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Review Article

Athletes and Experimental Pain: A Systematic Review and Meta-Analysis

Claire Thornton,* Andrew Baird,† and David Sheffield†

**Department of Sport, Exercise and Rehabilitation, Faculty of Health and Life Sciences, Northumbria University, Newcastle upon Tyne, UK, †School of Psychology, College of Health, Psychology and Social Care, University of Derby, Derby, UK*

Abstract: The evidence that athletes respond to and report indices of experimental pain differently to non-athlete populations was analysed. Databases screened were SPORTDiscus, PubMED, PsycArticles, the Cochrane Library (Cochrane Database of Systematic Reviews), Web of Science, Scopus, and CINAHL. Studies that compared experimentally induced pain responses (threshold, tolerance, intensity, unpleasantness, bothersomeness, and effect on performance) in athletes and controls were included. Meta-analyses were performed where appropriate and effects were described as standardised mean differences, pooled using random effects models. Thirty-six studies (2,492 participants) met the inclusion criteria comprising 19 pain tolerance, 17 pain threshold, 21 pain intensity, 5 pain unpleasantness, 2 performance in pain and 1 bothersomeness study. Athletes demonstrated greater pain tolerance (g = .88 [95% confidence interval [CI] .65, .13]) and reported less pain intensity (g = −.80, [95% CI −1.13, −.47]) compared to controls; they also had higher pain threshold but with smaller effects (g = .41, [95% CI .08, .75]). Differences for unpleasantness did not reach statistical significance but the effects were large (g = −1.23 [95% CI −2.29, .18]). Two studies reported that performance in pain was better in contact athletes than non-athletes, and one concluded that athletes find pain less bothersome than controls. There were considerable inconsistencies in the methods employed that were reflected in the meta-analyses' findings. Sub-group analyses of tolerance and intensity were conducted between endurance, contact, and other athlete groups, but were not significant. The data suggest that athletic participation is associated with altered pain responses, but mechanisms remain unclear and more transparent methods are recommended.

This study was registered on the PROSPERO site in January 2019 (ref ID: CRD42019119611).

Perspective:* *This review examined differences in pain outcomes (threshold, tolerance, intensity, unpleasantness, bothersomeness) and the effect of pain on performance, in athletes versus controls. Meta-analyses revealed athletes had higher threshold and tolerance and found pain less intense than controls; there was some evidence of differences in bothersomeness and performance.

Key Words: *Pain, Athletes, Perception, Meta-analysis, Systematic review*

The world of sport is littered with examples of athletes completing events despite apparently insurmountable injuries.[1] Indeed, on many occasions, performance can appear unaffected by pain, and this has led to a common perception that athletes are a 'different breed'. Exposure to pain is an inevitable consequence of athletic endeavour, whether that be from fatigue/exertion, injury or traumatic impact. The ability to maintain performance in painful conditions is crucial to continued participation in most sports and is a

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Address reprint requests to Claire Thornton, Department of Sport, Exercise and Rehabilitation, Northumbria University, City Campus, Newcastle upon Tyne NE1 8ST, UK. E-mail: Claire.thornton@northumbria.ac.uk

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deciding factor in whether an athlete is successful or not.[2] Athletes' typical exposure to pain will depend upon both their 'level' (elite athletes typically having a higher exposure) and the nature of the sport,[3] with contact and endurance sports being associated with higher exposures than non-contact and non-endurance sports. Whatever the activity however, pain can be a limiting factor in athletic achievement.[1]

Research in the field of pain in athletes can be traced back to the 1960s with numerous studies exploring aspects of pain threshold,[4–6] and pain tolerance[3,7–12] in athletic populations. In addition, studies have also examined intensity and affective domains such as unpleasantness.[13–17] More recently, there has been interest in attempting to understand the impact of pain on athletic performance[18–20] and how pain bothersomeness differs between athletes and other groups.[19–21]

Despite concerns over the heterogeneity in available research, there is evidence to suggest that athletes respond differently to pain compared to other populations (healthy controls, non-athletes). A review/meta-analysis published over a decade ago[22] considered fifteen studies and concluded that not only was there a statistically significant difference in pain tolerance scores, but that difference was meaningful—a large effect size (Hedges' g = .87). With pain threshold, research findings were much more varied and overall, there was no significant difference. However, the review did not consider further critical aspects of pain processing such as affective dimensions, bothersomeness, or any related behavioural responses. Given the range of data now available, it is timely to update and extend the previous review.

Whilst the evidence supporting differences in response to noxious stimuli amongst athlete populations is growing, evidence to illustrate the mechanisms underpinning such differences is relatively limited. Increasing use of conditioned pain modulation protocols[3,13,14,16,23] suggests more effective endogenous inhibition, and recent brain imaging studies using functional magnetic resonance imaging[23] and electroencephalogram[13] illustrated significant differences in neural processing. Longitudinal studies to explore the development of changes have yet to be undertaken, however.

The primary objectives were to examine differences between athletes and non-athlete controls for pain threshold, tolerance, intensity, unpleasantness, and bothersomeness as well as the performance of motor and cognitive tasks during pain. The secondary objectives were to explore the impact of pain stimulus used and to examine differences between athlete groups (endurance, contact and non-contact and non-endurance athletes).

Such a review is certainly warranted, given the potential implications for both athletic performance in the 'high-stakes' world of sport and for broader considerations in relation to effective pain management. The current review critically appraises the extant literature and considers key methodological and theoretical aspects of the research.

Methods

Procedures

The review was aligned with the Cochrane Collaboration recommendations. The study was registered (ref ID: CRD42019119611) and all steps were specified in advance on the Prospero website (University of York, 2022). The following databases were searched: SPORTDiscus, PubMED, PsycArticles, the Cochrane Library (Cochrane Database of Systematic Reviews), Web of Science, Scopus and CINAHL. The search strategy was adapted according to the requirements of each database. We included terms relating to sport, athletes, exercise and pain. There were no restrictions on publication status or publication type, but we restricted language to English. Studies published between 1900 and May 2023 were included. These searches were extended by scrutinising reference sections from articles found within the databases. Forward and backward searches were conducted and any additional papers were located as full text. Please see Supplementary Materials for full details of the searches.

Two reviewers independently examined titles and abstracts of eligible studies and following this, scanned the text to decide if inclusion criteria were met. Any disagreements were discussed, and a third reviewer was consulted where necessary. All potentially eligible papers were placed in EndNote for further scrutiny.

Inclusion Criteria

Studies were included if they compared adult (age 18+) athletes to other groups of non-exercisers or non-athletes (normally active controls). Athletes were classed as those participating in sports or exercise competitions or training for at least 3 hours per week[22] and must have been taking part in a physically active sport. Dancers were also included due to the physicality of the activity and the competitive nature of some forms of dance. Non-athletes or normally active controls were classed as those not engaging in any form of structured sport or exercise, and/or were not competitive in any physical activity, and/or did less than 3 hours of physical activity per week. Studies were excluded that used participants who engaged in activities that may be considered sports or games but were predominately physically inactive in nature (eg, chess, card playing, darts, e-sports), unless they were used as a control/comparator group. Papers with no normally active control group (eg, studies that compared different groups of athletes to one another) were excluded. Conference posters, presentations, and non-peer-reviewed dissertations were also excluded.

Studies were included from a range of experimental and field-based protocols that examined differences in pain reporting between athlete groups and non-athletes. For inclusion in the meta-analysis, studies must have measured either pain threshold, tolerance, intensity, unpleasantness, and/or bothersomeness using scale variables and provided means and standard deviations, F and t values or effect sizes (or have provided enough information for these to be calculated). Where multiple measures were taken, the first value was used; where different limbs/sites were reported, non-dominant limb score was used if was reported, and if they were not mean scores were calculated.

Outcomes

Reported outcome measures included pain threshold, pain tolerance, intensity, unpleasantness, and bothersomeness and effect on performance. Pain threshold is the point at which pain is first reported when a noxious stimulus is presented, and pain tolerance is the maximum duration of pain stimulus a person can withstand before they withdraw from a stimulus.[24] Examples of stimuli included the use of thermal, mechanical, pressure, chemical, electrical pain stimulation or the use of exercise to induce pain. Pain intensity, unpleasantness, and bothersomeness can be measured using self-report, paper, and pencil instruments such as the Visual Analog Scale or Numerical Rating Scale. Intensity refers to the relative scale of pain experienced, whereas pain unpleasantness relates to the noxious quality of the stimulus. Recently some authors have also used pain bothersomeness as a measure of the extent to which pain is perceived to interfere with performance or thoughts during the performance of experimental motor tasks.[20] The effect of pain on performance has also been examined to determine how pain interferes with motor and cognitive task performance.[25]

Risk of Bias

A pre-prepared form was developed based on the recommendations of Tesarz,[22] including—title, patient/population, intervention, comparison, outcome (up to 7). This included sampling method; participant characteristics (including how athletic status was defined/how athletes and non-athletes/controls were differentiated, types of sport played, gender split, ethnicity); noxious stimuli used; pain assessment methods; pain measurement tools (eg, questionnaire, Visual Analog Scale) methodology; pain outcome measurements (eg, tolerance, threshold); statistical methods (means and standard deviations, F and t values and effect size); suggested mechanisms. See Supplementary Material for further details of the assessment of quality.

The 2 independent reviewers rated each paper as low, moderate, or high-risk of bias for participant sampling, pain assessment method used, and analysis strategy. Only studies judged as low risk of bias on all 3 sections were classed low risk overall. Equally, studies with moderate or better for all 3 sections were classed as moderate. All other studies were classed as high-risk.

Statistical Analysis

Random effects meta-analyses were conducted focusing on each pain dimension for which adequate levels of data were available (tolerance, threshold, intensity and unpleasantness). There were not enough data for bothersomeness and the effect of pain on performance and accordingly, meta-analyses were not conducted. Data were entered into Meta-Essentials.[26] Mean effect sizes (Hedges g) and confidence intervals were calculated; mean effect sizes of .2 were interpreted as small, .5 were interpreted as medium, and .8 were interpreted as large.[27]

Where studies had multiple noxious stimuli or outcome measures, the sample size was adjusted accordingly to avoid double counting by dividing the number of participants by the number of stimuli[4,5,7,28–32] thus, numbers in the Preferred Reporting Items for Systematic Review and Meta-Analyses diagram differ from those in the meta-analyses. Mean outcome scores were calculated where multiple sites of the body were used[4,16] when the pain was taken at multiple time points, the baseline measure was used,[33] and scores relating to the non-dominant limb were used when measures from both limbs were taken.[12] In studies where multiple temperatures were reported,[34] scores associated with the highest temperature were used. For 2 studies, it was necessary to utilise graphs/charts (measurements were taken by each author to reduce the potential for measurement error.) to calculate means/standard deviations.[14,17]

Variability was examined using Cochran's Q and I^2. Heterogeneity among effect sizes was determined by a significant Q value ($P < .10$). The I^2 statistic indicates the degree of variability in effect sizes (low heterogeneity, 1–49; moderate heterogeneity, 50–74; high heterogeneity, 75–100).[34] In the case of significant heterogeneity, subgroup and moderator analyses were undertaken. Random effects models were used as the included studies were made up of diverse populations; thus, heterogeneity was assumed. As significant heterogeneity was identified for each pain measure, subgroup analyses were conducted based on the type of stimuli (cold pressor and ischemic), and type of athlete (contact athletes, endurance athletes, other athletes); studies with a high-risk of bias ratings were omitted from analyses to determine if they had a major impact upon the mean effects. Lastly, publication bias was examined using funnel plots and associated statistics (standard error, combined effect size, and imputed data points).

Results

Included Studies

A total of 16,156 articles were found in the initial database search. Of these, 8,450 were duplicates and were deleted, leaving 7,706. A large number of papers did not involve human participants resulting in a further 3,231 being discarded. Of the remaining 4,475, 4,025 were discarded because they did not meet the inclusion criteria based on their title. The abstracts of the remaining 450 articles were scrutinised and a further 389 were excluded. The full text of the remaining 61 studies was read in detail and a further 25 were excluded due to not meeting the inclusion criteria (see Fig 1 for Preferred Reporting Items for Systematic Review and Meta-Analyses diagram and Supplementary Material

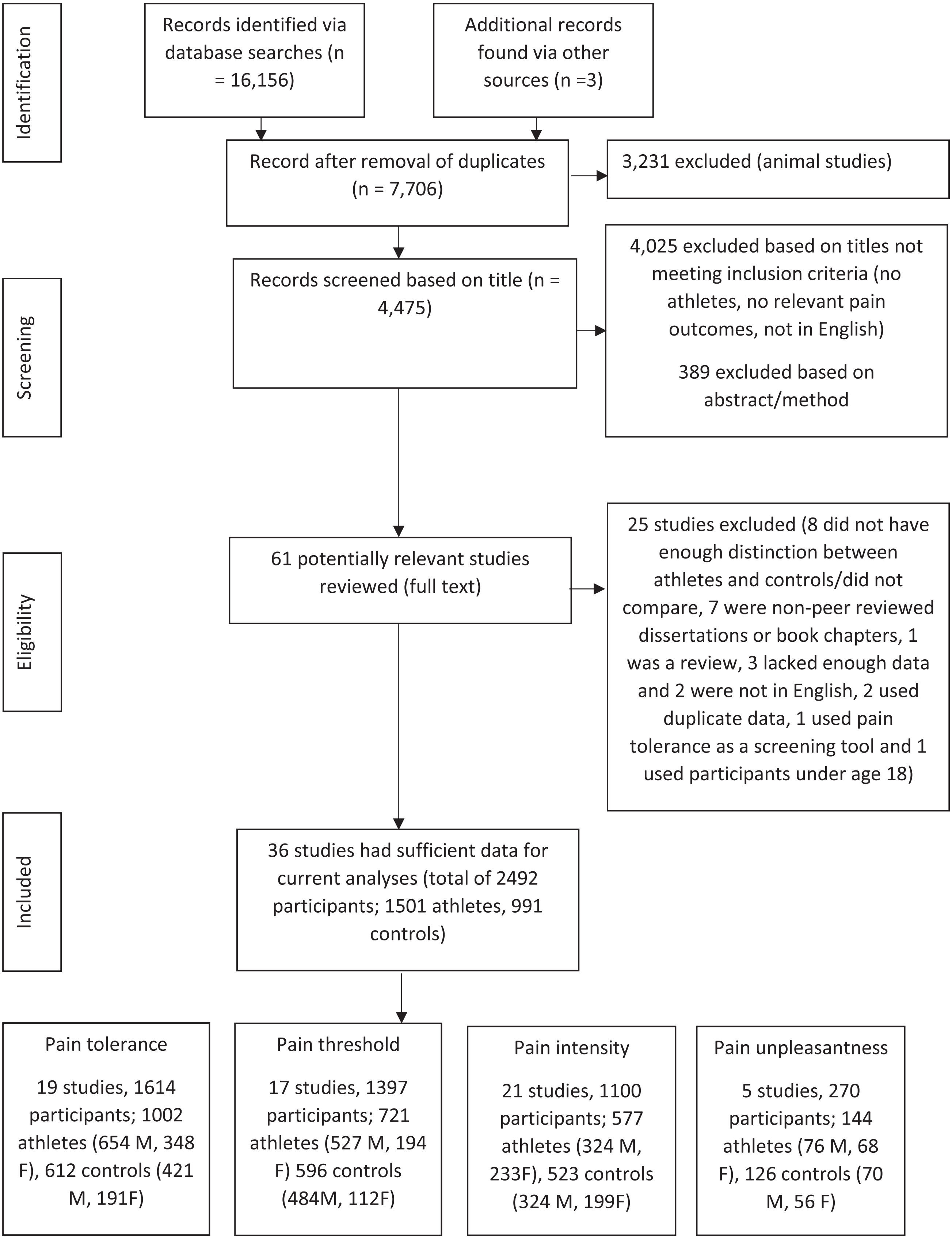


Figure 1. PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analyses) flow diagram. Study selection process. *Hoffman study did not include gender—so is not included in the breakdowns.

for reasons for exclusion). This resulted in a final total of 36 studies from 35 reports; Janal et al[7] contained 2 separate studies.

Three studies had a high-risk of bias, 26 studies had moderate risk of bias, and 7 studies had low risk of bias (see Supplementary Material for risk of bias table). In total, there were 2,492 participants (1,501 athletes; 1,111 M, 411 F, and 991 controls; 696 M, 295 F)—note that Hoffman et al[33] did not state gender and is therefore not included in the breakdown. See Table 1 for characteristics of studies.

The included group of studies considered a range of pain outcomes; 19 assessed pain tolerance[2,3,5,7–9,11,12,14,17,21,29,35–40]; 17 assessed pain threshold[3–6,8,9,11,12,14,16,29,30,32,36,37,40,41]; 21 assessed pain intensity[3,4,9,13–17,21,28,30–33,35,38–40,42–44]; 5 assessed pain unpleasantness[4,28,30,31,40], 2 assessed performance during pain,[11,19] and 1 assessed pain bothersomeness.[19] Meta analyses were conducted for the first 4 outcomes only, due to a lack of data for the other outcomes. In the 1 study that assessed pain bothersomeness, experienced contact athletes found pain less bothersome than novice contact athletes and non-contact athletes.[19] In the 2 studies that measured performance during pain, contact athletes performed better than non-contact athletes and non-athletes during pain on a motor task (in terms of accuracy and speed), and were able to maintain performance in pain compared to when not in pain.[11,19] However, this was not true for a cognitive task, where there were no differences between athletes and non-athletes (Table 2).

All included studies had control groups. However, in many cases, the characteristics of control participants were inadequately reported. Seven studies, mostly those published before 2,000, included non-exercising participants within control groups whereas more recent studies have included active/exercising participants as the control group.

Meta Analysis

Pain Threshold

The total sample size for studies examining pain threshold was 1397 (range 13–321) from 17 studies with 19 estimates. Fig 2 illustrates the associated forest plot and effects for each study. There was a small to medium positive mean effect, g = .41 [95% CI .08, .75], which was significant. The heterogeneity of effects was significant (Q = 130.76, $P < .001$), and inconsistency was high (I^2 = 86.23%). The funnel plot for the effect sizes appeared to be symmetric, suggesting little evidence of publication bias (see Fig 3). In addition, both Begg and Mazumdar adjusted rank correlation (τ = -.13, P = .42) and Egger's intercept = −3.48, t = −1.13, P = .27, were not significant, which indicates no evidence of publication bias for these data.

Excluding the 2 studies with a high-risk of bias,[5,39] resulted in a similar g of .32 [95% CI −.03, .66], which was not significant, and heterogeneity was reduced (Q = 113.84, $P < .001$; I^2 = 85.95%).

Sub-group analyses were not conducted on pain threshold studies due to the small number of sample sizes.

Pain Intensity

The total sample size for studies examining pain intensity was 1,100 individuals (range 14–108) from 21 studies with 25 estimates. Fig 4 illustrates the associated forest plot and the effects reported for each study. There was a large negative mean effect, g = −.80 [95% CI −1.13, −.48], which was significant. The heterogeneity of effects was significant (Q = 140.01, $P < .001$) and inconsistency was high (I^2 = 82.86%). The funnel plot for the effect sizes appeared to be symmetric, suggesting little evidence of publication bias (see Fig 5). In addition, both Begg & Mazumdar adjusted rank correlation (τ = -.12, P = .40) and Egger's intercept (Intercept = −4.09, t = −.89, P = .38) were not significant, which indicates no evidence of a publication bias for these data. Excluding the one high-risk of bias study,[39] resulted in a similar g of −.86 [95% CI −1.18, −.54] and heterogeneity (Q = 101.79, $P < .001$; I^2 = 77.40%).

In endurance athletes, subgroup analysis (14 studies with 448 participants), indicated a high level of homogeneity and a large g = −.77, [95% CI −1.01, −1.53], which was significant. Q = 16.98, P = .20, I^2 = 23.45%. Begg and Mazumdar τ = .10, P = .62 and Eggers Intercept = .97, t = .43, P = .67 were not significant, which indicates no evidence of publication bias for these data.

In contact athletes, subgroup analysis (1 study with 104 participants), indicated a high level of homogeneity and a large g = −1.85, [95% CI −11.86, 8.15], which was not significant. Q = 10.81, P = .001, I^2 = 90.75%. Begg and Mazumdar τ = −1.0, P = .32.

In non-contact and non-endurance athletes, subgroup analysis (4 studies with 250 participants), subgroup analysis indicated a high level of homogeneity and a large g = −.82, [95% CI −2.84, 1.19], which was not significant. Q = 49.54, $P < .0001$, I^2 = 93.94%. Begg and Mazumdar τ = −.67, P = .17 and Eggers Intercept = −36.12, t = −3.54, P = .07 were not significant, which indicates no evidence of publication bias for these data. See Supplementary Materials for funnel, forest plots and sub-group meta-analysis results.

Pain Unpleasantness

The total sample size for studies examining pain unpleasantness was 270 (range 14–53) from 5 studies with 6 estimates. Fig 6 shows the associated forest plot and the effects reported for each study. There was a large negative mean effect, g = −.93 [95% CI −2.05, .19], which was not significant. Heterogeneity of effects were significant (Q = 61.23, $P < .001$) and inconsistency was high (I^2 = 91.83%). The funnel plot for the effect sizes appeared to be symmetric, suggesting little evidence of publication bias (see Fig 7). However, both Begg and Mazumdar adjusted rank correlation (τ = -.47, P = .19) and Egger's intercept (Intercept = −24.41, t = −1.93, P = .13) were not significant, which indicates

Table 1. Characteristics of Studies

Study	Noxious stimulus	Outcome measures	Participants	Characteristics of study and findings	Risk of bias
Anders et al (2023)[13]	Mechanical pain (pinprick) Constant force of 512 mN Heat 27 mm diameter thermode. Max temp 54 °C Cold (conditioned stimulus) 8 °C water bath (circulation not defined)	Intensity VAS with anchors of 0 = "no pain" and 100 = "worst pain".	Athletes 26 Elite endurance athletes (15 male & 11 female) Athletes from rowing (12), triathlon (9), speed skating (3) and running (2). Training included endurance, weight training and circuit training. Median age: 26.1 [23.5; 29.7] yrs. Controls 26 normally active controls (15 male & 11 female) Limited information, but median weekly training load 4 [2; 6] hrs and they had never competed in any type of sports with a training load > 15hrs per week Median age: 25.5 [24.6; 27.1] yrs.	The study adopted a conditioned pain modulation protocol combing both sequential and parallel elements. Pin prick was applied before and after heat and before, during and after cold. An area 9 cm × 8 cm on the dorsal area of the dominant foot was used for pinprick stimulation. Participants rated each stimulus approximately 2 s after VAS presentation. Each pinprick stimulation was preceded with a trigger word, approximately 1 s prior to stimulation. Intensity: Controls reported cold to be more painful than athletes ($P = .026$), but there were no differences for pinprick or heat pain. CPM was only evident within the control group. electroencephalogram data indicated greater activation the central processing units in the S2 region of the brain in athletes than controls, but a central sensitisation or a hyperalgesia could not be concluded from the subjective pain ratings.	Moderate
Assa, et al (2018)[14]	Heat (test stimulus) Peltier-based thermal stimulator Cold (conditioned stimulus) Circulating water bath at 12 °C	Threshold Button press recording temperature at which sensation painful Tolerance Button press recording highest tolerable temperature Intensity VAS with anchors of 0 = "no pain sensation" and 10 = "the most intense pain sensation imaginable".	Athletes 19 Endurance athletes (12 male & 7 female) Triathletes (inc. ironman). All trained regularly for last 3 years and had competed in at least 5 national/ international competitions a year. Mean age: 32.8 y ± 9 y. 17 Strength athletes (10 male & 7 female) Weightlifters, power lifters, hammer throwers and shot putters. Mean age: 28.3 ± 8y. Controls 17 non-athletes (7 male & 10 female) Active controls undertaking amateur physical activity, for example, running, aerobics, up to 3 times a week for 3 years prior to the study). Mean age: 36.5 ± 11 Ethnicity not stated for any group. No information re pain experience.	The study adopted a parallel conditioned pain modulation protocol—Heat was used as the test stimulus (starting at 35°C and increased at 2°C intervals) and cold as the conditioning stimulus. Threshold: Strength athletes had higher heat pain threshold than control group ($P < .05$, CI = 42.8–45.5) and endurance athletes ($P < .05$, CI = 41.3–43.9). Tolerance: Endurance athletes had higher heat pain tolerance than strength athletes and controls ($P < .0001$, CI = 49.6–50.6) *some M and Sd estimated from figures (charts) Intensity: Both groups of athletes reported less pain intensity than the non-athletes ($P < .001$) Endurance athletes had greater CPM than strength athletes and non-athletes ($P < .005$, CI = −2.68–.12 and CI = −2.47–.51 respectively). Endurance athletes had better pain inhibition Strength athletes had reduced pain sensitivity. Participants also completed the Fear of Pain Questionnaire and the Pain Catastrophizing Scale Endurance athletes reported less fear of pain than the other groups ($P < .05$). No differences in catastrophising between groups. Athlete groups rated Perceived Stress (physical & mental) using a numerical rating scale. Similar stress levels reported except for lower perceived physical stress during competition among strength athletes	Low

Table 1 (*Continued*)

Study	Noxious stimulus	Outcome measures	Participants	Characteristics of study and findings	Risk of bias
Diotaiuti et al (2022)[15]	Cold Circulating cold water bath at 8°C. Max duration 2 min.	Intensity 11 point NRS with anchors 0 = no perceived pain, 10 = maximum perceived pain Note: erroneously described as VAS in paper	Athletes (all male) 44 athletes from endurance and power sports. Mean age = 22.23 SD = 3.59 22 endurance runners Mean age = 22.36 SD = 2.59 22 competitive power lifters Mean age = 23.09 SD = 4.83 Controls (all male) 22 active controls involved in general fitness activities Mean age = 22.70 SD = 3.68	Participants immersed their non-dominant hand into the water bath and indicate the progression of pain intensity with the index finger of the other hand. If discomfort was considered unbearable, participants were able to withdraw their hands and stop the test. In case of withdrawal, the participant was given the maximum score on the final intensity recorded. Intensity: Perceived pain intensity increased from the powerlifters (M = 6.45, SD = 2.11) to runners (M = 7.73, SD = 1.96) and to controls (M = 9.36, SD = .58), in that order. Post hoc analysis revealed that the mean increase from runners to controls (1.64, SE = .43, 95% CI [.55, 2.72]) was statistically significant ($P = .003$), as was the increase from powerlifters to controls (2.91, SE = .47, 95% CI [1.74, 4.07], $P = .000$). However, the mean increase from powerlifters to runners was not significant (1.27, SE = .61, 95% CI [–.22, 2.76], $P = .107$). The study also considered analgesic effects of exercise (strength and aerobic training), but no significant differences between groups were identified.	Moderate
Egan (1987)[2]	Cold Cold pressor—Circulating cold water bath at 1–3°C. Max duration 12 min.	Tolerance (duration to withdrawal from stimulus)	Athletes (all male) 10 footballers 10 boxers 10 fencers 10 karateka 10 cross-country skiers All trained for at least 90 min 3x/week and competed regularly. Mean age: 22 (range 18–26). Controls (all male) 10 non-athletes (no information on activity levels). Mean age: 22 (range not provided). Ethnicity not stated for any group. No information re pain experience.	Participants immersed both feet into an ice bath (up to knee level). There was a blind ceiling time of 12 min. Tolerance: No significant difference between athletes and non-athletes. Sub-group analysis showed footballers had higher tolerance than fencers ($P < .05$, d = 1.56) and karateka ($P < .05$, d = 1.42)., as did cross-country skiers ($P < .05$, d = .84 and $P < .05$, d = .81) Note—high within groups variance for fencers and karateka	Moderate

Table 1 (*Continued*)

Study	Noxious stimulus	Outcome measures	Participants	Characteristics of study and findings	Risk of bias
Ellison and Freischlag (1975)[34]	Fatigue Muscle Contraction Pain	Tolerance (time to withdrawal)	Athletes (all male) 12 baseball players 12 basketball players 12 football linesmen 12 football backs 12 track distance runners 12 track and field sprinters Mean age not defined, but all undergraduates Controls (all male) 12 non-athletes Mean age not defined, but all undergraduates Ethnicity not stated for any group. No information re pain experience.	Experimental task involved flexing the fifth finger of the non-dominant hand against a trigger-like device to induce pain from protracted muscular contractions. A metronome was used to control frequency and duration of contractions. Participants were blind to the precise research questions. Tolerance: No significant differences found between athletes and non-athletes. No significant differences found between athlete groups. Arousal (GSR) and personality (Bernreuter Personality Inventory) also measured. Higher pain tolerance linked to lower arousal levels across groups.	Moderate
Flood et al (2017)[16]	Pressure (threshold and test stimulus) Cold (intensity and conditioned stimulus) Non-circulating cold water bath (2 ± 1°C).	Threshold (pressure level) Intensity (NRS 0 = no pain, 5 = moderate pain, 10 = most intense pain imaginable)	Athletes (all male) 15 athletes drawn from cycling, triathlon, swimming, football, weightlifting and martial arts. All trained at least 10 h per week and competed at or above the top tier of their local competition. Mean age not defined, but all students aged 18–40. Controls (all male) 15 active non-athletes, all engaged in amateur physical exercise for no more than 4 h per week. Mean age not defined, but all students aged 18–40. Ethnicity not stated for any group. No information re pain experience, but participants pain free upon commencing study.	Pain inhibitory capacity was assessed using a sequential CPM design, whereby a noxious test stimulus (pressure to index finger of right hand) was presented before and immediately after a noxious conditioning stimulus (cold for 4 min) was applied to a spatially remote bodily region (left hand). Threshold: Athletes had significantly higher pressure pain threshold than non-athletes ($P = .03$, d = .83). Intensity: Athletes rated cold pain significantly less intense than non-athletes ($P < .001$, d = 1.82) CPM scores were significantly higher in athletes compared to non-athletes ($P < .05$, d = .82).	Moderate

Table 1 (*Continued*)

Study	Noxious stimulus	Outcome measures	Participants	Characteristics of study and findings	Risk of bias
Freund et al (2013)[17]	Cold Non-circulating bucket of iced water <2°C	Tolerance (duration to withdrawal from stimulus) Intensity (NRS - 0 = no pain, 10 = worst pain imaginable)	Athletes (all male) 11 ultra-marathon runners, competing in TransEurope FootRace 2009. In the previous year all had trained on average 12.9 h/week (sd = 3.4). Mean age = 50.2, SD = 9.7. Controls (all male) 11 normally active controls (performed sports on average for 2.5 h/week SD = 1.4), matched for handedness and ethnicity. Mean age = 49.5, SD = 10.6. Exclusion criteria for controls—no participation in any long-distance runs in past 5 y. Ethnicity matched between groups but not defined. No information re pain experience	Participants placed left hand in iced water up to the wrist for maximum of 3 min. Pain intensity scored every 10 s. Participants could remove hand if score of 10 reached. Tolerance: Ultra-marathon runners had higher tolerance than control group ($P = .0002$) Intensity: Ultra-marathon runners perceived pain significantly less intense than controls ($P < .05$) Participants also completed the Temperament and Character Inventory test (TCI) and a Self-efficacy test. TCI analysis suggests athletes were less cooperative but more spiritually accepting and self-transcendent than controls. They were also less harm avoidant and reward dependent but more explorative than controls. Correlational analyses showed sub-scales 'dependence' and 'pure-hearted conscience' were significantly correlated with pain intensity at 3 min, but only for athletes.	Moderate
Geisler et al (2020)[41]	Pressure (test stimulus) 1 cm^2 tip Cold (conditioned stimulus) Cold water bath at 10°C (circulation not defined) Heat (placebo paradigm) 27 mm diameter Peltier thermode	Intensity (VAS) Anchors for pressure stimulus were "no pain" and "maximal pain". Anchors for cold stimulus were "no pain" and "unbearable pain". Anchors for heat stimulus were "no pain" and "unbearable pain".	Athletes (all male) 16 long-distance runners and triathletes, completing at least 6hrs per week endurance training for last 3 years Mean age = 27.9 ± 5.0y Controls (all male) 17 non-athletes (no regular participation in any kind of sport), matched to athletes for BMI. Mean age 26.9 ± 6.3 years Ethnicity not stated for any group. No information re pain experience.	Participants attended twice – during the first visit, a physical work capacity (PWC) test was conducted, and during the second visit, the main experiment (standard placebo and classical CPM paradigms) was undertaken. The placebo paradigm included both expectation and conditioning components and consisted of 3 phases: calibration, manipulation, and test. A sequential CPM design was used with a noxious test stimulus (to the tibia bone of the left leg using an algometer with a constantly increasing intensity of 50 kPa/s) presented before and immediately after a noxious conditioning stimulus (cold for 1 min) was applied to a spatially remote bodily region (right hand). Intensity: Athletes rated pressure pain as less intense ($\gamma02 = -19.764$, $P = .038$) than nonathletes and showed a lower slope of stimulus response curve ($\gamma12 = -11.353$, $P = .029$) compared to nonathletes. CPM: There was a significantly greater CPM effect in athletes vs. nonathletes ($\gamma03 = -16.4$, $P = .023$). No significant CPM effect in nonathletes ($\gamma01 = -.8$, $P > .1$. Placebo effect only significant in non-athletes. A positive association between CPM and placebo effects [$r(15) = .545$, $P = .02$] is present in nonathletes, and a negative trend is observed in athletes [$rs(14) = -.497$, $P = .052$.	Low

Table 1 (*Continued*)

Study	Noxious stimulus	Outcome measures	Participants	Characteristics of study and findings	Risk of bias
Geisler et al (2021)[33]	Heat 27 mm diameter Peltier thermode,	Intensity (VAS with anchors of 0 = no pain, 100 = unbearable pain)	Athletes (all male) 18 endurance athletes who trained at least 6 h per week in endurance activities for the previous 3 years. Mean age = 27.9 SD = 4.9. Controls (all male) 19 non-athletes (no regular participation in any kind of sport) who were age matched to athletes. Mean age = 26.1 y, sd = 3.1 y. Ethnicity not stated for any group. No information re pain experience, but participants pain free upon commencing study.	The study involved functional magnetic resonance imaging (fMRI) during painful stimulation. During fMRI, a pseudo-random sequence of twelve 20 s thermal stimuli with different intensities (38, 45, 47, and 48.9_C; 3 trials each) was applied using a 27 mm diameter fMRI-compatible Peltier thermode to a 4 × 4-cm square drawn on the subjects' left anterior thigh, dermatome L3. Intensity: Athletes rated higher temperatures as less intense than non-athletes (45, 47 and 48.9°C ($P = .33$, d = .72). Athletes had reduced activation in several brain regions that are associated with nociceptive stimulation compared to non-athletes.	Low
Geva and Defrin (2013)[3]	Heat (test stimulus) Peltier-based thermal stimulator with a 3 cm^2 surface. Cold (conditioned stimulus) Circulating cold water bath at 12°C	Threshold (button press recording temperature) Tolerance (button press recording temperature) Intensity (VAS with anchors of ''no pain sensation'' and ''the most intense pain sensation imaginable'')	Athletes 10 male and 9 female triathletes, all regularly training for triathlon/iron man and competed in at least 2 national competitions per year for the last 3 years. Mean age = 39.6 ± 12 years. Controls 7 males and 10 female active controls who had undertaken amateur physical exercise (running, swimming, aerobics classes) for 3 years. Mean age = 36.5 y ± 11. Ethnicity not stated for any group. No information re pain experience.	A parallel CPM design was used with a noxious test stimulus (heat beginning at 35°C, increasing at 2°C/s) applied to the forearm of the non-dominant arm presented before and during the application of a noxious conditioning stimulus (cold for 30 s) applied to a spatially remote bodily region (the dominant hand). Threshold: No significant differences between groups. Tolerance: Athletes had higher tolerance than non-athletes ($P < .0001$) Intensity: Athletes perceived heat significantly less painful than non-athletes ($P < .05$) that is, the temperature required to score a 7 on the VAS was significantly higher for athletes.	Low

Table 1 (*Continued*)

Study	Noxious stimulus	Outcome measures	Participants	Characteristics of study and findings	Risk of bias
Guieu et al (1992)[40]	Shock Electrical stimulation for leg flexion nociceptive reflex.	Threshold Reflex response	Athletes 2 female and 4 male athletes who all regularly participated in national or international events and did 1 or 2 intensive training sessions/day. Mean age = 22 (range18-27). Controls 1 female and 7 male non-athletes who did no intensive sports training. Mean age = 24 (range 22-27). Ethnicity not stated for any group. No information re pain experience.	An electrical stimulator with variable intensity, pulse width and rate, was used. Electrical stimulation of the sural nerve was applied in the external retromalleolar gutter in successive series of 5 rectangular pulses with a duration of 1 ms (interval of 2 ms). The stimulating electrodes were placed 2 cm apart. Athletes seated on an ergometric bicycle were asked to furnish a regular effort at 70 cycles/min, developing a force of 200 watts for 20 min. The nociceptive threshold was measured at rest and just after the end of the exercise in the athletes, and only at rest in the control subjects. Threshold: At rest, athletes had significantly nociceptive reflex threshold than controls (U = 7, $P < .05$). Physical activity led to a significant increase in the nociceptive reflex threshold in athletes (T = 0, $P < .05$) with a mean increase > 55%.	Moderate
Hall and Davies (1991)[27]	Cold Bucket of iced water, stirred continuously and maintained 1–2°C.	Intensity (VAS with anchors "no sensation" and "strongest sensation I can imagine") Affect (unpleasantness, VAS with anchors "not bad at all" and "most intense bad feeling for me")	Athletes 7 male and 7 female athletes who were all were varsity track NCAA div 1. Mean age not defined, but all were students. Controls 7 male and 7 female non-athletes who did not do any form of organised sport or training independently of class activities. Mean age not defined, but all were students. Ethnicity not stated for any group. No information re pain experience.	Participants placed their right arm into the ice bucket until the middle finger touched the bottom (immersing the hand, wrist, and lower forearm). Participants were directed to maintain this position until the pain could no longer be tolerated. A limit of 5 min was set to minimise any possible danger to the participant). At 1 min intervals participants completed VAS for pain intensity and pain affect. Intensity: Female non-athletes rated pain as more intense than male non-athletes ($P < .05$, d = 9.49), female athletes ($P < .05$, d = 12.05) and male athletes ($P < .05$, d = 19.13). No sex differences were evident within the athlete group. Pain Affect: Female non-athletes reported higher pain unpleasantness than male athletes ($P < .05$, d = 15.52) and female athletes ($P < .05$, d = 10.38). Male non-athletes reported higher pain unpleasantness than male athletes ($P < .05$, d = 9.63). No sex differences were evident within the control group.	Moderate

Table 1 (*Continued*)

Study	Noxious stimulus	Outcome measures	Participants	Characteristics of study and findings	Risk of bias
Hoffman et al (2007)[32]	Pressure 6 × .25 mm Lucite (Perspex) edge duration 2 min	Intensity (VAS with anchors of "no pain" and "worst possible pain")	Athletes 21 endurance athletes who were competing in Western States 100 Mile Endurance Run Mean age not defined Controls 11 controls drawn from crew members and race assistants who were awake for the duration of the race. No information on activity levels provided. Mean age not defined. Gender not stated Ethnicity not stated for any group. No information re pain experience.	Repeated measures field study with participants tested pre and post completion of a 100 mile race. A pressure pain stimulator was used, through which a constant force of 9.8 N was applied against the dorsal surface of the middle phalanx of the non-dominant index finger. Intensity: No difference between runners and controls pre-race ($P = .22$). The post-race comparisons are not reported. There was an observed analgesic effect of race completion, but this was only apparent in faster runners.	High
Janal et al (1994)[7] STUDY 1	Cold Non-circulating ice bath (temp. not reported) with limit of 3 min Heat Radiant heat through dolorimeter with 2 cm diameter (47°C and 48.2°C) Ischemic Tourniquet above elbow at 250 pressure and hand dynamometer with resistance set at 7.72 kg	Threshold Time to report cold as painful Tolerance For cold—time to withdrawal from stimulus. For heat—time to withdrawal from stimulus. For ischaemic – time to disengage from activity Intensity For cold, verbal scale – Warm, Nothing, Cool, Cold, Very Cold, Faint Pain, Moderate Pain and Severe Pain For heat, verbal scale – Hot, Very Faint Pain, Faint Pain, Painful and Very Painful For ischaemic, verbal scale – Nothing, Slight Sensation/Non-painful, Strong Sensation/Non-painful, Faint Pain, Definite Pain, Severe Pain	Athletes (all male) 12 runners who trained on average 69.2 km/week Mean age = 38.8 (no range or SD provided) Controls (all male) 18 active controls who did not participate in regular aerobic training programmes. Mean age = 26.7 (no range or SD provided) Ethnicity not stated for any group. No information re pain experience	Participants randomly assigned to one of the 6 possible orders of the 3 pain tests. Within cold application, participants asked to rotate ('wave') their hand continuously in ice bath. Once 'Severe Pain' was experienced, a scale of 1 to 10 was used to capture increments of the sensation. Within heat application, heat applied to 3 points of the volar surface of each forearm. For ischemic test, an Esmarch bandage applied to express venous blood before tourniquet applied then after bandage removed, participants squeezed a hand dynamometer for 20 × 2 s intervals (resistance 7.72 kg). Threshold: Runners had significantly higher threshold than active controls for cold pain only ($t(32) < 3.43$, $P < .01$). However we have not included this in the meta-analysis as this measure is not true pain threshold (and is more related to intensity). Tolerance: No difference between groups for any stimulus Intensity: No difference between groups for any stimulus	Moderate

Table 1 (*Continued*)

Study	Noxious stimulus	Outcome measures	Participants	Characteristics of study and findings	Risk of bias
Janal et al (1994)[7] STUDY 2*	Cold Non-circulating ice bath (temp. not reported) with limit of 3 min Heat Radiant heat through thermal stimulator with 1 cm diameter tip (temps 36.0, 37.5, 45 & 46.5°C) Ischemic Tourniquet above elbow at 250 pressure and hand dynamometer	Threshold Time to report cold as painful Tolerance For cold – time to withdrawal from stimulus. For heat – time to withdrawal from stimulus. For ischaemic—time to disengage from activity Intensity For cold, verbal scale – Warm, Nothing, Cool, Cold, Very Cold, Faint Pain, Moderate Pain and Severe Pain For heat, verbal scale – Warm, Hot, Very Faint Pain, Faint Pain, Moderate Pain and Severe Pain For ischaemic, verbal scale – Nothing, Slight Sensation/Non-painful, Strong Sensation/Non-painful, Faint Pain, Definite Pain, Severe Pain	Athletes (all male) 36 runners who trained at least 30 km/week for at least 3 months. Mean age = 30.4, SD = 4.5) Controls (all male) 24 active controls who were not engaged in a regular aerobic training programme Mean age = 27.7, SD = 5.7 Ethnicity not stated for any group. No information re pain experience	This was a second study reported within the paper. Procedures were similar to above, with the following differences – for cold, verbal reports gathered very 10 s during emersion, but also every 20 s for 5 min following withdrawal; for heat, 4 heat settings used with a 1 cm diameter probe and stimulus duration of 5 s (rating scale changed to reflect range of temperatures); for ischaemic, venous blood drained by raising the arm rather than using Esmarch bandage. Additional measures taken in the form of Heart Rate and Blood Pressure. Threshold: Runners had later reports for Faint Pain (F(1,53) = 7.2, $P < .01$) and Moderate Pain (F(1,48) = 6.3, $P < .02$. However we have not included this in the meta-analysis as this measure is not true pain threshold (and is more related to intensity) and we were reliant on figures. Tolerance: No difference between groups for any stimulus. We excluded heat tolerance in the meta-analysis as we considered the measure flawed. Intensity: Runners reported lower pain intensity 20 s after removal of cold stimulus ($P < .05$). Runners were more sensitive to heat than non-runners ($P < .01$). No difference between groups for ischemia.—However we have not included in the meta-analysis as the measure was considered flawed and there was not enough data.	Moderate
Johnson et al (2012)[35]	Electrical/Chemical Iontophoretic pain with electric current (max 25 mA) passed through a potassium chloride solution	Threshold Electrical current at which button pressed to indicate sensation painful Tolerance Electrical current at which button pressed to terminate stimulation	Athletes 19 male & 7 female endurance athletes who must have completed at least 2 marathons in the last 2 years and were currently training regularly Mean age = 46.2, SD= 10.2. Controls 19 male & 7 female participants who had never done a marathon or endurance sport and were not training for any sport. Mean age = 46.1 SD= 10.7. Ethnicity not stated for any group. No information re pain experience	Pain was induced using potassium iontophoresis with 2 electrodes placed directly opposite each other on the participant's forearm. Threshold: Athletes had lower threshold than non-athletes (t = 3.63, $P < .001$). Tolerance: Athletes had higher tolerance than non-athletes (t = 3.6, $P < .001$). Pain related self-efficacy (VAS with anchors of "no confidence" and "total confidence") was also measured alongside the Cognitive Coping Strategies Inventory. Marathon runners had higher pain self-efficacy than controls. Participants reporting more use of associative coping strategies alongside less evidence of dissociative strategies and catastrophizing appeared to exhibit higher pain tolerance.	Moderate

Table 1 (*Continued*)

Study	Noxious stimulus	Outcome measures	Participants	Characteristics of study and findings	Risk of bias
Leznicka et al (2016)[36]	Cold Iced water bath at 0–.5°C. Max duration 2 min. Pressure Algometer with 1 cm^2 tip	Threshold For cold – time to participant saying "Pain" For pressure – pressure being applied when participant said "Stop" Tolerance Time to withdrawal from cold stimulus	Athletes (all male) 140 combat athletes comprising 81 boxers, 31 karateka and 28 other martial artists with at least 5 years' experience. Mean age = 21.1 ± 2.4 Controls (all male) 181 non-athletes who were not involved in any sport at professional level. Mean age = 21.1 ± 1.8 Ethnicity not stated for any group. No information re pain experience.	Pressure stimulus test was conducted with participant in a sitting position, with the right upper limb, bent at the elbow, being placed on the table. The measurement was made on the back of the hand between the thumb and forefinger. For cold stimulus, participants' right hand was submerged in 37°C water for 2 min before being placed in the ice bath. Threshold: Martial artists had higher threshold for pressure pain only ($P < .0001$) Tolerance: Combat athletes had higher cold tolerance than non-athletes ($P = .0002$) The 2 groups were compared on BMI and no differences were found.	Moderate
Leznicka, Starkowska, Lulinska et al (2017)[28]	Pressure Algometer with 1 cm^2 tip	Threshold Pressure being applied when participant said "Stop" Tolerance Pressure being applied when participant withdrew from the stimulus	Athletes (all male) 203 male combat athletes. All had engaged in mixed martial arts, boxing or karate for at least 5 years. Mean age = 24.8 ± 6.7 Controls (all male) 70 male non-athletes who were not competitively engaged in any sport. Mean age = 21.12 ± 1.8 Ethnicity not stated for any group. No information re pain experience.	Testing was undertaken with participants in a sitting position, their right arm, flexed at the elbow, resting on the table. The measurements were taken on the back of the hand between the thumb and the index finger. The researcher palpably assessed the contact point, then placed the algometer perpendicular to the point and gradually applied pressure to the tissue at a rate of approximately 100 g/s. Threshold: Athletes had higher pain threshold than non-athletes ($P < .001$, no ES reported) Tolerance: Athletes had higher pain tolerance than non-athletes ($P < .001$, no ES reported). The study also examined coping styles, measured using The Brief Coping Inventory Note: On contacting the authors, we discovered that some participants also took part in 2 other studies published by the lead author in 2017. As such we used this paper as it had the most data available.	Moderate

Table 1 (*Continued*)

Study	Noxious stimulus	Outcome measures	Participants	Characteristics of study and findings	Risk of bias
Manning and Fillingim (2002)[4]	Pressure Algometer with 1 cm^2 tip. Max pressure of 20 kg/cm^2. Counterbalanced application over 4 sites Ischemic Tourniquet above elbow at 230 mmHg pressure and hand dynamometer Cold Circulating cold pressor at 1°C.	Threshold For pressure - force applied to the algometer at point of pain report. For ischaemic – time to first report of pain sensation. For cold – time to first report of pain sensation. Tolerance For ischaemic – time to report of pain as unbearable. For cold – time to withdrawal from stimulus. Intensity VAS (anchors not stated). Unpleasantness VAS (anchors not stated).	Athletes 12 male & 12 female athletes from soccer, gymnastics, football, tennis, fencing, crew and wrestling, competing at National Collegiate Athletic Association Division 1A level for at least 1 y. Mean age not defined, but range 20–24. Controls 12 male & 12 female active non-athletes who were active exercisers (at least 3 h/wk) but not involved in competitive sport. Mean age not defined, but all college students. Ethnicity not stated for any group. No information re pain experience.	Pressure applied at 4 sites (biceps, pectoralis, rear deltoid, quadriceps) with each site measured 2 to 5 times and mean score used. For ischaemic element, venous blood drained by raising the non-dominant upper arm for 30 s before inflation of the tourniquet. Participants then undertook 20 grip actions at 50% of max grip strength. For cold, Participants immersed the non-dominant hand into the ice bath until the middle finger contacted the bottom of the ice bath, submerging the forearm in iced water. Participants completed the experimental scenarios in random order and then took part in a follow up interview to discuss their experiences. HR and BP were taken in between pain tests to ensure participants had recovered (min 20 min). Threshold: Athletes had higher threshold in relation to cold than non-athletes ($P < .05$). No significant differences between groups for pressure and ischemia. However, there was not enough data in the paper to include cold or ischemic pain threshold in the meta-analysis. Only pressure was included; data taken from all 4 sites were averaged. Tolerance: Athletes had higher tolerance than non-athletes for both ischemia ($P < .05$) and cold ($P < .05$). However there was not enough data in the paper to include tolerance in the meta-analysis. Intensity: No difference between groups. Unpleasantness: No difference between groups. However, athletes described pain as less unpleasant than non-athletes during post-intervention interview.	Moderate
Monnier-Benoit et al (2006)[42]	Pressure Lucite (perspex) edge (6 mm x .25 mm) applied perpendicular to skin at 9.8 N for max 2 min.	Intensity Rating scale with 0 =No Pain, .5 =Just Noticeable, 2 = Light, 5 = Heavy, 10 = Maximum Pain and > 10 = Highest Pain Possible	Athletes (all male) 10 cyclists who were national level competitors and trained 10 h per week Mean age = 25.3, SD = 4.94. Controls (all male) 10 sedentary males Mean age = 24.5, SD = 2.22. Ethnicity not stated for any group. No information re pain experience.	Participants were initially tested to ascertain VO2 max. On a subsequent visit participants worked at 75% VO2 max on a for 30 min with a constant pedalling cadence of 80 rpm. Pressure testing was undertaken 5 and 30 min post exercise with Lucite edge applied to non-dominant index finger. Intensity: No significant difference between groups at either time point. Note: the authors refer to their rating scale as Borg CR10, but this is a measure of perceived exertion and doesn't have the rating labels defined. The modified exertion scale used may have impacted upon findings.	Moderate

Table 1 (*Continued*)

Study	Noxious stimulus	Outcome measures	Participants	Characteristics of study and findings	Risk of bias
Ord and Gijsbers (2003)[8]	Ischemic standard sphygmomanometer above elbow pressure set at 200 mmHg	Threshold Time to first report of pain sensation Tolerance Time between first report of pain sensation and reporting of pain as unbearable	Athletes (all male) 20 competitive rowers Mean age = 20 (range = 18–26) Controls (all male) 20 recreational sport participants m age = 22) range = 18–31. They were not in regular sport training Ethnicity not stated for any group. No information re pain experience.	Whether venous blood was drained not reported. After inflation of the tourniquet, participants directed to open and close the fist rhythmically until pain felt and then to tolerate pain for as long as possible. Threshold: No significant differences Tolerance: Competitive athletes had higher tolerance than control group ($P < .05$, d = .94) The paper also examined coping strategy use. Competitive rowers used mental strategies more than non-training group ($P < .05$), and used multiple strategies more often ($P < .05$). Pain tolerance was positively correlated with number of strategies used while in pain ($r = .70$, $P < .01$).	Moderate
Paparizos et al (2005)[37]	Cold Recirculating double-bucket system maintained at 1–3°C. Max 90 s	Tolerance Time to withdrawal from stimulus Intensity NRS 0 = No Pain to 10 = Extreme Pain.	Athletes (all female) 25 high skilled ballet dancers and 22 female low skilled ballet dancers High skilled dancers had 10 +years of training and were in advanced or intermediate classes. Low skilled dancers had less than 10 years training experience and were in beginner or intermediate classes. Mean age = 19.9, SD = .21. Controls (all female) 26 female non-dancers recruited from an undergraduate psychology programme. Mean age = 20.1, SD = .24. Ethnicity not stated for any group. No information re pain experience.	Participants initially placed their non-dominant hand and forearm into a water bath at 37°C for 2 min, before transferring the limb to the cold water bath where it was placed with fingers apart. Pain rated at 30, 60 and 90 s Tolerance: High skilled dancers had higher tolerance than low skilled and non-dancers ($P < .05$). All dancers had higher tolerance than non-dancers ($P < .05$). Intensity: No significant difference between groups Participants also completed the Pain catastrophizing scale, S-POMS, Short form McGill pian questionnaire and SFMPQ. Catastrophizing was a significant predictor of pain in dancers. Helplessness and total catastrophizing predicted pain in the control group.	Moderate

Table 1 (*Continued*)

Study	Noxious stimulus	Outcome measures	Participants	Characteristics of study and findings	Risk of bias
Petersen et al (2019)[29]	Pressure (test stimulus) Algometer with 1 cm diameter circular tip. Cold (conditioning stimulus) Ice bath at 2°C Fatigue (conditioning stimulus) Isometric hand gripping at 50% of maximum capacity. Treadmill running at 110% of gas exchange threshold for 30 min.	Threshold Button pressed when pressure perceived as painful Intensity NRS—1–20, but anchors not defined Unpleasantness NRS – 1-20, but anchors not defined	Athletes 2 female & 11 male endurance trained athletes(defined as collegiate track athletes who trained at least 3 h per week for the previous 3 years and competed at distance of >1,500 m). Mean age not defined. Controls 2 female & 11 male active controls (defined as active based on ACSM guidelines of 150 min moderate or 75 min vigorous intensity activity per week). Mean age not defined. Ethnicity not stated for any group. No information re pain experience.	Five visits used to cover 2 familiarisation sessions and 3 experimental sessions. Pressure applied to belly of the brachioradialis muscle of the dominant hand and the belly of the vastus lateralis of the dominant leg. The study adopted a sequential conditioned pain modulation protocol with cold, and fatigue used as conditioning stimuli. Females were tested during luteal phase of menstrual cycle. Threshold: No significant differences between groups Intensity: Endurance athletes reported less pain intensity ($P = .03$) than controls Unpleasantness: Endurance athletes reported less unpleasantness ($P = .009$) than controls There were no observed CPM differences between groups.	Moderate
Pettersen et al (2020)[9]	Heat (for threshold & intensity) 30×30mm aluminium contact thermode. Max 52°C. Cold (tolerance) Circulating cold water bath at 2°C. Max. duration 3 min	Threshold Button press when heat sensation became painful which recorded temperature. Tolerance Time to withdrawal from cold stimulus Intensity VAS with anchors of "No pain sensation" and "Most intense pain sensation imaginable" for response to heat stimulus	Athletes 32 athletes from soccer (17), distance running (3) and cross-country skiing (12). All were described as competing at the highest level and average training time was 16.5hrs/wk Mean age not defined. Controls 39 controls. These appear to be students. They are described as completing an average of 3.92 h per week exercising. Mean age not defined. Sex splits not clearly defined between groups but the participant group as a whole consisted of 38 men and 33 women with a mean age of 23.79 SD 4.43. Ethnicity not stated for any group. No information re pain experience.	For heat stimulus, thermode was attached to the left volar forearm except 2 subjects who had tattoos on that arm. For threshold testing, the thermode had a baseline temperature of 32°C when applied to the skin and temperature increased by 1°C/s. Mean of 5 tests taken used for analysis. For intensity testing, the process started at baseline temperature (32°C), increased by 10°C/s and kept a stable temperature of 47.5°C for 30 s, before returning to baseline. Intensity scores through VAS continuously recorded. For cold pressor, participants were instructed to submerge their right hand up to and including the wrist into water and told to keep their hand in the water as long as possible. Threshold: Athletes had higher heat pain thresholds ($P < .05$) than non-athletes. Tolerance: Endurance athletes (cross-country skiers and long-distance runners) were more likely to reach the maximum permitted duration in cold pressor (OR = 6.02, $P = .02$). Intensity: Endurance athletes reported lower pain intensity compared to non-athletes ($P < .05$). Physiological measures of blood pressure and heart rate were taken along with the psychological measures of Grit, BFI traits and Fear of Pain. Higher Grit scores were associated with increased time in the cold pressor. Increased fear of pain was associated with reduced tolerance of cold. Higher fear scores were also associated with increased pain intensity.	Low

Table 1 (*Continued*)

Study	Noxious stimulus	Outcome measures	Participants	Characteristics of study and findings	Risk of bias
Roebuck et al (2018)[38]	Cold Circulating bath set at .1–.5°C. Max duration 3 min.	Tolerance Time to withdrawal from cold stimulus Intensity (NRS - 11-point numerical pain rating scale (0 = No Pain to 10 = the Worst Pain Possible)	Athletes 9 male & 11 female endurance athletes - Ultra-runners who had undertaken more than one ultra in the previous year. Mean age not stated but range of 18-70 years defined. Controls 20 age (± 5 years) and sex matched active controls who had never run an ultra-marathon in their lifetime or a marathon or half marathon in the previous year. Mean age not stated but range of 18-70 years defined. Ethnicity not stated for any group. No information re pain experience, but chronic pain conditions and current pain medication use defined as exclusion criteria.	Participants initially placed their non-dominant hand and forearm into a water bath at 37°C for 3 min. They were then instructed to immerse the hand up to the ulnar styloid in the immersion compartment of the cold pressor and to keep it there for as long as they could Intensity was measured using the NRS every 10 s Tolerance: Endurance athletes had higher pain tolerance than controls (P = .007, r = .48) Intensity: Endurance athletes reported less pain intensity than controls (P = .012, partial η2 = .16) Participants also completed the Pain catastrophizing scale, Pain anxiety symptoms scale-20, Pain vigilance and awareness questionnaire and the Pain resilience scale. Endurance athletes reported less maladaptive symptoms than controls – less pain anxiety, cognitive anxiety, escape and avoidance, fearful thinking, physiologic anxiety. Reduced pain related escape and avoidance behaviours mediated the elevated pain tolerance in the endurance athletes.	Moderate
Ryan and Kovacic (1966)[5]	Heat 500w pre-focus projection lamp focused by a projector system condensing lens through a fixed aperture, 1 in. in diameter Pressure Pressure from standard clinical sphygmomanometer applied through a football cleat placed within the sphygmomanometer Ischemic standard sphygmomanometer above elbow pressure set at 300 mmHg.	Threshold Time to close lamp shutter at point sensation became painful Tolerance Highest tolerable pressure through cleat (mmHg) Number of fist clenches achieved before participant withdrawal from activity	Athletes (all male) 20 contact athletes (football, boxing and wrestling) & 20 non-contact athletes (golf and tennis). Mean age not defined. Controls (all male) 20 non-athletes who had not participated in any varsity athletics Mean age not defined. Ethnicity not stated for any group. No information re pain experience.	For threshold, participants were seated in front of the heat lamp and their forehead blackened to improve absorption. They were instructed that they would first experience a warm sensation, followed by heat, and then pain. They were instructed to close the shutter when the first sharp stab of pain was evident. For pressure tolerance, the pressure cleat was applied to the tibia and participant informed that pressure to the leg would be increased gradually until they reported that they could stand no more. For ischemic tolerance, the participant sat with the elbow of his preferred arm resting on a table and the arm was flexed at approximately a 90° angle. A sphygmomanometer cuff was applied to the upper arm and the participant asked to flex and extend their fingers at the rate of once per second. The rhythm was kept by the use of a metronome. Threshold: No significant differences between groups. Tolerance: High contact athletes had higher pressure tolerance than non-contact athletes ($P < .0001$, d = 1.033) and non-athletes ($P < .0001$, d = −.13). High contact athletes had higher ischemic tolerance than non-contact athletes ($P < .0001$, d = 1.13) and non-athletes ($P < .0001$, d = −1.44)	High

Table 1 (*Continued*)

Study	Noxious stimulus	Outcome measures	Participants	Characteristics of study and findings	Risk of bias
Scott and Gijsbers (1981)[11]	Ischemic standard sphygmomanometer above elbow pressure set at 100 mmHg	Threshold number of fist contractions that a sensation recognisable as pain Tolerance number of fist contractions before participant withdrew from experiment	Athletes 16 male & 14 female high-level competitive swimmers (Scottish national squad) 13 male & 17 female swimmers competing at club level Mean age not defined. Controls 10 male and 16 female active controls with no experience of competitive sport. Mean age not defined, but all first-year undergraduates. Ethnicity not stated for any group. No information re pain experience.	Participants were sat with their elbow supported and ischaemia was induced by having the subject open and close the hand into a fist at the rate of one fist contraction per second. A metronome helped to establish a regular rhythm. Threshold: No significant differences. Tolerance: Elite swimmers had higher pain tolerance than club swimmers ($P < .0001$, d = 1.03) and non-athletes ($P < .0001$, d = 1.74). Club swimmers had higher tolerance than non-athletes ($P \leq .05$, d = .62). Pain tolerance also increased in competitive swimmers over the season ($P < .001$).	Moderate
Sheffield et al (2020)[24]	Cold Circulating cold water bath at 2–3°C. Max duration 5 min	Intensity VAS with anchors of "No Pain" and "Most Pain Imaginable" Motor Performance Targets hit and time to completion Cognitive Performance Time to completion	Athletes (all male) 50 athletes, split between high contact and low-contact groups. 25 high contact athletes participating in rugby, American football, martial arts, Gaelic football, and hurling. Mean age = 20.4, SD = 2.3. 25 low-contact athletes competing in tennis, badminton, trampoline, or were regular exercisers not doing competitive sport. Mean age = 20.2, SD = 1.9. Controls (all male) 21 non-athletes who were not taking part in any structured sport, exercise or physical activity. Mean age = 20.1, SD = 1.7. Ethnicity not stated for any group. No information re pain experience, but all pain free at time of study.	Participants were required to performe motor and cognitive tasks in 'pain' and 'no pain' conditions. All tasks were performed seated. During pain conditions participants placed their dominant foot in the ice bath. Perceived effort in completing the tasks was measured alongside pain intensity. Performance in motor task (ball throwing) measured by time to complete and number of targets hit. Performance in cognitive task (number grid) measured in terms of time to find all numbers. Both tasks had 'easy' and 'hard' conditions. Intensity: High contact athletes reported less pain intensity that low-contact athletes and non-athletes during both motor ($F(2,68) = 26.435$, $P < .001$, $\eta 2 = .44$) and cognitive ($F(2,68) = 17.634$, $P < .001$, $\eta 2 = .34$) tasks. Low contact and non-athletes did not differ from one another in either condition. This was not included in meta-analysis as they were within task measures. Motor Performance: Contact athletes performed better (more quickly) in a motor task during pain compared to non-contact and non-athletes. Large effect $P < .0001$, (g = .77). High-contact athletes' performance was not hampered by pain whereas the performance of low-contact athletes and non-athletes was. Performance was both slower and poorer in the pain condition. Cognitive Performance: No difference between groups	Low

Table 1 (*Continued*)

Study	Noxious stimulus	Outcome measures	Participants	Characteristics of study and findings	Risk of bias
Sternberg et al (1998)[6]	Heat 2-cm radiant heat Source at 2 settings (20 and 40) Cold Ice bath at 0–2°C. Circulation not defined. Max duration 90 s	Threshold Time to withdrawal from heat stimulus (when perceived as painful) Intensity Gracely Box Scale - 13 descriptors spaced across a 0 to 20 scale. Unpleasantness Gracely Box Scale - 13 descriptors spaced across a 0 to 20 scale. Pain intensity was rated on a scale of; (0 = no pain, 20 = intense pain).	Athletes 33 female & 34 male athletes from basketball (21), fencing (11) and track (35). Mean age not defined, but all college students Controls 14 female & 6 male non-athletes from an introductory psychology class. Activity levels not defined. Mean age not defined, but all college students Ethnicity not stated for any group. No information re pain experience.	For heat exposure, participants alternated placing their fingers and forearms over the heat source and were instructed to remove the arm when the sensation they experienced became painful. For cold exposure, participants placed their non-dominant arm (to the elbow) in the ice bath. Ratings of intensity and unpleasantness were obtained every 15 s for 90 s Threshold: No significant differences between groups at baseline for heat (out of competition) Intensity: No significant differences between groups at baseline (out of competition). This was not included in the meta analysis as it was not possible to extract the data. Unpleasantness: No significant differences between groups at baseline (out of competition) However not enough data were reported to include in the meta-analysis As well as pain measures, athletic competition was examined as a modulator of pain responses. Competition was found to modulate responses to painful stimuli – dependent upon body site tested, type of sport and type of pain test.	Moderate
Sternberg, Bokat et al (2001)[30]	Cold Ice bath at 0–2°C (circulation not defined). Max duration 90 s Heat Radiant heat source – detail not provided, but described as comparable to previous study	Intensity Gracely Box Scale - 13 descriptors spaced across a 0 to 20 scale. Unpleasantness Gracely Box Scale - 13 descriptors spaced across a 0 to 20 scale.	Athletes 19 male & 22 female athletes from the varsity track team (NCAA division III). Mean age not defined, but all college students Controls 11 male & 11 female non-athletes (defined as not taking part in any organised college teams or club sports). Mean age not defined, but all college students Ethnicity not stated for any group. No information re pain experience.	For heat exposure, participants alternated placing their fingers and forearms over the heat source and were instructed to remove the limb when the sensation they experienced became painful. For cold exposure, participants placed their non-dominant arm (to the elbow) in the ice bath. Ratings of intensity and unpleasantness were obtained every 15 s for 90 s. Unpleasantness and intensity scales were presented in random order. Intensity: Non-athletes reported more pain intensity ($P = .01$) than athletes. Unpleasantness: Non-athletes reported higher unpleasantness ($P = .01$) than athletes The study's focus was sex differences in the scale of any competition induced analgesia. Athletes and non-athletes participated in a number of active and sedentary competitive conditions. The results supported previous findings of activity induced analgesia - cold pressor pain intensity and unpleasantness ratings for an athlete group significantly decreased following participation in a competitive activity compared to baseline ratings. Sex differences in analgesic effect were also noted, but they were activity dependent.	Moderate

Table 1 (*Continued*)

Study	Noxious stimulus	Outcome measures	Participants	Characteristics of study and findings	Risk of bias
Sullivan et al (2000)[43]	Cold Ice bath at 2–4°C. Circulation not defined. Duration 1 min	Intensity 11 pt NRS with anchors "No Pain" and "Extreme Pain"	Athletes 26 male & 28 female varsity-level athletes competing in university basketball or rugby teams. Mean age not defined, but all students aged 19-24. Controls 27 male & 27 female 'sedentary' controls undertaking exercise activity once or less a week. Mean age not defined, but all students aged 19-24. Mean age for whole sample = 21.2 SD = 4.3. Ethnicity not stated for any group. No information re pain experience.	Prior to the cold stimulus, participants immersed their dominant arm in room temperature water for 5 min at which point they recorded their current pain level. They were then instructed to place their arm into the ice water, and to keep their arm immersed until they were asked to remove it. They were instructed to give a verbal rating of their current level of pain at the end of one minute, after which they were directed to remove their arm from the water. Intensity: Athletes reported less pain than sedentary controls, (m = 7, sd = 1.7), F(1,103) = 17.3, $P < .001$. The study also used the Pain Catastrophizing Scale (PCS). Catastrophizing predicted pain experience but did not differentiate athletes and non-athletes. Athletes ruminated less than sedentary controls, t(106) = 1.9, $P < .05$ and they also scored lower one the helplessness scale, t(106) = 3.1, $P < .01$.	Moderate
Tajet-Foxell and Rose (1995)[39]	Cold Ice bath of undefined temperature	Threshold Time to report stimulus as painful Tolerance Duration to withdrawal from stimulus Intensity VAS with anchors of "No Pain" and "Worst possible Pain" Unpleasantness Pain affect (SFMPQ)	Athletes 26 male & 26 female professional ballet dancers from a national company Mean age = 25.3, SD = 6. Controls 27 male & 26 female university students. No information on activity levels provided. Mean age = 24.3, SD = 5.9 Ethnicity not stated for any group. No information re pain experience.	Prior to the cold stimulus, participants immersed their hand in water at 37°C for 2 min before transferring their hand to a bowl of iced water. Participants were asked to indicate both when they initially perceived the stimulus to be painful (pain threshold) and when they considered the stimulus intolerable (pain tolerance) at which point the participant removed their hand from the water. Threshold: Athletes had higher pain threshold than controls ($P < .001$, d = 1.17) Tolerance: Athletes had higher pain tolerance than controls ($P < .001$, d = 1.71) Intensity: Athletes perceived pain to be more intense that controls (F(1,101) = 5.83, $P < .05$). Participants also completed the Short Form McGill Pain Questionnaire (SFMPQ), Miller Behavioural Style Questionnaire and Eysenck Personality Inventory. On the SFMPQ dancers scored higher on: Total pain score (F(1,101) = 12.22, $P = .001$). Pain sensory score (F(1,101) = 8.75, $P < .01$). Affective pain score (F(1,101) = 7.1, $P < .01$). Present pain intensity score (F (1,101) = 4.35, $P < .05$). Dancers were also more neurotic than controls.	High

Table 1 (*Continued*)

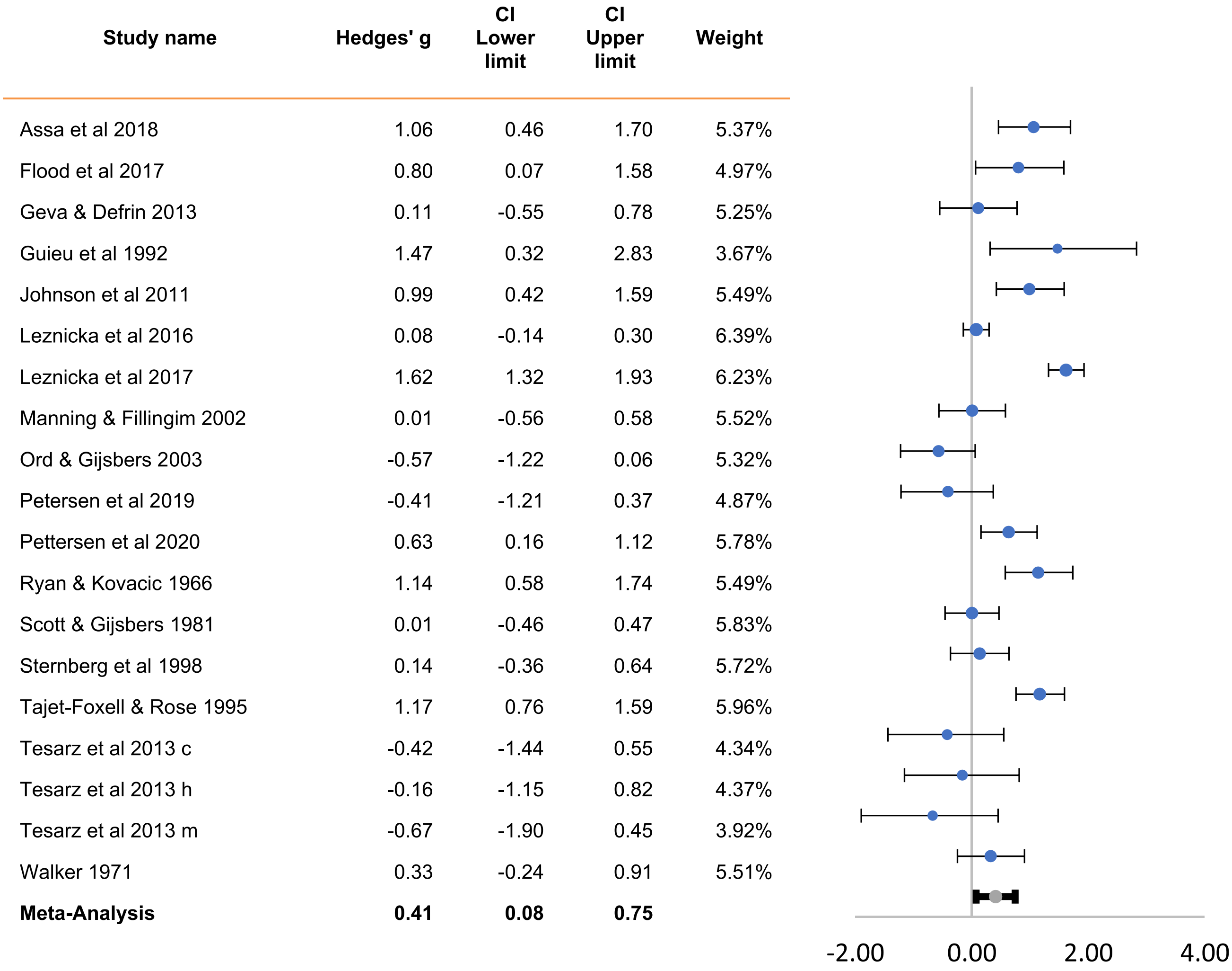
Study	Noxious stimulus	Outcome measures	Participants	Characteristics of study and findings	Risk of bias
Tesarz et al (2013)[31]	Heat Threshold - Thermal sensory device with 8 cm^2 thermode. Limit of 50°C. Test stimulus (CPM) - mean temperature eliciting a response of 50/100 on NRS. Cold Thermal sensory device with 8 cm^2 thermode. Limit of 0°C. Circulating cold water bath (12°C) used as conditioned stimulus Pressure No details provided, measured in kPa. 'Mechanical Pain' Weighted pinprick using flat contact area of .25 mm diameter and forces ranging from 8–512 mN	Threshold Temperature reported as painful in heat and cold directions. For mechanical pain - Mean of 5 series of ascending and descending stimulus intensities No details provided for pressure pain threshold Intensity NRS 0-100 with anchors of "no Pain" and "Most intense pain imaginable"	Athletes (all male) 25 endurance athletes who attended regional sports clubs and trained at least 3 h per week, with a V02 Max > 60 mL/min*kg. Mean age not defined, but range 18-35yrs. Controls (all male) 26 'normally active' controls (18-35 years old) who did not engage in regular physical activity Mean age not defined, but they were age and BMI matched. Ethnicity not stated for any group. No information re pain experience, but all pain free at time of study.	Thermal thresholds were obtained using ramped stimuli of 1°C/s, from a 32°C baseline which were terminated when participants pressed a button. The mean of 3 measurements was calculated. For mechanical pain threshold, the threshold was the geometric mean of 5 series of ascending/descending stimulus intensities. Threshold: Athletes had higher threshold for mechanical pain (weighted pinprick) ($P < .05$, ES= −.67). No differences between groups for heat, pressure or cold. Pressure pain threshold was not included in the meta-analysis as there was not enough information about the stimulus and site. Intensity: No significant differences between groups Conditioned pain modulation was assessed using a sequential design, whereby a noxious test stimulus (heat to dorsum of dominant hand) was presented before and immediately after a noxious conditioning stimulus (cold for 2 min) was applied to a spatially remote bodily region (non-dominant hand and wrist). Athletes had reduced CPM compared to controls – Athletes $P = .09$,D = .14. Controls, $P < .001$, D = .55.	Low
Thornton et al (2017)[21]	Cold Circulating cold-water bath at 2–3°C. Max duration 5 min Ischemic standard sphygmomanometer above elbow pressure set at 230 mmHg	Tolerance Time to withdrawal from stimulus. Intensity VAS with anchors 0 = "No pain" and 100 = "the most pain imaginable" Bothersomeness NRS with anchors of 0 = "Not at all bothersome" and 5 = "Extremely bothersome"	Athletes 47 male & 55 female student athletes, who were all were new to contact sports (rugby n = 62, American football n = 15, kickboxing n = 14, MMA n = 11). Mean age = 21.93 SD = 5.01 Controls Participants clustered at the end of the season into participating (adherers) (27 m, 20 F) athletes and non-participating (non-adherers) (20 m, 35 F) athletes based on attendance. Adhering athletes mean age = 23.12 SD = 6.21 Non-adherers mean age = 20.98 SD = 3.51 Ethnicity not stated for any group. No information re pain experience, but all pain free at time of study.	Participants were tested over the athletic season, whether continuing to participate or not (at start, 4 and 8 months). For cold, participants placed their dominant hand in the water up to the wrist and were instructed to keep it there for as long as possible and intensity ratings taken at 1 min intervals. For ischaemic, participants raised their non-dominant arm above their head for 30 s, after which a blood pressure cuff was placed round the upper arm and inflated to 230 mmHg at a rate of 40 mm Hg per second - full cuff inflation was taken as time 0 and participants rated intensity of their pain at this point. Participants then lowered their arm to the horizontal position and performed 20 handgrip dynamometer exercises at 50% of their maximum grip strength. Again, intensity ratings taken at 1 min intervals. Tolerance: Adhering athletes had higher ischemic pain tolerance at the start ($P = .27$, r = .05) middle ($P < .0001$, r = .41) and end of the season ($P < .0001$, r = .57) compared to non-adhering participants. Participating athletes were more tolerant to cold pain at the end of the season compared to non-participating athletes ($P < .0001$, r = .39). Intensity: No differences in pain intensity ratings were found between groups. Bothersomeness: Adhering athletes found contact pain less bothersome than non-adhering participants Coping styles were also measured. Adhering athletes exhibited higher direct coping and catastrophized less than non-adhering participants.	Moderate

Table 1 (*Continued*)

Study	Noxious stimulus	Outcome measures	Participants	Characteristics of study and findings	Risk of bias
Thornton, et al (2019)[19]	Pressure Digital algometer with 1 cm diameter circular tip	Tolerance Highest tolerable pressure Intensity VAS with anchors of "No pain at all" and "Worst pain imaginable". Motor Performance task completion time and accuracy (targets hit) Bothersomeness NRS with anchors of 0 = not at all bothersome, 5 = extremely bothersome	Athletes 63 male and 67 female athletes from a range of contact and non-contact sports Mean age = 22.1, SD = 3.8 Participants subdivided into 3 groups: 40 Experienced contact athletes (Mean experience = 112.2 mths, SD = 61.7). 40 novice contact athletes (Mean experience = 3.82 mths, SD = .85). 40 Non-contact athletes (Mean experience = 87.85 mths, SD = 35.8). Controls N/A The study compared different athlete groups Ethnicity not stated for any group. No information re pain experience, but all pain free at time of study.	Pain tolerance was measured by pressing towards the medial side of the radius from a position of 3 fingers above the radial styloid process. Pressure was applied in a vertical direction with increasing force at a rate of 1 N/cm^{2}s. Intensity rating was made immediately after the algometer was removed. To assess performance, twenty numbered targets were placed on a wall in a random order and at different heights. Participants were informed of which target to aim for immediately before each attempt. The sequence for the ten targets was random (i.e. not sequential), but was the same for each participant. Performance was measured based on how many targets were successfully hit and how long it took to complete ten targets. Tolerance: Experienced contact athletes had higher pain tolerance than both groups, F(2,117) = 41.63, $P < .0001$, r = .64. Intensity: Experienced contact athletes perceived less pain intensity than other groups, F(2,117) = 17.65, $P < .0001$, r = .48. There was no difference between non-contact and novice athlete groups. Performance: In the pain condition, experienced contact athletes hit significantly more targets than non-contact athletes, $P < .0001$, and novice contact athletes hit significantly more targets compared to the non-contact athletes, $P < .001$. Experienced contact athletes also completed the task significantly faster than non-contact athletes, $P < .001$. Novice contact athletes also completed the task significantly faster than the non-contact athletes, $P < .01$. In the no pain condition however, there was no performance difference between the athlete groups, $F(2,114) = 1.31$, $P = .27$ (targets hit) and $F(2,114) = 1.42$, $P = .24$ (time to complete). Bothersomeness: The experienced contact athlete group reported pain to be less psychologically bothersome than the other athlete groups $P < .0001$.	Moderate
Walker (1971)[12]	Electrical Low volt therapeutic generator using DC current. Max 30 mA	Threshold Current at which participant reported "just noticeable pain" Tolerance Current at which participant ended the test	Athletes (all female) 24 varsity-level basketball players Mean age not defined, but range 18–34 y. Controls (all female) 24 active controls (never participated in any inter-school athletic competition) drawn from a compulsory physical education class. Mean age not defined, but range 18–34 y. Ethnicity not stated for any group. No information re pain experience.	Both threshold and tolerance were obtained by electrical stimulation of the ulnar nerve, just proximal to the elbow, medial aspect. For threshold, the current was continuously increased until participants indicated a pain sensation. Both dominant and non-dominant arms were tested. For tolerance, the stimulus was increased from zero, by 1 mA/s until the participant terminated the process. Threshold: No differences between groups. Tolerance: Athletes had higher tolerance than controls ($P = .01$, d = 1.39).	Moderate

Table 2. Bothersomeness and Performance During Pain

Study	Results
Sheffield et al (2020)	Contact athletes performed better (more quickly) in a motor task during pain compared to non-contact and non-athletes. Large effect (g = .77)
Thornton et al (2018)	Experienced and novice contact athletes performed better (more quickly and accurately) in a motor task during pain than non-contact athletes. Small to medium effects (g = .52 for accuracy, g = .47 for time) Experienced contact athletes found pain less psychologically bothersome than novice contact and non-athletes. Small effect (g = .35).



Study name	Hedges' g	CI Lower limit	CI Upper limit	Weight
Assa et al 2018	1.06	0.46	1.70	5.37%
Flood et al 2017	0.80	0.07	1.58	4.97%
Geva & Defrin 2013	0.11	-0.55	0.78	5.25%
Guieu et al 1992	1.47	0.32	2.83	3.67%
Johnson et al 2011	0.99	0.42	1.59	5.49%
Leznicka et al 2016	0.08	-0.14	0.30	6.39%
Leznicka et al 2017	1.62	1.32	1.93	6.23%
Manning & Fillingim 2002	0.01	-0.56	0.58	5.52%
Ord & Gijsbers 2003	-0.57	-1.22	0.06	5.32%
Petersen et al 2019	-0.41	-1.21	0.37	4.87%
Pettersen et al 2020	0.63	0.16	1.12	5.78%
Ryan & Kovacic 1966	1.14	0.58	1.74	5.49%
Scott & Gijsbers 1981	0.01	-0.46	0.47	5.83%
Sternberg et al 1998	0.14	-0.36	0.64	5.72%
Tajet-Foxell & Rose 1995	1.17	0.76	1.59	5.96%
Tesarz et al 2013 c	-0.42	-1.44	0.55	4.34%
Tesarz et al 2013 h	-0.16	-1.15	0.82	4.37%
Tesarz et al 2013 m	-0.67	-1.90	0.45	3.92%
Walker 1971	0.33	-0.24	0.91	5.51%
Meta-Analysis	**0.41**	**0.08**	**0.75**	

Figure 2. Pain threshold forest plot showing the results of the meta-analysis.

no evidence of publication bias for these data. Further analysis with trim and fill did not indicate missing data points. Excluding the 1 study with a high-risk of bias,[40] also resulted in a large g of −1.23 [95% CI −2.29, .18], which was also non-significant, and reduced heterogeneity (Q = 16.32, $P = .03$; $I^2 = 75.50\%$).

Sub-group analyses were not conducted due to the small number of studies.

Pain Tolerance

The total sample size for studies examining pain tolerance was 1614 (range 10–321) from 19 studies with 24 estimates. Fig 8 illustrates the associated forest plot and the effects reported for each study. There was a large positive mean effect, g = .88 [95% CI .63, 1.13], which was significant. The heterogeneity of effects was significant (Q = 86.81, $P < .001$) and inconsistency was high ($I^2 = 73.51\%$). The funnel plot for the effect sizes appeared to be asymmetric, suggesting evidence of publication bias (see Fig 9). However, both Begg and Mazumdar adjusted rank correlation ($\tau = .09$, $P = .52$) and Egger's intercept (Intercept = 1.28, t = .74, $P = .47$) were not significant, which indicates no evidence of publication bias for these data. Nevertheless, trim and fill results indicated that there were 4 missing studies, so

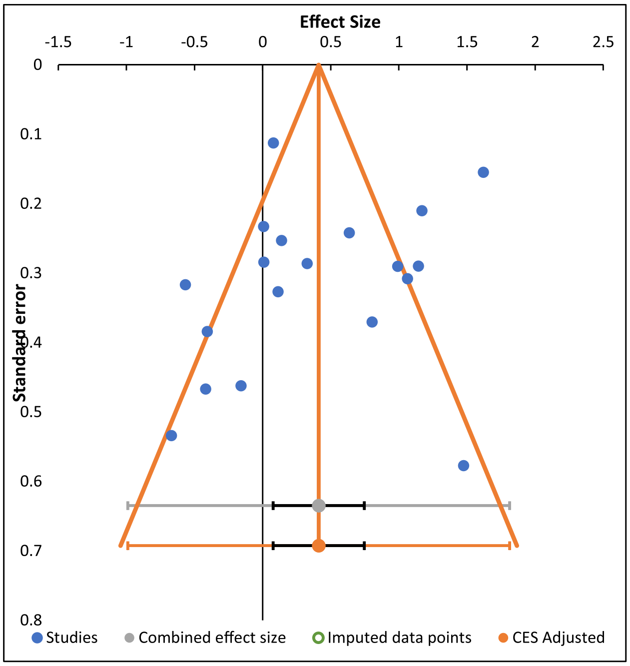


Figure 3. The funnel plot for pain threshold suggesting little evidence of publication bias. No additional data were imputed. Abbreviation: CES, combined effect size.

data were imputed on the left side of the mean. There was still a large positive mean effect, $g = .69$ [95% CI .43, .95], which was significant ($P < .001$). The heterogeneity of effects was significant ($Q = 102.42$, $P < .001$) and inconsistency was high ($I^2 = 73.64\%$). Excluding the 2 studies with a high-risk of bias,[5,40] resulted in a similar g of .80 [95% CI .55, 1.04] and reduced heterogeneity ($Q = 60.98$, $P < .001$; $I^2 = 67.20\%$).

In endurance athletes, subgroup analysis (11 studies with 331 participants), indicated a high level of homogeneity and a large $g = 1.03$, [95% CI .71, 1.35], which was significant. $Q = 13.00$, $P = .22$, $I^2 = 23.07\%$. Begg and Mazumdar $\tau = -.16$, $P = .48$ and Eggers Intercept $= -.98$, $t = -.62$, $P = .55$ were not significant, which indicates little evidence of publication bias for these data.

In contact athletes, subgroup analysis (8 studies with 810 participants) indicated a high level of heterogeneity and a large $g = 1.13$, [95% CI .51, 1.76], which was significant. $Q = 36.02$, $P < .001$, $I^2 = 80.56\%$. Begg and Mazumdar $\tau = .57$, $P = .05$ and Eggers Intercept $= 6.73$, $t = 4.52$, $P = .004$ indicating there is possible publication bias, however, the funnel plot was symmetric and no data were added via trim and fill.

In non-contact and non-endurance athletes, subgroup analysis (10 studies with 574 participants), indicated a indicated a high level of heterogeneity and a medium $g = .63$, [95% CI .11, 1.15], which was significant. $Q = 60.51$, $P < .001$, $I^2 = 81.82\%$. Begg and Mazumdar $\tau = -.24$, $P = .27$ and Eggers Intercept $= .97$, $t = .18$, $P = .86$ were not significant, which indicates little evidence of publication bias for these data. See Supplementary Materials for funnel, forest plots, and sub-group meta-analysis results.

Where cold was used as a pain stimulus, subgroup analysis (11 studies with 836 participants) indicated a high level of heterogeneity and a large $g = .80$, [95% CI .40, 1.20]. $Q = 48.18$, $P < .001$, $I^2 = 79.25\%$. Begg and Mazumdar $\tau = .20$, $P = .39$. Eggers Intercept $= 2.67$, $t = .96$, $P = .36$ suggested there was no evidence of possible publication bias, however, the funnel plot was asymmetric and one data point was added with trim and fill on the left-hand side of the mean, producing a revised $g = .71$, [95% CI .29, 1.13], $Q = 50.9$, $P < .001$, $I^2 = 78.39\%$.

Where ischemia was used as a pain stimulus, subgroup analysis (7 studies with 330 participants) indicated a high level of heterogeneity and a large $g = .87$, [95% CI .17, 1.57] which was significant. $Q = 24.10$, $P = .001$, $I^2 = 75.10\%$. Begg and Mazumdar $\tau = -.05$, $P = .88$ and Eggers Intercept $= -1.14$, $t = -.20$, $P = .85$ indicating there is no evidence of publication bias. However, the funnel plot was asymmetric suggesting evidence of publication bias with trim and fill indicating that there was one missing data point so data were imputed on the left side of the mean, producing a revised $g = .68$, [95% CI −.03, 1.39], $Q = 28.54$, $P < .001$, $I^2 = 75.47\%$.

Discussion

The meta-analyses indicate that athletes differ from non-athletes in response to noxious stimuli across a range of outcome measures. There were large differences for tolerance alongside smaller differences for threshold replicating Tesarz's[22] findings. Additionally, and for the first time, these analyses revealed significant large effects for intensity and non-significant, yet large effects for unpleasantness (based only on 5 studies). Only 1 study assessed pain bothersomeness, and 2 assessed performance in pain; there were medium effects for both outcomes.

There were differences in pain threshold, but these were smaller than for other pain outcomes; the reasons for these remain unclear. Ultimately, whilst clinicians and researchers may work to the International Association for the Study of Pain's definition, to participants, "pain is what the patient says it is"[45] and despite marked improvements in brain imaging, there remains no 'objective' measure of the pain experience.[46] Expressions of pain can be seen as performative,[47] but the context of experimental pain is very different from that of clinical encounters or sporting situations, which may influence the nature of participants' pain expression. Whether variations in threshold are best explained in terms of sensory differences or a re-definition of the pain experience (a change to what an athlete considers painful) therefore requires further research involving both Quantitative Sensory Testing and pain self-report (eg, to explore changes to perceived anchors).

An explanation for some differences in reporting of perceived pain intensity (which may also account for the heterogeneity observed), relates to the language used within experimental protocols. This is particularly significant in relation to the anchors used for intensity.

Study name	Hedges ' g	CI Lower limit	CI Upper limit	Weight
Anders et al. 2022 mech	-0.10	-1.06	0.85	3.57%
Anders et al. 2022 heat	-0.23	-1.19	0.72	3.56%
Anders et al. 2022 cold	-0.67	-1.68	0.28	3.51%
Assa et al 2018	-1.02	-1.65	-0.42	4.22%
Diotaiuti et al 2022	-1.32	-1.90	-0.77	4.32%
Flood et al 2017	-1.77	-2.69	-0.96	3.69%
Freund 2013	-1.06	-2.02	-0.18	3.61%
Geisler et al 2020	-0.83	-1.57	-0.12	4.00%
Geisler et al 2021	-0.38	-1.05	0.27	4.14%
Geva & Defrin 2013	-1.50	-2.29	-0.78	3.93%
Hall & Davies 1991	-2.06	-3.06	-1.18	3.52%
Hoffman et al 2007	-1.36	-2.21	-0.58	3.79%
Manning & Fillingim 2002 i	0.39	-0.42	1.23	3.80%
Manning & Fillingim 2002 c	0.35	-0.46	1.18	3.81%
Monnier-Benoit et al 2006	-0.24	-1.16	0.65	3.66%
Paparizos et al 2005	-0.04	-0.53	0.44	4.48%
Petersen et al 2019	-0.87	-1.72	-0.08	3.80%
Pettersen et al 2020	-0.41	-0.89	0.06	4.50%
Roebuck et al 2018	-0.81	-1.48	-0.18	4.14%
Sternberg et al 2000	-2.01	-2.67	-1.41	4.17%
Sullivan et al 2000	-0.78	-1.18	-0.39	4.64%
Tajet-Foxell & Rose 1995	0.46	0.07	0.85	4.65%
Tesarz et al 2013	-0.38	-0.95	0.17	4.34%
Thornton 2017 ischemic	-2.66	-3.46	-1.94	3.89%
Thornton 2017 cold	-1.08	-1.69	-0.51	4.27%
Meta Analysis	**-0.80**	**-0.48**	**-1.13**	

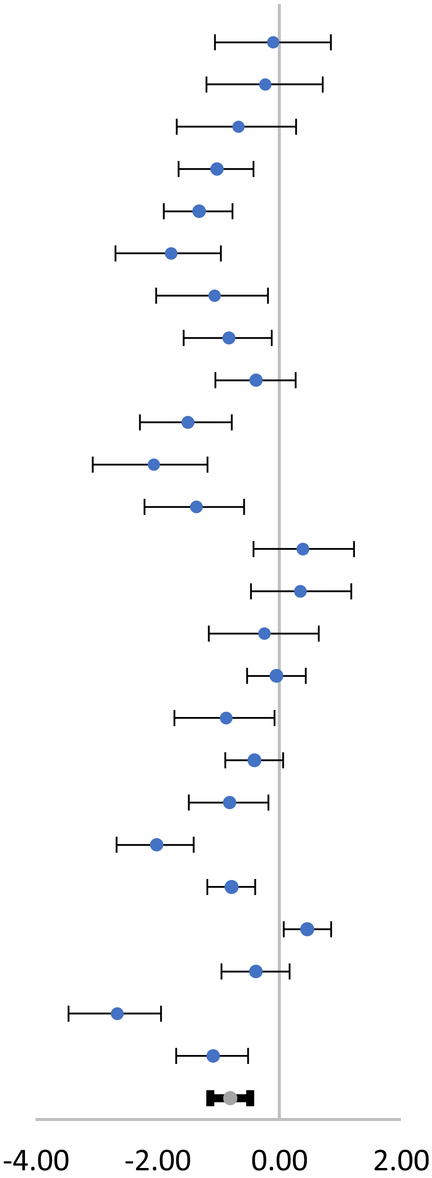


Figure 4. Pain intensity forest plot showing the results of the meta-analysis.

Whilst numerical rating scales for pain intensity are widely used, easy to administer, and offer adequate discriminant power,[48] some care must be taken when interpreting data from such scales, as they may not represent a true ratio measure,[49] are subject to sex differences[50] and may actually represent the emotional qualities of the pain more than true sensory intensity.[51] It is also well known that language influences responses to pain[52] so variation in scale anchors may well influence responses.[53] Some studies have used "worst pain imaginable" as the highest anchor,[21] whereas others have used terms less indicative of an upper ceiling. such as "severe pain"[38] or failed to provide anchor labels.[4] As athletes, particularly contact or endurance athletes, typically have more experience of high levels of pain, their appraisal of what constitutes "worst pain imaginable" or "severe pain" may be altered by those experiences.[21] Furthermore, experimental noxious stimuli cannot represent the uppermost regions of a pain scale as it would be ethically unacceptable to administer stimuli at a level of significant tissue damage or the most extreme exhaustion. Many participants will be aware of this, which may impact perceived threat and associated responses.

Differences in reported pain intensity are large but mechanisms are infrequently examined. Thornton et al[19] found experienced contact athletes perceived pain to be less intense than novice contact athletes and non-contact athletes, but there were no differences between novice contact athletes and non-contact athletes, suggesting that the experience of contact pain may account for pain intensity differences. However,

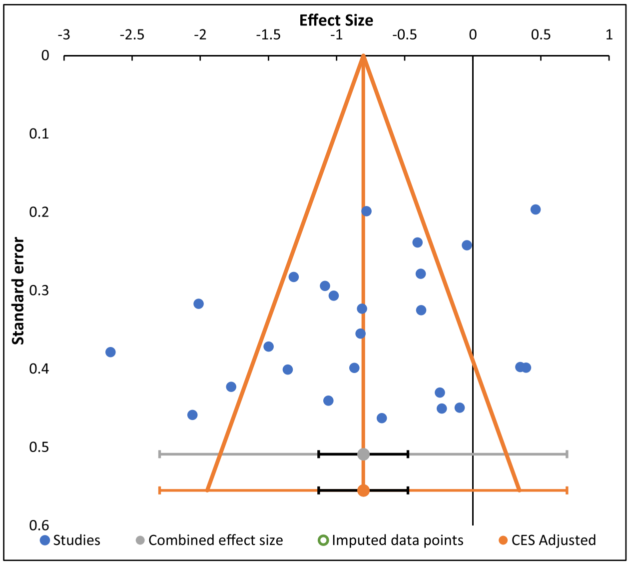


Figure 5. The funnel plot for pain intensity suggesting little evidence of publication bias. No additional data were imputed. Abbreviation: CES, combined effect size.

these findings were not corroborated in a longitudinal study of novice contact athletes across a season[21]; there were no differences in pain intensity to cold pressor or forearm ischemia at the start or end of the season, but there were differences in tolerance. Others have suggested conditioned pain modulation (CPM) as a mechanism.[3,32] However, a recent review, albeit of only 7 studies, suggests elite athletes may not have better CPM compared to controls,[53] however, the number of hours of training per week was related to CPM. Therefore, further research investigating the impact of routine exposure to pain on perceived pain intensity is required, incorporating longitudinal designs.

Meta-analyses of later processing (tolerance and unpleasantness) indicated that athletes had significantly higher pain tolerance than non-athletes. There were no differences for unpleasantness, but the effects were large and based only on 5 studies. Few studies suggest definitive mechanisms for the observed differences in tolerance. Some have measured additional variables alongside pain tolerance, for example, marathon runners had higher pain-specific self-efficacy than controls, which was associated with pain tolerance.[36] Adaptive coping strategies have been linked to pain tolerance in rowers[8] and contact athletes.[29] Pain-related fear and anxiety is lower in ultra-runners compared to controls.[39] Increased pain tolerance may also be associated with ‘Grit’ (a trait of perseverance).[9]

It is unclear however, how these suggested mechanisms develop over time. Only 2 longitudinal studies have examined changes in pain tolerance over a period of competition.[11,21] Both found that pain tolerance increased in athletes over that period. Scott and Gijsbers[11] reported that tolerance increased in competitive swimmers through the season, in line with training load, which also supports the link between training volume and tolerance.[9] In Thornton et al[21], those who continued to participate in a contact sport had increasing pain tolerance. Therefore, whilst tolerance differences are clear and can change over time, future research should explore the psychological adaptations associated with improved tolerance in relation to exposure duration linked to both the course of a competitive season and the volume of training undertaken.

The larger number of participants and effects associated with tolerance and intensity differences afforded a small number of subgroup analyses. Tolerance data comparing endurance athletes with non-athletes were homogenous and had a large mean effect. The effects for contact athletes were heterogeneous but of a similar magnitude. The non-contact and non-endurance athlete group differed least with non-athletes. There were no clear differences in intensity, however, endurance athletes did demonstrate differences compared to controls. Few studies have looked to compare contact athletes, endurance athletes, ‘other athletes’ and non-athletes/active controls within the same study. In the limited number that have, different group comparisons were made.[2,5,14,35] One study found that football players and cross-country skiers had higher tolerance than fencers and karateka.[2] Another reported that endurance athletes had higher tolerance than strength athletes and controls.[14] One study indicated that contact athletes had higher tolerance than non-contact athletes and non-athletes.[5] Another however, found no differences.[35] Research to date therefore does not

Study name	Hedges' g	CI Lower limit	CI Upper limit	Weight
Hall & Davies 1991	-2.52	-3.62	-1.57	15.51%
Manning & Fillingim 2002 i	-0.72	-1.59	0.10	16.38%
Manning & Fillingim 2002 c	-0.27	-1.10	0.54	16.49%
Petersen et al 2019	-1.10	-1.98	-0.29	16.37%
Sternberg et al 2000	-1.67	-2.29	-1.09	17.29%
Tajet-Foxell & Rose 1995	0.52	0.14	0.92	17.96%
Meta-Analysis	**-0.93**	**-2.05**	**0.19**	

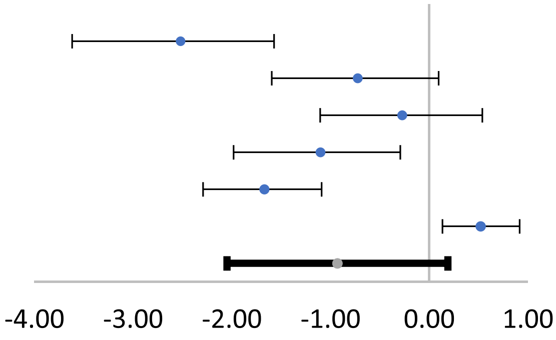


Figure 6. Pain unpleasantness forest plot showing the results of the meta-analysis.

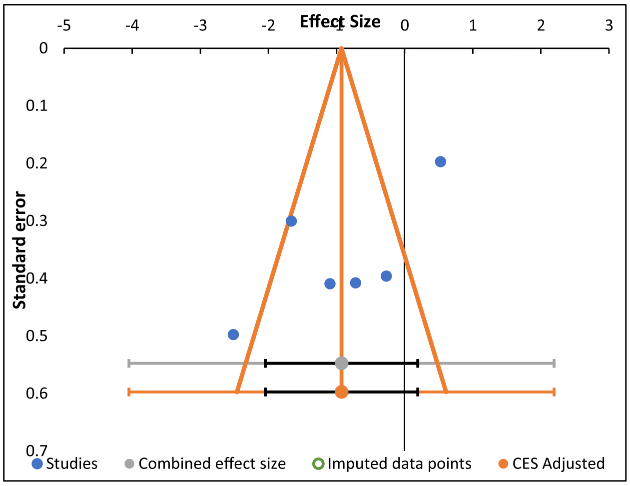


Figure 7. The funnel plot for pain unpleasantness suggesting little evidence of publication bias. No additional data were imputed. Abbreviation: CES, combined effect size.

reveal a clear pattern of pain tolerance differences between athlete groups.

Only 2 studies detailed differences in the impact (perceived or observable) of noxious stimuli—one study examined performance in pain and one study examined both performance in pain and bothersomeness.[19,25] Experienced contact athletes found pain less psychologically bothersome than novice contact and non-athletes.[19] Contact athletes, regardless of experience, performed better on a motor task during pain compared to non-contact athletes[19] and non-athletes.[25] Additionally, both experienced and novice contact athletes showed a smaller drop in performance on a motor task in pain compared to non-athletes.[19] However, Sheffield et al[25] assessed but did not find performance differences in pain during a cognitive task. Further work is therefore required, using a variety of tasks, both to confirm these apparent differences in perceived impact and observed performance, and to explore underlying mechanisms.

Study name	Hedges g	CI Lower limit	CI Upper limit	Weight
Assa et al 2018	1.06	0.46	1.70	4.44%
Egan 1987	0.45	-0.23	1.15	4.12%
Ellison & Frieschlag 1975	0.17	-0.45	0.78	4.43%
Freund et al 2013	1.97	0.99	3.10	2.91%
Geva & Defrin 2013	1.77	1.03	2.60	3.76%
Janal et al 1994 c1	0.78	-0.54	2.27	2.34%
Janal et al 1994 h1	0.89	-0.44	2.40	2.31%
Janal et al 1994 i1	0.06	-1.28	1.41	2.47%
Janal et al 1994 c2	0.36	-0.38	1.12	3.94%
Janal et al 1994 i2	0.15	-0.59	0.90	3.96%
Johnson et al 2011	0.99	0.42	1.58	4.60%
Leznicka et al 2016	0.41	0.18	0.63	6.06%
Leznicka et al 2017	0.75	0.47	1.03	5.87%
Ord & Gijsbers 2003	0.92	0.28	1.60	4.27%
Paparizos et al 2005	0.43	-0.05	0.93	5.01%
Pettersen et al 2020	-0.03	-0.50	0.44	5.09%
Roebuck et al 2018	1.07	0.42	1.76	4.23%
Ryan & Kovacic 1966 p	0.58	-0.22	1.42	3.66%
Ryan & Kovacic 1966 i	1.99	1.08	3.03	3.11%
Scott & Gijsbers 1981	0.99	0.51	1.49	5.01%
Tajet-Foxell & Rose 1995	1.70	1.27	2.17	5.17%
Thornton et al 2017 c	1.07	0.50	1.68	4.57%
Thornton et al 2017 i	1.73	1.11	2.41	4.31%
Walker 1971	1.34	0.73	1.99	4.38%
Meta-Analysis	0.88	0.63	1.13	

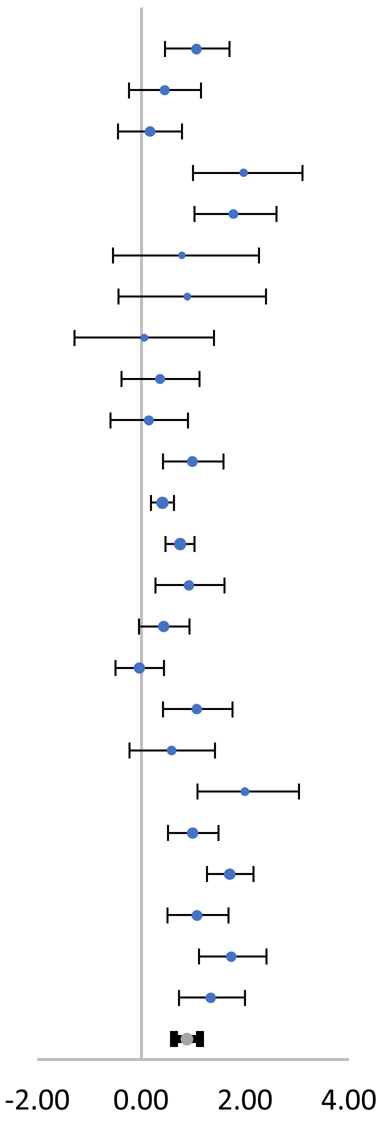


Figure 8. Pain tolerance forest plot showing the results of the meta-analysis.

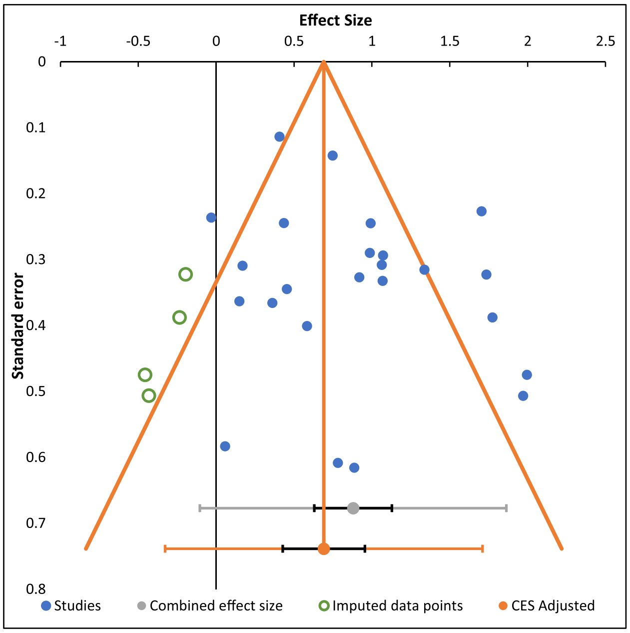


Figure 9. Funnel plot for pain tolerance, with 4 imputed data points. Abbreviation: CES, combined effect size.

The review highlighted discrepancies in how methods and results were reported. For sampling, risk of bias was introduced through a lack of detail on both athlete group/s and non-athlete controls (eg, the amount and type of training, years of experience, competitive level of athletes; for controls amount of exercise undertaken and whether they were former athletes was inconsistently described).[2] Other omissions for the sample included injury history, previous or ongoing pain, and demographic characteristics.[7,35] Protocols for pain assessment methods were often not clearly defined (eg, ice bath temperatures, circulation methods and the nature of ceiling limits).[40] In addition, anchors for pain assessment scales were often not stated.[4] Many older studies did not report power calculations, effect sizes,[5] or statistical assumptions. There was also selective reporting of outcomes[11,12] and some studies did not report sufficient data to be included in the meta-analysis.[54,55] Future studies should aim to address these methodological concerns and move towards measuring the impact of pain on performance in sport. Research into the interaction between exposure to e-sports and pain processing could also be considered.

In this review a limited number of databases were searched, however back and forward searches were conducted, and no additional studies were identified. Furthermore, articles were excluded if they were not written in English. Meta-regression approaches were not employed to examine between-subjects heterogeneity, but subgroup analyses were performed where possible. Nevertheless, we focused on a range of pain-reporting assessments and identified a considerably larger number of articles than previous reviews.

Conclusions

Athletes have higher pain thresholds and tolerances than non-athletes, and they report pain to be less intense. However, heterogeneity within the data limits the number of conclusions that can be confidently stated. For most athletes and coaches, the greatest interest is likely to be based around the least explored aspect of pain in athletes—the impact of pain upon performance. Available data does suggest that pain has less impact upon athletes in terms of both bothersomeness (perceived impact) and measured task performance.

Whilst differences can be assuredly stated, underlying mechanisms have yet to be fully defined and future research must examine key psychological variables alongside outcome measures. Athletes may well be considered a ‘different breed’, but as yet it is not entirely clear why, or how the difference develops.

Disclosures

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jpain.2023.12.007.

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