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Literature Review

Individuals with chronic ankle instability exhibit dynamic postural stability deficits and altered unilateral landing biomechanics: A systematic review

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ABSTRACT

Objective: To evaluate the literature regarding unilateral landing biomechanics and dynamic postural stability in individuals with and without chronic ankle instability (CAI).
Methods: Four online databases (PubMed, ScienceDirect, Scopus, and SportDiscus) were searched from the earliest records to 31 January 2018, as well as reference sections of related journal articles, to complete the systematic search. Studies investigating the influence of CAI on unilateral landing biomechanics and dynamic postural stability were systematically reviewed and evaluated.
Results: Twenty articles met the criteria and were included in the systematic review. Individuals with CAI were found to have deficits in dynamic postural stability on the affected limb with medium to large effect sizes and altered lower extremity kinematics, most notably in the ankle and knee, with medium to large effect sizes. Additionally, greater loading rates and peak ground reaction forces, in addition to reductions in ankle muscle activity were also found in individuals with CAI during unilateral jump-landing tasks.
Conclusions: Individuals with CAI demonstrate dynamic postural stability deficits, lower extremity kinematic alterations, and reduced neuromuscular control during unilateral jump-landings. These are likely factors that contribute recurrent lateral ankle sprain injuries during dynamic activity in individuals with CAI.

1. Introduction

The lateral ankle sprain is a common orthopedic injury sustained in athletics (Doherty et al., 2014; Roos et al., 2017). While often viewed by the general population as an inconsequential injury that resolves quickly with no long-term consequences, high rates of recurrent injury (Yeung, Chan, So, & Yuan, 1994; van Rijn et al., 2008) and a spectrum of sensorimotor deficits that manifest for months, or even years, post-injury are frequently reported (Hertel, 2002, 2008). Approximately 33% of individuals that sustain a lateral ankle sprain will develop chronic ankle instability (CAI) (Hiller et al., 2011; Tanen, Docherty, Van Der Pol, Simon, & Schrader, 2014), a condition characterized by a continuum of residual impairments resulting in recurrent ankle sprains or episodes of the ankle "giving way" during functional or dynamic activities (Hertel, 2002). In attempt to mitigate time lost due to injury, many athletes do not complete rehabilitative modalities intended to restore the concurrent sensorimotor deficts that manifest following lateral ankle ligament trauma (Roos et al., 2017; Hertel, 2002, 2008), and consequently, leads to subsequent lateral ankle sprain injuries and the development of CAI (Hertel, 2008).

Prior studies provide evidence of centrally mediated alterations resulting in sensorimotor deficits, primarily in alpha motor neuron pool excitability, static postural control, and gait dynamics in individuals affected by CAI (Hass, Bishop, Doidge, & Wikstrom, 2010; Herb et al., 2014; Hertel, 2008; Hiller et al., 2011; Sedory, McVey, Cross, Ingersoll, & Hertel, 2007). Unilateral jump-landings, which impose large and rapid impulse loads to the ankle complex, are a commonly reported dynamic maneuver that initiates the

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mechanism of a lateral ankle sprain (Doherty et al., 2016a; Terada & Gribble, 2015). Impairments in sensorimotor function resulting from the constraints of CAI has been shown to impair dynamic postural stability (Gribble & Robinson, 2009, 2010), movement mechanics (Caulfield & Garrett, 2002; Doherty et al., 2016b) and neuromuscular control (Caulfield, Crammond, O'Sullivan, Reynolds, & Ward, 2004; Delahunt, Monaghan, & Caulfield, 2006) during unilateral jump-landings. Furthermore, proximal segment alterations and reduced neuromuscular control during the preparatory phase of jump-landings highlights that feed-forward motor control, as mediated by spinal or supraspinal mechanisms, may also become changed (Brown, Ross, Mynark, & Guskiewicz, 2004; Caulfield & Garrett, 2002; Doherty et al., 2016b; Gribble & Robinson, 2009; Hass et al., 2010; Monaghan, Delahunt, & Caulfield, 2006). This suggests that the presence of chronic ankle joint instability influences centrally mediated motor control strategies, resulting in maladaptive movement patterns that may increase the risk of recurrent lateral ankle sprains.

While deficits in dynamic postural stability and altered unilateral landing strategies are evident in individuals with CAI, differences in experimental procedures, selection criteria of CAI cohorts, data processing techniques and reported dependent measures across studies makes it difficult to provide an empirical consensus of the dynamic postural stability deficits and altered movement mechanics that manifest in CAI populations. Evaluating differences in unilateral landing biomechanics will further assist researchers and clinicians in the development of effective rehabilitation programs intended to improve dynamic postural stability and alter movement mechanics in individuals affected by CAI. Accordingly, this study sought to systematically review and evaluate the literature to determine if individuals with CAI demonstrate altered unilateral landing biomechanics and deficits in dynamic postural stability in comparison to individuals without CAI. It was hypothesized that individuals with CAI would exhibit deficits in dynamic postural stability and altered unilateral landing biomechanics in comparison to healthy controls and/or ankle sprain copers.

2. Methods

2.1. Search strategy

A systematic search strategy was performed to identify studies to examine dynamic postural stability and unilateral jump-landing biomechanics in individuals with and without CAI in which the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines were followed (Moher, Liberati, Tetzlaff, Altman, & Group, 2010). The online databases of PubMed, ScienceDirect, Scopus, and SportDiscus were searched from the earliest records until 31 January 2018. Key words such as chronic ankle instability, functional and mechanical instability, ankle sprain, single leg landing, and drop-landing were used independently, or in combination. Reference sections of manuscripts that were identified in the literature search were also searched for additional publications.

2.2. Eligibility criteria

Eligibility of studies that were discovered during the original systematic search was determined by two investigators using detailed inclusion and exclusion criteria. All study titles and abstracts of identified articles were thoroughly screened for eligibility. Furthermore, when titles or abstracts did not provide adequate information for eligibility, full text articles were examined by the same two investigators. If no agreement between the two investigators could be reached regarding eligibility a third investigator decided the outcome.

The following inclusion criteria was implemented to screen studies for eligibility: articles with a cross-sectional study design; articles with participants that had a history of at least one ankle sprain injury and classified as having CAI, functional instability, or mechanical instability; articles reporting dynamic postural stability, kinematic, kinetic, and/or muscle activity variables during a unilateral jump-landing task; articles that provided a control vs. CAI and/or an ankle sprain coper vs. CAI between group comparison; peer-reviewed full-text manuscripts.

The following exclusion criteria were also implemented to screen studies: articles that implemented a prospective cohort study design; articles that investigated landing biomechanics following an initial ankle sprain injury; articles that investigated the effects of prophylactic bracing on landing biomechanics in individuals with and without CAI; articles that examined kinematic, kinetic, and/or muscle activity variables during bilateral jumping or hopping tasks; articles that investigated the effects of fatigue on landing biomechanics; published abstracts, conference proceedings, or position statements.

2.3. Quality and risk of bias assessment

Studies that met the inclusion criteria and included in the systematic review were assessed for quality and risk of bias using the Quality Index check list (Downs & Black, 1998). Although several items of the check list were not applicable to the current systematic review, we adopted a modified version of the Quality Index checklist that has previously been used in a recent systematic review examining the effects of CAI on walking and running biomechanics (Moisan, Descarreaux, & Cantin, 2017). This resulted in 14 out of 27 checklist items (1,2,3,5,6,7,10, 11, 12,16, 18, 20,21,22) that were used to assess the methodological quality and reporting bias. The same two investigators that assessed studies for eligibility also scored each study that was included in the systematic review. If disagreements on scores greater than 10% occurred, the two investigators discussed the differences to reach a final decision. In the instance that a final decision could not be determined, a third investigator decided the outcome. Studies that met the inclusion criteria and scored greater than 50% on the modified Quality Index assessment were included in this review.

2.4. Data extraction

Each study that met the inclusion criteria and scored greater than 50% on the Quality Index assessment had the following data extracted and merged into summary tables: type of study design, participant cohorts, sample size, jump-landing task, main dependent variables, and significant findings with *p*-values. Cohen's D effect sizes (ES) were also merged into the summary table if raw data was available to the investigators or it was already reported in the articles. When raw data was available, ES were calculated by dividing the raw difference in means by the pooled standard deviation of each group (Cohen, 1992).

3. Results

3.1. Search results

The initial search provided a total of 862 potential articles, which resulted in 595 being kept for title and abstract screening after duplicates were removed. Title and abstract screening reduced the number of potential articles to 56, which underwent full-text review. After consideration of the previously mentioned selection criteria, the modified Quality Index checklist was used to assess for risk of bias in 20 studies that met the eligibility criteria. All 20 studies that met the inclusion criteria scored greater than 50% on the modified Quality Index checklist and were kept for data extraction. No additional studies were identified from the reference sections of the articles that underwent full-text review. A comprehensive flow diagram of the study selectin process, as recommended by PRISMA (Moher et al., 2010), is presented in Fig. 1.

3.2. Quality assessment

The modified Quality Index check list yielded an average quality 74 ± 8% for all articles included in this review. Quality of the studies ranged from 60 to 93% and the observed agreement between both raters was 97%. During the consensus meeting between the two investigators, agreement was reached regarding the 8 items that provided different ratings resulting in a final agreement of 100% between raters. A total of 16 out of 20 articles scored greater than 70% and results from the Quality Index check listed indicated that the internal validity (items 21 and 22) were the greatest limitation of the included studies.

3.3. Dynamic postural stability

Eleven studies in this review examined dynamic postural stability during a unilateral jump-landing task (Brown, Bowser, & Orellana, 2010, 2004; Gribble & Robinson, 2009, 2010; Kunugi, Masunari, Yoshida, & Miyakawa, 2017; Ross & Guskiewicz, 2004; Ross, Guskiewicz, & Yu, 2005; Shiravi, Shadmehr, Moghadam, & Moghadam, 2017; Wikstrom et al., 2010, 2007; Wright, Arnold, & Ross, 2016). A total of 7 studies quantified dynamic postural stability using time to stabilization (TTS) (Brown et al., 2004; Gribble & Robinson, 2009, 2010; Kunugi et al., 2017; Ross & Guskiewicz, 2004; Ross et al., 2005; Wright et al., 2016), while 4 studies used the dynamic postural stability index (DPSI) (Brown et al., 2010; Shiravi et al., 2017; Wikstrom et al., 2010, 2007). Seven studies used a 70-cm anterior stop jump (Gribble & Robinson, 2009, 2010; Brown et al., 2004; Ross & Guskiewicz, 2004; Ross et al., 2005; Wikstrom, Tillman, Chmielewski, Cauraugh, & Borsa, 2007, 2010), one study used a 70 cm jump-landing in multiple directions (Brown et al., 2010), while one used a drop landing from a height of 40 cm (Wright et al., 2016).

Significantly longer TTS in the anterior/posterior or medial/

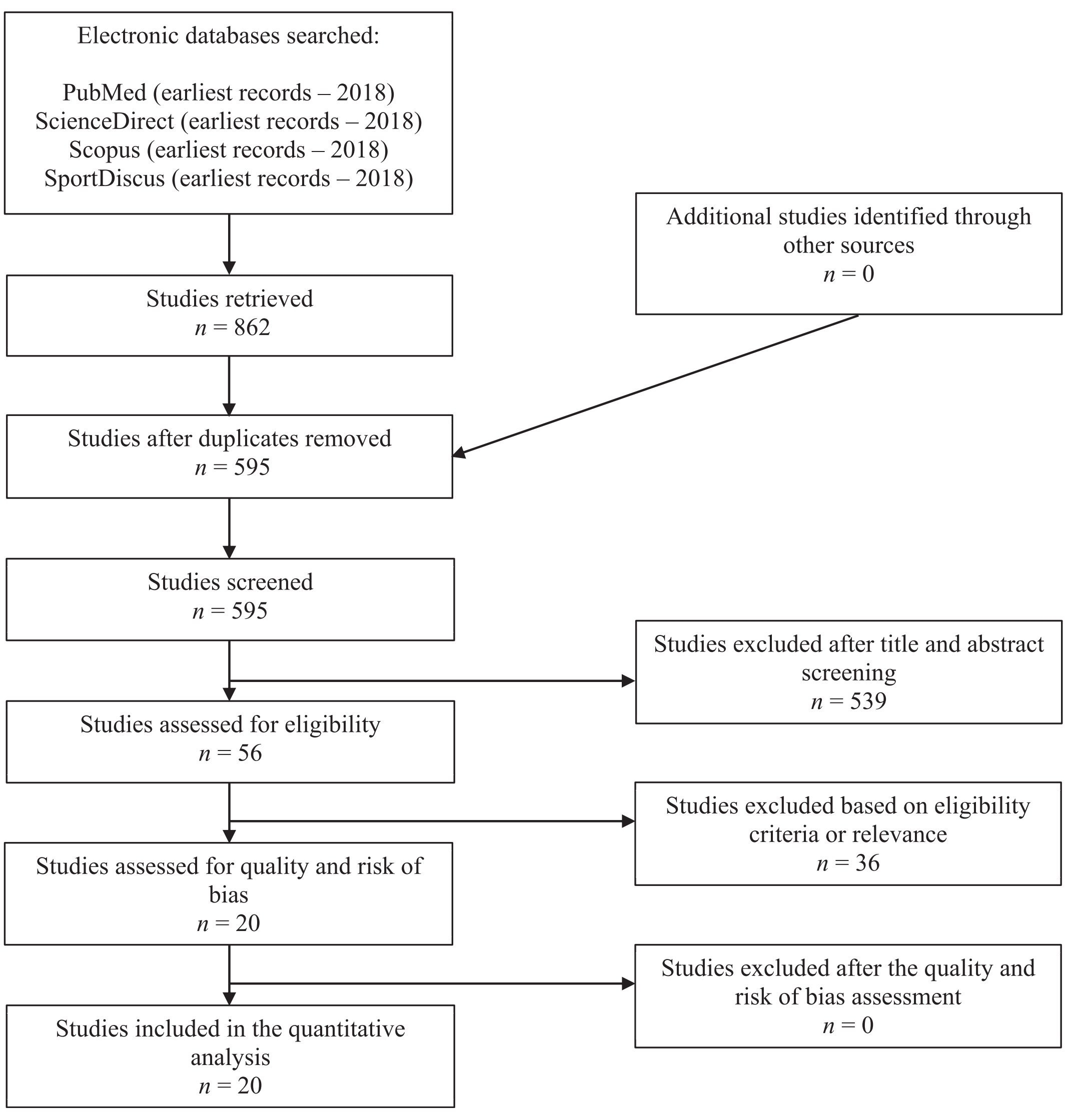

Fig. 1. Flow diagram of the study selection process.

lateral directions in individuals with CAI was found in multiple studies (Brown et al., 2004; Gribble & Robinson, 2009; Kunugi et al., 2017; Ross et al., 2005; Wright et al., 2016), while two studies reported significantly longer TTS in both anterior/posterior and medial/lateral directions (Gribble & Robinson, 2010; Ross & Guskiewicz, 2004). Increased anterior/posterior (Wikstrom et al., 2007, 2010), vertical (Brown et al., 2010; Wikstrom et al., 2007), and composite DPSI (Brown et al., 2010; Wikstrom et al., 2007, 2010) scores were also reported for individuals with CAI compared to controls. Effect sizes for studies examining dynamic postural stability ranged from moderate to large effects (0.45–4.57). Table 1 provides a summary of studies reporting dynamic postural stability during a unilateral jump-landing task.

3.4. Kinematics

Ten studies included in this review examined kinematics during a unilateral jump-landing task (Brown, Bowser, & Simpson, 2012, 2008; Caulfield & Garrett, 2002; De Ridder, Willems, Vanrenterghem, Robinson, & Roosen, 2015; Doherty et al., 2016b; Gribble & Robinson, 2009, 2010; Kipp & Palmieri-Smith, 2012; Monaghan et al., 2006; Wright et al., 2016). A drop landing task ranging from heights of 32–40 cm was utilized in 5 of the 10 studies (Brown, Padua, Marshall, & Guskiewicz, 2008; Caulfield & Garrett, 2002; Doherty et al., 2016b; Monaghan et al., 2006; Wright et al., 2016). Stop jumps of 70-cm in the anterior direction were utilized in 4 of the 10 studies (De Ridder et al., 2015; Gribble & Robinson, 2009, 2010; Kipp & Palmieri-Smith, 2012), while only one study investigated a stop jump task in the anterior, lateral, and medial directions (Brown et al., 2012). Out of the 10 studies that reported lower extremity kinematic parameters, 6 studies (Brown et al., 2012; De Ridder et al., 2015; Doherty et al., 2016b; Gribble & Robinson, 2009, 2010; Monaghan et al., 2006) reported ankle, knee, and hip kinematics, one study (Caulfield & Garrett, 2002) reported ankle and knee kinematics, while the remaining 3 studies (Brown et al., 2008; Kipp & Palmieri-Smith, 2012; Wright et al., 2016) reported only ankle kinematics. Moreover, 4 studies (Brown et al., 2012; De Ridder et al., 2015; Doherty et al., 2016b; Monaghan et al., 2006) reported kinematics in the sagittal, frontal, and transverse planes, 3 studies (Brown et al., 2008; Kipp & Palmieri-Smith, 2012; Wright et al., 2016) reported sagittal and frontal plane kinematics, while the remaining 3 studies (Caulfield & Garrett, 2002; Gribble & Robinson, 2009, 2010) only reported sagittal plane kinematics.

At the ankle, individuals with CAI demonstrated greater dorsiflexion (Brown et al., 2008; Caulfield & Garrett, 2002; Wright et al., 2016) and inversion (Monaghan et al., 2006) angles during various phases pre-landing to post-landing of the unilateral landing task. Additionally, significant reductions in sagittal plane displacement and angular velocity at the ankle was also found post-landing in the CAI group (Brown et al., 2008; Monaghan et al., 2006). However, Brown et al. reported greater angles of ankle eversion in participants with MI compared to FI and copers during a drop landings (Brown et al., 2008), while other studies did not report significant differences in frontal plane ankle kinematics between CAI and control groups (Doherty et al., 2016b; Wright et al., 2016). Regarding the knee, Caufield and Garrett reported the CAI group demonstrated significantly greater knee flexion angles 20 ms pre-landing to 60 ms post-landing in comparison to controls (Caulfield & Garrett, 2002), while other studies did not report significant differences in sagittal plane knee kinematics (Doherty et al., 2016b; Monaghan et al., 2006). Finally, Doherty et al. reported significantly greater hip flexion in individuals with CAI 148 ms pre-landing to 4 ms post-landing compared to an ankle sprain coper group (Doherty et al., 2016b). While Delahunt et al. did not find significant differences in hip flexion pre-landing to post-landing between CAI and controls (Monaghan et al., 2006), greater hip internal rotation 200 to 55 ms pre-landing was noted in CAI participants (Doherty et al., 2016b).

Regarding studies examining unilateral stop jump kinematics, significantly greater inter-trial sagittal and frontal plane ankle variability was found in participants with CAI (Kipp & Palmieri-Smith, 2012). However, Brown et al. reported that there was no difference in ankle kinematic variability in the anterior, lateral, and medial stop jumps between MI, FI, coper, and controls (Brown et al., 2012). No studies reported significant differences in sagittal or frontal plane ankle angles pre-landing to post-landing, peak angles, or time to peak angles between CAI and control groups (De Ridder et al., 2015; Gribble & Robinson, 2009, 2010). At the knee, individuals with FI had significantly less internal/external rotation variability pre-landing during an anterior stop jump in comparison to controls, while also demonstrating less internal/external rotation variability post-landing during stop jumps in the anterior, medial, and lateral directions (Brown et al., 2012). Greater knee extension angles have also been observed pre-landing in CAI groups in comparison to controls (Gribble & Robinson, 2009, 2010). However, no significant differences in knee kinematic patterns, peak knee flexion at initial contact, or time to peak knee flexion post-landing were observed (De Ridder et al., 2015; Gribble & Robinson, 2009, 2010). Regarding hip kinematics, Brown et al. reported that MI, FI, and ankle sprain coper groups exhibited significantly less hip flexion variability pre-landing for all directions of the stop jump task (Brown et al., 2012). Furthermore, both MI and FI groups displayed significantly less hip abduction variability post-landing in comparison to controls (Brown et al., 2012). Summaries and estimated ES related to studies reporting kinematics during unilateral jump-landing tasks are presented in Table 2.

3.5. Muscle activity

Four studies included in this review examined neuromuscular activity during unilateral drop landings or stop jump tasks (Brown et al., 2004; Caulfield et al., 2004; Kunugi et al., 2017; Monaghan et al., 2006). Unilateral drop landings ranging from heights of 35–40 cm were utilized in 2 of the 3 studies (Caulfield et al., 2004; Monaghan et al., 2006), while the other study utilized a 70-cm anterior stop jump task (Brown et al., 2004). All studies reported tibialis anterior, peroneus longus, soleus, and gastrocnemius neuromuscular activity pre-landing to post-landing (Brown et al., 2004; Caulfield et al., 2004; Monaghan et al., 2006), while one study also reported peroneus brevis muscle activity pre-to post-landing (Kunugi et al., 2017). Out of the four studies that examined neuromuscular activity during a unilateral landing, only a single study reported neuromuscular activity proximal to the ankle, which was from the rectus femoris pre-landing to post-landing (Monaghan et al., 2006).

One study reported significantly less activity of the peroneus longus on the affected limb during the 150 ms pre-landing (Caulfield et al., 2004), while another study also reported significant reductions in peroneus longus activity during the 200 ms pre-landing on the affected limb in individuals with CAI during a drop landing when compared to healthy controls (ES:0.98–2.53) (Caulfield et al., 2004; Monaghan et al., 2006). Significant reductions in soleus activity on the affected limb was also noted on the affected limb in individuals with CAI during the 100 ms post-landing phase during an anterior stop jump (Brown et al., 2004). Summaries and estimated ES in studies reporting neuromuscular activity during unilateral landing tasks are presented in Table 3.

Table 1
Summary of studies that examined dynamic postural stability.

Author(s)	Study Design	Participants	Landing Task	Outcome Variables	Main Results
Brown et al. 2004	Cross-sectional	$n = 20$ Control 10 FI 10	Anterior unilateral SJ on affected limb	ML and AP components of TTS	FI had longer TTS in the AP direction ($p = 0.001$, ES = 2.27). No group difference in ML TTS ($p = 0.29$)
Brown et al. 2010	Cross-sectional	$n = 48$ Control 24 CAI 24	Anterior, medial, & lateral unilateral SJ	DPSI for each jump direction	*Anterior:* CAI had greater VSI ($p = 0.04$, ES = 0.57) and DPSI ($p = 0.04$, ES = 0.56) scores than controls. No difference in MLSI ($p = 0.96$) or APSI ($p = 0.63$) CAI and controls. *Lateral:* CAI had greater VSI ($p = 0.04$, ES = 0.53) and DPSI ($p = 0.04$, ES = 0.53) scores than controls. No difference in MLSI ($p = 0.32$) or APSI ($p = 0.50$) CAI and controls. *Medial:* No group differences in MLSI ($p = 0.94$), APSI ($p = 0.29$), VSI ($p = 0.18$) or DPSI ($p = 0.16$).
Gribble & Robinson 2010	Cross-sectional	$n = 38$ Control 19 CAI 19	Anterior unilateral SJ on both limbs	RV component of TTS	CAI had a greater RVTTS compared to controls ($p = 0.03$, ES = 0.76).
Gribble & Robinson, 2009	Cross-sectional	$n = 38$ Control 19 CAI 19	Anterior unilateral SJ on both limbs	ML and AP components of TTS	CAI had longer AP TTS affected limb compared to controls ($p = 0.003$, ES = 4.57). No limb × group interaction or main effects in ML TTS ($p > 0.05$).
Kunugi et al. 2017	Cross-sectional	$n = 22$ Control 11 FI 11	Diagonal unilateral SJ on affected limb	ML and AP components of TTS	FI had longer TTS ML (p = 0.010; ES = 1.08) compared to control. No group difference in TTS AP ($p = 0.390$; ES = 0.39).
Ross & Guskiewicz 2004	Cross-sectional	$n = 28$ Control 14 FI 14	Anterior unilateral SJ on affected limb	ML and AP components of TTS	FI had longer TTS in AP ($p < 0.001$, ES = 1.79) and ML ($p = 0.04$, ES = 0.83) compared to the control group.
Ross et al. 2005	Cross-sectional	$n = 20$ Control 10 FI 10	Anterior unilateral SJ on affected limb	ML and AP components of TTS	FI had longer AP ($p = 0.030$, ES = 0.40) and ML TTS ($p = 0.02$, ES = 0.30) compared to controls.
Shiravi et al. 2017	Cross-sectional	$n = 24$ Control 12 CAI 12	Lateral unilateral SJ on both limbs	Each component of DPSI	No significant group × limb interactions or main effects for group or limb for each component of DPSI ($p > 0.05$).
Wikstrom et al. 2007	Cross-sectional	$n = 108$ Control 54 FI 54	Anterior unilateral SJ on affected limb	Each component of DPSI	CAI had greater APSI ($p < 0.01$, ES = 0.73), VSI ($p < 0.01$, ES = 0.74), and DPSI ($p < 0.01$, ES = 0.73) compared to controls.
Wikstrom et al. 2010	Cross-sectional	$n = 72$ Control 24 Copers 24 CAI 24	Anterior unilateral SJ on affected limb	Each component of DPSI	Coper and CAI groups had a greater APSI ($p < 0.05$, ES = 1.20) & DSPI ($p < 0.05$, ES = 0.56) compared to controls. CAI had greater MLSI than copers ($p < 0.05$, ES = 0.45).
Wright et al. 2016	Cross-sectional	$n = 69$ Control 23 Copers 23 FI 23	Unilateral drop landing on affected limb	ML and AP components of TTS	Copers had longer AP TTS than FAI and control groups ($p < 0.05$). FAI had longer ML TTS than the control group ($p < 0.05$).

List of Abbreviations: AP – anterior/posterior; APSI – anterior/posterior stability index; CAI – chronic ankle instability; DPSI – dynamic postural stability index; ES – effect size; FI – functional instability; ML – medial/lateral; MLSI – medial/lateral stability index; RVTTS – resultant vector time to stabilization; SJ – stop jump; TTS – time to stabilization; VSI – vertical stability index.

Table 2
Summary of studies that examined lower extremity kinematics.

Author(s)	Study Design	Participants	Landing Task	Outcome Variables	Main Results
Brown et al. 2012	Cross-sectional	$n = 88$ Control 24 Copers 20 MI 21 FI 23	Anterior, lateral, & lateral unilateral SJ	Sagittal, frontal, and transverse plane CV pre- & post-landing	*Ankle:* No between group differences for ankle CV pre- or post-landing ($p > 0.05$). *Knee:* FI and copers had less rotation pre-contact during anterior jump (FI-Control: $p = 0.007$, ES = 0.26; Coper-Control: $p = 0.001$, ES = 0.60). FI and copers had less rotation than controls during stance for all landing tasks (FI-Control: $p = 0.003$, ES = 0.45; Coper-Control: $p = 0.009$, ES = 0.40). *Hip:* MI, FI, and copers had less flexion pre-contact for all landing tasks (MI-control: $p = 0.006$, ES = 0.42; FI-Control: $p = 0.001$, ES = 0.55; Coper-Control: $p = 0.004$, ES = 0.43). MI and FI had less abduction during stance of the anterior landing task than controls (MI-Control: $p = 0.003$; ES = 0.77; FI-Control: $p = 0.009$; ES = 0.81).
Brown et al. 2008	Cross-sectional	$n = 63$ Copers 21 MI 21 FI 21	Unilateral drop landing on affected limb	Sagittal & frontal plane kinematics	MI had greater ankle eversion ($p = 0.009$, ES = 0.63), less ankle plantar flexion ($p = 0.047$, ES = 0.87), and sagittal plane displacement ($p = 0.005$, ES = 0.89) than FI and copers.
Caufield & Garrett 2002	Cross-sectional	$n = 24$ Control 10 FI 14	Unilateral drop landing on affected limb	Ankle & knee sagittal plane kinematics	*Ankle:* FI had greater dorsiflexion 10 ms pre- to 20 ms post-landing than controls ($p < 0.05$). *Knee:* FI had greater knee flexion 20 ms pre- to 60 ms post-landing than controls ($p < 0.05$).
Delahunt et al. 2006	Cross-sectional	$n = 48$ Control 24 FI 24	Unilateral drop landing on affected limb	Sagittal, frontal, & transverse plane kinematics	*Ankle:* FI had greater inversion 200-95 ms pre-landing ($p < 0.05$), less dorsiflexion 90–200 ms post-landing ($p < 0.05$), less sagittal plane ankle joint angular velocity 50–125 ms post-landing ($p < 0.05$). *Knee:* No between group differences ($p > 0.05$). *Hip:* FI less hip external rotation 200-55 ms pre-landing than controls ($p < 0.05$).
De Ridder et al. 2015	Cross-sectional	$n = 56$ Control CAI 28	Anterior unilateral SJ on affected limb	Sagittal, frontal, & transverse plane kinematics using curve analysis	No significant differences in ankle, knee, or hip kinematic curves pre- or post-landing between groups ($p > 0.05$).
Doherty et al. 2016	Cross-sectional	$n = 70$ Copers 42 CAI 28	Unilateral drop landing on both limbs	Sagittal, frontal, & transverse plane kinematics	*Ankle:* No limb or between group differences ($p > 0.05$). *Knee:* No limb or between group differences ($p > 0.05$). *Hip:* CAI had greater hip flexion 148 ms pre-landing to 4 ms post-landing compared to copers ($p < 0.05$).
Kipp & Palmieri-Smith 2012	Cross-sectional	$n = 22$ Control 11 CAI 11	Anterior unilateral SJ on affected limb	Sagittal & frontal plane ankle inter-trial variability	CAI demonstrated greater dorsiflexion/plantarflexion inter-trial variability 100 ms pre-landing ($p = 0.001$, ES = 1.73) and greater inversion/eversion inter-trial variability during the entire 300 ms time frame than controls ($p = 0.02$, ES = 1.16).
Gribble & Robinson 2009	Cross-sectional	$n = 38$ Control 19 CAI 19	Anterior unilateral SJ on both limbs	Ankle & knee sagittal plane kinematics	*Ankle:* No interaction ($p = 0.41$, ES = 0.004), limb ($p = 0.29$, ES = 0.26) or group ($p = 0.59$, ES = 0.25) differences for ankle plantarflexion at landing. *Knee:* CAI had less knee flexion at landing than controls ($p = 0.008$, ES = 0.72). *Hip:* No interaction ($p = 0.79$, ES = 0.15), limb ($p = 0.77$, ES = 0.06) or group ($p = 0.72$, ES = 0.11) differences for hip flexion at landing.
Gribble & Robinson 2010	Cross-sectional	$n = 38$ Control 19 CAI 19	Anterior unilateral SJ on both limbs	Ankle, knee, & hip sagittal plane kinematics	*Ankle:* No significant differences for ankle plantarflexion angle 100 ms pre-landing, peak plantarflexion angle, or time to peak plantarflexion. *Knee:* CAI had less knee flexion 100 ms pre-landing (p = 0.005, ES = 0.77). No significant differences for peak knee flexion angle or time to peak knee flexion. *Hip:* No significant differences for hip flexion angle 100 ms pre-landing, peak hip flexion angle, or time to peak hip flexion.
Wright et al. 2016	Cross-sectional	$n = 69$ Control 23 Copers 23 FI 23	Unilateral drop landing on affected limb	Sagittal & frontal plane kinematics of rearfoot and forefoot	*Sagittal Plane:* Copers had greater forefoot dorsiflexion than FI ($p < 0.05$, ES = 0.61) and control ($p < 0.05$, ES = 0.71) at IC. FAI had greater hindfoot dorsiflexion than coper ($p < 0.05$, ES = 0.86) and controls ($p < 0.05$, ES = 0.93) at IC. *Frontal Plane:* No group differences for forefoot at initial contact ($p = 0.245$).

List of Abbreviations: CAI – chronic ankle instability; CV – coefficient of variation; ES – effect size; FI – functional instability; IC – initial contact; MI – mechanical instability; SJ – stop jump.

Table 3
Summary of studies that examined muscle activity and kinetics.

Author(s)	Study Design	Participants	Landing Task	Outcome Variables	Main Results
Brown et al. 2004	Cross-Sectional	$n = 20$ Control 10 FI 10	Anterior unilateral SJ on affected limb	Ankle muscle activity pre-landing to post-landing	*TA:* No between group differences pre- ($p = 0.59$) or post-landing ($p = 0.90$). *PL:* No between group differences pre- ($p = 0.37$) or post-landing ($p = 0.56$). *LG:* No between group differences pre- ($p = 0.07$) to post-landing ($p = 0.17$). *SOL:* FI had less SOL activity 100 ms post-landing ($p = 0.050$, ES = 0.94).
Brown et al. 2008	Cross-sectional	$n = 63$ Control 21 FI 21 MI 21	Unilateral drop landing on affected limb	Rate and magnitude of GRF parameters	No between group differences for rate or magnitude of GRF parameters ($p > 0.05$).
Caufield & Garrett 2004	Cross-sectional	$n = 24$ Control 10 FI 14	Unilateral drop landing on affected limb	Rate and magnitude of GRF parameters	Peak lateral and anterior GRF occurred earlier in FI (lateral GRF: $p = 0.007$, ES = 1.02; anterior GRF: $p = 0.030$, ES = 0.94). The FI produced greater peak vertical GRF at 24–36 and 85–150 ms post-landing ($p < 0.05$).
Caufield et al. 2004	Cross-sectional	$n = 22$ Control 10 FI 12	Unilateral drop landing and anterior SJ on affected limb	Ankle muscle activity pre-landing to post-landing	FI had less PL activity pre-landing (Drop Landing: $p = 0.03$, ES = 2.47; Anterior Landing: $p = 0.04$, ES = 2.53). No between group differences in PL, SOL, or TA post-landing for either landing task.
Delahunt et al. 2006	Cross-sectional	$n = 48$ Control 24 FI 24	Unilateral drop landing on affected limb	Rate and magnitude of GRF parameters and muscle activity pre-landing to post-landing	*EMG:* FI had less PL activity pre-landing ($p < 0.01$, ES = 0.98). *Kinetics:* FI had greater vertical GRF 35–60 ms post-landing ($p < 0.05$) and reached peak vertical GRF quicker ($p = 0.007$, ES = 1.05). FI had greater medial GRF 85–105 post-landing ($p < 0.05$), greater posterior GRF 75–90 ms ($p < 0.05$) and reached peak posterior GRF quicker ($p = 0.001$, ES = 1.50).
Doherty et al. 2016	Cross-sectional	$n = 70$ Coper 42 CAI 28	Unilateral drop landing on both limbs	Rate and magnitude of GRF parameters and joint stiffness	No between group differences for rate and magnitude of GRF parameters ($p > 0.05$). CAI had greater hip joint stiffness compared to copers ($p = 0.03$; ES = 0.60).
Kipp & Palmineri-Smith 2012	Cross-sectional	$n = 22$ Control 11 CAI 11	Anterior unilateral SJ on affected limb	Inter-trial variability of peak sagittal and frontal plane moments	No between group differences for peak sagittal and frontal plane ankle moments ($p > 0.05$).
Kunugi et al. 2017	Cross-sectional	$n = 22$ Control 11 FI 11	Diagonal unilateral SJ on affected limb	Ankle muscle activity pre-landing to post-landing	FI had significantly less PL activity from 75 ms pre-landing to 60 ms post-landing ($p < 0.05$; ES > 0.80) compared to controls. FI had significantly less PB activity from 151 ms pre-landing to 116 ms post-landing ($p < 0.05$; ES > 0.80) compared to controls. FI had significant less TA activity from 69 ms post-landing to 203 ms post-landing ($p < 0.05$; ES > 0.80).

List of Abbreviations: CAI – chronic ankle instability; EMG – electromyography; ES – effect size; FI – functional instability; GRF – ground reaction force; LG – lateral gastrocnemius; MI – mechanical instability; PB – peroneus brevis; PL – peroneus longus; SOL – soleus; TA – tibialis anterior.

3.6. Kinetics

Five studies reported ground reaction force (GRF) parameters during unilateral drop landings or anterior stop jump tasks (Brown et al., 2008; Caulfield & Garrett, 2004; Doherty et al., 2016b; Kipp & Palmieri-Smith, 2012; Monaghan et al., 2006). Most studies examined GRF parameters during a drop landing task (Brown et al., 2008; Caulfield & Garrett, 2004; Doherty et al., 2016b; Monaghan et al., 2006), while only 1 study examined GRFs during an anterior stop jump task (Kipp & Palmieri-Smith, 2012). In addition to GRF parameters, peak sagittal and front plane ankle moments (Kipp & Palmieri-Smith, 2012) and joint stiffness of the ankle, knee, and hip were also reported (Doherty et al., 2016b).

Delahunt et al. observed greater vertical GRF magnitudes during a 35 cm unilateral drop landing from 35 to 60 ms post-landing and faster time to peak vertical GRF in individuals with CAI (Monaghan et al., 2006). Caufield and Garrett reported greater vertical GRF magnitudes during a 40 cm unilateral drop landing in individuals with CAI in comparison to controls (Caulfield & Garrett, 2004). Greater magnitudes of the medial and posterior components of the GRF and faster time to peak lateral, anterior, and posterior GRF were also reported (Caulfield & Garrett, 2004; Monaghan et al., 2006). Another study reported the CAI group demonstrated significantly increased hip joint stiffness in comparison to ankle sprain copers during a unilateral drop landing on the affected limb (Doherty et al., 2016b), while another study reported no differences in sagittal or frontal plane ankle moments between CAI and control groups during an anterior stop jump (Kipp & Palmieri-Smith, 2012). Studies that provided raw data demonstrated large effects sizes (0.94–1.50) in loading rates and peak GRFs during unilateral jump-landings between CAI and controls (Caulfield & Garrett, 2004; Monaghan et al., 2006). Summaries and ES of studies reporting kinetic parameters during unilateral jump-landing tasks are presented in Table 3.

4. Discussion

This study systematically reviewed and evaluated studies that investigated the effects of CAI on dynamic postural stability, kinematics, kinetics, and muscle activity during unilateral jump-landing tasks. The current literature revealed that individuals with CAI demonstrate dynamic postural stability deficits (Brown et al., 2010, 2004; Gribble & Robinson, 2009, 2010; Kunugi et al., 2017; Ross & Guskiewicz, 2004; Ross et al., 2005; Wikstrom et al., 2010, 2007; Wright et al., 2016), as well as kinematic alterations, most notably in sagittal plane ankle and knee kinematics during various unilateral jump-landing tasks (Brown et al., 2008; Caulfield & Garrett, 2002; Gribble & Robinson, 2009, 2010; Kipp & Palmieri-Smith, 2012; Monaghan et al., 2006; Wright et al., 2016). Furthermore, greater magnitudes of peak vertical GRF and greater vertical and lateral loading rates were also noted in CAI cohorts (Brown et al., 2008; Caulfield & Garrett, 2004; Monaghan et al., 2006). Literature that has reported on muscle activity parameters during unilateral jump-landing tasks has been limited, however, studies have reported reductions in peroneus longus and peroneus brevis activation prior to ground contact when landing in the unilateral stance (Caulfield & Garrett, 2004; Kunugi et al., 2017; Monaghan et al., 2006). Impairments in dynamic postural stability, altered movement mechanics, and neuromuscular control prior to and during landing indicate alterations in feed-forward and feedback motor control strategies in individuals with CAI.

4.1. Effects of CAI on dynamic postural stability

Several studies have quantified dynamic postural stability using both TTS and DPSI methods. Time to stabilization assesses the amount of time it takes an individual to stabilize the medial/lateral and anterior/posterior components of the GRF after landing from a jump in the unilateral stance (Ross & Guskiewicz, 2003). Moreover, the DPSI method calculates mean square deviations from a reference point of zero to measure fluctuations from a stable position, rather than examining the standard deviation around a group mean (Wikstrom, Tillman, Smith, & Borsa, 2005). Regardless of the quantitative method used to assess dynamic postural stability, previous studies have consistently shown that in individuals with CAI demonstrate longer TTS and greater DPSI scores with moderate to large effects (ES:0.45–4.57) during a unilateral stop jump tasks (Brown et al., 2010, 2004; Gribble & Robinson, 2009, 2010; Kunugi et al., 2017; Ross & Guskiewicz, 2004; Ross et al., 2005; Wikstrom et al., 2010, 2007; Wright et al., 2016). The proprioceptive and neuromuscular control deficits that are associated with CAI likely contribute to the diminished ability to regulate rapid center of mass accelerations relative to the person's limits of stability during a unilateral landing.

Some researchers have hypothesized that altered feed-forward motor control may manifest as changes in the positioning of the proximal segments in preparation for ground contact during landing to reduce the impact forces on the unstable ankle (Gribble & Robinson, 2009, 2010). Greater knee extension on the affected limb has been reported in individuals with CAI when landing from a jump, which might indicate that individuals with CAI have a higher center of mass during initial ground contact. This would result in the lower extremity segments being in a less advantageous position to dissipate and control rapid impulse loads when landing, resulting in reduced dynamic postural stability (Gribble & Robinson, 2009, 2010). Although the current evidence indicates dynamic postural stability deficits are present in individuals with CAI, limited investigations have examined the potential relationships between reduced neuromuscular control, lower extremity kinematic and joint kinetic compensatory strategies that result in these dynamic postural stability defects. Without this evidence, it is difficult to conclude based on the limited available literature that kinematic alterations are the underlying causative factor that result in reduced dynamic postural stability. As such, further examination is warranted to investigate these potential relationships to further understand the mechanisms associated with the reported deficits in dynamic postural stability.

4.2. Effects of CAI on unilateral landing kinematics

Prior studies have extensively examined potential differences in ankle, knee and hip kinematic patterns pre-to post-landing during unilateral jump-landing landing tasks in individuals with and without CAI. Regarding altered ankle kinematics, greater ankle inversion pre-landing and greater ankle plantar flexion post-landing during a unilateral drop landing has been reported in individuals with CAI (Monaghan et al., 2006). However, studies reporting ankle kinematic alterations during jump-landing tasks have not supported these findings (Brown et al., 2012, 2008; De Ridder et al., 2015; Doherty et al., 2016b; Gribble & Robinson, 2009, 2010; Wright et al., 2016). One specific landing strategy on the affected limb that has been consistently reported in individuals with CAI is greater ankle dorsiflexion and reduced ankle sagittal plane displacement pre-to post-landing (Brown et al., 2008; Caulfield & Garrett, 2002; Kipp & Palmieri-Smith, 2012; Wright et al., 2016). This ankle strategy provides evidence of centrally mediated alterations to the motor program, which manifests from the chronically unstable ankle, to place the talocrural joint in a tightly packed position to further protect the lateral ankle ligaments from excessive frontal plane movement (Brown et al., 2008;

Caulfield & Garrett, 2002; Doherty et al., 2016a; Monaghan et al., 2006; Wright et al., 2016). However, these ankle kinematic adaptations directly influence proximal segment positioning when landing from a jump. The reductions in ankle sagittal plane range of motion during the post-landing period reduces impact forces imposed on the ankle complex, but a greater reliance is transferred to the proximal segments to attenuate these rapid impulse loads when landing to further protect the unstable ankle from unexpected joint perturbations when landing (Doherty et al., 2016b; Gribble & Robinson, 2009, 2010; Monaghan et al., 2006).

While the constraints of CAI on the sensorimotor system have resulted in the adoption of knee and hip dominant landing strategies (Brown et al., 2012; Caulfield & Garrett, 2002; Doherty et al., 2016b; Gribble & Robinson, 2009, 2010), these proximal segment adaptations appear to be influenced by the type of jump-landing task. Studies that have examined unilateral anterior stop jumps have reported CAI participants exhibit greater knee and hip extension (Brown et al., 2012; Gribble & Robinson, 2009, 2010), while other studies utilizing drop landings have reported greater knee and hip flexion prior to and during ground contact (Caulfield & Garrett, 2002; Doherty et al., 2016b). The differences in findings across these studies regarding knee and hip kinematics makes it difficult to draw definitive conclusions regarding proximal segment movement strategies that manifest in CAI cohorts during unilateral landings (Brown et al., 2012; De Ridder et al., 2015; Doherty et al., 2016b; Gribble & Robinson, 2009, 2010; Monaghan et al., 2006). However, it seems logical to hypothesize based on the current scientific evidence that specific movement adaptations may arise due to the demands of the jump-landing task and the constraints of a chronically unstable ankle. While drop landings and anterior stop jumps allow for a laboratory examination of movement strategies that may be associated recurrent ankle sprain injuries during dynamic movements in individuals with CAI, each task places different demands on the lower extremity. Therefore, the proximal segment adaptations that are reported may be attributed to the different landing tasks utilized across the current body of literature. Regardless, the differences observed in lower extremity kinematic patterns prior to ground provides evidence of alterations in feed-forward motor control strategies in individuals with CAI (Brown et al., 2008; Caulfield & Garrett, 2002; Doherty et al., 2016b; Gribble & Robinson, 2009, 2010; Hertel, 2008; Monaghan et al., 2006).

4.3. Effects of CAI on unilateral landing kinetics

While much emphasis in the literature has focused on the kinematic adaptations that result from the constraints of CAI, the resultant movement adaptations have also been suggested to alter loading rates and peak GRFs during ground contact (Brown et al., 2008; Doherty et al., 2016b; Kipp & Palmieri-Smith, 2012; Monaghan et al., 2006). A few studies have demonstrated large effects (ES:0.94–1.50) in loading rates and peak GRFs during unilateral jump-landings between CAI and controls (Caulfield & Garrett, 2004; Monaghan et al., 2006), while other studies have not reported any differences in loading rates or peak GRFs (Brown et al., 2008; Doherty et al., 2016b; Kipp & Palmieri-Smith, 2012). Caufield and Garrett reported that individuals with CAI produced significantly greater peak vertical GRF at two discrete time points of 24–35 ms and 85–150 ms post-landing, as well as reached peak lateral GRF faster in comparison to controls (Caulfield & Garrett, 2004). Delahunt et al. also reported that individuals with CAI produced a greater magnitude of the vertical GRF from 35 to 60 ms post-landing and reached peak vertical GRF quicker than controls (Monaghan et al., 2006). Additionally, greater peak medial and posterior ground reaction forces in comparison to controls during a unilateral jump-landing have also been observed (Monaghan et al., 2006).

The alterations in the vertical and medial-lateral GRF patterns in individuals with CAI during a unilateral jump-landing could potentially generate excessive supination moments of the ankle complex that result in the ankle giving way (Monaghan et al., 2006). Based on the available literature regarding GRFs, as well as the documented kinematic adaptations, it seems reasonable that individuals with CAI may utilize various movement strategies in attempt to effectively attenuate GRFs when landing in the unilateral stance (Brown et al., 2008; Caulfield & Garrett, 2004; Monaghan et al., 2006). However, further examination is warranted to assess the potential link between lower extremity kinematics and kinetics to empirically support the clinical implications of these findings.

4.4. Effects of CAI on unilateral landing muscle activity

There has been minimal literature that has reported on neuromuscular activity parameters during a unilateral jump-landing task. Three studies have reported large effects (ES:0.98–2.53) of reduced peroneus longus and/or peroneus brevis muscle activity prior to ground contact in individuals with CAI (Caulfield et al., 2004; Kunugi et al., 2017; Monaghan et al., 2006), while the other study did not observe any differences in peroneus longus muscle activity (Brown et al., 2004). While Brown et al. did report that individuals with CAI demonstrated reduced soleus muscle activity during ground contact (Brown et al., 2004), the other studies reporting muscle activity of the ankle musculature have not reported this same finding (Caulfield et al., 2004; Monaghan et al., 2006). The lack of significant differences observed in peroneus longus activity during ground contact might indicate that reflexive activation of the primary evertor musculature might not be affected, but rather, an altered feed-forward motor control strategy could manifest in individuals that develop CAI (Brown et al., 2004; Caulfield et al., 2004; Monaghan et al., 2006). The primary role of the peroneus longus is to help control rapid and/or excessive supination of the ankle complex (Hertel, 2002). Therefore, the reduced preparatory peroneus longus activity, which is necessary to provide dynamic joint stabilization to prevent a lateral ankle sprain (Hertel, 2002), might be an indicator of reduced neuromuscular control and an increased risk of the ankle complex giving way into excessive inversion when ground contact is unexpected, such as landing on another individuals' foot, resulting in recurrent lateral ankle sprain injuries (Caulfield et al., 2004; Hertel, 2008; Monaghan et al., 2006).

4.5. Limitations

The main limitation of this systematic review was the use of the modified Quality Index checklist to assess the risk of bias. Although this checklist has been validated to assess methodological quality, some items of the checklist were not applicable and were removed. Therefore, the methodological quality scores may not entirely reflect of the actual quality of studies included in this review. An additional limitation was the unilateral jump-landing task used across studies, differences in reporting of dependent variables, and the selection criteria of CAI cohorts varied widely in the studies included making statistical pooling of the dependent measures difficult. Therefore, we were unable to perform a meta-analysis for this systematic review.

5. Conclusion

This review provides considerable evidence of dynamic postural stability deficits, as well as lower extremity kinematic alterations in individuals with CAI during various unilateral jump-landing tasks. Despite the limited literature regarding muscle activity and kinetics, altered loading rates and peak GRFs, as well as impairments in neuromuscular control appear to affect individuals with CAI. These findings could assist clinicians in identifying maladaptive movement patterns associated with recurrent lateral ankle sprains and develop effective rehabilitation programs intended to restore the sensorimotor deficits that develop following an initial ankle sprain injury that could manifest into CAI. Future studies should further examine the relationships between lower extremity movement patterns, neuromuscular control, and joint kinetics to further elucidate recurrent lateral ankle sprains in populations that regularly perform repeated jump-landings.

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Conflicts of interest

The authors declare no conflict of interest associated with this review.

Ethical statement

This systematic review did not require approval from the Institutional Review Board at the authors' university.

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