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REVIEW ARTICLE

Effectiveness of active stretching during training for injury prevention and performance enhancement in sports: A systematic review and meta-analysis

Sporcularda antrenman sırasında aktif germe egzersizlerinin sakatlıkların önlenmesi ve performansın artırılmasındaki etkinliği: Sistematik derleme ve meta-analiz

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ABSTRACT

Stretching, usually done during warm-up to lengthen the musculotendinous unit, aims to reduce injuries and improve performance, but evidence for active stretching (AS) remains conflicting. This review aims to evaluate the literature assessing the effectiveness of AS, defined here as stretching techniques involving active muscle engagement by the individual, defined as stretching techniques involving voluntary muscle engagement by the individual, including both dynamic and active static stretching, in reducing injuries and enhancing performance in athletes. Randomized controlled trials (RCTs) of AS interventions, including dynamic and active static stretching, were searched in databases: PubMed, Web of Science, and SciVerse Scopus from 2015 to 2024. A meta-analysis was conducted to evaluate the impact of AS on sports performance using RevMan 5.4 software. Nine RCTs were included in this review. The ages of the athletes participating in the studies ranged from 13.5 to 27 years, with sample sizes varying from 8 to 148 across soccer, handball, volleyball, and resistance training. Individualized static stretching for tight muscles was more effective than routine exercises in reducing lower extremity and trunk injuries. The meta-analysis revealed a significant increase in maximal isometric strength (MIS) by 3.6 N (95% CI, 0.28-6.93, $p = 0.01$) and an increase of 1.79 cm in ankle dorsiflexion range of motion (DF ROM) in the intervention group compared to controls (95% CI, 0.85-2.73, $p < 0.001$). AS appears to be effective in reducing injuries and enhancing performance parameters, including MIS and ankle DF ROM, among athletes from a variety of sports disciplines.

Keywords: Stretching, sports injury, sports performance

ÖZ

Isınma sırasında genellikle kas-tendon ünitesini uzatmak için yapılan germe, yaralanmaları azaltmayı ve performansı artırmayı amaçlar; ancak aktif germe (AG) ile ilgili kanıtlar hâlâ çelişkilidir. Bu derleme, burada kişinin istemli kas aktivasyonunu içeren germe teknikleri olarak tanımlanan ve dinamik ile aktif statik germeyi kapsayan AG'nin, sporcularda yaralanmaları azaltma ve performansı artırmadaki etkinliğini değerlendiren literatürü analiz etmeyi amaçlamaktadır. PubMed, Web of Science ve SciVerse Scopus veri tabanlarında 2015-2024 yılları arasında yayımlanan dinamik ve aktif statik germeyi içeren AG müdahalelerine ilişkin randomize kontrollü çalışmalar (RKÇ) taranmıştır. Sporda performans üzerindeki AG etkisini değerlendirmek için RevMan 5.4 yazılımı kullanılarak bir meta-analiz yapılmıştır. Bu derlemeye dokuz RKÇ dahil edilmiştir. Çalışmalara katılan sporcuların yaşları 13,5 ile 27 arasında değişmekte olup, örneklem büyüklükleri futbol, hentbol, voleybol ve direnç antrenmanı gibi branşlarda 8 ile 148 arasında değişmektedir. Gergin kaslar için uygulanan bireyselleştirilmiş statik germe, rutin egzersizlere kıyasla alt ekstremite ve gövde yaralanmalarını azaltmada daha etkili bulunmuştur. Meta-analiz sonuçları, maksimal izometrik kuvvette (MİK) 3,6 N'lik anlamlı bir artış (95% GA, 0,28-6,93; $p = 0,01$) ve müdahale grubunda kontrol grubuna kıyasla ayak bileği dorsofleksiyon eklem hareket açıklığında (DF ROM) 1,79 cm artış olduğunu göstermiştir (95% GA, 0,85-2,73; $p < 0,001$). AG'nin, çeşitli spor disiplinlerinden sporcularda yaralanmaları azaltmada ve MİK ile ayak bileği DF ROM dahil olmak üzere performans parametrelerini artırmada etkili olduğu görülmektedir.

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INTRODUCTION

Stretching is a form of exercise often performed during a warm-up before a training session and is defined as the action of moving a joint through its complete range of motion (ROM) [1]. Athletes commonly incorporate stretching into their training routines, primarily aiming to increase the length of the musculotendinous unit or expand the distance between a muscle's origin and insertion [2]. Furthermore, stretching applies tension to structures such as the joint capsule and fascia, with each possessing distinct biomechanical properties [2]. There are three primary types of muscle stretching techniques: static, dynamic, and pre-contraction stretching [2]. Static stretching (SS) can be performed either by actively contracting the agonist muscles (referred to as active SS) or by utilizing external forces such as gravity, a partner, or stretching aids like stretch bands (referred to as passive SS with stretch bands) [1]. Once in the end position, the individual holds the muscle in a lengthened position for a specified duration [3]. Interestingly, the sports science literature reports that active SS reduces the risk and rate of injury, thereby enhancing sporting performance [3]. Dynamic stretching (DS) can be executed in two forms: actively by the individual or through ballistic stretching, which involves attempting to extend a body part beyond its normal range of motion (ROM)[2]. A range of intervention studies have demonstrated that DS significantly enhances muscle strength [4], power [5], sprint performance [6], vertical jump height [7], and golf swing performance [8]. Pre-contraction stretching also comprises two types: proprioceptive neuromuscular facilitation (PNF) techniques and other methods including post-isometric relaxation and post-facilitation stretching [2].

Active stretching (AS) techniques, such as SS and DS, have gained attention as methods of injury prevention in sports [2]. A prospective cohort study [9], revealed that a decrease in flexibility by one centimetre increased the risk of injury by 6%, while previous injuries amplified the risk of injury recurrence by 6.4 times. The study concluded that low flexibility and previous injuries are associated with an increased risk of injury. Disparities in flexibility measures have also been observed in elite athletes. For instance, Indigenous Australian Football players demonstrated reduced hip internal rotation and adductor strength compared to non-Indigenous counterparts [10]. This disparity was associated with higher levels of groin pain, indicating an increased risk of hip and groin injuries compared to their non-Indigenous counterparts and pointed to the need for athlete-tailored stretching programs [10]. Intervention studies involving AS have reported improvements in performance-related outcomes. Among female soccer players, dynamic stretching routines led to significant gains in ankle dorsiflexion range of motion, balance, and jump performance [11]. Similarly, another trial reported that stretching and strength training interventions were associated with improved joint flexibility in athletically active individuals [12]. These findings suggest that improvements in flexibility may be linked to the warm-up effects induced by high mechanical tension at large ankle joint angles [12].

However, not all evidence supports the benefits of stretching. A 12-week trial involving stretching of the six major leg muscle groups during every warm-up [13] failed to demonstrate a clinically significant reduction in the overall incidence of lower limb injuries including lower body stress fractures, muscle strains and ligament sprains. Moreover, another trial reported no significant or clinically meaningful positive effects on all-cause injury risk following SS of major lower limb and trunk muscle groups performed before and after physical activity [14]. In addition, a separate study explored the effects of high- and low-intensity SS of the dominant leg hamstrings on contralateral limb performance in non-athletes, finding no significant improvement in contralateral ROM [15]. Similarly, a study in physically active young adults assessing the impact of prolonged SS on the quadriceps and hamstrings reported no significant changes in knee function or performance measures, with only a small improvement in post-warm-up hip flexion ROM [16]. However, a systematic review [5] on a general adult population provided moderate evidence that increased hamstring and plantar flexor extensibility was associated with a decreased musculoskeletal injury risk. Despite the available data, Weldon and Hill [17] expressed concerns about the scarcity of well-controlled studies and even speculated that pre-exercise stretching might increase the risk of injury.

Although AS is widely recognized for its potential to reduce injury risk and enhance athletic performance, conflicting evidence exists in the literature. While many studies report benefits such as improved range of motion and reduced injury risk, some RCTs report no clinically meaningful effects or suggest potential adverse effects, including increased injury incidence. Furthermore, existing reviews often generalize stretching without focusing on active techniques specifically. This systematic review and meta-analysis aim to critically assess the effectiveness of AS in injury prevention and performance enhancement among athletes by synthesizing findings from RCTs. The analysis will provide a detailed evaluation of the evidence, addressing inconsistencies and offering evidence-based insights to guide training practices.

MATERIAL AND METHODS

A systematic review and meta-analysis were performed following the guidelines provided by the PRISMA 2020 statement for systematic reviews in sport and exercise medicine, musculoskeletal rehabilitation, and sports science [18]. The PRISMA checklist for this review is provided in Supplementary Table 1. This study was prospectively registered with PROSPERO (CRD42023460949) to ensure methodological transparency and to minimize bias.

Search strategy

The following databases were searched for articles published between July 1, 2015, and July 1, 2024: PubMed® (U.S. National Library of Medicine, USA), Web of Science® (v.5.4) (Thomson Reuters, USA), and SciVerse Scopus® (Elsevier Properties S.A., USA). Both Medical Subject Headings (MeSH) terms and free-text keywords were employed to enhance search comprehensiveness. The search terms included "active stretching" OR "static stretching" OR "dynamic stretching" AND injury AND athletes OR sports OR exercises.

Search strategies were tailored to each database. In the PubMed database, MeSH terms and keywords were applied to article titles and abstracts. In the Web of Science® database, the advanced search operator TS (Title, abstract, author keywords, keywords plus) was used. In the Scopus® database, search terms were applied to article titles, abstracts, and keywords. The search was restricted to articles published in English and studies conducted on humans to ensure relevance.

Two co-authors (KW and RJ) independently conducted the literature search. Discrepancies were resolved through discussion. Citations from all three databases were combined, and duplicates were removed using reference management software. Remaining articles were screened for eligibility in a stepwise manner by reviewing titles, abstracts, and full texts, following the pre-defined inclusion and exclusion criteria. Additionally, reference lists of included studies were manually searched to identify any further relevant articles.

Inclusion and exclusion criteria

Randomized controlled parallel group studies were selected based on the population, intervention, comparison, outcome, and study design (PICOS) strategy [19].

- **Population (P):** Studies on elite athletes or recreational sports participants engaged in competitive sports (with or without injuries) were included. Studies involving non-athlete populations or healthy individuals were excluded.
- **Intervention (I):** Included were any intervention studies involving solely AS intervention during training, including SS and DS, regardless of frequency, intensity, type, or duration. Studies where AS was combined with other exercise interventions were excluded.
- **Comparator/Control (C):** Included studies where participants did not receive an AS intervention or a placebo. Excluded were studies comparing other types of stretching exercises.

- **Outcomes (O):** Included studies measured any injury-related or sports performance-related outcome, such as anthropometric, biochemical, or physical outcomes. Excluded were studies that did not directly measure injury or sports performance outcomes (e.g., joint position sensation and biomechanical factors without a link to performance).
- **Study design (S):** Included human randomized controlled studies evaluating the efficacy of AS during training for injury reduction and performance enhancement, following the PICO strategy. Excluded were observational studies (e.g., cohort, case-control, and cross-sectional studies), animal studies, in vitro models, case reports, case series, letters to the editor, reviews, and unpublished data.

Table 1. Evidence of the effects of stretching on injury rates and sports performance

Author, Year, Country	Study design, PEDro score (out of 10)	Sport/ fitness training type	Gender, age (years)	Sample size (n), intervention		Frequency, time-period	Significant results
				IG	CG		
1. Alimoradi et al., 2023, Iran (PMID: 37505625)	R, P, SB, 6 points	Soccer	F, 22.9 ± 1.4	IG_1: n= 15, Regular DS, IG_2: n= 15, Regular DS + Soleus DS	n=15, Routine exercises (NS)	3 sessions/W, 4 W	1. AJ DF ROM ↑ in cm (IG_1: 9.79, IG_2: 10.29, CG: 9.13), IG_1 vs CG; p=0.002, IG_1 vs IG_2; p=0.014, IG_2vs CG; p=0.001. 2. Y-balance ↑ in cm (IG_1: 84.38, IG_2: 86.35, CG: 78.2), IG_1 vs CG; p=0.001, IG_2 vs CG; p=0.001. 3. Drop jumps ↑ in RSI (IG_1: 0.92 ±0.03, IG_2: 0.90 ±0.02, CG: 0.92 ±0.02; IG_1 vs CG; p=0.036, IG_1 vs IG_2; p=0.046, IG_2 vs CG; p=0.001) 4. Illinois Agility Running Test ↑ in s (IG_1: 14.96 s, IG_2: 13,79 s, CG: 18.96 s), IG_2 vs CG; p=0.032.
2. Azuma and Someya, 2020, Japan, (PMID: 33463794)	R, NB, P, 5 points	Soccer	M, 16.1 ± 0.8	78, Individualized SS for tight muscles	70, RE	3 sessions/W, 12 W,	1. LE and trunk injuries ↓ (40W) in, -Rate by 1.97/1000 person-hours; p<0.05 -Incidence by 30% (IG: 60, CG: 101 injuries; p<0.05) 2. Muscle tightness ↑ in, -HBD in mm at 12W (IG: 11.5 ± 6.2, CG: 18.6 ± 6.3; p<0.01) at 52 W (IG: 9.4 ± 6.0, CG: 19.0 ± 6.1; p<0.01) -SLR angle in degrees at 12 W (IG: 79.5 ± 7.6, CG: 70.5 ± 8.1; p<0.01), at 52 W (IG: 83.8 ± 7.7, CG: 70.0 ± 7.8; p<0.01)
3. Haddad et al., 2017, Qatar (PMID: 30682044)	R, C, NB 5 points	Handball	M, 17.33±1.07	n=8, SS+DS+NS; randomized, counterbalanced sequence for QUAD and HAM		1 session/W (SS: 2 reps of 75s and DS: 5 reps of 30s), 4 W	1. Knee Flexor Isokinetic 60 Pt ↓ (Pre: -8.5%, post-24: -9.6%), p = 0.00021; Relative Pt ↓ (Pre: -8.1%, post-24: -8.6%), p = 0.00027; Work ↓ (Pre: -10.1%, post-24: -9.7%), p = 0.0006. 2. Knee Extensor Isokinetic at 60 Pt ↓ (Post: -10.3%), p = 0.04; at 300 Pt ↓ (Post: -12.9%), p = 0.006; Power ↓ (Post: -11.7%), p = 0.04; Work ↓ (Post: -17.7%), p = 0.006.
4. Heisey et al., 2016, USA (PMC5065324)	R, P, NB 5 points	Volleyball, Soccer, Hockey, Softball, track and field.	F, 20±1	n= 9, SS of the LE	n= 9, Routine exercises (NS)	3 sessions/W (for 30 s+ 10s rest), 3 W	Back squat flexibility; ↑ (sit-and-reach test) in cm; (IG: 4.68%, CG: 0.88%; p=0.05).

Table 1. Continue

Author, Year, Country	Study design, PEDro score (out of 10)	Sport/ fitness training type	Gender, age (years)	Sample size (n), intervention		Frequency, time-period	Significant results
				IG	CG		
5. Panidi et al., 2021, Greece (PMID: 34335307)	R, P, SB 6 points	Volleyball	F, 13.5±1.4	n=21, SS of the plantar flexors: IL Routine exercises (NS): C/L leg		5 sessions/W (total duration of SS↑ from 540 s: W1 to 900 s: W12), 12 W	1. AJ DF ROM ↑ in degrees (IG: 50.4 ± 3.7, CG: 56.6 ± 3.9); p < 0.001 2. One-leg jumping height ↑ (27 ± 30% vs. 17 ± 23%, IG vs. CG); p < 0.001
6. Warneke et al., 2022, Germany (PMID: 35694390)	R, P, NB 5 points	Team sports, gym-based fitness/ resistance training	NM, 27.0 ± 3.1	n=27, SS of the plantar flexors of one leg using an orthosis	n=25, Routine exercises (NS)	Daily (1h/ session), 6 W	1. MIS for leg press ↑ in N (IG IL pre: 1478.4 ± 309.7, IG CL:1726.8 ± 315; p < 0.001) 2. MDS for leg press↑ in kg (IG IL: 115.0 ± 32.3, IG CL: 104.2 ± 34.4; p < 0.001) 3. AJ DF ROM ↑ in cm (IG: 13.7 ± 2.6, CG: 12.6 ± 3.7; p < 0.001)
7. Warneke et al., 2023, Germany (PMID: 38045741)	R, P, NB 4 points	Gymnastics, swimming, gym-based fitness/ resistance training	M and F, IG: 25.17 ± 3.81, CG: 25.38 ± 3.38	n=18, SS of pectoralis muscles using a resistance band	n=13, Routine exercises (NS)	Daily/ multiple times/W (3 SS exercises each: 5 min and 30 s rest, 8 W	1. 1RM ↑ in kg (IG: 79.69 ± 34.0, CG: 69.19 ± 26.11; p < 0.001) 2. Shoulder ROM ↑ in cm (IG: 49.28 ± 8.7, CG: 49.69 ± 5.7; p < 0.001) 3. MIS ↑ in N (IG: 685.53 ± 325.11, CG: 643.61 ± 241.67; p < 0.001)
8. Wohlann et al., 2022, Germany (PMID: 37139297)	R, P, NB 5 points	Running, gym-based fitness/ resistance training	M, F IG: 24.2 ± 2.9, CG: 24.8 ± 3.1	n=22, SS for LE muscles	n=22, Routine exercises (NS)	Daily; 3 times per week (20 min/d), 6W	1. MIS ↑ in N (IG: DL: 823.8 ± 190.5, NDL: 698.2 ± 181.5, CG: DL: 817.8 ± 179.9 N, NDL: 742.9 ± 189.5 N; p < 0.001) 2. AJ DF ROM ↑ in cm (IG DL: 17.5 ± 2.6, NDL: 15.0 ± 2.3, CGDL: 15.8 ± 2.5, NDL: 15.1 ± 2.0), IG vs CG for DL and NDL: p<0.001. 3. KJ ROM ↑ (IG: 1.239, CG: 1.374), IG vs CG dominant leg; p<0.001, IG vs CG non-dominant leg; p<0.001 4. HAM ROM ↑ (IG: 1.247, CG: 1.39), IG vs CG dominant leg; p<0.001, IG vs CG non-dominant leg; p<0.001.
9. Zhang et al., 2022, China (http://dx.doi.org/10.1590/1517-8692202228062022_0086)	R, P, NB 4 points	Sports dancing	NM,	n=30, DS of the AJ	n=30,	Twice/W (45 min), 8 W	1. Affected side AJ stability (8W): Cumberland score ↑ (IG: 37.1% vs. CG: 13.0%); p < 0.01. 2. Dynamic equilibrium stability index ↓ (IG: 39.8% vs. CG: 10.0%); p < 0.05.

AJ: Ankle Joint, CG: Control Group, C: Crossover, C/L: Contralateral, CL: Control Leg, C-R: Cluster-Randomized Trial, DL: Dominant Leg, DF: Dorsiflexion, DS: Dynamic Stretching, F: Female, HAM: Hamstring Muscle, HBD: Heel Buttock Distance, IL: Intervened Leg, IG: Intervention Group, IG1: Intervention Group 1, IG2: Intervention Group 2, IR: Incidence Rate, KJ: Knee Joint, LE: Lower Extremity, MSt: Maximum Strength, M: Male, M: Months, MDS: Maximal Dynamic Strength, MIS: Maximal Isometric Strength, N: Newtons, NB: Not Blinded, NDL: Non-dominant Leg, NM: Not Mentioned, NS: No Stretching, P: Parallel, PEDro: Physiotherapy Evidence Database, Pt: Peak Torque, QUAD: Quadriceps muscle, R: Randomized Trial, Reps: Repetitions, 1RM: One Repetition Maximum, ROM: Range of Motion, S: Seconds, SB: Single Blinded, SLR: Straight Leg Raise, SS: Static Stretching, UE: Upper Extremity, W: Weeks.

Data extraction

Data extraction was performed by one investigator (KW), who recorded key study variables including author, year, country, design, sport type, participant demographics, sample size, intervention details, duration, and significant outcomes. A second investigator (RJ) verified the data accuracy, and any discrepancies were resolved by consensus or with input from a third investigator. Statistical significance was determined by comparing intervention and control groups.

Assessment of quality

Study quality was independently assessed by two investigators using the Physiotherapy Evidence Database (PEDro) scale [20]. Studies were classified as 'poor' [0-3], 'fair' [4-5], 'good' [6-8], or 'excellent' [9-10]. Disagreements in scoring were resolved through discussion.

Data analysis

The effectiveness of AS on training performance improvement was analyzed using RevMan 5.4 software (Cochrane Collaboration, Oxford, UK). The meta-analysis encompassed studies that met the eligibility criteria and compared experimental groups with control groups regarding improvements in ankle dorsiflexion (DF) range of motion (ROM) and maximal isometric strength. Data on continuous variables were extracted as mean changes and standard deviations, ensuring consistency across studies. Heterogeneity was assessed using both the Chi-square (X^2) test and the I^2 statistic. A fixed-effects model was employed when homogeneity was present ($p > 0.05$, $I^2 < 60\%$); otherwise, a random-effects model was utilized to account for between-study variability. A p-value of less than 0.05 was considered statistically significant. Publication bias was evaluated using funnel plots, and potential asymmetry was examined visually.

RESULTS

The systematic review across the databases generated the following results: SciVerse Scopus® (n=161 studies), PubMed® (n=200 studies), and Web of Science® (n=129 studies). After removing duplicates, 244 potentially relevant articles were screened for eligibility. In the first round of screening based on titles and abstracts, 56 articles were deemed eligible for full-text evaluation. After obtaining and reviewing the full texts, seven studies met all inclusion criteria. Additionally, two articles were identified through manual searching, resulting in a total of nine studies included in this review. A summary of the search process is presented in Figure 1.

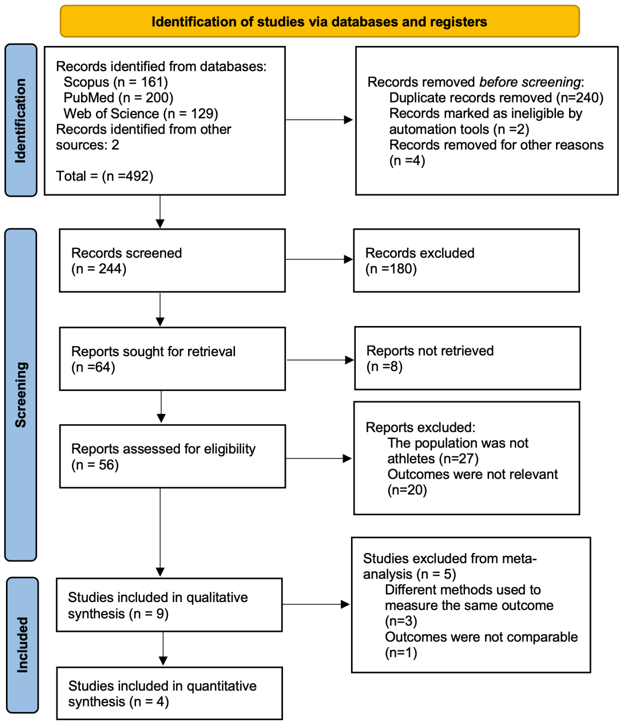

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-analyses flow diagram detailing the review filtering process [18].

This systematic review and meta-analysis included nine RCTs published between 2017 and 2023. These studies were conducted in various countries: one study each from Iran [11], Qatar [21], Japan [22], the USA [23], China [24], and Greece [25], and three studies from Germany [26-28]. Eight out of the nine trials were parallel-group RCTs, while one study utilized a crossover design [21].

According to the PEDro scale, two trials [11, 25] were rated as 'good,' while the remaining seven were rated as 'fair' quality (see Supplementary Table 2). The age of the athletes participating in the included studies ranged from 13.5 to 27 years, while the study involving sports dancers did not specify the age or gender of the participants [24]. Regarding athlete recruitment in the selected RCTs, sample sizes varied from 8 [21] to 148 participants [22]. Sports represented included soccer [11, 22], handball [21], and volleyball [25]. Additionally, three trials focused on gym-based fitness and resistance training [26-28]. The study by Heisey et al. included 18 athletes from diverse sports disciplines, such as volleyball, soccer, hockey, softball, and track and field [23].Various types of AS interventions were implemented, as shown in Table 1. Interventions included solely SS [22-28], solely DS [11, 24], and a combination of SS, DS, and no stretching in a randomized counterbalanced design in the cross-over study [21]. The muscle groups targeted in these stretching interventions primarily involved lower body muscles, such as quadriceps, hamstrings, gluteals [23, 28], and plantar flexors [11, 25, 26], and one study used upper body muscles, including pectorals [27]. The study by Zhang and colleagues focused on a broader range of lower extremity muscle groups including gastrocnemius and soleus, tibialis anterior, peroneal, flexor and extensor muscles of the toes, hip flexors, and quadriceps [24]. Additionally, Azuma and Someya implemented individualized SS targeting the stiff muscles of each athlete [22].

The duration of the AS interventions varied from 3 weeks [23] to 12 weeks [22, 25]. Among the significant outcomes, one study demonstrated that individualized SS for tight muscles was more effective than routine exercises in reducing lower extremity and trunk injury rates by 1.97 per 1,000 person-hours ($p < 0.05$) and decreasing the incidence of injuries by 30% (IG: 60 injuries, CG: 101 injuries; $p < 0.05$) [22]. The primary significant outcome of interest in four out of the nine studies was ankle DF ROM. Different methods were utilized to assess DF ROM, including the weight-bearing lunge test (WBLT) measured in centimetres [11, 27, 28] and digital photography measured in degrees [25]. Regarding the effect of AS on performance metrics, three studies reported a significant improvement in MIS across various muscle groups [26-28]. Another performance metric that showed improvement following AS intervention was vertical jump height. This was measured in two studies using the reactive strength index ratio [11] and the force-time curve of the highest jump for each leg, measured in centimetres [25]. Furthermore, Heisey and colleagues [23] reported that SS of the lower extremity significantly increased back squat flexibility, as assessed by the sit-and-reach test (IG: 4.68%, CG: 0.88%; $p = 0.05$). Additionally, in the cross-over trial involving SS + DS + no stretching in a randomized counterbalanced design for the quadriceps and hamstrings, both the SS and control conditions exhibited that both DS (12.07% and 10.47%) and SS (13.7% and 14.6%) enhanced knee flexor isokinetic force and power-related measures at $300°\cdot s^{-1}$ compared to the control group ($p = 0.006$) [21].

The efficacy of AS in enhancing MIS was investigated in three studies [26-28], and these studies were included in the meta-analysis. Similarly, of the four trials [11, 25, 27, 28] that examined the effect of AS on improving ankle DF ROM, only three were selected for the meta-analysis. These studies measured ankle DF ROM in centimetres [11, 26, 27], while the trial that was excluded [25] used high-resolution photographs to measure DF ROM in degrees. A random-effects analysis was conducted due to high I^2 values obtained from the fixed-effects analysis, indicating considerable heterogeneity among the studies. Compared to the CG, the IG demonstrated a significant increase in MIS by 3.6 N (95% CI, 0.28-6.93, $p=0.01$; $I^2=98\%$, $p<0.001$) (Figure 2). Regarding the effect of AS on DF ROM, a significant increase of 1.79 cm was observed in the IG compared to the parallel counterparts (95% CI, 0.85-2.73, $p<0.001$; $I^2=98\%$, $p<0.001$) (Figure 3). The I^2 values for both meta-analyses were notably high (98%), indicating substantial heterogeneity. While formal subgroup or meta-regression analyses were not feasible due to the limited number of studies, potential sources of heterogeneity include differences in participant characteristics (e.g., age range from 13.5 to 27 years, varied athletic levels, and mixed-sex samples), variation in stretching intervention types (SS vs DS) and durations (ranging from 3 to 12 weeks), as well as differences in outcome measurement tools such as centimetres vs degrees for ankle DF ROM.

Funnel plots revealed a symmetrical distribution of studies around the overall effect size, suggesting no evidence of publication bias (Supplementary Tables 1 and 2).

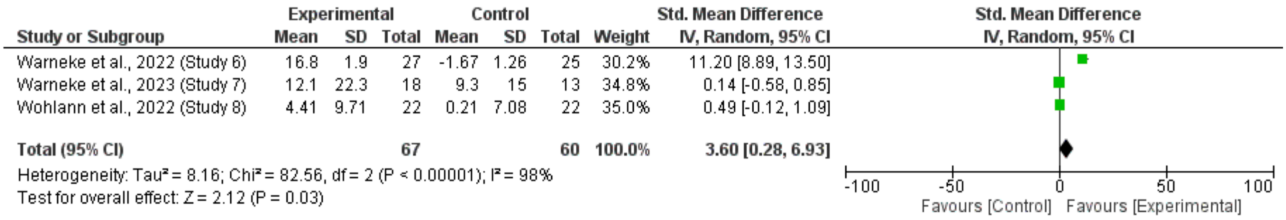

Figure 2. Forest plot of comparison of maximal isometric strength (N).

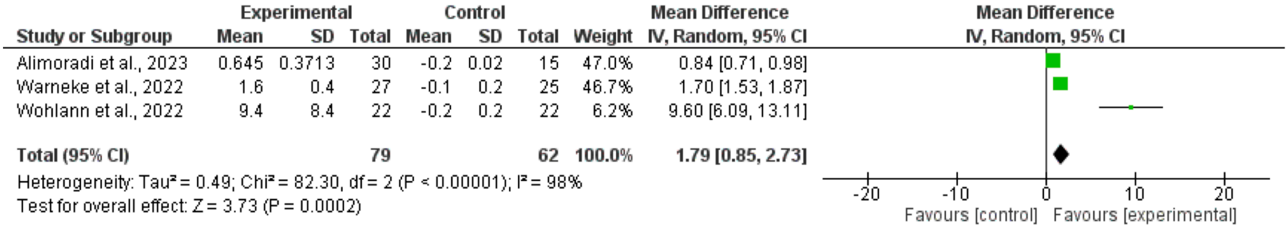

Figure 3. Forest plot of comparison of ankle dorsiflexion range of motion (cm).

DISCUSSION

To the best of our knowledge, this is among the first systematic reviews and meta-analyses to assess the effectiveness of AS for injury reduction and performance enhancement in the sports population. While a formal scoping review was not conducted to confirm the absence of prior reviews, our extensive literature search did not identify any previous systematic reviews addressing this specific focus. In summary, the findings demonstrate that AS is more effective than control interventions in reducing injury rates and incidence while improving performance parameters such as MIS, ankle DF ROM, and vertical jump height among elite and recreational athletes. Our meta-analysis showed a significant increase in maximal isometric strength (MIS) by 3.6 N (95% CI, 0.28-6.93, p=0.01) and a significant improvement of 1.79 cm (95% CI, 0.85-2.73, p<0.001) in ankle DF ROM in the intervention group compared to controls.

Our findings on the effect of stretching in reducing injury risk align with results from an RCT that assessed the impact of SS on preventing training-related injuries among Japan ground self-defence force military recruits [29]. The study reported a significantly lower incidence of muscle/tendon injuries and low back pain in the stretching group (p < 0.05). Similarly, a trial involving elite competitive sailors showed that a pre-race stretching intervention reduced the rate of injured sailors per competition day from 1.66 to 0.60 [30]. The percentage of athletes with multiple injuries also significantly dropped from 53% (8 out of 15) to 6.5% (2 out of 12).

Furthermore, these findings also align with the results of a systematic review and meta-analysis by Arntz et al., which examined the effects of chronic SS on muscle strength [31]. The study reported a significant association between the proportion of female participants and strength gains (β=0.004, p=0.042), with higher proportions of women showing greater improvements [31]. Additionally, another systematic review and meta-analysis investigating the impact of various stretching techniques on DF ROM found SS to be effective, yielding an increase of 5.17° (95% CI: 4.39-5.95, I^2: 0%) [32]. Similarly, a meta-analysis revealed that an acute session of DS enhanced performance in various physical tasks, including countermovement jumps, sprints, agility, and force output (isometric, iso-inertial, and isokinetic) in 20 studies, showing small or larger effects. Meanwhile, 21 studies reported trivial effects, and 7 showed performance impairments, resulting in an overall mean performance enhancement of trivial-to-small (1.3%) [1].

Research suggests that ≤60 seconds of SS per muscle group leads to an improved ROM [33]. One plausible explanation for the benefits of SS is that it increases the compliance of the muscle-tendon unit [34]. This increased compliance shifts the angle-torque relationship, allowing muscles to produce relatively more force at longer lengths [34]. Consequently, muscles may become better able to resist excessive elongation, potentially reducing the risk of strain injuries. Moreover, incorporating SS into pre-exercise warm-up routines may help reduce the risk of musculotendinous injuries [1]. It is recommended that SS be used alongside aerobic and dynamic activities, as well as sport-specific exercises, as part of a comprehensive warm-up [35]. Participants in the study by Blazevich et al. [36] also reported positive psychological benefits, feeling more confident in their performance when SS was included in their warm-up, which highlights the importance of psychological readiness in achieving optimal performance.

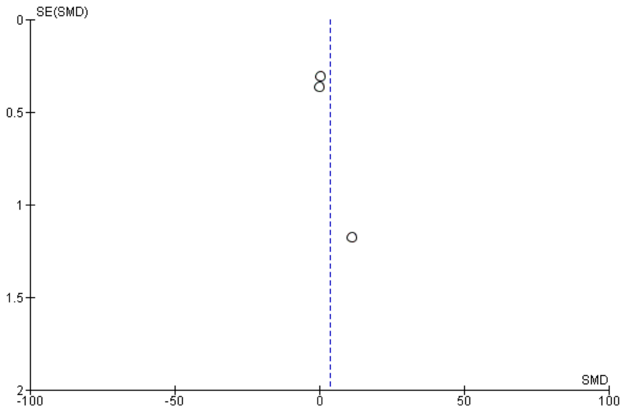

Figure 4. Funnel plot of comparison of maximal isometric strength (N).

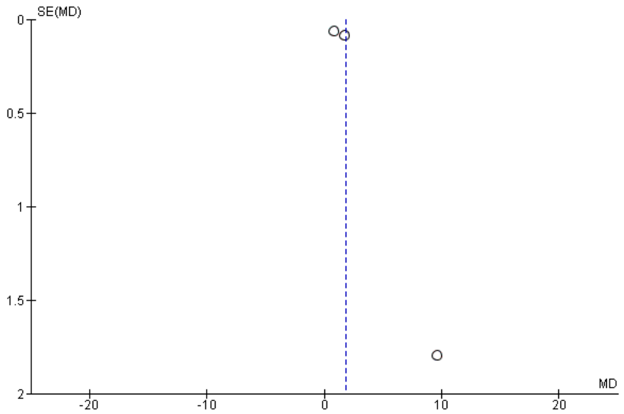

Figure 5. Funnel plot of comparison of ankle dorsiflexion range of motion (cm).

DS may enhance muscular performance through increased muscle and core temperature, improved neuromuscular activation, and heightened readiness via mechanisms like post-activation potentiation and reflex activity [37, 38]. These effects may contribute to improvements in speed, power, and coordination when DS is performed before activity [1]. A meta-analysis that investigated the effects of both acute and long-term SS on muscle-tendon unit stiffness (MTS) showed that acute SS led to a moderate decrease in MTS, and a meta-regression indicated that the total duration of stretching was significantly related to MTS reduction in acute stretching, but not in long-term stretching [39]. While the current review suggests that pre-exercise AS could lower the likelihood of muscle strain injuries, this has not been fully explored in the literature. It is also important to note that this rationale does not extend to other injury types, such as ligament tears, fractures, or overuse injuries like tendinopathies.

Despite its promising results, this review also identified critical gaps. Limited high-quality evidence exists on the effects of AS in real-world competitive sports settings, with most studies conducted in controlled environments. Additionally, the small number of trials, heterogeneity in intervention protocols, and focus on English-language publications restrict the generalizability of our findings. Notably, only one trial specifically assessed the impact of AS on injury reduction, and no studies explored its effects on injuries beyond musculotendinous strains, such as ligament tears or overuse injuries.

The observed high heterogeneity (I^2=98%) in the meta-analyses deserves further consideration. A plausible contributor is the variability in participant demographics and athletic backgrounds across studies, which ranged from adolescent to adult elite athletes. Moreover, intervention protocols varied significantly in duration (from 3 to 12 weeks) and type (SS alone, DS alone, or combined). Differences in outcome measurement tools; such as photographic angle assessments versus WBLT in centimetres; also likely influenced the pooled results. While such diversity highlights the broad application of AS, it also limits comparability and may mask the true magnitude of its effects.

Strengths

This review and meta-analysis have several strengths. A comprehensive search was conducted across major health-related databases (SciVerse Scopus®, PubMed®, Web of Science®) and sport-specific databases, including manual searches and reference list checks. Both MeSH terms and title/abstract search criteria were used to ensure thorough coverage.

Limitations

However, limitations include the small number of available studies and significant heterogeneity in study populations and measured variables. Only two similar outcomes; MIS and DF ROM, were reported, restricting the meta-analysis, while only one trial assessed the effect of AS on injury reduction. Additionally, methodological inconsistencies such as variations in stretching protocols (e.g., static vs. dynamic, duration ranging from 3 to 12 weeks) and diversity in outcome measurement tools (e.g., WBLT in cm vs. photographic angle assessments) may have influenced the generalizability of the findings and reduced comparability between studies. The focus on studies in English may also introduce language bias. Furthermore, most studies were not conducted in competitive settings, limiting real-world applicability, and only two RCTs met 'good' quality criteria, highlighting the need for more high-quality research.

Practical recommendations

Based on the findings of this study, several practical recommendations can be proposed for AS interventions and future research. First, future interventions should assess the efficacy of athlete tailored AS programs that specifically target tight muscle groups to maximize injury prevention and performance benefits, particularly in competitive settings where current research is limited. Additionally, incorporating both SS and DS techniques into training regimens may provide a more comprehensive evaluation of the effect of AS on flexibility and injury reduction. High-quality studies with larger sample sizes and more diverse populations are necessary to further validate the effectiveness of AS across different sports and to identify optimal intervention durations and intensities. Moreover, athletes are encouraged to collaborate with qualified sports professionals, such as sports medicine specialists and physiotherapists, to develop stretching protocols that address their unique physiological needs and athletic goals. Our findings suggest that intervention durations ranging from 3 to 12 weeks can produce measurable improvements in performance metrics such as MIS and DF ROM. However, due to variation in study designs, the optimal frequency (e.g., daily vs. 3x/week) and intensity (e.g., perceived effort, stretch discomfort) remain unclear. Practitioners should begin with moderate-duration, moderate-intensity protocols and adjust based on athlete feedback and response. Monitoring the frequency, intensity, time, and type (FITT) of stretching exercises is crucial, as variability in these factors was evident across included studies and may account for differences in outcomes [40]. Future research should explore how manipulating individual FITT elements influences AS efficacy across athletic populations.

CONCLUSION

This systematic review and meta-analysis confirm the effectiveness of AS in reducing injuries and improving sports performance metrics, including MIS, DF ROM, and vertical jump height. The meta-analysis revealed a significant increase in MIS by 3.6 N (95% CI, 0.28-6.93, p=0.01) and in ankle DF ROM by 1.79 cm (95% CI, 0.85-2.73, p<0.001) in intervention groups compared to controls. No adverse effects were reported during AS interventions, highlighting their safety for sports populations. These findings underscore the potential of AS as a valuable component of training programs for both injury prevention and performance enhancement. However, due to the heterogeneity in study protocols and the limited number of high-quality trials, these findings should be interpreted with caution. Future high-quality trials should be designed to address the identified gaps, including exploring the effects of AS in competitive settings and on a broader spectrum of injury types.

Supplementary Table 1. PRISMA Checklist [18]

Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	1-2
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	22-40
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	44-113
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	114-122
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	155-173
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	130-134
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	134-154
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	175-181
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	175-181
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	175-181
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	175-181
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	182-186
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	NA
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	188-197
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	188-197
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	188-197
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	188-197
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	188-197
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	188-197
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	182-186
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	NA

Supplementary Table 1. Continue

Section and Topic	Item #	Checklist item	Location where item is reported
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	198-206
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	198-206
Study characteristics	17	Cite each included study and present its characteristics.	208-222
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	244-246
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	208-222, Table 1
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	208-222, Table 1
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	237-246
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	244-246
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	NA
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	244-246
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	NA
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	250-315
	23b	Discuss any limitations of the evidence included in the review.	316-327
	23c	Discuss any limitations of the review processes used.	350-358
	23d	Discuss implications of the results for practice, policy, and future research.	360-380
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	125-128
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	125-128
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	125-128
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	388-390
Competing interests	26	Declare any competing interests of review authors.	386-387
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	NA

Supplementary Table 2. Physiotherapy Evidence Database scores of the included studies

Author, year, Country	Random allocation	Concealed allocation	Baseline comparability	Blinding of subjects	Blinding of therapists	Blinding of assessors	Adequate follow-up	Intention to treat analysis	Between-group statistical comparison	Point measures and variability data	Total score, quality grade
1. Alimoradi et al., 2023, Iran (PMID: 37505625)	1	0	1	1	0	0	1	0	1	1	6, Good quality
2. Azuma and Someya, 2020, Japan, (PMID: 33463794)	1	0	1	0	0	0	1	0	1	1	5, Fair quality
3. Haddad et al., 2017, Qatar (PMID: 30682044)	1	0	1	0	0	1	1	0	0	1	5, Fair quality
4. Heisey et al., 2016, USA (PMC5065324)	1	0	1	0	0	0	1	0	1	1	5, Fair quality
5. Panidi et al., 2021, Greece (PMID: 34335307)	1	0	1	0	0	0	1	1	1	1	6, Good quality
6. Warneke et al., 2022, Germany (PMID: 35694390)	1	0	1	0	0	0	1	0	1	1	5, Fair quality
7. Warneke et al., 2023, Germany (PMID: 38045741)	1	0	0	0	0	0	1	0	1	1	4, Fair quality
8. Wohlann et al., 2022, Germany (PMID: 37139297)	1	0	0	0	0	1	0	1	1	1	5, Fair quality
9. Zhang et al., 2022, China	1	0	0	0	0	0	1	0	1	1	4, Fair quality

Ethics Committee Approval

As this study is a systematic review and meta-analysis, ethical approval and participant consent were not required.

Conflict of Interest

The authors declared no conflicts of interest with respect to authorship and/or publication of the article.

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Author Contributions

Concept: KW; Design: KW; Supervision: RJ, APH; Materials: KW; Data collection and/or processing: KW, RJ; Analysis and interpretation: KW, RJ; Literature review: KW; Writing manuscript: KW; Critical reviews: RJ, APH. All authors contributed to the final version of the manuscript, discussed the results, and approved the final manuscript.

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