Review Article

Effects of Ankle Plantar Flexion Position During Squatting on Tibialis Anterior and Triceps Surae Muscle Activity in Healthy Adults: A Systematic Review and Meta-Analysis

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Running title: Ankle Position Alters Tibialis Anterior Activity

Abstract
Background: Squatting is a fundamental movement in which ankle position is frequently modified with external tools such as shoes, insoles, or wedges. However, the effects of these modifications on shank muscle electromyographic (EMG) activity remain unclear. This systematic review and meta-analysis aimed to examine how changes in sagittal ankle position influence shank muscle EMG activity during squatting.
Material and Methods: A systematic search of six databases was conducted from inception until August 2026. Included studies reported EMG activity of the tibialis anterior (TA), gastrocnemius (GA), or soleus (SOL) during squats performed in plantar flexion or dorsiflexion, compared with a neutral ankle position.
Results: Analysis of eleven studies (141 participants) revealed that the plantar flexion position significantly decreased dorsiflexor (TA) activity (Hedges' g = -1.048; $P < 0.001$) but had no significant effect on plantar flexor (GA, SOL) activity (Hedges' g = 0.069; $P = 0.672$). High heterogeneity ($I^2 > 75\%$) was observed for both meta-analyses. Limited evidence also suggested that dorsiflexed positions may reduce plantar flexor activity.

Conclusions: Ankle plantar flexion during squatting significantly reduces dorsiflexor activity without systematically altering plantar flexor activation. These findings provide preliminary support for the clinical use of heel lifts to offload the TA but question their efficacy for modifying calf muscle recruitment. Future research should prioritize standardizing EMG methodologies and investigating these effects in clinical populations.
Keywords: Electromyography, Muscle, Ankle Joint, Foot, Exercise.

Introduction

The squat is a fundamental human movement that occurs frequently in daily living, the work environment, athletic training, and clinical rehabilitation. Epidemiological studies indicate that an average individual performs approximately 60 squatting movements daily during sitting-to-standing transitions and object manipulation [1,2]. In some occupational tasks, workers may spend up to 42% of their time in a squatting posture [3]. In athletic settings, the squat is considered a fundamental exercise and is routinely incorporated into strength and conditioning programs across a wide range of sports because of its effectiveness in developing lower-body strength, power, and overall athletic performance [4–7]. In a rehabilitation context, the squat serves as a cornerstone exercise for the lower limb [8,9].

The squat is typically a closed-kinetic-chain movement, so altering the position of one joint can affect the mechanics of the entire system. From a neuromechanical perspective, ankle positioning during squatting markedly alters lower extremity [10–15] and spinal kinematics [10,14,16] and muscle activation patterns [17]. Alterations in ankle angle modify the lever arms and moment demands across the ankle joint, consequently affecting neuromuscular recruitment strategies [13]. Particularly, plantar flexion positions achieved through heel wedges or elevated surfaces are frequently employed to accommodate the limited dorsiflexion range of motion or to alter biomechanical stress distribution [18].

Despite the widespread use of ankle position modifications, electromyographic (EMG) evidence of their effects on shank musculature is inconsistent. While contemporary systematic reviews have synthesized evidence on squatting biomechanics [19,20] and thigh muscle activity [17], none have specifically focused on the EMG literature of shank muscles in relation to interventions that modify ankle position during squatting. This gap is particularly noteworthy given the critical role of the tibialis anterior, gastrocnemius, and soleus muscles in ankle stabilization and movement control.

The existing literature demonstrates considerable methodological heterogeneity in EMG normalization techniques, squat variations, and experimental protocols, contributing to conflicting findings. However, the existing literature reports inconsistent findings for both plantar flexor [13,14,18,21–25] and dorsiflexor activity [13,14,21,23–27] in response to altered ankle positions. These inconsistencies preclude definitive conclusions and highlight the necessity for a comprehensive quantitative synthesis.

The clinical significance of understanding these neuromuscular responses is substantial. Conditions such as anterior compartment syndrome and medial tibial stress syndrome (shin splints) are characterized by excessive or prolonged tibialis anterior activity, where offloading this muscle through heel lifts during squatting could provide therapeutic benefit [28]. Conversely, Achilles tendinopathy, a common overuse injury, is intimately linked to calf muscle loading patterns, and understanding how ankle position modulates plantar flexor recruitment could inform more effective rehabilitation protocols [29]. Additionally, in post-operative rehabilitation following ankle or foot surgery, specific muscle activation patterns may need to be either emphasized or avoided to optimize recovery while protecting healing tissues [30]. Therefore, the findings of this meta-analysis have direct implications for clinicians designing rehabilitation programs for these specific patient populations.

Therefore, the primary objective of this systematic review and meta-analysis is to quantitatively synthesize available EMG evidence to determine the effects of ankle plantar flexion and dorsiflexion positions on shank muscle activity during squatting. We hypothesized that changing sagittal ankle position would modulate the activity level of prime shank muscles, including plantar flexors and dorsiflexors.

Materials and Methods

Literature search strategy

This systematic review was performed in accordance with established methodological standards, following both the Cochrane Handbook for Systematic Reviews and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [31]. Two independent investigators (UMY and ME) systematically searched six electronic databases, PubMed, Web of Science, ScienceDirect, Scopus, and the Cochrane Library, as primary databases, with Google Scholar used as a supplementary source to enhance search sensitivity and identify potentially relevant grey literature [32] for literature published from its initiation through August 2026. The search strategy employed a structured approach using carefully selected keywords and Medical Subject Headings (MeSH) terms organized into four primary domains: squatting movements, ankle positioning variations, electromyographic measurement, and shank muscles. Search terms were strategically combined using Boolean operators, with the core search syntax being: ("squat" OR “lifting”) AND ("ankle position" OR "heel lift" OR "foot wedge" OR "foot placement") AND ("electromyograph" OR "EMG" OR "muscle activity") AND (“shank” OR “dorsiflex*” OR “plantar flex*”). The screening process involved independent title and abstract review by two investigators (UMY and ME), followed by full-text assessment, with any discrepancies resolved through consensus with a third reviewer (MG).

Study selection criteria

Study eligibility was determined using the PICOS (population, Intervention, Comparison, Outcomes, and Study design) framework: 1: population: studies involving healthy human adults (15-60) without gender restrictions; 2: intervention: squat exercises performed under varying ankle positions, including plantar flexion and dorsiflexion (achieved through external tools (e.g., wedges, insoles, boards, shoes, etc.), dorsiflexion (using decline surfaces), and natural positioning as the reference condition; 3: comparator: the neutral ankle position (0° inclination, no elevation) served as the control comparator; 4: outcomes: primary interest was surface or fine-wire EMG measurements from key shank muscles (tibialis anterior, medial/lateral gastrocnemius, and soleus), requiring reporting amplitude-domain variables; 5: study design: consideration was given to randomized controlled trials, cross-sectional designs, and cohort studies published in peer-reviewed journals. The 15-60 age range is consistent with previous definitions of adulthood [17,33], although most participants in this review were within the narrower 18–30-year age range. Cross-sectional designs with repeated measures were included as they represent the most appropriate methodology for examining acute neuromuscular responses to biomechanical interventions, where each participant serves as their own control (within-subject design), thereby reducing between-subject variability and increasing statistical power [34]. Furthermore, randomized controlled trials are not feasible for this type of research question due to practical and ethical considerations [35]. The inherent limitations of cross-sectional designs, including the inability to establish causality and the potential for selection bias and confounding [36], are acknowledged and discussed in the Limitations section. Only studies published in English were eligible for inclusion in this review. Studies were excluded if they: (a) failed to provide quantitative EMG outcomes; (b) implemented combined interventions that confounded ankle position effects; or (c) presented insufficient statistical data for effect size computation.

Data extraction

A standardized data extraction protocol was implemented by two independent reviewers (UMY and ME) using a customized Microsoft Excel template. The extraction captured four primary domains: (1) bibliographic information (authors, publication year, origin); (2) participant characteristics (sample size, demographic details); (3) methodological parameters (squat type and depth, external loading, ankle positions tested, EMG protocols including normalization approaches, and analyzed movement phases); and (4) outcome metrics (mean and standard deviation values for EMG signals across experimental conditions). To ensure data completeness, we contacted corresponding authors when primary data were incomplete or only available graphically. When no response was received, we extracted data from graphs using WebPlot Digitizer (version 4.1, Texas, USA). This is a validated and reliable tool for this purpose [37] and has also been used for EMG data extraction in previous meta-analyses [17,38]. When a study reported more than one measurement (e.g., different parts of the plantar flexors or different squat phases), a combined average of the reported outcomes was calculated using Comprehensive Meta-Analysis (CMA) software (Version 3.0) to obtain a single overall outcome.

Quality assessment

Methodological rigor was evaluated independently by two assessors (UMY and ME), with a third assessor (MG) resolving disagreements, using an adapted 14-item quality appraisal tool [39], which has been adopted and used in EMG studies during squatting [17] and walking [38]. This tool examined critical dimensions, including participant characterization, EMG instrumentation details, experimental protocol validity, analytical appropriateness, and clinical relevance reporting. Each criterion was scored on a standardized scale, with cumulative scores indicating overall study quality.

Statistical synthesis

Quantitative synthesis was performed using CMA software. CMA estimates effect sizes using descriptive statistics, including means, standard deviations, correlations, and sample sizes. In the absence of sufficient data, CMA estimates effect sizes by combining available data (e.g., mean differences). A random-effects model was applied to account for anticipated methodological heterogeneity. Between-study variance was quantified using I^2 statistics and Cochran's Q tests. Effect sizes (Hedges' g) were interpreted based on established guidelines as small ($g \leq 0.20$), medium ($0.20 < g < 0.80$), and large ($g \geq 0.80$) [38,40].

To assess robustness, sensitivity analyses were conducted by excluding studies with quality scores below the median, with effect estimates recalculated for each outcome (e.g., muscle groups) [15]. Publication bias was assessed using funnel plots of effect sizes against standard errors, with symmetry suggesting low risk and asymmetry indicating potential bias. However, as asymmetry may have multiple causes, it was interpreted as suggestive rather than definitive evidence of publication bias [41]. Egger's regression tests with two-tailed p-values were also conducted separately for each muscle group.

Results

Participants' characteristics

The systematic literature search yielded 1024 potential records, and the study selection process is detailed in the PRISMA flow diagram (Fig 1). After eligibility screening, 11 studies with 141 subjects were included in the systematic review and meta-analysis. The sample sizes ranged from 8 to 26 participants, comprising 71 males, 34 females, and 36 participants of unspecified sex. All participants were classified as novice lifters, defined as individuals with less than one year of regular resistance training experience or a maximum squat capacity of less than 1.5 times their body weight, based on criteria used in the studies included within this review. Pooled means for participant characteristics were as follows: age, 25.73 ± 7.77 years (10 studies, n = 133; not reported in 1 study); height, 172.32 ± 8.66 cm (9 studies, n = 115; not reported in 2 studies); and body mass, 70.92 ± 12.27 kg (9 studies, n = 115; not reported in 2 studies).

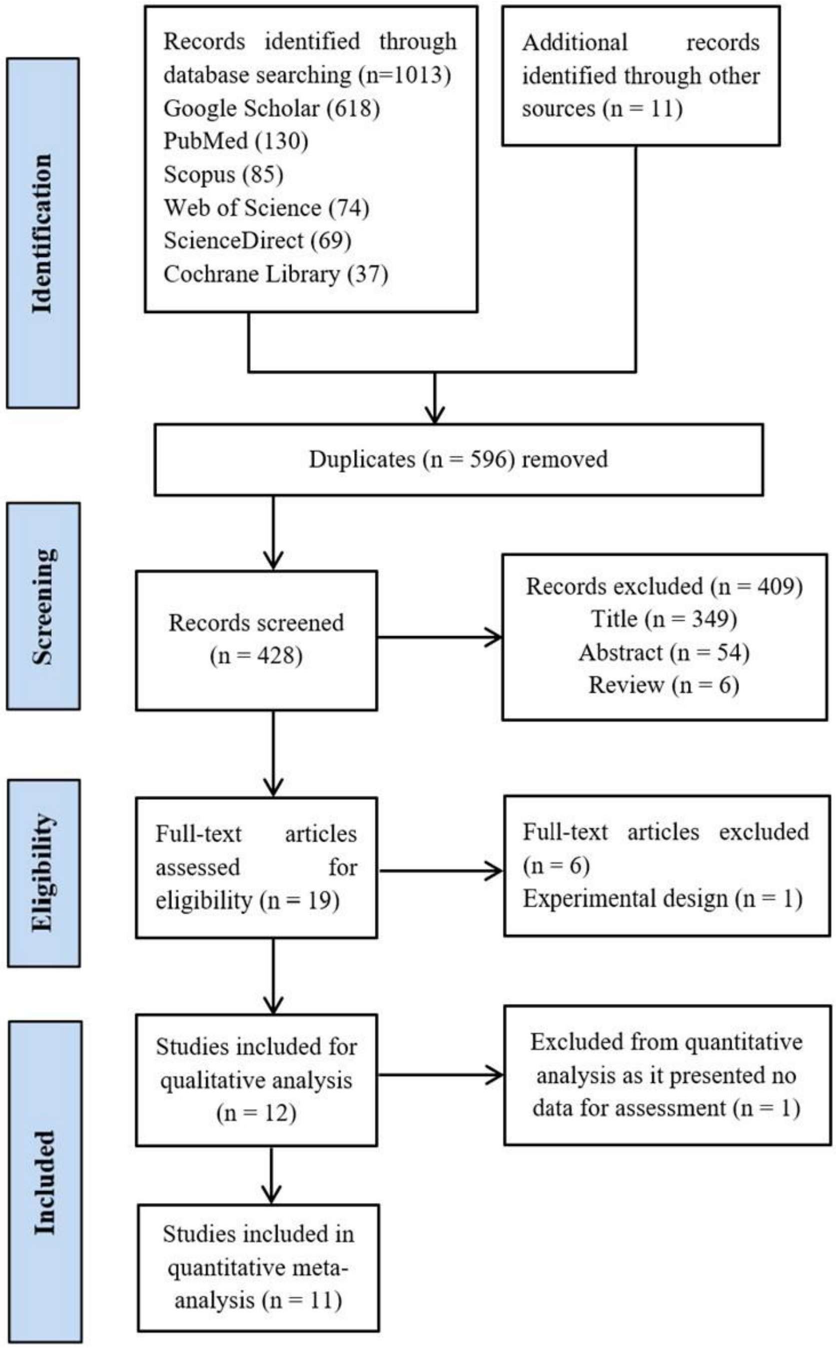


Fig 1. Flowchart of the search and selection process for studies included in this review.

Study characteristics

The study characteristics of the included studies are summarized in Table 1. It documents the shank muscles studied, reported outcome measures, and exercise specifications (squat type, depth, weight, surface level, and ankle position). Knee flexion angles of 45, 60, and 90º were implemented for static squats in one study [24], while the knee flexion range for dynamic squats varied from zero to < 45° (shallow) [24,26,27,42], < 90° (medium) [13,18,21,22,24] or > 90° (deep) [14,23,25].

Table 1. The characteristics of studies included in this review.

Author (Year)	n	Male/ female	Muscle assessed	Outcome measure	Squat type	Squat depth	Squat weight	Squat surfaces	Ankle positions
Lu et al. (2022) [25]	20	10/ 10	TA, GA and SOL	% MVIC (mean)	Two-leg barbell back squat (dynamic)	Deep	70% of 1RM	Shoe vs. shoe	Flat: 0 cm; PF: 1.5 and 3 cm
Ghasemi et al. (2018) [18]	9	9/ 0	GA and SOL	% MVIC (mean)	Two-leg squat (dynamic)	Normal	1.36 Kg	Barefoot vs. wooden board	Flat: 0 cm; PF: 1 and 3 cm, DF: 1 cm
Richards et al. (2016) [13]	18	9/ 9	TA and GA	% Peak activity	Two-leg squat (dynamic)	Normal	NR	Rehab device	Flat: 0°; PF: 5, 10, 15, 20 and 25°
Lee et al. (2015) [24]	26	NR	TA and GA	% MVIC (mean)	Two-leg squat (static)	Normal and shallow	NR	NR vs. wooden board	Flat: 0°; PF: 25°
Alves et al. (2009) [27]	8	3/ 5	TA and SOL	Microvolt	Two-leg squat (dynamic)	Shallow	NR	NR vs. decline board	Flat: 0°; PF: 25°
Sriwarno et al. (2008) [14]	8	8/ 0	TA and GA	% Mean amplitude	Two-leg squat (dynamic)	Deep	BW	NR vs. decline board	Flat: 0°; PF: 15°
Sriwarno et al. (2008) [23]	8	8/ 0	TA, GA and SOL	% Peak activity	Two-leg squat (static)	Deep	BW	Barefoot vs. foot slope	Flat: 0°; PF: 15°
Richards et al. (2008) [42]	10	NR	GA	% Peak of activity and integrated	One-leg squat (dynamic)	Shallow	BW	Shoe vs. shoe plus decline board	Flat: 0°; PF: 8, 16 and 24°
Ribeiro et al. (2007) [26]	8	4/ 4	TA and GA	Microvolt	One-leg squat (dynamic)	Shallow	NR	NR vs. wooden board	Flat: 0°; PF: 10°; DF: 10°
Frohm et al. (2007) [22]	13	13/ 0	GA	Mean activity	Bromsman and free weight squat (dynamic)	Normal	320 Kg (Bromsman) and 10 Kg	Shoe vs. shoe plus wooden board	Flat: 0°; PF: 25°
Kongsgaard et al. (2006) [21]	13	7/ 6	TA, SOL and GA	% Peak amplitude	One-leg squat (dynamic)	Normal	NR	Flat vs. decline board	Flat: 0°; PF: 25°

Abbreviations: GA: gastrocnemius; TA: tibialis anterior; SOL: soleus; BW: body weight; MVIC: maximum voluntary isometric contraction; NR: not reported case. PF: plantar flexion position; DF: dorsiflexion position.

The squat speed was not reported in five studies [13,14,25,26,42], while it was 0.11 m/s [22], natural speed [23], 2 or 6 seconds for the holding phase [24,27], and 4.5 or 5 seconds for the whole phase [18,21]. The EMG unit was a percentage of either peak activity [13,14,21,42], mean activity

[22,23], MVIC (maximum voluntary isometric contraction) [18,24,25] or a non-identified unit (microvolt) [26,27]. The muscle activity was reported in different phases of squatting, including ascending [18,26,27], holding [14,18,24], descending [18,21,26,27], whole phase [13,22,25,42] or other time points (e.g., initial time, 60º or peak of knee angle) [23,42]. The following data were used in CMA to compute effect sizes: means and standard deviations of non-wedge and wedge conditions for 10 studies [13,14,18,21,23–27,42]. For the remaining study [22], effect sizes were calculated from mean differences, t-statistics, and P-values. For studies reporting independent groups, separate effect sizes were calculated for each group [38,40].

3.3. Risk of bias assessment

The results of the methodological quality assessment, based on the modified 14-item tool, are presented in Table 2. Most studies included in this review received a good score, ranging from 8.07 to 11.1 (out of a maximum score of 14). All studies clearly stated their research aims (Q1), addressed their research questions in the discussion (Q11), supported their main findings with results (Q12), and interpreted logical conclusions supported by relevant references (Q13). Most studies also provided full or partial information about participants (Q2), key outcome variables (Q6), and the clinical or practical implications of their findings (Q14). Methodological characteristics (Q3–5, Q7–8) varied across studies. Except for one study, none of them reported data on internal validity (Q10) or reliability (Q9).

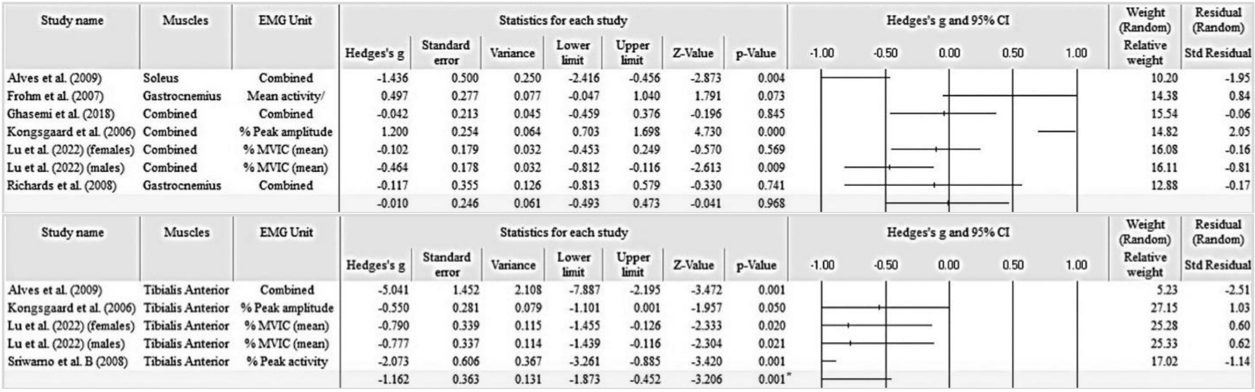
Table 2. Quality appraisal of the studies included in this review.

Author (Year)	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Total
Lu et al. (2022) [25]	1	1	1	1	0.5	0.5	0.8	0.8	0	1	1	1	1	0.5	11.1
Ghasemi et al. (2018) [18]	1	1	0.5	0.5	0.5	1	0.8	1	0	0	1	1	1	0.5	9.8
Richards et al. (2016) [13]	1	0.5	0.5	0	0.17	1	0.8	1	0	0	1	1	1	0.5	8.47
Lee et al. (2015) [24]	1	0.75	0.5	0.5	0.17	1	0.6	0.6	0	0	1	1	1	0.5	8.62
Alves et al. (2009) [27]	1	1	0	1	0.33	1	0.6	0.6	0	0	1	1	1	0.5	9.03
Sriwarno et al. (2008) [14]	1	1	0.5	0	0.5	1	0.4	0.4	0	0	1	1	1	0.5	8.3
Sriwarno et al. (2008) [23]	1	1	0.5	0.5	0.33	1	0.4	0.4	0	0	1	1	1	0.5	8.63
Richards et al. (2008) [42]	1	0.5	0.5	0	0.33	1	0.8	1	0	0	1	1	1	1	9.13
Ribeiro et al. (2007) [26]	1	1	0	0	0.17	1	0.6	0.8	0	0	1	1	1	0.5	8.07
Frohm et al. (2007) [22]	1	1	0.5	0	0.67	0.5	0.8	1	0	0	1	1	1	0.5	8.97
Kongsgaard et al. (2006) [21]	1	1	0.5	0.5	0.33	1	0.8	0.8	1	0	1	1	1	1	10.93

Each item was scored as 0 (no/poor quality), 0.5 or close to it (partially fulfilled/moderate quality), or 1 (yes/high quality), with higher total scores indicating better methodological quality.

Sensitivity analysis and risk of publication bias

Sensitivity analyses were performed by excluding studies with quality scores below the median for each variable. The results remained consistent in direction and statistical significance, supporting the robustness of the primary findings (Fig 2). Qualitative assessment of the funnel plots showed no notable asymmetry, and Egger's regression indicated no significant publication bias for plantar flexors ($t = 0.554$, $p = 0.593$) and dorsiflexors ($t = 1.901$, $p = 0.099$) (Fig 3).



Study name	Muscles	EMG Unit	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value	Weight (Random) Relative weight	Residual (Random) Std Residual
Alves et al. (2009)	Soleus	Combined	-1.436	0.500	0.250	-2.416	-0.456	-2.873	0.004	10.20	-1.95
Frohm et al. (2007)	Gastrocnemius	Mean activity/	0.497	0.277	0.077	-0.047	1.040	1.791	0.073	14.38	0.84
Ghasemi et al. (2018)	Combined	Combined	-0.042	0.213	0.045	-0.459	0.376	-0.196	0.845	15.54	-0.06
Kongsgaard et al. (2006)	Combined	% Peak amplitude	1.200	0.254	0.064	0.703	1.698	4.730	0.000	14.82	2.05
Lu et al. (2022) (females)	Combined	% MVIC (mean)	-0.102	0.179	0.032	-0.453	0.249	-0.570	0.569	16.08	-0.16
Lu et al. (2022) (males)	Combined	% MVIC (mean)	-0.464	0.178	0.032	-0.812	-0.116	-2.613	0.009	16.11	-0.81
Richards et al. (2008)	Gastrocnemius	Combined	-0.117	0.355	0.126	-0.813	0.579	-0.330	0.741	12.88	-0.17
			-0.010	0.246	0.061	-0.493	0.473	-0.041	0.968		

Study name	Muscles	EMG Unit	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value	Weight (Random) Relative weight	Residual (Random) Std Residual
Alves et al. (2009)	Tibialis Anterior	Combined	-5.041	1.452	2.108	-7.887	-2.195	-3.472	0.001	5.23	-2.51
Kongsgaard et al. (2006)	Tibialis Anterior	% Peak amplitude	-0.550	0.281	0.079	-1.101	0.001	-1.957	0.050	27.15	1.03
Lu et al. (2022) (females)	Tibialis Anterior	% MVIC (mean)	-0.790	0.339	0.115	-1.455	-0.126	-2.333	0.020	25.28	0.60
Lu et al. (2022) (males)	Tibialis Anterior	% MVIC (mean)	-0.777	0.337	0.114	-1.439	-0.116	-2.304	0.021	25.33	0.62
Sriwarno et al. B (2008)	Tibialis Anterior	% Peak activity	-2.073	0.606	0.367	-3.261	-0.885	-3.420	0.001	17.02	-1.14
			-1.162	0.363	0.131	-1.873	-0.452	-3.206	0.001*		

Fig 2. Forest plots of the sensitivity analyses examining the effects of ankle plantar flexion (vs. flat) on plantar flexor (top) and dorsiflexor (bottom) activity during squatting, after excluding studies with quality scores below the median. The sign * indicates a significant p-value.

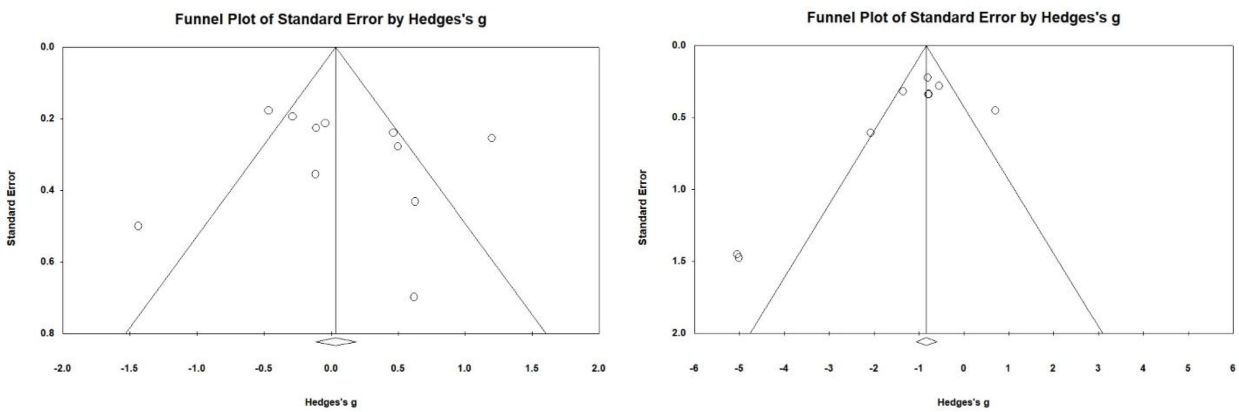
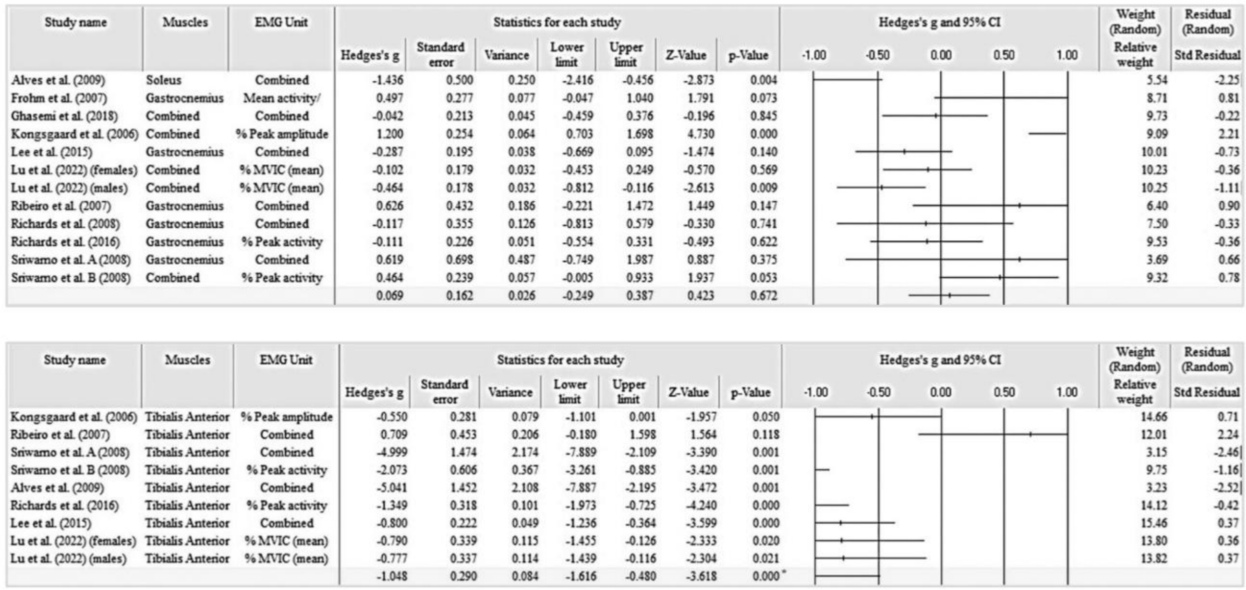


Fig 3. Funnel plots assessing publication bias for the effects of ankle plantar flexion (vs. flat) on plantar flexor (right) and dorsiflexor (left) activity during squatting. Symmetry of the plots indicates no apparent evidence of publication bias.

Effects of ankle plantar flexion (vs. neutral) on dorsi and plantar flexor activity

The overall random-effects meta-analysis revealed that ankle plantar flexion position does not significantly change plantar flexor activity compared to the neutral position during squatting (Hedges' g = 0.069; 95% CI: -0.249 to 0.387; P = 0.672; 11 studies) (Fig 4). Significant heterogeneity was observed across studies (QT = 50.150, df = 11, p < 0.001, I^2 = 78.066). In contrast, the overall random-effects meta-analysis revealed that ankle plantar flexion position significantly decreased dorsiflexor activity compared to the neutral position during squatting (Hedges' g = -1.048; 95% CI: -1.616 to -0.480; P < 0.001; eight studies; high effect size) (Fig 4). Significant heterogeneity was observed across studies (QT = 35.842, df = 8, p < 0.001, I^2 = 77.680).



Study name	Muscles	EMG Unit	Statistics for each study							Weight (Random)	Residual (Random)
			Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value	Relative weight	Std Residual
Alves et al. (2009)	Soleus	Combined	-1.436	0.500	0.250	-2.416	-0.456	-2.873	0.004	5.54	-2.25
Frohm et al. (2007)	Gastrocnemius	Mean activity/	0.497	0.277	0.077	-0.047	1.040	1.791	0.073	8.71	0.81
Ghasemi et al. (2018)	Combined	Combined	-0.042	0.213	0.045	-0.459	0.376	-0.196	0.845	9.73	-0.22
Kongsgaard et al. (2006)	Combined	% Peak amplitude	1.200	0.254	0.064	0.703	1.698	4.730	0.000	9.09	2.21
Lee et al. (2015)	Gastrocnemius	Combined	-0.287	0.195	0.038	-0.669	0.095	-1.474	0.140	10.01	-0.73
Lu et al. (2022) (females)	Combined	% MVIC (mean)	-0.102	0.179	0.032	-0.453	0.249	-0.570	0.569	10.23	-0.36
Lu et al. (2022) (males)	Combined	% MVIC (mean)	-0.464	0.178	0.032	-0.812	-0.116	-2.613	0.009	10.25	-1.11
Ribeiro et al. (2007)	Gastrocnemius	Combined	0.626	0.432	0.186	-0.221	1.472	1.449	0.147	6.40	0.90
Richards et al. (2008)	Gastrocnemius	Combined	-0.117	0.355	0.126	-0.813	0.579	-0.330	0.741	7.50	-0.33
Richards et al. (2016)	Gastrocnemius	% Peak activity	-0.111	0.226	0.051	-0.554	0.331	-0.493	0.622	9.53	-0.36
Sriwarno et al. A (2008)	Gastrocnemius	Combined	0.619	0.698	0.487	-0.749	1.987	0.887	0.375	3.69	0.66
Sriwarno et al. B (2008)	Combined	% Peak activity	0.464	0.239	0.057	-0.005	0.933	1.937	0.053	9.32	0.78
			0.069	0.162	0.026	-0.249	0.387	0.423	0.672		

Study name	Muscles	EMG Unit	Statistics for each study							Weight (Random)	Residual (Random)
			Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value	Relative weight	Std Residual
Kongsgaard et al. (2006)	Tibialis Anterior	% Peak amplitude	-0.550	0.281	0.079	-1.101	0.001	-1.957	0.050	14.66	0.71
Ribeiro et al. (2007)	Tibialis Anterior	Combined	0.709	0.453	0.206	-0.180	1.598	1.564	0.118	12.01	2.24
Sriwarno et al. A (2008)	Tibialis Anterior	Combined	-4.999	1.474	2.174	-7.889	-2.109	-3.390	0.001	3.15	-2.46
Sriwarno et al. B (2008)	Tibialis Anterior	% Peak activity	-2.073	0.606	0.367	-3.261	-0.885	-3.420	0.001	9.75	-1.16
Alves et al. (2009)	Tibialis Anterior	Combined	-5.041	1.452	2.108	-7.887	-2.195	-3.472	0.001	3.23	-2.52
Richards et al. (2016)	Tibialis Anterior	% Peak activity	-1.349	0.318	0.101	-1.973	-0.725	-4.240	0.000	14.12	-0.42
Lee et al. (2015)	Tibialis Anterior	Combined	-0.800	0.222	0.049	-1.236	-0.364	-3.599	0.000	15.46	0.37
Lu et al. (2022) (females)	Tibialis Anterior	% MVIC (mean)	-0.790	0.339	0.115	-1.455	-0.126	-2.333	0.020	13.80	0.36
Lu et al. (2022) (males)	Tibialis Anterior	% MVIC (mean)	-0.777	0.337	0.114	-1.439	-0.116	-2.304	0.021	13.82	0.37
			-1.048	0.290	0.084	-1.616	-0.480	-3.618	0.000*		

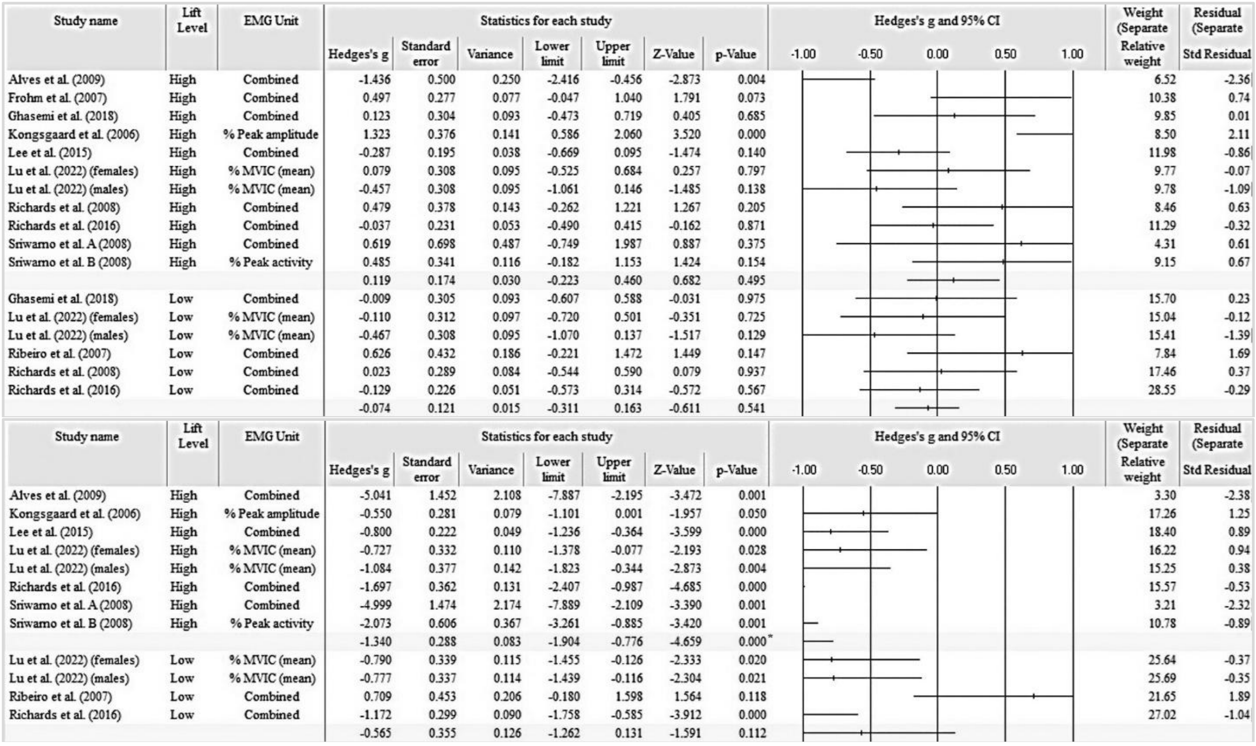
Fig 4. Effects of ankle plantar flexion (vs. flat) on plantar (top) and dorsi (bottom) flexor activity. The sign * indicates a significant p-value.

Effects of ankle dorsiflexion (vs. neutral) on dorsi and plantar flexor activity

Only two studies [18,26] investigated the impact of ankle dorsiflexion position on shank muscle activity during squatting. Due to the limited number of available studies, conducting a meta-analysis for this specific condition was not feasible. However, both investigations consistently reported reduced plantar flexor activation in the dorsiflexed position. Additionally, one study found decreased activity in the dorsiflexor muscles [26].

Subgroup analysis for effects of ankle plantar flexion (vs. neutral) on dorsi and plantar flexor activity

To explore potential sources of heterogeneity, subgroup analyses based on EMG variables and squat type were considered; however, the limited number of studies and methodological heterogeneity precluded meaningful analyses. Therefore, subgroup analysis was restricted to heel-lift level (low: ≤10° or ≤1.5 cm; high: >10° or >1.5 cm), with the results presented in Fig 5. Plantar flexor muscle activity did not significantly change in the low (Hedges' g = -0.074; 95% CI: -0.311 to 0.163; P = 0.541; five studies) and high (Hedges' g = 0.119; 95% CI: -0.223 to 0.460; P = 0.495; 10 studies) heel-lift conditions. In contrast, dorsiflexor muscle activity was significantly altered only under the high heel-lift condition (Hedges' g = -1.340; 95% CI: -1.904 to -0.776; P < 0.001; seven studies), but not for the low (Hedges' g = -0.565; 95% CI: -1.262 to 0.131; P = 0.112; three studies) heel-lift condition.



Study name	Lift Level	EMG Unit	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value	Weight (Separate Relative weight	Residual (Separate Std Residual
Alves et al. (2009)	High	Combined	-1.436	0.500	0.250	-2.416	-0.456	-2.873	0.004	6.52	-2.36
Frohm et al. (2007)	High	Combined	0.497	0.277	0.077	-0.047	1.040	1.791	0.073	10.38	0.74
Ghasemi et al. (2018)	High	Combined	0.123	0.304	0.093	-0.473	0.719	0.405	0.685	9.85	0.01
Kongsgaard et al. (2006)	High	% Peak amplitude	1.323	0.376	0.141	0.586	2.060	3.520	0.000	8.50	2.11
Lee et al. (2015)	High	Combined	-0.287	0.195	0.038	-0.669	0.095	-1.474	0.140	11.98	-0.86
Lu et al. (2022) (females)	High	% MVIC (mean)	0.079	0.308	0.095	-0.525	0.684	0.257	0.797	9.77	-0.07
Lu et al. (2022) (males)	High	% MVIC (mean)	-0.457	0.308	0.095	-1.061	0.146	-1.485	0.138	9.78	-1.09
Richards et al. (2008)	High	Combined	0.479	0.378	0.143	-0.262	1.221	1.267	0.205	8.46	0.63
Richards et al. (2016)	High	Combined	-0.037	0.231	0.053	-0.490	0.415	-0.162	0.871	11.29	-0.32
Sriwarno et al. A (2008)	High	Combined	0.619	0.698	0.487	-0.749	1.987	0.887	0.375	4.31	0.61
Sriwarno et al. B (2008)	High	% Peak activity	0.485	0.341	0.116	-0.182	1.153	1.424	0.154	9.15	0.67
			0.119	0.174	0.030	-0.223	0.460	0.682	0.495		
Ghasemi et al. (2018)	Low	Combined	-0.009	0.305	0.093	-0.607	0.588	-0.031	0.975	15.70	0.23
Lu et al. (2022) (females)	Low	% MVIC (mean)	-0.110	0.312	0.097	-0.720	0.501	-0.351	0.725	15.04	-0.12
Lu et al. (2022) (males)	Low	% MVIC (mean)	-0.467	0.308	0.095	-1.070	0.137	-1.517	0.129	15.41	-1.39
Ribeiro et al. (2007)	Low	Combined	0.626	0.432	0.186	-0.221	1.472	1.449	0.147	7.84	1.69
Richards et al. (2008)	Low	Combined	0.023	0.289	0.084	-0.544	0.590	0.079	0.937	17.46	0.37
Richards et al. (2016)	Low	Combined	-0.129	0.226	0.051	-0.573	0.314	-0.572	0.567	28.55	-0.29
			-0.074	0.121	0.015	-0.311	0.163	-0.611	0.541		

Study name	Lift Level	EMG Unit	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value	Weight (Separate Relative weight	Residual (Separate Std Residual
Alves et al. (2009)	High	Combined	-5.041	1.452	2.108	-7.887	-2.195	-3.472	0.001	3.30	-2.38
Kongsgaard et al. (2006)	High	% Peak amplitude	-0.550	0.281	0.079	-1.101	0.001	-1.957	0.050	17.26	1.25
Lee et al. (2015)	High	Combined	-0.800	0.222	0.049	-1.236	-0.364	-3.599	0.000	18.40	0.89
Lu et al. (2022) (females)	High	% MVIC (mean)	-0.727	0.332	0.110	-1.378	-0.077	-2.193	0.028	16.22	0.94
Lu et al. (2022) (males)	High	% MVIC (mean)	-1.084	0.377	0.142	-1.823	-0.344	-2.873	0.004	15.25	0.38
Richards et al. (2016)	High	Combined	-1.697	0.362	0.131	-2.407	-0.987	-4.685	0.000	15.57	-0.53
Sriwarno et al. A (2008)	High	Combined	-4.999	1.474	2.174	-7.889	-2.109	-3.390	0.001	3.21	-2.32
Sriwarno et al. B (2008)	High	% Peak activity	-2.073	0.606	0.367	-3.261	-0.885	-3.420	0.001	10.78	-0.89
			-1.340	0.288	0.083	-1.904	-0.776	-4.659	0.000*		
Lu et al. (2022) (females)	Low	% MVIC (mean)	-0.790	0.339	0.115	-1.455	-0.126	-2.333	0.020	25.64	-0.37
Lu et al. (2022) (males)	Low	% MVIC (mean)	-0.777	0.337	0.114	-1.439	-0.116	-2.304	0.021	25.69	-0.35
Ribeiro et al. (2007)	Low	Combined	0.709	0.453	0.206	-0.180	1.598	1.564	0.118	21.65	1.89
Richards et al. (2016)	Low	Combined	-1.172	0.299	0.090	-1.758	-0.585	-3.912	0.000	27.02	-1.04
			-0.565	0.355	0.126	-1.262	0.131	-1.591	0.112		

Fig 5. Subgroup analyses of the effects of heel-lift level on plantar (top) and dorsi (bottom) flexor activity during squatting. The sign * indicates a significant p-value.

Summary of outcome measures

A narrative summary of the direction and mean differences of shank muscle activity reported in the individual studies included in this review is provided in Table 3. The findings illustrate variability in results across studies, with some reporting increases, others reporting decreases, or no change in the activity levels of ankle dorsiflexors and plantar flexors.

Table 3. Changes in muscle activity level from flat level to ankle plantar position.

Author (Year)	Plantar flexor activity		Dorsiflexor activity	
	Plantar flexion	Dorsiflexion	Plantar flexion	Dorsiflexion
Lu et al. (2022) [25]	94.272	Not reported	49.949	Not reported
Ghasemi et al. (2018) [18]	103.385	91.792	Not reported	Not reported
Richards et al. (2016) [13]	96.774	Not reported	72.527	Not reported
Lee et al. (2015) [24]	81.482	Not reported	54.635	Not reported
Alves et al. (2009) [27]	92.321	Not reported	73.509	Not reported

Sriwarno et al. (2008) [14]	112.016	Not reported	44.733	Not reported
Sriwarno et al. (2008) [23]	61.755	Not reported	20.434	Not reported
Richards et al. (2008) [42]	111.852	Not reported	Not reported	Not reported
Ribeiro et al. (2007) [26]	117.127	93.218	118.851	96.552
Frohm et al. (2007) [22]	110	Not reported	Not reported	Not reported
Kongsgaard et al. (2006) [21]	126.214	Not reported	76.812	Not reported

Muscle activity was expressed as a percentage of the neutral condition: (ankle-position value / neutral-position value) × 100.

Discussion

The current meta-analysis demonstrates that ankle plantar flexion during squatting significantly reduces dorsiflexor activity (Hedges' g = -1.048) while not significantly altering plantar flexor activation (Hedges' g = 0.069). The substantial reduction in tibialis anterior activity likely reflects decreased demand for eccentric control against anterior tibial translation in plantar flexed positions. Biomechanically, anterior heel elevation shifts the center of pressure, reducing the dorsiflexion moment arm and, consequently, diminishing the mechanical demand on the dorsiflexors [13]. This finding aligns with musculoskeletal modeling studies showing reduced tibialis anterior force production during plantar flexion squat positions [25]. However, this biomechanical interpretation should be considered a hypothesis, as concurrent kinematic data were not available in most included studies. It is important to emphasize that this interpretation is speculative, as we did not directly measure joint kinematics or muscle-tendon dynamics during squatting. Future studies incorporating synchronized kinematic and electromyographic measurements are needed to confirm or refute this hypothesis.

Beyond the biomechanical explanations, the observed alterations in muscle activity may also reflect underlying neuromuscular adjustments. The plantar flexion position, by altering the afferent sensory input from mechanoreceptors in the foot sole and the Achilles tendon, likely modulates the neural drive from supraspinal centers to the tibialis anterior [43]. This reduction in neural drive could be attributed to a decreased demand for active postural control in the new ankle configuration. Similarly, a shift in inter-muscular coordination strategy in response to the altered kinetic chain may have led to a redistribution of activity across muscle groups, explaining the lack of systematic change in plantar flexor activity despite the altered biomechanical demands. To fully elucidate these mechanisms, future studies with the following features are warranted: simultaneous investigation of multi-muscle EMG activity across lower-limb joints, combined with neurophysiological techniques such as H-reflex or transcranial magnetic stimulation.

Furthermore, seven studies reported a reduction in tibialis anterior muscle activity with a plantar-flexed position or heel lift. In contrast, Ribeiro et al. (2007) reported no comparable reduction [26], which may be related to methodological differences, including the relatively small 10° heel lift, small sample size (n = 8), lower mechanical demand of the body-weight single-leg squat, and analysis limited to the eccentric phase, when muscle activation may be relatively lower.

Importantly, our subgroup analysis suggests that a 10° heel lift may be insufficient to induce a substantial reduction in tibialis anterior muscle activity.

Although evidence from dorsiflexed positions remains limited (only two studies available), a trend was observed suggesting that this ankle posture may reduce EMG activity in both plantar flexor and dorsiflexor muscle groups during squatting. One possible, yet preliminary, explanation for this trend is that the dorsiflexed posture may enhance passive stability at the ankle joint, potentially reducing the need for active muscular stabilization [44]. However, it is important to emphasize that this interpretation remains speculative, as we did not directly measure osteoarticular stability or joint congruence. Furthermore, alternative explanations cannot be ruled out, including changes in muscle length-tension relationships or altered afferent feedback in the dorsiflexed position. Future research integrating simultaneous biomechanical (kinematic, kinetic) and electromyographic measurements across a broader range of ankle positions is necessary to test these hypotheses.

The present study showed high heterogeneity ($I^2 > 75\%$) for both meta-analyses. Methodological variations appear to be primary contributors to this inconsistency. Notably, studies employing normalized EMG (percentage of MVIC) showed different effect magnitudes compared with those using absolute microvolt values or alternative normalization schemes. Furthermore, the type of heel elevation intervention (wedge, board, or shoe modification) introduced additional variability in biomechanical constraints and sensory feedback, as detailed in Table 1.

Clinical Applications and Practical Recommendations

The findings of this meta-analysis have potential clinical implications; however, they should be interpreted cautiously, as the current review only included healthy young adults. For patients with conditions characterized by excessive tibialis anterior activity, such as anterior compartment syndrome or shin splints, heel lifts may provide therapeutic benefit by significantly reducing dorsiflexor demand (Hedges' g = -1.048). Clinicians may consider heel elevations (higher than 10° or 1.5 cm) as a temporary modification to reduce anterior shank loading during squatting. Conversely, for patients with Achilles tendinopathy or post-operative conditions requiring calf strengthening, heel lifts do not significantly alter plantar flexor recruitment (Hedges' g = 0.069), so clinicians may use other strategies (e.g., modifying squat depth, speed, or load to target calf muscles). Heel lifts should be used cautiously in patients with patellofemoral pain (may increase anterior knee loading) and avoided in those with acute ankle instability, significant leg length discrepancies, or diabetic neuropathy, as well as during the acute inflammatory phase following injury or surgery. A practical approach may be to begin with neutral ankle position, gradually introduce heel lifts in 1 cm increments, individualize based on patient tolerance and clinical goals, and monitor for pain and compensatory movements.

Limitations

This review has several limitations that should be acknowledged when interpreting our findings. First, inherent limitations of our review include the exclusion of non-English literature, which may have introduced language bias, and the scarcity of studies examining dorsiflexed positions (only two studies available), which precluded a meta-analysis for this condition. Additionally, the small number of studies per outcome (≤12) and small sample sizes (8-26 participants per study) limit the precision of our estimates and the generalizability of our findings. Given the limited number of studies and participants and the substantial heterogeneity ($I^2 = 78.1\%$), the precision and statistical power of the pooled estimate were limited. Therefore, the non-significant finding for plantar flexor activity should be interpreted cautiously and cannot be taken as definitive evidence of the absence of an effect.

Second, our findings are constrained by methodological shortcomings identified in the included literature. Notably, only 9% of studies reported reliability measures for EMG data collection, and none validated electrode placement procedures. The lack of blinding in most studies, while challenging in EMG research due to the nature of the intervention, represents a potential source of bias. Variations in EMG processing methodologies, normalization techniques (e.g., MVIC, peak activity, or microvolts), and squat protocols may have contributed to the observed heterogeneity and complicated cross-study comparisons, yet paired-data analysis helped minimize these effects. Although the random-effects model accounts for between-study variability, it cannot eliminate heterogeneity arising from these methodological differences. Meta-regression was also not performed because the limited number of studies would provide insufficient statistical power and unreliable moderator estimates. Furthermore, the absence of a priori power calculations in all included studies raises concerns about Type II errors.

Third, the absence of synchronized kinematic data in most studies restricted comprehensive biomechanical interpretation. The frequent use of novice/untrained participants may limit the generalizability of findings to trained athletes or clinical populations, as novice lifters may exhibit different movement strategies compared to experienced lifters [45]. The present study was also unable to perform a meta-analysis across squatting phases, as the included studies varied in their definitions and durations of distinct phases (e.g., eccentric, isometric, concentric), and few reported ankle position effects on muscle activity within specific sub-phases, preventing phase-specific subgroup analyses.

Fourth, the lack of data on long-term effects means our conclusions are limited to acute, immediate responses to ankle position changes. We cannot infer whether chronic adaptation occurs with repeated exposure to these ankle positions. Finally, the small number of studies per outcome precluded a formal evaluation of publication bias, and thus, its possible effect cannot be excluded. Although exploratory tests using Egger's and Begg's methods did not reveal significant asymmetry, the low statistical power of these tests means we cannot definitively rule out publication bias.

Future research should address these limitations by: (a) integrating biomechanical and EMG analyses; (b) investigating trained athletes and clinical populations; (c) examining neuromuscular adaptations across different squat phases; (d) standardizing EMG methodology through consensus guidelines; (e) including a priori power calculations; and (f) evaluating long-term effects of ankle position modifications.

Conclusion

This meta-analysis provides quantitative evidence that ankle plantar flexion during squatting significantly reduces dorsiflexor activity without consistently altering plantar flexor engagement under the conditions studied. These findings offer electromyographic rationale for selective use of heel modifications in training and rehabilitation contexts, particularly for offloading the anterior shank compartment. However, the high methodological heterogeneity and limited evidence regarding dorsiflexed positions highlight the need for more standardized research approaches. Future investigations should establish methodological standards through consensus guidelines and expand research to diverse populations, including athletes and patients with musculoskeletal disorders. These efforts are crucial for enhancing clinical applicability and optimizing movement prescription strategies.

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Author Contribution
Mohammadhossein Ghasemi: Conceptualization, Methodology, Formal analysis, Supervision, Project administration, Writing – review & editing. **Usef Mohammadi Yaghoubi:** Data curation, Writing – original draft, Writing – review & editing. **Maryam Emami:** Data curation, Writing – review & editing.

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This study is a systematic review and meta-analysis based exclusively on previously published data. No new human or animal participants were involved, and therefore ethical approval was not required. All procedures were conducted in accordance with relevant guidelines and regulations.

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