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Title: Gait Training Interventions for Individuals with Chronic Ankle Instability: A Systematic Review & Meta-Analysis

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Gait Training Interventions for Individuals with Chronic Ankle Instability: A Systematic Review & Meta-Analysis

Abstract

Objective: This review aimed to determine if gait training interventions influence lower extremity biomechanics during walking in individuals with chronic ankle instability (CAI).

Methods: A literature search was conducted in PubMed, CINAHL, SPORTDiscus, and MEDLINE to identify English-language studies from inception through September 2022. Eligible studies included randomized control trials, repeated measures design, and descriptive laboratory studies measuring the effects during or following a gait training intervention on biomechanical outcomes (kinematics, kinetics, electromyography) during walking in individuals with CAI. Gait training interventions were broadly categorized into devices (destabilization devices, novel gait training device) and biofeedback (visual, auditory, and haptic delivery modes). Meta-analyses were conducted when appropriate using random-effects to compare pre- and post- gait training intervention mean differences and standard deviations.

Results: Thirteen studies were included. Meta-analyses were conducted for single session gait training studies only. Eleven studies reported kinetic outcomes. Our meta-analyses showed location of center of pressure (COP) was shifted medially from 0-90% (Effect Size [ES] range=0.35-0.82) of stance, contact time was decreased in medial forefoot (ES=0.43), peak pressure was decreased for lateral midfoot (ES=1.18) and increased for hallux (ES=0.59), pressure time integral was decreased for lateral heel (ES=0.33) and lateral midfoot (ES=1.22) and increased for hallux (ES=0.63). Three studies reported kinematic outcomes. Seven studies reported electromyography outcomes. Our meta-analyses revealed increased activity following initial contact (IC) for fibularis longus (ES=0.83).

Conclusions: Gait training protocols improved some lower extremity biomechanical outcomes in individuals with CAI. Plantar pressure outcome measures seem to be most impacted by gait training programs with improvements in decreasing lateral pressure associated with increased risk for lateral ankle sprains. Gait training increased EMG activity post-IC for the fibularis longus. Few studies have assessed the impact of multi-session 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

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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.
- Significant gait improvements were evident utilizing a variety of gait training devices and biofeedback.

- There is limited evidence on kinematic outcomes of gait training interventions for CAI.
- Gait training would benefit from homogeneity between protocols and techniques suitable for clinical implementation.

Introduction

Lateral ankle sprains (LAS) 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[4] and in one prospective study, 40% of individuals who sustained their first ever LAS developed a condition known as chronic ankle instability (CAI).[5] CAI is characterized as having repetitive episodes of giving way, decreased self-reported function, ongoing symptoms such as pain or weakness, and recurrent ankle sprains for at least one year following the initial LAS.[6] Individuals with CAI will all have primary tissue injury to the lateral ankle ligament(s), however, impairments will be unique to each individual.[3] Hertel and Corbett[3] categorize these impairments found within individuals with CAI as motor-behavioral, sensory-perceptual, and pathomechanical impairments. Motor-behavioral impairments that often present as aberrant biomechanical patterns during functional and dynamic movements have been well-documented in CAI.[3]

Several altered gait characteristics have been observed during walking in individuals with CAI compared to individuals with a history of no LAS and individuals that have a history of LAS but who return to pre-injury health status (termed copers). Individuals with CAI often display greater ankle inversion throughout the gait cycle[7–9] which may coincide with a lateral deviation in the center of pressure (COP)[10,11] and increased plantar pressure along the lateral column of the foot during walking.[10,12] This biomechanical profile of gait is associated with an elevated risk of LAS and may contribute to the earlier onset of ankle posttraumatic osteoarthritis (PTOA) in individuals with CAI.[13–15] When the location of COP approaches the lateral boundary of the foot, it places the ankle in a position similar to that of a 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 while decreased supination decreased the occurrence of LAS.[16] Unfortunately, this position can also result in abnormal stress distribution throughout the talar cartilage, thereby influencing the development of ankle PTOA.[17,18] Therefore, it is crucial to restore gait patterns in individuals with CAI to maintain long-term joint health of the ankle.

Various approaches have been utilized to address these abnormal gait patterns in individuals with CAI, including traditional rehabilitation techniques such as strength and balance training,[19,20] as well as targeted gait training strategies involving the use of devices or biofeedback methods.[21,22] While traditional rehabilitation strategies are successful at improving strength and balance when trained, they have not shown evidence of improving gait biomechanics.[19,20] Recently published critically appraised topics have evaluated the effectiveness of taping and bracing,[23] neuromuscular training,[24] and gait biofeedback training[21] for improving gait impairments in individuals with CAI. Of the aforementioned interventions, only biofeedback training showed efficacy at improving the specific gait pattern (i.e. lateralized COP) associated with CAI.[21]

Biofeedback training involves providing a stimulus (visual, auditory, haptic) to correct unwanted movement patterns and appears to be effective at improving 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 destabilization devices[25–27] and a custom gait training device using resistance bands.[28] Destabilization devices are worn by individuals to create an unstable surface under the foot with the goal of improving neuromuscular control in patients with CAI that exhibit symptoms associated with sensory-perceptual impairments such as perceived instability. Sensory-perceptual impairments have been defined as how the individual senses or feels about the body, 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 yet to be conducted to synthesize this information and provide a synopsis on the effectiveness of these gait training interventions in individuals with CAI. The purpose of this study was to systematically review the literature on the efficacy of gait training interventions (devices, biofeedback) for improving altered gait biomechanics in individuals with CAI.

Methods

Search Strategy

This systematic review with meta-analysis was registered with the International Prospective Register of Systematic Reviews (PROSPERO, CRD4202XXXXXXX) on September 12, 2022. Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) 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 filtered for English language and full-text available. Following the initial search, screening of the literature and data extraction were completed. Two authors (XX, XX) 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 (XX) 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) included individuals with CAI (as determined using the International Ankle Consortium guidelines),[6] 2) a gait training intervention was administered using devices or biofeedback methods, 3) outcome measures included gait kinetics, kinematics, and/or muscle activity during walking, 4) study was published in peer-reviewed journal, and 5) full-text was published in English. Randomized controlled trails, cross-over design, quasi-experimental 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, not available in English, and/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 nonrandomized comparative studies.[30] Questions were scored as yes (1), no (0), or not applicable (/) with the exception of question 5, which was scored as yes (2), partially (1), no (0), or not applicable with a maximum total score of 28 points.[30] Higher scores indicated higher methodological quality.[30] Two authors (XX, XX) independently scored all included studies. If scores did not align, a third author (XX) was consulted.

Data extraction

Study design, participant demographics, sample sizes, intervention type (device, biofeedback), intervention length, and biomechanical outcome measures (kinematics, kinetics, electromyography (EMG)) were extracted by one author (XX) for all included studies (Tables 2-4). Authors were contacted if values were not reported in the text or were presented as graphs. When at least 3 studies reported on the same outcomes, the mean and standard deviations were extracted for potential meta-analyses.

Data analysis

When 3 or more studies reported on the same outcome measure using consistent units or units that could be derived for equivocal comparisons, meta-analyses were conducted. Meta-analyses were performed using a random-effects model in JASP software (JASP Team 2023, version 0.17.2.1, University of Amsterdam, Netherlands) to compare differences before and during administration of gait training for studies involving a single session for the following variables: kinetics (COP gait line, peak pressure, contact area, contact time, pressure time integral) and EMG (root mean square [RMS] amplitude pre-initial contact [IC] and post-IC). Meta-analyses were considered statistically significant when p<.05. There were not enough multi-session gait training studies for meta-analyses to be conducted on any variables. Meta-analysis ES and associated 95% confidence intervals were displayed using forest plots (Figures 2-4). Effect sizes (ES) and standard error of ES using the pooled standard deviation were calculated to determine that magnitude of difference between time points (pre- vs. post-gait training) or between groups (gait training vs. no gait training). ES 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 summarize the variation across studies due to difference rather than chance as recommended by the Cochran Handbook for Systematic Reviews of Interventions.[32] Interpretation of the I^2 test statistic used the following guidelines: 0-40% may not be important, 30-60% may represent moderate heterogeneity, 50-90% may represent substantial heterogeneity, 75-100% considerable heterogeneity.[32] When heterogeneity was considerable (I^2>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's regression test for variables identified as statistically significant by the meta-analyses. Significant publication bias was considered present when p<.05 for Egger's regression test.[34]

Results

Study Selection & Characteristics

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

Methodological Quality Assessment

Downs and Black scores for the included studies ranged from 16-25 points out of a maximum 28 points. The 3 studies with randomized controlled trial study designs had the highest overall scores with a range of 24 points[43] to 25 points.[25,39] Reviewers scored all studies "yes" or "not applicable" to all questions within the reporting section of the checklist with the exception of if adverse events that may impact the intervention were reported (Question [Q] 8). For the external validity section, all studies scored "yes" for subjects representative of the population they were recruited from (Q11) and subjects who were prepared to participate represented the population from which they were recruited (Q12). All studies scored "no" for if staff, places, and facilities where patients were treated were representative of the treatment majority of the patients received (Q13). The studies were scored "no" for Q13 because the gait training methods employed in the research studies were not representative of treatments in common use in clinical practice settings for individuals with CAI. Additionally, 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. When considering internal validity subscale, no studies made an attempt to blind the study subjects to the intervention (Q14). In the randomized controlled trials only,[25,39,43] attempts were made to blind the individual measuring the main outcome measures of the intervention (Q15). All studies scored "yes" or "not applicable" for the remaining internal validity questions (Q16-20). When considering the internal validity – confounding (selection bias) subscale, all studies subjects in intervention groups were recruited from the same population (Q21) and all studies accounted for subjects lost to follow-up (Q26). All randomized controlled trials[25,39,43] randomized subjects into intervention groups (Q23), randomization was concealed (Q24), and adequate adjustments for confounding in the analyses for main findings were made (Q25). Only 3 studies[26,27,39] reported a sample size estimate needed to meet the power calculation requirement for Q27.

Heterogeneity

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

Publication Bias Assessment

Funnel plots and associated Egger's regression test results for the meta-analyses are reported in the supplemental figure. Publication bias was present for the location of COP during 0-10% of the stance phase (p=.015), for peak pressure in the lateral midfoot (p<.001), and for the PTI in the lateral midfoot (p<.001). There were no other significant findings for publication bias for any other measures included in our meta-analyses.

Gait Training Approaches

Five studies utilized gait training devices[25–28,36] and 8 studies utilized biofeedback[35,37–43] for gait training. Among the gait training device studies, 2 used destabilization boots and sandals,[25,27] 1 used a wearable multi-axis destabilization device,[26] and 2 used a custom-built gait training device with resistance bands.[28,36] Among the biofeedback gait training studies, 3 used visual biofeedback,[37,39,42] 2 used auditory biofeedback,[35,43] and 3 used haptic biofeedback.[38,40,41] For the visual biofeedback, 1 study 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,"[42] 1 study used real-time 2D 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,"[37] and 1 study 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."[39] For the auditory biofeedback, 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 the participant's vertical force exceed the set threshold.[35,43] For the haptic biofeedback, 3 studies used a custom device similar to the auditory biofeedback studies, however, instead of delivering an auditory tone, vibration was provided on the lateral malleolus of the test limb when the participant's vertical force exceeded the set threshold under the lateral aspect of the foot.[38,40,41]

Kinetic Outcomes

Eleven studies examining kinetic outcomes met the inclusion criteria for this systematic review (table 2). Six studies reported on the COP gait line.[26,28,36,40,42,43] The COP gait line was defined as the location of COP from most medial border of the foot at 10% increments in 5 studies[26,28,36,42,43] and the location of COP in the lateral-medial direction from the position of the marker at the 5th metatarsal head with the foot modeled as a rectangle at 10% increments in 1 study.[40] Of these studies, 4 were single session[26,28,40,42] and results were pooled for meta-analyses (Figure 2). The meta-analyses revealed there were small to large medial shifts in the location of COP at each 10% increment from 0-90% (ES range: -0.35 to -0.82, I^2 range: 0 to 35.911, p-value range: <.001 to .041, Egger's regression p-value range: .015 to .125) for the COP gait line. Seven studies reported on traditional plantar pressure measures (contact area, contact time, peak pressure, pressure time integral [PTI], 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 (cm^2).[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 (ms).[28,35–37] 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 (kPa).[26,28,35–37,42,43] PTI was defined as the total plantar pressure applied to a specific region of the foot multiplied by the time spent in the stance phase of gait and was measured in kilopascals multiplied by seconds (kPa*s).[28,35–37,42] Time to peak pressure was defined as the % of stance when peak pressure occurred for the specified region of the foot.[28,35,36] Meta-analyses revealed that contact time was significantly decreased in the medial forefoot (ES: -0.43 [-0.86,0.00], I^2=36.997, p=.049, Egger's regression p=.260). Peak pressure was significantly increased in the hallux (ES: 0.59 [0.21,0.96], I^2= 17.624, p=.002, Egger's regression p=.156) and significantly decreased in the lateral midfoot (ES: -1.18 [-2.24,-0.12], I^2= 87.438, p=.029, Egger's regression p<.001). Pressure time integral was increased in the hallux (ES: 0.63 [0.30,0.97], I^2= 3.556, p<.001, Egger's regression p=.144) and decreased in the lateral heel (ES: -0.33 [-0.66,0.00], I^2= 3.775, p=.050, Egger's regression p=.066) and lateral midfoot (ES: -1.22 [-2.43,0.00], I^2= 90.757, p=.049, Egger's regression p<.001). There were no other significant differences from the meta-analyses for any other kinetic parameters. Two studies reported on internal joint moments and found no significant differences after gait training.[25,39] Only one study reported on impact peak, time to impact peak, impact loading rate, propulsive peak, time to propulsive peak, propulsive loading rate, ankle joint contact force peak, ankle joint contact force impulse, and ankle joint contact force loading rate.[38]

Kinematic Outcomes

Three studies examining kinematic outcome measures met the inclusion criteria for the systematic review (Table 3).[25,39,41] Three studies measured 3-Dimensional (3D) ankle joint angles (º)[25,39,41] and 2 of those studies measured 3D joint angles at the knee and hip.[25,39] All studies reported 3D ankle kinematics at IC and throughout the loading phase (first 10% of stance), however, only one study was a single session gait training study so meta-analyses were not performed.[41] Decreased ankle inversion during the loading response was reported by 2 studies[39,41] and 1 study found no differences in ankle inversion.[25] Only one study reported on hindfoot and forefoot joint angles and found increased forefoot abduction during the loading phase in the laboratory and real world settings and increased forefoot abduction during the loading phase in the laboratory setting.[41] Two studies reported on ankle, knee, and hip kinematics throughout the stride cycle (0-100%).[25,39] One study reported increased external rotation at the knee during terminal swing[39] with a medium ES while the other study found no significant differences.[25] Significant differences were not identified by either study for hip joint angles.[25,39]

Muscle Activity Outcomes

Seven studies measured muscle activity using and met the inclusion criteria for the systematic review (Table 4).[25–28,35,36,39] Of the included studies, 4 reported EMG RMS amplitudes for the 50-200ms pre-IC and 200ms post-IC, 2 studies reported EMG RMS amplitudes throughout the stride cycle (0-100%),[25,39] and 1 study reported EMG RMS amplitudes during the stance phase (0-100%).[36] Meta-analyses were conducted for the EMG RMS amplitudes pre-IC and post-IC for the tibialis anterior, fibularis longus, and gluteus medius muscles. During the 200ms post-IC, muscle activity was increased during gait training for the fibularis longus muscle (ES: 0.83 [0.43, 1.22], I^2=0, p<.001, Egger's regression p=.986) (Figure 4). There were no other significant differences identified by the meta-analyses for any other muscle activity parameters. Prior to IC, 2 studies reported increased fibularis longus activity[27,28] with large ES and 2 reported no differences for fibularis longus activity.[26,35] During the stance phase, 1 study reported increased fibularis longus activity with medium to large ES,[36] while another study reported decreased fibularis longus activity with large ES,[25] and a third study reported no significant differences.[39] For the tibialis anterior muscle activity, 1 study reported increased activity pre-IC[26] with a large ES, while 3 studies reported no significant differences.[27,28,35] One study reported decreased gluteus medius activity during late stance[36] with medium to large ES and 2 studies reported no significant differences.[25,39]

Discussion

This systematic review with meta-analysis identified 13 studies that 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 studies included, 11 measured kinetics, 3 measured kinematics, and 7 measured muscle activity making meta-analyses possible for several outcome measures. Gait training techniques included wearing destabilization devices,[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 aimed 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 200ms post-IC. Targeted gait training improved corresponding gait biomechanics in almost all studies. Few studies required multiple sessions of gait training[25,36,39,43] 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 & Black scoring system. Study quality using the Downs & 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 16-25 points out of a possible 28 points demonstrating fair to good methodological quality (Table 1). The randomized controlled trials had the highest methodological quality (24-25 points) followed by the quasi-experimental trial (17 points) and descriptive laboratory study designs (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, the majority of studies scored “yes” or “not applicable” for all questions, except for if adverse events were reported. None of the included studies reported or mentioned any adverse events associated with gait training which may suggest that the gait training techniques employed by the studies are not high risk for the given population. The included studies scored “yes” to all questions in the external validity section except for if 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 utilized techniques that are not currently available to most practicing clinicians. Additionally, gait training methods explored in the research studies were not representative of current treatments used in treating individuals with CAI. While study methods do not reflect current treatment methods in the clinical setting, these studies provide the 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 explore gait training methods that can be easily implemented in clinical practice for individuals with CAI. Scores were high within the internal validity section, however, no studies blinded subjects to the intervention. This would be a considerable challenge given 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 next internal validity section, scores were low. Most studies did not report the timeframe 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, all studies showed the same direction of effect and were therefore still considered appropriate for inclusion in the meta-analyses. Higher levels of heterogeneity may indicate that studies are measuring different underlying effects or there are methodological differences between the studies. Upon further inspection of the individual studies included in the meta-analyses for peak pressure and PTI,[28,35,37,42] all studies utilized the Pedar-X plantar pressure system to measure and analyze plantar pressure outcomes, however, the gait training interventions varied greatly between studies. For example, Donovan et al.[35] utilized an auditory biofeedback device placed under the 5th metatarsal, Feger and Hertel[28] created a custom gait training device using resistance bands, Ifarraguerri et al.[37] projected a live video of a posterior view of the foot in front of the treadmill, and Torp et al.[42] placed a crossline laser on top of the foot. The studies utilizing auditory feedback and the custom gait training device found significant reductions in peak pressure and PTI in the lateral midfoot while the studies using the live video and crossline laser found no significant differences while receiving gait training. It is possible that the substantial variations in gait training methods contributed to the considerable heterogeneity found by the meta-analyses.

Publication Bias Assessment

Publication bias was evaluated using funnel plots and Egger's regression tests in our meta-analyses. Notably, significant publication bias was detected regarding the location of the

COP from 0-10% 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, thus potentially inflating the results and inaccurately suggesting a stronger ES that may be attributable to random chance. The detection of publication bias suggests there may be an overrepresentation of studies reporting positive outcomes for these measures. 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 studies included in this systematic review. The COP gait line is described as the mediolateral location of COP at 10% increments during the stance phase[10] and was the most frequently reported kinetic variable. All studies[26,28,36,42,43] utilized the Pedar-X plantar pressure system to measure and analyze the location of 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] multi-axis destabilization devices,[26] visual biofeedback,[42] haptic biofeedback,[40] and auditory biofeedback.[43] The meta-analyses revealed that from 0-90% of the stance phase, gait training shifted the COP gait line medially while participants received gait training. The pooled ES ranged from -0.35 to -0.82 throughout the stance phase suggesting small to large improvements. Studies involving multiple gait training sessions[36,43] tended to show greater medial shifts in the COP gait line as seen with the larger MD following gait training sessions (table 2). The medium to large medial shift in 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, time to peak pressure) were often reported for nine specified regions of the foot including: medial heel, lateral heel, medial midfoot, lateral midfoot, medial forefoot, central forefoot, lateral forefoot, hallux, and toes 2-5 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] multi-axis 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 shifted medially which is the desired outcome for gait training in individuals with CAI. 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 following 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 total foot was reported by 2 studies.[28,35] Although not investigated among patients with CAI, the overall increase in peak pressure may be a beneficial adaptation when regarding PTOA. 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 significant publication bias were identified for the meta-analyses for these outcomes and suggest that the larger ES for these outcomes may be due to chance rather than an actual observed change. Future studies involving larger sample sizes assessing the effects of gait training on these plantar pressure outcome measures are therefore warranted.

The results from our meta-analyses suggest that several plantar pressure measures are significantly improved by various gait training methods involving devices or biofeedback techniques. Many individuals with CAI demonstrate 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 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, it is crucial to restore gait patterns in individuals with CAI to maintain long-term joint health of the ankle which appears to be possible through the utilization of gait training.

Kinematics

Kinematics were the least reported outcome measures with only 3 studies meeting the inclusion criteria for the systematic review.[26,28,35–37,42,43] Gait training strategies to target the kinematic measures included destabilization devices,[25] visual biofeedback[39] and haptic biofeedback.[41] Two studies found that gait training with biofeedback (haptic and visual) reduced ankle inversion by 2.5-7.3^{o}[39,41] while 1 study using destabilization devices found no significant changes in ankle inversion following gait training but found increased ankle dorsiflexion by 5.4º during mid-late stance.[25] Of the studies included, only 1 specifically targeted the reduction of ankle inversion as part of the gait training protocol.[39] Because only 3 studies utilizing gait training to improve biomechanics in individuals with CAI measured kinematic outcomes, it is difficult to understand the utility of gait training for improving ankle kinematics at this time, however, it is likely that the medial shift in the COP gait line and additional plantar pressure outcome measures 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 for individuals with CAI measuring kinematic outcomes should consider techniques targeting ankle inversion specifically.

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 that data were reported for differed among studies making meta-analyses possible only for short time periods pre-IC and post-IC. [26,28,35–37,42,43] Gait training strategies were not specifically used to target muscle activity, however, 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 200ms post-IC while receiving gait training. Increased fibularis longus activity immediately following IC during the loading response may be beneficial in contributing 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 stabilizing the first ray during propulsion.[49]

There were several limitations that should be considered when interpreting the results of this study. Individual study sample sizes were relatively small and only included 10-27 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. Several studies measured gait outcomes while participants were wearing devices[26,28] or receiving biofeedback[37,38,42,43] while other studies measured outcomes after gait training had commenced.[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 displayed in front of the treadmill,[39] real time video of the posterior aspect of the ankle,[37] and using a cross-line 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 a single session up to 12 total sessions which may influence the effects of gait training on biomechanical outcomes. Lastly, the gait training methodology utilized by many studies is not currently clinically accessible which makes implementation unrealistic for athletic trainers or other health care professionals treating individuals with CAI. Future studies should consider gait training techniques that would be feasible for clinical implementation.

There are several future directions to consider 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 consider assessing long-term outcomes, dosage, measures of joint health, and the risk reduction of subsequent LAS associated with gait training. While this study has established that gait training can be utilized to improve a variety 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 are 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 following the cessation of gait training programs to maintain desired gait changes. The overarching goal of gait training should not only be to improve biomechanics, but also to improve ankle joint health and reduce the risk of future LAS. Future research should address these critical areas to continue facilitating gait training and its broader adoption in clinical practice for patients with CAI.

Conclusion

Gait training protocols included in the systematic review utilized 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.[17,18] It is worth noting that current gait training strategies may present practical challenges within the clinical setting. Therefore, future research endeavors should investigate alternative techniques that are more accessible for clinical implementation. It is critical to restore gait patterns in individuals with CAI which appears to be possible through the utilization of gait training.

Conflicts of interest

The authors have no conflict of interest to declare in relation to this article.

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Table 1. Summary of articles related to kinetic outcome measures. All results are reported in comparison to baseline values.

Authors	Participants	Study Information	Main Findings
Donovan et al.	26 CAI (13 control, 13 intervention)	***Design:*** Randomized controlled trial ***Gait Training:*** 12 sessions with device (destabilization boot and sandal) ***Outcome Measures:*** vGRF, internal joint moments ***Data Collection Timepoints:*** Baseline, 2-7 days after last gait training session	***vGRF (N/kg):*** No significant differences ***Internal joint moments (Nm/kg):*** No significant differences
Donovan et al.	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 (cm^2):*** Decreased in lateral midfoot (MD=-4.3, ES=-1.3) and toes 2-5 (MD=-2.1, ES=-0.7) ***Contact time (ms):*** No significant differences ***Peak pressure (kPa):*** Decreased in lateral midfoot (MD=-52.8, ES=-2.8), central forefoot (MD=-29.8, ES=-1.4), and lateral forefoot (MD=-57.8, ES=-2.4), increased at hallux (MD=91.7, ES=1.0) ***PTI (kPa*s):*** Decreased at lateral midfoot (MD=-28.4, ES=-3.1) and lateral forefoot (MD=-29.1, ES=-2.6), increased for hallux (MD=31.3, ES=1.1) and total foot (MD=18.6, ES=1.0) ***Time to peak pressure (% of stance):*** Reached earlier in lateral midfoot (MD=-15.9, ES=-1.0)

Feger & Hertel	10 CAI	***Design:*** Descriptive laboratory study ***Gait Training:*** 1 session with device (novel gait trainer with resistance bands) ***Outcome Measures:*** COP gait line, contact area, contact time, peak pressure, PTI, time to peak pressure ***Data Collection Timepoints:*** Baseline, while using device	***COP gait line (mm):*** Medial shift from 0-100% of stance phase: 0-10% (MD=-4.7, ES=-1.7), 11-20% (MD=-3.8, ES=-1.1), 21-30% (MD=-3.6, ES=-0.9), 31-40% (MD=-4.6, ES=-1.0), 41-50% (MD=-5.4, ES=-1.2), 51-60% (MD=-6.4, ES=-1.4), 61-70% (MD=-7.0, ES=-1.6), 71-80% (MD=-7.1, ES=-1.6), 81-90% (MD=-6.4, ES=-1.5), 91-100% (MD=-5.2, ES=-1.2) ***Contact area (cm^2):*** Decrease in lateral midfoot (MD=-0.8, ES=-0.5) ***Contact time (ms):*** No significant differences ***Peak pressure (kPa)*****:** Decreased in lateral midfoot (MD=-29.8, ES=-1.5) and lateral forefoot (MD=-27.4, ES=-0.9), increased at lateral heel (MD=18.2, ES=1.0), medial heel (MD=23.2, ES=1.4), hallux (MD=72.9, ES=0.9), and total foot (MD=52.2, ES=0.7) ***PTI (kPa*s):*** Decreased in lateral midfoot (MD=-13.8, ES=-1.4) and lateral forefoot (MD=-9.8, ES=-0.7) increased in medial forefoot (MD=7.4, ES=0.5), hallux (MD=22.3, ES=1.0), and total foot (MD=19.3, ES=0.9) ***Time to peak pressure (% of stance):*** Occurred earlier in lateral midfoot (MD=-13.1, ES=-0.7)
Feger et al.	16 CAI	***Design:*** Quasi-experimental trial ***Gait Training:*** 5 sessions with device (novel gait trainer with resistance bands) ***Outcome Measures:*** COP gait line, contact area, contact time, peak pressure, PTI, time to peak pressure	***COP gait line (mm)*****:** Medial shift from 11-100% of stance phase: 11-20% (MD=-1.6, ES=-0.4), 21-30% (MD=-2.8, ES=-0.8), 31-40% (MD=-4.3, ES=-1.1), 41-50% (MD=-6.5, ES=-1.1), 51-60% (MD=-7.8, ES=-2.0), 61-70% (MD=-6.7, ES=-1.8), 71-80% (MD=-5.2, ES=-1.5), 81-90% (MD=-4.7, ES=-1.5), 91-100% (MD=-5.3, ES=-1.5) ***Contact area (cm^2):*** Increase in medial midfoot

		Data Collection Timepoints: Baseline, 24-72 hours after last gait training session	(MD=3.0, ES=0.4) ***Contact time (ms):*** No significant differences ***Peak pressure (kPa):*** Increased at hallux (MD=15.3, ES=0.4) ***PTI (kPa*s):*** Increased in medial forefoot (MD=4.4, ES=0.3) ***Time to peak pressure (% of stance):*** No significant differences
Ifarraguerri et al.	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 significant differences ***Contact time (ms):*** No significant differences ***Peak pressure (kPa):*** Decreased in medial forefoot (MD=-15.7, ES=-0.3) ***PTI (kPa*s)***: Decreased in medial forefoot (MD=-2.3, ES=-0.1)
Jang et al.	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)	***Impact peak vGRF (N/BW):*** No significant differences ***Time to impact peak vGRF (s):*** No significant differences ***Impact loading rate vGRF (BW/s):*** No significant differences ***Propulsive peak vGRF (N/BW):*** Decreased during early (MD=-0.04, ES=-0.6) and late periods (MD=-0.04, ES=-0.5)

		Data Collection Timepoints: Baseline, while receiving biofeedback (early period = minute 1-2, late period = minute 9-10 of receiving biofeedback)	***Time to propulsive peak vGRF (s):*** Decreased during early (MD=-0.02, ES=-0.4) and late periods (MD=-0.02, ES=-0.5) ***Propulsive loading rate vGRF (BW/s):*** Decreased during early period (MD=-0.24, ES=-0.4) ***Ankle JCF peak (N/BW):*** Decreased during early period (MD=-0.24, ES=-0.4) ***Ankle JCF impulse (BW*s):*** Decreased during early (MD=-0.09, ES=-0.6) and late periods (MD=-0.14, ES=-0.9) ***Ankle JCF loading rate (BW/s):*** No significant differences
Knuckles et al.	12 CAI	***Design:*** Descriptive laboratory study ***Gait Training:*** 1 session with device (multi-axis destabilization device) ***Outcome Measures:*** COP gait line, peak pressure ***Data Collection Timepoints:*** Baseline, while wearing device, immediately after devices removed	***COP gait line (mm):*** *Wearing device*: Medial shift from 11-60% of stance phase: 11-20% (MD=-5.7, ES=-1.1), 21-30% (MD=-6.3, ES=-1.2), 31-40% (MD=-6.2, ES=-1.2), 41-50% (MD=-5.8, ES=-1.1), 51-60% (MD=-5.0, ES=-0.9) *Post gait training:* No significant differences ***Peak pressure (kPa %):*** *Wearing device*: Decrease in lateral midfoot (MD=-21.5, ES=-1.3), lateral forefoot (MD=-22.4, ES=-1.2), and central forefoot (MD=-17.5, ES=-1.0) *Post gait training:* No significant differences

Koldenhoven et al.	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, hip throughout for 0-100% of stride cycle ***Data Collection Timepoints:*** Baseline, 24-72 hours after last gait training session	***Internal joint moments (Nm/kg):*** No significant differences
Migel et al.	19 CAI	***Design:*** Descriptive laboratory study with repeated measures ***Gait Training:*** 2 sessions (1 laboratory, 1 real world) with biofeedback (haptic) ***Outcome Measures:*** COP gait line ***Data Collection Timepoints:*** Baseline, immediately after gait training, 5-minutes after gait training	***COP gait line (mm):*** *Laboratory immediately post:* Medial shift from 0-90% of stance phase: 0-10% (MD=-3.6, ES=-0.4), 11-20% (MD=-4.3, ES=-0.4), 21-30% (MD=-4.6, ES=-0.5), 31-40% (MD=-5.1 ES=-0.6), 41-50% (MD=-5.1, ES=-0.7), 51-60% (MD=-4.2, ES=-0.7), 61-70% (MD=-2.8, ES=-0.6), 71-80% (MD=-1.7, ES=-0.4), 81-90% (MD=-1.6, ES=-0.3) *Laboratory 5-minutes post:* Medial shift from 21-90% of stance: 21-30% (MD= -3.3, ES=-0.4), 31-40% (MD=-5.1, ES=-0.6), 41-50% (MD=-5.1, ES=-0.7), 51-60% (MD=-3.8, ES=-0.6), 61-70% (MD=-2.8, ES=-0.6), 71-80% (MD=-2.2, ES=-0.4), 81-90% (MD=-1.6, ES=-0.3) *Real world immediately post:* Medial shift 0-70% of stance phase: 0-10% (MD=-6.0, ES=-0.8), 11-20% (MD=-7.3, ES=-0.8), 21-30% (MD=-

			7.8, ES=-1.1), 31-40% (MD=-8.3, ES=-1.0), 41-50% (MD=-8.2, ES=-1.1), 51-60% (MD=-6.6, ES=-1.0), 61-70% (MD=-4.2, ES=-0.7), 71-80% (MD=-2.3, ES=-0.4) *Real world 5-minutes post:* Medial shift 0-60% of stance: 0-10% (MD=-4.7, ES=-0.5), 11-20% (MD=-5.6, ES=-0.6), 21-30% (MD=-6.1, ES=-0.8), 31-40% (MD=-6.5, ES=-0.7), 41-50% (MD=-5.9, ES=-0.7), 51-60% (MD=-4.1, ES=-0.6)
Torp et al.	26 CAI	***Design:*** Descriptive laboratory study ***Gait Training:*** 1 session with biofeedback (visual) ***Outcome Measures:*** COP gait line, contact area, contact time, peak pressure, pressure time integral ***Data Collection Timepoints:*** Baseline, while receiving biofeedback	***COP gait line (mm)*****:** Medial shift from 0-80% of stance: 0-10% (MD=-1.4, ES=-0.3), 11-20% (MD=-1.4, ES=-0.3), 21-30% (MD=-1.8, ES=-0.4), 31-40% (MD=-2.0 ES=-0.5), 41-50% (MD=-2.2, ES=-0.5), 51-60% (MD=-2.4, ES=-0.5), 61-70% (MD=-2.6, ES=-0.5), 71-80% (MD=-2.4, ES=-0.5), 81-90% (MD=-1.4, ES=-0.3) ***Contact area (cm^2)*****:** Increased in medial midfoot (MD=2.1, ES=0.3) and hallux (MD=0.1, ES=0.1) ***Peak pressure (kPa):*** Decreased at lateral midfoot (MD=-10.8, ES=-0.6), central forefoot (MD=-51.9, ES=-1.2), and lateral forefoot (MD=-19.1, ES=-0.6), increased at hallux (MD=39.4, ES=0.7) ***PTI (kPa*s):*** Decreased at lateral heel (MD=-7.4, ES=-0.5) and lateral midfoot (MD=-6.8, ES=-0.5), increased at hallux (MD=18.6, ES=0.7)

Torp et al.	18 CAI (7 control, 11 biofeedback)	***Design:*** Randomized controlled trial ***Gait Training:*** 8 sessions with biofeedback (auditory) ***Outcome Measures:*** COP gait line, peak pressure, maximum force ***Data Collection Timepoints:*** Baseline, 24-48 hours after last gait training session, 1-week after last gait training session	***COP gait line (mm):*** *Immediately post:* Medial shift from 41-100% of stance: 41-50% (MD=-4.9, ES=-1.5), 51-60% (MD=-6.5, ES=-1.7), 61-70% (MD=-8.2, ES=-1.9), 71-80% (MD=-9.6, ES=-2.1), 81-90% (MD=-9.8, ES=-2.1), 91-100% (MD=-8.8, ES=-1.6) *1-week post:* Medial shift from 31-50% and at 81-90% of stance: 31-40% (MD=-4.0, ES=-1.5), 41-50% (MD=-5.2, ES=-1.6), 81-90% (MD=-7.8, ES=-1.7) ***Peak pressure (kPa):*** *Immediately post:* Decrease in lateral midfoot (MD=-22.2, ES=-1.3) and lateral forefoot (MD=-28.1, ES=-0.9), increased at medial forefoot (MD=36.0, ES=0.9) *1-week post:* Decrease in lateral midfoot (MD=-20.0, ES=-1.1) and lateral forefoot (MD=-16.4, ES=-0.4) ***Maximum Force (N):*** *Immediately post:* Reduced in lateral midfoot (MD=-6.0, ES=-1.1) and lateral forefoot (MD=-6.8, ES=-1.5), increased in medial forefoot (MD=7.1, ES=1.47) *1-week post:* Reduced in lateral midfoot (MD=-5.4, ES=-1.0) and lateral forefoot (MD=-4.3, ES=-1.1), increased in medial forefoot (MD=4.9, ES=1.0)

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

Table 2. Summary of articles related to kinematic outcome measures. All results are reported in comparison to baseline values.

Authors	Participants	Study Information	Main Findings
Donovan et al.	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, hip for 1-100% of stride cycle ***Data Collection Timepoints:*** Baseline, 2-7 days after last gait training session	**Ankle Joint Angles (º):** Increased dorsiflexion (MD=5.4, ES=3.4) during mid-late stance **Knee Joint Angles (º):** No significant differences **Hip Joint Angles (º):** No significant differences
Koldenhoven et al.	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, hip for 0-100% of stride cycle ***Data Collection Timepoints:*** Baseline, 24-72 hours after last gait training session	**Ankle Joint Angles (º):** 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 (º):** Increased external rotation (MD=3.2, ES=0.7) during terminal swing **Hip Joint Angles (º):** No significant differences
Migel et al.	19 CAI	***Design:*** Descriptive laboratory study with repeated measures ***Gait Training:*** 2 sessions (1 laboratory, 1 real world) with biofeedback (haptic) ***Outcome Measures:*** 3D ankle, hindfoot, and forefoot joint angles during stance ***Data Collection Timepoints:*** Baseline, immediately after	**Ankle Joint Angles (º):** *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

gait training	**Hindfoot Joint Angles (º):** *Laboratory* No significant differences *Real World* No significant differences **Forefoot Joint Angles (º):** *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: CAI = chronic ankle instability, ES = effect size, IC = initial contact, MD = mean difference, 3D = three-dimensional.

Table 3. Summary of articles related to electromyography outcome measures. All results are reported in comparison to baseline values.

Author	Participants	Study Information	Main Findings
Donovan et al.	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 100ms pre-IC and 200ms post-IC for tibialis anterior, fibularis longus, lateral gastrocnemius, rectus femoris, and gluteus medius ***Data Collection Timepoints:*** Baseline, 2-7 days 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.	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 days 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 mid-swing (MD=1.0, ES=2.5) phases of gait

Donovan et al.	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 200ms pre-IC and 200ms post-IC for tibialis anterior, fibularis longus, medial gastrocnemius, and gluteus medius ***Data Collection Timepoints:*** Baseline, while receiving biofeedback	**RMS Amplitude Pre-IC** No significant 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 & Hertel	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 200ms pre-IC and 200ms 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.	16 CAI	***Design:*** Quasi-experimental 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 hours after last gait training session	**RMS Amplitude** **0-100% of Stance** Increased for fibularis longus from 21-60% and 82-90% 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), 81-90% (MD=2.1, ES=0.4) Decrease for gluteus medius 71-100% of stance phase: 71-80% (MD=-0.9, ES=-0.7), 81-90% (MD=-1.0, ES=-0.9), 91-100% (MD=-1.6, ES=-0.9)
Knuckles et al.	12 CAI	***Design:*** Descriptive laboratory study ***Gait Training:*** 1 session with device (multi-axis destabilization device) ***Outcome Measures:*** RMS amplitude normalized to quiet standing 50ms pre-IC and 200ms post-IC for tibialis anterior, fibularis longus, soleus, gluteus medius ***Data Collection Timepoints:*** Baseline, while wearing device, immediately after devices removed	**RMS Amplitude Pre-IC** *Wearing device:* Increased for tibialis anterior (MD=3.6, ES=0.9) *Post gait training:* No significant differences **RMS Amplitude Post-IC** No significant differences *Post gait training:* No significant differences

Koldenhoven et al.	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, gluteus medius ***Data Collection Timepoints:*** Baseline, 24-72 hours after last gait training session	**RMS Amplitude** **0-100% of gait cycle** No significant differences

Abbreviations: CAI = chronic ankle instability, EMG = electromyography, ES = effect size, IC = initial contact, MD = mean difference, RMS = root mean square.

Figure 1. Flowchart of included studies

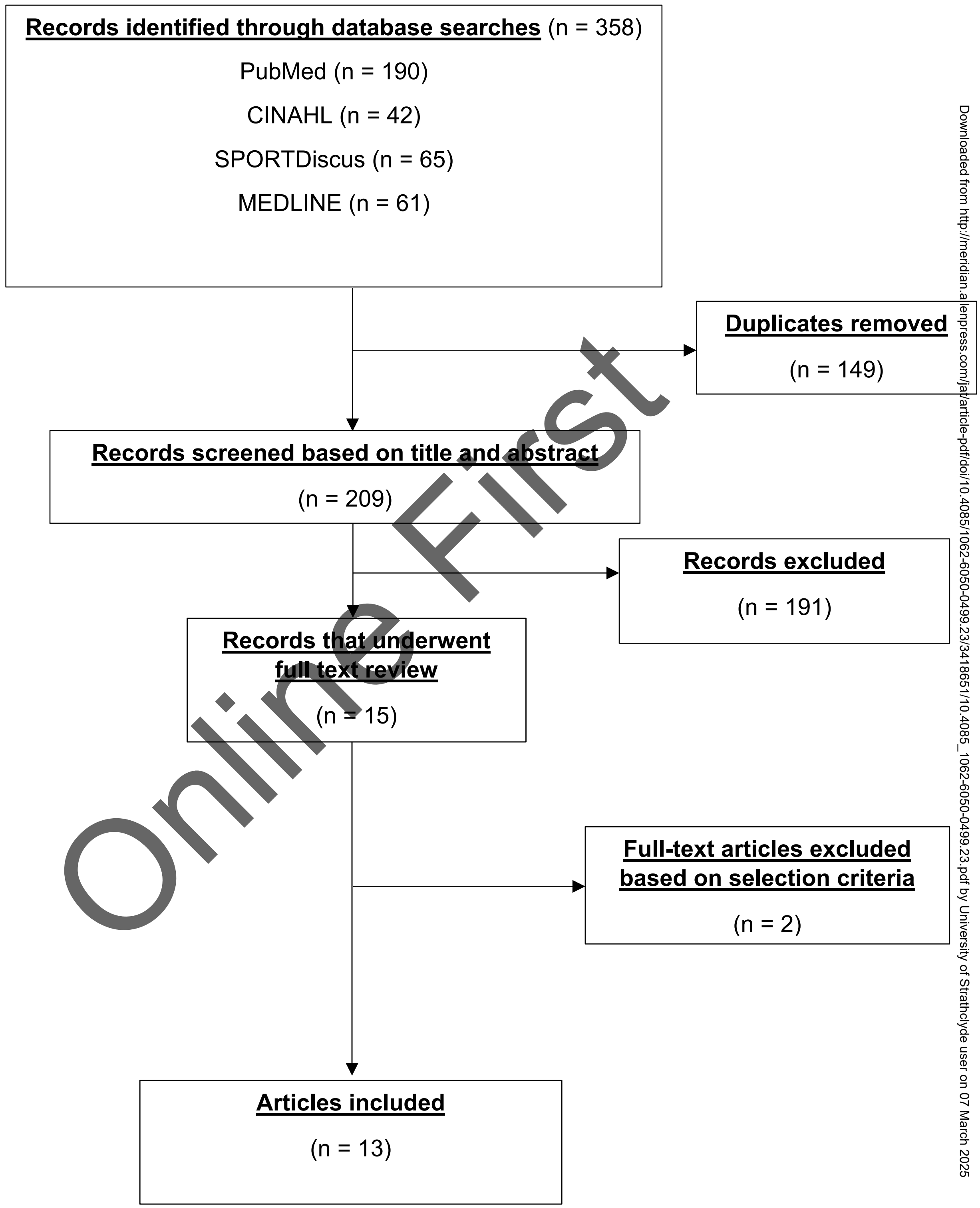
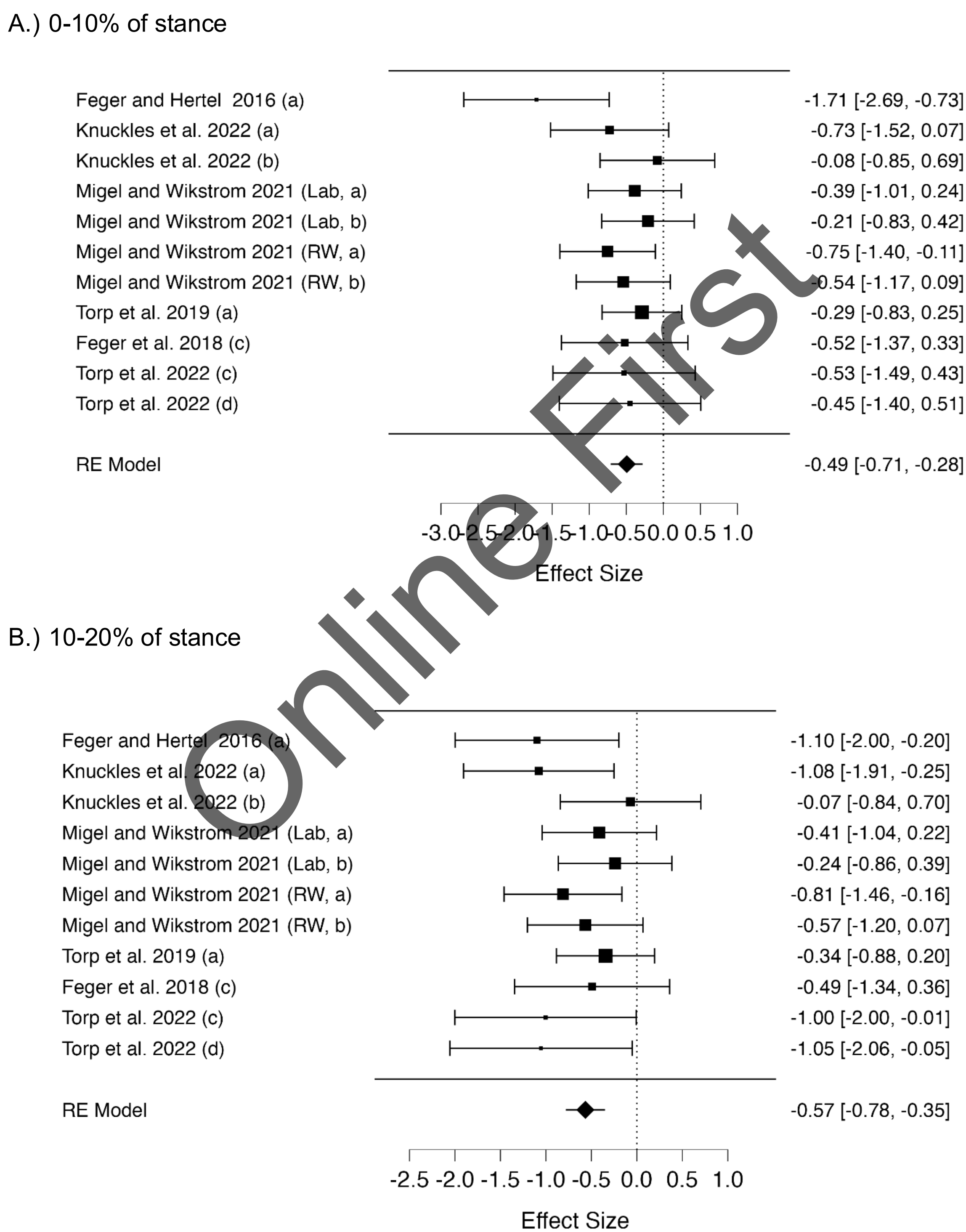
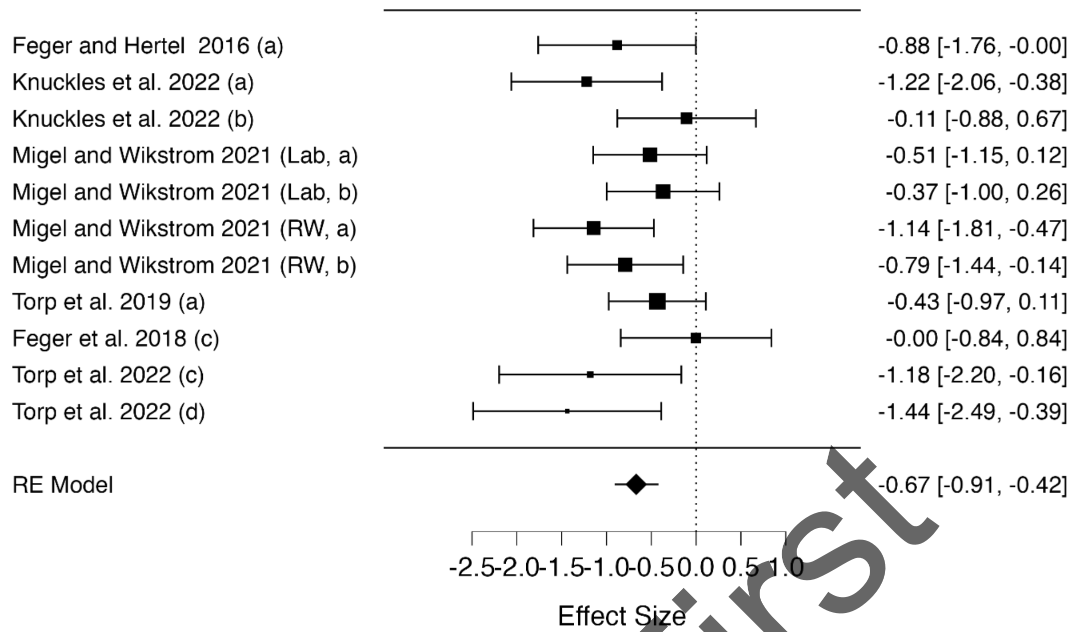


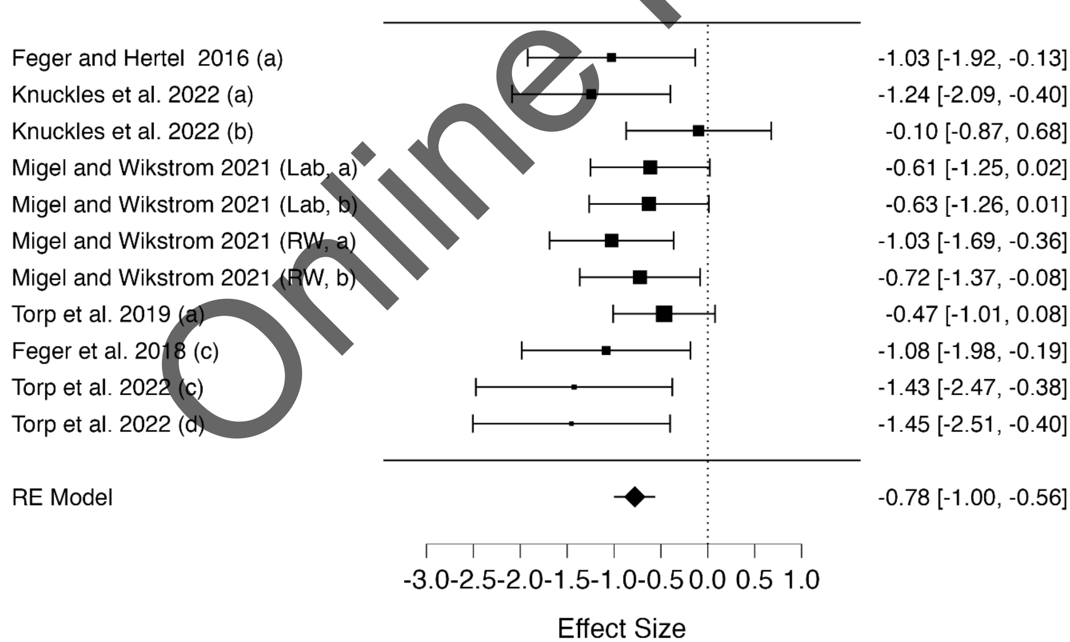
Figure 2. Meta-analysis results for the center of pressure (COP) gait line. Positive effect sizes indicate a lateral shift in COP. Negative effect sizes indicate a medial shift in COP. (a) indicates single session of gait training and data collected while receiving gait training. (b) indicates single session of gait training and data collected after gait training. (c) indicates multiple sessions of gait training, data collected 24-72 hours after gait training. (d) indicates multiple sessions of gait training, data collected 1-week after gait training.



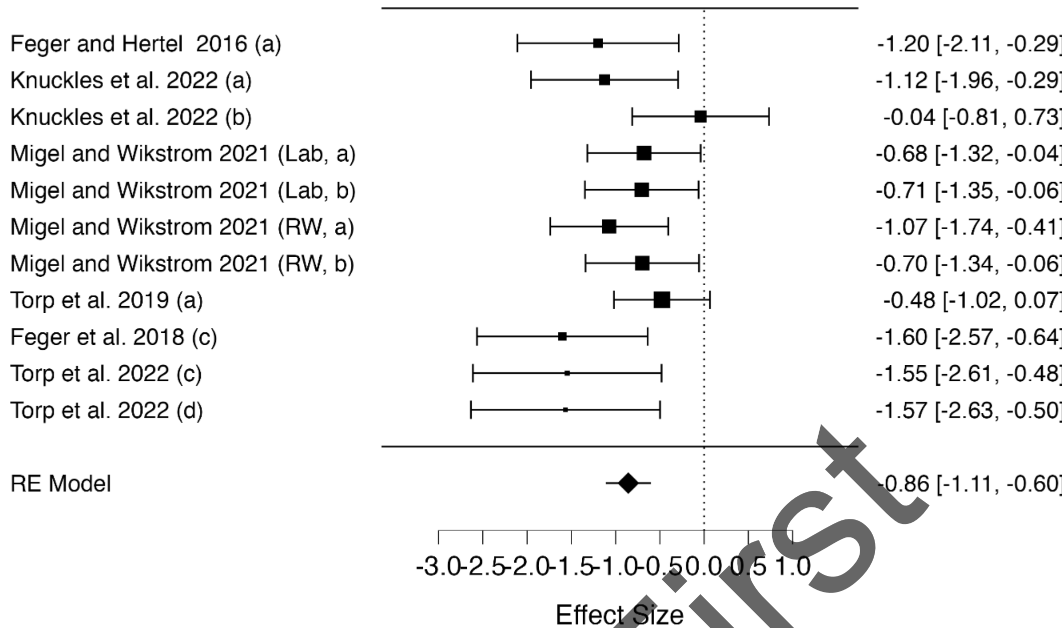
C. 20-30% of stance



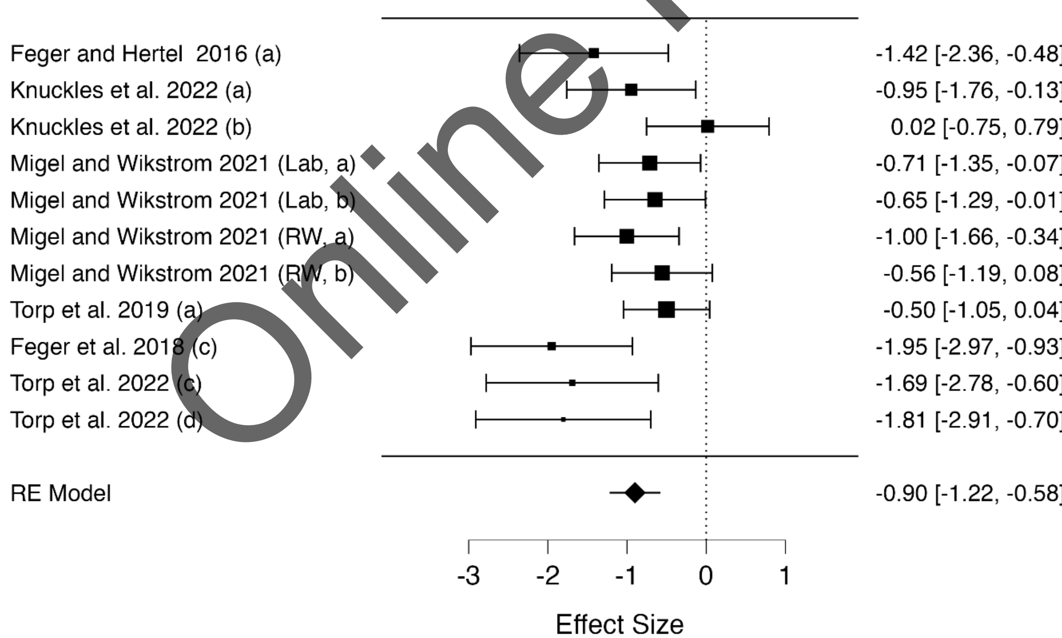
D. 30-40% of stance



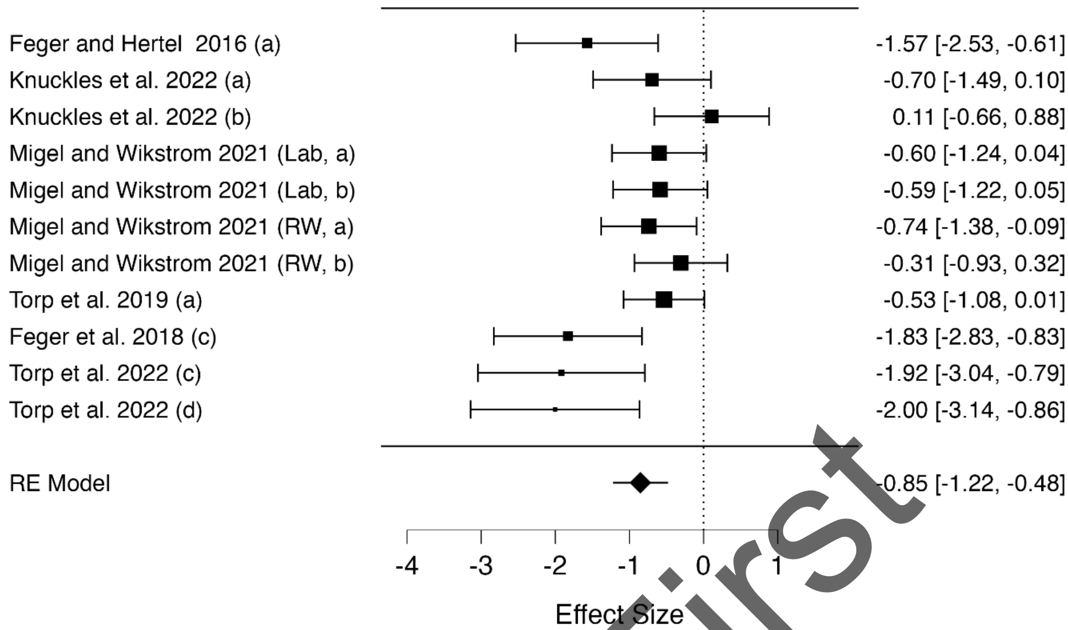
E. 40-50% of stance



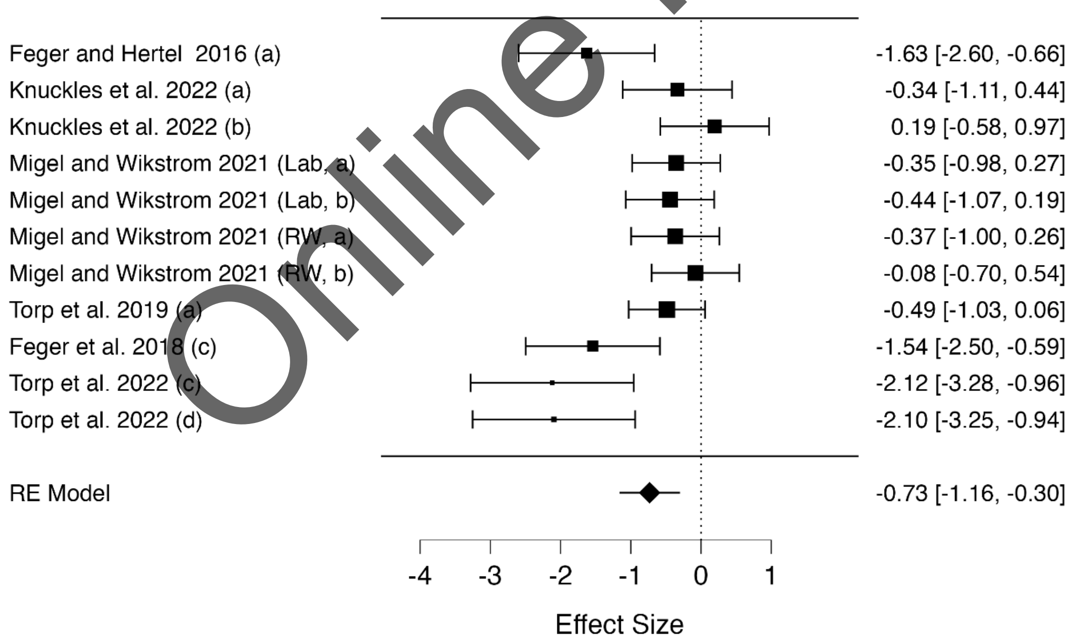
F. 50-60% of stance



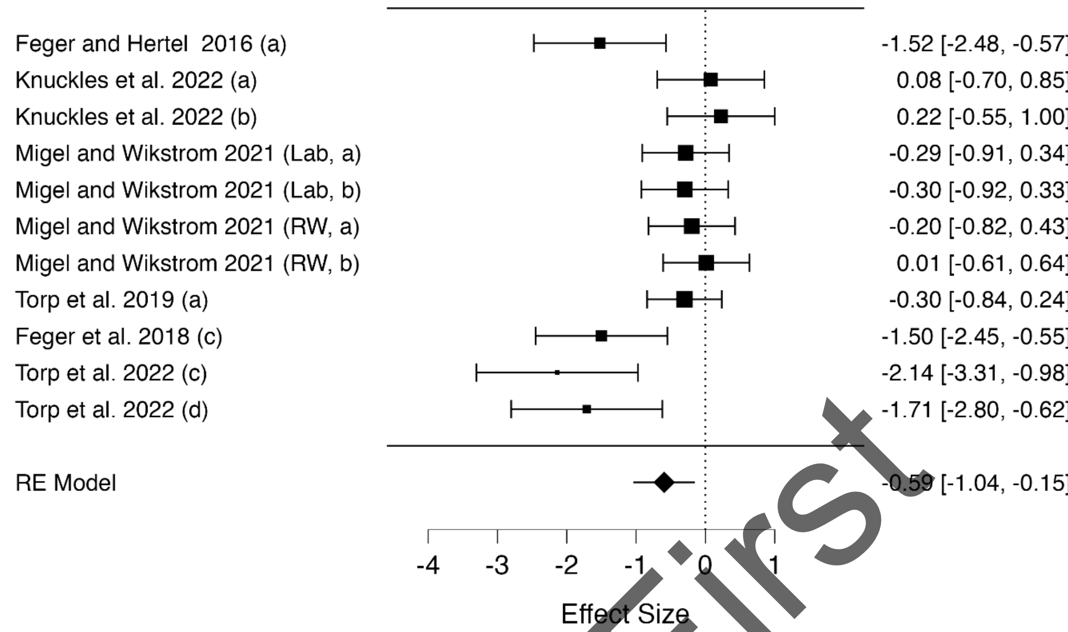
G. 60-70% of stance



H. 70-80% of stance



I. 80-90% of stance



J. 90-100% of stance

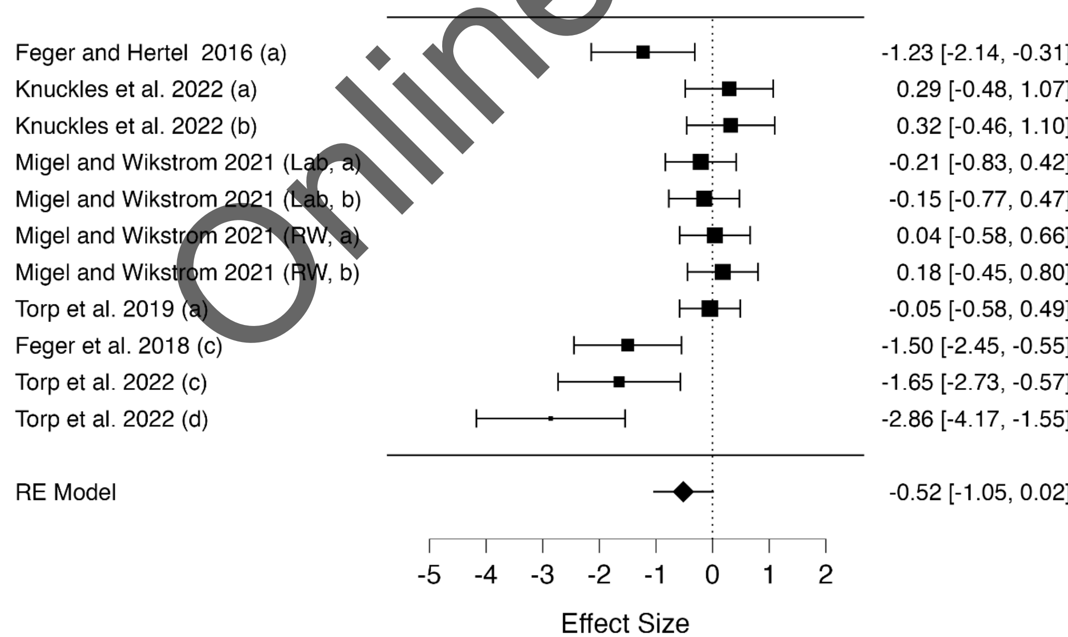
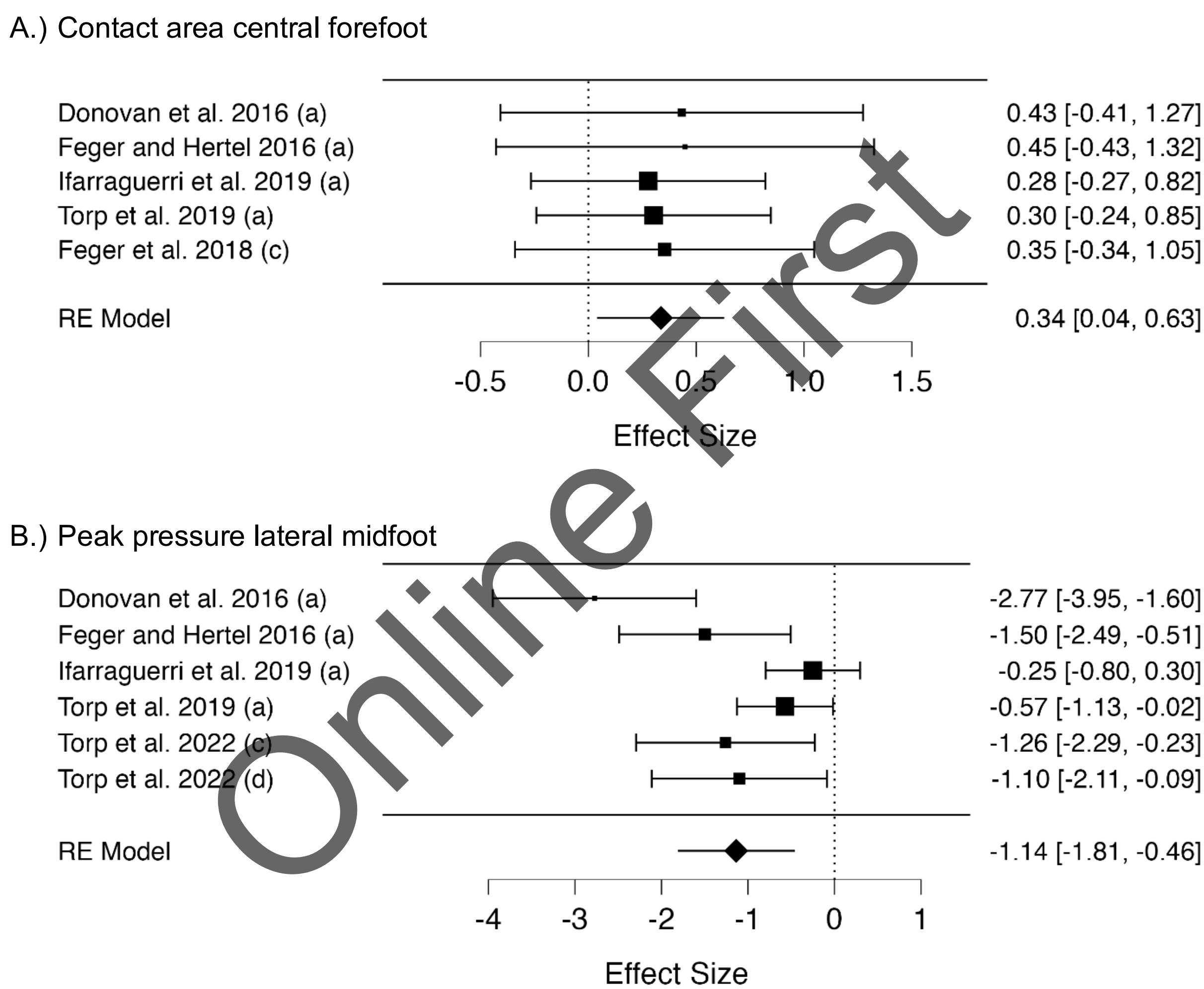
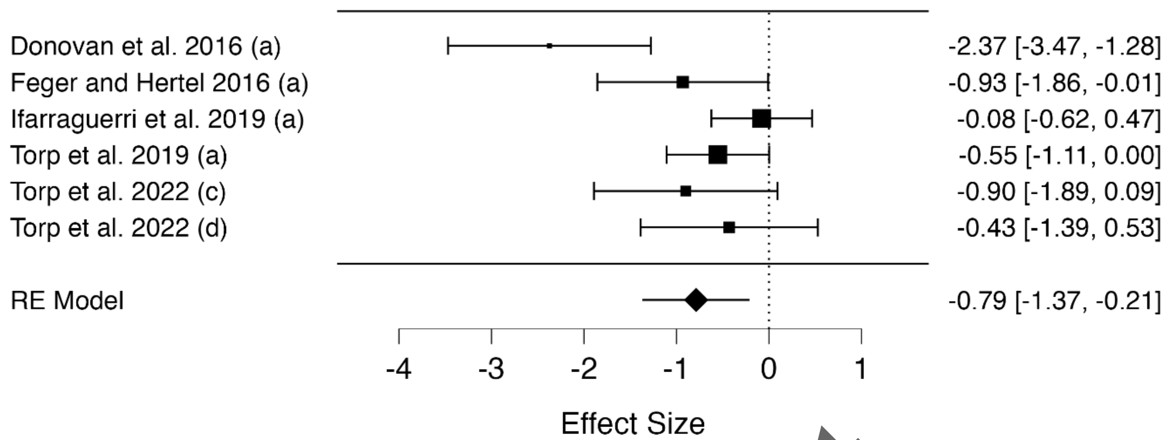


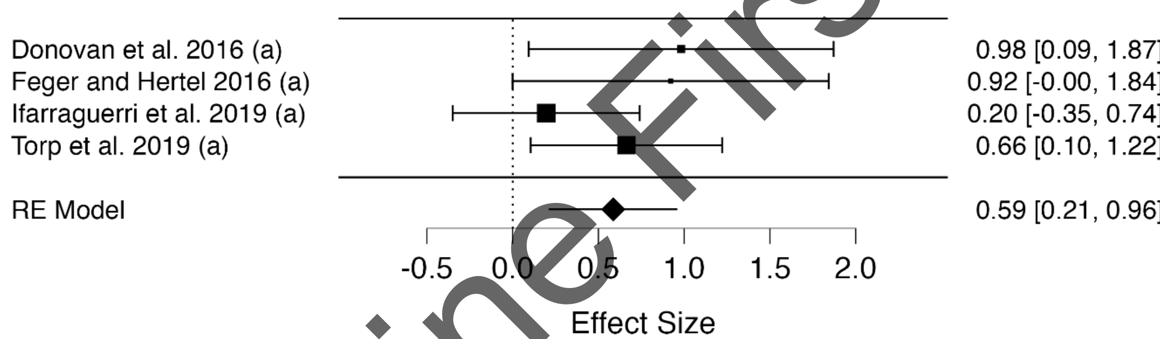
Figure 3. Meta-analysis results for the plantar pressure outcome measures. Positive effect sizes indicate an increase in pressure. Negative effect sizes indicate a decrease in pressure. (a) indicates single session of gait training and data collected while receiving gait training. (b) indicates single session of gait training and data collected after gait training. (c) indicates multiple sessions of gait training, data collected 24-72 hours after gait training. (d) indicates multiple sessions of gait training, data collected 1-week after gait training.



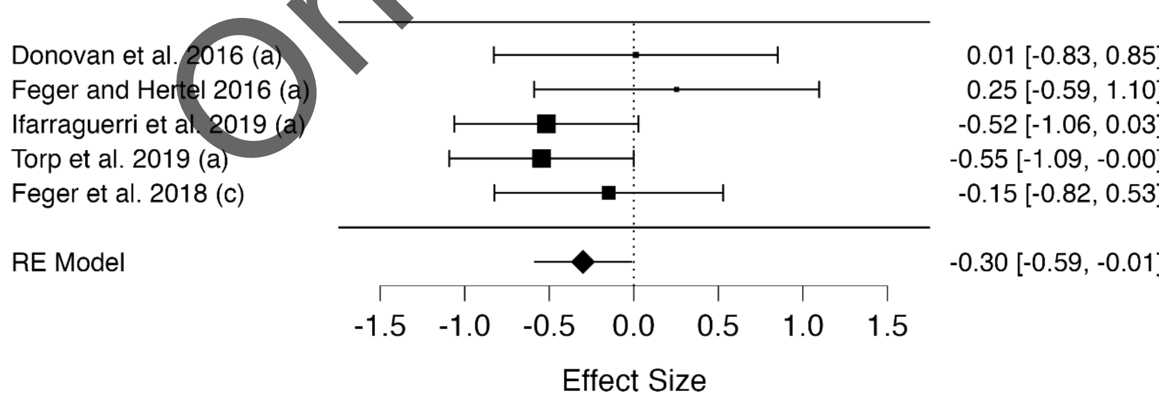
C.) Peak pressure lateral forefoot



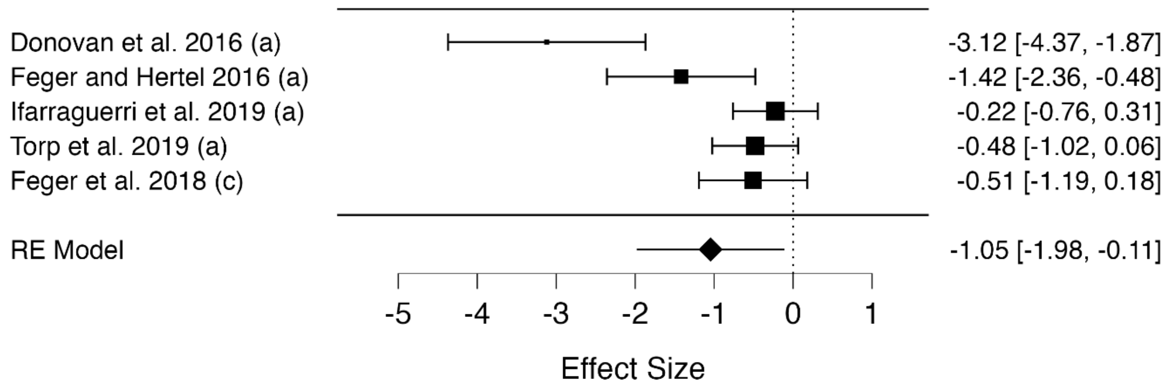
D.) Peak pressure hallux



E.) Pressure time integral lateral heel



F.) Pressure time integral lateral midfoot



G.) Pressure time integral hallux

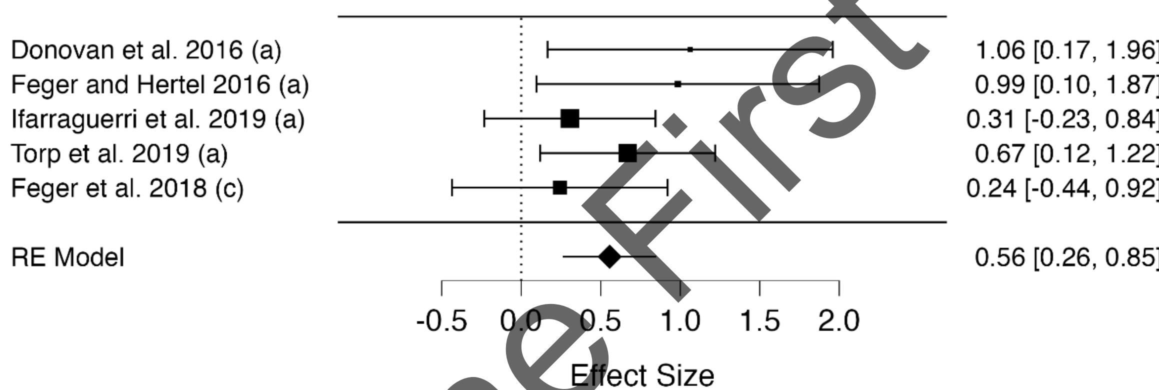
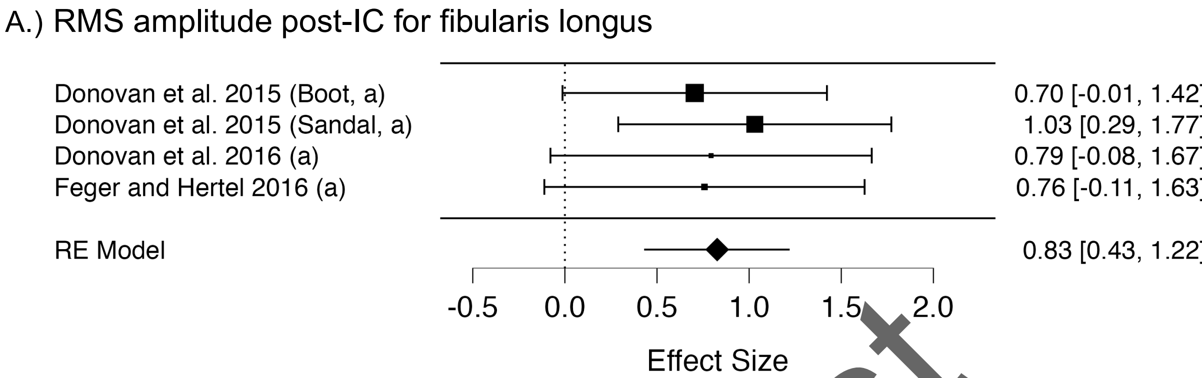


Figure 4. Meta-analysis results for the EMG outcome measures. Positive effect sizes indicate an increase in EMG activity. Negative effect sizes indicate a decrease in EMG activity. (a) indicates single session of gait training and data collected while receiving gait training.

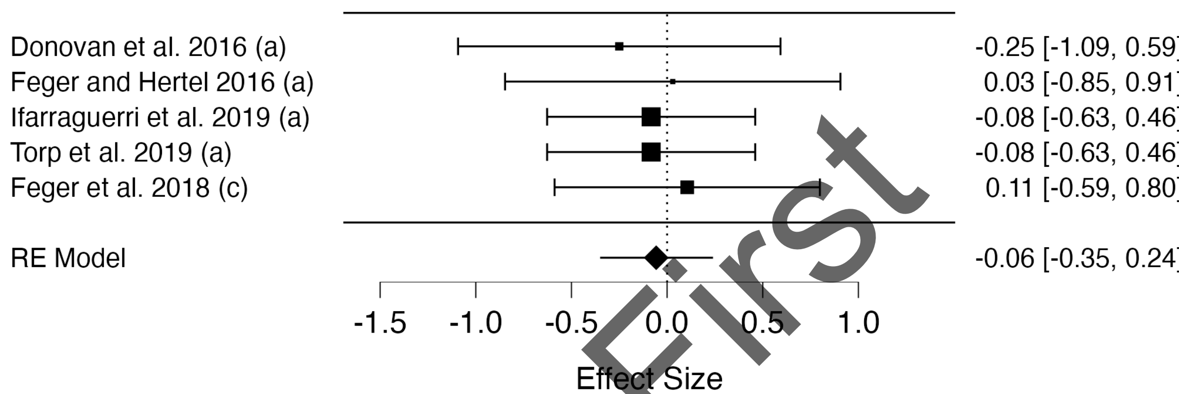


Abbreviations: EMG = electromyography, IC = initial contact, RMS = root mean square.

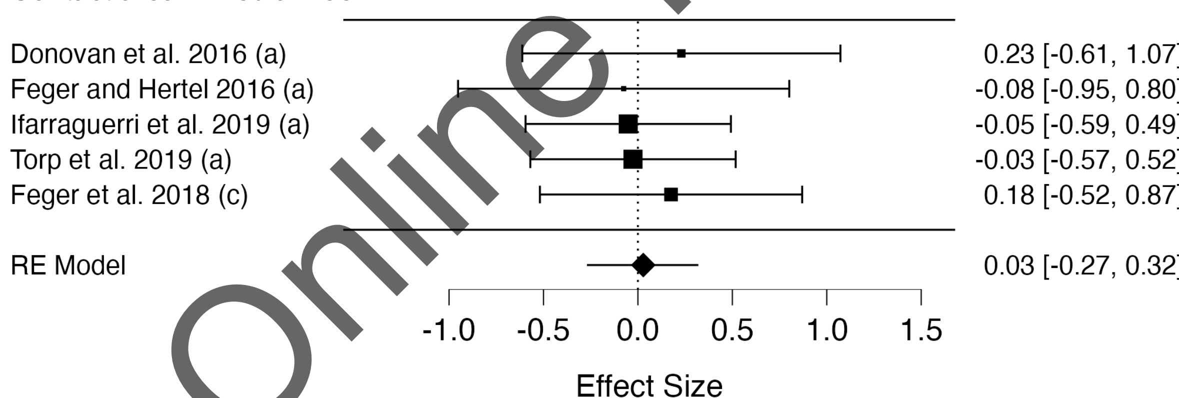
Supplemental. Meta-analysis results for the non-significant findings for kinetic, kinematic, and electromyography outcome measures. (a) indicates single session of gait training and data collected while receiving gait training. (b) indicates single session of gait training and data collected after gait training. (c) indicates multiple sessions of gait training, data collected 24-72 hours after gait training. (d) indicates multiple sessions of gait training, data collected 1-week after gait training.

Kinetics

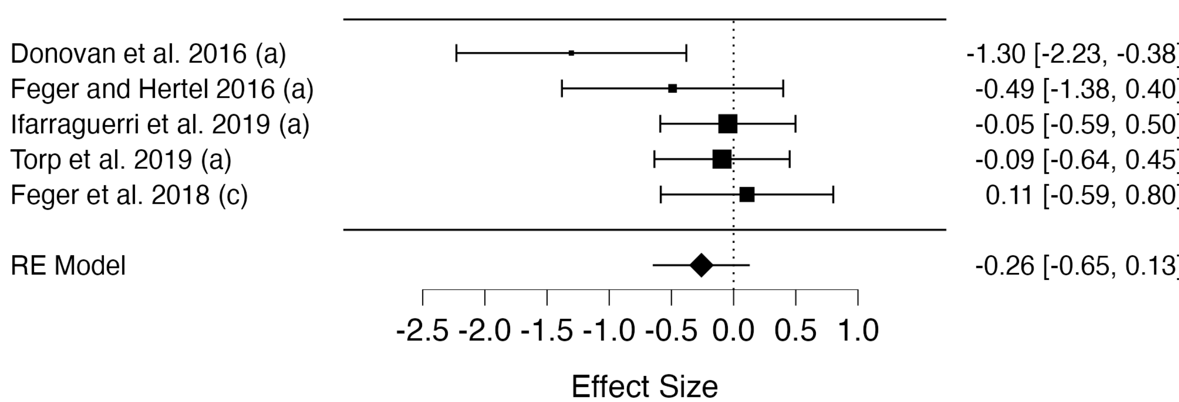
A.) Contact area – Lateral heel

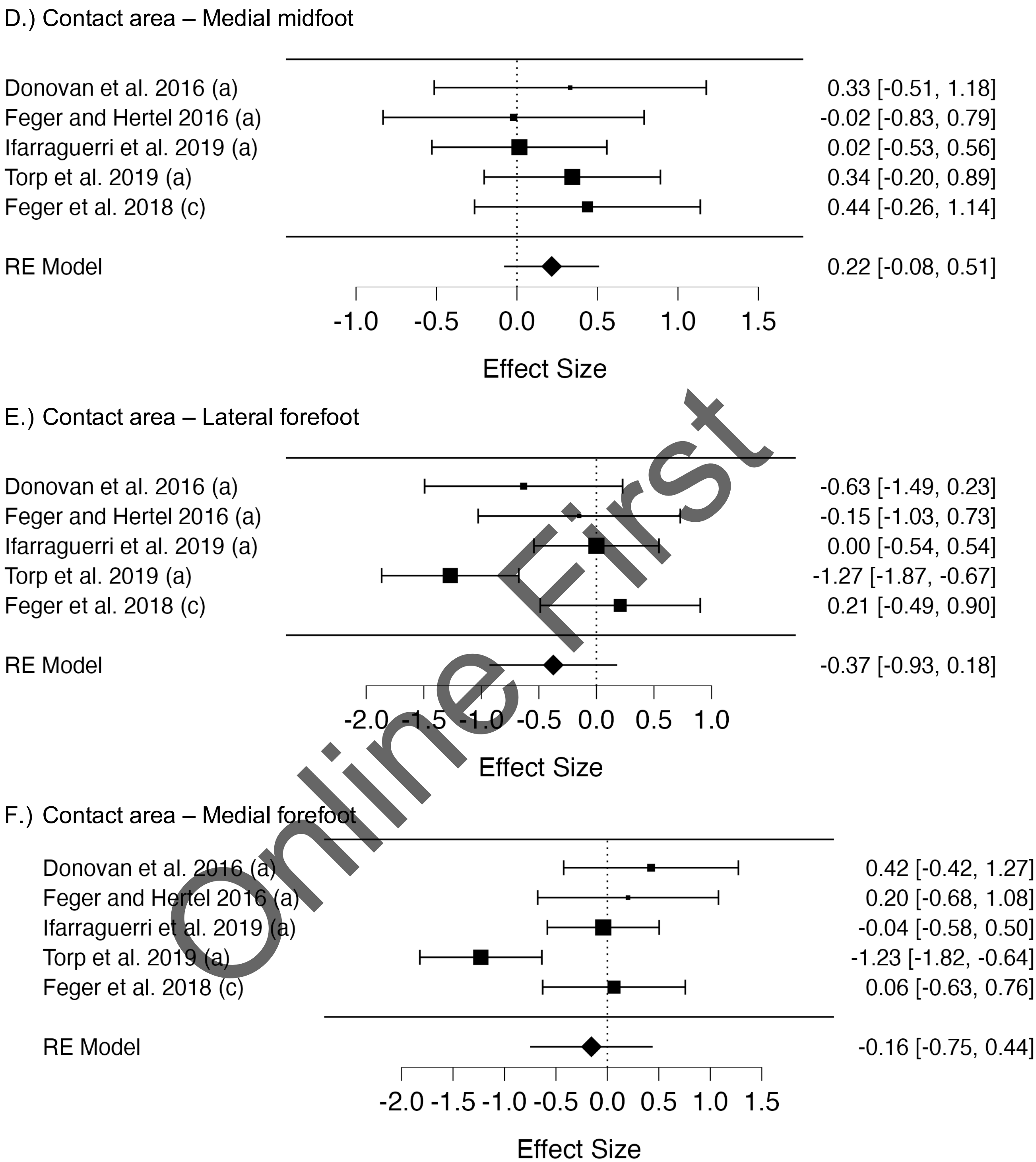


B.) Contact area – Medial heel

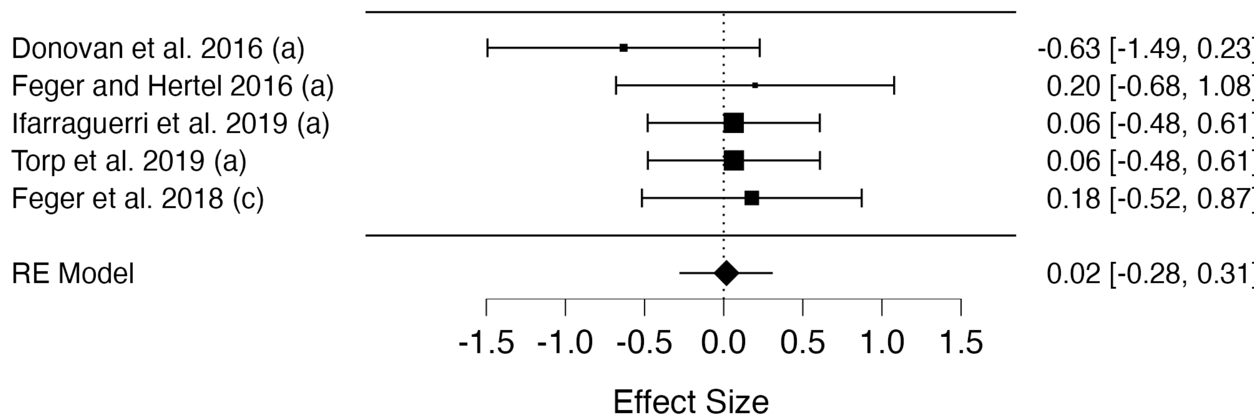


C.) Contact area – Lateral midfoot

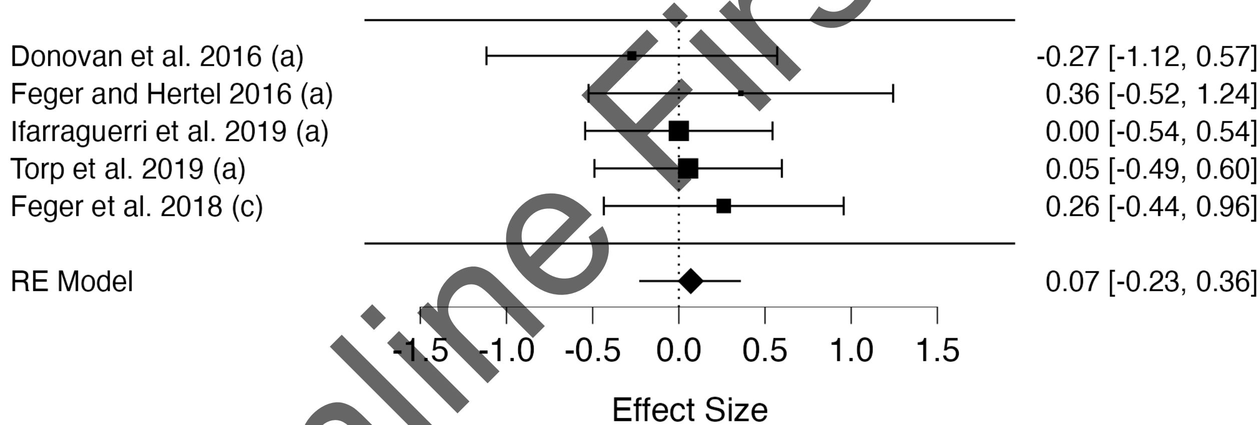



D.) Contact area – Medial midfoot
Donovan et al. 2016 (a)
Feger and Hertel 2016 (a)
Ifarraguerri et al. 2019 (a)
Torp et al. 2019 (a)
Feger et al. 2018 (c)
RE Model
0.33 [-0.51, 1.18]
-0.02 [-0.83, 0.79]
0.02 [-0.53, 0.56]
0.34 [-0.20, 0.89]
0.44 [-0.26, 1.14]
0.22 [-0.08, 0.51]
-1.0 -0.5 0.0 0.5 1.0 1.5
Effect Size
E.) Contact area – Lateral forefoot
Donovan et al. 2016 (a)
Feger and Hertel 2016 (a)
Ifarraguerri et al. 2019 (a)
Torp et al. 2019 (a)
Feger et al. 2018 (c)
RE Model
-0.63 [-1.49, 0.23]
-0.15 [-1.03, 0.73]
0.00 [-0.54, 0.54]
-1.27 [-1.87, -0.67]
0.21 [-0.49, 0.90]
-0.37 [-0.93, 0.18]
-2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0
Effect Size
F.) Contact area – Medial forefoot
Donovan et al. 2016 (a)
Feger and Hertel 2016 (a)
Ifarraguerri et al. 2019 (a)
Torp et al. 2019 (a)
Feger et al. 2018 (c)
RE Model
0.42 [-0.42, 1.27]
0.20 [-0.68, 1.08]
-0.04 [-0.58, 0.50]
-1.23 [-1.82, -0.64]
0.06 [-0.63, 0.76]
-0.16 [-0.75, 0.44]
-2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5
Effect Size

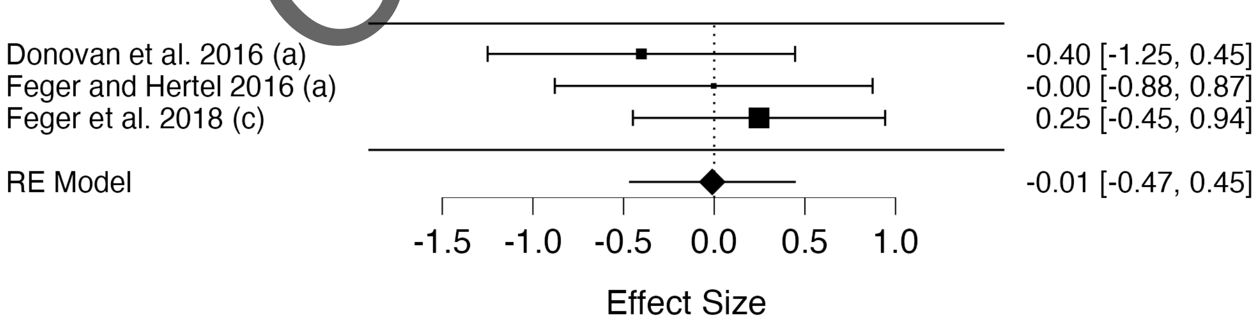
G.) Contact area – Toes 2-5

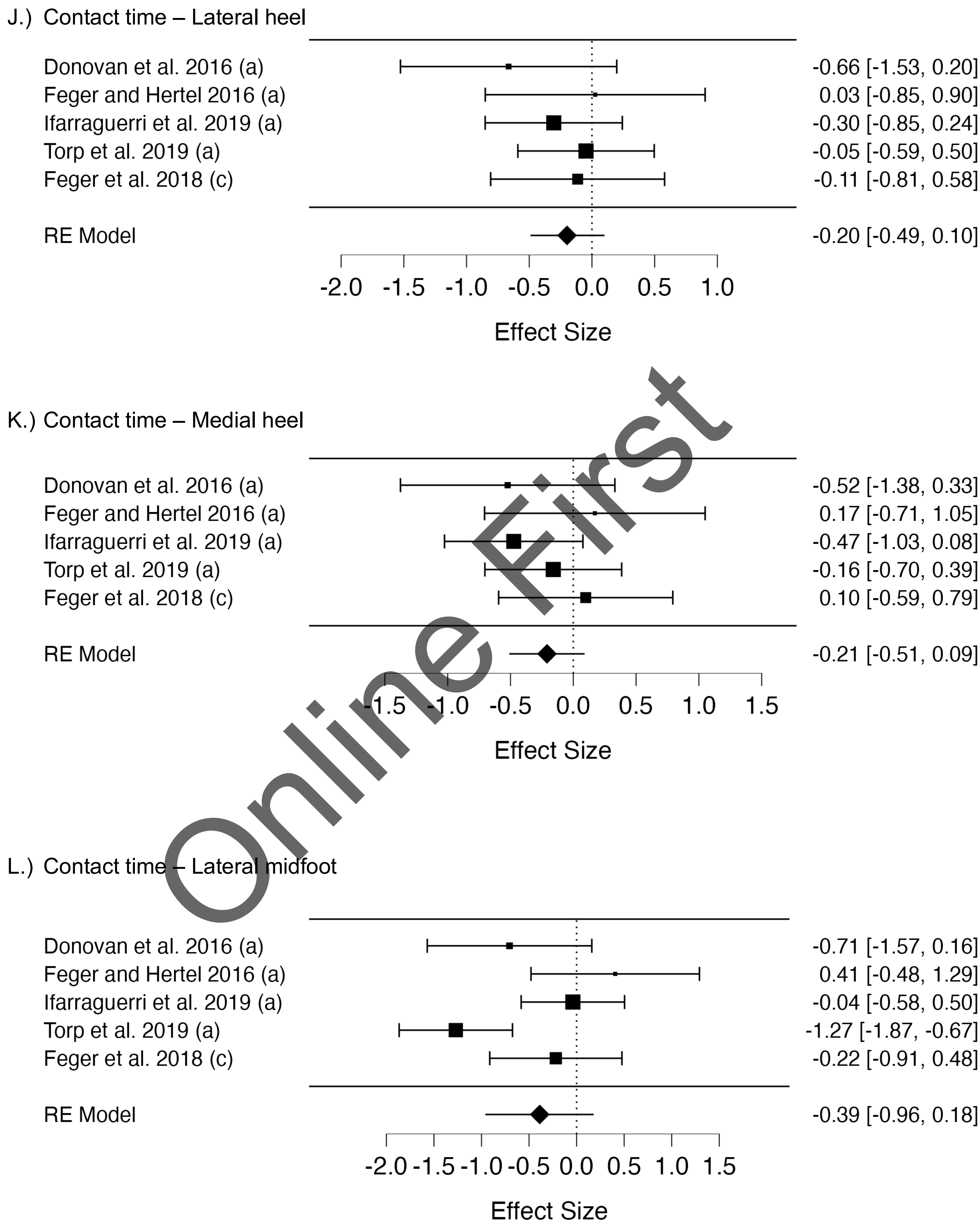


H.) Contact area – Hallux

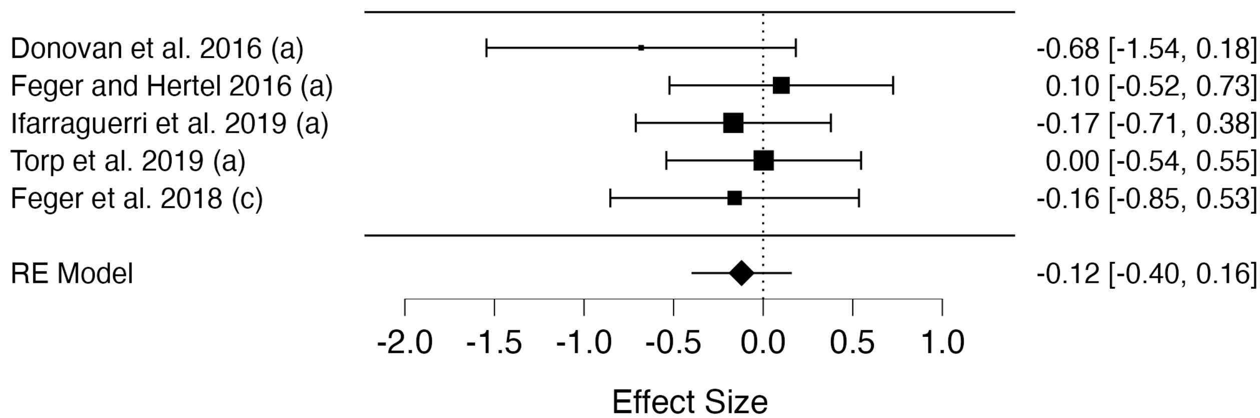


I.) Contact area – Total foot

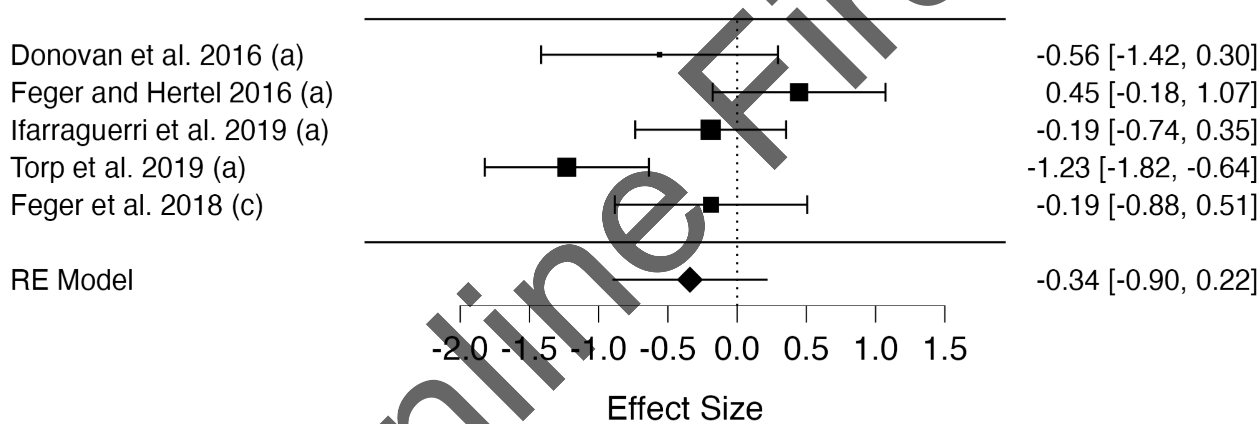



J.) Contact time – Lateral heel
Donovan et al. 2016 (a)
Feger and Hertel 2016 (a)
Ifarraguerri et al. 2019 (a)
Torp et al. 2019 (a)
Feger et al. 2018 (c)
RE Model
-0.66 [-1.53, 0.20]
0.03 [-0.85, 0.90]
-0.30 [-0.85, 0.24]
-0.05 [-0.59, 0.50]
-0.11 [-0.81, 0.58]
-0.20 [-0.49, 0.10]
-2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0
Effect Size
K.) Contact time – Medial heel
Donovan et al. 2016 (a)
Feger and Hertel 2016 (a)
Ifarraguerri et al. 2019 (a)
Torp et al. 2019 (a)
Feger et al. 2018 (c)
RE Model
-0.52 [-1.38, 0.33]
0.17 [-0.71, 1.05]
-0.47 [-1.03, 0.08]
-0.16 [-0.70, 0.39]
0.10 [-0.59, 0.79]
-0.21 [-0.51, 0.09]
-1.5 -1.0 -0.5 0.0 0.5 1.0 1.5
Effect Size
L.) Contact time – Lateral midfoot
Donovan et al. 2016 (a)
Feger and Hertel 2016 (a)
Ifarraguerri et al. 2019 (a)
Torp et al. 2019 (a)
Feger et al. 2018 (c)
RE Model
-0.71 [-1.57, 0.16]
0.41 [-0.48, 1.29]
-0.04 [-0.58, 0.50]
-1.27 [-1.87, -0.67]
-0.22 [-0.91, 0.48]
-0.39 [-0.96, 0.18]
-2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5
Effect Size

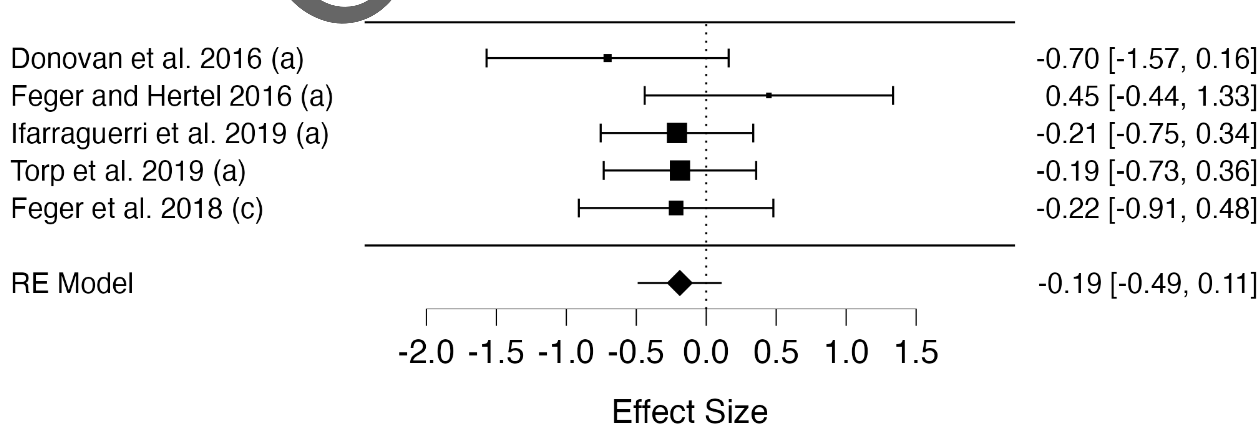
M.) Contact time – Medial midfoot



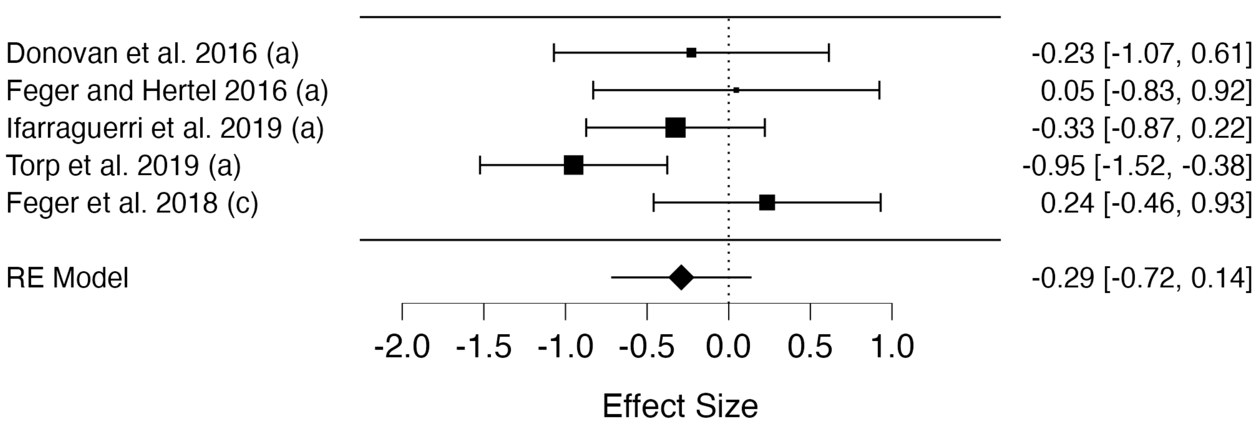
N.) Contact time – Lateral forefoot



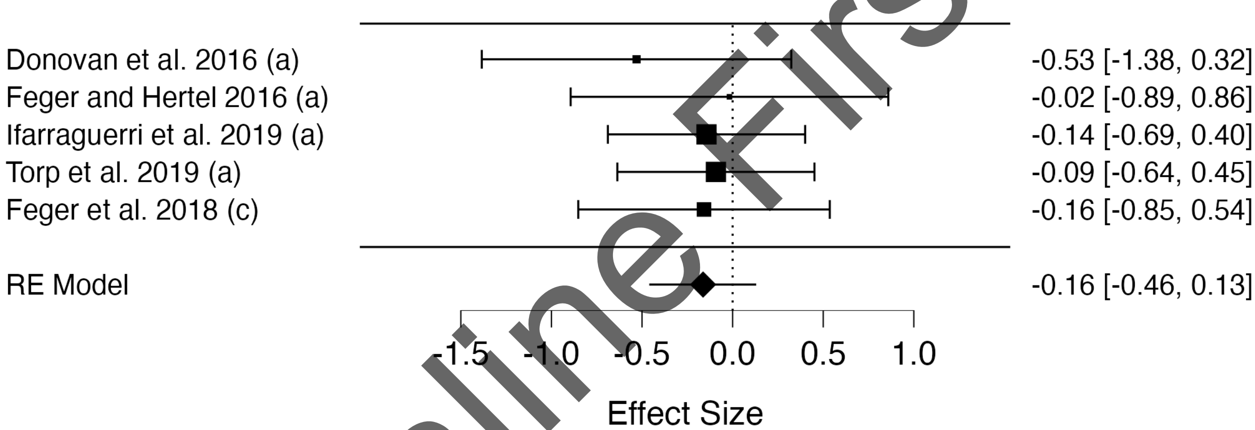
O.) Contact time – Central forefoot



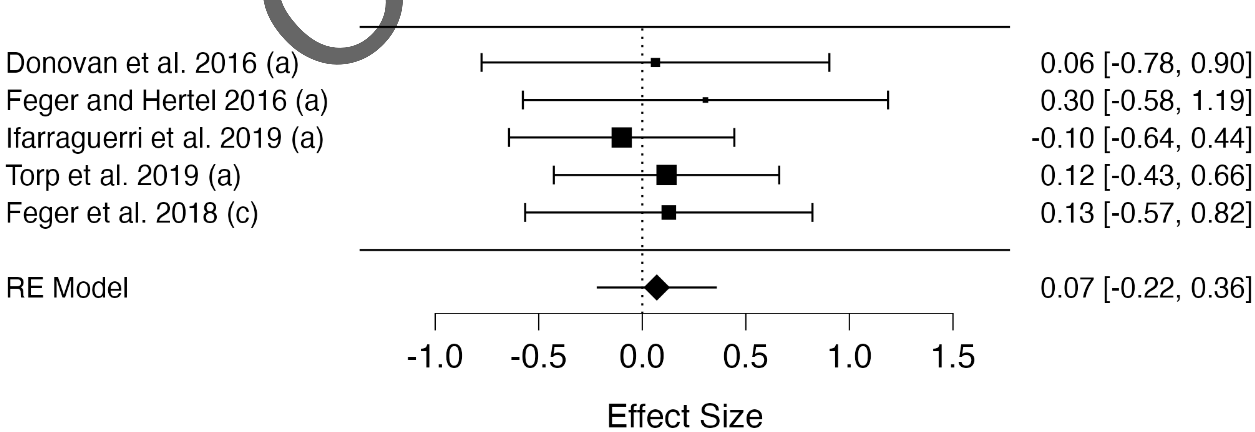
P.) Contact time – Medial forefoot



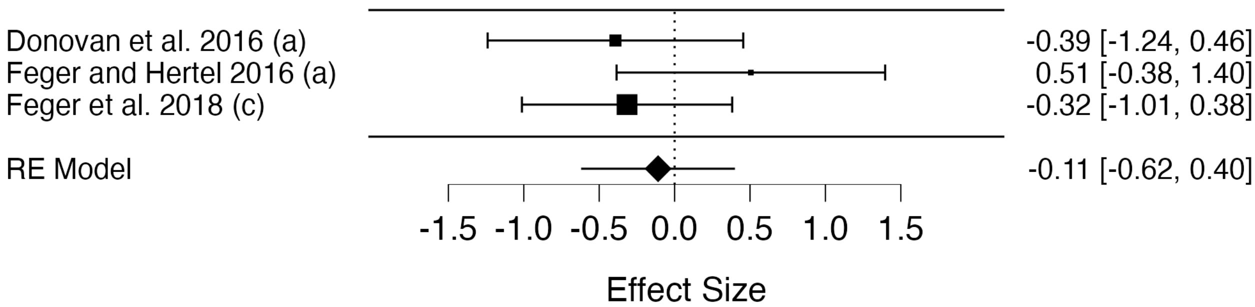
Q.) Contact time – Toes 2-5



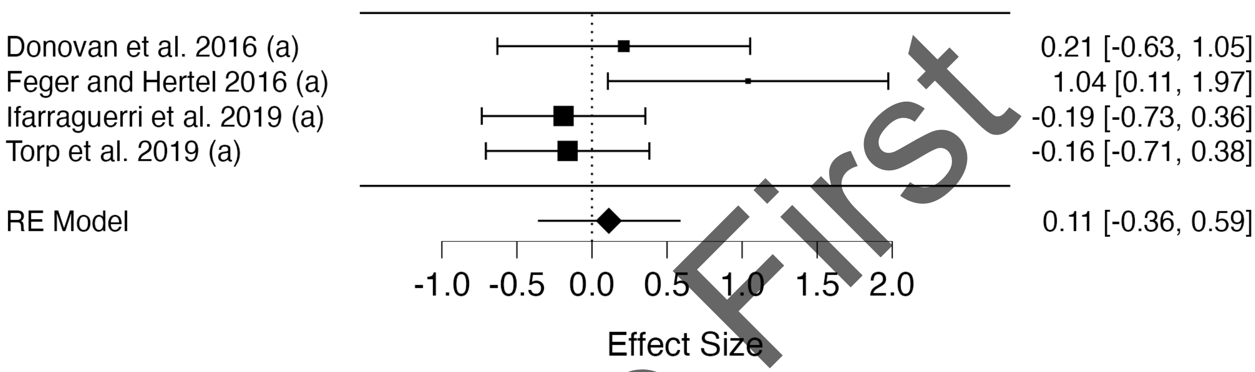
R.) Contact time – Hallux



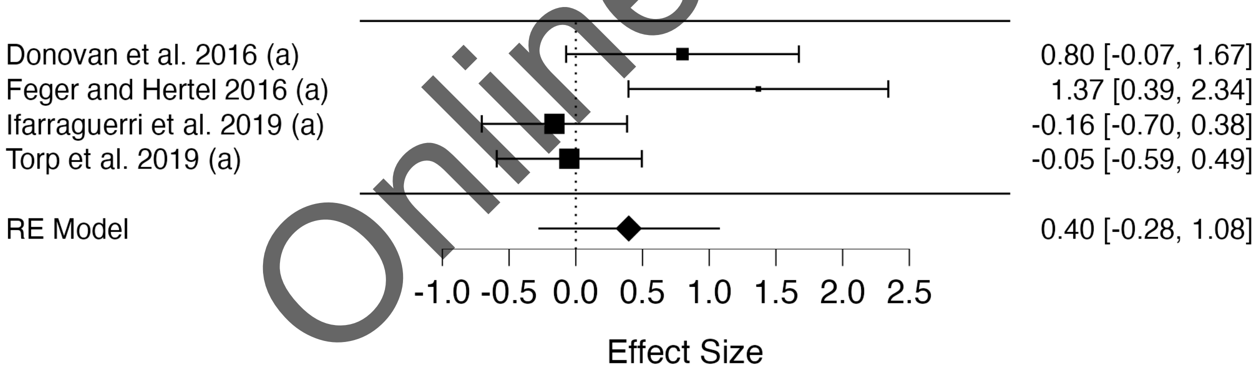
S.) Contact time – Total foot



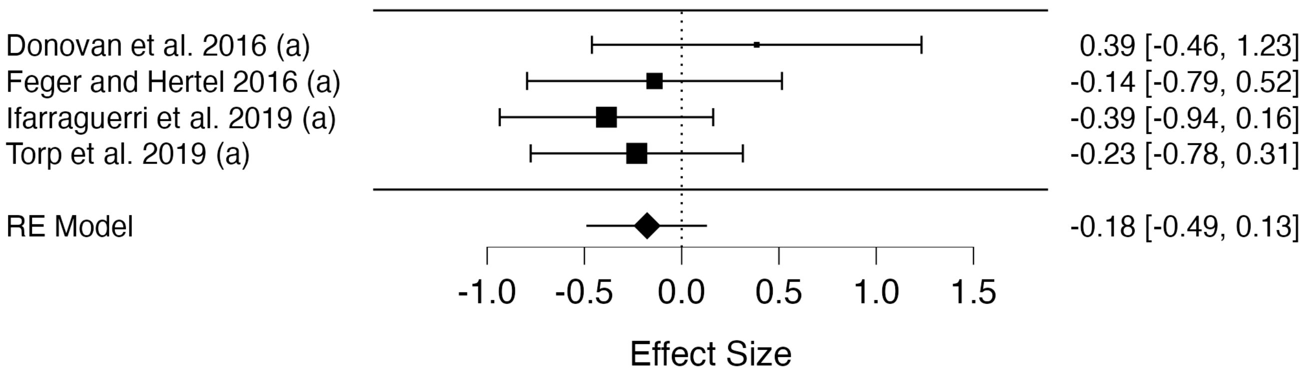
T.) Peak Pressure – Lateral heel



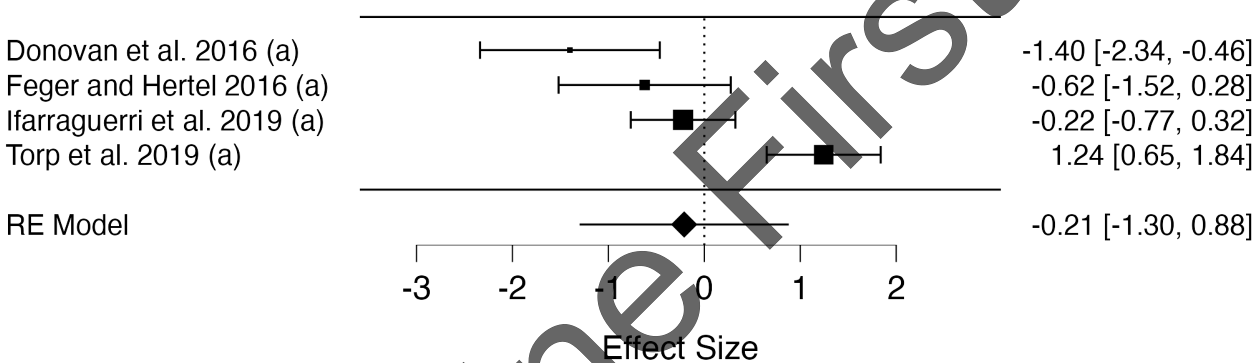
U.) Peak Pressure – Medial heel



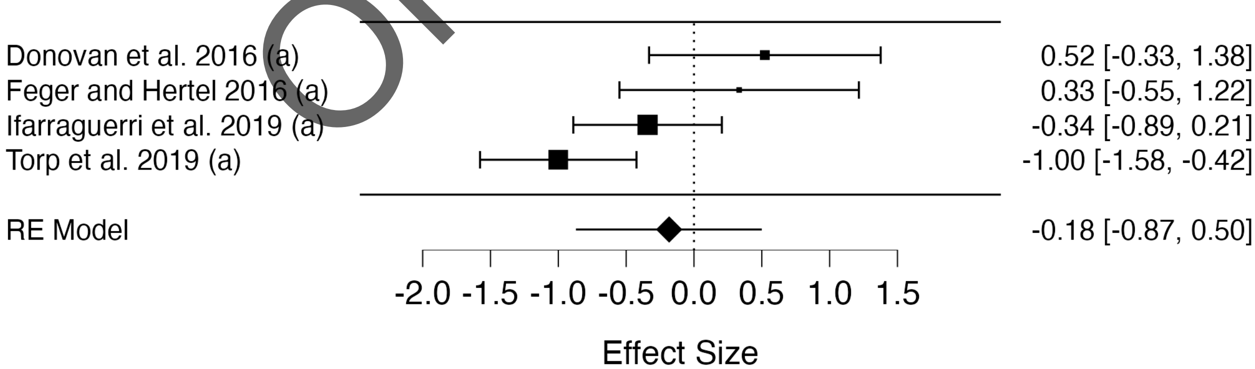
V.) Peak Pressure – Medial midfoot



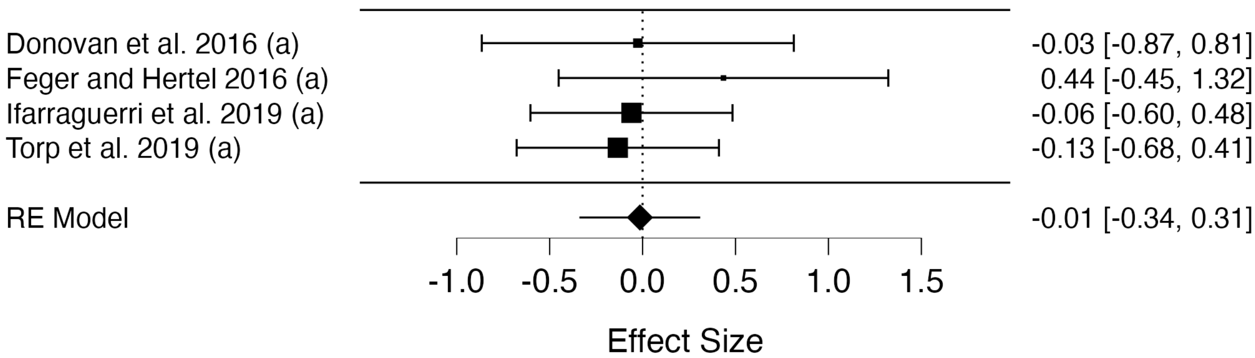
W.)Peak Pressure – Central forefoot



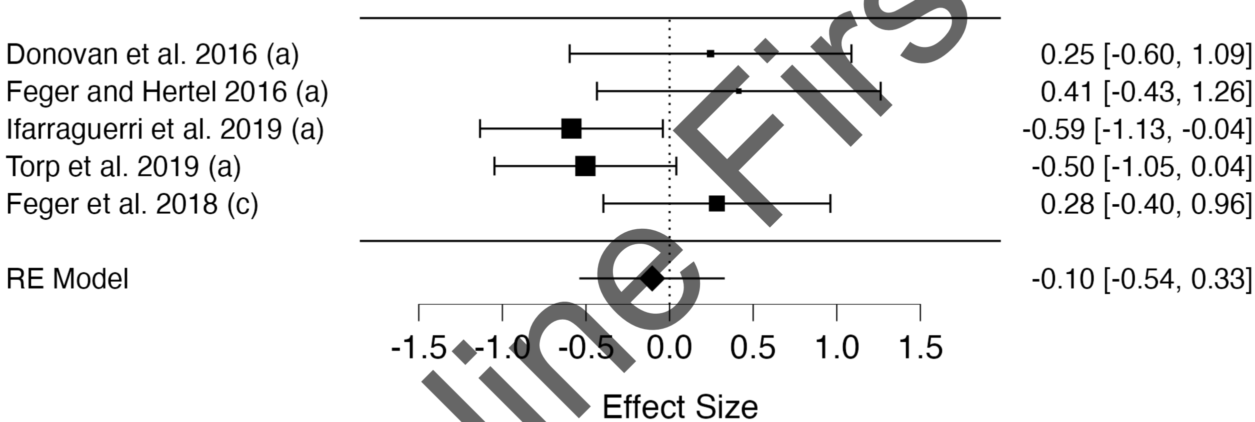
X.) Peak Pressure – Medial forefoot



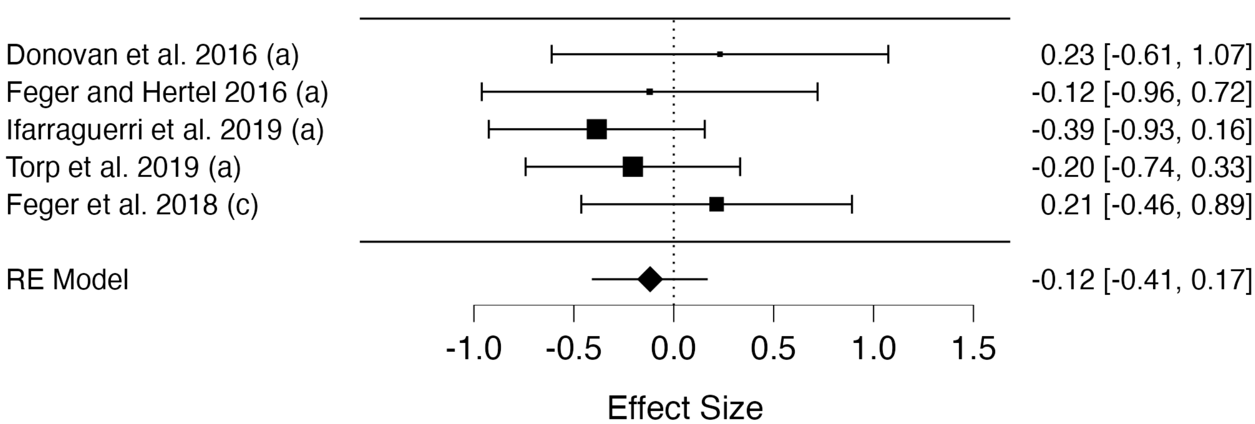
Y.) Peak Pressure – Toes 2-5

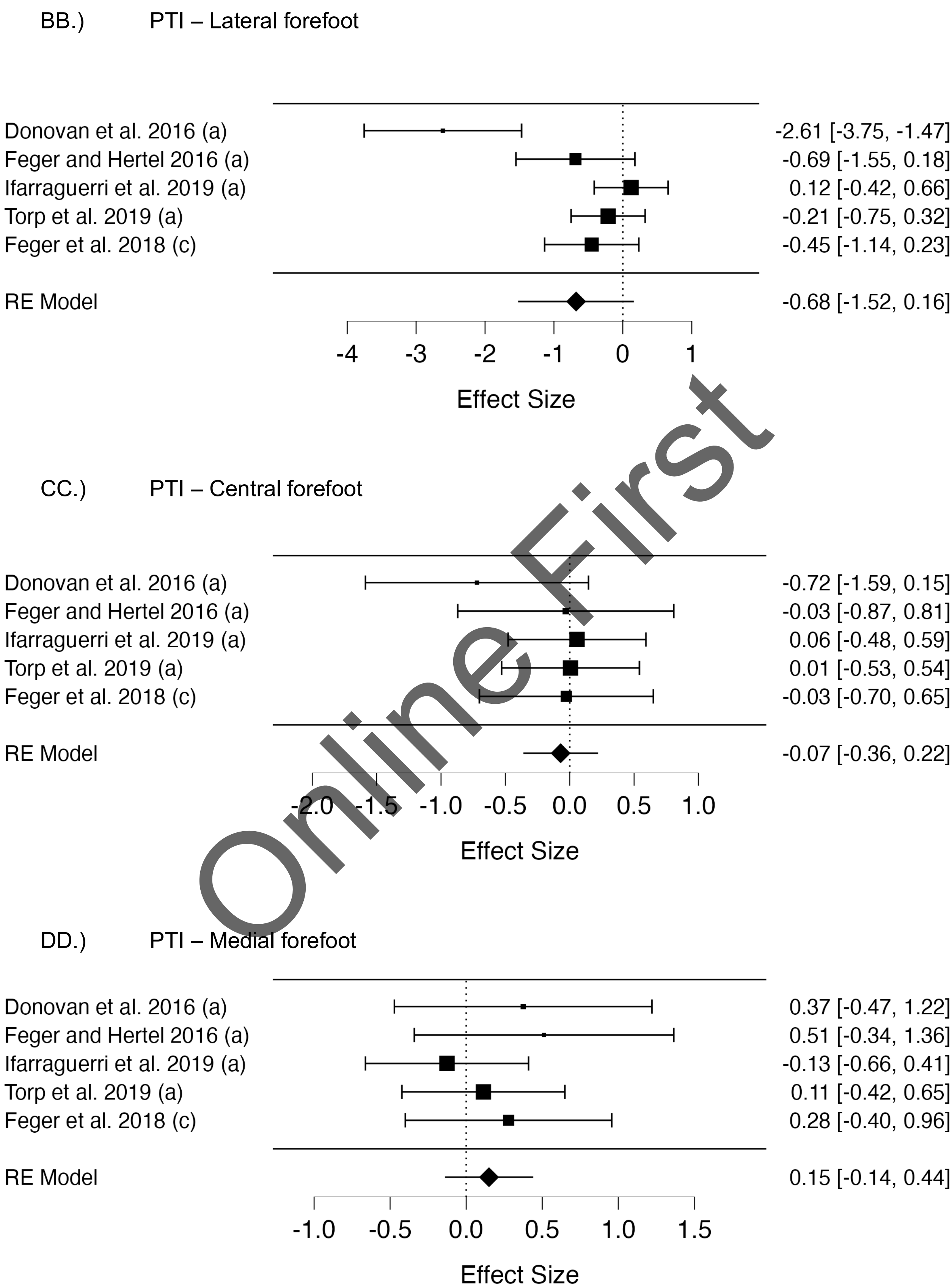


Z.) PTI – Medial heel

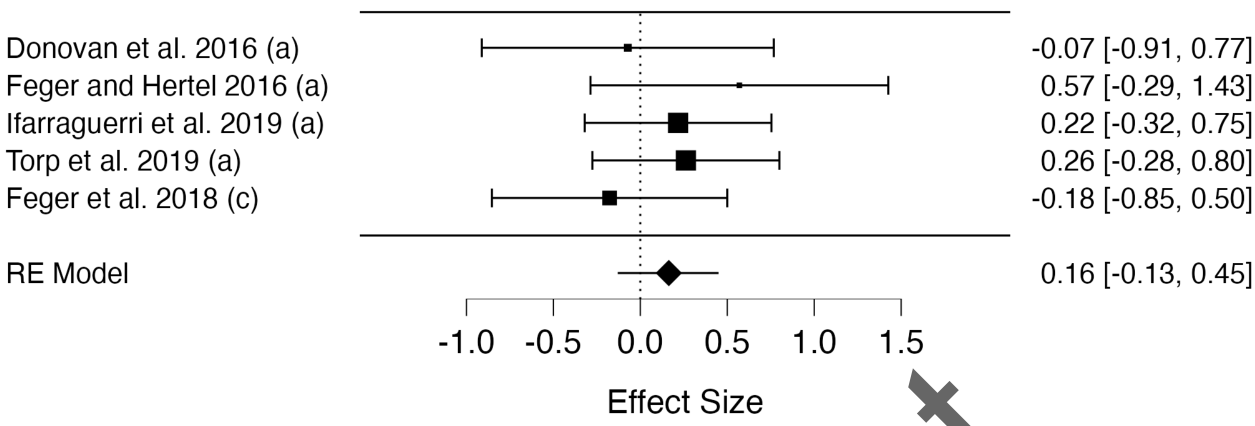


AA.) PTI – Medial midfoot

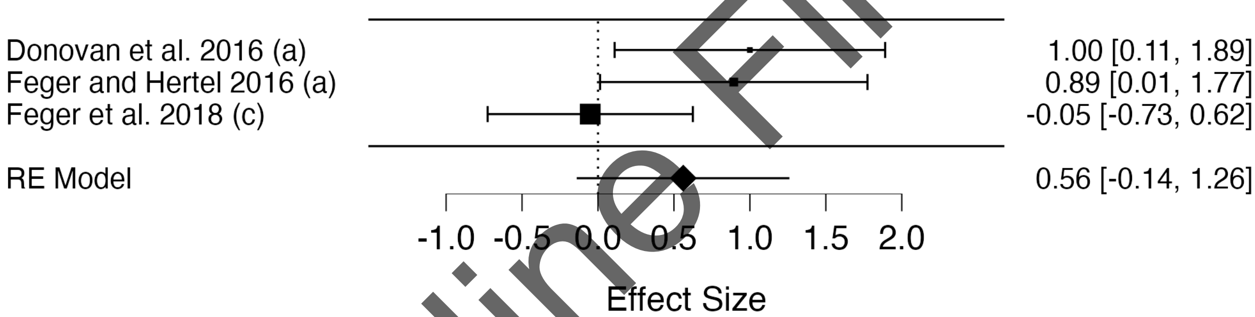



BB.) PTI – Lateral forefoot
Donovan et al. 2016 (a) -2.61 [-3.75, -1.47]
Feger and Hertel 2016 (a) -0.69 [-1.55, 0.18]
Ifarraguerri et al. 2019 (a) 0.12 [-0.42, 0.66]
Torp et al. 2019 (a) -0.21 [-0.75, 0.32]
Feger et al. 2018 (c) -0.45 [-1.14, 0.23]
RE Model -0.68 [-1.52, 0.16]
-4 -3 -2 -1 0 1
Effect Size
CC.) PTI – Central forefoot
Donovan et al. 2016 (a) -0.72 [-1.59, 0.15]
Feger and Hertel 2016 (a) -0.03 [-0.87, 0.81]
Ifarraguerri et al. 2019 (a) 0.06 [-0.48, 0.59]
Torp et al. 2019 (a) 0.01 [-0.53, 0.54]
Feger et al. 2018 (c) -0.03 [-0.70, 0.65]
RE Model -0.07 [-0.36, 0.22]
-2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0
Effect Size
DD.) PTI – Medial forefoot
Donovan et al. 2016 (a) 0.37 [-0.47, 1.22]
Feger and Hertel 2016 (a) 0.51 [-0.34, 1.36]
Ifarraguerri et al. 2019 (a) -0.13 [-0.66, 0.41]
Torp et al. 2019 (a) 0.11 [-0.42, 0.65]
Feger et al. 2018 (c) 0.28 [-0.40, 0.96]
RE Model 0.15 [-0.14, 0.44]
-1.0 -0.5 0.0 0.5 1.0 1.5
Effect Size

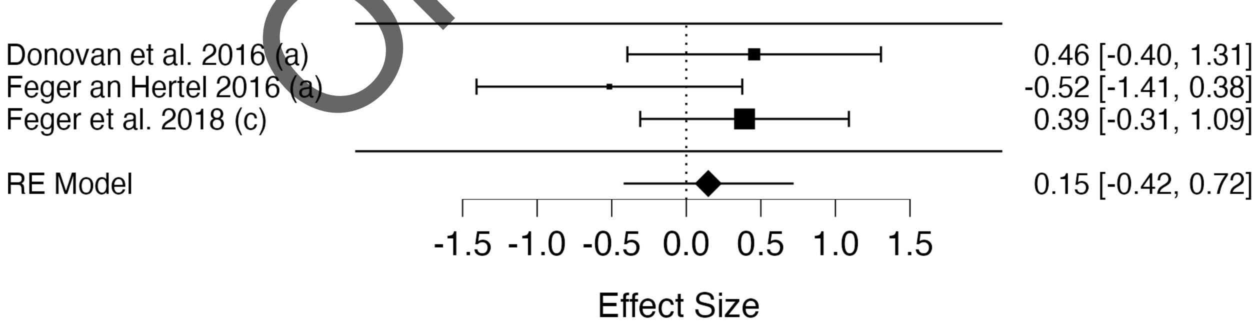
EE.) PTI – Toes 2-5



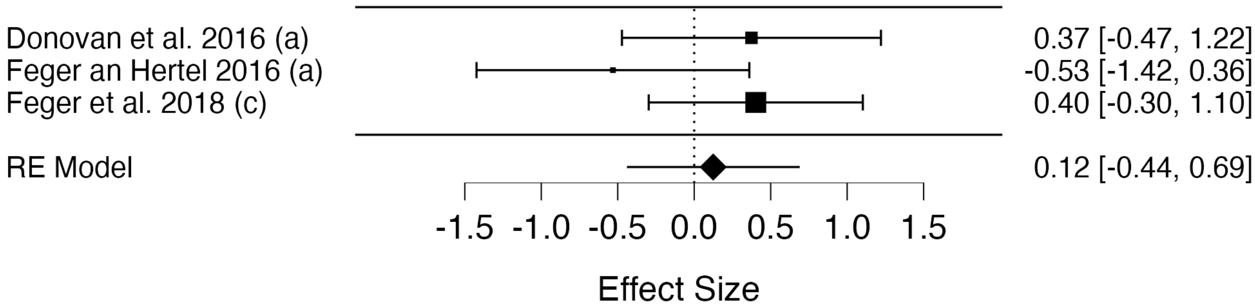
FF.) PTI – Total foot



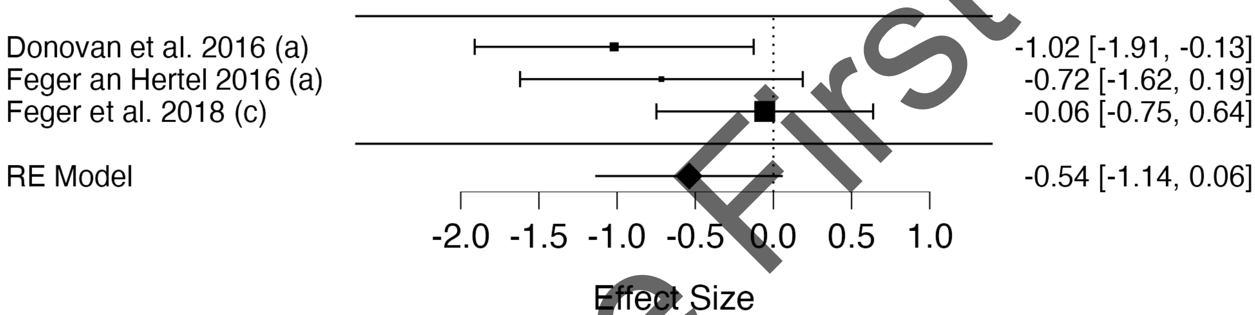
GG.) Time to Peak Pressure – Lateral heel



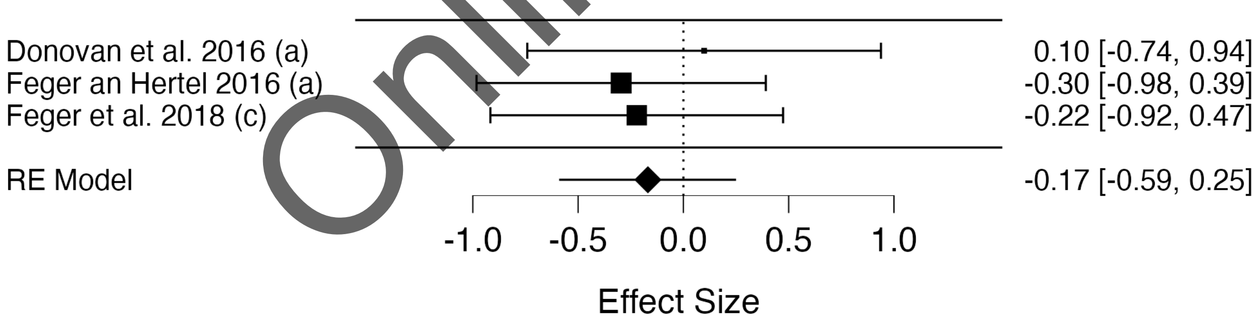
HH.) Time to Peak Pressure – Medial heel



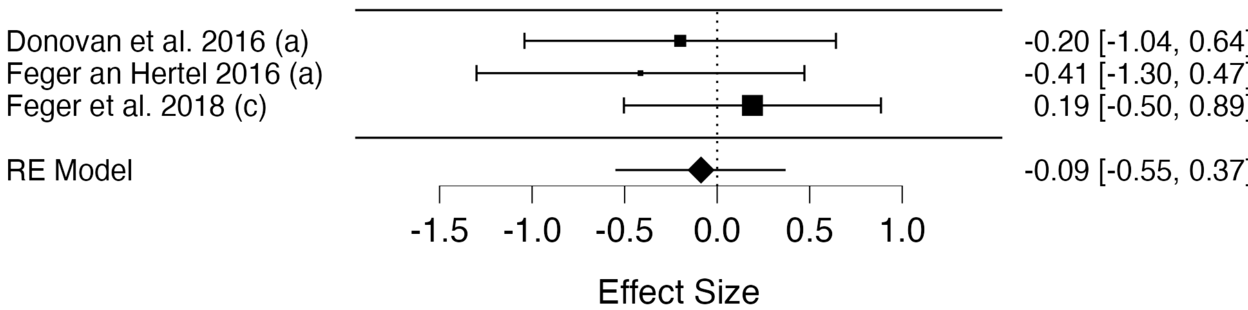
II.) Time to Peak Pressure – Lateral midfoot



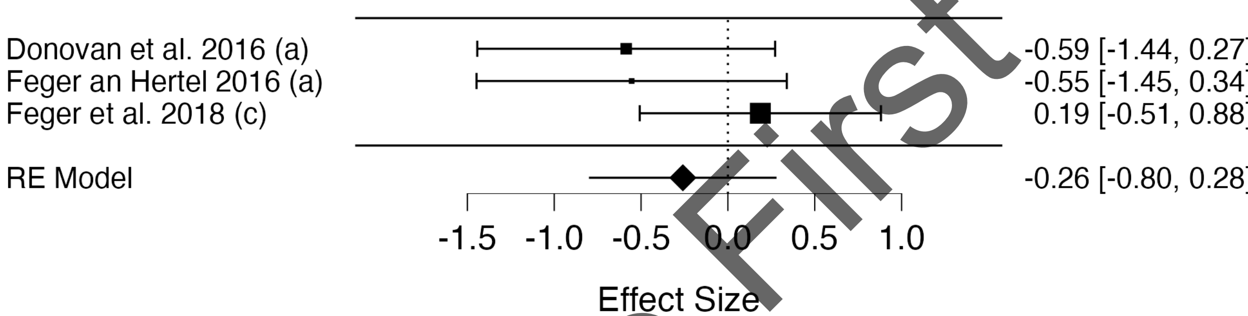
JJ.)Time to Peak Pressure – Medial midfoot



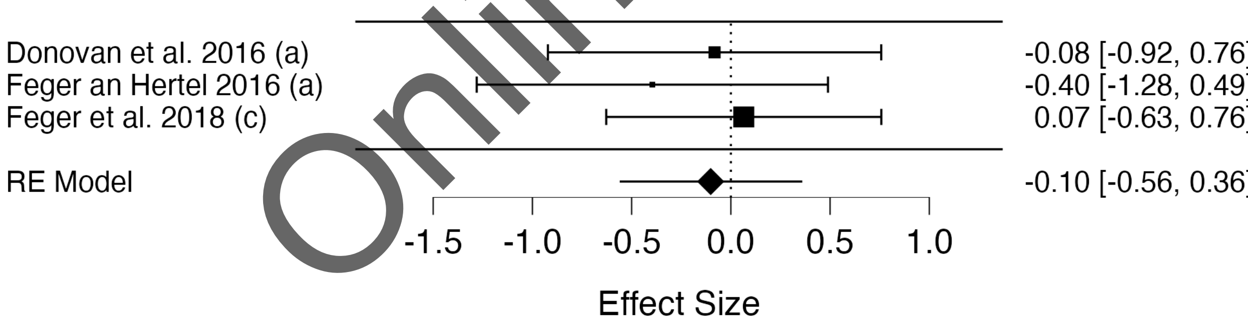
KK.) Time to Peak Pressure – Lateral forefoot



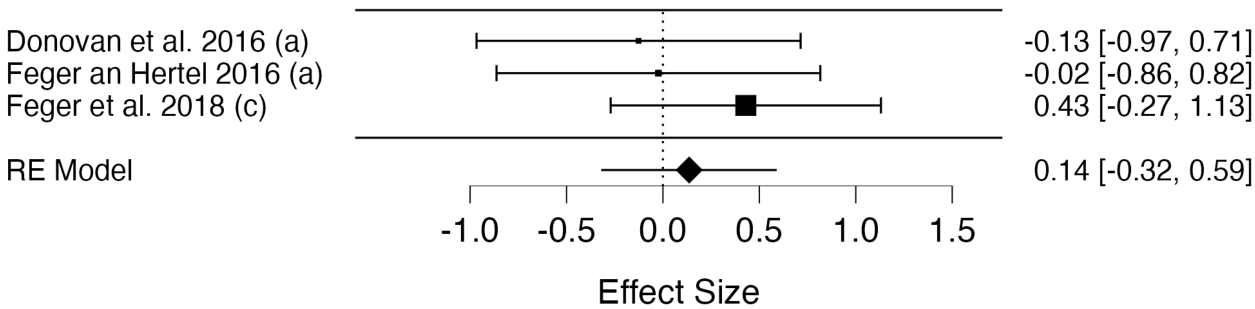
LL.) Time to Peak Pressure – Central forefoot



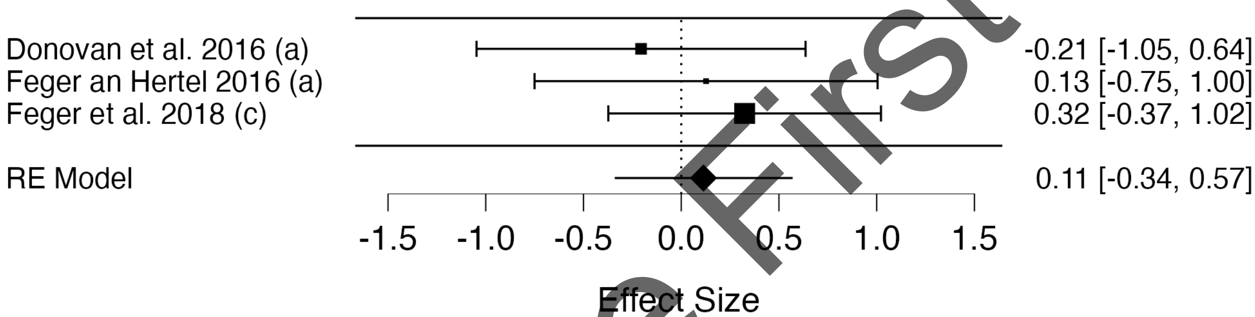
MM.) Time to Peak Pressure – Medial forefoot



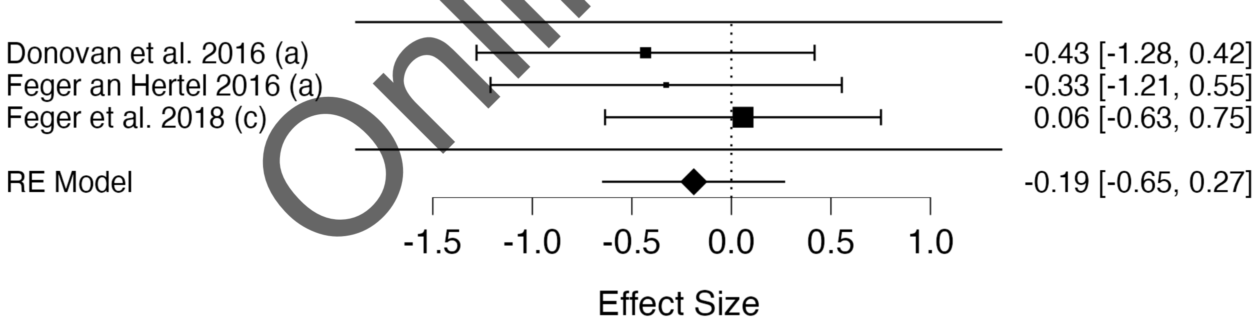
NN.) Time to Peak Pressure – Toes 2-5



OO.) Time to Peak Pressure – Hallux

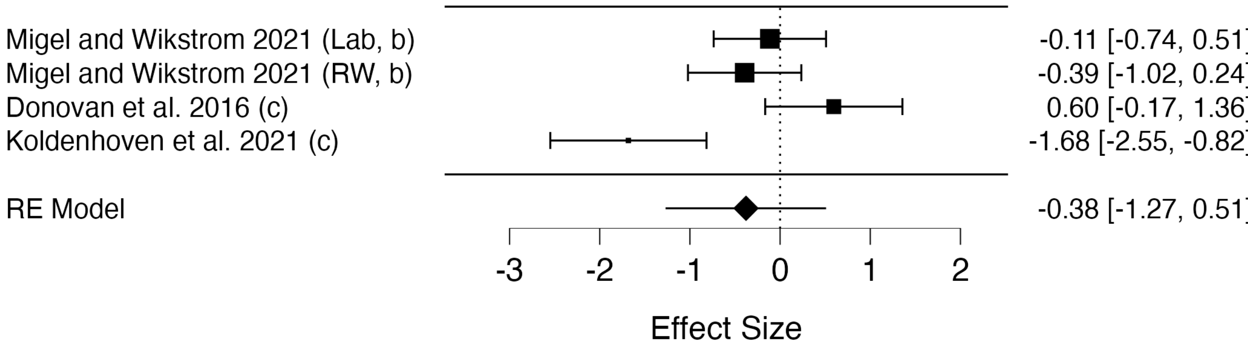


PP.) Time to Peak Pressure – Total foot

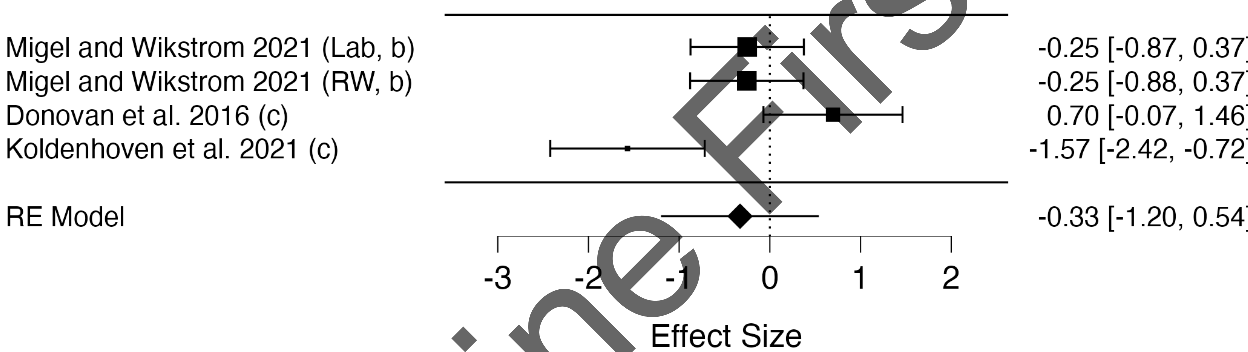


Kinematics

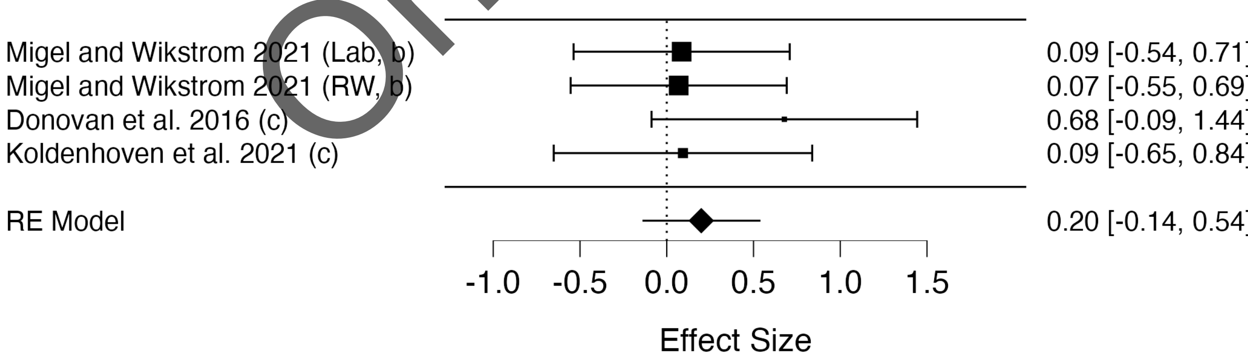
A.) Ankle Frontal Plane – Initial Contact



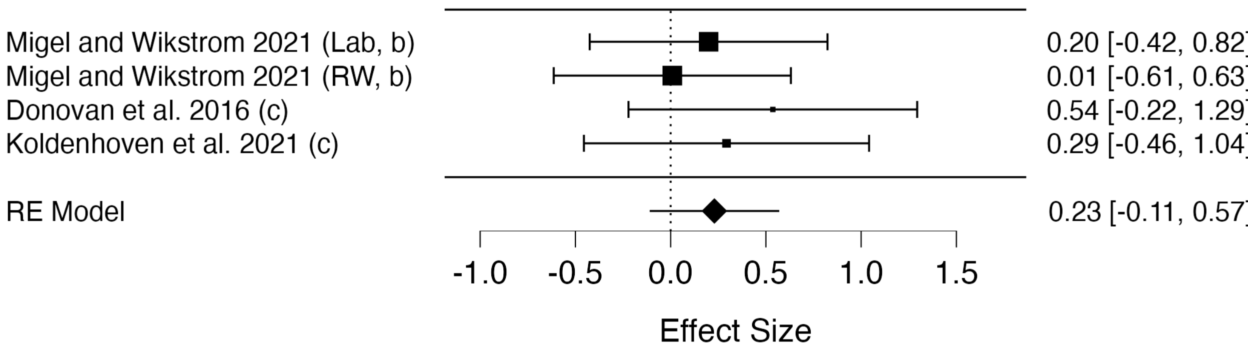
B.) Ankle Frontal Plane – Loading Phase



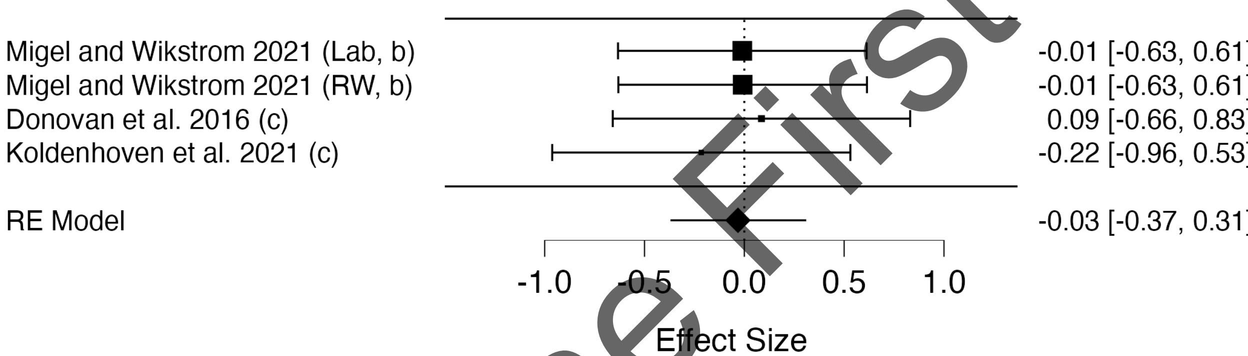
C.) Ankle Sagittal Plane – Initial Contact



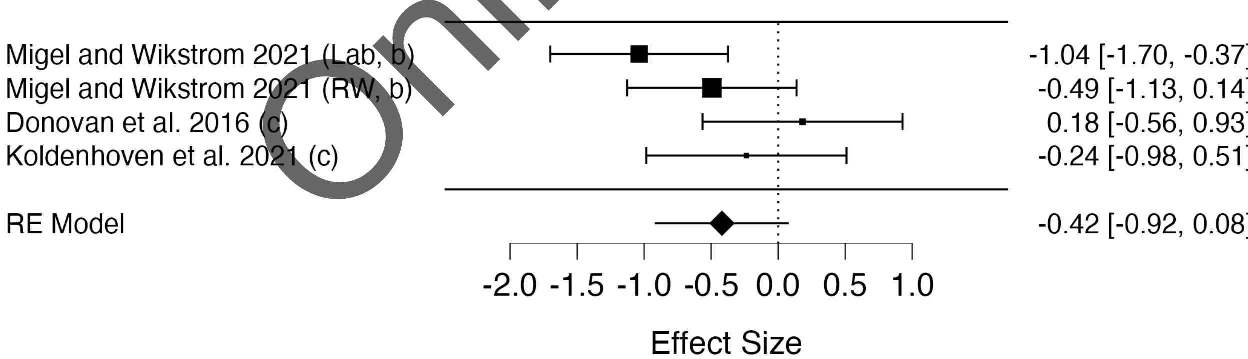
D.) Ankle Sagittal Plane – Loading Phase



E.) Ankle Transverse Plane – Initial Contact

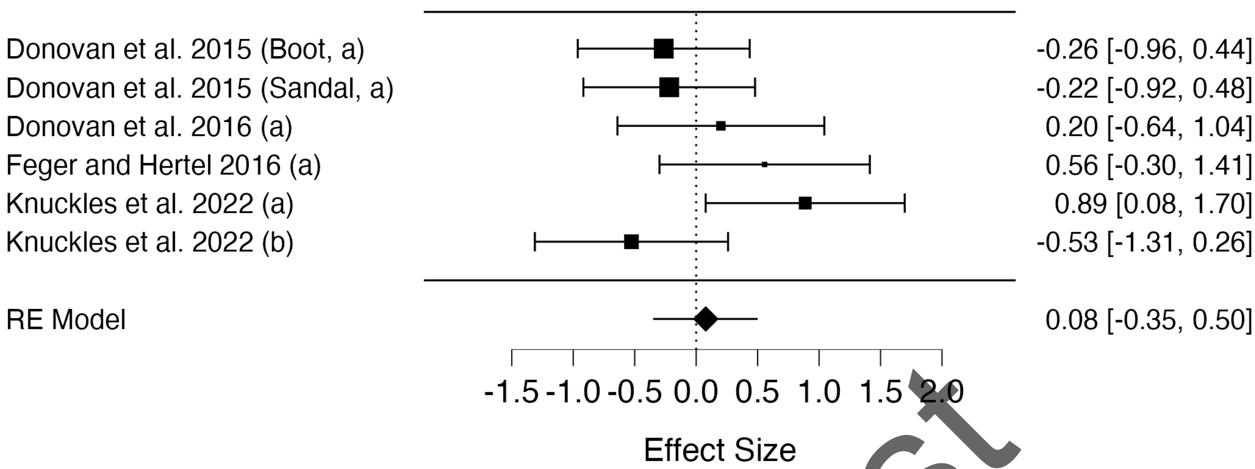


F.) Ankle Transverse Plane – Loading Phase

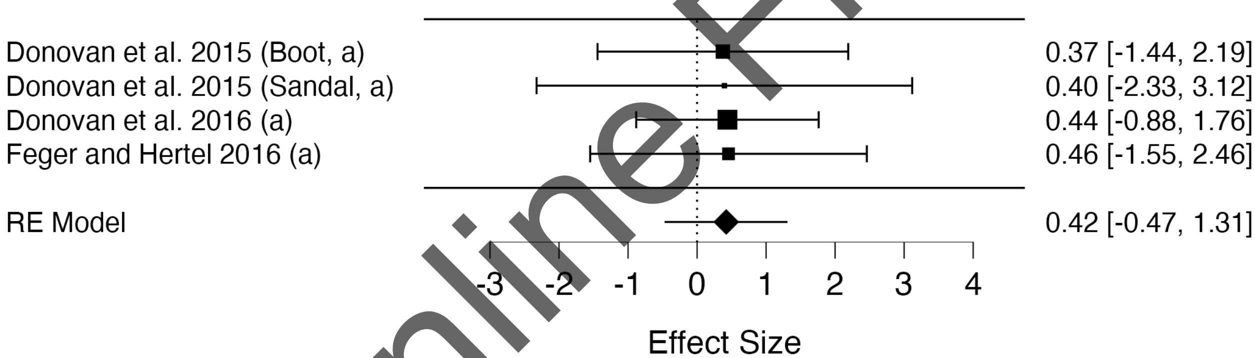


Electromyography

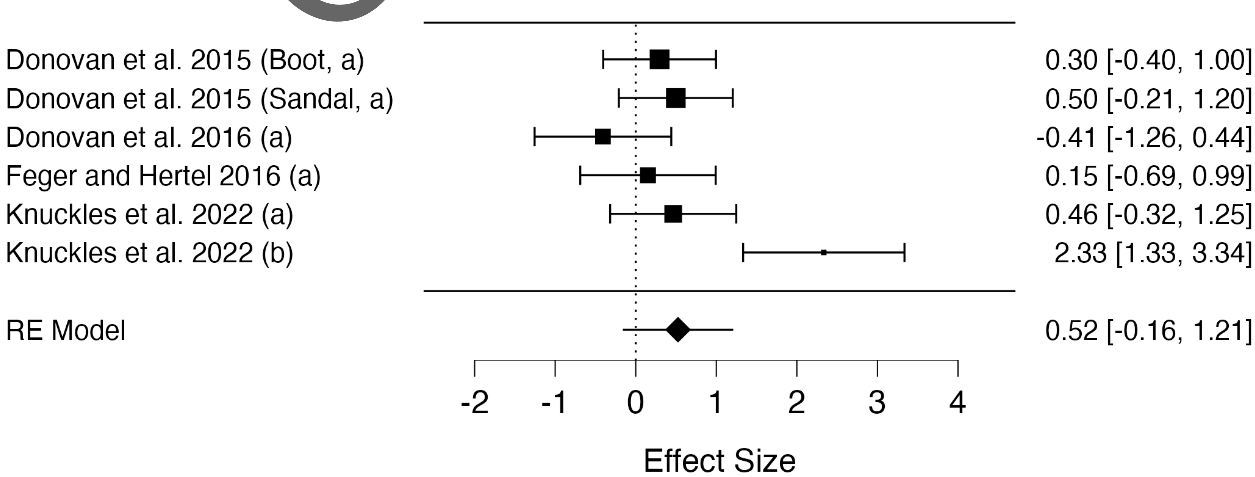
A.) RMS Amplitude Pre-IC – Tibialis Anterior



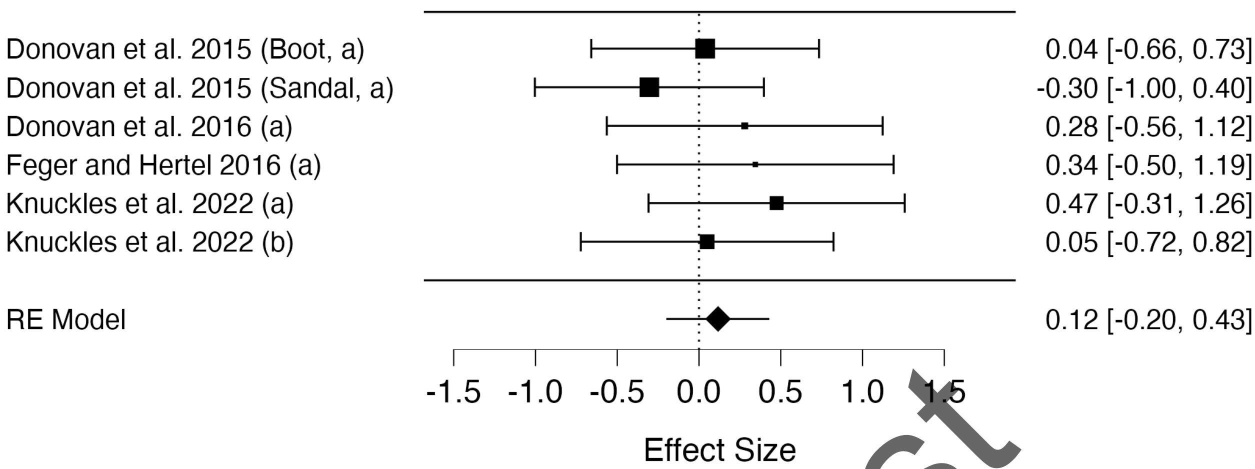
B.) RMS Amplitude Pre-IC – Fibularis Longus



C.) RMS Amplitude Pre-IC – Gluteus Medius



D.) RMS Amplitude Post-IC – Tibialis Anterior



E.) RMS Amplitude Post-IC – Gluteus Medius