

Full title: The relationships between internal and external measures of training load and intensity in team sports: A meta-analysis.

Running heading: Internal–external load relationships in team sports.

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1 **ABSTRACT**

2 **Background:** The associations between internal and external measures of training load and intensity
3 are important in understanding the training process and the validity of specific internal measures.

4 **Objectives:** We aimed to provide meta-analytic estimates of the relationships, as determined by a
5 correlation coefficient, between internal and external measures of load and intensity during team-sport
6 training and competition. A further aim was to examine the moderating effects of training mode on
7 these relationships.

8 **Data Sources:** Six electronic databases (Scopus, Web of Science, PubMed, MEDLINE, SPORTDiscus,
9 CINAHL) were searched for original research articles published up to September 2017. A Boolean
10 search phrase was created to include search terms relevant to team-sport athletes (population; 37
11 keywords), internal load (dependent variable; 35 keywords) and external load (independent variable;
12 81 keywords).

13 **Study Selection:** Articles were considered for meta-analysis when a correlation coefficient describing
14 the association between at least one internal and one external measure of session load or intensity,
15 measured in the time or frequency domain, was obtained from team-sport athletes during normal
16 training or match-play (i.e. unstructured observational study).

17 **Data Extraction:** The final data sample included 122 estimates from 13 independent studies describing
18 15 unique relationships between 3 internal and 9 external measures of load and intensity. This sample
19 included 295 athletes and 10418 individual session observations. Internal measures were session ratings
20 of perceived exertion (sRPE), sRPE training load (sRPE-TL) and heart-rate-derived training impulse
21 (TRIMP). External measures were total distance (TD), the distance covered at high- and very-high
22 speeds (HSRD; ≥ 13.1 – 15.0 km·h⁻¹, and VHSRD; ≥ 16.9 – 19.8 km·h⁻¹, respectively), accelerometer load
23 (AL) and the number of sustained impacts (Impacts; > 2 – 5 G). Distinct training modes were identified
24 as either Mixed (reference condition), Skills, Metabolic or Neuromuscular.

25 **Data Analysis:** Separate random effects meta-analyses were conducted for each dataset ($n = 15$) to
26 determine the pooled relationships between internal and external measures of load and intensity. The
27 moderating effects of training mode were examined using random-effects meta-regression for datasets
28 with ≥ 10 estimates ($n = 4$). Magnitude-based inferences were used to interpret analyses outcomes.

29 **Results:** During all training modes combined, the external load relationships for sRPE-TL were
30 possibly very large with TD ($r = 0.79$; 90% confidence interval 0.74 to 0.83), possibly large with AL
31 (0.63; 0.54 to 0.70) and Impacts (0.57; 0.47 to 0.64), and likely moderate with HSRD (0.47; 0.32 to
32 0.59). The relationship between TRIMP and AL was possibly large (0.54; 0.40 to 0.66). All other
33 relationships were unclear or not possible to inference (r range = 0.17 to 0.74, $n = 10$ datasets). Between-
34 estimate heterogeneity (SDs representing unexplained variation; τ) in the pooled internal–external
35 relationships were trivial to extremely large for sRPE ($\tau = 0.00$ to 0.47), small to large for sRPE-TL (τ
36 = 0.07 to 0.31), and trivial to moderate for TRIMP ($\tau = 0.00$ to 0.17). The internal–external load
37 relationships during Mixed training were possibly very large for sRPE-TL with TD (0.82; 0.75 to 0.87)
38 and AL (0.81; 0.74 to 0.86), and TRIMP with AL (0.72; 0.55 to 0.84), and possibly large for sRPE-TL
39 with HSRD (0.65; 0.44 to 0.80). A reduction in these correlation magnitudes was evident for all other
40 training modes (range of the change in r when compared with Mixed training = -0.08 to -0.58), with
41 these differences being unclear to possibly large. Training mode explained 24–100% of the between-
42 estimate variance in the internal–external load relationships.

43 **Conclusion:** Perceived-exertion- and heart-rate-derived measures of internal load show consistently
44 positive associations with running- and accelerometer-derived external loads and intensity during team-
45 sport training and competition, but the magnitude and uncertainty of these relationships are measure
46 and training mode dependent.

KEY POINTS

- Total running distance has the strongest association with sRPE, sRPE-TL and TRIMP during team-sport training and competition.
- External load relationships appear stronger with sRPE-TL when compared with TRIMP.
- Internal–external load relationships differ depending on the mode of training.

1.0 INTRODUCTION

The training process describes the systematic and periodized application of physiological and biomechanical stress in pursuit of functional training outcomes [1]. The development or maintenance of fitness and the potentiation of biomotor abilities are two such outcomes that are important to prepare intermittent team-sport athletes for the frequent and substantial demands of competition [2]. Such adaptations are determined by a combination of training volume, intensity and frequency [3], collectively referred to as training load [4]. Moderate to high training loads are required to drive positive training-induced adaptations, yet may increase the likelihood of fatigue, impaired wellbeing, injury or illness [5-8]. Indeed, the relationships between training load and training outcomes have been systematically reviewed [9-12], with moderate evidence supporting the benefits and risks associated with high and also low training loads. The quantification and monitoring of training load is therefore an important aspect of athlete management [5-7,13,14] and has the potential to provide practitioners and coaches with an objective framework for evidence-based decisions [15-17].

Training load encompasses both external and internal dimensions, with external training loads representing the physical work performed during the training session or match and internal training loads being the associated biochemical (physical and physiological) and biomechanical stress responses [1,18]. Acute and chronic changes in the training outcome are ultimately the result of an athlete's cumulative internal load over a given time period [1,3,18], which therefore places great importance on the measurement of internal load and its influential factors. It is understood that greater external loads, particularly those common to the stochastic demands of team-sport training and competition, increase metabolic energy costs and soft tissue force absorption/production [18], thereby increasing internal loads. This acute dose-response paradigm forms the basis of training theory [1] and is important for understanding the specific internal responses associated with various external training doses [19]. A knowledge of the relationships between internal and external training loads therefore has the potential to enhance training prescription, periodization and athlete management through a detailed assessment of training fidelity and efficacy [17,19-21]. As an adjunct to this, internal-external load relationships can provide evidence for the construct validity and sensitivity of specific internal load indicators [22], which is important in absence of any 'gold-standard' criterion measure.

The relationships between internal and external loads in team-sport athletes have received much attention to date, with a myriad of studies reporting correlation magnitudes ranging from trivial to very large [19,22-36]. The dispersion in these effect sizes would suggest that internal-external load relationships are not yet fully understood, which has led some authors to question the validity of specific internal load measures [37,38]. These findings may be a consequence of the varied training typologies observed in previous research, however, which would suggest that exercise structure, goals, activities and work-rest ratios could reasonably moderate the relationships between internal and external loads. Given that team-sport athletes regularly undertake a diverse range of training activities [22,31], the effects of training mode on internal-external load relationships would appear important in understanding the training process and the measurement of internal training load. An appropriate synthesis of the current literature to date is therefore timely. Accordingly, the aims of our meta-analysis were to establish pooled estimates of the relationships between internal and external loads during intermittent team-sport training and competition, while also exploring the putative moderating effects of training mode.

43 2.0 METHODS

44 2.1 Search Strategy

45 Our review was carried out in accordance with the ‘Preferred Reporting Items for Systematic
46 Reviews and Meta-Analyses’ (PRISMA) guidelines [39]. A search of six electronic databases (Scopus,
47 Web of Science, PubMed, MEDLINE, SPORTDiscus, CINAHL) was conducted independently by two
48 of the authors (SJM, TWM) to identify original research articles published from the earliest available
49 records up to September 2017. The authors were not blinded to journal names or manuscript authors.
50 We created a Boolean search phrase to include search terms relevant to team-sport athletes (population),
51 internal load (dependent variable) and external load (independent variable). Relevant keywords for each
52 search term were determined through pilot searching (screening of titles/abstracts/key words/full texts
53 of previously known articles). Keywords were combined within-terms using the ‘OR’ operator and the
54 final search phrase was constructed by combining the three search terms using the ‘AND’ operator
55 (Table 1).

56

57 2.2 Screening Strategy and Study Selection

58 To select relevant articles, two of the authors (SJM, TWM) independently exported the electronic
59 search results to an Excel spreadsheet (Microsoft Excel, Microsoft, Redmond, USA). Duplicate records
60 were identified and removed before the remaining records were screened against the inclusion-
61 exclusion criteria using a hierarchical approach (Table 2). We chose to omit any studies whose mean
62 athlete age was ≤ 18 years old or otherwise defined as adolescents, juniors, youth or children, as shifts
63 in cognitive development (between the preoperational and formal intelligence stages) may influence the
64 accuracy in ratings of perceived exertion (RPE) [40]. This also allowed us to maximise the likelihood
65 that athletes included in our analyses were fully habituated with the entire range of sensations that
66 correspond to each category of effort within the RPE scales (i.e. ‘anchoring’) [41,42]. In agreement
67 with modern psychophysical theory [42], we chose to only include studies that employed level-anchored
68 semi-ratio scales (i.e. Borg CR10[®] and CR100[®]) for the assessment of session RPE (sRPE) [43]. Studies
69 using bespoke or modified scales, or those using non-category-ratio scales (e.g. Borg 6–20 RPE scale[®]),
70 were therefore excluded. Accordingly, articles were considered for meta-analysis when a correlation
71 coefficient describing the association between at least one internal and one external measure of session
72 load or intensity, measured in the time or frequency domain, was obtained from team-sport athletes
73 during normal, non-manipulated, training or match-play (i.e. unstructured observational study).

74 Titles and abstracts were initially screened and excluded against criteria 1–7 where applicable
75 (Table 2). Full texts of the remaining papers were then accessed and screened against inclusion criteria
76 1–10 to determine their final inclusion-exclusion status. The reference lists of relevant review articles
77 and eligible original research articles were also screened in an identical manner. The two author’s
78 independent search results were then combined and any dispute on the final inclusion-exclusion status
79 were resolved through discussion (n = 27). Following this selection process, there were 351 (28 of
80 which had no numeric correlation coefficient reported) potential estimates from 18 independent studies
81 that met our inclusion criteria (Figure 1).

82

83 2.3 Selection of Datasets and Estimates

84 In line with the aims of our meta-analysis and as a means of data reduction, we grouped internal
85 and external measures of load and intensity based on their construct (e.g. heart-rate-derived training
86 impulse [TRIMP]), rather than their specific measurement (e.g. Banister’s [44], Edwards’ [45], or

87 individualised [46]). When a study reported more than one relationship describing the same internal
88 and external construct, we elected to discard the estimates with the weakest correlation magnitude ($n =$
89 19 estimates). The mean difference in discarded versus retained data was trivial ($r = 0.06$, range = 0.01
90 to 0.23). We further identified five studies [22,23,26,27,35] meeting our inclusion criteria in which
91 duplicate data were evident. To avoid the issue of double counting in our meta-analyses [47], we made
92 informed decisions to discard these data. One study [27] reported the relationships between sRPE
93 training load (sRPE-TL) and three external load indicators using different measures of session volume
94 in the calculation of sRPE-TL (i.e. total match duration, minutes played, and the addition of halftime
95 and warm-up periods). To comply with the methodologies of our other included studies, we chose to
96 only include estimates incorporating minutes played in the calculation of sRPE-TL (21 estimates
97 removed). Another study [23] reported the relationships between internal and external measures of
98 intensity during small-sided games of different formats (3 vs 3, 5 vs 5 and 7 vs 7) as well as the
99 relationships for all formats combined. We chose to only include the relationships for all formats
100 combined since no other study differentiated between variations of small-sided gameplay (36 estimates
101 removed). A third study [22] reported the relations between internal and external loads and intensities
102 for five discrete training modes (conditioning, skill-based conditioning, skills, speed and wrestling) as
103 well as the pooled relationships for all training modes combined. In accordance with our aims, we
104 discarded the pooled estimates and retained the estimates from each training mode for our analyses (8
105 estimates removed). Finally, two studies [26,35] reported both within-athlete and partial correlations
106 (i.e. the relationship between two variables while controlling for one or more other variables) for the
107 same internal–external load relationships. Since no other studies meeting our inclusion criteria utilised
108 partial correlations, we retained only the within-athlete correlations for our analyses (30 estimates
109 removed). Of the remaining data, only datasets with two or more estimates from at least two
110 independent studies were considered for meta-analysis (115 estimates, 107 datasets and 5 studies
111 removed). This resulted in 15 final datasets containing 122 estimates (2 of which not reported) from 13
112 independent studies, with a total of 3 internal load/intensity measures and 9 external load/intensity
113 measures (Table 4). Internal measures were sRPE, sRPE-TL and TRIMP. External measures were total
114 distance (TD), the distance covered at high- and very-high speeds (HSRD and VHSRD, respectively),
115 accelerometer load (AL) and the number of sustained impacts (Impacts).

116

117 **2.4 Data Extraction**

118 We sought to extract the Pearson’s product moment correlation coefficient (r) and the associated
119 sample size that described the internal–external load/intensity relationships for each estimate. Within-
120 athlete correlations are recommended as the appropriate method for analysing repeated measures data
121 [48], yet we faced the issue that some of our included studies employed a mixed correlation analyses—
122 whereby all data are treat indiscriminately as a single sample [49]. This approach could be misleading
123 when attempting to determine if higher external loads are associated with higher internal loads because
124 the correlation magnitude may be influenced by between-athlete differences [48]. Re-analysis of
125 indiscriminate correlation data and athlete-level meta-analysis were precluded on the presumption that
126 our included studies’ raw data would be under embargo from the clubs that samples were drawn [50].
127 Instead, we elected to assume that the between-athlete variability of internal and external loads is
128 unlikely to outweigh the within-athlete variability over repeated observations [51,52], and the mixed-
129 athlete correlation analyses from some of our included studies would therefore be free from violations
130 of independence inherent in analysing repeated measures data [49]. In agreement with this and to
131 mitigate the issue of disproportionate sample allocations [53], we specified the total number of athletes
132 (as opposed to the total number of observations) as the sample size for each estimate within the meta-
133 analyses. Accordingly, Pearson’s product moment correlation coefficients were converted to Fisher’s z
134 values for analysis and subsequently back-converted for post-analysis interpretation. Fisher’s z standard
135 errors and variances were also calculated for estimate weightings and determination of uncertainty and

136 heterogeneity in the pooled effects. Finally, we extracted descriptive information relating to the training
137 activities performed in our included studies and categorised each estimate under one of the following
138 four distinct training modes:

- 139 – **Mixed:** Field- or court-based training incorporating at least two of the training modes defined
140 below. Competitive match-play is also categorised as mixed.
- 141 – **Skills:** Focus on enhancing sport-specific skills and team technical-tactical strategies.
- 142 – **Metabolic:** Intermittent small-sided games or high-intensity interval running, primarily aimed
143 at improving players' aerobic fitness, prolonged high-intensity intermittent running ability and
144 repeated effort ability.
- 145 – **Neuromuscular:** Speed, wrestle or strongman training, primarily aimed at improving players'
146 force production, force transfer, movement and functional strength.

147 The corresponding authors of studies without the required data or where further clarity was
148 necessary were contacted by email [19,22-26,29-32] and we received all relevant information from
149 these studies. Graph digitizer software (DigitizeIt, Brainschweig, Germany) was used to obtain data
150 from two studies where descriptive [28] and correlation [30] data were only available in figures. The
151 final meta-analyses of the 15 datasets included 10418 individual session observations from 295 athletes.
152 Descriptive information for the 13 studies included in our meta-analyses are displayed in Table 4.

153

154 **2.5 Data Analysis**

155 **2.5.1 Publication Bias**

156 To investigate the extent of publication bias in datasets with more than two estimates, we
157 examined funnel plots of individual Fisher z values versus their corresponding standard errors for signs
158 of asymmetrical scatter [54]. Asymmetrical scatter was evident in 1 (sRPE vs TD per min) of the 12
159 examined datasets (Supplementary File 1).

160

161 **2.5.2 Meta-Analytic and Meta-Regression Models**

162 Separate random effects meta-analyses were conducted for each dataset ($n = 15$) to determine the
163 pooled internal–external load and intensity relationships. Uncertainty in the pooled correlation effects
164 was expressed as 90% confidence intervals (CI), calculated using the Knapp and Hartung [55] approach.
165 Between-estimate heterogeneity was then specified as an SD (Tau: τ) [56], calculated using
166 DerSimonian and Laird's generalised method of moments [57]. Meta-regression was deemed possible
167 when a dataset included ≥ 10 estimates [58]. We chose not to meta-regress the relationship describing
168 sRPE-TL and Impacts as 11 of the 12 estimates came from 2 studies only. Accordingly, four separate
169 random effects meta-regression models were conducted to explore the effects training mode on the
170 pooled relationships of sRPE-TL with TD, HSRD and AL, and TRIMP with AL. Training modes were
171 coded as dummy variables (categorical moderators) and their effects were evaluated as the difference
172 between levels. We defined the reference condition for training mode as mixed team training, with the
173 moderating effects of all other training modes expressed as the difference in correlation magnitude when
174 compared with this reference condition. Uncertainty in these differences and between-estimate
175 heterogeneity were expressed as 90% CI and τ , respectively, calculated as previously described. Finally,
176 model strength was quantified as the proportion of between-estimate variance explained by training
177 mode (i.e. unadjusted τ^2 vs fully adjusted τ^2 ; R^2_{Meta} [59]). All analyses were conducted using
178 Comprehensive Meta-Analysis software, Version 3 (Biostat Inc., Englewood, NJ, USA).

179

180 **2.5.3 Inferences**

181 We used magnitude-based inferences [60,61] to provide a practical, real-world interpretation of
182 our analyses. Correlation magnitudes and the effects of training mode were scaled against standardized
183 threshold values of 0.10, 0.30, 0.50, 0.70 and 0.90 to represent small, moderate, large, very large and
184 extremely large effects, respectively [54]. Effects were then evaluated mechanistically and deemed
185 unclear if the 90% CI overlapped substantially positive and negative effect thresholds by a likelihood
186 of $\geq 5\%$ [54]. Otherwise, the chances of the true effect being at least that of the observed magnitude
187 was interpreted using the following scale of probabilistic terms: 5–94.9%, possibly; 75–94.9%, likely;
188 95–99.4%, very likely; $\geq 99.5\%$, most likely [54]. Inferences were not possible for datasets with ≤ 3
189 estimates since the standard error of a Fishers z transformed correlation coefficient is equal to the
190 inverse square root of $n-3$ [62]. Finally, to infer on the true unexplained variation in each relationship,
191 we doubled the back-converted τ statistic before interpreting its magnitude [63] using the above scale
192 of correlation effect sizes [54].

193 3.0 RESULTS

194 3.1 Relationships between Internal and External Measures of Load and Intensity

195 Forest plots displaying the weighted point estimates with 90% CI for each meta-analysis are
196 available in Supplementary File 2. The meta-analysed relationships between internal and external loads
197 and intensities are shown in Table 5. The direction of all pooled estimates was positive. Relationships
198 with sRPE-TL were possibly very large with TD, likely large with AL and Impacts, and likely moderate
199 with HSRD. The relationship between TRIMP and AL was possibly large. All other relationships were
200 unclear or not possible to inference. True unexplained variation (between-estimate SDs) in the pooled
201 internal-external relationships was extremely large for sRPE vs TD, very large for sRPE vs HSRD,
202 large for sRPE-TL vs HSRD, moderate for sRPE-TL vs VHSRD and AL, and TRIMP vs AL, and small
203 for sRPE-TL vs TD and Impacts, and TRIMP vs HSRD and VHSRD. All other between-estimate SDs
204 were trivial (Table 5).

205

206 3.2 Moderating Effects of Training Mode

207 The relationship between sRPE-TL and TD for Mixed training was possibly very large ($r = 0.82$;
208 90% CI 0.75 to 0.87). There were possibly moderate reductions in this correlation magnitude for Skills
209 (change in r when compared with Mixed training = -0.30 ; 90% CI: -0.61 to 0.08) and Neuromuscular
210 training (-0.42 ; -0.72 to 0.02). The difference between Mixed and Metabolic training was unclear ($-$
211 0.08 ; -0.27 to 0.41). Training mode explained 100% of the between-estimate variance in the relationship
212 between sRPE-TL and TD ($R^2_{\text{Meta}} = 1.00$, $\tau = 0.00$).

213 The relationship between sRPE-TL and HSRD for Mixed training was possibly large ($r = 0.65$;
214 90% CI 0.44 to 0.80). There was a possibly large reduction (change in r when compared with Mixed
215 training = -0.55 ; 90% CI -0.79 to -0.17) in this correlation magnitude for Neuromuscular training and a
216 possibly moderate reduction for Skills training (-0.29 ; -0.69 to 0.25). The difference between Mixed
217 and Metabolic training was unclear (-0.21 ; -0.58 to 0.25). Training mode explained 24% of the between-
218 estimate variance in the relationship between sRPE-TL and HSRD ($R^2_{\text{Meta}} = 0.24$) and the remaining
219 unexplained variation was large ($\tau = 0.28$).

220 The relationship between sRPE-TL and AL for Mixed training was possibly very large ($r = 0.81$;
221 90% CI 0.74 to 0.86). There were possibly large reductions in this correlation magnitude for Skills
222 (change in r when compared with Mixed training = -0.58 ; 90% CI: -0.73 to -0.37) and Neuromuscular
223 training (-0.55 ; -0.71 to -0.32), and a likely moderate reduction for Metabolic training (-0.49 ; -0.66 to $-$
224 0.28). Training mode explained 100% of the between-estimate variance in the relationship between
225 sRPE-TL and AL ($R^2_{\text{Meta}} = 1.00$, $\tau = 0.00$).

226 The relationship between TRIMP and AL for Mixed training was possibly very large ($r = 0.72$;
227 90% CI 0.55 to 0.84). There was a possibly large reduction in this correlation magnitude for
228 Neuromuscular training (change in r when compared with mixed training = -0.58 ; 90% CI: -0.79 to $-$
229 0.25) and a possibly moderate reduction for Skills training (-0.43 ; -0.72 to -0.01). The difference
230 between Mixed and Metabolic training was unclear (-0.12 ; -0.48 to 0.28). Training mode explained
231 100% of the between-estimate variance in the relationship between TRIMP and AL ($R^2_{\text{Meta}} = 1.00$, $\tau =$
232 0.00).

233 4.0 DISCUSSION

234 Associations between internal and external measures of training load and intensity are important
235 in understanding the dose–response nature of team-sport training and competition. These relationships
236 may also provide evidence for the validity of specific internal load measures. Our meta-analysis is the
237 first to provide a quantitative synthesis of such data from 295 athletes and 10418 individual session
238 observations. The main findings from our analyses were that perceived-exertion- and heart-rate-derived
239 measures of internal load show consistently positive associations with running- and accelerometer-
240 derived external loads and intensity during team-sport training and competition, but the magnitude and
241 uncertainty of these relationships is measure and training mode dependent.

242 The results of our meta-analysis reveal total distance to have the strongest associations with
243 internal load and intensity indicators (Table 5). These data suggest that the internal responses to training
244 and match-play are strongly associated with the amount of running completed—more so than the myriad
245 of other external load measures typically monitored in team-sport athletes. Conceptually, this
246 association seems logical, as the ability to sustain muscle contractions during locomotion is largely
247 dependent on the cumulative provision of substrate and oxygen to the peripheral systems, thereby
248 increasing oxygen consumption and cardiac output [18]. Furthermore, the demands of locomotion are
249 largely driven by central motor commands to the lower-limb and respiratory muscles, to which a
250 neuronal process of the corollary discharge is believed to drive perception of effort [64]. Taken together,
251 these physiological and psychophysical mechanisms create intuitive rationales for the large to very large
252 associations between internal intensity/load and total distance found in our analyses.

253 It is likely that our other meta-analysed external load and intensity measures are highly dependent
254 on total distance and their relationships with internal load/intensity are partially a consequence of
255 similar mechanisms. Session distances covered above arbitrary high-speed thresholds are strongly
256 associated with session total distance in team-sport athletes [25,65]. The less substantial relationships
257 between these measures and internal load/intensity could, however, be explained by: a) increased
258 measurement error of GPS devices with high movement velocities [66,67], b) individual differences in
259 maximum running velocity or the velocity at which physiologically high-intensities are attained [68,69],
260 or c) the typical non-linear association between running velocity and internal exercise intensity [42,70].
261 Furthermore, accelerometer-derived load and impacts are likely to be influenced by activities other than
262 locomotion [71] that are commonplace to team-sports, such as some physical collisions, static exertions,
263 jumping, etc. [65,72], which may not have a proportionate influence on sRPE-TL and TRIMP.
264 Collectively, these suppositions may explain the findings of our meta-analyses and provide some
265 understanding of the dose–response nature of team-sport training and competition.

266 Internal training load is a complex and multifactorial construct, making its direct measurement
267 difficult if at all possible using a single modality of assessment [18,73]. Nonetheless, establishing the
268 construct validity and sensitivity of individual measures, such as sRPE-TL and TRIMP, is an important
269 aspect of athlete monitoring [74]. Since the acute biochemical and biomechanical responses to exercise
270 should be associated, in some capacity, with the volume and intensity of the activities performed
271 [1,3,18], internal–external load/intensity relationships provide a means of assessing the construct
272 validity of specific internal measures to be used either in isolation or as part of a more holistic appraisal.
273 We provide the first meta-analytic evidence to show that the correlation magnitudes between sRPE-TL
274 and various external load indicators are consistently stronger when compared with the same TRIMP–
275 external load associations in team-sport athletes. Contrary to others [37,38], we believe this provides
276 evidence for the validity of sRPE-TL as an indicator of internal training load in team sport athletes.

277 The relationships between sRPE and external measures of intensity were of considerably weaker
278 magnitude when compared with external measures of load in our analyses. Several of factors may
279 explain these findings. Firstly, a single measure of external intensity could substantially

280 underrepresented the stochastic movement demands of field- or court-based team-sports that are likely
281 to influence the perception of effort [26]. Frequent changes in movement, characterized by
282 multidirectional high-magnitude accelerations and decelerations, elicit mechanical stress through
283 increased force absorption/production and cause a subsequent increase in metabolic demands that are
284 required to drive muscle contractions even when running at low velocities [18]. This is important, as
285 many additional psychobiological factors such as blood lactate, metabolic acidosis, ventilatory drive,
286 respiratory gases, catecholamines, β -endorphins, and body temperature are also associated with
287 perception of effort during intermittent exercise [41]. Secondly, previous research has established large
288 associations between sRPE and sport-specific non-locomotive activities, such as the number of tackles
289 completed in a rugby league match [34]. Finally, many studies included in our analyses did not state
290 the omission of between-drill rest periods or ball out-of-play time when analysing relative movement
291 demands (i.e. per minute), which could underestimate the true performed external intensities of the
292 training session or match [75,76].

293 A lack of any ‘near perfect’ association between sRPE (as a measure of intensity or load) and
294 external intensity or load indicators is, of course, not surprising given also the many non-load-related
295 factors that influence an individual’s perceived exertion [41]. Indeed, while our analyses do support the
296 construct validity of sRPE, it is plausible that this measure may still lack sensitivity [52] to account for
297 all the highly variable physical demands of team sport training and competition [51,77-79]. Specifically,
298 a global score may be insufficient to accurately appraise the entire range of both physiological and
299 biomechanical exertion signals during exercise [80]. This could be problematic when using sRPE-
300 derived data to inform the planning of training or recovery interventions because a gestalt measure of
301 effort perception is likely to be influenced by the most dominant psychophysiological sensation [81],
302 yet the response rates of internal biochemical and mechanical stresses are considerably different [18].
303 Differential RPE—separate session scores for central and peripheral perceived exertion [33]—may well
304 be a suitable indirect alternative to help mitigate such an issue by separating a player’s perceptions of
305 physiological and biomechanical load [18]. Independent ratings of perceived breathlessness, leg muscle
306 exertion and upper-body muscle exertion have been proposed as a worthwhile addition to internal load
307 monitoring procedures in team sports [33,81,82] and may help both practitioners and researchers further
308 understand the dose–response nature of training and competition [52], changes in fitness [11], fatigue
309 [83], and the risk of injury or illness [10,84].

310 The strength of internal–external load relations in our meta-analyses encompasses almost an
311 entire magnitude scale, indicating that the unexplained variance between any single measure of internal
312 and external load or intensity may range between ~40–100%. While some of this could be attributed to
313 individual characteristics or simply noise (either measurement error or biological variation), it may well
314 indicate the omission of potentially valuable information contained both within and between training
315 load measures when using a single item to represent internal or external constructs. We have discussed
316 the implications of our findings in relation to the specific measures used, yet our data could also support
317 the notion that multiple measures are needed to accurately quantify internal and external training loads
318 in team sports [31,32,73]. Since it is already common practice to routinely collect several training load
319 measures [85]—which are often based on perceived clinical or practical importance [26]—a pertinent
320 challenge is understanding the most parsimonious and statistically sound variable selection that best
321 represent ‘internal’ and ‘external’ constructs for the differing training modes undertaken by team-sport
322 athletes [31,32].

323 Our analyses revealed much stronger internal–external load relationships (e.g. sRPE-TL and TD)
324 in comparison to the corresponding internal–external intensity relationships (e.g. sRPE and TD per
325 min). This potentially indicates an issue of mathematical coupling—the effect occurring when one
326 variable directly or indirectly contains the whole or part of the other and the two variables are analysed
327 using standard correlation or regression techniques [86]. Mathematical coupling can result in
328 correlations that appear far more substantial than any true biological/physiological association between

329 the two variables [87]. In the context of training monitoring, internal and external loads are not
330 mathematically distinct from one another since session volume (duration) is a constant factor within
331 both constructs. We feel that this represents an important yet overlooked issue within training
332 monitoring that may extend to many analyses of training load. Practitioners and researchers should
333 therefore be aware and cautious of this fact to avoid making erroneous conclusions when interpreting
334 data on individuals or from research.

335 There was considerable uncertainty (ranging up to extremely large in magnitude) in the SDs
336 representing true between-estimate variation in some of our meta-analysed internal–external load and
337 intensity relationships. This could suggest that team-sport athletes’ internal responses to training and
338 competition are multifactorial and influenced by several factors. Our meta-regression analyses indicated
339 substantial moderating effects of training mode on the sRPE-TL–TD, sRPE-TL–HSRD, sRPE-TL–AL
340 and TRIMP–AL relationships. Here, training mode explained 24–100% of the observed between-
341 estimate heterogeneity when compared with the unadjusted pooled estimates (i.e. all training modes
342 combined). Internal–external load relationships were typically weaker when concentrating on discrete
343 training modes. This could indicate that the correlations in the unadjusted analyses (combining multiple
344 training modes) are spuriously high and only confirm already obvious differences between
345 homogeneous subsets [88], such as the difference in internal and external loads between disparate
346 training typologies.

347 Our defined training modes primarily differ in output goals, which influences the structure and
348 selection of training activities along with the associated work-rest ratios. It is possible that these
349 discrepancies explain the moderating effects of training mode observed on the relationships between
350 internal and external training load in our present analyses. Reductions in work-to-rest ratio during small-
351 sided gameplay have previously been shown to increase heart rate in spite of reduced distances covered
352 at high- and very-high speeds [89], while the addition of physical collisions during repeated sprint
353 exercise has shown to markedly increase internal loads for the same distances covered [90].
354 Furthermore, training modes utilising closed kinetic chain exercises (typical to neuromuscular
355 conditioning) often require high levels of force and velocity to be produced or resisted [91,92], resulting
356 in frequent bouts of peripherally demanding activities that can be independent of locomotion [72]. Here,
357 an uncoupling of the relationship between internal and external loads could be a consequence of
358 measurement insensitivity [81]. In agreement with previous research [31], these results imply that
359 internal–external load relations are specific to the mode of training and the load measures that best
360 represent one training mode may not do so for others.

361 There are several limitations with our current meta-analysis that could largely be the consequence
362 of varied data collection and reporting from our included studies. This is inevitable when synthesising
363 data from unstructured observational research designs that are not governed by strict reporting standards
364 such observational epidemiological studies (e.g. STROBE) or randomized controlled trials (e.g.
365 CONSORT) [93]. We grouped our internal and external measures of load and intensity measures based
366 on their constructs as a means of providing a more concise analysis that met our research aims. Despite
367 this, some measurement methods (e.g. CR100-derived sRPE or individualised TRIMP) clearly show
368 improved sensitivity and precision over their traditional counterparts [94,95]. The grouping of external
369 loads between different manufacturers has notable flaws, particularly with the variety of sampling rates,
370 chipsets, filtering methods and data processing algorithms observed between athlete tracking devices
371 [93]. A key discrepancy between our included studies was the mixed correlation calculation methods,
372 with some studies reporting within-athlete correlations and others pooling their repeated measures as
373 though all the data were drawn from a single sample. Finally, our relatively low number of estimates
374 per dataset restricted any examination of the many other factors that may reasonably moderate the
375 relationships between internal and external training loads/intensity in team-sport athletes.

376 We propose several suggestions for practitioners wishing to analyse their training load data as a
377 means of assuring an evidenced-based approach to the delivery of performance-focused outcomes. A
378 knowledge of the specific internal responses associated with various external training doses has the
379 potential to enhance training evaluation, prescription, periodization and athlete management through a
380 detailed assessment of training fidelity and efficacy [17,19,20]. Specifically, changes in internal load
381 with respect to a standard external load may be used to infer on an athletes fitness or fatigue over time
382 or in comparison to their peers [14]. The simplicity of using an external:internal load ratio to provide a
383 normalised metric that may be indicative of fitness or fatigue is conceptually appealing [83,96-99] and
384 lends to dashboard-level analyses. This approach violates fundamental theoretical and empirical
385 assumptions inherent to ratios [100,101], however, since most internal–external load relationships are
386 substantially disproportionate. To avoid this leading to errors in interpreting training loads on individual
387 athletes [100], we recommend that practitioners avoid ratios and look to independently analyse
388 continuous measures of internal and external load using a more progressive approach. This could
389 include the assessment of individual changes in daily, weekly or cumulative load [102] that are
390 meaningful and free from typical variation [103,104] that is inherent to training and competition in team
391 sports [33,81]. For the retrospective analyses of larger datasets, we again recommend that ratios are
392 avoided and that practitioners seek to explore their data through more appropriate means. These may
393 include, but are not limited to: within- [48] or between-athlete [105] correlations, generalized estimating
394 equations [100], mixed effect linear modelling [106] or dimension reduction techniques (e.g. principal
395 component analysis [31,32]).

396 The wide magnitude dispersion and relative lack of precision in some of our meta-analysed
397 correlation coefficients would suggest that further research is warranted to improve the understanding
398 of internal–external load relationships in team sport athletes. We recommend that such work should aim
399 to explore the reasons why this dispersion and imprecision exists, rather than simply if a relationship is
400 evident. The substantial moderating effects of training mode in our analyses indicate that any such
401 research should be conducted on homogeneous subsets of training activities, rather than combining
402 several diverse training modes. Further examination of other conceptual and technical moderating
403 factors, such as specific fitness qualities, athlete experience, fatigue, prior training load, measurement,
404 and the magnitude of load may also prove to be useful. The inevitable repeated measures nature of this
405 work should be met with the appropriate analyses to avoid inference error arising from
406 pseudoreplication [107]. Furthermore, we recommend issues of mathematical coupling should be
407 appropriately considered and avoided. Finally, in agreement with others, we encourage the collection
408 of differential RPE in both research and practice as a means of separating an athlete’s perception of
409 physiological and biomechanical internal loads to help further understand the dose–response nature of
410 team-sport training.

411 **5.0 CONCLUSIONS**

412 Our study is the first to provide a quantitative synthesis of evidence examine the relationships
413 between internal and external measures of load and intensity during team-sport training and
414 competition. While such associations appear consistently positive, their magnitudes are dependent on
415 the specific measures used and are substantially moderated by training mode. Total running distance
416 appears to have the strongest association with internal training load and intensity, and the relationships
417 with measures of external load are stronger with sRPE-TL when compared with TRIMP. Our findings
418 have implications for the dose–response nature of team-sport training and competition as well as the
419 measurement of internal load. Further work is recommended to improve the accuracy in measuring
420 internal load in team-sport athletes.

DECLARATIONS

Compliance with Ethical Standards

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Conflict of Interest

Shaun J. McLaren, Tom W. Macpherson, Aaron J. Coutts, Christopher Hurst, Iain R. Spears and Matthew Weston declare they have no conflict of interest relevant to the content of this article.

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TABLES AND FIGURES

Figure 1. Flow diagram of the study, dataset and estimate selection process.

[Footnote]

*Refer to Table 2.

**Refer to methods.

***< 2 datasets from < 2 independent studies describing a relationship between internal and external load/intensity.

Abbreviations: sRPE: session rating of perceived exertion, sRPE-TL: session rating of perceived exertion training load, TRIMP: heart-rate-derived training impulse, TD: total distance covered, HSRD: distance covered at high speeds ($\geq 13.1\text{--}15.0 \text{ km}\cdot\text{h}^{-1}$), VHSD: distance covered at very high speeds ($\geq 16.9\text{--}19.8 \text{ km}\cdot\text{h}^{-1}$), AL: accelerometer-derived load, Impacts: total number of sustained impacts ($> 2\text{--}5 \text{ G}$).

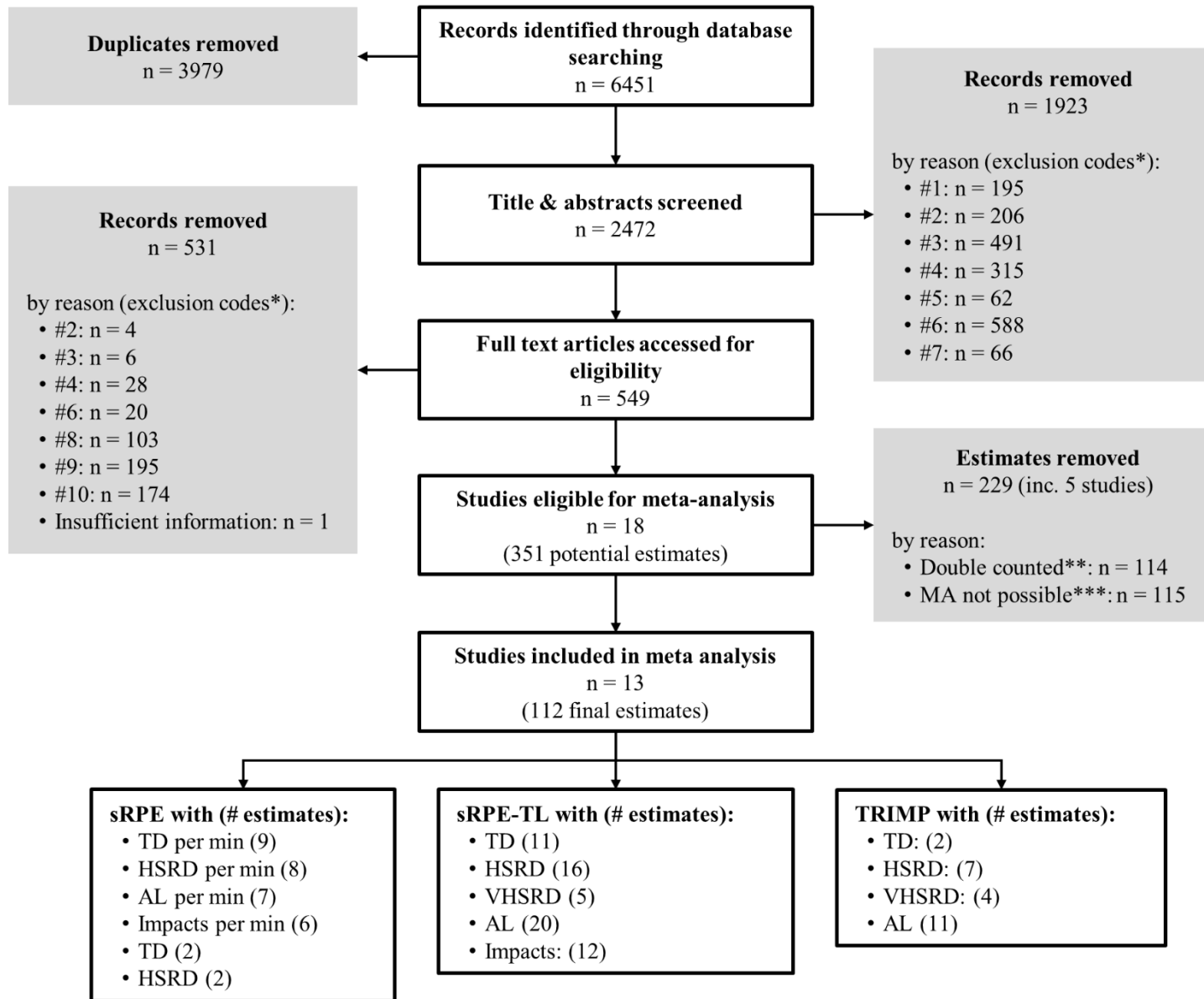


Table 1. Database search strategy.

Search Term	Keywords
1. Team-sport	team-sport OR soccer OR "soccer player*" OR footballer* OR "football player*" OR futsal OR "futsal player*" OR rugby OR "rugby football*" OR "rugby player*" OR "rugby football player*" OR "rugby union" OR "rugby union player*" OR "rugby league" OR "rugby league player*" OR "Australian rules football*" OR "Australian football*" OR "Australian rules football player*" OR "Australian football player*" OR "Gaelic football*" OR "Gaelic football player*" OR hurling OR "hurling player*" OR hurler* OR basketball OR basketballer* OR "basketball player*" OR handball* OR "handball player*" OR handballer* OR hockey OR "hockey player*" OR lacrosse OR "lacrosse player*" OR netball OR "netball player*" OR netballer*
2. Internal load	"internal load*" OR "internal training load*" OR "internal TL" OR "internal intensit*" OR "internal work*" OR "perceived exertion" OR RPE OR sRPE OR "s-RPE" OR "sRPE-TL" OR dRPE OR "d-RPE" OR "RPE-B" OR "RPEres" OR "RPE-L" OR "RPEmus" OR "subjective intensit*" OR "perceived intensit*" OR "subjective load*" OR "perceived load*" OR "subjective training load*" OR "perceived training load*" OR "Heart rate" OR HR OR "HRmax" OR %HRmax OR "HRpeak" OR %HRpeak OR "HRmean" OR "Training impulse" OR TRIMP OR iTRIMP OR "Summated heart rate zones" OR "Summated HR zones" OR SHRZ
3. External load	"external load*" OR "external training load*" OR "external TL" OR "external intensit*" OR "external work*" OR workload* OR "physical performance*" OR "physical demand*" OR "match performance*" OR "match demand*" OR "match activit*" OR "match intensit*" OR "game performance*" OR "game demand*" OR "game activit*" OR "game intensit*" OR "training performance*" OR "training demand*" OR "training activit*" OR "training intensit*" OR "training output*" OR "tracking system*" OR "video" OR "camera*" OR "time-motion" OR "image recognition system" OR "match analysis system" OR "notational analysis" OR "multi-camera system*" OR "global positioning system*" OR GPS OR "micromechanical-electrical system*" OR MEMS OR microsensor* OR microtechnology OR accelerometry OR "inertial measurement unit*" OR IMU OR distance* OR TD OR meters OR "low-speed*" OR LSR OR LSA OR "low-intensit*" OR LIR OR LIA OR "high-speed*" OR HSR OR HSA OR "high-intensit*" OR HIR OR HIA OR "maximal-speed*" OR "maximal-intensit*" OR "maximal-effort*" OR sprint* OR "repeated sprint*" OR "repeated high-intensity effort*" OR RHIE OR "repeated maximal effort*" OR "repeated maximal bout" OR velocit* OR speed* OR "work:rest" OR "work-to-rest" OR accelerat* OR decelerat* OR impact* OR tackl* OR collision OR "accelerometer load*" OR "body load*" OR "Player Load*" OR "PlayerLoad*" OR "metabolic power" OR "metabolic load" OR "high power distance*" OR "equivalent distance*" OR Pmet OR "exertion index"
Search Phrase:	1 AND 2 AND 3

Table 2. Study inclusion-exclusion criteria

Criteria	Inclusion	Exclusion	Primary Screen Type
1	Article is related to human physical performance.	Studies with non-human subjects or with no outcome measures relating to physical performance (e.g. physiological, health markers, etc.).	
2	Original research article	Reviews, surveys, opinion pieces, books, periodicals, editorials, case studies, non-academic/non-peer-reviewed text.	
3	Competitive team-sport athletes (intermittent, field- or court-based invasion sports).	Non-team sports (e.g. solo, racquet/bat, or combat sports, etc.), ice-, sand-, or water-based team sports, match officials, recreational athletes or non-athletic populations.	
4	Participants \geq 18 years old or defined as senior athletes.	Participants $<$ 18 years old or defined as adolescent, junior, youth or child athletes.	Title & abstract
5	Healthy, able-bodied, non-injured athletes	Special populations (e.g. clinical, patients), athletes with a physical or mental disability, and athletes considered to be injured or returning from injury.	
6	Normal team-sport training or match-play.	Experimental trials (e.g. crossover, controlled trial), including lab-based studies and field-based studies where a) usual training was coupled with an experimental intervention (e.g. environment manipulation, nutritional or recovery interventions, use of ergogenic aids, etc.), or b) only data from performance testing was reported (e.g. pre-post fitness changes).	
7	Full text available in English	Cannot access full text in English.	
8	Reported a measure of RPE (category-ratio scaled) or heart rate as an indicator of internal load or intensity	Did not report a measure of category-ratio scaled RPE or heart rate measured in the time or frequency domain as an indicator of internal load/intensity.	
9	Reported at least one a measure of external load or intensity	Did not report at least measure of external load/intensity measured in the time or frequency domain.	Full text
10	Report of a correlation statistic between internal and external measures of session load or intensity.	No report of a correlation statistic between an RPE- or heart-rate-based measure of internal load/intensity and at least one external measure of load/intensity measured in the same session, or correlations drawn from cumulative (e.g. weekly) or intrasession subsamples.	

Abbreviations. RPE: rating of perceived exertion.

Table 3. Summary of the meta-analysed measures of internal and external load and intensity.

Construct	Measure	Measurement	Threshold or Metric Calculation Method	
Internal	Intensity	sRPE	CR10, CR100 [42]	
	Load	sRPE-TL	CR10, CR100 [42]	Foster et al. [4]
		TRIMP	Heart rate telemetry (Polar, Catapult Sports)	Banister* [44], Edwards** [45], Modified Edwards** [32], Individualised* [46],
External	Intensity	TD per min	5–10 Hz GPS (Catapult Sports, GPSports)	
		HSRD per min	5–10 Hz GPS (Catapult Sports, GPSports, STATSport)	$\geq 13.1\text{--}15.0 \text{ km}\cdot\text{h}^{-1}$; arbitrary
		AL per min	100 Hz MEMS (Catapult Sports, GPSports)	PlayerLoad ^{TM***} , Body Load ^{TM**}
		Impacts per min	100 Hz MEMS (GPSports, STATSports)	$> 2\text{--}5 \text{ G}$
	Load	TD	5–10 Hz GPS (Catapult Sports, GPSports)	
		HSRD	5–10 Hz GPS (Catapult Sports, GPSports, STATSport)	$\geq 13.1\text{--}15.0 \text{ km}\cdot\text{h}^{-1}$; arbitrary
		VHSRD	5–10 Hz GPS (Catapult Sports)	$\geq 16.9\text{--}19.8 \text{ km}\cdot\text{h}^{-1}$; arbitrary and individualised
		AL	100 Hz MEMS (Catapult Sports, GPSports, Freescale)	PlayerLoad ^{TM***} , Body Load ^{TM**}
	Impacts	100 Hz MEMS (GPSports, STATSports)	$> 2\text{--}5 \text{ G}$	

*Exponentially weighted

**Summated zones

***Vector magnitude calculation

Abbreviations. AL: accelerometer-derived load, CR10: Borg's Category-Ratio 10 (deci-Max) scale, CR100: Borg's Category-Ratio 100 (centi-Max) scale, GPS: global positioning system, HSRD: distance covered at high speeds, Impacts: total number of sustained impacts, MEMS: micro-electrical mechanical system, sRPE: session rating of perceived exertion, sRPE-TL: session rating of perceived exertion training load, TD: total distance covered, TRIMP: heart-rate-derived training impulse, VHSRD: distance covered at very high speeds.

Table 4. Descriptive study information.

Reference	Sport	Athletes			Study Defined Training Mode(s)	Observation Sample		Session duration (minutes; mean \pm SD)	Measures of Intensity and Load*				
		n	Competitive Level	Age (years; mean \pm SD)		Obs. Per athlete (mean \pm SD)	Total individual Obs.		Internal		External		
									Intensity	Load	Intensity**	Load	Device specification, (manufacturer, model)
Bartlett et al. [19]	AF	41	Australian Football League	23 \pm 4	Field-based AF sessions	66 \pm 13	2711	59 \pm 25	sRPE (CR10)	-	Relative distance, percentage of total distance covered > 14.4 km·h ⁻¹	Total distance, distance covered > 14.4 km·h ⁻¹	10 Hz GPS & 100 Hz MEMS (Catapult Sports, Optimeye S5)
Casamichana & Castellano [23]	SO	14	Spanish Regional	21 \pm 2	SSG	not reported	217	not reported	sRPE (CR10) mean %HR _{max}	-	Relative distance, relative distances and frequency of efforts > 18.0 and > 21.0 km·h ⁻¹ , accelerometer load ^c	-	10 Hz GPS & 100 Hz MEMS (Catapult Sports, MinimaxX v.4.0)
Casamichana et al. [24]	SO	28	Spanish Third Division	23 \pm 4	SSG, running exercises, technical & tactical drills	not reported	210	90 \pm 23	-	sRPE-TL (CR10)	Work: rest ratio (≥ 4 : < 4 km·h ⁻¹)	Total distance, distances and frequency of efforts > 18.0 and > 21.0 km·h ⁻¹	10 Hz GPS & 100 Hz MEMS (Catapult Sports, MinimaxX v.4.0)
Gallo et al. [25]	AF	39	Australian Football League	23 \pm 3	SSG, technical & tactical drills & match practice scenarios	7 \pm 6	270	59 \pm 14	-	sRPE-TL (CR10)	Relative distance	Total distance, distance covered at individualised high-speeds ^f , total and low velocity (< 7.2 km·h ⁻¹) accelerometer load ^c	10 Hz GPS & 100 Hz MEMS (Catapult Sports, MinimaxX team 2.5)
Gaudino et al. [26]	SO	22	English Premier League	26 \pm 6	Team field-based training sessions	86 \pm 28	1892	57 \pm 16	sRPE (CR10)	sRPE-TL (CR10)	Relative distance covered > 14.4 km·h ⁻¹ , relative number of impacts (> 2 G), relative number of accelerations (> 3 m·s ⁻²)	Total distance covered > 14.4 km·h ⁻¹ , total number of impacts (> 2 G), total number of accelerations (> 3 m·s ⁻²)	10 Hz GPS & 100 Hz MEMS (STATSports, Viper)

Lovell et al. [22]	RL	32	National Rugby League	24 ± 4	Conditioning	15 ± 3	398	28 ± 14	sRPE (CR10) mean %HR _{max}	sRPE-TL (CR10) TRIMP (Banister)	Relative distance covered at speeds > 15.0 km·h ⁻¹ , relative accelerometer load ^d , relative number of impacts (> 5 G)	Total distance covered at speeds > 15.0 km·h ⁻¹ , total accelerometer load ^d , total number of impacts (> 5 G)	5 Hz GPS & 100 Hz MEMS (GPSports, SPI Pro)
					Skills	34 ± 13	1097	44 ± 11					
					Skills-conditioning	14 ± 2	365	46 ± 19					
					Speed	11 ± 1	262	17 ± 7					
					Wrestle	12 ± 1	278	18 ± 7					
Pustina et al. [27]	SO	20	NCAA Division I	22 ± 2	NCAA Division I match-play	15 ± 2	304	75 ± 24	-	sRPE-TL (CR10) ^a	-	Total distance covered, total distance covered at speeds > 14.4 km·h ⁻¹ , accelerometer load ^c	10 Hz GPS & 100 Hz MEMS (Catapult Sports, MinimaxX v.4.0)
					Field-based team training	30 ± 2	598	69 ± 17					
Scanlan et al. [28]	BB	8	Australian 2 nd tier	26 ± 7	Court-based team training	6 ± 3	44	42 ± 7	-	sRPE-TL (CR10) TRIMP (Banister & Edwards)	-	Total accelerometer load ^c	4 x 100 Hz tri-axial accelerometers, Freescale (Semiconductor, MMA7361L)
Scott et al. [29]	SO	15	Australian A-League	25 ± 5	Field-based team training	7 ± 3	99	73 ± 17	-	sRPE-TL (CR10) TRIMP (Banister & Edwards)	-	Total distance covered, total distance covered and time spent at speeds < 14.4, ≥ 14.4 and ≥ 19.8 km·h ⁻¹ , accelerometer load ^c	5 Hz GPS & 100 Hz MEMS (Catapult Sports, MinimaxX 2.0)
Scott et al. [30]	AF	10	Australian Football League	19 ± 2	Skill-based training	18 ± 3	183	63 ± 23	sRPE (CR10 & CR100) mean %HR _{max}	sRPE-TL (CR10 & CR100) TRIMP (Banister & Edwards)	Relative distance covered, relative distance covered at speeds ≥ 13.1 km·h ⁻¹ , relative accelerometer load ^c	Total distance covered, total distance covered at speeds ≥ 13.1 km·h ⁻¹ , total accelerometer load ^c	10 Hz GPS & 100 Hz MEMS (Catapult Sports, MinimaxX team 2.5)

Weaving et al. [31]	RL	17	English Super League	25 ± 3	Skills-conditioning	5 ± 1	88	37 ± 14	-	sRPE-TL (CR10) TRIMP (individualised ^b)	Total distance covered > 15 km·h ⁻¹ , total number of impacts (> 5 G), total accelerometer load ^d	5 Hz GPS & 100 Hz MEMS (GPSports, SPI Pro XII)		
					Conditioning	10 ± 3	170	52 ± 22						
					Skills	15 ± 4	263	40 ± 24						
					Speed	6 ± 2	99	28 ± 8						
					Wrestle	2 ± 1	41	19 ± 8						
			Strongman	4 ± 1	60	21 ± 8								
Weaving et al. [32]	RL	23	English Championship	24 ± 3	Skills	19 ± 4	448	40 ± 24	-	sRPE-TL (CR10) TRIMP (Modified Edwards)	Total distance covered at individualised high-speeds ^e , total accelerometer load ^c	10 Hz GPS & 100 Hz MEMS (Catapult Sports, Optimeye X4)		
					Conditioning	8 ± 2	192	25 ± 12						
Weston et al. [33]	AF	26	Australian Football League	22 ± 3	Australian Football League match-play	5 ± 2	129	104 ± 9		sRPE (CR100) sRPE-B (CR100) sRPE-L (CR100)	-	Relative distance covered, relative distance covered at speeds ≥ 14.4 km·h ⁻¹ , relative distance covered at high instantaneous metabolic power (> 20 W·kg ⁻¹)	Total distance, total distance covered at speeds < 14.4 and ≥ 14.4 km·h ⁻¹ , total tri- and bi-axil accelerometer load ^e , total distance covered at high instantaneous metabolic power (> 20 W·kg ⁻¹), equivalent total distance covered for steady-state running, average metabolic power, estimated energy expenditure	10 Hz GPS & 100 Hz MEMS (Catapult Sports, Minimax S4)

*Only measures that were examined via correlation analyses are reported. Some studies [19,26] report other measures that were not analysed

**external measures of intensity are expressed per-minute or as a proportion (%)

^aMatch sRPE-TL calculated as sRPE × a) minutes played, b) minutes played + halftime, c) minutes played + warm-up, d) minutes played + halftime and warm-up, e) match duration, f) match duration + halftime, g) match duration + warm-up, h) match duration + halftime and warm-up.

^bIndividually weighted using each player's exponential blood lactate–HR relationship (derived from a staged treadmill test) [46].

^cCatapult Sports PlayerLoad™ (vector magnitude)

^dGPSports Body Load™ (summated zones)

^eMeasured using Freescale Semiconductor accelerometers (MMA7361L) and calculated using Catapult Sports' PlayerLoad™ algorithm (vector magnitude)

^fIndividualised as each player's mean 2-km time trial speed. Mean = 18.1 km·h⁻¹, range = 16.9–19.7 km·h⁻¹.

^gIndividualised as each player's final running speed during the 30–15 intermittent fitness test. Mean ± SD = 19.6 ± 0.6 km·h⁻¹, range = 18.5–20.5 km·h⁻¹.

Abbreviations. %HR_{max}: percentage of maximum heart rate, AF: Australian Football, BB: Basketball, Banister's: exponentially weighted TRIMP calculated according to Banister [44], CR10: Borg's Category-Ratio 10 (deci-Max) scale [42], CR100: Borg's Category-Ratio 100 (centi-Max) scale [42], Edwards: summated zones TRIMP calculated according to Edwards [45], GPS: global positioning system, MEMS: micro-electrical mechanical system, Modified Edwards: summated zones TRIMP calculated according to Edwards [45], but utilising arbitrary exponential weighting factors [32], RL: Rugby League, SD: standard deviation, SO: Soccer, sRPE: session rating of perceived exertion, sRPE-B: session rating of perceived breathlessness, sRPE-L: session rating of perceived leg muscle exertion, sRPE-TL: session rating of perceived exertion training load, SSG: small-sided games, TRIMP: heart-rate-derived training impulse.

Table 5. Meta-analysed relationships between internal and external measures of load and intensity in team-sport athletes during training and competition.

Relationship		Number of...		Meta-Analyses		
Internal	External	Estimates	Studies	Pooled Effect (<i>r</i> [90% CI])	Inference	τ (<i>r</i>)
sRPE	TD per min	9	5	0.29 (0.16 to 0.42)	unclear	0.00
	HSRD per min	8	4	0.22 (0.08 to 0.34)	unclear	0.00
	AL per min	7	3	0.25 (0.10 to 0.40)	unclear	0.00
	Impacts per min	6	2	0.27 (0.12 to 0.42)	unclear	0.00
	TD	2	2	0.57 (0.02 to 0.86)	-	0.47
	HSRD	2	2	0.51 (0.08 to 0.78)	-	0.36
sRPE-TL	TD	11	6	0.79 (0.74 to 0.83)	possibly very large	0.10
	HSRD	16	6	0.47 (0.32 to 0.59)	likely moderate	0.31
	VHSRD	5	4	0.25 (0.03 to 0.45)	unclear	0.22
	AL	20	9	0.63 (0.54 to 0.70)	likely large	0.22
	Impacts	12	3	0.57 (0.47 to 0.64)	possibly large	0.07
TRIMP	TD	2	2	0.74 (0.56 to 0.86)	-	0.00
	HSRD	7	2	0.28 (0.10 to 0.45)	unclear	0.14
	VHSRD	4	3	0.17 (-0.04 to 0.36)	unclear	0.08
	AL	11	5	0.54 (0.40 to 0.66)	possibly large	0.17

- inference not possible ($n \leq 3$)

Abbreviations. sRPE: session rating of perceived exertion, sRPE-TL: session rating of perceived exertion training load, TRIMP: heart-rate-derived training impulse, TD: total distance covered, HSRD: distance covered at high speeds (≥ 13.1 – 15.0 km·h⁻¹), VHSRD: distance covered at very high speeds (≥ 16.9 – 19.8 km·h⁻¹), AL: accelerometer-derived load, Impacts: total number of sustained impacts (> 2 – 5 G), *r*: Pearson's product moment correlation coefficient, τ : Tau (between-estimate heterogeneity [standard deviation representing unexplained variation]), CI: confidence interval.

Name: Supplementary File 1. Funnel plots of mean point estimates versus standard errors for the relationships between internal and external measures of load and intensity during team-sport training and competition.

Article Title: The relationships between internal and external measures of training load and intensity in team sports: A meta-analysis.

Journal: Sports Medicine.

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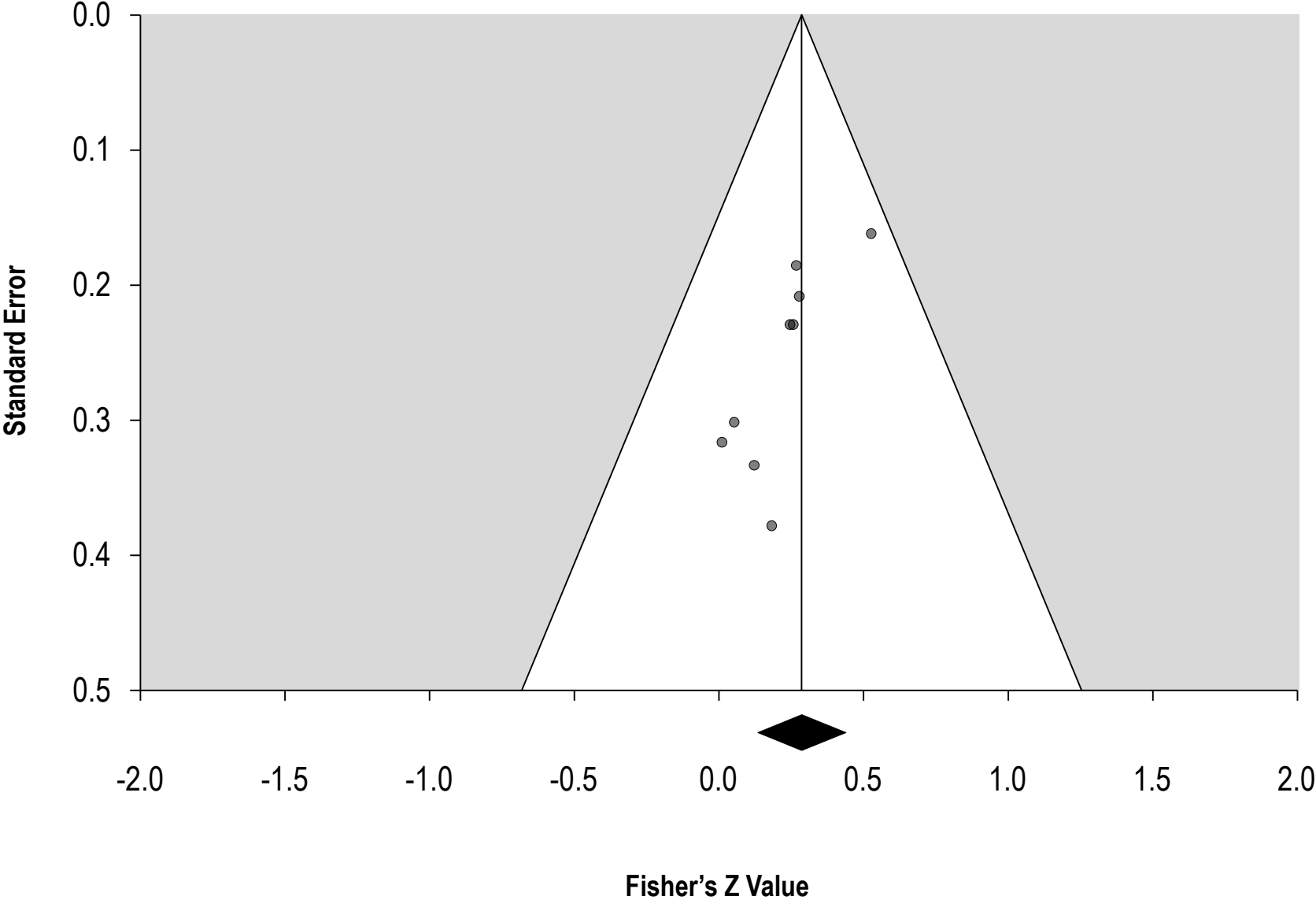
Affiliations: ¹Department of Psychology, Sport & Exercise, School of Social Sciences, Humanities and Law, Teesside University, Middlesbrough, United Kingdom.

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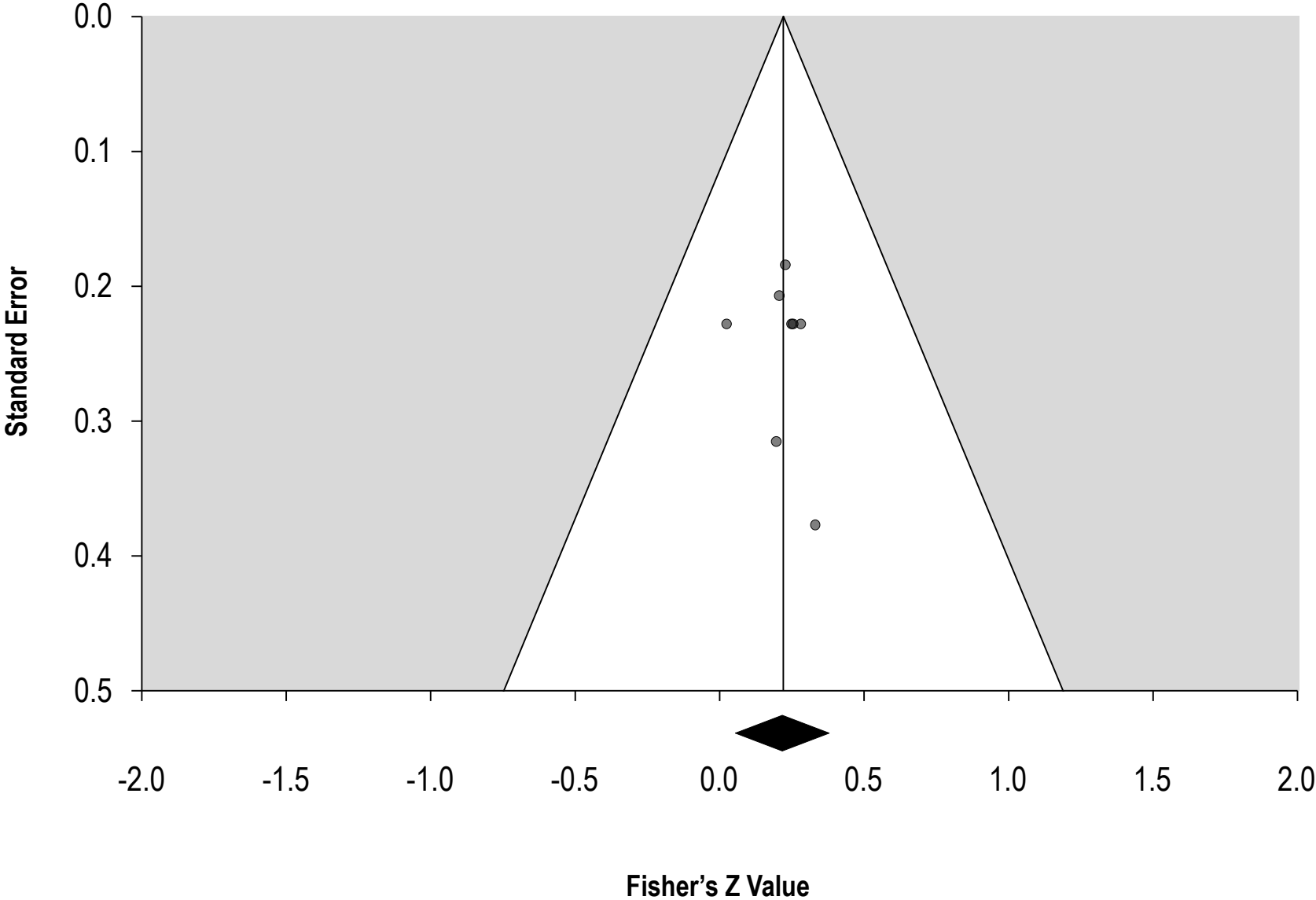
³Sport and Exercise Discipline Group, Faculty of Health, University of Technology Sydney (UTS), Sydney, Australia.

⁴Pro-Football Support, Huddersfield, United Kingdom.

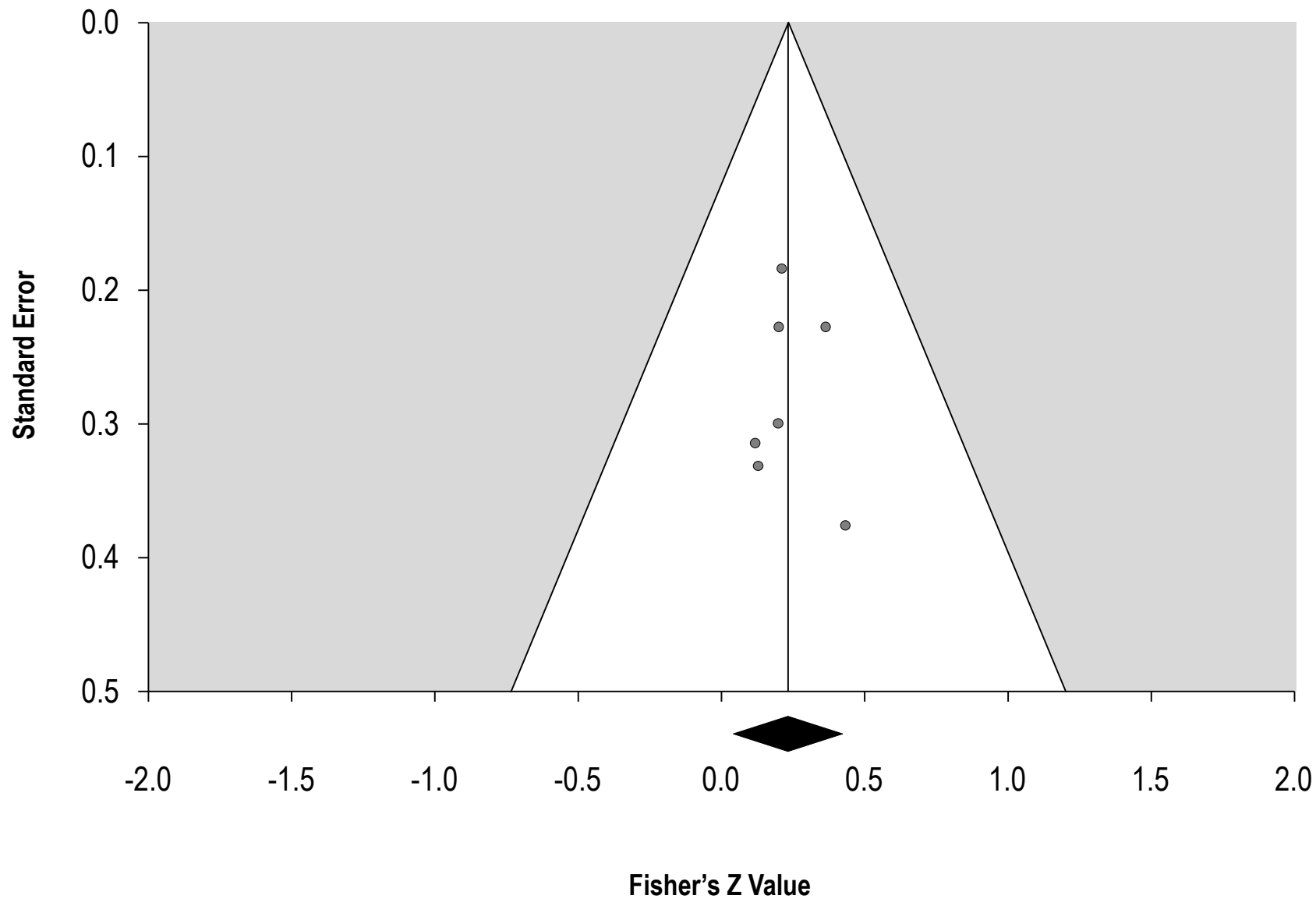
Supplementary Figure 1. Funnel plot of mean point estimates versus standard errors for the relationship between session rating of perceived exertion (sRPE) and total distance (TD) per minute during team-sport training and competition.



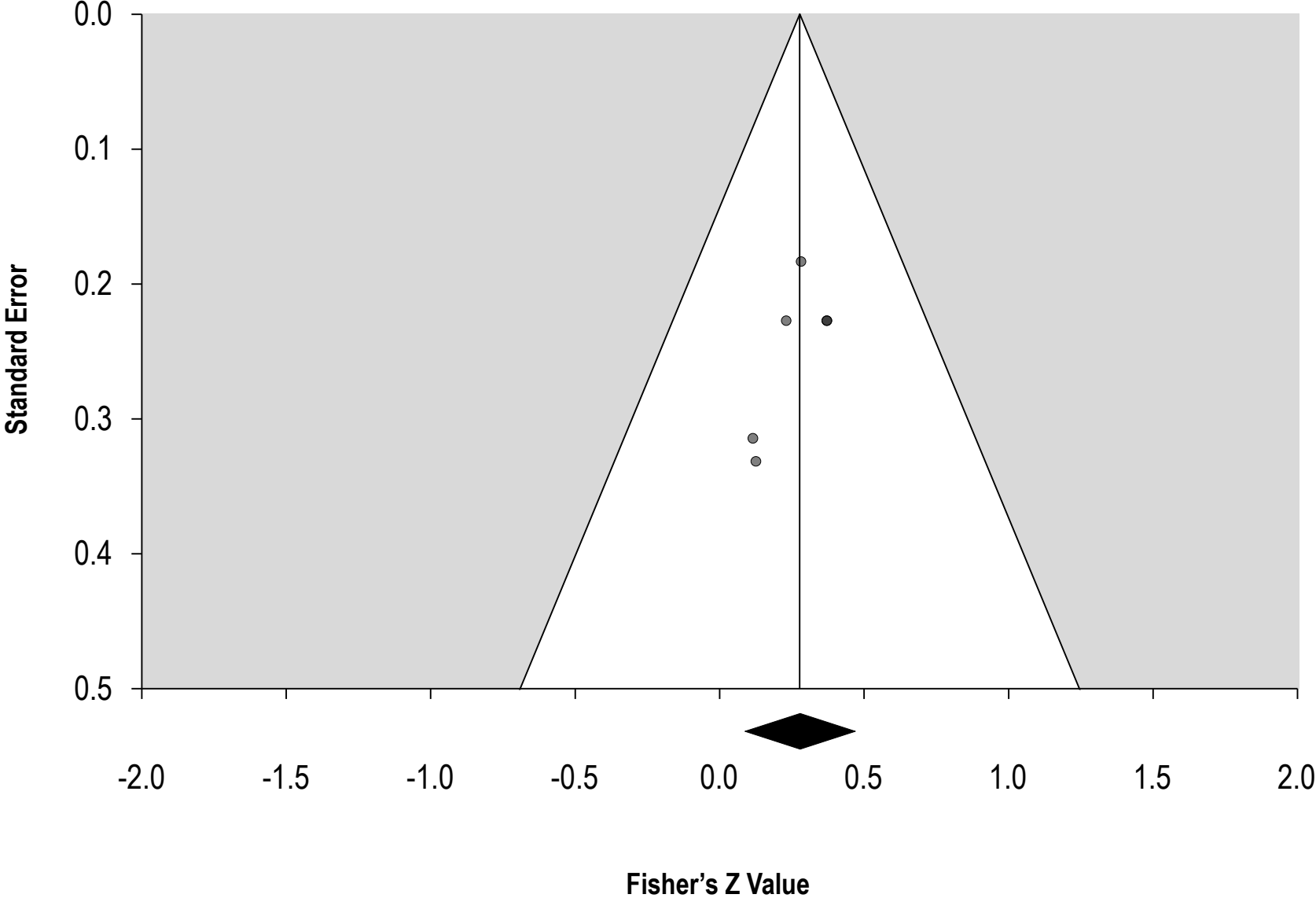
Supplementary Figure 2. Funnel plot of mean point estimates versus standard errors for the relationship between session rating of perceived exertion (sRPE) and high-speed running distance (HSRD; $\geq 13.1\text{--}15.0 \text{ km}\cdot\text{h}^{-1}$) per minute during team-sport training and competition.



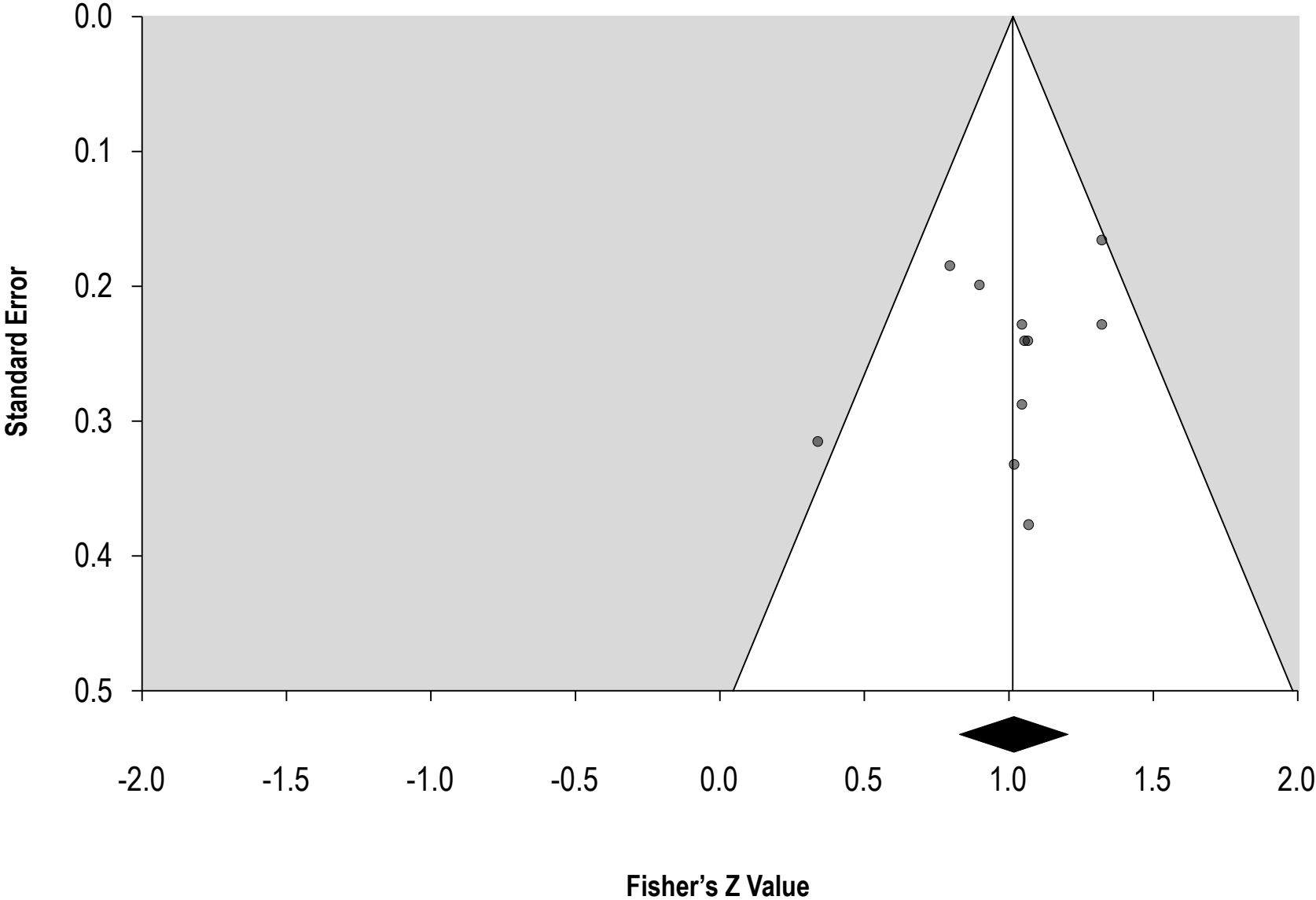
Supplementary Figure 3. Funnel plot of mean point estimates versus standard errors for the relationship between session rating of perceived exertion (sRPE) and accelerometer load (AL) per minute during team-sport training and competition.



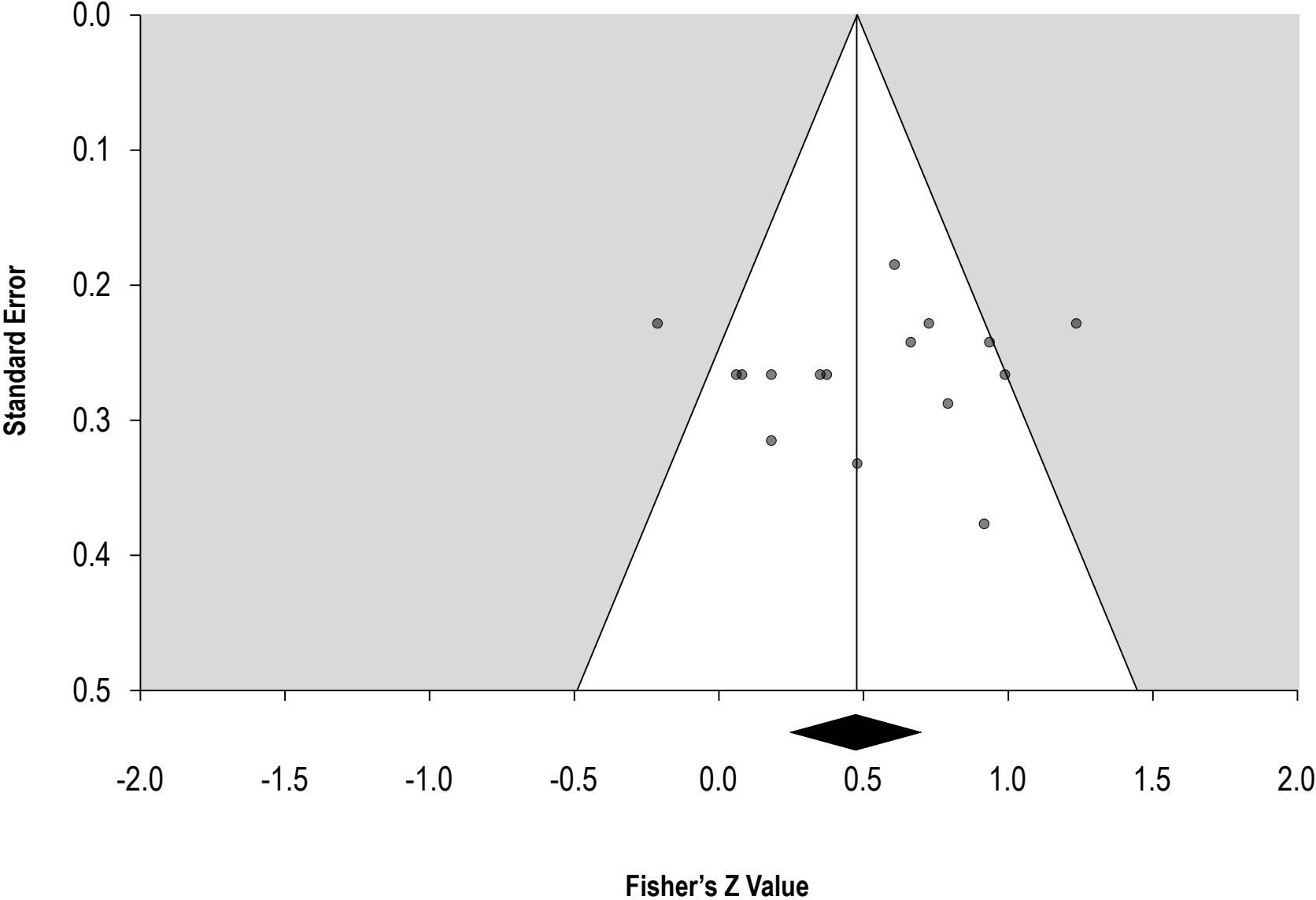
Supplementary Figure 4. Funnel plot of mean point estimates versus standard errors for the relationship between session rating of perceived exertion (sRPE) and Impacts (> 2–5 G) per minute during team-sport training and competition.



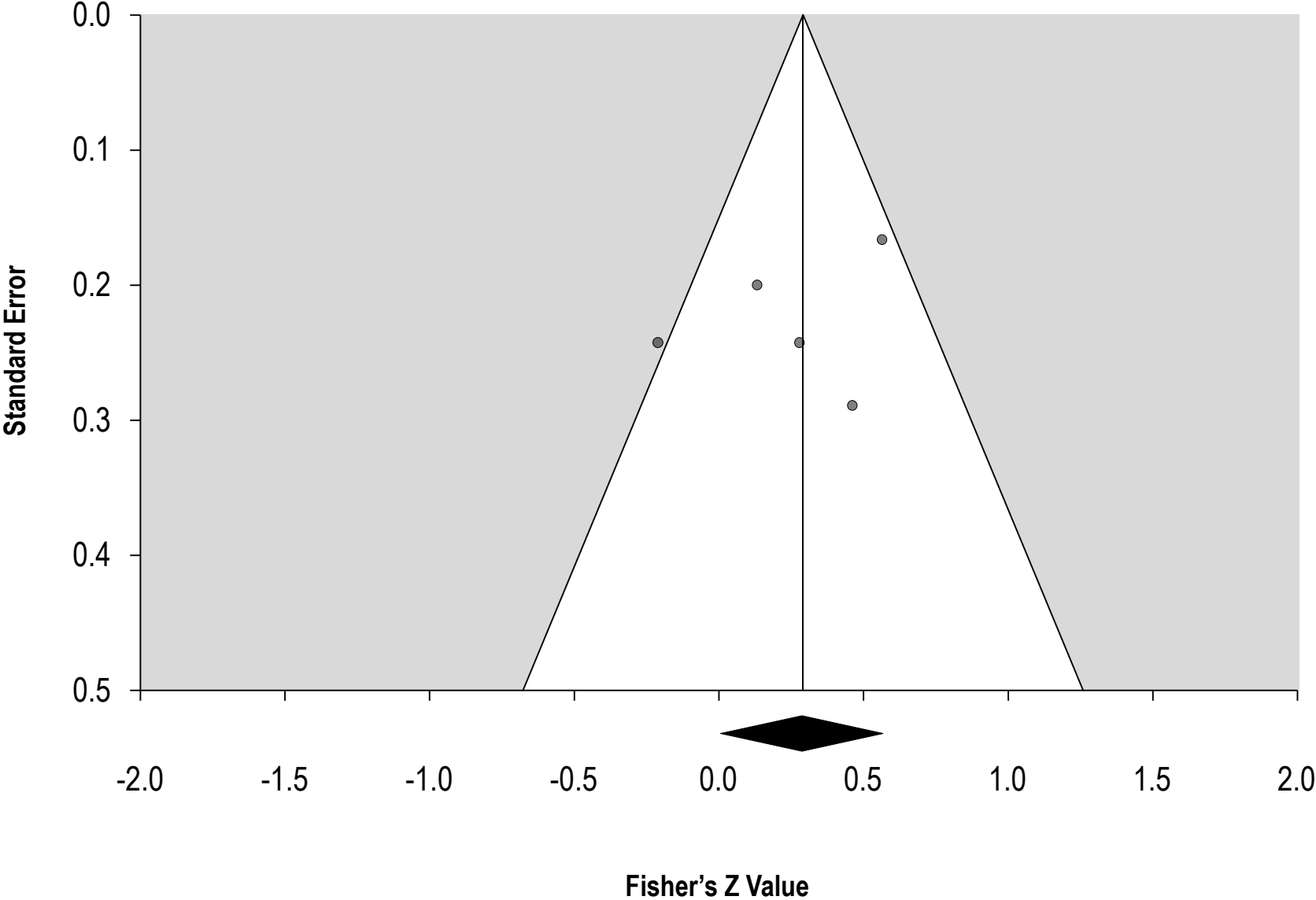
Supplementary Figure 5. Funnel plot of mean point estimates versus standard errors for the relationship between session rating of perceived exertion training load (sRPE-TL) and total distance (TD) during team-sport training and competition.



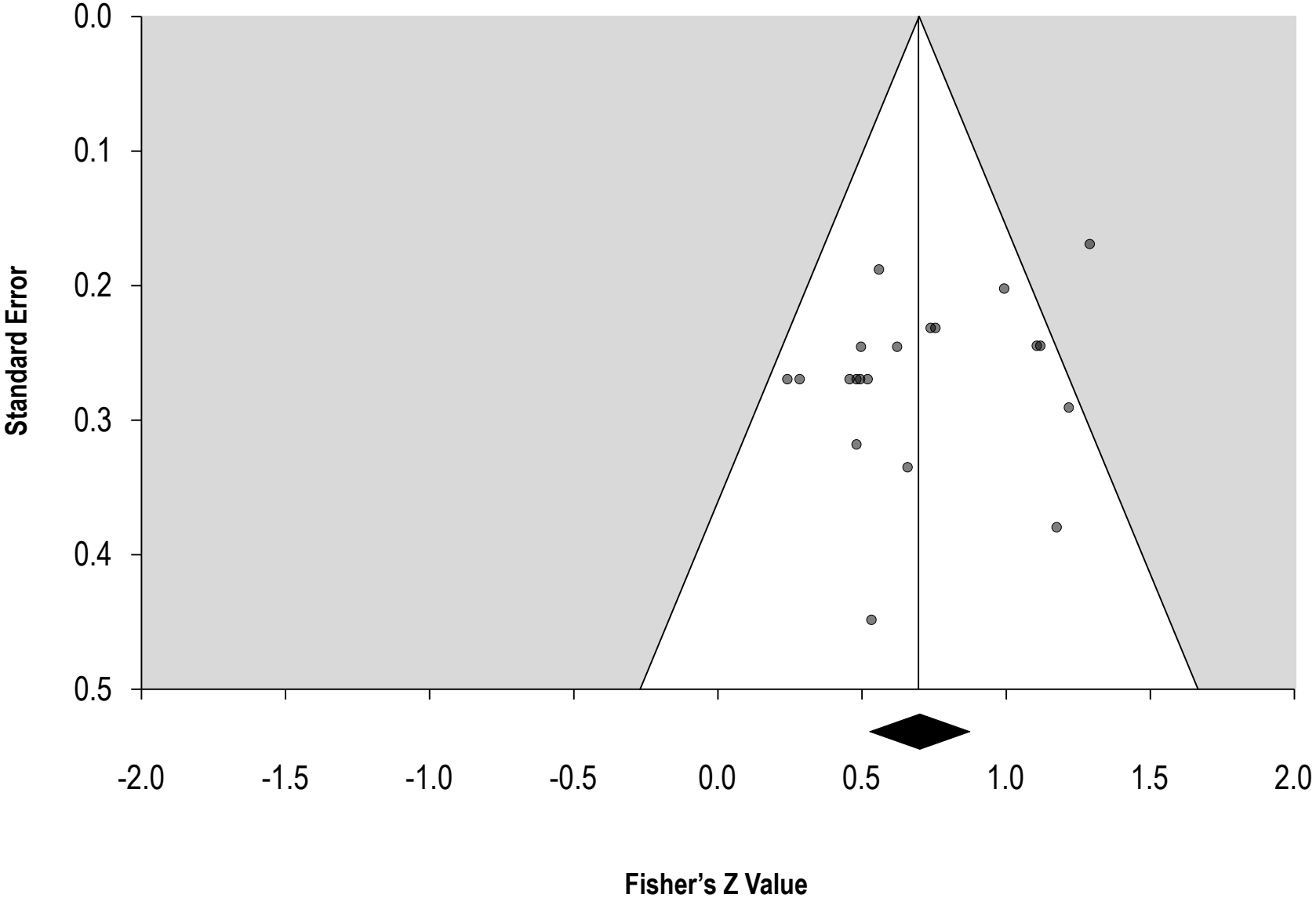
Supplementary Figure 6. Funnel plot of mean point estimates versus standard errors for the relationship between session rating of perceived exertion training load (sRPE-TL) and high-speed running distance (HSRD; $\geq 13.1\text{--}15.0 \text{ km}\cdot\text{h}^{-1}$) during team-sport training and competition.



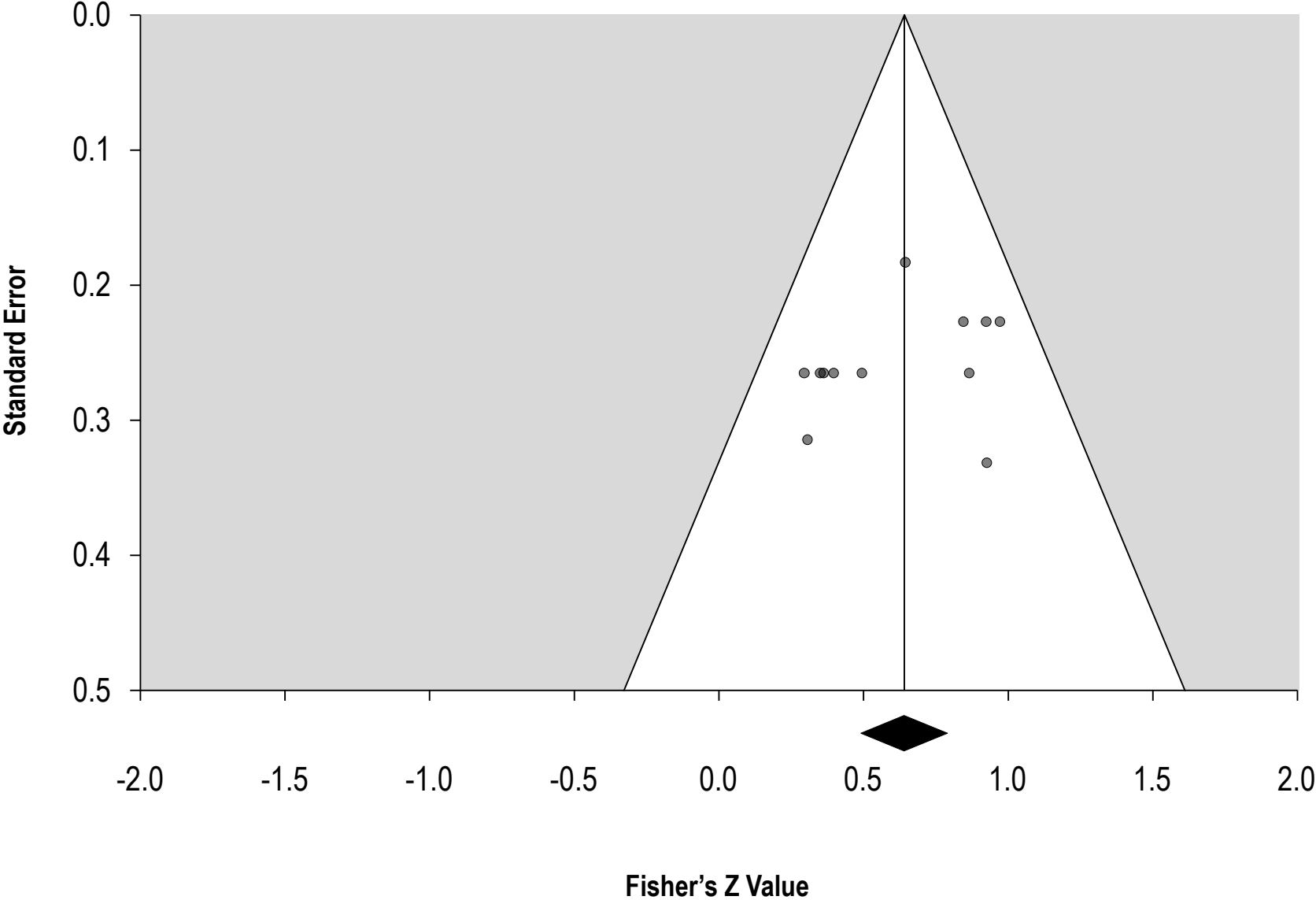
Supplementary Figure 7. Funnel plot of mean point estimates versus standard errors for the relationship between session rating of perceived exertion training load (sRPE-TL) and very high-speed running distance (VHSRD; $\geq 16.9\text{--}19.8 \text{ km}\cdot\text{h}^{-1}$) during team-sport training and competition.



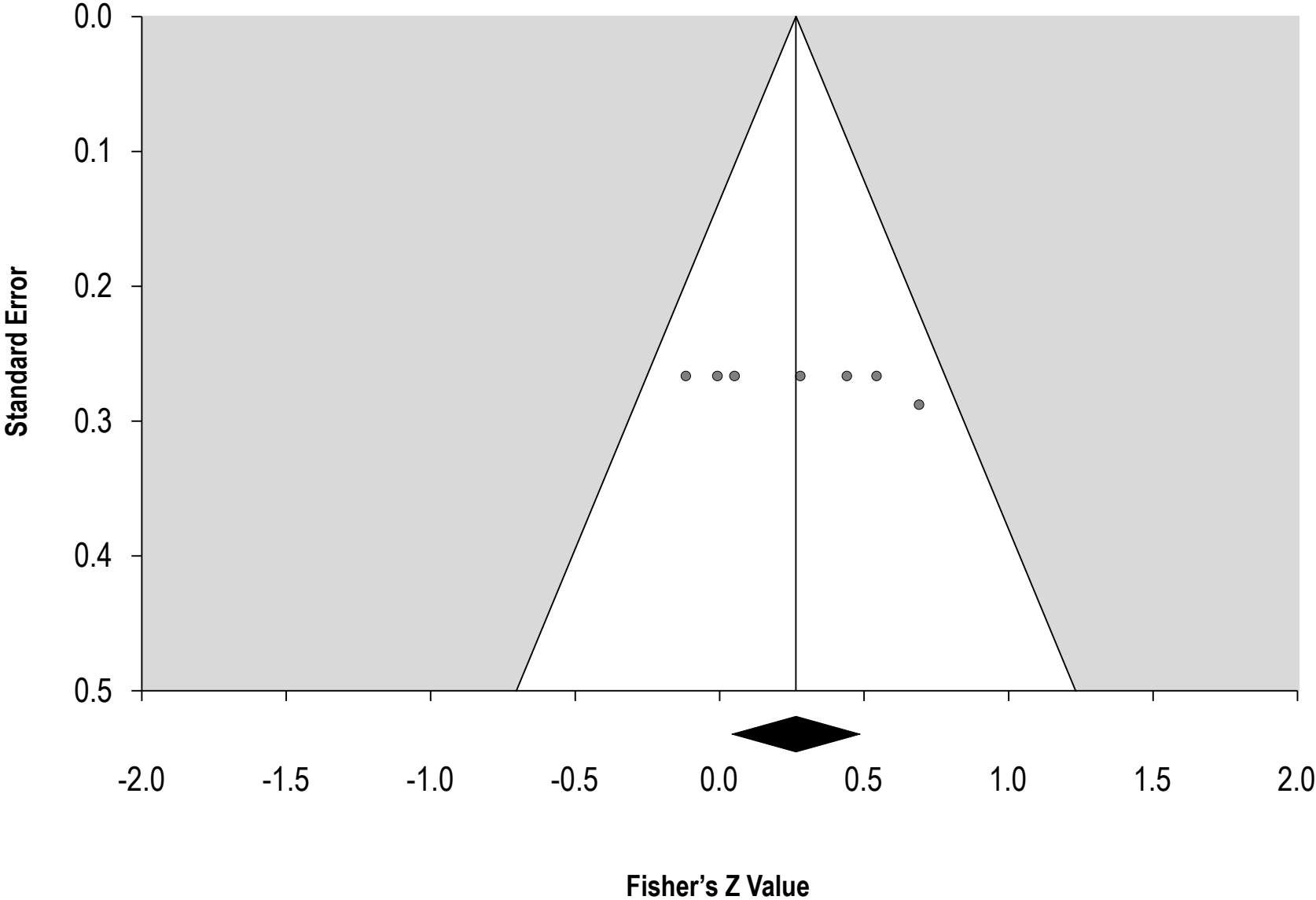
Supplementary Figure 8. Funnel plot of mean point estimates versus standard errors for the relationship between session rating of perceived exertion training load (sRPE-TL) and accelerometer load (AL) during team-sport training and competition.



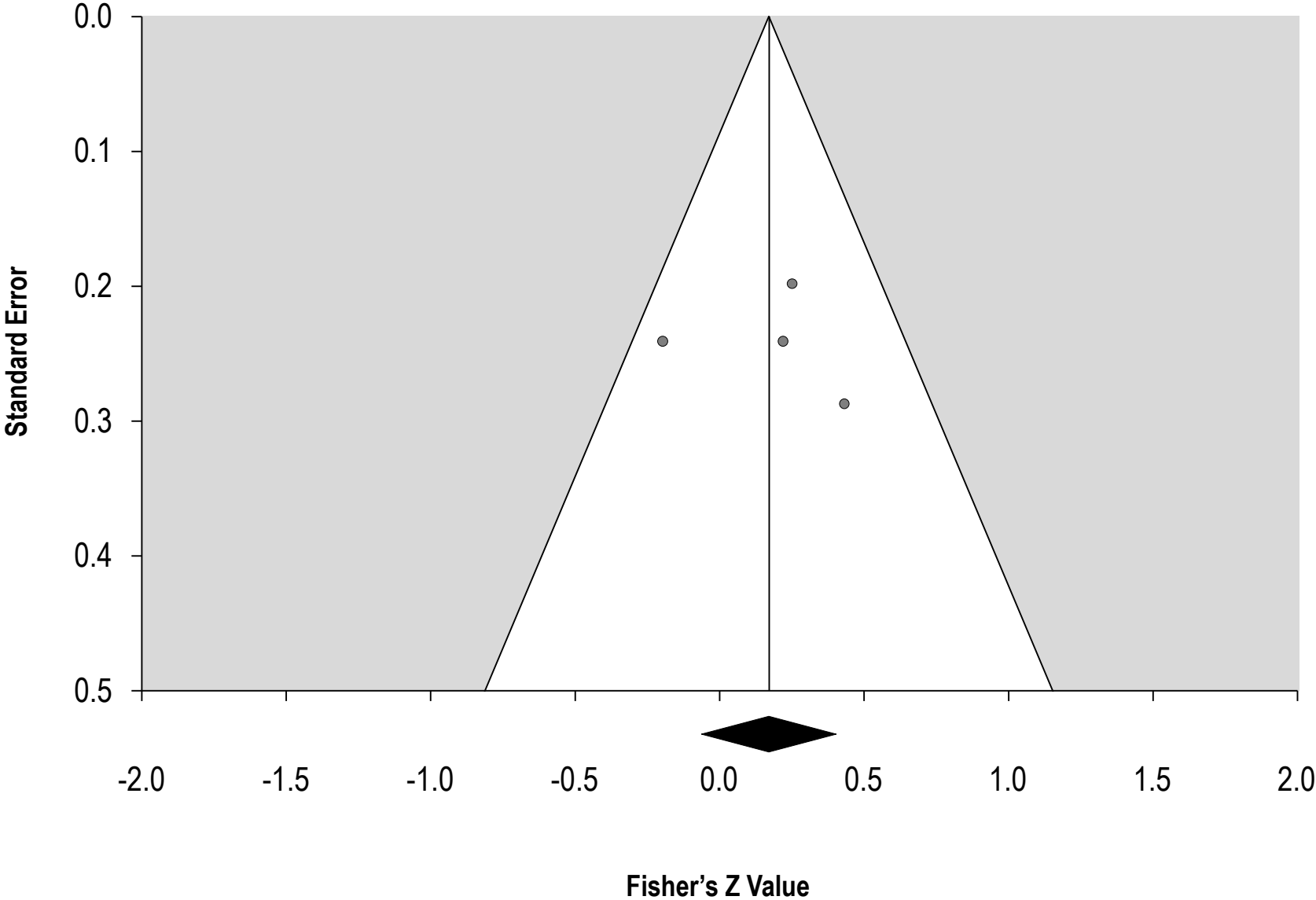
Supplementary Figure 9. Funnel plot of mean point estimates versus standard errors for the relationship between session rating of perceived exertion training load (sRPE-TL) and Impacts (> 2–5 G) during team-sport training and competition.



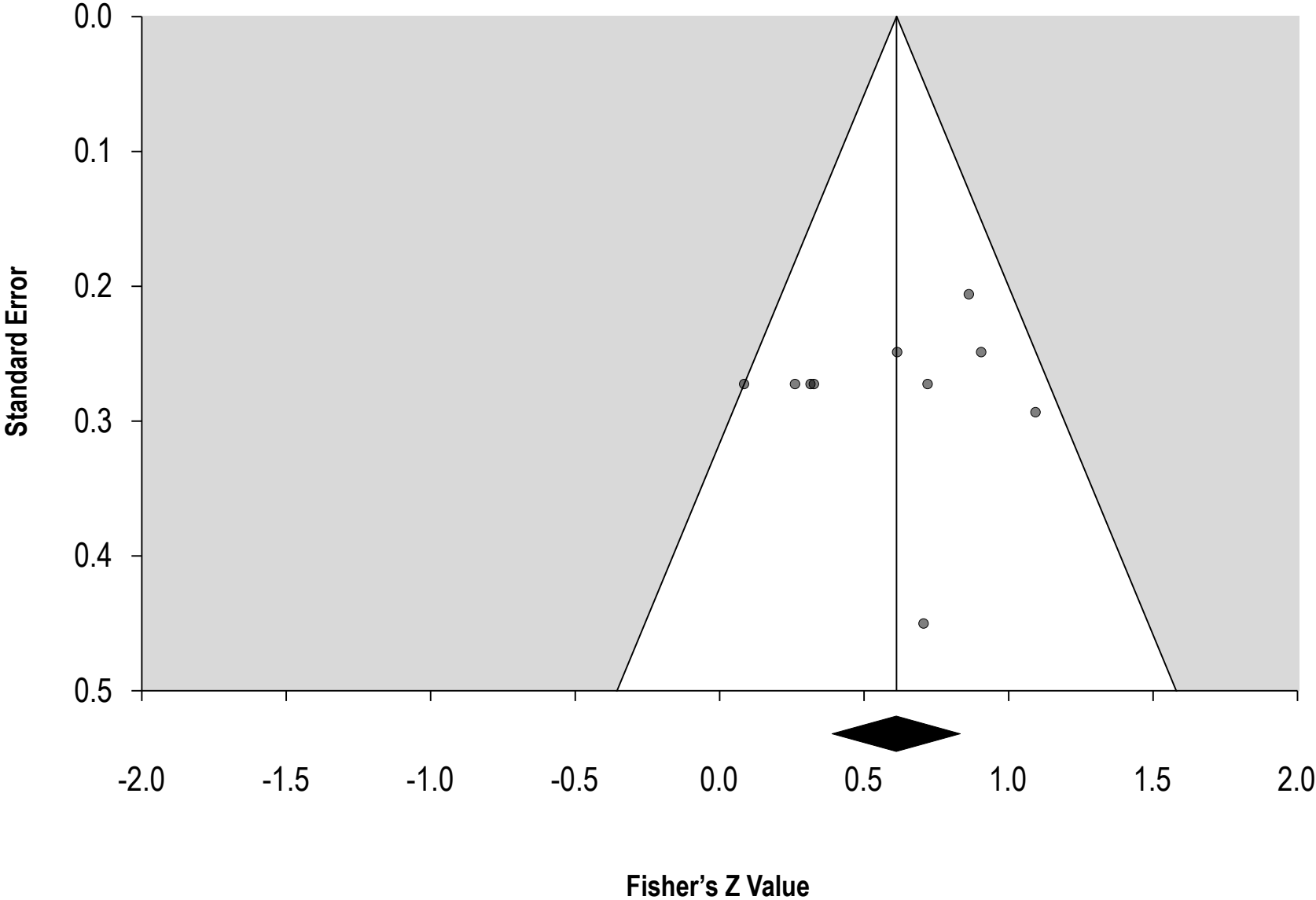
Supplementary Figure 10. Funnel plot of mean point estimates versus standard errors for the relationship between heart-rate-derived training impulse (TRIMP) and high-speed running distance (HSRD; $\geq 13.1\text{--}15.0 \text{ km}\cdot\text{h}^{-1}$) during team-sport training and competition.



Supplementary Figure 11. Funnel plot of mean point estimates versus standard errors for the relationship between heart-rate-derived training impulse (TRIMP) and very high-speed running distance (VHSRD; $\geq 16.9\text{--}19.8 \text{ km}\cdot\text{h}^{-1}$) during team-sport training and competition.



Supplementary Figure 12. Funnel plot of mean point estimates versus standard errors for the relationship between heart-rate-derived training impulse (TRIMP) and accelerometer load (AL) during team-sport training and competition.



Name: Supplementary File 2. Weighted raw point estimates and the meta-analysed relationship between internal and external measures of load and intensity during team-sport training and competition.

Article Title: The relationships between internal and external measures of training load and intensity in team sports: A meta-analysis.

Journal: Sports Medicine.

Authors: Shaun J. McLaren^{1,2,*}, Tom W. Macpherson¹, Aaron J. Coutts³, Christopher Hurst¹, Iain R. Spears⁴, Matthew Weston¹.

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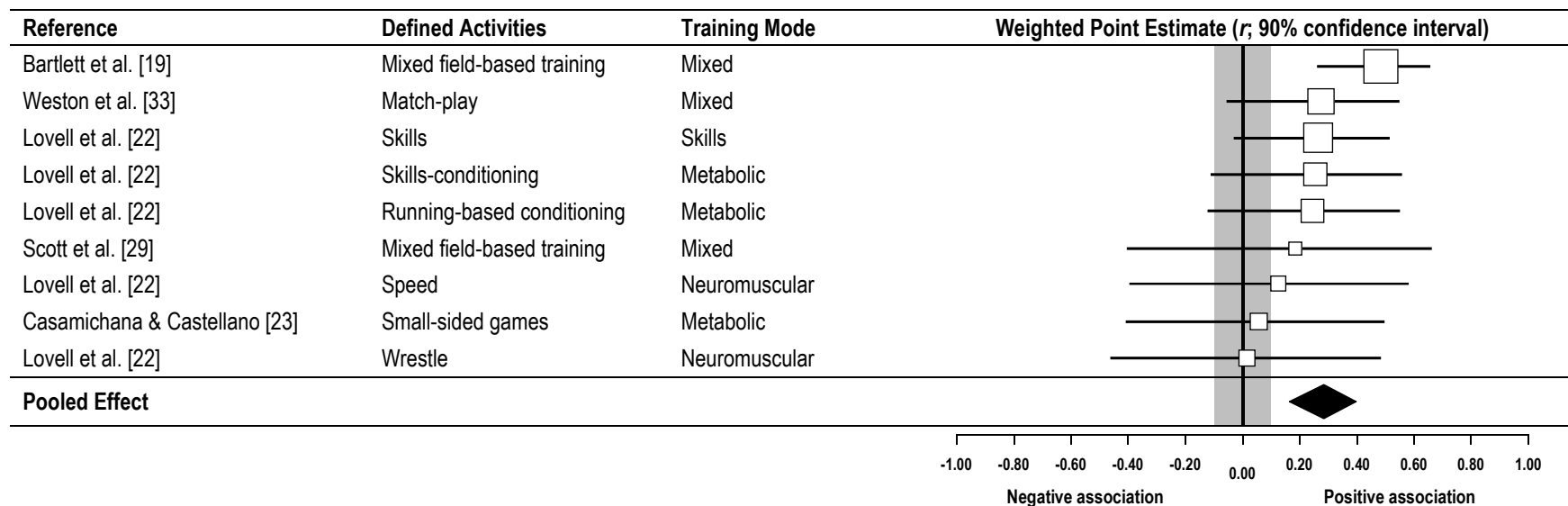
Affiliations: ¹Department of Psychology, Sport & Exercise, School of Social Sciences, Humanities and Law, Teesside University, Middlesbrough, United Kingdom.

²Sport Science and Medical Department, Hartlepool United Football Club, Hartlepool, United Kingdom.

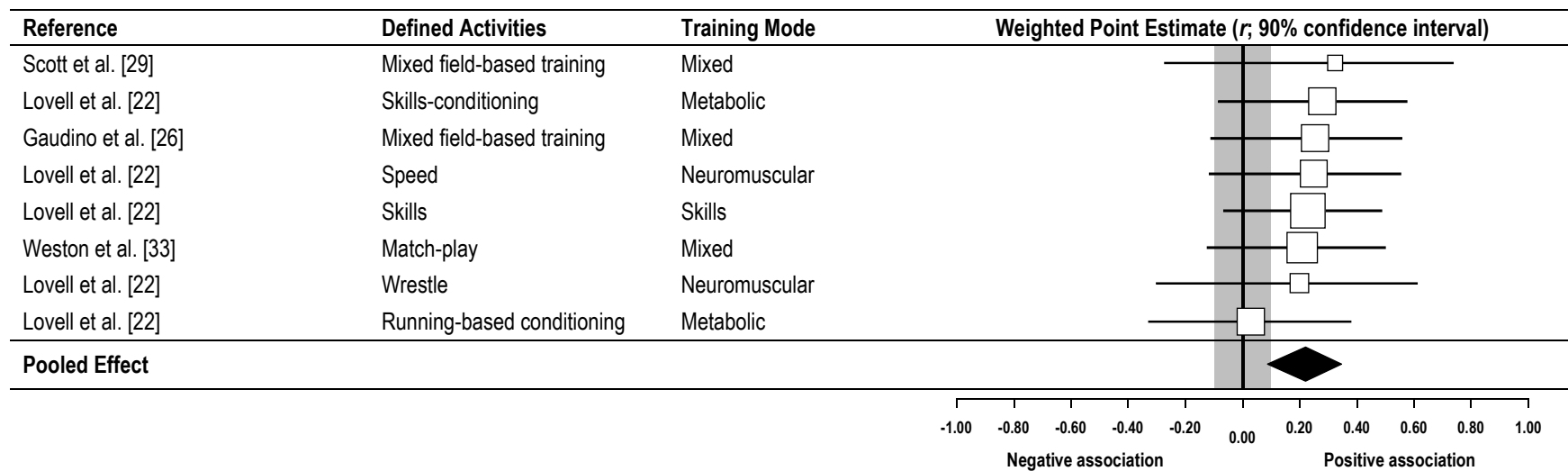
³Sport and Exercise Discipline Group, Faculty of Health, University of Technology Sydney (UTS), Sydney, Australia.

⁴Pro-Football Support, Huddersfield, United Kingdom.

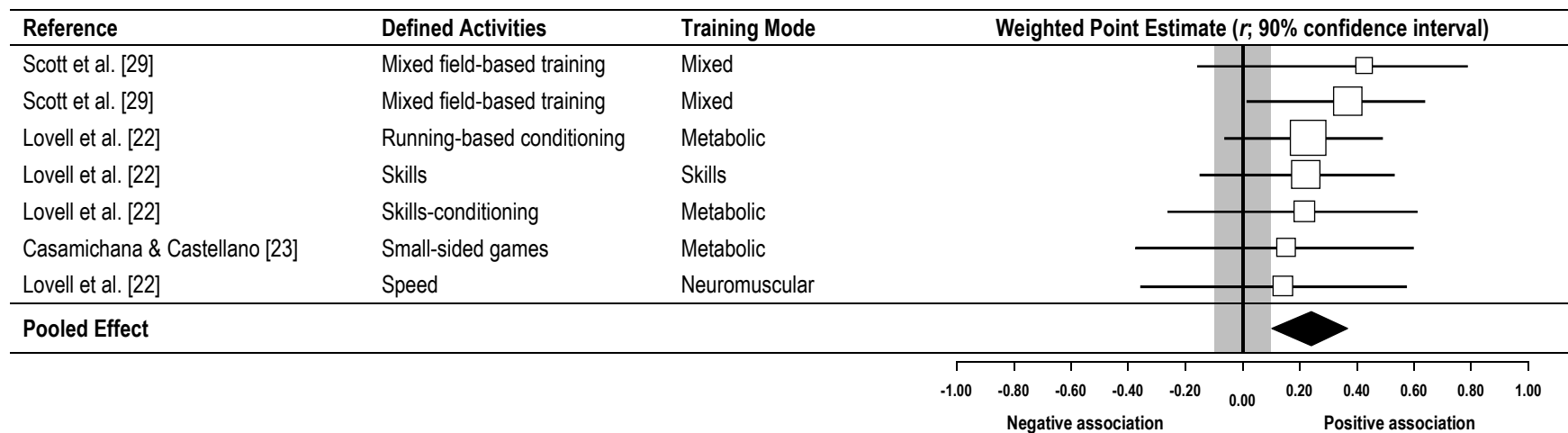
Supplementary Table 1. Weighted raw point estimates and the meta-analysed relationship between session rating of perceived exertion (sRPE) and total distance (TD) per minute during team-sport training and competition.



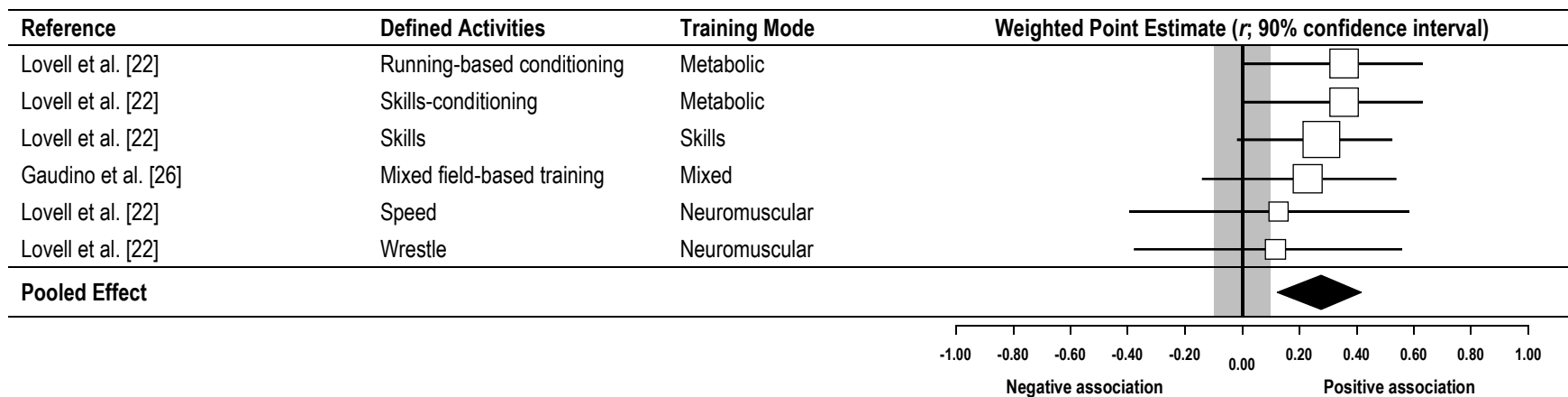
Supplementary Table 2. Weighted raw point estimates and the meta-analysed relationship between session rating of perceived exertion (sRPE) and high-speed running distance (HSRD; ≥ 13.1 – 15.0 km·h⁻¹) per minute during team-sport training and competition.



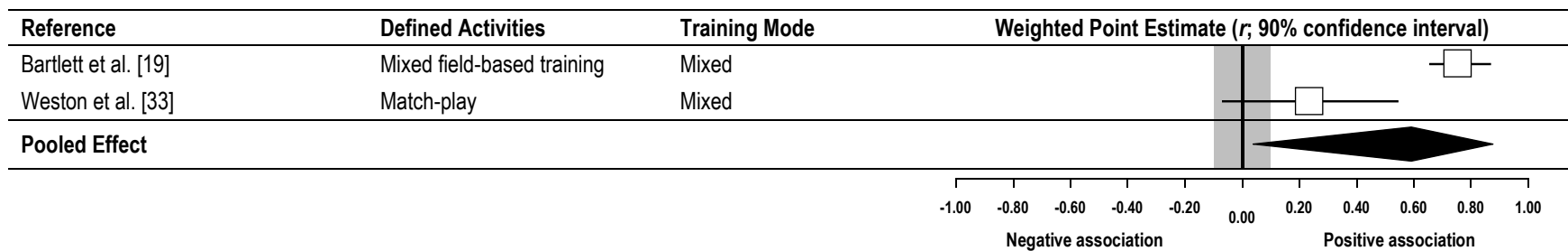
Supplementary Table 3. Weighted raw point estimates and the meta-analysed relationship between session rating of perceived exertion (sRPE) and accelerometer load (AL) per minute during team-sport training and competition.



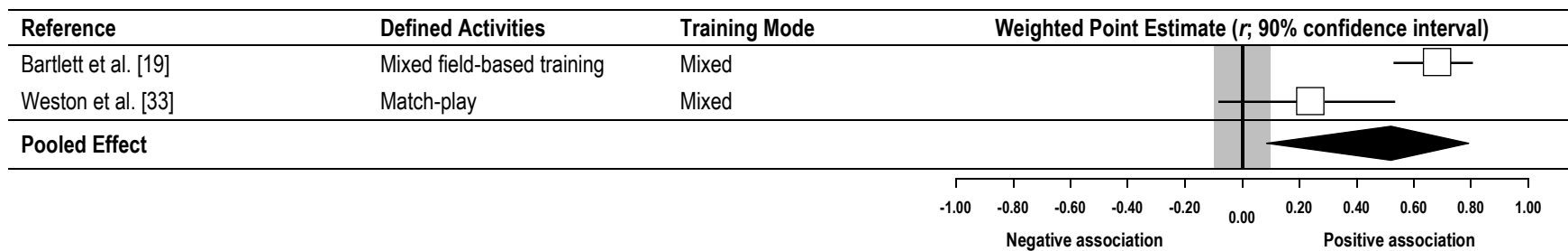
Supplementary Table 4. Weighted raw point estimates and the meta-analysed relationship between session rating of perceived exertion (sRPE) and Impacts (> 2–5 G) per minute during team-sport training and competition.



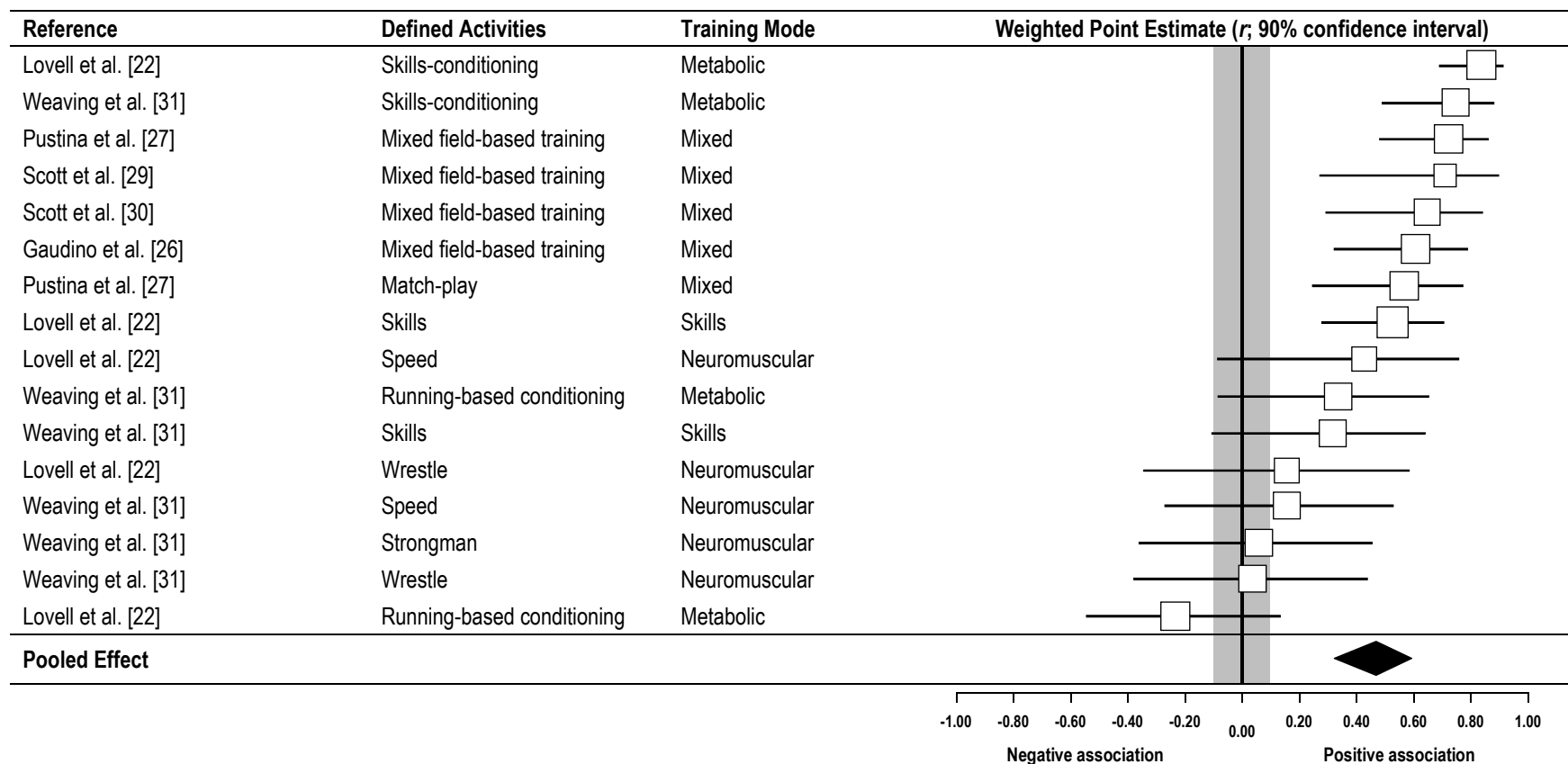
Supplementary Table 5. Weighted raw point estimates and the meta-analysed relationship between session rating of perceived exertion (sRPE) and total distance (TD) during team-sport training and competition.



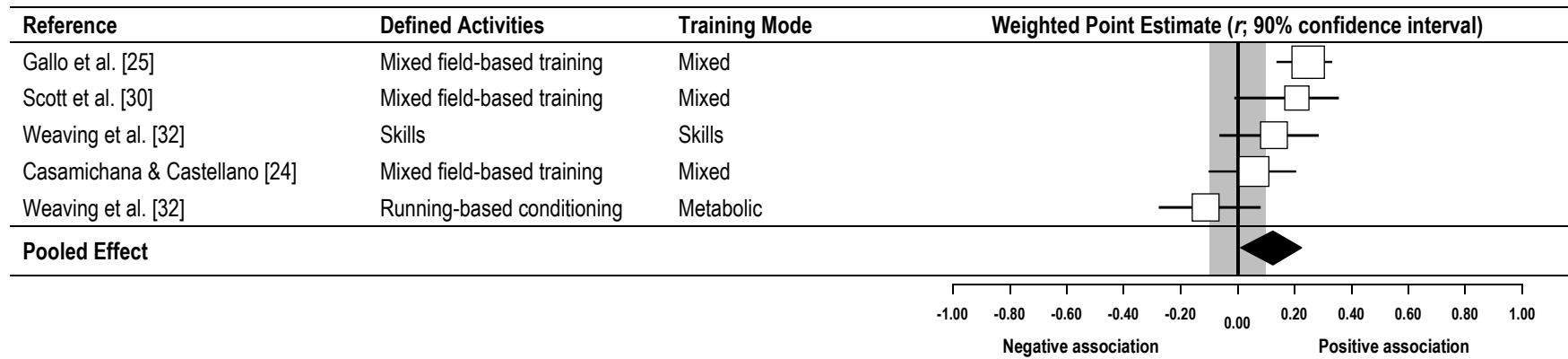
Supplementary Table 6. Weighted raw point estimates and the meta-analysed relationship between session rating of perceived exertion (sRPE) and high-speed running distance (HSRD; ≥ 13.1 – 15.0 km·h⁻¹) during team-sport training and competition.



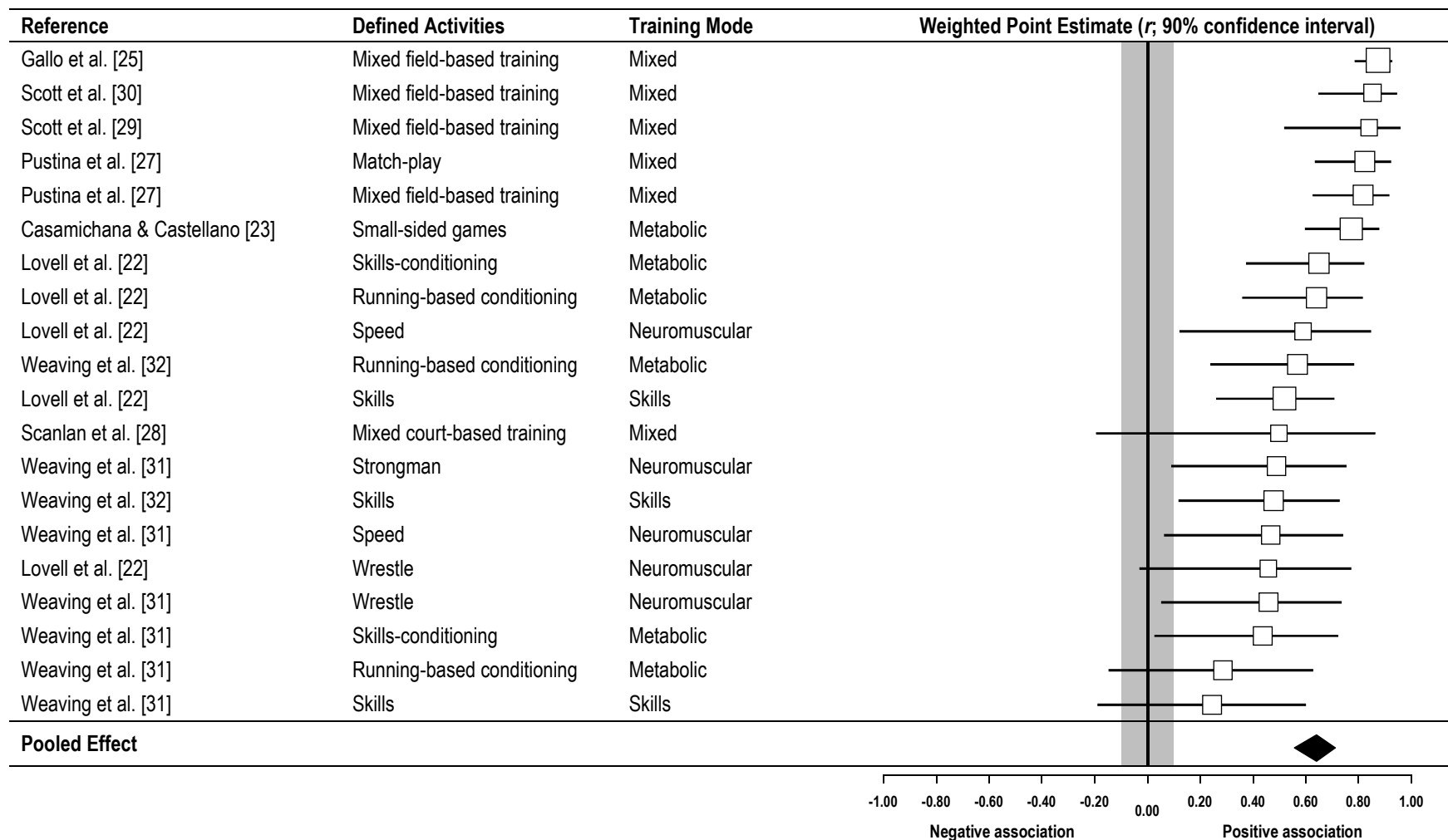
Supplementary Table 8. Weighted raw point estimates and the meta-analysed relationship between session rating of perceived exertion training load (sRPE-TL) and high-speed running distance (HSRD; ≥ 13.1 – 15.0 km·h⁻¹) during team-sport training and competition.



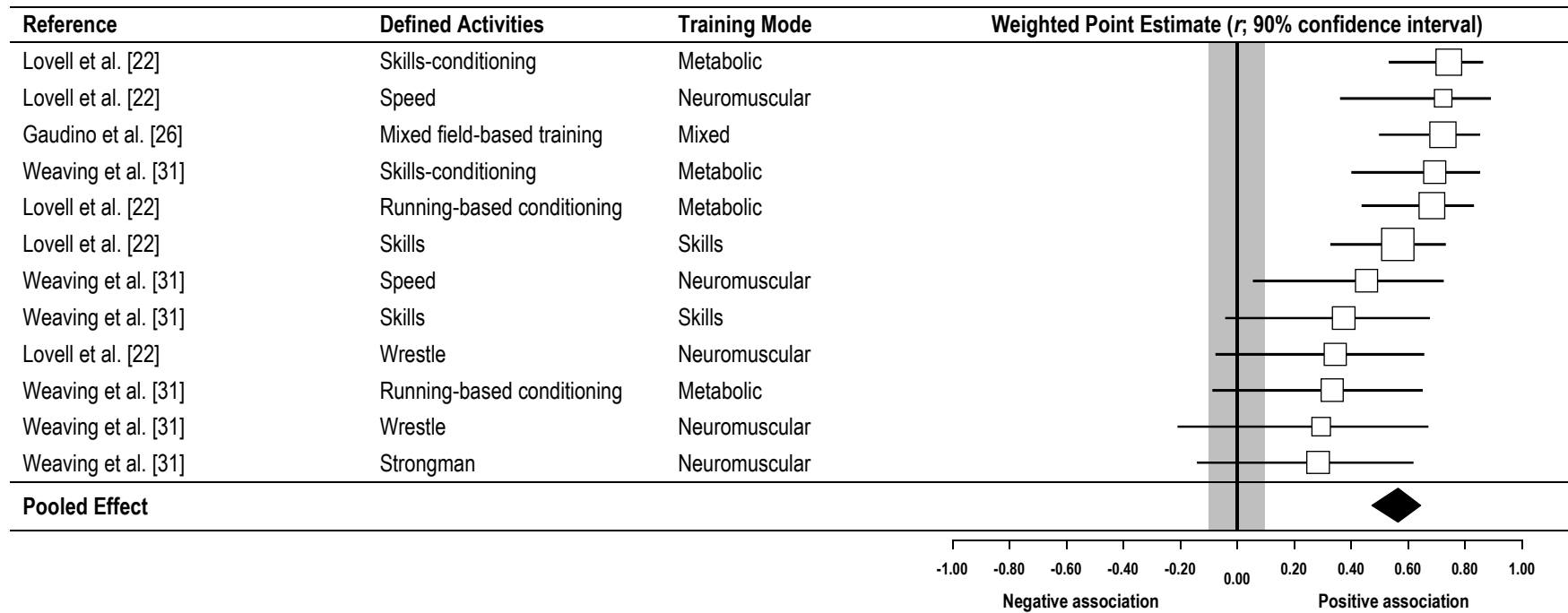
Supplementary Table 9. Weighted raw point estimates and the meta-analysed relationship between session rating of perceived exertion training load (sRPE-TL) and very high-speed running distance (VHSRD; ≥ 16.9 – 19.8 k·mh⁻¹) during team-sport training and competition.



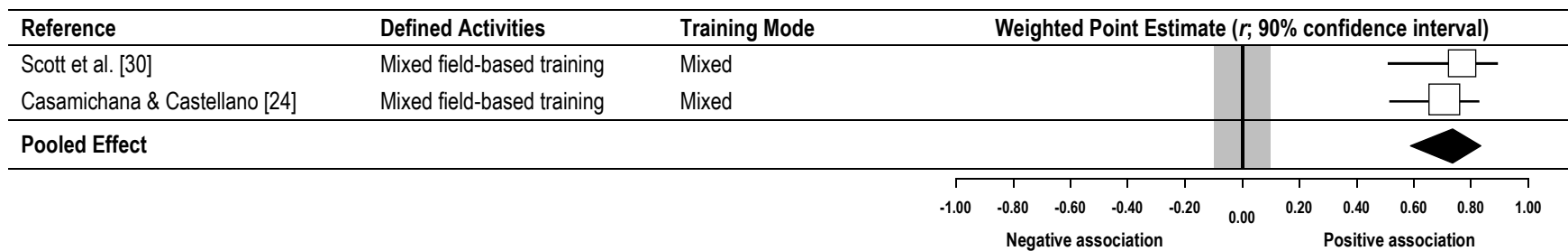
Supplementary Table 10. Weighted raw point estimates and the meta-analysed relationship between session rating of perceived exertion training load (sRPE-TL) and accelerometer load (AL) during team-sport training and competition.



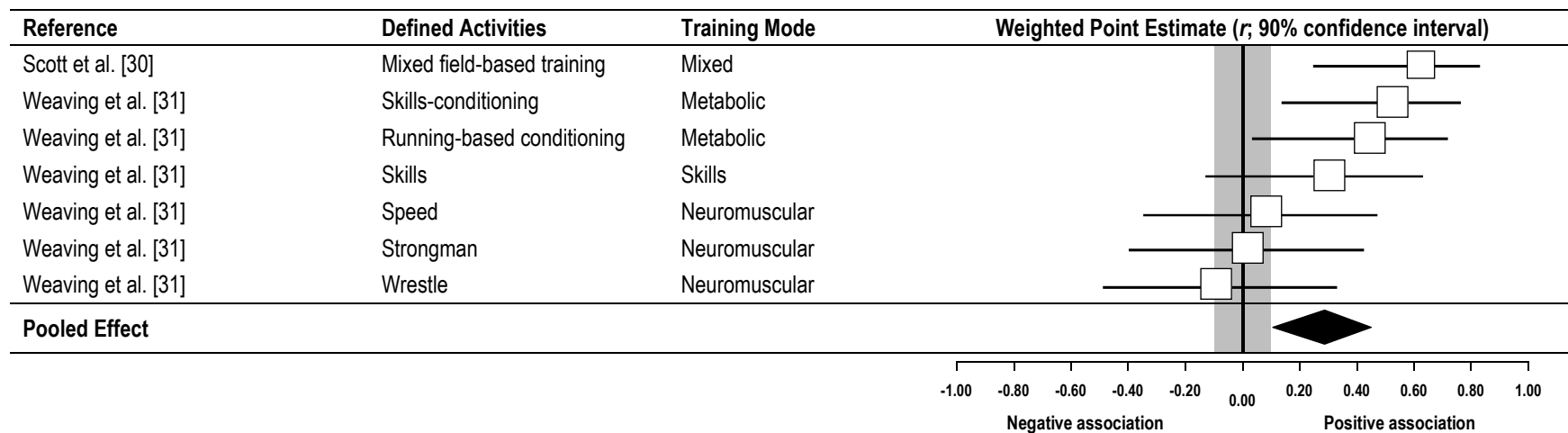
Supplementary Table 11. Weighted raw point estimates and the meta-analysed relationship between session rating of perceived exertion training load (sRPE-TL) and Impacts (> 2–5 G) during team-sport training and competition.



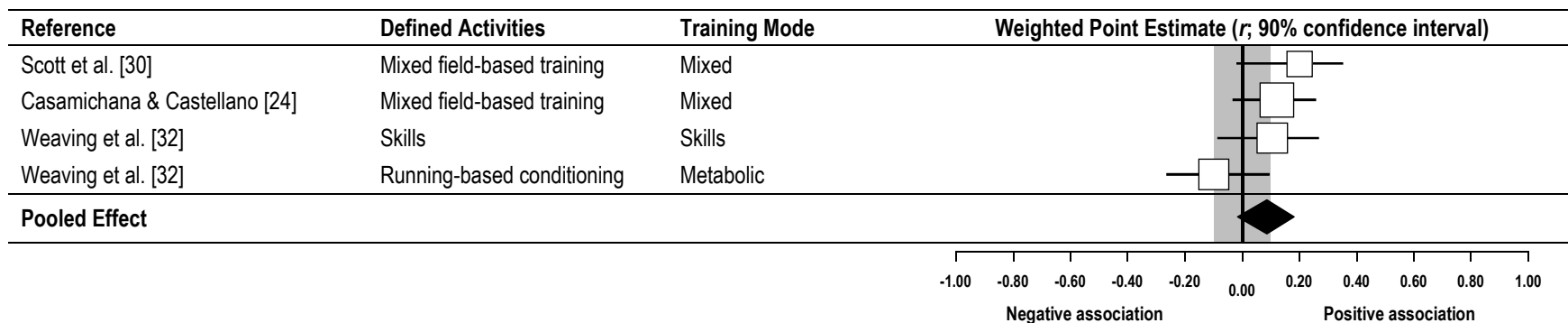
Supplementary Table 12. Weighted raw point estimates and the meta-analysed relationship between heart-rate-derived training impulse (TRIMP) and total distance (TD) during team-sport training and competition.



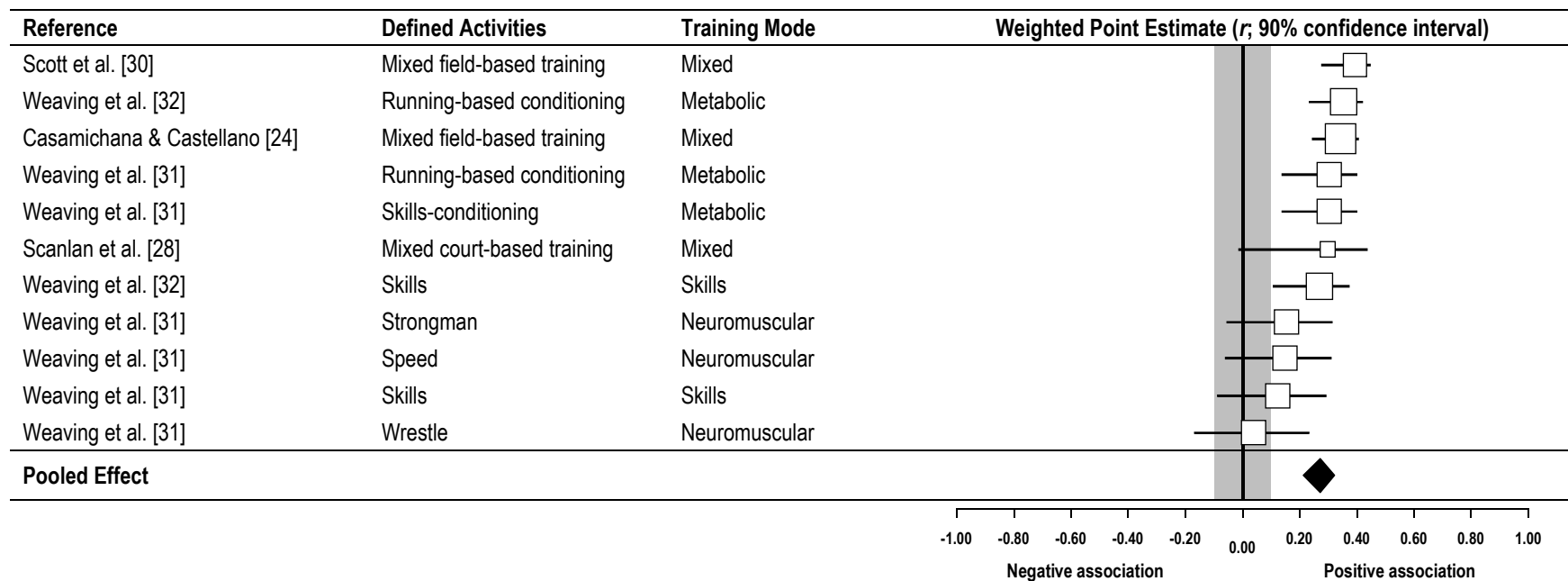
Supplementary Table 13. Weighted raw point estimates and the meta-analysed relationship between heart-rate-derived training impulse (TRIMP) and high-speed running distance (HSRD; $\geq 13.1\text{--}15.0 \text{ km}\cdot\text{h}^{-1}$) during team-sport training and competition.



Supplementary Table 14. Weighted raw point estimates and the meta-analysed relationship between heart-rate-derived training impulse (TRIMP) and very high-speed running distance (VHSRD; ≥ 16.9 – 19.8 k·mh⁻¹) during team-sport training and competition.



Supplementary Table 15. Weighted raw point estimates and the meta-analysed relationship between heart-rate-derived training impulse (TRIMP) and accelerometer load (AL) during team-sport training and competition.



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