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Gait-Training Interventions for Individuals With Chronic Ankle Instability: A Systematic Review and Meta-Analysis

Christine E. Ortega, MS, ATC*; Danielle M. Torp, PhD, ATC†; Luke Donovan, PhD, ATC‡; Jeffrey D. Simpson, PhD§; Lauren Forsyth, PhD||; Rachel M. Koldenhoven, PhD, ATC*

*Department of Health and Human Performance, Texas State University, San Marcos; †Department of Athletic Training and Clinical Nutrition, University of Kentucky, Lexington; ‡Department of Applied Physiology, University of North Carolina at Charlotte; §Department of Movement Sciences and Health, University of Western Florida, Pensacola; ||Department of Biomedical Engineering, University of Strathclyde, Glasgow, UK

Background: Chronic ankle instability (CAI) is a condition known to negatively affect lower extremity gait biomechanics during walking. Gait-training interventions have been proposed as a potential strategy to improve faulty movement patterns associated with CAI.

Objective: To determine if gait-training interventions influence lower extremity biomechanics during walking in individuals with CAI.

Design: Systematic review and meta-analysis.

Data Sources: Literature searches were conducted in PubMed, CINAHL, SPORTDiscus, and MEDLINE from database inception through September 15, 2022.

Study Selection: Eligible studies were published in English and included randomized controlled trials, studies with a repeated-measures design, and descriptive laboratory studies in which authors measured the biomechanical outcomes (kinematics, kinetics, and electromyography) of a gait-training intervention during walking in individuals with CAI.

Data Extraction: One author extracted study design, participant characteristics, sample size, intervention type (device and biofeedback), intervention length, and biomechanical outcome measures (kinematics, kinetics, and electromyography).

Data Synthesis: Gait-training interventions were broadly categorized into device (destabilization and novel gait-training devices) and biofeedback (visual, auditory, and haptic delivery modes). When appropriate, meta-analyses were conducted using a random-effects model to compare mean differences and SDs before and after the gait-training intervention.

Results: Thirteen studies were included. Meta-analyses were conducted only for single-session gait-training studies. Authors of 11 studies reported kinetic outcomes. Meta-analyses showed the location of center of pressure was shifted medially from 0% to 90% of stance (effect size [ES] range, −0.35 to −0.82), contact time was decreased in the medial forefoot (ES = −0.43), peak pressure was decreased for the lateral midfoot (ES = −1.18) and increased for the hallux (ES = 0.59), and the pressure time integral was decreased for the lateral heel (ES = −0.33) and the lateral midfoot (ES = −1.22) and increased for the hallux (ES = 0.63). Authors of 3 studies reported kinematic outcomes. Authors of 7 studies reported electromyography outcomes. Meta-analyses revealed increased activity for 200 milliseconds after initial contact for the fibularis longus muscle (ES = 0.83).

Conclusions: Gait-training protocols improved some lower extremity biomechanical outcomes in individuals with CAI. Plantar-pressure outcome measures seemed to be most affected by gait-training programs, with improvements including decreasing the lateral pressure associated with increased risk for lateral ankle sprains. Gait training increased electromyographic activity after initial contact for the fibularis longus muscle. Authors of few studies have assessed the effect of multisession gait training on biomechanical outcome measures. Targeted gait training should be considered when treating patients with CAI.

Key Words: ankle sprain, biomechanics, biofeedback, rehabilitation, gait-training device

Key Points

- Gait training improved lower extremity biomechanics associated with risk for lateral ankle sprains, including medial shifts in plantar pressure, decreased ankle inversion, and increased fibularis longus activity with medium to large effect sizes.
- Gait improvements were evident when using a variety of gait-training devices and biofeedback.
- Evidence on kinematic outcomes of gait-training interventions for chronic ankle instability is limited.
- Gait training would benefit from homogeneity between protocols and techniques suitable for clinical implementation.

Lateral ankle sprains (LASs) are a prevalent musculoskeletal injury among the general population and physically active individuals.[1,2] These injuries can be temporarily disabling, hinder physical activity, and contribute to long-term ankle-joint problems.[2,3] Recurrent LAS rates are high, and in 1 prospective study, 40% of individuals who sustained their first LAS developed a condition known as *chronic ankle instability* (CAI).[4,5] This condition is characterized by repetitive episodes of giving way, decreased self-reported function, ongoing symptoms such as pain or weakness, and recurrent ankle sprains for at least 1 year after the initial LAS.[6] All individuals with CAI have primary

tissue injury to the lateral ankle ligament(s), but impairments are unique to each individual.[3] Hertel and Corbett categorized these impairments found in individuals with CAI as motor-behavioral, sensory-perceptual, and pathomechanical impairments.[3] Motor-behavioral impairments, which often present as aberrant biomechanical patterns during functional and dynamic movements, have been well documented in individuals with CAI.[3]

Several altered gait characteristics have been observed during walking in individuals with CAI compared with individuals without a history of LAS and individuals with a history of LAS who return to their preinjury health status (termed *copers*). Individuals with CAI often display greater ankle inversion throughout the gait cycle that may coincide with a lateral deviation in the center of pressure (COP) and increased plantar pressure along the lateral column of the foot during walking.[7–12] This biomechanical profile of gait is associated with an elevated risk of LAS and may contribute to earlier onset of ankle posttraumatic osteoarthritis (PTOA) in individuals with CAI.[13–15] When the location of the COP approaches the lateral boundary of the foot, it places the ankle in a position similar to that of an LAS and may lead to recurrent sprains. Similarly, increased subtalar joint supination at touch down during a side-shuffling task simulation has been shown to increase the occurrence of LAS, and decreased supination has been shown to decrease the occurrence of LAS.[16] Unfortunately, this position can also result in abnormal stress distribution throughout the talar cartilage, influencing the development of ankle PTOA.[17,18] Therefore, restoring gait patterns in individuals with CAI is crucial to maintaining long-term ankle-joint health.

Various approaches have been used to address these abnormal gait patterns in individuals with CAI and include traditional rehabilitation techniques such as strength and balance training as well as targeted gait-training strategies involving the use of devices or biofeedback methods.[19–22] Whereas traditional rehabilitation strategies can improve strength and balance in individuals when trained, they have not been shown to improve gait biomechanics.[19,20] Authors of recently published critically appraised topics have evaluated the effectiveness of taping and bracing, neuromuscular training, and gait-biofeedback training for improving gait impairments in individuals with CAI.[21,23,24] Of these interventions, only biofeedback training showed efficacy at improving the specific gait pattern (ie, lateralized COP) associated with CAI.[21]

Biofeedback training involves providing a stimulus (visual, auditory, or haptic) to correct unwanted movement patterns and appears to effectively improve respective gait biomechanical outcome measures (kinematics and plantar pressure).[21] Another technique to address gait alterations has been the implementation of gait-training devices such as a destabilization device and a custom gait-training device using resistance bands.[25–28] Destabilization devices are worn to create an unstable surface under the foot with the goal of improving neuromuscular control in patients with CAI who exhibit symptoms associated with sensory-perceptual impairments such as perceived instability. *Sensory-perceptual impairments* have been defined as how individuals sense or feel about the body, the injury, or themselves.[3]

Several gait-training strategies have been investigated for improving aberrant biomechanics in individuals with CAI; however, a systematic review of the literature with meta-analysis has not been conducted to synthesize this information and provide a synopsis on the effectiveness of these gait-training interventions in individuals with CAI. Therefore, the purpose of our study was to systematically review the literature on the efficacy of gait-training interventions (devices and biofeedback) for improving altered gait biomechanics in individuals with CAI.

METHODS

Search Strategy

This systematic review with meta-analysis was registered in the International Prospective Register of Systematic Reviews (CRD42022357526) database on September 12, 2022. Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines were followed while conducting this systematic review and meta-analysis.[29] A health sciences librarian was consulted for the development of a systematic search of electronic databases. The search was performed in the online search engines PubMed, CINAHL, SPORTDiscus, and MEDLINE from database inception through September 15, 2022, using the following search terms: ([Chronic ankle instability OR CAI OR functional ankle instability OR recurrent ankle sprain] AND [gait training OR gait devices OR biofeedback OR feedback] AND [biomechanics OR kinetics OR kinematics OR electromyography]). Searches were limited to studies published in English with full text available. After the initial search, literature screening and data extraction were completed. Two authors (C.O. and R.M.K.) independently screened all titles, abstracts, and full-text records for eligible studies (Figure 1). If conflicts existed, the authors discussed the study to reach consensus. If consensus was not achieved, a third author (J.D.S.) was consulted. Manual reference-list screening was performed to identify any additional studies.

Study Selection Criteria and Quality Assessment

Studies were included if they met the following criteria: (1) individuals with CAI (as determined using the International Ankle Consortium guidelines) were included; (2) a gait-training intervention was administered using devices or biofeedback methods; (3) outcome measures included gait kinetics, kinematics, muscle activity during walking, or a combination; (4) the study was published in a peer-reviewed journal; and (5) the full text was published in English.[6] Randomized controlled trials, studies with a crossover or a quasiexperimental design, and descriptive laboratory or field studies were included. Studies were excluded if individuals with CAI were not included, interventions did not involve gait training, biomechanical outcomes were not measured, they were not available in English, or the full text was unavailable.

The Downs and Black quality-assessment checklist was used to evaluate the included studies (Table 1).[30] The checklist consists of 27 questions within 5 sections (reporting, external validity, internal validity, internal validity—confounding [selection bias], and power) and was designed to assess the methodological quality of randomized and

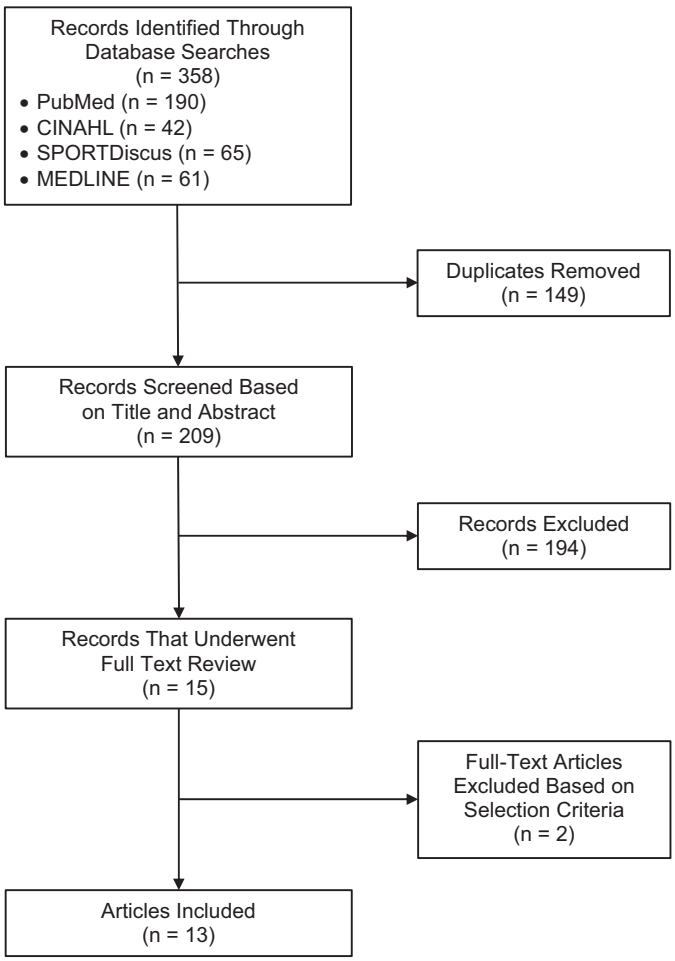


Figure 1. Flowchart of included studies.

nonrandomized comparative studies.[30] Questions were scored as *yes* (1), *no* (0), or *not applicable* (NA) with the exception of question 5, which was scored as *yes* (2), *partially* (1), *no* (0), or *not applicable* (NA), with a maximum total score of 28 points.[30] Higher scores indicated higher methodological quality.[30] Two authors (C.O. and R.M.K.) independently scored all included studies. If scores did not align, a third author (J.D.S.) was consulted.

Data Extraction

Study design, participant characteristics, sample sizes, intervention type (device or biofeedback), intervention length, and biomechanical outcome measures (kinematics, kinetics, and electromyography [EMG]) were extracted by 1 author (R.M.K.) for all included studies (Tables 2 through 4). Authors were contacted if values were not reported in the text or were presented as graphs. When authors of 3 or more studies reported on the same outcomes, the means and SDs were extracted for potential meta-analyses.

Data Analysis

When authors of 3 or more studies reported on the same outcome measure using consistent units or units that could be derived for equivocal comparisons, we conducted meta-analyses. We performed meta-analyses using a random-effects model in JASP software (JASP Team 2023, version 0.17.2.1; University of Amsterdam) to compare differences before and during or immediately after administration of gait training for studies involving a single session for the following variables: kinetics (COP gait line, contact area, contact time, peak pressure, pressure-time integral [PTI]) and EMG (root-mean-square [RMS] amplitude before initial contact [IC] and post-IC). The α level was set at .05. We did not find enough multisession gait-training studies for meta-analyses to be conducted on any variables. Meta-analysis effect sizes (ES) and associated 95% confidence intervals (CIs) were displayed using forest plots (Figures 2 through 4). The ES and standard error of ES using the pooled SD were calculated to determine the magnitude of difference between time points (before versus after gait training) or between groups (gait training versus no gait training). These ESs were interpreted as *very small* ($\leq$0.20), *small* (0.21–0.39), *medium* (0.40–0.79), and *large* ($\geq$0.80).[31] Heterogeneity was analyzed using the I^2 test statistic and summarized the variation across studies due to difference rather than chance as recommended by the *Cochrane Handbook for Systematic Reviews of Interventions*.[32] We used the following guidelines to interpret the I^2 test statistic: 0% to 40%, *might not be important*; 30% to 60%, *may represent moderate heterogeneity*; 50% to 90%, *may represent substantial heterogeneity*; and 75% to 100%, *considerable heterogeneity*.[32] When heterogeneity was considerable ($I^2 \geq 75\%$), studies showing the same direction of effect were still considered appropriate for meta-analysis.[33] Publication bias was assessed using funnel plots and associated Egger regression tests for variables identified as statistically significant by the meta-analyses. Publication bias was considered present when $P < .05$ for the Egger regression test.[34]

RESULTS

Study Selection and Characteristics

Our initial search yielded 358 studies (Figure 1). After removal of duplicates, abstract screening, and full-text review, 13 studies were included.[25–28,35–43] Of the studies included, authors of 11 studies[25,26,28,35–40,42,43] reported on kinetic outcome measures, authors of 3 studies[25,39,41] reported on kinematic outcome measures, and authors of 7 studies[25–28,35,36,39] reported on muscle activity outcome measures. Authors of 5 studies[25–28,36] used a gait-training device, such as a destabilization sandal or boot, and authors of 8 studies[35,37–43] used a form of biofeedback (visual, auditory, or haptic). Summaries of the study characteristics; outcome measures; and results for kinetics, kinematics, and muscle activity are presented in Tables 2 through 4, respectively.

Methodological Quality Assessment

Downs and Black scores ranged from 16 to 25 points out of a maximum of 28 points. The 3 studies with a randomized controlled trial design had the highest overall scores, ranging from 24 points[43] to 25 points.[25,39] Reviewers scored all studies *yes* or *not applicable* for all questions within the Reporting section of the checklist except for "adverse events that may be a consequence of the intervention

Table 1. Downs and Black[30] Quality Assessment of Included Research Studies **Continued on Next page**

Question[a]	Donovan et al[27]	Donovan et al[35]	Donovan et al[25]	Feger and Hertel[28]	Feger et al[36]	Ifarraguerri et al[37]	Jang et al[38]	Knuckles et al[26]	Koldenhoven et al[39]	Migel and Wikstrom[40]	Migel and Wikstrom[41]	Torp et al[42]	Torp et al[43]
Reporting													
1. Hypothesis/aim/objective of the study clearly described?	1	1	1	1	1	1	1	1	1	1	1	1	1
2. Main outcomes to be measured clearly described in the introduction or methods section?	1	1	1	1	1	1	1	1	1	1	1	1	1
3. Characteristics of the subjects included in the study clearly described?	1	1	1	1	1	1	1	1	1	1	1	1	1
4. Interventions of interest clearly described?	1	1	1	1	1	1	1	1	1	1	1	1	1
5. Distributions of principal confounders in each group to be compared clearly described?	NA	NA	2	NA	NA	NA	NA	NA	2	NA	NA	NA	2
6. Main findings of the study clearly described?	1	1	1	1	1	1	1	1	1	1	1	1	1
7. Study provides estimates of the random variability in data for main outcomes?	1	1	1	1	1	1	1	1	1	1	1	1	1
8. Adverse events that may be a consequence of the intervention reported?	0	0	1	0	0	0	0	0	1	0	0	0	0
9. Characteristics of subjects lost to follow-up described?	1	1	1	1	1	1	1	1	1	1	1	1	1
10. Actual probability values been reported for the main outcomes except where the probability value is $<.001$?	1	1	1	1	1	1	1	1	1	1	1	1	1
Subscale score	8	8	11	8	8	8	8	8	11	8	8	8	10
External validity													
11. Subjects representative of the entire population from which they were recruited?	1	1	1	1	1	1	1	1	1	1	1	1	1
12. Subjects who were prepared to participate representative of the entire population from which they were recruited?	1	1	1	1	1	1	1	1	1	1	1	1	1
13. Staff, places, and facilities where the patients were treated representative of the treatment the majority of patients receive?	0	0	0	0	0	0	0	0	0	0	0	0	0
Subscale score	2	2	2	2	2	2	2	2	2	2	2	2	2
Internal validity													
14. Attempt made to blind study subjects to the intervention they have received?	0	0	0	0	0	0	0	0	0	0	0	0	0
15. Attempt made to blind those measuring main outcomes of the intervention?	0	0	1	0	0	0	0	0	1	0	0	0	1
16. If any of the results of the study were based on "data dredging," was this made clear?	1	1	1	1	1	1	1	1	1	1	1	1	1
17. In trials and cohort studies, do analyses adjust for different lengths of follow-up, or in case-control studies, is the time between the intervention and outcome the same for cases and controls?	1	1	1	NA	1	NA	NA	NA	1	1	1	1	1
18. Statistical tests used to assess the main outcomes appropriate?	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 1. Continued From Previous Page

Question[a]	Donovan et al[27]	Donovan et al[35]	Donovan et al[25]	Feger and Hertel[28]	Feger et al[36]	Ifarraguerri et al[37]	Jang et al[38]	Knuckles et al[26]	Koldenhoven et al[39]	Migel and Wikstrom[40]	Migel and Wikstrom[41]	Torp et al[42]	Torp et al[43]
19. Compliance with the intervention/s reliable?	1	1	1	1	1	1	1	1	1	1	1	1	1
20. Main outcome measures used accurate (valid and reliable)?	1	1	1	1	1	1	1	1	1	1	1	1	1
Subscale score	5	5	6	4	5	4	4	4	6	5	5	5	6
Internal validity—confounding (selection bias)													
21. Subjects in different intervention groups or recruited from the same population?	1	1	1	1	1	1	1	1	1	1	1	1	1
22. Subjects in different intervention groups or recruited over the same period of time?	0	0	1	0	0	0	0	0	0	0	0	0	1
23. Subjects randomized to intervention groups?	0	0	1	0	0	0	0	0	1	0	0	0	1
24. Randomized intervention assignment concealed from both patients and health care staff until recruitment was complete and irrevocable?	0	0	1	0	0	0	0	0	1	0	0	0	1
25. Adequate adjustment for confounding in the analyses from which main findings were drawn?	NA	NA	1	NA	NA	NA	NA	NA	1	NA	NA	NA	1
26. Losses of subjects to follow-up taken into account?	1	1	1	1	1	1	1	1	1	1	1	1	1
Subscale score	2	2	6	2	2	2	2	2	5	2	2	2	6
Power													
27. Study has sufficient power to detect a clinically important effect where the probability value for a difference being due to chance is less than 5%?	1	0	0	0	0	0	0	1	1	0	0	0	0
Total score	18	17	25	16	17	16	16	17	25	17	17	17	24

[a] Questions 1–4 and 6–27 were scored as follows: 1 = *yes*, 0 = *no*, and NA = *not applicable*. Question 5 was scored as follows: 2 = *yes*, 1 = *partially*, 0 = *no*, and NA = *not applicable*.

Table 2. Summary of Articles Related to Kinetic Outcome Measures **Continued on Next page**

Study (Year)	Participants	Study Information	Main Findings[a]
Donovan et al[25] (2016)	26 CAI (13 control, 13 intervention)	Design: randomized controlled trial Gait training: 12 sessions with device (destabilization boot and sandal) Outcome measures: vGRF normalized to body mass, 3D internal joint moments normalized to height and body mass for ankle, knee, and hip from 1% to 100% of stride cycle Data-collection timepoints: Baseline, 2–7 d after last gait-training session	vGRF (N/kg): no differences Internal joint moments (Nm/kg): no differences
Donovan et al[35] (2016)	10 CAI	Design: descriptive laboratory study Gait training: 1 session with biofeedback (auditory) Outcome measures: contact area, contact time, peak pressure, PTI, time to peak pressure Data collection timepoints: baseline, while receiving biofeedback	Contact area: decreased in lateral midfoot (MD = −4.3 cm^2, ES = −1.3) and toes 2–5 (MD = −2.1 cm^2, ES = −0.7) Contact time (ms): no differences Peak pressure: decreased in lateral midfoot (MD = −52.8 kPa, ES = −2.8), central forefoot (MD = −29.8 kPa, ES = −1.4), and lateral forefoot (MD = −57.8 kPa, ES = −2.4) and increased at hallux (MD = 91.7 kPa, ES = 1.0) PTI: decreased at lateral midfoot (MD = −28.4 kPa·s, ES = −3.1) and lateral forefoot (MD = −29.1 kPa·s, ES = −2.6) and increased for hallux (MD = 31.3 kPa·s, ES = 1.1) and total foot (MD = 18.6 kPa·s, ES = 1.0) Time to peak pressure (% of stance): reached earlier in lateral midfoot (MD = −15.9%, ES = −1.0)
Feger and Hertel[28] (2016)	10 CAI	Design: descriptive laboratory study Gait training: 1 session with device (novel gait trainer with resistance bands) Outcome measures: COP gait line for location of COP from most medial border of the foot at 10% increments for 0%–100% of the stance phase, contact area, contact time, peak pressure, PTI, time to peak pressure Data collection timepoints: baseline, while using device	COP gait line: medial shift from 0%–100% of stance phase: 0%–10% (MD = −4.7 mm, ES = −1.7), 11%–20% (MD = −3.8 mm, ES = −1.1), 21%–30% (MD = −3.6 mm, ES = −0.9), 31%–40% (MD = −4.6 mm, ES = −1.0), 41%–50% (MD = −5.4 mm, ES = −1.2), 51%–60% (MD = −6.4 mm, ES = −1.4), 61%–70% (MD = −7.0 mm, ES = −1.6), 71%–80% (MD = −7.1 mm, ES = −1.6), 81%–90% (MD = −6.4 mm, ES = −1.5), and 91%–100% (MD = −5.2 mm, ES = −1.2) Contact area: decrease in lateral midfoot (MD = −0.8 cm^2, ES = −0.5) Contact time (ms): no differences Peak pressure: decreased in lateral midfoot (MD = −29.8 kPa, ES = −1.5) and lateral forefoot (MD = −27.4 kPa, ES = −0.9) and increased at lateral heel (MD = 18.2 kPa, ES = 1.0), medial heel (MD = 23.2 kPa, ES = 1.4), hallux (MD = 72.9 kPa, ES = 0.9), and total foot (MD = 52.2 kPa, ES = 0.7) PTI: decreased in lateral midfoot (MD = −13.8 kPa·s, ES = −1.4) and lateral forefoot (MD = −9.8 kPa·s, ES = −0.7) and increased in medial forefoot (MD = 7.4 kPa·s, ES = 0.5), hallux (MD = 22.3 kPa·s, ES = 1.0), and total foot (MD = 19.3 kPa·s, ES = 0.9) Time to peak pressure (% of stance): occurred earlier in lateral midfoot (MD = −13.1%, ES = −0.7)
Feger et al[36] (2018)	16 CAI	Design: quasiexperimental trial Gait training: 5 sessions with device (novel gait trainer with resistance bands) Outcome measures: COP gait line for location of COP from most medial border of the foot at 10% increments for 0%–100% of the stance phase, contact area, contact time, peak pressure, PTI, time to peak pressure	COP gait line: medial shift from 11%–100% of stance phase: 11%–20% (MD = −1.6 mm, ES = −0.4), 21%–30% (MD = −2.8 mm, ES = −0.8), 31%–40% (MD = −4.3 mm, ES = −1.1), 41%–50% (MD = −6.5 mm, ES = −1.1), 51%–60% (MD = −7.8 mm, ES = −2.0), 61%–70% (MD = −6.7 mm, ES = −1.8), 71%–80% (MD = −5.2 mm, ES = −1.5), 81%–90% (MD = −4.7 mm, ES = −1.5), and 91%–100% (MD = −5.3 mm, ES = −1.5)

Table 2. Continued From Previous Page

Study (Year)	Participants	Study Information	Main Findings[a]
		Data collection timepoints: baseline, 24–72 h after last gait-training session	Contact area: increase in medial midfoot (MD = 3.0 cm^2, ES = 0.4) Contact time (ms): no differences Peak pressure: increased at hallux (MD = 15.3 kPa, ES = 0.4) PTI: increased in medial forefoot (MD = 4.4 kPa·s, ES = 0.3) Time to peak pressure (% of stance): no differences
Ifarraguerri et al[37] (2019)	26 CAI	Design: descriptive laboratory study Gait training: 1 session with biofeedback (visual) Outcome measures: contact area, contact time, peak pressure, PTI Data collection timepoints: baseline, while receiving biofeedback	Contact area (cm^2): no differences Contact time (ms): no differences Peak pressure: decreased in medial forefoot (MD = −15.7 kPa, ES = −0.3) PTI: decreased in medial forefoot (MD = −2.3 kPa·s, ES = −0.1)
Jang et al[38] (2021)	10 CAI	Design: descriptive laboratory study Gait training: 1 session with biofeedback (haptic) Outcome measures: vGRF (impact peak, time to impact peak, impact loading rate, propulsive peak, time to propulsive peak, propulsive loading rate), ankle JCF (peak, impulse, loading rate) Data collection timepoints: baseline, while receiving biofeedback (early period = minute 1–2, late period = minute 9–10 of receiving biofeedback)	Impact peak vGRF (N/BW): no differences Time to impact peak vGRF (s): no differences Impact loading rate vGRF (BW/s): no differences Propulsive peak vGRF: decreased during early (MD = −0.04 N/BW, ES = −0.6) and late periods (MD = −0.04 N/BW, ES = −0.5) Time to propulsive peak vGRF: decreased during early (MD = −0.02 s, ES = −0.4) and late periods (MD = −0.02 s, ES = −0.5) Propulsive loading rate vGRF: decreased during early period (MD = −0.24 BW/s, ES = −0.4) Ankle JCF peak: decreased during early period (MD = −0.24 N/BW, ES = −0.4) Ankle JCF impulse: decreased during early (MD = −0.09 BW·s, ES = −0.6) and late periods (MD = −0.14 BW·s, ES = −0.9) Ankle JCF loading rate (BW/s): no differences
Knuckles et al[26] (2022)	12 CAI	Design: descriptive laboratory study Gait training: 1 session with device (multiaxis destabilization device) Outcome measures: COP gait line for location of COP from most medial border of the foot at 10% increments for 0%–100% of the stance phase, peak pressure Data collection timepoints: baseline, while wearing device, immediately after device removed	COP gait line Wearing device: medial shift from 11%–60% of stance phase: 11%–20% (MD = −5.7 mm, ES = −1.1), 21%–30% (MD = −6.3 mm, ES = −1.2), 31%–40% (MD = −6.2 mm, ES = −1.2), 41%–50% (MD = −5.8 mm, ES = −1.1), and 51%–60% (MD = −5.0 mm, ES = −0.9) After gait training: no differences Peak pressure Wearing device: decrease in lateral midfoot (MD = −21.5 kPa, ES = −1.3), lateral forefoot (MD = −22.4 kPa, ES = −1.2), and central forefoot (MD = −17.5 kPa, ES = −1.0) After gait training: no differences
Koldenhoven et al[39] (2021)	27 CAI (14 control, 13 intervention)	Design: randomized controlled trial Gait training: 8 sessions with biofeedback (visual) Outcome measures: 3D internal joint moments for ankle, knee, and hip for 0%–100% of stride cycle Data collection timepoints: baseline, 24–72 h after last gait-training session	Internal joint moments (Nm/kg): no differences
Migel and Wikstrom[40] (2021)	19 CAI	Design: descriptive laboratory study with repeated measures Gait training: 2 single sessions (1 laboratory, 1 real world) with biofeedback (haptic) Outcome measures: COP gait line for lateral-medial	COP gait line Laboratory Immediately after gait training: medial shift from 0%–90% of stance phase: 0%–10% (MD = −3.6 mm, ES = −0.4), 11%–20% (MD = −4.3 mm, ES = −0.4), 21%–30% (MD = −4.6 mm, ES = −0.5), 31%–40% (MD =

Table 2. Continued From Previous Page

Study (Year)	Participants	Study Information	Main Findings[a]
		location of COP from position of marker on fifth metatarsal at 10% increments for 0%-100% of the stance phase Data collection timepoints: baseline, immediately after gait training, 5 min after gait training	−5.1 mm, ES = −0.6), 41%–50% (MD = −5.1 mm, ES = −0.7), 51%–60% (MD = −4.2 mm, ES = −0.7), 61%–70% (MD = −2.8 mm, ES = −0.6), 71%–80% (MD = −1.7 mm, ES = −0.4), and 81%–90% (MD = −1.6 mm, ES = −0.3) 5 min after gait training: medial shift from 21%–90% of stance: 21%–30% (MD = −3.3 mm, ES = −0.4), 31%–40% (MD = −5.1 mm, ES = −0.6), 41%–50% (MD = −5.1 mm, ES = −0.7), 51%–60% (MD = −3.8 mm, ES = −0.6), 61%–70% (MD = −2.8 mm, ES = −0.6), 71%–80% (MD = −2.2 mm, ES = −0.4), and 81%–90% (MD = −1.6 mm, ES = −0.3) Real world Immediately after gait training: medial shift 0%–80% of stance phase: 0%–10% (MD = −6.0 mm, ES = −0.8), 11%–20% (MD = −7.3 mm, ES = −0.8), 21%–30% (MD = −7.8 mm, ES = −1.1), 31%–40% (MD = −8.3 mm, ES = −1.0), 41%–50% (MD = −8.2 mm, ES = −1.1), 51%–60% (MD = −6.6 mm, ES = −1.0), 61%–70% (MD = −4.2 mm, ES = −0.7), and 71%–80% (MD = −2.3 mm, ES = −0.4) 5 min after gait training: medial shift 0%–60% of stance: 0%–10% (MD = −4.7 mm, ES = −0.5), 11%–20% (MD = −5.6 mm, ES = −0.6), 21%–30% (MD = −6.1 mm, ES = −0.8), 31%–40% (MD = −6.5 mm, ES = −0.7), 41%–50% (MD = −5.9 mm, ES = −0.7), and 51%–60% (MD = −4.1 mm, ES = −0.6)
Torp et al[42] (2019)	26 CAI	Design: descriptive laboratory study Gait training: 1 session with biofeedback (visual) Outcome measures: COP gait line for location of COP from most medial border of the foot at 10% increments for 0%–100% of the stance phase, contact area, contact time, peak pressure, PTI Data collection timepoints: baseline, while receiving biofeedback	COP gait line: medial shift from 0%–90% of stance: 0%–10% (MD = −1.4 mm, ES = −0.3), 11%–20% (MD = −1.4 mm, ES = −0.3), 21%–30% (MD = −1.8 mm, ES = −0.4), 31%–40% (MD = −2.0 mm, ES = −0.5), 41%–50% (MD = −2.2 mm, ES = −0.5), 51%–60% (MD = −2.4 mm, ES = −0.5), 61%–70% (MD = −2.6 mm, ES = −0.5), 71%–80% (MD = −2.4 mm, ES = −0.5), 81%–90% (MD = −1.4 mm, ES = −0.3) Contact area: increased in medial midfoot (MD = 2.1 cm^2, ES = 0.3) and hallux (MD = 0.1 cm^2, ES = 0.1) Peak pressure: decreased at lateral midfoot (MD = −10.8 kPa, ES = −0.6), central forefoot (MD = −51.9 kPa, ES = −1.2), and lateral forefoot (MD = −19.1 kPa, ES = −0.6) and increased at hallux (MD = 39.4 kPa, ES = 0.7) PTI: decreased at lateral heel (MD = −7.4 kPa·s, ES = −0.5) and lateral midfoot (MD = −6.8 kPa·s, ES = −0.5) and increased at hallux (MD = 18.6 kPa·s, ES = 0.7)
Torp et al[43] (2022)	18 CAI (7 control, 11 biofeedback)	Design: randomized controlled trial Gait training: 8 sessions with biofeedback (auditory) Outcome measures: COP gait line for location of COP from most medial border of the foot at 10% increments for 0%–100% of the stance phase, peak pressure, maximum force Data collection timepoints: baseline, 24–48 h after last gait-training session, 1 wk after last gait-training session	COP gait line Immediately after gait training: medial shift from 41%–100% of stance: 41%–50% (MD = −4.9 mm, ES = −1.5), 51%–60% (MD = −6.5 mm, ES = −1.7), 61%–70% (MD = −8.2 mm, ES = −1.9), 71%–80% (MD = −9.6 mm, ES = −2.1), 81%–90% (MD = −9.8 mm, ES = −2.1), and 91%–100% (MD = −8.8 mm, ES = −1.6) 1 wk after gait training: medial shift from 31%–50% and at 81%–90% of stance: 31%–40% (MD = −4.0 mm, ES = −1.5), 41%–50% (MD = −5.2 mm, ES = −1.6), and 81%–90% (MD = −7.8 mm, ES = −1.7)

Table 2. Continued From Previous Page

Study (Year)	Participants	Study Information	Main Findings[a]
			Peak pressure
			Immediately after gait training: decrease in lateral midfoot (MD = −22.2 kPa, ES = −1.3) and lateral forefoot (MD = −28.1 kPa, ES = −0.9) and increase at medial forefoot (MD = 36.0 kPa, ES = 0.9)
			1 wk after gait training: decrease in lateral midfoot (MD = −20.0 kPa, ES = −1.1) and lateral forefoot (MD = −16.4 kPa, ES = −0.4)
			Maximum force
			Immediately after gait training: reduced in lateral midfoot (MD = −6.0 N, ES = −1.1) and lateral forefoot (MD = −6.8 N, ES = −1.5) and increased in medial forefoot (MD = 7.1 N, ES = 1.47)
			1 wk after gait training: reduced in lateral midfoot (MD = −5.4 N, ES = −1.0) and lateral forefoot (MD = −4.3 N, ES = −1.1) and increased in medial forefoot (MD = 4.9 N, ES = 1.0)

Abbreviations: 3D, 3-dimensional; CAI, chronic ankle instability; COP, center of pressure; ES, effect size; IC, initial contact; JCF, joint contact force; MD, mean difference; PTI, pressure-time integral; vGRF, vertical ground reaction force.

[a] All results are reported in comparison with baseline values.

reported" (question 8 [Q8]). For the external validity section, all studies were scored *yes* for "subjects representative of the entire population from which they were recruited" (Q11) and "subjects who were prepared to participate representative of the entire population from which they were recruited" (Q12). All studies were scored *no* for "staff, places, and facilities where the patients were treated, representative of the treatment the majority of patients receive" (Q13). The studies were scored *no* for Q13 because the gait-training methods used in the research studies were not representative of treatments in common use in clinical practice settings for individuals with CAI. In addition, gait-training visits were conducted under the supervision of a research team using unique equipment for administering gait training that is not currently available to clinicians or individuals with CAI. Considering the internal validity subscale, authors of no studies attempted to blind the study participants to the intervention (Q14). In the randomized controlled trials only, attempts were made to blind those measuring the main outcome measures of the intervention (Q15).[25,39,43] All studies were scored *yes* or *not applicable* for the remaining internal validity questions (Q16–Q20). Considering the internal validity—confounding (selection bias) subscale, in all studies, participants in intervention groups were recruited from the same population (Q21), and authors of all studies accounted for participants lost to follow-up (Q26). In all randomized controlled trials, participants were randomized into intervention groups (Q23), randomization was concealed (Q24), and adequate adjustment for confounding in the analyses for main findings was made (Q25).[25,39,43] Authors of only 3 studies reported a sample-size estimate needed to meet the power calculation requirement for Q27.[26,27,39]

Heterogeneity

Heterogeneity ranged from 0% to 40% and was interpreted to be *not important* for the 10% increments of the COP gait line at all time points (range, 0%–35.9%), contact time for the medial forefoot (37.0%), peak pressure for the hallux (17.6%), and PTI for the lateral heel (3.8%) and hallux (3.6%). Heterogeneity was >75% and was interpreted as *considerable* for peak pressure and PTI in the lateral midfoot (87.4% and 90.8%, respectively).

Publication Bias Assessment

Funnel plots and associated Egger regression test results for the meta-analyses are reported in Supplemental Figures 1 through 5. Publication bias was present for the location of the COP during 0% to 10% of the stance phase ($P = .02$), peak pressure in the lateral midfoot ($P < .001$), and the PTI in the lateral midfoot ($P < .001$). We did not find publication bias for any other measures included in our meta-analyses.

Gait-Training Approaches

Authors of 5 studies[25–28,36] used gait-training devices, and authors of 8 studies[35,37–43] used biofeedback for gait training. Among the studies in which authors used gait-training devices, authors of 2 studies[25,27] used destabilization boots and sandals, authors of 1 study[26] used a wearable multiaxis destabilization device, and authors of 2 studies[28,36] used a custom-built gait-training device with resistance bands.

Table 3. Summary of Studies Related to Kinematic Outcome Measures

Study (Year)	Participants	Study Information	Main Findings[a]
Donovan et al[25] (2016)	26 CAI (13 control, 13 intervention)	Design: randomized controlled trial Gait training: 12 sessions with device (destabilization boot and sandal) Outcome measures: 3D joint angles for ankle, knee, and hip for 1%–100% of stride cycle Data collection timepoints: baseline, 2–7 d after last gait-training session	Ankle-joint angles: increased dorsiflexion (MD = 5.4°, ES = 3.4) during mid- to late stance Knee-joint angles (°): no differences Hip-joint angles (°): no differences
Koldenhoven et al[39] (2021)	27 CAI (14 control, 13 intervention)	Design: randomized controlled trial Gait training: 8 sessions with biofeedback (visual) Outcome measures: 3D joint angles for ankle, knee, and hip for 0%–100% of stride cycle Data collection timepoints: baseline, 24–72 h after last gait-training session	Ankle-joint angles: decreased ankle inversion at IC (MD = −7.3°, ES = −1.6) and throughout entire stride cycle (MD = −5.9°, ES = −1.2) Knee-joint angles: increased external rotation (MD = 3.2°, ES = 0.7) during terminal swing Hip-joint angles (°): no differences
Migel and Wikstrom[41] (2021)	19 CAI	Design: descriptive laboratory study with repeated measures Gait training: 2 single sessions (1 laboratory, 1 real world) with biofeedback (haptic) Outcome measures: 3D ankle, hindfoot, and forefoot joint angles during stance at IC and average joint angle during the loading response (0%–10% of stance phase) Data collection timepoints: baseline, immediately after gait training	Ankle-joint angles Laboratory: increased abduction (MD = −1.7°, ES = −1.0) during loading response Real world: decreased inversion (MD = −2.5°, ES = −0.3) and increased abduction (MD = 2.3°, ES = 0.5) during loading response Hindfoot-joint angles (°) Laboratory: no differences Real world: no differences Forefoot-joint angles Laboratory: increased abduction (MD = 1.7°, ES = 0.9) during loading phase Real world: increased eversion (MD = 1.9°, ES = 0.6) and abduction (MD = 2.8°, ES = 0.5) during loading phase

Abbreviations: 3D, 3-dimensional; CAI, chronic ankle instability; ES, effect size; IC, initial contact; MD, mean difference.
[a] All results are reported in comparison with baseline values.

Table 4. Summary of Articles Related to EMG Outcome Measures Continued on Next page

Study (Year)	Participants	Study Information	Main Findings
Donovan et al[27] (2015)	15 CAI	Design: randomized crossover laboratory study Gait training: 1 session with device (destabilization boot and sandal) Outcome measures: RMS amplitude normalized to MVIC for 100 ms pre-IC and 200 ms post-IC for tibialis anterior, fibularis longus, lateral gastrocnemius, rectus femoris, and gluteus medius Data collection timepoints: baseline, 2–7 d after last gait-training session	RMS amplitude pre-IC Boot: increased for fibularis longus (MD = 0.10, ES = 0.9) Sandal: increased for fibularis longus (MD = 0.06, ES = 0.7) RMS amplitude post-IC Boot: increased for fibularis longus (MD = 0.23, ES = 1.3) Sandal: increased for fibularis longus (MD = 0.14, ES = 1.0)
Donovan et al[25] (2016)	26 CAI (13 control, 13 intervention)	Design: randomized controlled trial Gait training: 12 sessions with device (destabilization boot and sandal) Outcome measures: RMS amplitude normalized to quiet standing for 1%–100% of stride cycle for tibialis anterior, fibularis longus, fibularis brevis, and medial gastrocnemius Data collection timepoints: baseline, 2–7 d after last gait-training session	RMS amplitude 1%–100% gait cycle: decreased for fibularis longus during early stance (MD = 2.9, ES = 4.8) and midswing (MD = 1.0, ES = 2.5) phases of gait
Donovan et al[35] (2016)	10 CAI	Design: descriptive laboratory study Gait training: 1 session with biofeedback (auditory) Outcome measures: RMS amplitude (not normalized due to within-session testing design) for 200 ms pre-IC and 200 ms post-IC for tibialis anterior, fibularis longus, medial gastrocnemius, and gluteus medius Data collection timepoints: baseline, while receiving biofeedback	RMS amplitude pre-IC: no differences RMS amplitude post-IC: increased for fibularis longus (MD = 200.1, ES = 0.8) and medial gastrocnemius (MD = 233.3, ES = 0.7)
Feger and Hertel[28] (2016)	10 CAI	Design: descriptive laboratory study Gait training: 1 session with device (novel gait trainer with resistance bands) Outcome measures: RMS amplitude (not normalized due to within-session testing design) for 200 ms pre-IC and 200 ms post-IC for tibialis anterior, fibularis longus, medial gastrocnemius, and gluteus medius Data collection timepoints: baseline, while using device	RMS amplitude pre-IC: increased for fibularis longus (MD = 80.2, ES = 1.0) RMS amplitude post-IC: increased for fibularis longus (MD = 129.1, ES = 0.8)
Feger et al[36] (2018)	16 CAI	Design: quasiexperimental trial Gait training: 5 sessions with device (novel gait trainer with resistance bands) Outcome measures: RMS amplitude normalized to quiet standing for 0%–100% of stance phase for tibialis anterior, fibularis longus, medial gastrocnemius, and gluteus medius Data collection timepoints: baseline, 24–72 h after last gait-training session	RMS amplitude 0%–100% of stance Increased for fibularis longus from 21%–60% and 81%–90% of stance phase: 21%–30% (MD = 2.4, ES = 0.8), 31%–40% (MD = 2.2, ES = 0.7), 41%–50% (MD = 3.1, ES = 0.9), 51%–60% (MD = 2.8, ES = 0.6), and 81%–90% (MD = 2.1, ES = 0.4) Decreased for gluteus medius from 71%–100% of stance phase: 71%–80% (MD = −0.9, ES = −0.7), 81%–90% (MD = −1.0, ES = −0.9), and 91%–100% (MD = −1.6, ES = −0.9)

Table 4. Continued From Previous Page

Study (Year)	Participants	Study Information	Main Findings
Knuckles et al[26] (2022)	12 CAI	Design: descriptive laboratory study Gait training: 1 session with device (multiaxis destabilization device) Outcome measures: RMS amplitude normalized to quiet standing 50 ms pre-IC and 200 ms post-IC for tibialis anterior, fibularis longus, soleus, and gluteus medius Data collection timepoints: baseline, while wearing device, immediately after device removed	RMS amplitude pre-IC Wearing device: increased for tibialis anterior (MD = 3.6, ES = 0.9) After gait training: no differences RMS amplitude post-IC Wearing device: no differences After gait training: no differences
Koldenhoven et al[39] (2021)	27 CAI (14 control, 13 intervention)	Design: randomized controlled trial Gait training: 8 sessions with biofeedback (visual) Outcome measures: RMS amplitude normalized to quiet standing for 0%–100% of stride cycle for tibialis anterior, fibularis longus, medial gastrocnemius, and gluteus medius Data collection timepoints: baseline, 24–72 h after last gait-training session	RMS amplitude 0%–100% of gait cycle: no differences

Abbreviations: CAI, chronic ankle instability; EMG, electromyography; ES, effect size; IC, initial contact; MD, mean difference; MVIC, maximum voluntary isometric contraction; RMS, root mean square.

[a] All results are reported in comparison with baseline values.

Among the studies in which authors used biofeedback gait training, authors of 3 studies[37,39,42] used visual biofeedback, authors of 2 studies[35,43] used auditory biofeedback, and authors of 3 studies[38,40,41] used haptic biofeedback. For visual biofeedback, authors of 1 study[42] used a shoe-mounted cross-line laser with instructions to "walk in a manner in which the vertical laser line aligns with the piece of tape on the wall," authors of 1 study[37] used real-time 2-dimensional video from the posterior aspect of the treadmill with instructions to "walk in a manner where you can no longer view the outside or inside of your foot on the television screen while you walk," and authors of 1 study[39] used a custom real-time display of ankle-inversion angles that turned red for steps with ankle inversion above the set threshold (too much inversion) or green for steps within the desired range for ankle inversion with instructions to "avoid walking on the outside of your foot so as not to exceed the inversion threshold." For auditory biofeedback, authors of 2 studies used a custom device that was created to set a pressure threshold under the lateral aspect of the foot and provide an auditory tone when participants' vertical force exceeded the set threshold.[35,43] For haptic biofeedback, authors of 3 studies used a custom device similar to that used in the auditory biofeedback studies; however, instead of delivering an auditory tone, the device provided vibration on the lateral malleolus of the test limb when participants' vertical force exceeded the set threshold under the lateral aspect of the foot.[38,40,41]

Kinetic Outcomes

Eleven studies in which authors examined kinetic outcomes met the inclusion criteria for this systematic review (Table 2).[25,26,28,35–40,42,43] Authors of 6 studies[26,28,36,40,42,43] reported on the *COP gait line*, which was defined as the location of the COP from the most medial border of the foot at 10% increments in 5 studies[26,28,36,42,43] and the location of the COP in the lateral-medial direction from the position of the marker at the fifth metatarsal head with the foot modeled as a rectangle at 10% increments in 1 study.[40] Of these studies, 4 studies were single session, and results were pooled for meta-analyses (Figure 2).[26,28,40,42] The meta-analyses revealed small to large medial shifts in the location of the COP at each 10% increment from 0% to 90% (ES range, −0.35 to −0.82; I^2 range, 0–35.911; P range, <.001–.04; Egger regression P range, .02–.13) for the COP gait line.

Authors of 7 studies reported on traditional plantar-pressure measures (contact area, contact time, peak pressure, PTI, and time to peak pressure), and results were pooled for meta-analyses (Figure 3).[26,28,35–37,42,43] *Contact area* was defined as how large of an area of each region of the foot was in contact with the ground during the stance phase and was measured in centimeters squared.[28,35–37,42] *Contact time* was defined as how much time each region of the foot was in contact with the ground during the stance phase and was measured in milliseconds.[28,35–37,42] *Peak pressure* was defined as the highest amount of pressure in a given region of the foot during the stance phase of gait and was measured in kilopascals.[26,28,35–37,42,43] *Pressure-time integral* was defined as the total plantar pressure applied to a specific region of the foot multiplied by the

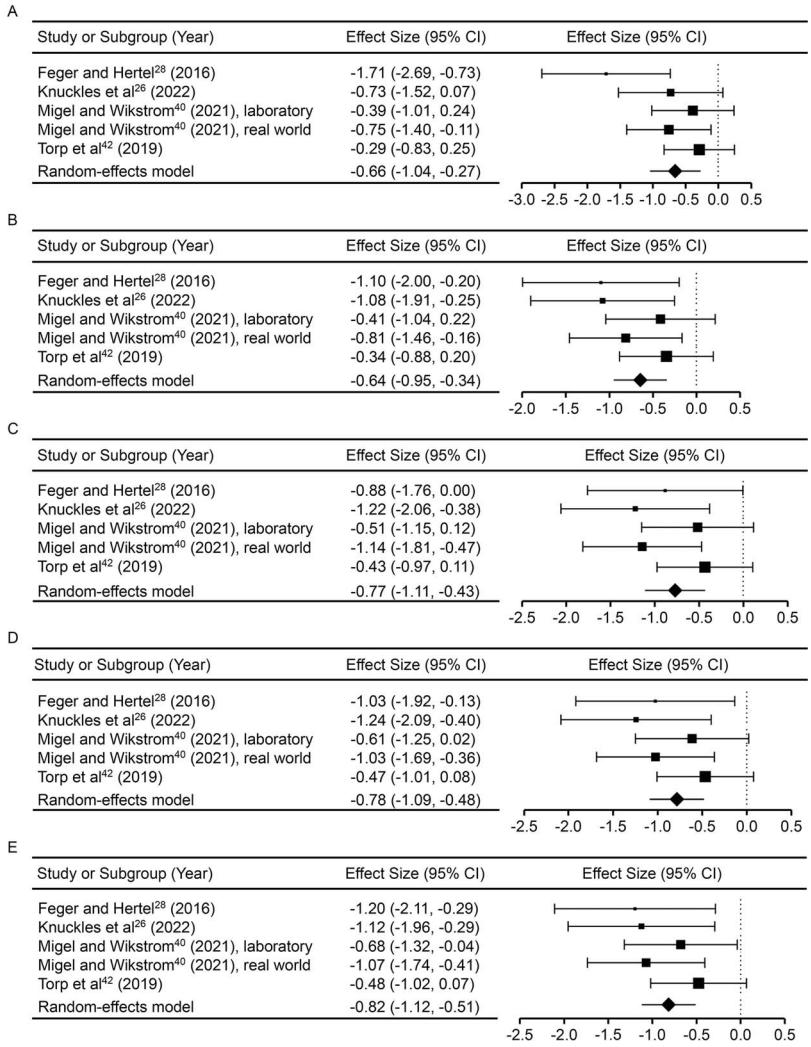
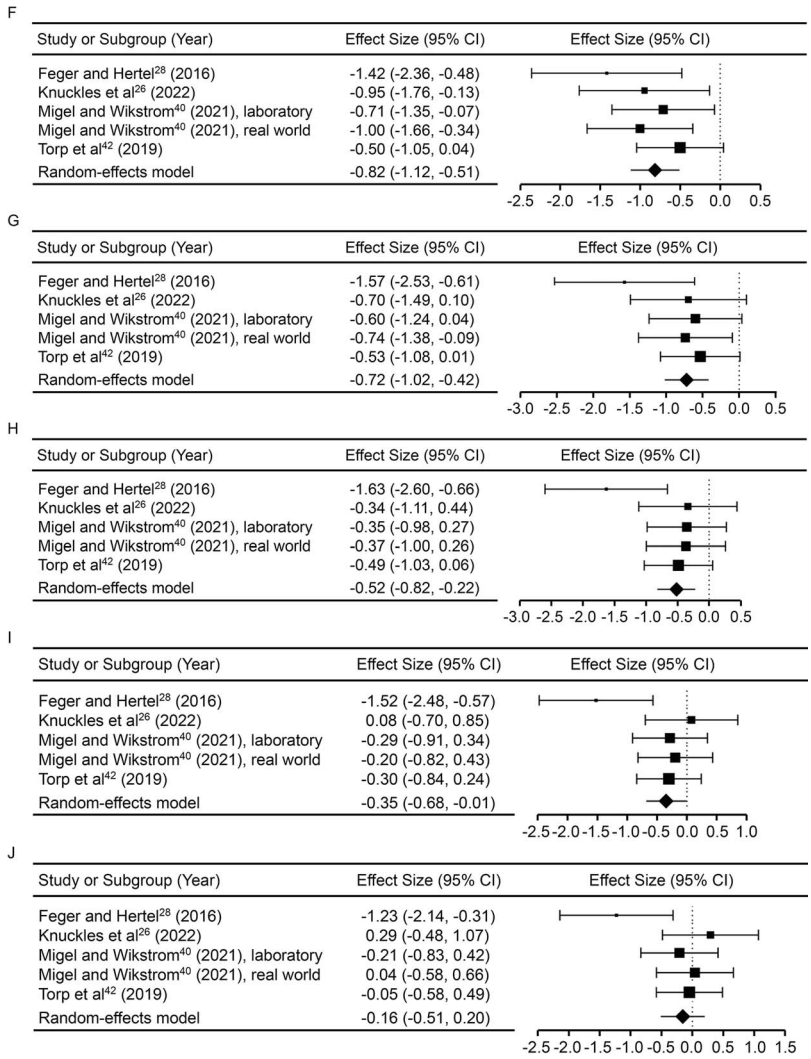


Figure 2. Meta-analysis results for the medial-lateral location of the center of pressure (COP) during 10% increments for 0%–100% of the stance phase: A, 0%–10%; B, 11%–20%; C, 21%–30%; D, 31%–40%; E, 41%–50%; F, 51%–60%; G, 61%–70%; H, 71%–80%; I, 81%–90%; and J, 91%–100%. Positive effect sizes (ESs) indicate a lateral shift in the COP. Negative ESs indicate a medial shift in the COP. **Continued on next page.**

time spent in the stance phase of gait and was measured in kilopascals multiplied by seconds.[28,35–37,42] *Time to peak pressure* was defined as the percentage of stance when peak pressure occurred for the specified region of the foot.[28,35,36] Meta-analyses revealed that contact time was decreased in the medial forefoot (ES = −0.43 [95% CI = −0.86, 0.00]; $I^2 = 36.997$; $P = .049$; Egger regression $P = .26$). Peak pressure was decreased in the lateral midfoot (ES = −1.18 [95% CI = −2.24, −0.12]; $I^2 = 87.438$; $P = .03$; Egger regression $P < .001$) and increased in the hallux (ES = 0.59 [95% CI = 0.21, 0.96]; $I^2 = 17.624$; $P = .002$; Egger regression $P = .16$). Pressure-time integral was decreased in the lateral heel (ES = −0.33 [95% CI = −0.66, 0.00]; $I^2 = 3.775$; $P = .050$; Egger regression $P = .07$) and lateral midfoot (ES = −1.22 [95% CI = −2.43, 0.00]; $I^2 = 90.757$; $P = .049$; Egger regression $P < .001$) and increased in the hallux (ES = 0.63 [95% CI = 0.30, 0.97]; $I^2 = 3.556$; $P < .001$; Egger regression $P = .14$). No other differences from the meta-analyses were found for any other kinetic parameters. Authors of 2 studies reported on internal joint moments and found no differences after gait training.[25,39] Authors of only 1 study reported on impact peak; time to impact peak; impact loading rate; propulsive peak; time to propulsive peak; propulsive loading rate; and ankle-joint contact force peak, impulse, and loading rate.[38]

Kinematic Outcomes

Three studies in which authors examined kinematic outcome measures met the inclusion criteria for the systematic review (Table 3).[25,39,41] Authors of 3 studies[25,39,41] measured 3-dimensional (3D) ankle-joint angles, and authors of 2 of those studies[25,39] measured 3D joint angles at the knee and hip. Authors of all studies reported 3D ankle kinematics at IC and throughout the loading phase (first 10% of stance), but given that only 1 study was a single-session gait-training study, meta-analyses were not performed.[41] Decreased ankle inversion during the loading response was reported by authors of 2 studies,[39,41] and authors of 1 study[25] found no differences in ankle inversion. Authors of only 1 study reported on hindfoot- and forefoot-joint angles and found increased forefoot abduction during the loading



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phase in the laboratory and real-world settings and increased forefoot eversion during the loading phase in the real-world setting.[41] Authors of 2 studies reported on ankle, knee, and hip kinematics throughout the stride cycle (0% or 1% to 100%).[25,39] Authors of 1 study[39] reported increased external rotation at the knee during terminal swing with a medium ES, and authors of the other study[25] found no differences. No differences were identified by authors of either study for hip-joint angles.[25,39]

Muscle Activity Outcomes. Seven studies in which authors measured muscle activity met the inclusion criteria for the systematic review (Table 4).[25–28,35,36,39] Of those included, authors of 4 studies[26–28,35] reported EMG RMS amplitudes for the 50 to 200 milliseconds pre-IC and the 200 milliseconds post-IC, authors of 2 studies[25,39] reported EMG RMS amplitudes throughout the stride cycle (0% or 1% to 100%), and authors of 1 study[36] reported EMG RMS amplitudes during the stance phase (0% to 100%). Meta-analyses were conducted for the EMG RMS amplitudes pre- and post-IC for the tibialis anterior, fibularis longus, and gluteus medius muscles. During the 200 milliseconds post-IC, muscle activity was increased during gait training for the fibularis longus muscle (ES = 0.83 [95% CI = 0.43, 1.22]; $I^2 = 0$; $P < .001$; Egger regression $P = .99$; Figure 4). No other differences were identified by the meta-analyses for any other muscle activity variables. Before IC, authors of 2 studies[27,28] reported increased fibularis longus activity with large ESs, and authors of 2 studies[26,35] reported no differences for fibularis longus activity. During the stance phase, authors of 1 study[36] reported increased fibularis longus activity with medium to large ESs, authors of 1 study[25] reported decreased fibularis longus activity with large ESs, and authors of 1 study[39] reported no differences. For the tibialis anterior muscle activity, authors of 1 study[26] reported increased activity pre-IC with a large ES, and authors of 3 studies[27,28,35] reported no differences. Authors of 1 study[36] reported decreased gluteus medius activity during late stance with medium to large ESs, and authors of 2 studies[25,39] reported no differences.

DISCUSSION

In this systematic review with meta-analysis, we identified 13 studies in which authors measured biomechanical outcomes before and after gait training in individuals with CAI. We categorized biomechanical outcome measures into kinetics, kinematics, and muscle activity. Among the

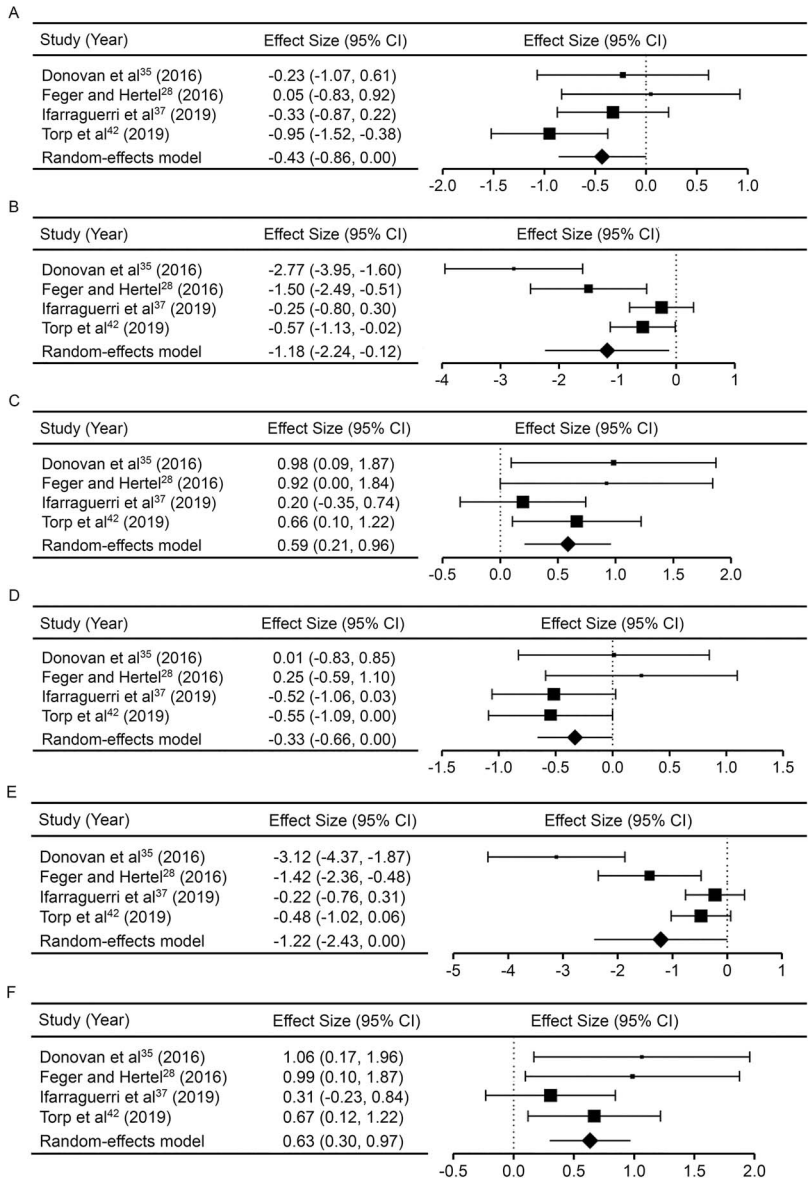

Figure 3. Meta-analysis results for the plantar pressure outcome measures. A, Contact time medial forefoot. B, Peak pressure lateral midfoot. C, Peak pressure hallux. D, Pressure-time integral (PTI) lateral heel. E, PTI lateral midfoot. F, PTI hallux. Positive effect sizes (ESs) indicate an increase in pressure. Negative ESs indicate a decrease in pressure.

included studies, authors of 11 measured kinetics, authors of 3 measured kinematics, and authors of 7 measured muscle activity, making meta-analyses possible for several outcome measures. Gait-training techniques included wearing a destabilization device[25–27]; using a custom gait-training device with resistance bands[28,36]; or using biofeedback including auditory,[35,43] visual,[37,39,42] or haptic[38,40,41] biofeedback modes to improve various biomechanical outcome measures. Based on the results from the meta-analyses, a single session of gait training improved COP location, reduced lateral plantar pressure, and increased muscle activity in the fibularis longus muscle during the 200 milliseconds post-IC. Targeted gait training improved corresponding gait biomechanics in almost all studies. Authors of few studies[25,36,39,43] required multiple sessions of gait training, and longer-term effects of gait training were not well documented, with the longest follow-up time being 1 week.[43]

Methodological Quality

Studies included in our systematic review and meta-analysis were critically appraised using the Downs and Black scoring system. Study quality using the Downs and Black scoring has previously been categorized as *excellent* (26–28), *good* (20–25), *fair* (15–19), and *poor* (<15).[44] The scores of the included studies ranged from 16 to 25 points out of a possible 28 points, demonstrating fair to good methodological quality (Table 1). The randomized controlled trials[25,39,43] had the highest methodological quality (24–25 points), followed by the quasiexperimental trial[36] (17 points) and descriptive laboratory studies[26,28,35,37,38,40,42] (16–18 points). Studies did not satisfy all criteria because information was not included or explicitly stated within the published manuscript and, therefore, could not earn points for that question. For the Reporting section, most studies scored *yes* or *not applicable* for all questions, except for whether adverse events

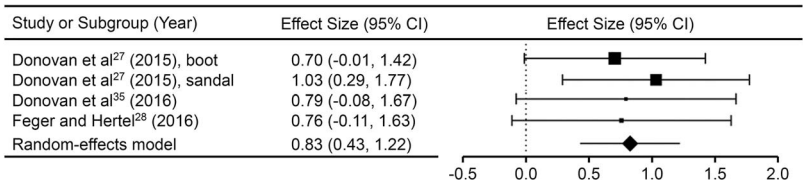

Figure 4. Meta-analysis results for the electromyography (EMG) outcome measures. Positive effect sizes (ESs) indicate an increase in EMG activity. Negative ESs indicate a decrease in EMG activity.

were reported. None of the authors of the included studies reported or mentioned any adverse events associated with gait training, which may suggest that the gait-training techniques used by those authors are not high risk for the given population. The included studies scored *yes* to all questions in the external validity section except for whether the staff, places, and facilities were representative of treatments patients receive. This is not surprising as all studies took place in a laboratory setting, and all authors used techniques that are not currently available to most practicing clinicians. In addition, gait-training methods explored in the research studies were not representative of current treatments used for individuals with CAI. Whereas study methods do not reflect current treatment methods in the clinical setting, the authors of these studies provided foundational evidence to support that gait biomechanics in individuals with CAI may be improved through various gait-training methods. To improve external validity, future studies should be done to explore gait-training methods that can be easily implemented in clinical practice for individuals with CAI. Scores were high within the internal validity section, but no authors blinded participants to the intervention. This would be a considerable challenge given that the primary modes of gait training involve wearing devices or responding to some form of immediate biofeedback. When considering the confounding or selection bias within the internal validity—confounding section, scores were low. Authors of most studies did not report the time frame in which participants were recruited, did not randomize participants into intervention groups, and did not conceal randomization apart from the randomized controlled trials.

Heterogeneity

For peak pressure and PTI in the lateral midfoot, heterogeneity was considerable (87.4% and 90.8%, respectively); however, authors of all studies showed the same direction of effect, and all studies were, therefore, still considered appropriate for inclusion in the meta-analyses. Higher levels of heterogeneity may indicate that authors were measuring different underlying effects or methodological differences existed between studies. On further inspection of the individual studies included in the meta-analyses for peak pressure and PTI, authors of all studies used the Pedar-X (Novel Inc) plantar-pressure system to measure and analyze plantar-pressure outcomes, but the gait-training interventions varied greatly between studies.[28,35,37,42] For example, Donovan et al used an auditory biofeedback device placed under the fifth metatarsal, Feger and Hertel created a custom gait-training device using resistance bands, Ifarraguerri et al projected a live video of a posterior view of the foot in front of the treadmill, and Torp et al placed a crossline laser on top of the foot.[28,35,37,42] Authors of studies using auditory feedback and the custom gait-training device found reductions in peak pressure and PTI in the lateral midfoot, whereas authors of studies using the live video and crossline laser found no differences while participants were receiving gait training. The substantial variations in gait-training methods possibly contributed to the considerable heterogeneity found by the meta-analyses.

Publication Bias Assessment

Publication bias was evaluated using funnel plots and Egger regression tests in our meta-analyses. Notably, publication bias was detected regarding the location of the COP from 0% to 10% of the stance phase, peak pressure in the lateral midfoot, and PTI in the lateral midfoot. These findings indicate a potential overstatement of results pertaining to these measures within our meta-analyses. Such bias may skew the meta-analysis ES upward, potentially inflating the results and inaccurately suggesting a stronger ES that may be attributable to random chance. The detection of publication bias suggests an overrepresentation of studies in which authors reported positive outcomes for these measures may be present. This bias may distort the overall findings, leading to an inflated perception of the ES and potentially resulting in misleading conclusions.

Kinetics

Kinetic variables were the most frequently reported by authors of studies included in this systematic review. The *COP gait line* has been described as the mediolateral location of the COP at 10% increments during the stance phase and was the most frequently reported kinetic variable.[10] Authors of all studies[26,28,36,42,43] used the Pedar-X plantar-pressure system to measure and analyze the location of the COP except for Migel and Wikstrom.[40] Gait-training strategies to target the COP gait line included a custom gait-training device with resistance bands,[28,36] a multiaxis destabilization device,[26] visual biofeedback,[42] haptic biofeedback,[40] and auditory biofeedback.[43] The meta-analyses revealed that, from 0% to 90% of the stance phase, gait training shifted the COP gait line medially while individuals received gait training. The pooled ES ranged from −0.35 to −0.82 throughout the stance phase, suggesting small to large improvements. Authors of studies involving multiple gait-training sessions tended to show greater medial shifts in the COP gait line as seen with the larger mean differences after gait-training sessions (Table 2).[36,43] The medium to large medial shift in the COP is considered beneficial because, when the center of gravity approaches or exceeds the lateral boundary of the foot, an episode of giving way or LAS may occur.[14] Various gait-training

strategies were effective at reducing laterally deviated COP and should be implemented when indicated for individuals with CAI.

Traditional plantar-pressure measures (contact area, contact time, peak pressure, PTI, and time to peak pressure) were often reported for 9 specified regions of the foot, including the medial heel, lateral heel, medial midfoot, lateral midfoot, medial forefoot, central forefoot, lateral forefoot, hallux, and toes 2 to 5 in 7 studies.[26,28,35–37,42,43] Gait-training strategies to target the traditional plantar-pressure measures included a custom gait-training device with resistance bands,[28,36] multiaxis destabilization devices,[26] visual biofeedback,[37,42] and auditory biofeedback.[35,43] Generally speaking, traditional plantar-pressure measures were reduced in the lateral aspect of the foot and pressure was shifted medially, which is the desired outcome for gait training in individuals with CAI. Authors of individual studies reported decreased contact area for the lateral midfoot[28,35] or increased contact area in the medial midfoot,[36,42] suggesting a medial shift in pressure area may exist after gait training.

Peak pressure was considered the maximum loading in an area under the foot.[26,28,35–37,42,43] The meta-analyses revealed decreased pressure in the lateral midfoot with a large ES and a medium increase in peak pressure for the hallux. Increased peak pressure for the total foot was reported by authors of 2 studies.[28,35] Although not investigated among patients with CAI, the overall increase in peak pressure may be a beneficial adaptation regarding PTOA. Authors of studies have found that greater mechanical loading during walking is associated with less type II collagen turnover among patients who underwent anterior cruciate ligament reconstruction.[45,46] Similar to peak pressure, PTI was described as the total amount of pressure for a specific region of the foot multiplied by the time spent in stance.[28,35–37,42,43] The meta-analyses revealed that PTI decreased in the lateral heel and lateral midfoot and increased in the hallux, again suggesting a shift from lateral to medial plantar pressure. The results for the peak pressure and PTI in the lateral midfoot should be interpreted with caution. Considerable heterogeneity and publication bias were identified in the meta-analyses for these outcomes and suggest that the larger ESs for these outcomes may be due to chance rather than an actual observed change. Future studies involving larger sample sizes in which authors assess the effects of gait training on these plantar-pressure outcome measures are warranted.

The results from our meta-analyses suggest that several plantar-pressure measures are improved by various gait-training methods involving devices or biofeedback techniques. Many individuals with CAI demonstrated increased plantar pressure along the lateral column of the foot, which may be associated with an elevated risk of LAS and could contribute to the earlier onset of ankle PTOA in individuals with CAI.[13–15] Shifting the pressure medially reduces the risk of the COP approaching the lateral boundary of the foot and potentially resulting in an LAS. This altered ankle position can also result in abnormal stress distribution throughout the talar cartilage, thereby influencing the development of ankle PTOA.[17,18] Therefore, restoring gait patterns in individuals with CAI is crucial to maintaining long-term ankle-joint health, which appears to be possible using gait training.

Kinematics

Kinematics were the least reported outcome measures, with only 3 studies meeting the inclusion criteria for the systematic review.[25,39,41] Gait-training strategies to target the kinematic measures included destabilization devices,[25] visual biofeedback,[39] and haptic biofeedback.[41] Authors of 2 studies[39,41] found that gait training with biofeedback (visual and haptic) reduced ankle inversion by 2.5° to 7.3°, and authors of 1 study[25] using destabilization devices found no changes in ankle inversion after gait training but found increased ankle dorsiflexion by 5.4° during mid to late stance. Of those included, authors of only 1 study specifically targeted the reduction of ankle inversion as part of the gait-training protocol.[39] Because authors of only 3 studies using gait training to improve biomechanics in individuals with CAI measured kinematic outcomes, understanding the utility of gait training for improving ankle kinematics is difficult, but the medial shift in the COP gait line and additional plantar-pressure outcome measures likely could be associated with shifting from an inverted to everted ankle position. Walking with the foot in an everted position has been shown to create more contact under the medial aspect of the foot, and thus, the COP was located on the medial aspect of the foot.[47] Future gait-training studies in which authors measure kinematic outcomes in individuals with CAI should be done to consider techniques specifically targeting ankle inversion.

Muscle Activity

Muscle activity was measured in 7 studies[25–28,35,36,39] using EMG, and RMS amplitude was reported for all included studies; however, the timing during the stride cycle for which data were reported differed among studies, making meta-analyses possible only for short periods pre- and post-IC.[26,28,35–37,42,43] Gait-training strategies were not specifically used to target muscle activity, but authors of several studies measured muscle activity as a primary outcome measure and included a custom gait-training device with resistance bands,[28,36] destabilization devices,[25–27] visual biofeedback,[39] and auditory biofeedback.[35] Our meta-analyses revealed a large increase in fibularis longus activity during the 200 milliseconds post-IC while individuals received gait training. Increased fibularis longus activity immediately post-IC during the loading response may contribute to increased ankle stability and the medial shift in plantar pressure.[10,48] Individuals without a history of LAS have been shown to activate their fibularis longus during midstance to assist with pronation and stabilize the first ray during propulsion.[49]

Limitations

Several limitations should be considered when interpreting the results of this study. The sample size in each study was relatively small and only included 10 to 27 participants. Results from these studies should be interpreted with caution, and further research is needed in this area. The timing in which biomechanical outcomes were measured varied among studies. Authors of several studies measured gait outcomes while participants were wearing devices[26,28] or receiving biofeedback,[37,38,42,43] and authors of some studies measured outcomes after gait training had

ended.[25–27,36,39–41,43] Gait-training protocols differed substantially between studies. For example, studies in the visual biofeedback category involved a variety of techniques including projecting real-time ankle kinematics in front of the treadmill,[39] projecting real-time video of the posterior aspect of the ankle,[37] and using a crossline laser attached to the dorsal aspect of the foot.[42] In addition, the number of gait-training sessions implemented for each study protocol ranged from 1 to 12 total sessions, which may have influenced the effects of gait training on biomechanical outcomes. Lastly, the gait-training methodology that authors of many studies used is not currently clinically accessible, which makes implementation unrealistic for athletic trainers or other health care professionals treating individuals with CAI. Future studies should be done to consider gait-training techniques that would be feasible for clinical implementation.

Future Directions

Several future directions should be considered for gait-training implementation for individuals with CAI. New gait-training strategies should attempt to transition concepts from laboratory-based interventions to strategies using minimal or no equipment to increase the feasibility of implementation in the clinical setting. Future studies should also be done to consider assessing long-term outcomes, dosage, measures of joint health, and the risk reduction of subsequent LAS associated with gait training. Whereas, in this study, we have established that gait training can be used to improve various lower extremity gait biomechanics immediately and for a short duration (up to 1 week), long-term outcomes are not yet understood. Another component of gait training to consider is the total number of gait-training sessions and the length of sessions needed to improve and maintain desired gait changes. This information may be useful in determining if additional sessions are needed as a booster or refresher after the cessation of gait-training programs to maintain desired gait changes. The overarching goal of gait training should be not only to improve biomechanics but also to improve ankle-joint health and reduce the risk of future LAS. Future research should be done to address these critical areas to continue facilitating gait training and its broader adoption in clinical practice for patients with CAI.

CONCLUSIONS

Gait-training protocols included in our systematic review used devices or biofeedback to effectively improve lower extremity biomechanics in individuals with CAI. These interventions resulted in notable improvements such as medial shifts in plantar pressure, decreased ankle inversion, and increased fibularis longus activity, which may be associated with reducing the risk of LAS and development of ankle PTOA. Current gait-training strategies may present practical challenges within the clinical setting. Therefore, future research endeavors are needed to investigate alternative techniques that are more accessible for clinical implementation. Restoring gait patterns in individuals with CAI is critical and appears to be possible by using gait training.

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SUPPLEMENTAL MATERIAL

Supplemental Figure 1. Funnel plots with Egger regression test results for assessing risk of publication bias for center-of-pressure gait line, medial-lateral location of center of pressure, at 10% increments for 0% to 100% of the stance phase: A, 0%–10%; B, 11%–20%; C, 21%–30%; D, 31%–40%; E, 41%–50%; F, 51%–60%; G, 61%–70%; H, 71%–80%; I, 81%–90%; and J, 91%–100%.

Supplemental Figure 2. Funnel plot with Egger regression test results for assessing risk of publication bias for contact time of the medial forefoot.

Supplemental Figure 3. Funnel plots with Egger regression test results for assessing risk of publication bias for peak pressure of the A, lateral midfoot and B, hallux.

Supplemental Figure 4. Funnel plots with Egger regression test results for assessing risk of publication bias for pressure-time integral of the A, lateral heel; B, lateral midfoot; and, C, hallux.

Supplemental Figure 5. Funnel plot with Egger regression test results for assessing risk of publication bias for the fibularis longus after initial contact.

Address correspondence to Rachel M. Koldenhoven, PhD, ATC, Department of Health and Human Performance, Texas State University, Jowers A134, 601 University Drive, San Marcos, TX 78666-4684. Address email to Rmr214@txstate.edu.