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The effectiveness of neuromuscular training in preventing sports injuries of different genders, body parts, and types in adolescents: a systematic review of meta-analysis

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Keywords: Neuromuscular training; injury care; sports rehabilitation; meta-analysis

Abstract

Objective: Neuromuscular training is a relatively new comprehensive rehabilitation treatment method in recent years. Although its preventive effect on adolescent sports injuries is indisputable, its specific effects on gender, injury site, and type are still poorly understood. This study evaluated the clinical efficacy of neuromuscular training on adolescents of different genders, injury sites, and types through systematic meta-analysis.

Method: A comprehensive search was conducted on clinical randomized controlled trials related to the prevention of adolescent sports injuries through neuromuscular training in databases such as PubMed, Web of Science, EBSCO, and Scopus. The databases were established until May 2024. The neuromuscular training group (experimental group) used neuromuscular training or neuromuscular training as the main intervention method; The control group is either a blank group or a routine exercise group, without paying special attention to neuromuscular control. Outcome measures include any form of muscle, ligament, or bone injury, including acute or chronic injury data. The quality of the included literature was determined using the Cochrane bias risk assessment tool and the physical therapy evidence database scale, and statistical analysis was conducted using RevMan 5.4 and Stata 16.0 software.This study is registered with the International Platform of Registered Systematic Review and Meta-analysis Protocols (INPLASY), INPLASY2024110054.

Result: A total of 32 clinical randomized controlled trials were included, with a sample size of 34581 cases. The meta-analysis results showed that: 1. The overall effect of neuromuscular training: the experimental group was better than the control group, with a combined IRR of 0.67 (95% CI2 0.57-0.79); $Z = 4.78$;$P < 0.00001$). The male group had a higher risk of loss compared to females in the experiment; 2. Upper limb motor injury: combined IRR of 0.73

(95% CI2 0.59-0.9); Z = 3.12;P =0.002). The male group had a lower risk of injury compared to females in the experiment. 3. Lower limb motor injury: combined IRR of 0.66 (95% CI2 0.56-0.77); Z = 5.12;P< 0.00001). The male group had a higher risk of loss compared to the female group in the experiment. 4. Knee movement injury: combined IRR of 0.73 (95% CI2 0.63-0.84); Z = 4.44;P< 0.00001). The female group had a higher risk of loss compared to the male group in the experiment. 5. Ankle sports injury: combined IRR of 0.54 (95% CI2 0.40-0.74); Z = 3.90;P< 0.00001). The male group had a higher risk of loss compared to females in the experiment. 6. Acute sports injury: The combined IRR is 0.60 (95% CI2 0.49-0.74); Z = 4.84;P< 0.00001), The male group had a similar reduced risk of loss compared to females in the experiment. 7. Chronic sports injury: The combined IRR was 0.72 (95% CI2 0.52-0.98; Z=2.07; P=0.04), and the female group had a higher risk of loss compared to males in the trial.

Conclusion: Neuromuscular training has significant effects in preventing upper and lower limbs, knees, ankles, and acute and chronic sports injuries of different genders. Research has shown that neuromuscular training has similar effects on different genders, effectively reducing the burden of public health and promoting participation in sports activities. However, more high-quality randomized controlled trials are still needed to further validate these findings.

Keywords: Neuromuscular training; injury care; sports rehabilitation; meta-analysis

1. Introduction

The rate of sports participation among adolescents is very high, significantly impacting th eir health. It provides psychosocial benefits such as increased self-esteem, motor skill development, socialization, teamwork, competitiveness, and stress reduction. However, sports are also a major cause of injury among adolescents, accounting for 30% of all adolescent injuries in many countries [1-4]. Annually, 35% of adolescents injured in sports require medical rehabilitation, with lower extremity injuries being the most common, constituting over 60% of all youth sports injuries [5, 6]. Sports injuries can lead to decreased participation and are associated with all-cause morbidity, overweight or obesity, and post-traumatic osteoarthritis [7, 8]. Hence, reducing the public health burden from youth sports injuries is critical. The combination of high sport-specific participation rates and high injury rates results in adolescents producing the highest volume of injuries in related sports, especially in team sports for both boys and girls. Boys experience the highest injury rates in ice hockey, rugby, basketball, soccer, wrestling, and running. Girls face the highest injury rates in basketball, soccer, ice hockey, European handball, running, and field hockey [9, 10]. Reducing injury rates in high-burden sports can promote physical activity and significantly improve the quality of life.

Completely eliminating all injuries in adolescent sports is impossible, but adopting injury prevention strategies can reduce the number and severity of injuries. In recent years, an increasing number of injury prevention programs have been developed. Among these, neuromuscular training has been shown to positively impact adult injury rates [11-14]. A recent meta-analysis found that neuromuscular training for soccer can reduce injury rates by 20-50% [11]. Regarding ankle injuries, neuromuscular interventions and proprioception programs have been found to reduce the risk for physically active adults by 35-50% [12, 14]. Similar effects have been reported for adolescent athletes, with three meta-analyses showing a reduction in lower extremity injury risk by approximately 25-35% [15-17].

Although the preventative and therapeutic effects of neuromuscular training on adolescent sports injuries are well-established, little is known about its specific impact on gender, injury site, and type. Neuromuscular injury prevention programs for adolescent athletes have been studied across various spo rts, including basketball [18-21], soccer [21-26], and volleyball [26, 27]. In addition to specific sports content, these programs often include multiple components or focus on balance exercises [28, 29]. Common elements of multi-intervention programs include strength, balance, flexibility, plyometric, speed, and agility training, emphasizing neuromuscular control and proactive joint stability. Consequently, it is challenging to deduce methods for different genders or sports-specific injury sites or types based on individual studies. From a practical perspective, a deeper understanding of the specific effects of neuromuscular training on gender, injury site, and type is crucial for tailoring training programs to specific populations, thereby increasing the confidence of coaches and athletes in implementing these programs.

In summary, although neuromuscular training has been shown to have preventative effects in adolescent athletes, existing literature does not provide consistent recommendations regarding its impact on different genders, injury sites, and types. This understanding aids practitioners in designing tailored programs and enhances the compliance of coaches and athletes with these interventions [30, 31]. This is particularly important for young athletes, as differences in their maturation status can lead to significant individual variations in anthropometric and neuromuscular performance. Therefore, this study primarily reviews the aspects of different genders, injury sites, and injury types, revealing the effects and potential mechanisms of neuromuscular training in preventing adolescent sports injuries. This provides critical insights for future prevention and management of sports injuries in adolescents.

2. METHODS

We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines[32] in this systematic review. As this study was a review, no ethical approval was necessary. The methods and protocol registration were preregistered prior to conducting the review: INPLASY, no.2024110054, DOI:10.37766/inplasy2024.11.0054.

2.1 Data sources and search strategy

Two researchers independently searched PubMed, Web of Science, EBSCO, and Scopus databases for literature on using neuromuscular training to prevent lower limb sports injuries i n adolescent athletes. The search scope included published clinical studies, with the search per iod extending from the establishment of each database to May 2024. The search languages we re English. The search terms combined subject terms and free terms. The search keywords inc luded: "Neuromuscular training, balance training, proprioceptive training, wobbleboard traini ng, athletic injuries, sport injury, injury, child, youth, team sport, injury prevention, interventi on, warm-up". The search strategy is detailed in Table 1.

Table 1 English Search Strategies

#1“neuromuscular training”[Mesh] OR (balance training OR proprioceptive training) [Title/Abstract]
#2“athletic injuries”[Mesh]OR (sport injury OR injury) [Title/Abstract]
#3“child”[Mesh] OR (youth OR team sport) [Title/Abstract]
#4“injury prevention”[Mesh] OR (intervention OR warm-up) [Title/Abstract]
#5 #1 AND #2 AND #3 AND #4

2.2 Selection Criteria

Based on the PICOS strategy, the following criteria had tobe fulfilled in order for studies to be considered in thismeta-analysis: (i) the study population consisted of youths of 21 years or younger, participating instructured/organized sport programs on a competitive level (P);(ii) a neuromuscular training program (including componentssuch as balance, agility, strength, neuromuscular control) wasevaluated with no co-interventions (e.g., education) provided(I); (iii) the study contained a control arm either performingusual practice routine or sham exercises without specific focuson neuromuscular control (C); (iv) any form of muscle, ligament, or bone injury in different genders, including acute or chronic injury data (O); (v)an analytical design was used (RCTs, quasi-experimental trials,cohort studies) (S). Studies without original data (review articles)or without obtainable data for meta-analysis were excluded.

2.3 Risk of Bias Assessment

We analyzed risk of bias of included studies using the PEDroscale. This scale consists of eleven items,addressing internal validity (8 items), interpretability (2 items),and external validity (1 item). A point was scored for each itemclearly fulfilling the criterion, allowing a maximal score of 11points. Two reviewers (SST, ALR) independently performed thequality rating. Disagreements between ratings were discussedand solved via consensus. This process was piloted on threestudies not included in the review before actual quality rating wasperformed.

2.4 Data Extraction

Two researchers independently reviewed the titles and abstracts of the literature according to the inclusion and exclusion criteria, excluding irrelevant studies. After reading the full texts, they further screened and identified the final included studies. Once literature screening was completed, two researchers independently extracted data, including: 1) general information such as the first author and publication date; 2) study design and groups; 3) sample size, gender, type of sport, and level; 4) intervention methods and duration; 5) outcome measures, including types and sites of injuries. In case of any discrepancies, decisions were made through discussion with other research team members.

2.5 Statistical analyses

Statistical analyses were conducted using RevMan 5.4 and Stata 16.0 software. Multiple researchers verified data entry to ensure accuracy. The injury rate ratio (IRR) and corresponding 95% confidence interval (CI) were calculated, representing the effect estimate for each included study. The IRR was determined as follows: IRR = (number of injuries in the NMT group / player exposure) / (number of injuries in the control group / player exposure). When player exposure time was unavailable, the IRR was calculated based on the number of practice and game exposures. An IRR value less than 1 indicates a reduction in injury risk favoring neuromuscular training, with values closer to 0 showing greater effectiveness. Heterogeneity among the included studies was quantitatively analyzed using the I^2 statistic. When $I^2 \leq 50\%$, a fixed-effects model was used; otherwise, a random-effects model was employed [33]. Sensitivity analyses tested the stability of the results, and subgroup analyses by gender, injury site, and type explored the impact of study characteristics on outcome variables and sources of heterogeneity. Publication bias was assessed using Egger's test.

3. Results

3.1 Trial Flow

A total of 544 studies were initially screened. After removing 333 duplicates and excluding 264 studies based on their titles and abstracts, 69 studies were selected for full-text evaluation. Ultimately, 32 studies were included in the meta-analysis [27, 34-63], with a combined sample size of 34,581 participants.

The literature screening process is illustrated in Figure 1, and the basic information of the included studies is summarized in Table 2.

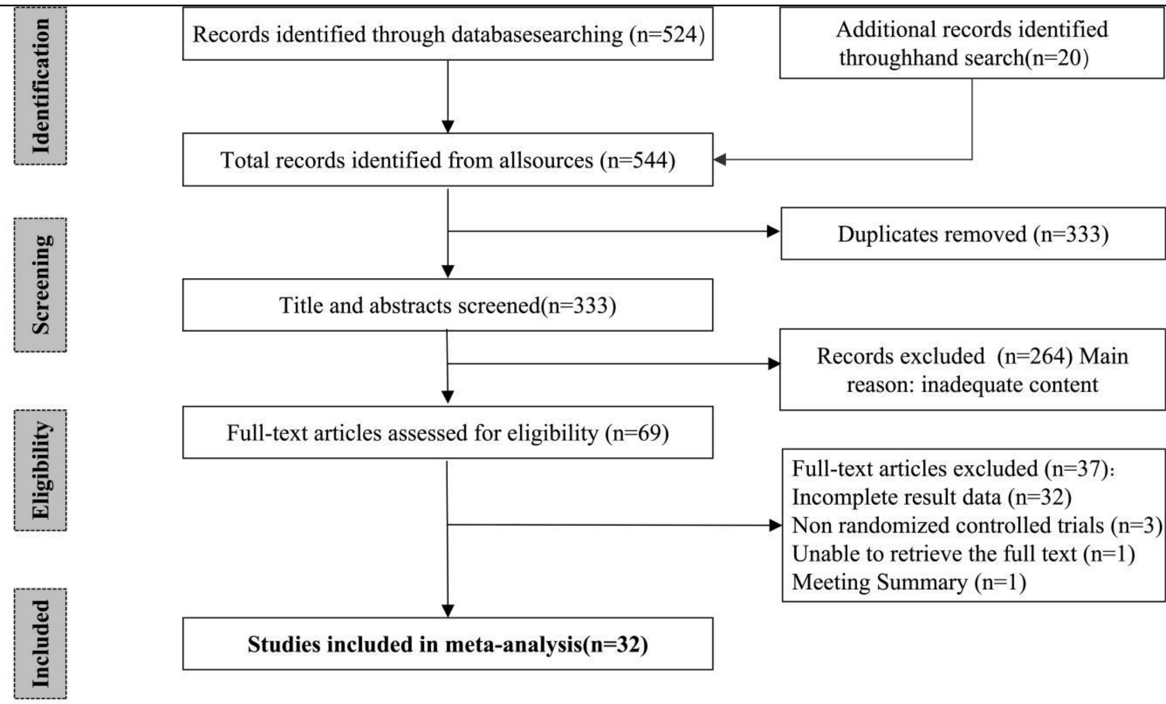


FIGURE 1 | PRISMA flow chart.

Table 2. Basic characteristics of the included studies

Author, year	Sample size(n)	Sport	Interventiongroup	Duration (minutes)	Primary outcome
Ashkan et al., 2010[43]	F:1506	Soccer	NMT	20-25	Knee injury
Astridet et al., 2002[44]	M:194	Soccer	NMT+RW	/	Overall injury
Bertet al., 2005[56]	F:15703	Soccer	NMT+RW	20	Knee injury
Emery and Meeuwisse，2012[38]	M&F: 1744	Soccer	NMT	30	Overall injury, acute injury, lower extremity injury, ankle injury, knee injury
Carolyn et al., 2022[41]	M&F: 1809	Basketball	NMT	10	Lower extremity injury

Carolyn et al., 2019[50]	M&F: 11076	/	NMT+RW	15	Overall injury, chronic injury, lower extremity injury, ankle injury, knee injury, Different genders injury
Carolyn et al., 2007[63]	M&F: 1920	Basketball	NMT+RW	25	Overall injury, acute injury, lower extremity injury, an kle injury
Cynthia et al., 2011[57]	F:1149 2	Soccer	NMT	20	Acute injury, chronic injury, lower extremity injury, a nkle injury, knee injury
Dorine et al., 2010[55]	M&F: 12011	/	NMT	10	Overall injury
Scase et al., 2006[64]	M:723	Soccer	NMT	30	Upper extremity injury, lower extremity injury
Elke et al., 2007[54]	M&F: 154	Basketball	NMT+RW	5-10	Overall injury
Guillermo et al., 2021[35]	F:122	Athletics	NMT	30	Ankle injury, knee injury
Jun et al., 2019[34]	M:237	Baseball	NMT	10	Upper extremity injury
Steffen et al., 2008[47]	F:1209 2	Soccer	FIFA 11+	15	Overall injury, acute injury, chronic injury, upper extre mity injury, lower extremity injury, ankle injury, knee injury
Kathrin et al., 2015[52]	F:1385	Soccer	NMT	20	Overall injury, lower extremity injury
Kim et al., 2018[61]	F:1474	Basketbal l, soccer, volleyball	NMT	10-15,20 -25	Overall injury, ankle injury, knee injury
Lesley et al., 2021[37]	F:1109	/	NMT	10、20、40	Overall injury, acute injury, chronic injury, lower extre mity injury, ankle injury, knee injury
McHugh et al., 2 007[39]	M:175	American football	NMT	10	Ankle injury
Hilska et al., 2021[48]	M:112 3 F:1280	Soccer	NMT	20	Lower extremity injury
Hislop et al., 2017[42]	M:318 8	American football	NMT	20	Overall injury, upper extremity injury, lower extremity injury
Wedderkopp et al., 1999[27]	F:1237	Handball	NMT	10-15	Overall injury, chronic injury
Wedderkopp et al., 2003[59]	F:1163	Handball	NMT	10-15	Overall injury
Olsen et al., 2005[51]	M&F: 11837	Handball	NMT	15-20	Overall injury, acute injury, chronic injury, lower extre mity injury
Owoeye et al., 2 014[53]	M:416	Soccer	FIFA 11+	/	Overall injury, upper extremity injury
Owoeye et al., 2 017[46]	M&F: 12265	Basketbal l，soccer	NMT	15	Ankle injury
Pfeiffer et al., 2006[49]	F:1143 9	Basketbal l, soccer, volleyball	NMT	20	Knee injury
Richmond et al., 2015[62]	M&F: 1725	/	NMT	/	Overall injury, chronic injury, lower extremity injury, ankle injury, knee injury
Saulo et al., 2019[60]	M&F: 1291	Hockey	NMT	12	Overall injury, acute injury, chronic injury, upper extre mity injury, lower extremity injury
Timothy et al., 2 006[40]	M&F: 1765	Basketbal l，soccer	NMT	10	Ankle injury
Hewett et al., 1999	F:1829	Basketbal l, soccer, volleyball	NMT	60-90	Knee injury
Soligard et al., 2 008[58]	F:1189 2	Soccer	FIFA 11+	20	Overall injury,acute injury, chronic injury, ankle injur y, knee injury
Umile et al., 2012[36]	M:121	Basketball	NMT	20	Overall injury,acute injury, chronic injury, ankle injur y, knee injury

M: male, F: female, NMT: neuromuscular training, RW: regular warm-up

3.2 Methodological Quality

Among the included studies, 32 mentioned "randomization" or "randomized controlled trials" (RCTs). Twelve studies specified allocation concealment measures [34, 36, 38, 40, 41, 46, 48, 50, 52, 57, 62, 63], with one study using blinding for physical therapists[57] and another for assessors[35]. None of the studies exhibited selective reporting or incomplete data, nor did they mention other sources of bias. The proportion of bias risk and study results are presented in Figures 3 and 4. According to the PEDro scale, all 32 included studies were of high quality, scoring above 6. The overall quality of the included studies was high, with scores concentrated between 6 and 7. The PEDro scale scores are detailed in Table 3.

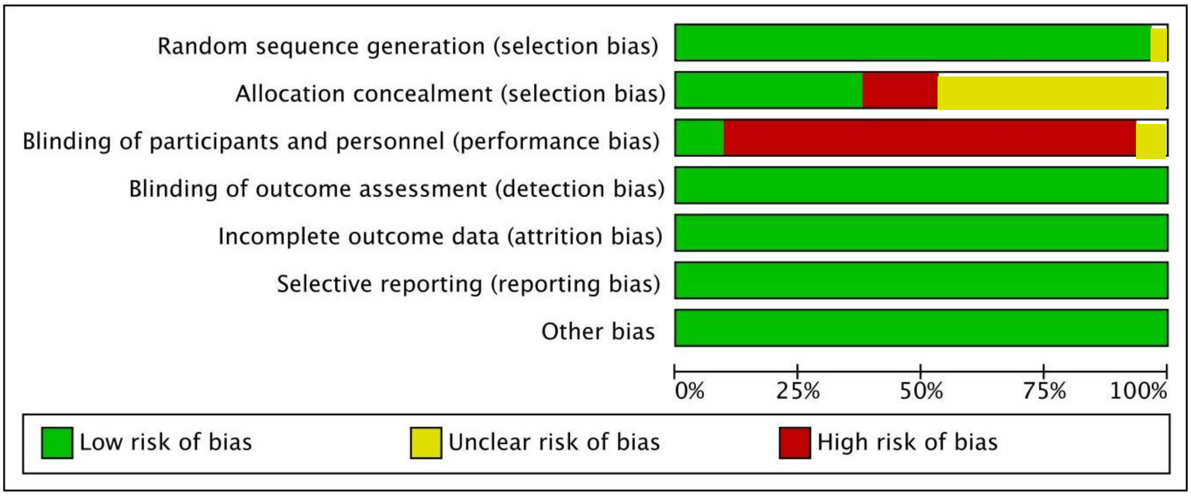


Figure 3 | Risk of bias as a percentage graph

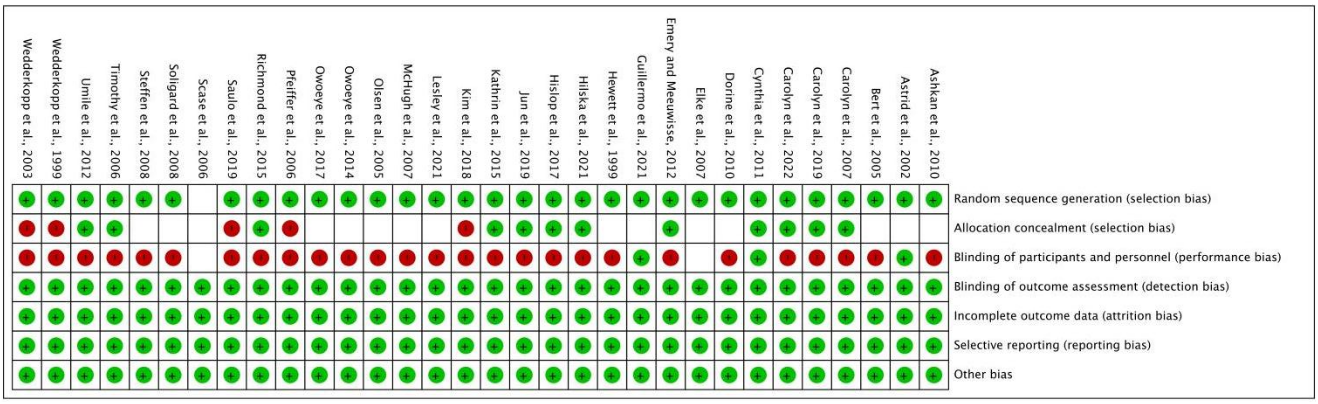


Figure 4 | Risk of bias summary

Table 3 | Physiotherapy Evidence Database score of the included studies

First author, year	Eligibility criteria specified	Randomization	Concealed allocation	Baseline comparability	Patients blinded	Care provider blinded	Adequate follow up	Intention-to-treat	Between-group comparisons	Score
Ashkan et al., 2010[43]	+	+	-	+	- - -	+	+	+	+	6
Astrid et al., 2002[44]	+	+	-	+	- - -	+	+	+	+	6

Bert et al., 2005[56]	+	+	-	+	-	-	-	+	+	+	+	6
Emery and Meeuwisse, 2012[38]	+	+	+	+	-	-	-	+	+	+	+	6
Carolyn et al., 2022[41]	+	+	+	+	-	-	-	+	+	+	+	6
Carolyn et al., 2019[50]	+	+	+	+	-	-	-	+	+	+	+	6
Carolyn et al., 2007[63]	+	+	+	+	-	-	-	+	+	+	+	6
Cynthia et al., 2011[57]	+	+	+	+	-	-	+	+	+	+	+	7
Dorine et al., 2010[55]	+	+	-	+	-	-	-	+	+	+	+	6
Scase et al., 2006[64]	+	+	-	+	-	-	-	+	+	+	+	6
Elke et al., 2007[54]	+	+	-	+	-	-	-	+	+	+	+	6
Guillermo et al., 2021[35]	+	+	-	+	-	+	-	+	+	+	+	7
Jun 等, 2019[34]	+	+	+	+	-	-	-	+	+	+	+	6
Steffen et al., 2008[47]	+	+	-	+	-	-	-	+	+	+	+	6
Kathrin et al., 2015[52]	+	+	-	+	-	-	-	+	+	+	+	6
Kim et al., 2018[61]	+	+	-	+	-	-	-	+	+	+	+	6
Lesley et al., 2021[37]	+	+	+	+	-	-	-	+	+	+	+	6
McHugh et al., 2007[39]	-	+	-	+	-	-	-	+	+	+	+	6
Hilska et al., 2021[48]	+	+	+	+	-	-	-	+	+	+	+	6
Hislop et al., 2017[42]	+	+	+	+	-	-	-	+	+	+	+	6
Wedderkopp et al., 1999[27]	-	+	-	+	-	-	-	+	+	+	+	6
Wedderkopp et al., 2003[59]	+	+	-	+	-	-	-	+	+	+	+	6
Olsen et al., 2005[51]	+	+	-	+	-	-	-	+	+	+	+	6
Owoeye et al., 2014[53]	+	+	-	+	-	-	-	+	+	+	+	6
Owoeye et al., 2017[46]	-	+	-	+	-	-	-	+	+	+	+	6
Pfeiffer et al., 2006[49]	-	+	+	+	-	-	-	+	+	+	+	6
Richmond et al., 2015[62]	+	+	+	+	-	-	-	+	+	+	+	6
Saulo et al., 2019[60]	+	+	-	+	-	-	-	+	+	+	+	6
Timothy et al., 2006[40]	+	-	+	+	-	-	-	+	+	+	+	6
Hewett et al., 1999	-	+	-	+	-	-	-	+	+	+	+	6
Soligard et al., 2008[58]	+	+	-	+	-	-	-	+	+	+	+	6
Umile et al., 2012[36]	+	+	+	+	-	-	-	+	+	+	+	6

3.3 Meta-Analysis Results

3.3.1 Overall Effect of NMT

A total of 21 randomized controlled trials (RCTs) encompassing 4,375 sports injuries were included, resulting in a combined Incidence Rate Ratio (IRR) of 0.67 (95% CI 0.57-0.79; $Z = 4.78$; $P < 0.00001$), indicating a statistically significant 33% reduction in overall sports injury risk. There was significant heterogeneity among gender subgroups (I^2 = 74.0; Q = 4.54; P = 0.1), suggesting differences in the combined effect estimates within subgroups (Figure 5). Trials involving male (IRR = 0.69; 95% CI 0.54-0.88) or mixed-gender participants (IRR = 0.57; 95% CI 0.43-0.76) showed a greater reduction in injury risk compared to those involving females (IRR = 0.84; 95% CI 0.69-1.02). To explore the source of heterogeneity, a sensitivity analysis was conducted by sequentially excluding each study included in the overall analysis to evaluate its impact on the IRR. The results indicated minimal heterogeneity among the studies, with the exclusion of any single study having a negligible impact on the IRR effect size. Thus, the results of the meta-analysis were relatively stable (Figure 6).

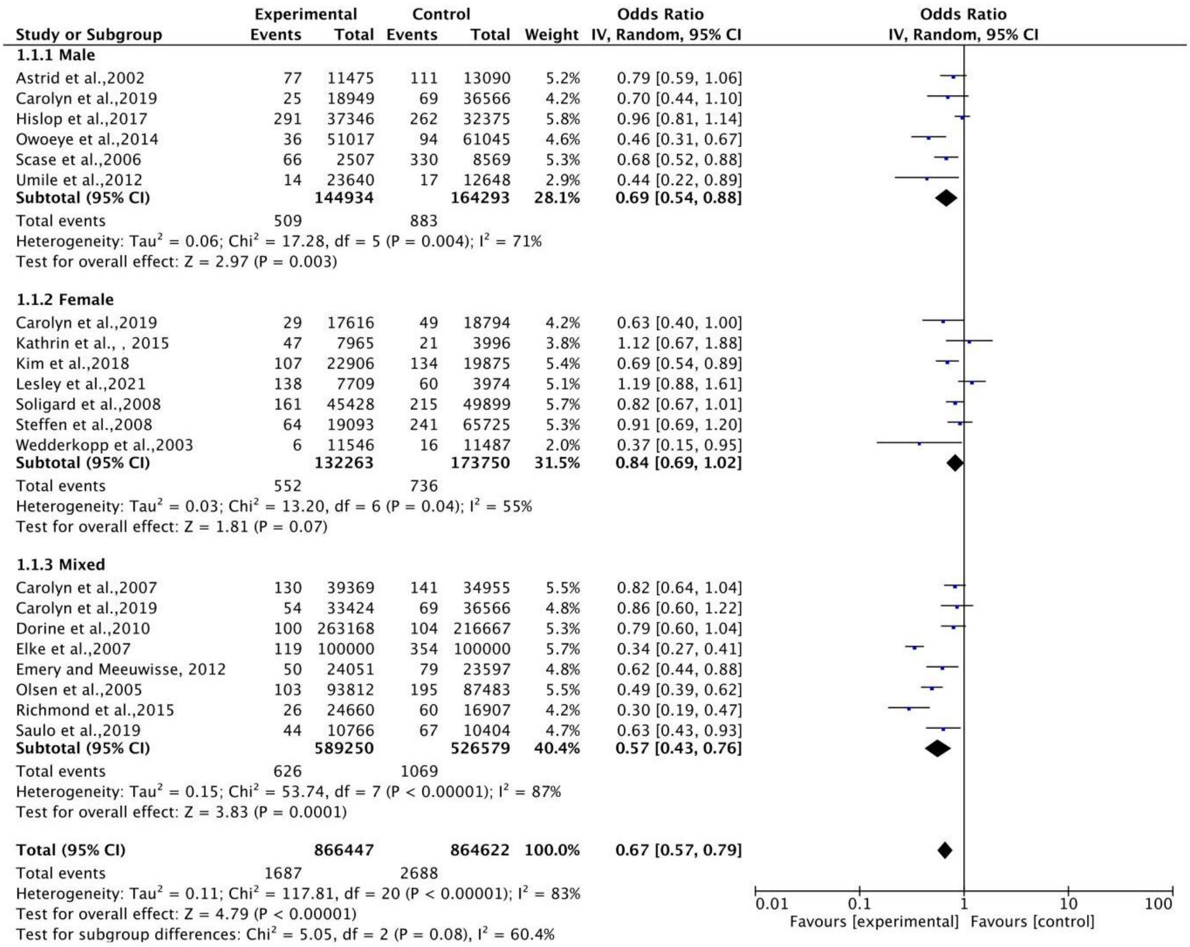


Figure 5 ｜ Subgroup analysis of the IRR effect of gender on the overall injury effect of neuromuscular training

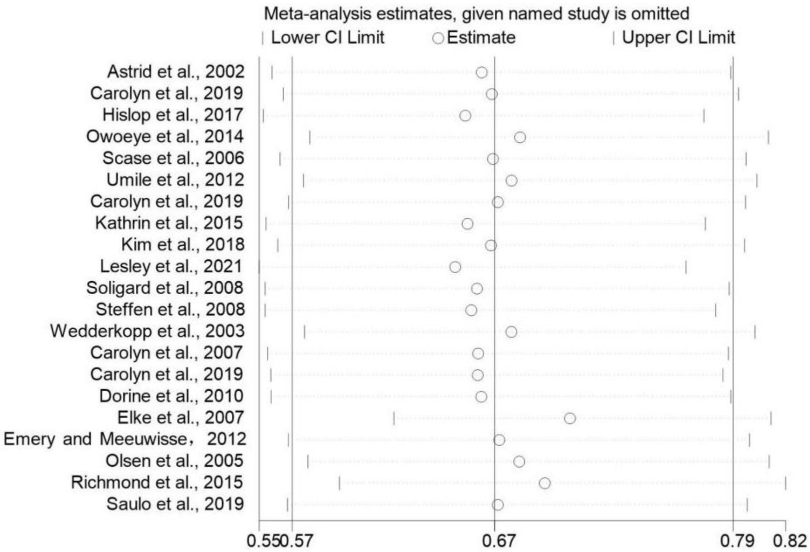


Figure 6 ｜Sensitivity analysis of overall damage effect

3.3.2 Effect of upper limb sports injury

A total of six RCTs involving 432 sports injuries were included, resulting in a combined Incidence Rate Ratio (IRR) of 0.73 (95% CI 0.59-0.9; Z = 3.12; P = 0.002), indicating a statistically significant 27% reduction in upper limb sports injury risk. Heterogeneity among gender subgroups was not significant (I^2 = 0; Q = 2.00; P = 0.37), suggesting no notable differences in combined effect estimates within subgroups (Figure 7). Trials involving male participants (IRR = 0.76; 95% CI 0.59-0.99) or mixed-gender groups (IRR = 0.73; 95% CI 0.59-0.89) showed a lower reduction in injury risk compared to those involving female participants (IRR = 0.36; 95% CI 0.13-1.00).

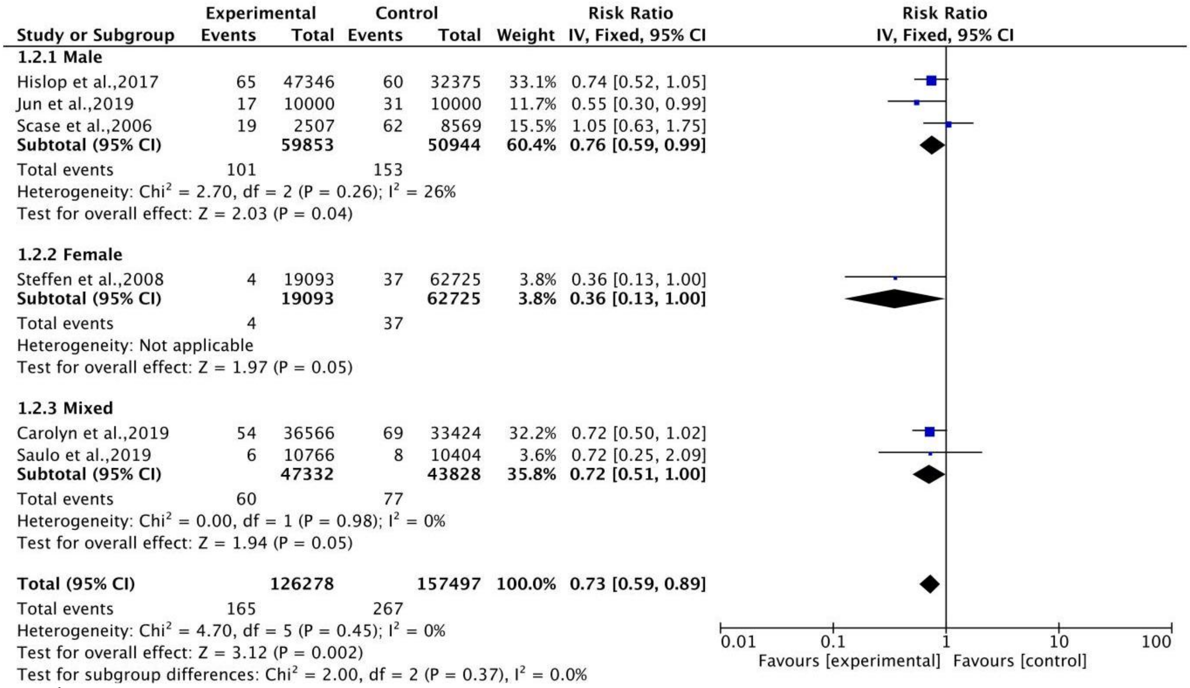


Figure 7 ｜ Subgroup analysis of the impact of gender on the IRR of upper limb sports injuries

3.3.3 Effect of lower limb sports injury

A total of 23 RCTs involving 3,187 sports injuries were included, resulting in a combined Incidence Rate Ratio (IRR) of 0.66 (95% CI 0.56-0.77; Z = 5.12; P < 0.00001), indicating a statistically significant 34% reduction in upper limb sports injury risk. Heterogeneity among gender subgroups was not significant (I^2 = 0; Q = 0.51; P = 0.78), suggesting no notable differences in combined effect estimates within subgroups (Figure 8). Trials involving male participants (IRR = 0.61; 95% CI 0.48-0.76) or mixed-gender groups (IRR = 0.64; 95% CI 0.50-0.82) showed a greater reduction in injury risk compared to those involving female participants (IRR = 0.70; 95% CI 0.50-0.99).

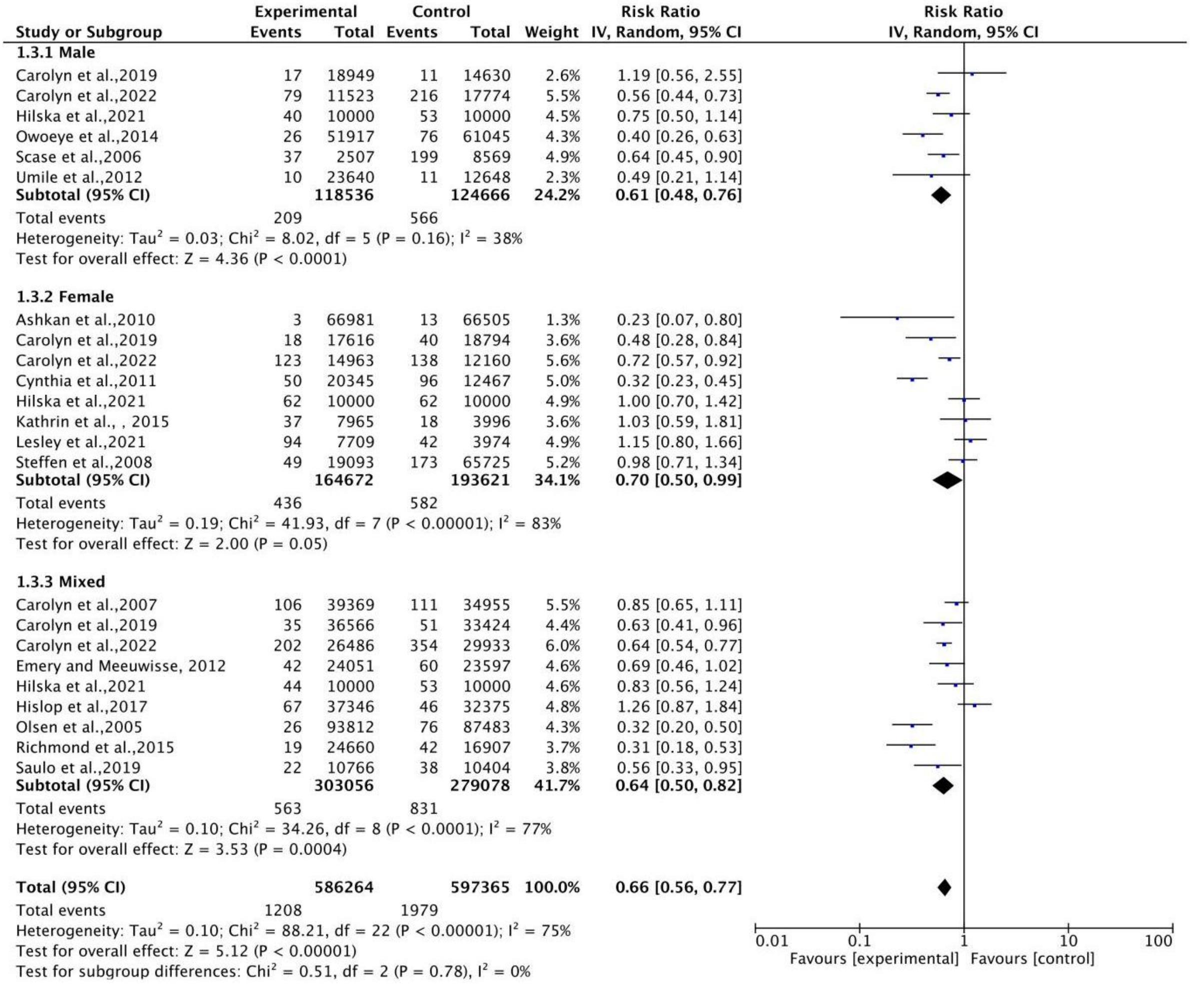


Figure 8 | Subgroup analysis of the impact of gender on the IRR of lower limb sports injuries

3.3.4 Effect of knee sports injury

A total of 16 RCTs involving 856 sports injuries were included, resulting in a combined Incidence Rate Ratio (IRR) of 0.73 (95% CI 0.63-0.84; Z = 4.44; P < 0.00001), indicating a statistically significant 27% reduction in upper limb sports injury risk. Heterogeneity among gender subgroups was not significant (I^2 = 10.2; Q = 2.23; P = 0.33), suggesting no notable differences in combined effect estimates within subgroups (Figure 9). Trials involving female participants (IRR = 0.54; 95% CI 0.37-0.81) or mixed-gender groups (IRR = 0.40; 95% CI 0.23-0.70) showed a greater reduction in injury risk compared to those involving male participants (IRR = 0.97; 95% CI 0.34-2.80).

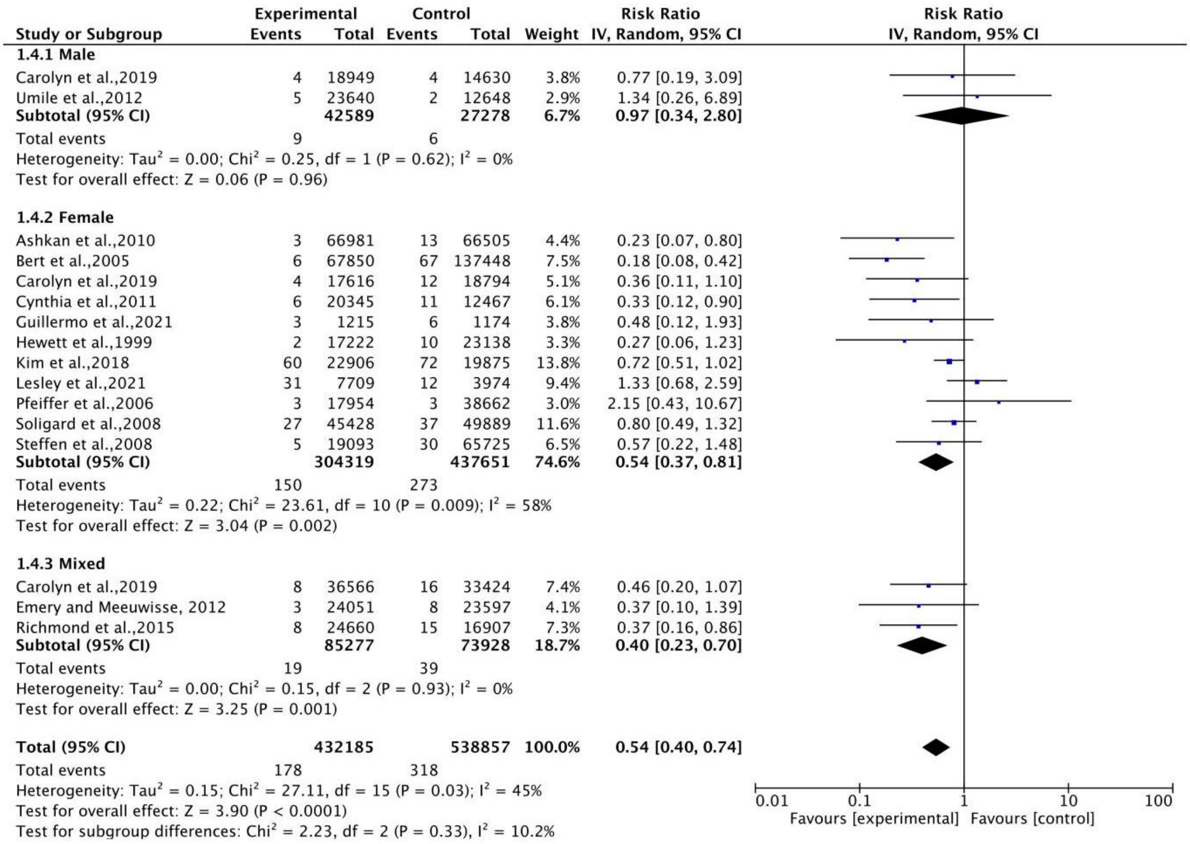


Figure 9 | Subgroup analysis of the impact of gender on the IRR of knee sports injuries

3.3.5 Effect of ankle sports injury

A total of 16 RCTs involving 496 sports injuries were included, resulting in a combined Incidence Rate Ratio (IRR) of 0.54 (95% CI 0.40-0.74; Z = 3.90; P < 0.00001), indicating a statistically significant 46% reduction in upper limb sports injury risk. Significant heterogeneity was observed among gender subgroups (I2 = 77.9; Q = 9.05; P = 0.01), suggesting notable differences in combined effect estimates within subgroups (Figure 10). Trials involving male participants (IRR = 0.32; 95% CI 0.16-0.67) or mixed-gender groups (IRR = 0.67; 95% CI 0.55-0.80) showed a greater reduction in injury risk compared to those involving female participants (IRR = 0.90; 95% CI 0.72-1.13). To explore the source of heterogeneity, a sensitivity analysis was conducted by sequentially excluding each study included in the overall analysis to evaluate its impact on the IRR. The results indicated minimal heterogeneity among the studies, with the exclusion of any single study having a negligible impact on the IRR effect size. Thus, the results of the meta-analysis were relatively stable (Figure 11).

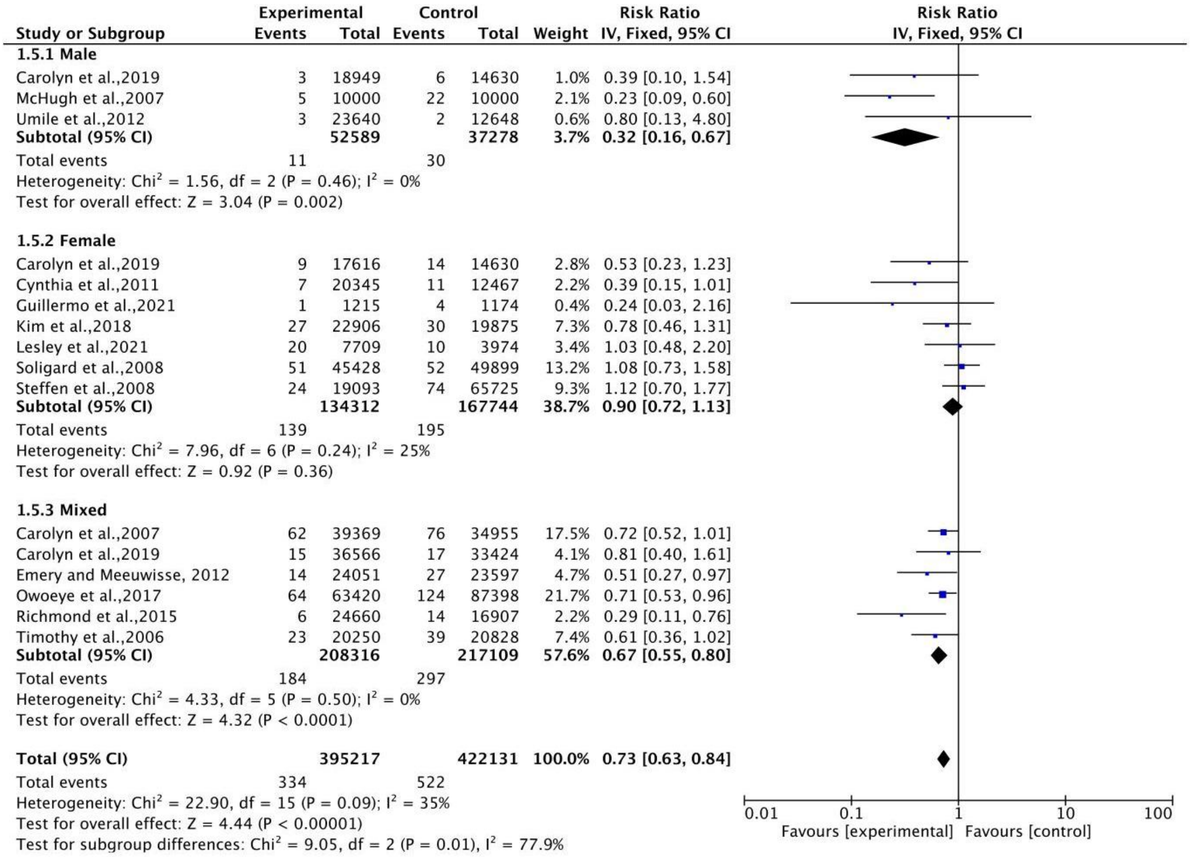


Figure 10 | Subgroup analysis of the impact of gender on the IRR of ankle sports injuries

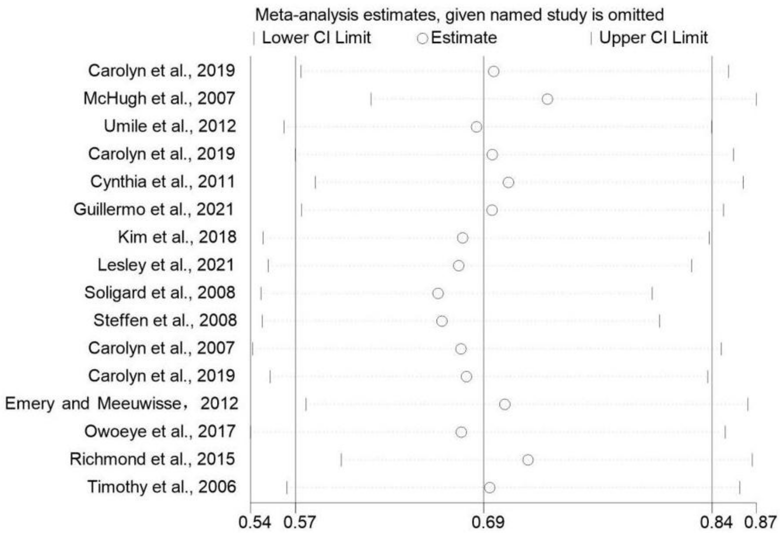


Figure 11 | Sensitivity analysis of aankle sports injuries

3.3.6 Effect of acute sports injury

A total of 13 randomized controlled trials (RCTs) involving 1,690 sports injuries were included, resulting in a combined Incidence Rate Ratio (IRR) of 0.60 (95% CI 0.49-0.74; Z = 4.84; P < 0.00001), indicating a statistically significant 40% reduction in upper limb sports injury risk. Heterogeneity among gender subgroups was not significant (I^2 = 0; Q = 0.07; P = 0.97), suggesting no notable differences in combined effect estimates within subgroups (Figure 12). Trials involving male participants (IRR = 0.59; 95% CI 0.19-1.81), female participants (IRR = 0.62; 95% CI 0.43-0.88), and mixed-gender groups (IRR = 0.58; 95% CI 0.45-0.75) showed similar reductions in injury risk. To explore the source of heterogeneity, a sensitivity analysis was conducted by sequentially excluding each study included in the overall analysis to evaluate its impact on the IRR. The results indicated minimal heterogeneity among the studies, with the exclusion of any single study having a negligible impact on the IRR effect size. Thus, the results of the meta-analysis were relatively stable (Figure 13).

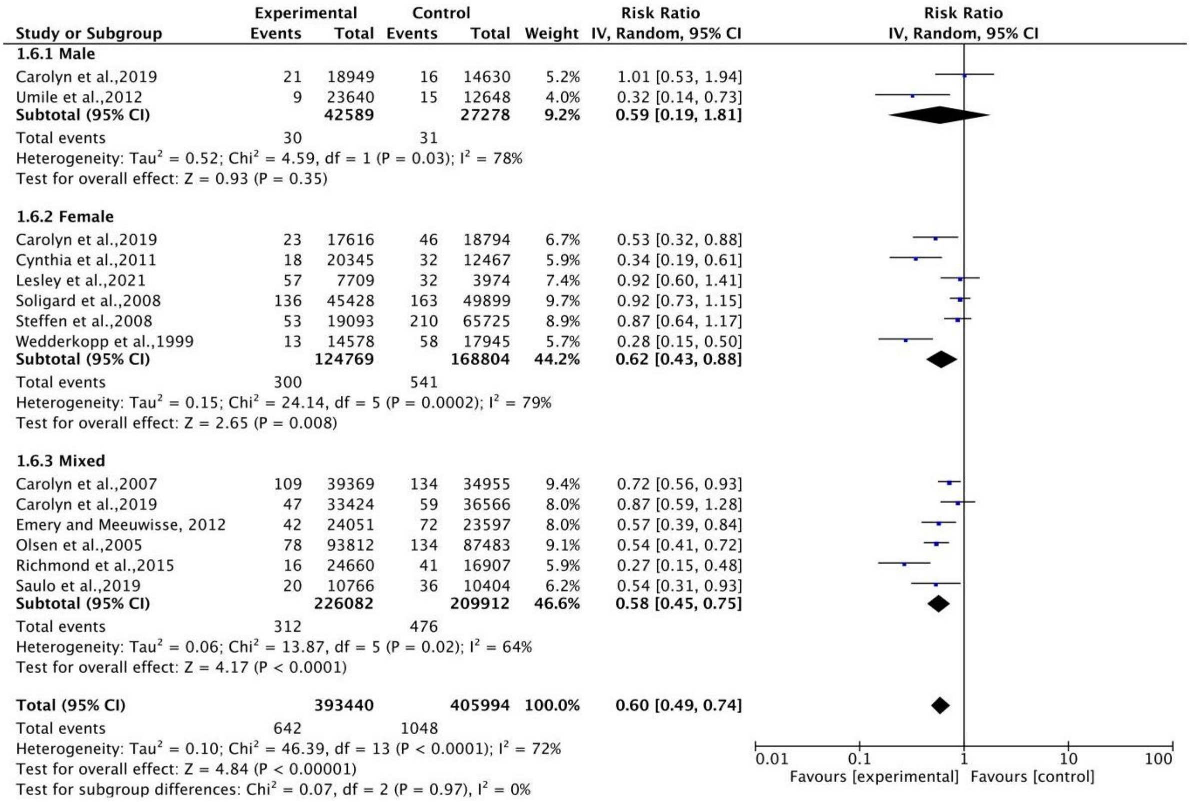


Figure 12 | Subgroup analysis of the impact of gender on the IRR of acute sports injuries

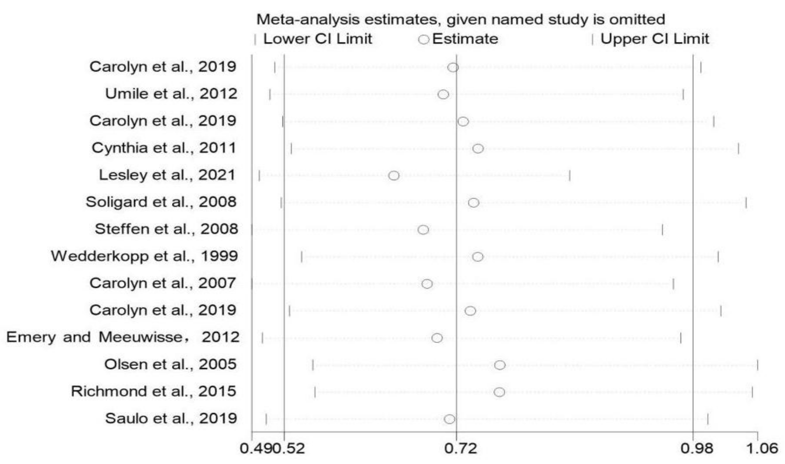
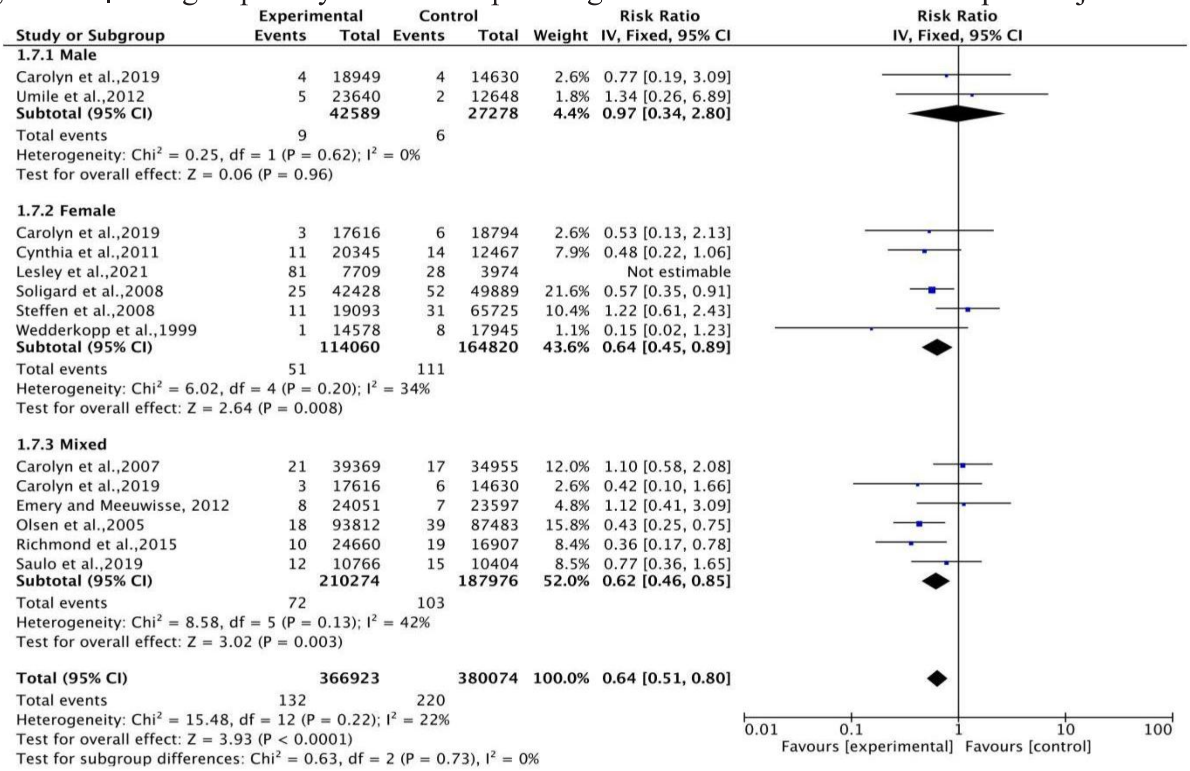


Figure 13 | Sensitivity analysis of acute sports injuries

3.3.7 Effect of chronic sports injury

A total of 14 RCTs involving 461 sports injuries were included, resulting in a combined Incidence Rate Ratio (IRR) of 0.72 (95% CI 0.52-0.98; Z = 2.07; P = 0.04), indicating a statistically significant 28% reduction in upper limb sports injury risk. Heterogeneity among gender subgroups was not significant (I^2 = 0; Q = 0.65; P = 0.72), suggesting no notable differences in combined effect estimates within subgroups (see Figure 14). Trials involving female participants (IRR = 0.75; 95% CI 0.44-1.28) or mixed-gender groups (IRR = 0.63; 95% CI 0.42-0.98) showed a greater reduction in injury risk compared to those involving male participants (IRR = 0.97; 95% CI 0.34-2.80).

Figure 14 | Subgroup analysis of the impact of gender on the IRR of chronic sports injuries



3.4 Risk of Publication Bias Assessment

Using the Egger's test to evaluate publication bias in the included studies, the results are shown in Table 3. The P-values for overall injuries (P=0.405), upper limb injuries (P=0.419), lower limb injuries (P=0.494), knee injuries (P=0.582), and chronic injuries (P=0.307) are all greater than 0.05, indicating no significant publication bias in the included studies for these outcome indicators, and the results are relatively stable. However, the P-values for ankle injuries (P=0.034) and acute injuries (P=0.022) are less than 0.05, indicating significant publication bias.

Table 3 丨 Meta-analysis of Egger test results

结局指标	Std_Eff	Coef.	Std.Err	t 值	*P* 值	95%*CI*
整体损伤	slope	-0.176922	0.2271373	-0.78	0.446	-0.6523259 — 0.2984819
	bias	-1.306713	1.533905	-0.85	0.405	-4.517214—1.903787
上肢损伤	slope	-0.0987609	0.2674994	-0.37	0.731	-0.8414584 — 0.6439367
	bias	-0.9547981	1.060447	-0.90	0.419	-3.899071—1.989475
下肢损伤	slope	-0.2586579	0.2028871	-1.27	0.216	-0.6805847 — 0.1632689
	bias	-0.7762531	1.116434	-0.70	0.494	-3.098005—1.545498
膝盖损伤	slope	-.1596636	0.2832558	-0.56	0.582	-.7671869 — 0 .4478597
	bias	-.9444249	0.6995385	-1.35	0.198	-2.444786—0.555936
脚踝损伤	slope	0.0339364	0.1685086	0.20	0.843	-.3274785—0.3953514
	bias	-1.383283	0.5883232	-2.35	0.034*	-2.645111—-.1214555
急性损伤	slope	0.1558872	0.2231528	0.70	0.498	-.330321—0.6420953
	bias	-3.046717	1.157345	-2.63	0.022*	-5.568355—-.525078
慢性损伤	slope	0.0816667	0.3567236	0.23	0.823	-.6955674—0.8589007
	bias	-1.01316	0.9493771	-1.07	0.307	-3.081676—1.055355

表注：*代表显著差；Std_Eff 代表斜率；Slope 代表截距；Bias 代表偏倚；Coef.代表回归系数；Std.Err 代表标准误。

4. Discussion

In the early stages of training, adolescents should engage in a variety of sports and movement patterns, gradually increasing training intensity as they age and adapt physiologically to develop comprehensive physical capabilities. Initially, they should learn basic movement techniques and train their physical abilities, transitioning these abilities to specialized sports techniques to optimize athletic performance. Literature suggests that diverse training helps build the physical foundation of young athletes, serving as the basis for specialized sports skills and reducing the risk of sports injuries. Neuromuscular adaptation is a crucial factor in the progress of children's and adolescents' athletic performance, so training during this period should emphasize neuromuscular stimuli. NMT, which incorporates various physical elements such as strength, explosiveness, speed, agility, and balance, is often used as a warm-up before specialized training or as an independent training session. Additionally, practicing the basic techniques of various physical elements in NMT promotes athletic performance and prevents sports injuries. One notable and effective NMT program is the injury prevention initiative (FIFA 11+ Kids) developed by the International Federation of Association Football (FIFA), combining core stability, eccentric strength, balance, plyometrics, and fall techniques to prevent injuries and enhance performance.

The primary objective of this meta-analysis is to determine the efficacy of NMT in different genders, body parts, and injury types to develop more targeted training methods to reduce the risk of sports injuries in adolescents. Overall, consistent with previous research, the included studies show that NMT significantly prevents injuries (IRR 0.67, 95% CI 0.57-0.79), reducing injury risk by 33%. Subgroup analysis reveals that the reduction in sports injury risk is more pronounced in male and mixed-gender groups, with effect sizes within these groups all less than 1. In contrast, two studies in the female group indicate that NMT is ineffective in preventing sports injuries. In Steffen et al.'s study, the compliance rate of coaches and players was only 52%, which might explain the non-significant results. Differences in attitudes and beliefs about the importance of injury prevention training and injury prevention among youth sports coaches and adolescents may exist[74-78]. The study suggests that coaches who undergo methods such as coaching workshops to learn preventive programs are more likely to effectively implement prevention plans based on a correct understanding of the techniques. Given the lack of injury prevention training and medical follow-up resources for adolescents, it is crucial to make injury prevention a mandatory part of coach education certification at all levels.

In young female football, basketball, and gymnastics athletes, the ankle, knee, and thigh are the most common injury sites. Another study indicates that the ankle and knee are the most common injury sites in young females, further supporting the need for lower limb injury prevention programs in young females. In subgroup analyses by site and gender, almost all groups show that NMT significantly prevents injuries and greatly reduces injury risk. However, we found no significant differences in the prevention of male knee injuries (P=0.96) and female ankle injuries (P=0.36). The limited number of studies reporting male knee injury outcomes (only two) may affect the results, highlighting the need for further studies. In the studies included for female ankle injuries, three studies reported IRR effect sizes greater than 1. In Steffen and Soligard et al.'s studies, issues with low compliance among coaches and adolescents during training might contribute to the ineffectiveness of NMT in reducing injury probability. Finally, in studies on injury types, NMT significantly prevents both acute and chronic injuries.

Despite the increasing number of studies providing effective methods for preventing adolescent sports injuries, there is still a lack of learning, absorption, and continued use of these methods after systematic evaluation. This highlights the need to focus on the implementation context and real-world effectiveness when evaluating adolescent sports injury prevention programs[82-84]. In team sports like football, these programs must be customized for specific sports, particularly emphasizing coach training to ensure effective implementation. It is also important to propose a tiered responsibility system, assigning the lowest responsibility to adolescents and the highest responsibility to organizations or groups that can have the most significant impact. This approach is based on the rationale that simply relying on behavior changes from adolescents and parents and the cognitive development level of adolescents to demonstrate the program's effectiveness is insufficient, as their level is inadequate to bear primary responsibility for their safety in sports. Additionally, more attention should be paid to implementation-related research, including fundamental behavior changes in the adolescent athletic population and the key role of coaches in injury prevention, which is critical for knowledge dissemination, behavior change, and sustainable injury prevention practices and policies.

In conclusion, NMT can prevent the occurrence of sports injuries in adolescents. Given the issues of limited studies in certain subgroups and low methodological quality in this meta-analysis, large-sample, high-quality clinical randomized controlled trials are still needed to further explore the impact of NMT on sports injuries of different genders, sites, and types. Overall, NMT is an effective and safe intervention that can be implemented before specialized training or as an independent training session to prevent sports injuries in adolescents.

5. Limitations

Some of the included studies had low quality and did not specify the implementation of allocation concealment and blinding. Significant heterogeneity existed among the included studies, affecting the reliability of the results. The intervention frequency, duration, and intensity varied among the studies, introducing potential bias. The participants exhibited diversity in sports type and level, ranging from amateur to high school and professional. Soomro et al.[87] and Rössler et al.[88] noted that studies involving amateurs showed a more significant risk reduction compared to those targeting professional-level adolescents. Body weight and prior injury history also play crucial roles in sports injuries. Therefore, the heterogeneity observed in the meta-analysis may not only be due to differences in the content and dosage of neuromuscular training programs but also the specific characteristics of the study populations. Adherence is a key factor in evaluating the effectiveness of injury prevention programs[89, 90]. Coach-reported adherence may be overestimated since most coaches did not use all prescribed exercises, and several studies failed to collect adherence data from coaches and adolescents, thus not included in the analysis. Future research should focus on large-scale, high-quality randomized controlled trials to further investigate the effects of neuromuscular training on preventing sports injuries in different populations and intervention methods.

6. Conclusion

This paper analyzes recent advancements in the application of NMT for preventing sports injuries among adolescents, initially describing its positive effects. Studies indicate that NMT effectively prevents upper and lower limb, knee, ankle, as well as acute and chronic sports injuries across different genders, with similar efficacy. This training ensures safety during sports, improves physical and mental health, reduces public health burdens, and promotes participation in physical activities. However, the effectiveness of NMT is influenced by factors such as age, body weight, sports level, injury history, and training content design. Therefore, future research should develop more refined NMT programs tailored to different types of participants, providing more evidence for clinical practice to achieve optimal prevention outcomes.

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