at the end of a trial or a block of trials. Eight studies used primarily internally focused feedback (Etnoyer et al., 2013; Munro et al., 2014; Myer et al., 2013; Onate et al., 2001, 2005; Parsons & Alexander, 2012; Prapavessis & McNair, 1999; Walsh et al., 2007), three studies used externally focused feedback only (Beaulieu & Palmieri-Smith, 2014; Dallinga et al., 2017; Tate et al., 2013) and three studies used a combined IF and EF (Ericksen et al., 2015, 2016; Nyman et al., 2015). Key AF information is included in Appendix B.

Data at immediate post-test for AF and control groups were reported in 12 studies. Seven studies also performed delayed post-tests to assess skill retention, although one of these was excluded from meta-analyses as the control group did not complete the retention test (Ericksen et al., 2016). Four of the six studies assessed retention after one week (Dallinga et al., 2017; Onate et al., 2001, 2005; Tate et al., 2013), while the remaining two performed assessments at two-three days and one month (Beaulieu & Palmieri-Smith, 2014; Etnoyer et al., 2013) (Appendix B). Key biomechanical variables (peak and at initial contact) reported by the selected papers are: knee, hip and ankle flexion angles and moments in the sagittal plane (KFA, HFA, ADFA, KFM and HFM); knee and hip abduction angles and moments (KAbA, HAbA, KAbM and HAbM); and vertical ground reaction force (vGRF). An overall effect test score of $P \leq 0.01$ indicated a significant between-group difference.

3.3. Results from studies with two-dimensional kinematic data

Four studies used 2D measurement systems to obtain kinematic data (Munro et al., 2014; Myer et al., 2013; Parsons & Alexander, 2012; Walsh et al., 2007). These data were not subject to meta-analysis due to inconsistencies in the outcome measures used.

Significant improvements in sagittal plane hip and trunk flexion angles in the AF group compared to the control group at delayed post-test were reported in one study that used combined video and verbal feedback (Parsons & Alexander, 2012). Verbal feedback for two groups of men and women was used in another study (Walsh et al., 2007), resulting in no significant changes in sagittal plane parameters for either group compared to their control groups.

Frontal plane kinematics were reported in three studies. Two studies reported significant improvements in frontal plane kinematics for AF groups compared to control groups (Munro et al., 2014; Myer et al., 2013). A significant improvement was found in a woman AF group in minimum knee separation distance; however, no significant improvements in frontal plane knee angles were reported (Walsh et al., 2007).

3.4. Meta-analyses at immediate post-test

A random-effect model was used for the meta-analysis of key ACL injury biomechanical parameters in the sagittal and frontal planes and ground reaction forces. Of 12 parameters measured, only three (peak knee and hip flexion angles and peak vertical ground reaction force) showed significant improvements (Table 4). Forest plots of the parameters which showed no significant changes can be found in Appendix C.

3.4.1. Peak knee flexion angle

Six studies with low risk of bias reported significant increases in peak KFA ($P < 0.01$, Fig. 2a). (Ericksen et al., 2015, 2016; Etnoyer et al., 2013; Nyman et al., 2015; Onate et al., 2005; Tate et al., 2013) There was substantial heterogeneity within the data (*I* (Beaulieu & Palmieri-Smith, 2014) = 70%). Subgroup analyses were conducted to separate data reported by Onate et al. (Onate et al., 2005) from the rest of the studies. Heterogeneity of the remaining combined five studies reduced significantly (*I* (Beaulieu & Palmieri-Smith, 2014) = 41%) but was still at a moderate level. These studies had low risk of bias and together showed a significant increase in KFA (Std MD: 0.98, $P < 0.01$). (Ericksen et al., 2015, 2016; Etnoyer et al., 2013; Nyman et al., 2015; Tate et al., 2013).

Therefore, there was moderate evidence that the AF resulted in significant improvement in peak KFA in training jump-landing tasks at immediate post-test.

Table 4
A summary of meta-analysis comparing ACL injury biomechanical variables in augmented feedback (AF) groups to control groups at immediate post-test.

Variables	Study references	Z	P	Std mean difference	95% CI	I (Beaulieu & Palmieri-Smith, 2014)	Result after AF	Level of evidence
Overall effect								
knee flexion angle (peak)[a]	(Ericksen et al., 2015, 2016; Etnoyer et al., 2013; Nyman et al., 2015; Onate et al., 2005; Tate et al., 2013)	5.10	<0.01	1.38	[0.87, 1.88]	70%	Improved[b]	Moderate
knee flexion angle (IC)	(Etnoyer et al., 2013; Onate et al., 2005; Tate et al., 2013)	0.88	0.38	0.18	[-0.21, 0.56]	26%	No effect	Strong
hip flexion angle (peak)	(Ericksen et al., 2015, 2016; Etnoyer et al., 2013)	5.57	<0.01	0.92	[0.59, 1.24]	0%	Improved	Strong
hip flexion angle (IC)	Etnoyer et al. (2013)	0.59	0.57	–	–	–	No effect	Limited
knee flexion moment (peak)	(Ericksen et al., 2015, 2016; Tate et al., 2013)	0.01	0.99	0.00	[-0.49, 0.5]	52%	No Effect	Conflicting
hip flexion moment (peak)	(Ericksen et al., 2015, 2016)	1.32	0.19	0.25	[-0.12, 0.62]	0%	No effect	Moderate
knee abduction angle (peak)	(Ericksen et al., 2015, 2016; Etnoyer et al., 2013; Tate et al., 2013)	1.81	0.07	0.26	[-0.02, 0.55]	0%	No effect	Strong
hip abduction angle (peak)	(Ericksen et al., 2015, 2016)	0.03	0.21	0.01	[-0.44, 0.45]	33%	No effect	Moderate
knee abduction moment (peak)	(Ericksen et al., 2016; Tate et al., 2013)	1.09	0.28	−0.5	[-1.4, 0.4]	77%	No effect	Conflicting
vGRF (peak)[a]	(Ericksen et al., 2015, 2016; Munro et al., 2014; Onate et al., 2001, 2005; Prapavessis & McNair, 1999; Tate et al., 2013; Walsh et al., 2007)	4.47	<0.01	−0.64	[-0.92, −0.36]	41%	Improved	Moderate

[a] Subgroup analysis was performed for this variable, level of evidence was rated for overall analysis of all subgroups.
[b] An "improvement" would be reflected in increased KFA, HFA and/or ADFA, and/or reductions in the rest of the variables.

3.4.2. Peak hip flexion angle

Three studies with low risk of bias reported that AF groups had increased peak HFA at immediate post-test compared to control groups ($P < 0.01$) (Ericksen et al., 2015, 2016; Etnoyer et al., 2013). Results were statistically homogeneous (*I* (Beaulieu & Palmieri-Smith, 2014) = 0%) (Fig. 2b); therefore, there was strong evidence that peak HFA was increased at immediate post-test with the use of AF.

3.4.3. Peak vertical ground reaction force

Eight studies reported peak vGRF at immediate post-test. Of these, six were with low risk of bias (Ericksen et al., 2015, 2016; Munro et al., 2014; Onate et al., 2005; Tate et al., 2013; Walsh et al., 2007) and two were with high risk of bias (Onate et al., 2001; Prapavessis & McNair, 1999). Results shown in Fig. 2c illustrate that a moderate level of heterogeneity existed (*I* (Beaulieu & Palmieri-Smith, 2014) = 41%). Further subgroup analysis separated studies into verbal feedback only and mixed feedback groups. Results (Fig. 2c) for the verbal feedback only group were statistically homogenous (*I* (Beaulieu & Palmieri-Smith, 2014) = 5%). Therefore, there was strong evidence that the use of verbal feedback significantly reduced peak vGRF (Std. MD: −0.68, $P < 0.01$). The mixed feedback group contained a moderate level of heterogeneity (*I* (Beaulieu & Palmieri-Smith, 2014) = 56%, Fig. 2c), indicating moderate evidence for the use of visual or mixed feedback significantly reducing peak vGRF (Std. MD: −0.6, $P < 0.01$).

3.5. Meta-analyses at delayed post - test

Of the 13 parameters measured, only two parameters (peak KFA; peak vGRF) showed improvements with AF (Table 5). Forest plots of the parameters which showed no significant changes are in Appendix C.

3.5.1. Peak knee flexion angle

Four studies with low risk of bias reported significant increases in peak KFA ($P < 0.01$) (Dallinga et al., 2017; Etnoyer et al., 2013; Onate et al., 2005; Tate et al., 2013). Results were statistically heterogeneous (*I* (Beaulieu & Palmieri-Smith, 2014) = 79%, Fig. 3a). Subgroup analyses were conducted to separate data reported in Onate et al. (Onate et al., 2005) from the rest of the studies. Results without data reported in Onate et al. were homogeneous (*I* (Beaulieu & Palmieri-Smith, 2014) = 0%) and showed a significant increase in KFA ($P < 0.01$). Overall, there was a high level of evidence showing that the use of AF resulted in a significant improvement in peak KFA at retention.

3.5.2. Peak vertical ground reaction force

Of five studies that reported peak vGRF at delayed post-test, four with low risk of bias (Beaulieu & Palmieri-Smith, 2014; Dallinga et al., 2017; Onate et al., 2005; Tate et al., 2013), and one with high risk of bias (Onate et al., 2001). Results were statistically homogeneous (*I* (Beaulieu & Palmieri-Smith, 2014) = 0%) (Fig. 3b). There was strong evidence showing the use of AF reduced the peak vGRF significantly at delayed post-test ($P < 0.01$).

4. Discussion

The primary objective of this review was to examine whether the use of AF could improve ACL injury parameters in jump landing tasks. The included studies were mostly high quality with low risk of bias. The studies primarily focused on women, as women have a higher risk of ACL injury than men (Toth & Cordasco, 2001). The training protocols used in the studies were generally simple: the majority used verbal and/or visual AF, and a small number of training sessions (range: 1–12 sessions). Results of the meta-

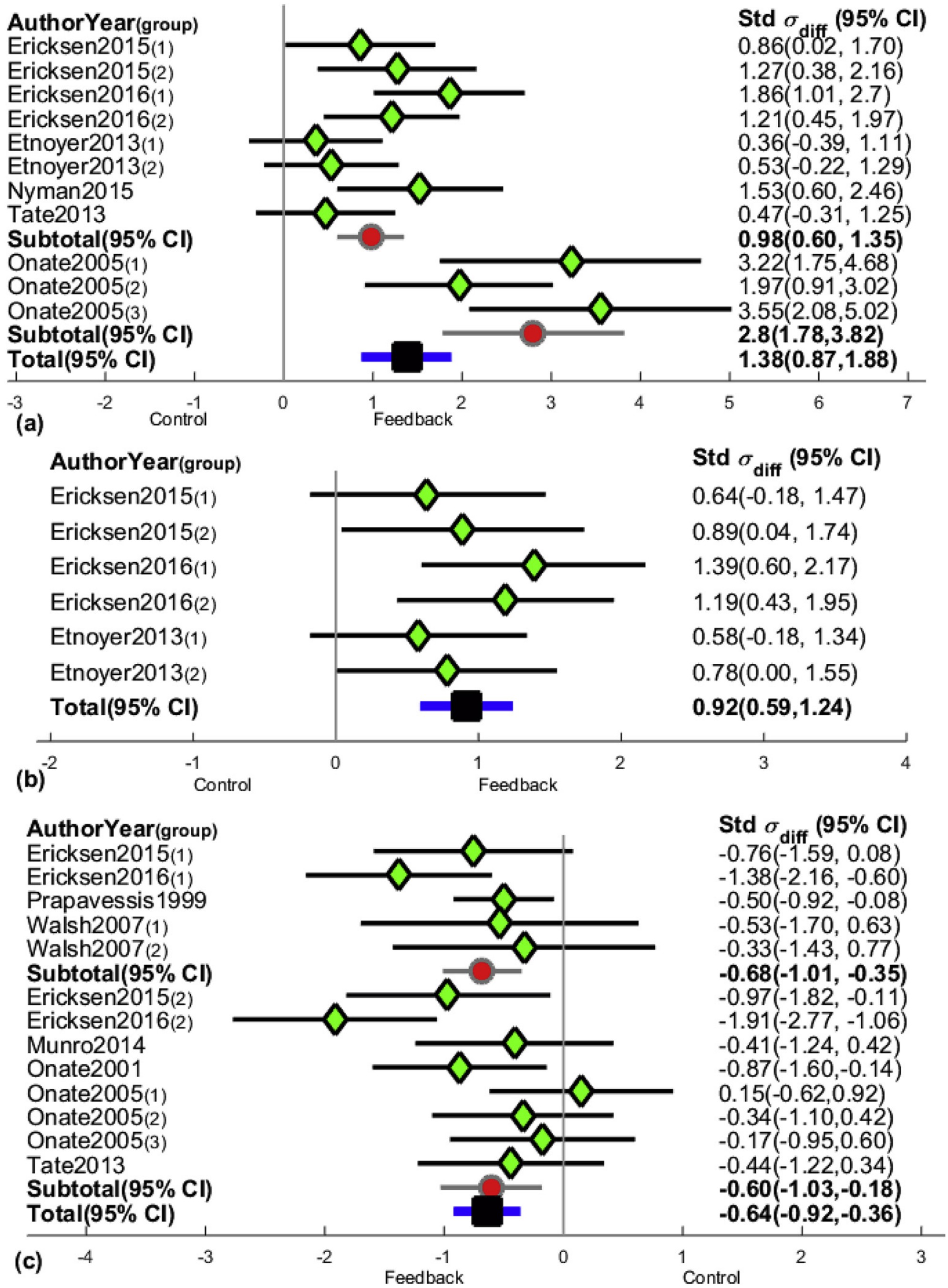

Fig. 2. Forest plot for variables exhibited significant improvements in AF groups during a jump landing phase at immediate post-test: (a) peak knee flexion angle (KFA); (b) peak hip flexion angle (HFA); (c). peak vertical ground reaction force (vGRF).

analyses suggest that AF can lead to significant improvements in peak KFA and vGRF immediately following training, and that improvements are retained. Retention of these improvements suggests the effect of motor learning is relatively permanent, and the athlete is more resilient to an ACL injury when performing risky manoeuvres. Studies have reported shallow knee flexion angles during ACL injury events (Boden, Dean, Feagin, & Garrett, 2000; Cochrane, Lloyd, Buttfield, Seward, & McGivern, 2007; Olsen, Myklebust, Engebretsen, & Bahr, 2004), and a high vGRF was associated with an increased risk of ACL injury (Ericksen, Gribble, Pfile, & Pietrosimone, 2013; Hewett et al., 2005; Hewett & Johnson, 2010). The results suggest that AF can be beneficial for improving these specific risk factors. The use of AF did not result in long-term improvements for other sagittal plane injury parameters. The effects on frontal plane parameters were inconclusive due to measurement inconsistencies, and no transverse plane injury parameters were reported.

There was moderate to strong evidence to suggest that AF can lead to a significant improvement in peak KFA at both immediate and delayed post-test intervals. Significant heterogeneity was introduced to the overall results due to findings by Onate et al. (Onate et al., 2005), potentially because the movement simulated was a basketball snatching jump landing task that differed from the jump tasks used in the other studies. Subgroup analysis of the

Table 5
A Summary of meta-analysis comparing ACL injury biomechanical variables in augmented feedback (AF) groups to control groups at delayed post-test.

Overall effect								
Variables	Study references	Z	P	Std mean difference	95% CI	I (Beaulieu & Palmieri-Smith, 2014)	Result after AF	Level of evidence
knee flexion angle[a] (peak)	(Dallinga et al., 2017; Etnoyer et al., 2013; Onate et al., 2005; Tate et al., 2013)	2.77	<0.01	1.22	[0.52, 1.92]	79%	Improved[b]	Moderate
knee flexion angle (IC)	(Dallinga et al., 2017; Etnoyer et al., 2013; Onate et al., 2005; Tate et al., 2013)	1.48	0.64	0.25	[-0.08, 0.58]	0%	No Effect	Strong
hip flexion angle[a] (peak)	(Dallinga et al., 2017; Etnoyer et al., 2013)	1.42	0.16	0.38	[-0.15, 0.91]	50%	No Effect	Conflicting
knee flexion moment (peak)	(Dallinga et al., 2017; Tate et al., 2013)	1.17	0.24	−0.25	[-0.68, 0.17]	0%	No effect	Moderate
knee abduction angle (peak)	(Beaulieu & Palmieri-Smith, 2014; Etnoyer et al., 2013; Tate et al., 2013)	2.05	0.04	0.37	[0.02, 0.73]	0%	No effect	Strong
knee abduction angle (IC)	(Beaulieu & Palmieri-Smith, 2014; Etnoyer et al., 2013)	0.1	0.92	0.02	[-0.38, 0.42]	0%	No effect	Moderate
knee abduction moment[a] (peak)	(Beaulieu & Palmieri-Smith, 2014; Dallinga et al., 2017; Tate et al., 2013)	1.56	0.12	0.28	[-0.07, 0.63]	0%	No Effect	Strong
vGRF[a] (peak)	(Beaulieu & Palmieri-Smith, 2014; Dallinga et al., 2017; Onate et al., 2001, 2005; Tate et al., 2013)	2.72	<0.01	−0.37	[-0.63, −0.1]	0%	Improved	Strong

[a] Subgroup analysis was performed for this variable, level of evidence was rated for overall analysis of all subgroups.
[b] An "improvement" would be reflected in increased KFA, HFA and/or ADFA, and/or reductions in the rest of the variables.

remaining trials still showed moderate to strong evidence that the use of AF resulted in immediate improvements in KFA and improvements were retained. There was also strong evidence that HFA improved at immediate post-test, however, the improvements were not retained. No improvements were found in other sagittal plane kinematic or kinetic parameters. One possible reason was that the AF provided placed much less emphasis on the hip or trunk compared to the knee. For example, the verbal instruction list used in the studies by Ericksen et al. provided six instructions with only one concerning the hips (Ericksen et al., 2015, 2016), while two other studies provided verbal feedback solely focused on the knees and feet (Prapavessis & McNair, 1999; Walsh et al., 2007). A further two studies using Landing Error Scoring System (LESS) (Welling et al., 2016) based instructions mentioned the hips or trunk less than half of the time (Etnoyer et al., 2013; Munro et al., 2014). It was demonstrated that an increased KFA and HFA are correlated to an increase in energy absorption by the hip extensors during landing, thus minimising strain on the ACL (Norcross, Blackburn, Goerger, & Padua, 2010; Noyes & Barber-Westin, 2018). Small KFAs were found to increase the anterior tibial shear force, which would lead to increases in ACL strain (Sell et al., 2007). Additionally, landing at shallow KFAs has been associated with increased vGRF compared to landing softly with more flexed knees (Devita & Skelly, 1992; McNitt-Gray, Hester, Mathiyakom, & Munkasy, 2001).

There was moderate to strong evidence that the peak vGRF was significantly improved when using AF. The peak vGRF was reported by the majority of the included studies (Beaulieu & Palmieri-Smith, 2014; Dallinga et al., 2017; Ericksen et al., 2015, 2016; Munro et al., 2014; Onate et al., 2001, 2005; Prapavessis & McNair, 1999; Tate et al., 2013; Walsh et al., 2007). Within the included studies, the improvement in vGRF was measurable immediately following training, and was retained regardless of the type of feedback used. This result agrees with findings from a systematic review by Ericksen et al. (Ericksen et al., 2013), where all studies included reported significant decreases in vGRF for all groups that received AF. Further subgroup analysis separated the AF groups into those given verbal feedback only and those with combined AF. Results indicated peak vGRF was reduced significantly even when only verbal feedback was provided (Ericksen et al., 2015, 2016; Prapavessis & McNair, 1999; Walsh et al., 2007). However, the verbal feedback trials were not tested for retention; therefore, the improvement in peak vGRF using verbal feedback was only observable at immediate post-test, whereas trials that included visual feedback showed improvement at immediate and delayed post-tests. These findings are important in reducing non-contact ACL injury risk as vGRF has been repeatedly reported as one of main modifiable biomechanical risk factors (Boden et al., 2000; Hewett et al., 2006b). During a non-contact ACL injury event, the GRF is the only external force applied on the athlete; moments at the knee that cause the injury directly is a result of both GRF (force vector) and position of the body (moment arm) (Hewett & Myer, 2011; Shimokochi & Shultz, 2008; Sigward & Pollard, 2012). In one study, vGRF was found to be 20% higher in a population that had previously sustained an ACL injury compared to a healthy cohort (Hewett et al., 2005). In addition, forward translation of the anterior tibia, which is restricted by the ACL, is increased in acceleration as vGRF is increased (McNair & Marshall, 1994). Therefore, the significant decrease in vGRF using verbal and visual feedback is likely to reduce ACL injury risk.

Furthermore, the meta-analysis results indicated that none of the frontal plane injury risk parameters improved at either immediate or delayed post-test. There was strong evidence that KAbA and KAbM did not improve when using AF. This finding is important because KAbA and KAbM are one of the primary ACL injury risk predictors (Hewett et al., 2005), and the use of AF does not appear to improve them. A lack of improvement in KAbA was partly

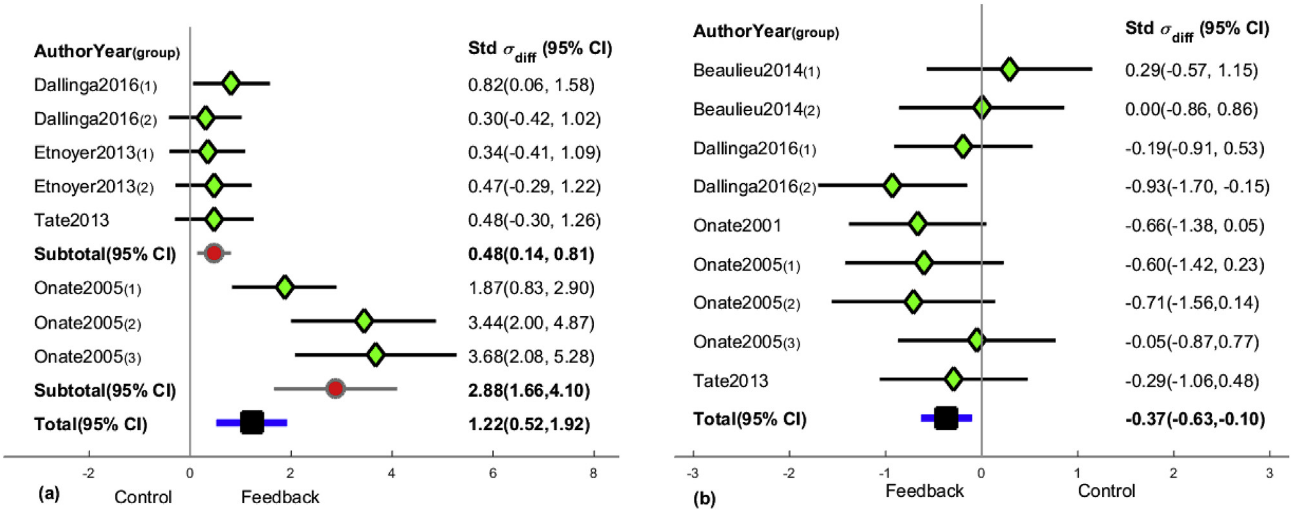

Fig. 3. Forest plot for variables exhibited significant improvements in AF groups during a jump landing phase at delayed post-test: (a) peak knee flexion angle (KFA); (b). peak vertical ground reaction force (vGRF).

because fewer studies reported frontal plane kinematic parameters compared to sagittal plane, e.g. six (Ericksen et al., 2015, 2016; Etnoyer et al., 2013; Nyman et al., 2015; Onate et al., 2005; Tate et al., 2013) and four (Dallinga et al., 2017; Etnoyer et al., 2013; Onate et al., 2001; Tate et al., 2013) studies reported KAbA at immediate and delayed post-tests, compared to four (Ericksen et al., 2015, 2016; Etnoyer et al., 2013; Tate et al., 2013) and three (Beaulieu & Palmieri-Smith, 2014; Etnoyer et al., 2013; Tate et al., 2013) studies reported KAbA at immediate and delayed post-tests. Three studies that used 2-D measurement systems did report improvements in frontal plane knee kinematics (Munro et al., 2014; Myer et al., 2013; Nyman et al., 2015). Unfortunately, these results could not be combined in the meta-analysis as angles were not consistently defined. One study excluded the frontal plane kinematics collected from a volleyball spike landing training due to large measurement error (Parsons & Alexander, 2012).

Moderate to significant levels of heterogeneity were found in KFA, HAbA, KAbM and vGRF, particularly at immediate post-test. Two likely factors contributing to heterogeneity are the use of different types of AF and sex differences. A range of AF interventions were used in the studies, and participants may have responded to them differently, thus resulting in heterogeneity among studies. Two studies used visual feedback only (Beaulieu & Palmieri-Smith, 2014; Dallinga et al., 2017) and two studies used verbal feedback only (Prapavessis & McNair, 1999; Walsh et al., 2007); the rest used a combination of visual and verbal feedback. Additionally, the content of the AF with the same modality differed. For example, the two studies engaging visual feedback only used 2D graphical feedback focused on frontal plane dynamics (Beaulieu & Palmieri-Smith, 2014; Dallinga et al., 2017), whereas several studies used 3D video feedback in both frontal and sagittal planes (Etnoyer et al., 2013; Munro et al., 2014; Myer et al., 2013; Onate et al., 2005). The frequency with which the AF was provided was also different. While most of the included studies provided terminal feedback, several studies included concurrent visual feedback (Beaulieu & Palmieri-Smith, 2014; Dallinga et al., 2017; Ericksen et al., 2015; Etnoyer et al., 2013; Tate et al., 2013). Two studies concluded that the addition of concurrent visual feedback did not improve the ACL risk factors at immediate post-test compared to using terminal verbal feedback only (Ericksen et al., 2015, 2016), but one of the study found that it gave better results for retention (Ericksen et al., 2016). Differences in effects of terminal and concurrent feedback depend on several factors, including the nature of the movement and the participant's ability (Guadagnoli & Lee, 2004). While concurrent feedback can improve learning of complex motor skills (Wulf, Shea, & Matschiner, 1998), it can degrade learning of simple tasks (Maslovat, Brunke, Chua & Franks, 2009; Ranganathan & Newell, 2009). Studies also found that concurrent feedback may help beginners starting to learn (Chiviacowsky, Wulf, de Medeiros, Kaefer, & Wally, 2008; Marchal-Crespo et al., 2015), while experts may benefit more from less frequent terminal feedback (Marchal-Crespo et al., 2015; Moran, Murphy, & Marshall, 2012). The peak vGRF was reported by a sufficient number of studies to provide some insight into how different AF could affect outcome (Beaulieu & Palmieri-Smith, 2014; Dallinga et al., 2017; Ericksen et al., 2015, 2016; Munro et al., 2014; Onate et al., 2001, 2005; Prapavessis & McNair, 1999; Tate et al., 2013; Walsh et al., 2007). Subgroup analysis demonstrated that both verbal feedback and combined feedback groups showed significant reductions in vGRF at immediate post-test. However, most of the heterogeneity lay within the combined feedback group: I (Beaulieu & Palmieri-Smith, 2014) = 56% compared to I (Beaulieu & Palmieri-Smith, 2014) = 5% from the verbal feedback only group. This suggests that participants responded differently to mixed feedback, meaning that some participants may be more sensitive to one mode of feedback than another. One possibility is that women and men responded differently to different feedback. Of the included studies, two investigated effects of the same AF on men and women separately (Dallinga et al., 2017; Walsh et al., 2007). While men improved their jump landing strategy when provided with visual feedback only, women did not (Dallinga et al., 2017). Another study reported significant changes in risk parameters for women using verbal feedback only, whereas no effects were found for men (Walsh et al., 2007). Results from these two studies could not be combined given different reporting of immediate post-test data only, or delayed post-test (one week after the last training session) reporting. Further understanding of differing effects of AF on sex was gained in a recent study on a sidestep manoeuvre, in which visual and verbal feedback were provided separately to women and men basketball players (Benjaminse et al., 2015b). The men responded better than women to the same type of visual feedback; women in the verbal feedback group improved more than those in the visual feedback group, but no difference was found between men and women in the verbal feedback group. It can be concluded from these studies that men may respond better to visual feedback whereas women may benefit from verbal feedback. Future jump landing studies should examine in more depth the type of AF that is the most efficacious for each sex.

In relation to external and internally focused feedback, it was not possible to complete a subgroup analysis of this given the few studies that only provided externally focused feedback. However, it was evident that studies using both internally (Etnoyer et al., 2013; Onate et al., 2001, 2005) and externally (Beaulieu & Palmieri-Smith, 2014; Dallinga et al., 2017; Tate et al., 2013) focused augmented feedback showed beneficial effects as shown by enhanced retention.

5. Limitations

Non-randomised controlled trials (NCTs) were not included in this review. This limited the number of AF modalities investigated. For example, a NCT used drop vertical jump trial testing with concurrent feedback using inertia measurement units, whereas all non-verbal feedback in the included studies were given through camera based measurement systems (Dowling et al., 2012).

The review only explored biomechanics of jump-landing tasks. Sidestepping is also a high-risk movement associated with ACL injury, and could be explored in future reviews (Benjaminse et al., 2015a; Carlson, Sheehan, & Boden, 2016; Dempsey, Elliott, Munro, Steele, & Lloyd, 2014).

Only a limited number of sports were highlighted in the included studies: volleyball, basketball, soccer and gymnastics. The findings may not be applicable to professional athletes from other sports.

This review excluded pre-pubertal and senior participants (age<12 or >65) since it was an initial attempt to understand how AF affects jump training in a general population. Future analyses should include children and seniors.

Studies included in the delayed post-test analyses employed different time periods to assess retention, which may have influenced study findings.

Finally, the literature search and initial title screening were undertaken by a single author; therefore, the robustness of the search was not corroborated by an independent author.

6. Conclusions

The primary outcome of this systematic review was that combined verbal and visual AF strategies resulted in sustained (24 h) improvements in peak KFA and vGRF. ACL injury programs should include both verbal and visual AF for men and women. However, given there was some evidence to suggest men and women respond differently to visual and verbal types of feedback (Benjaminse et al., 2015b; Dallinga et al., 2017; Walsh et al., 2007), optimal individualised feedback strategies are likely needed. The findings are agreeable with several systematic reviews that recommended AF to be integrated to ensure the effectiveness of an ACL injury prevention program (Hewett et al., 2006a; Sugimoto et al., 2016; Ter Stege et al., 2014). What our analysis adds to knowledge on AF is that there is evidence for improved retention with AF, and, based on the findings of two studies, there is evidence of sex differences in the most effective form of AF, although further research is needed to better understand this finding." (Dallinga et al., 2017; Walsh et al., 2007).

AF strategies have less conclusive effects on frontal plane kinematics and kinetics. Meta-analyses of injury risk parameters from studies that used 3D measurement systems did not show significant improvements with the use of AF. However, studies using 2D measurement systems reported improvements in frontal plane knee angles or minimum knee separation distances. More RCTs measuring the same injury parameters should be conducted in the future to determine effects of AF on frontal plane kinematics and kinetics.

Declarations of interest

None.

Ethical approval

None declared.

Conflicts of interest

None.

Ethical approval

Not application.

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Appendix A. Supplementary data

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