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Impact of sport training on adaptations in neural functioning and behavioral performance: A scoping review with meta-analysis on EEG research

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ABSTRACT

Background/objective: Investigating the neural mechanisms underlying sport performance has been a research focus in the field of sport science. The current review aims to identify distinct characteristics between athletes and non-athletes at behavioral and neural levels. Further analysis was conducted as to potential reasons that contributed to the differences.

Methods: Literature was searched through PubMed, ScienceDirect, Cochrane, EBSCO, and Web of Science for EEG studies that compared athletes with non-athletes or novices in behavioral performance and brain function.

Results: The process of literature search and selection identified 16 studies that satisfied the predetermined inclusion criteria. Theta, alpha, and beta frequency bands were employed as the primary EEG measures of cortical activities in the included studies. Athletes indicated significant advantages over controls in behavioral performance, *Hedges'g* $= 0.42$, $p = 0.02$, and brain function, *Hedges'g* $= 0.49$, $p = 0.03$. Moderator analysis on behavioral performance indicated a large effect size in sport-related performance, *Hedges'g* $= 0.90$, $p = 0.01$, but a small, non-significant effect size in general tasks, *Hedges'g* $= 0.14$, $p = 0.44$.

Conclusions: Superior performance in sport-related tasks mostly contributed to athletes' significant advantage in behavioral performance. Additionally, favorable profiles of brain function associated with athletes included neural efficiency, increased cortical asymmetry, greater cognitive flexibility, and precise timing of cortical activation. Applying EEG technique to sport has shown promising directions in performance improvement and talent identification for young athletes.

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1. Introduction

Sport is more than competitions in skills and physical capacities (i.e., speed, strength, and endurance). Cognitive functions, such as information pick-up, anticipation, and decision making within game settings, also play a significant role in sport performance. Cognitive profiles of athletes have been an interest of study in sport psychology. A recent meta-analysis identified superior cognitive performance in athletes over amateurs or non-athletes, indicating that cognitive performance is a function of sport expertise.[1] It is well-known that cognitive performance involves a series of complex neural processing. Brain activity governs sporting behaviors and makes a difference between winning and losing in the competition.[2] With the rapid development in neuroimaging technologies, researchers nowadays can observe neural activities in concurrent with behavioral performance.[3,4] Among the neuroimaging techniques such as functional magnetic resonance imaging (fMRI), electroencephalography (EEG), and functional near infrared spectroscopy (fNIRS), EEG has been widely applied in the emerging field of sport science because of portability, non-invasive nature, and a high temporal resolution in milliseconds.[5,6] The application

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of EEG allows researchers to gain insights into neural mechanisms underlying sport performance.

Superior behavioral performance in athletes implies neural advantage over non-athletes. EEG-based studies in task performance have been designed to examine impact of sport experience on brain functioning.[7,8] Sprot-related neural adaptations can be represented by distinct EEG profiles between athletes and non-athletes. The distinct cortical activation profiles associated with superior performance suggest advantages at the neural level.[9] Brain functioning of athletes has raised increasing attention among neuroscientists because elite sport provides an ideal model for understandings of neural adaptations associated with intensive training over time,[2] and the increased knowledge on brain-behavior links helps to improve the effect of training and thus enhance sport performance.[4]

Rationales for the current review study account for two contributions to the field of sport science. Two narrative reviews with respect to EEG profiles of athletes are available so far.[2,4] However, a systematic approach for literature search and analysis is still absent. The current study consists of scoping review and meta-analysis, which provides a comprehensive review on both qualitative and quantitative evidence. Another reason can be attributed to the rapidly growing interest in brain function and sport performance. With the accumulating research findings on neuroscience and sport performance, an up-to-date review is needed since the latest review paper published more than five years ago.[4] Therefore, the current review is warranted due to the above-mentioned reasons.

While the scoping review summarizes distinct neural and behavioral profiles between athletes and non-athletes, the meta-analysis quantifies the between-group difference. General conclusions can be derived from the results of meta-analysis regarding (i) whether athletes outperform non-athletes in behavioral tasks; and (ii) whether athletes show significant advantages over non-athletes in brain functioning. Based on the meta-analysis results, qualitative analysis led to in-depth discussions on implications of the findings and limitations of the existing studies that need to be addressed in future.

2. Methods

2.1. Search strategy

The scoping review was conducted in accordance with the Extended Preferred Reporting Items for Systematic Reviews and Meta-Analyses Statement for Scoping Reviews (PRISMA-ScR).[10] Literature was searched through PubMed, ScienceDirect, Cochrane, EBSCO, and Web of Science for original research published in peer-reviewed journals by May 2021. The current review aims to include EEG studies that compare athletes with non-athletes or novices in behavioral performance and brain function. To identify the studies that fit into the main purpose of the review, the search strategy focused on three constructs regarding subjects, neuroimaging technique, and brain activation. A combination of the following key terms was used for literature search: “athlete OR sport OR player” AND “electroencephalography OR EEG″AND “brain activation OR cortical activation OR brain oscillation OR cortical oscillation OR brain function”.

2.2. Study selection

Studies considered for inclusion should meet all the following eligibility criteria: (1) original research published in peer-reviewed journals in English; (2) experimental design included both athlete group and non-athlete (control) group; and (3) brain activities were measured by EEG. Accordingly, studies may be excluded for one of the following criteria. First, only athletes or non-athletes were recruited, leaving no comparisons between athletes and controls. Second, the study involved subjects after sport-related injury such as concussion. Third, no EEG data were reported in the study.

The initial screening removed duplicates by means of title examination. Further analysis based on title and abstract assessment was performed to evaluate relevance of the articles. After removing irrelevant records, authors conducted full-text evaluation to assess eligibility of the remained articles. Two authors worked independently for study selection. Any disagreement was resolved by having a discussion with other authors in a consensus meeting.

2.3. Data extraction and synthesis

Essential details of the reviewed studies were extracted and summarized in the items of subjects, task, behavioral performance, EEG measures, and difference between athletes and controls. The item of subjects extracted demographic data regarding sport, sample size and mean age of athletes and controls. The task information summarized critical characteristics of the tasks, such as the number of trials and the procedures for data collection. Behavioral performance and EEG measures presented task-related outcomes at both behavioral and neural levels. Behavioral performance examined performance outcomes in cognitive or motor tasks, indicating whether significant difference exists between athletes and controls. The item of EEG measures indicated EEG frequency bands which were applied to the individual studies as measures of cortical activation during task performance. The item of difference between athletes and controls summarized distinct cortical activation patterns between the two groups.

2.4. Statistical analysis

Statistical analysis was conducted by Comprehensive Meta-Analysis (CMA) − Version 3 (BioStat Inc., Englewood, NJ, USA). Statistics of individual studies that revealed the main effect of group difference in relation to behavioral performance and EEG parameters were synthesized to calculate the effect size.[11] Multiple effects within the same study were combined before calculating the meta-analytic effect size. Considering the small sample size, we selected Hedges' g as a conservative estimate for effect size.[12] In addition, a random model was used for the consideration of variance across the studies.[13] The overall effect size was categorized as small (Hedges' $g = 0.2-0.5$), moderate (Hedges' $g = 0.5-0.8$), and large effect (Hedges' $g > 0.8$).

The value of I^2 was used to assess heterogeneity, with 25%, 50%, and 75% as the cutoff points for low, moderate, and high heterogeneity.[14] The Egger's regression was performed to evaluate publication bias. A two-tailed test with p-value less than 0.05 presented evidence for significant publication bias in the reviewed literature.[15]

3. Results

3.1. Study characteristics

Literature search through the databases identified 1597 records. Initial examination removed 936 duplicates, leaving 661 records for further analysis based on title and abstract screening. The screening phase excluded 570 records, resulting in 91 articles for full-text assessment. There were 75 articles excluded after full-text assessment because of the following reasons: no control ($N = 12$) or no athlete ($N = 20$) was involved; no EEG data were reported ($N = 15$); and research examined EEG data of athletes with concussion ($N = 28$). The selection process eventually resulted in 16 studies

which met the inclusion criteria. Fig. 1 displays the flow of study selection.

The reviewed studies involved a total of 423 subjects (225 athletes and 198 controls) across seven sports including shooting (N = 5), karate (N = 4), golf (N = 3), gymnastics (N = 1), soccer (N = 1), badminton (N = 1), and table tennis (N = 1). Alpha frequency is the primary EEG measure, which was used in 14 studies to reflect cortical activities during task performance. Compared with alpha band, theta (N = 6) and beta (N = 5) were reported in fewer studies. Delta and gamma frequencies were not reported as frequently as the other EEG measures in the reviewed studies, with one study on each of the frequency bands.[16,17] Whereas delta waveform is related to unconsciousness, gamma waveform is associated with intense mental workload.[18,19] However, the experimental tasks of the included studies were designed at a moderate difficulty level which allowed participants to perform in a usual mental state rather than put intense mental efforts into the task. The two EEG frequency bands did not fully represent the mental states during the tasks, which may explain the limited number of studies using delta and gamma as measures of cortical activities.

The experimental tasks of the included studies were categorized into sport-related tasks and general tasks. Sport-related tasks were designed by requesting participants to perform sport skills or simulating cognitive process in game situations. The sport skills causing minimal head movement during execution are appropriate for the motor task design. Eight of the included studies recorded real-time cortical activities while participants performing shooting[16,20–22] and golf putting.[23–26] The cognitive tasks were typically designed by requesting participants to make a judgment or anticipation based on a short video presented. Response time and accuracy were used as measures of task performance.[7,27]

The general tasks also measured motor and cognitive performance. The motor tasks included wrist movement[28] and postural control in standing,[8,29] while the cognitive tasks assessed participants' performance in working memory, attention, and arithmetical tests.[17,30] Characteristics of the included studies were presented in Table 1.

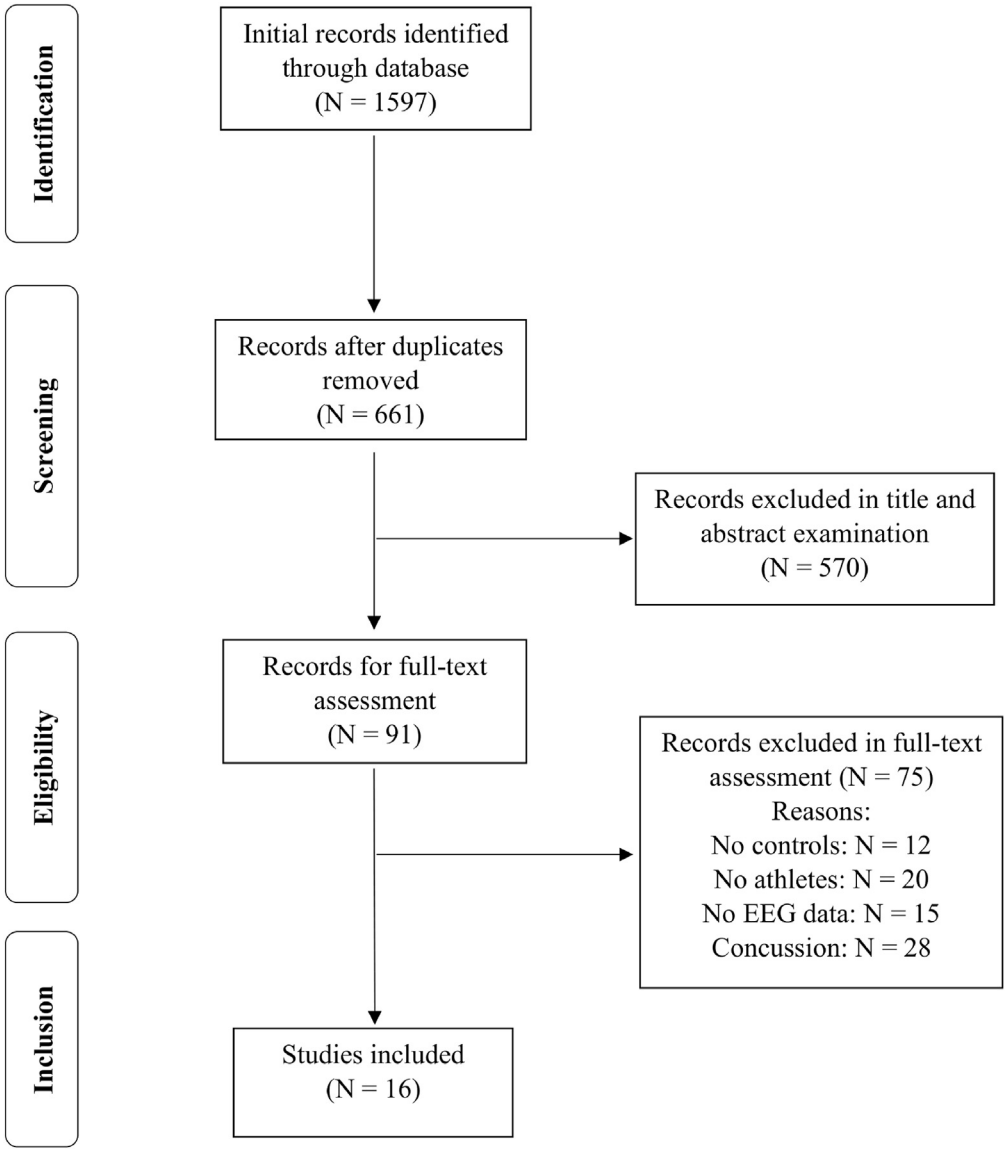

Fig. 1. Flowchart of literature search and selection.

Table 1
Characteristics of the included studies.

Study	Subjects	Task	Behavioral performance	EEG measures	Difference between athletes and controls
Haufler et al. (2000),[14]	Athletes: N = 15 Age = 26.5 Controls: N = 21 Age = 23.1	Shooting task: 40 shootings. Comparative task: 15 trials of dot localization and word finding.	Experts indicated better shooting performance than novices. No significant difference was found in verbal and spatial tasks.	Theta Alpha Beta Gamma	Athletes showed lower cortical activation in shooting task than verbal and spatial tasks. Non-athletes indicated similar cortical activation in both tasks.
Janelle et al. (2000),[15]	Athletes: N = 12 Age = 26.4 Controls: N = 13 Age = 24.6	Participants performed 40 shots in standing position.	Athletes indicated significantly better shooting performance than novices.	Alpha Beta	Athletes were characterized by increased hemispheric asymmetry in shooting.
Del Percio et al. (2007),[26]	Athletes: N = 37 Age: 19-32 Controls: N = 10 Age: 21-34	Participants stood on a force platform with eyes closed and open.	No significant difference was identified between groups during standing.	Alpha	Athletes indicated stronger alpha ERD than non-athletes during postural control.
Baumeister et al. (2008),[19]	Athletes: N = 9 Age = 26.4 Controls: N = 9 Age = 24.6	Participants performed 5 blocks of golf putting. Each block lasted 4 min.	Golfers performed with significantly higher accuracy than novices.	Theta Alpha	Golfers indicated higher theta and alpha powers than novices in golf putting.
Doppelmayr et al. (2008),[16]	Athletes: N = 8 Age = 21.4 Controls: N = 10 Age = 20.8	Participants completed 50–70 shots in 60 min.	Experts indicated significantly better performance than novices.	Theta	Experts indicated a stronger theta activity than novices in preparation of shooting.
Babiloni et al. (2009),[37]	Athletes: N = 15 Age = 21.4 Controls: N = 13 Age = 20.8	Participants judged rhythmic gymnastic performance presented in videos.	Rhythmic gymnasts indicated higher judgment accuracy than non-athletes.	Alpha	Rhythmic gymnasts indicated lower alpha ERD than non-athletes in judgment.
Del Percio et al. (2009a),[17]	Athletes: N = 8 Age = 29.2 Controls: N = 10 Age = 33.1	Participants completed a total of 120 shots.	Elite athletes performed with significantly higher accuracy than novices.	Alpha	Elite athletes indicated lower alpha ERD than non-athletes over the whole scalp.
Del Percio et al. (2009b),[27]	Athletes: N = 20 Age: 19-32 Controls: N = 12 Age: 21-34	Participants stood on a force platform with one foot and both feet.	No significant difference was identified between groups during standing.	Alpha	Athletes indicated lower alpha ERD than non-athletes during postural control.
Babiloni et al. (2010),[22]	Athletes: N = 17 Age = 23.8 Controls: N = 17 Age = 24.6	Participants judged the expertise level of karate players according to the performance presented in videos.	Karate players indicated higher judgment accuracy than non-athletes.	Alpha	Karate players performed the task with lower alpha ERD than non-athletes.
Del Percio et al. (2010),[25]	Athletes: N = 17 Age = 23.8 Controls: N = 17 Age = 24.6	Participants performed repeat wrist extension as fast as possible in 10 s.	Not reported	Alpha	Athletes indicated lower alpha ERD than non-athletes during postural control.
Cooke et al. (2014),[20]	Athletes: N = 10 Age = 20.9 Controls: N = 10 Age = 19.0	Participants completed 2 blocks of 60 putts.	No significant difference was found between the two groups.	Theta Alpha Beta	Golfers indicated greater reduction in theta, alpha, and beta powers than novices in golf putting.
Wolf et al. (2014),[24]	Athletes: N = 14 Age = 20.9 Amateurs: N = 15 Age =	Participants watched videos of a table tennis serve and imagined themselves responding with a specific stroke.	Not reported	Alpha	Alpha (8–10 Hz) ERD is stronger in elite table tennis players compared to amateurs at the<!–Soft-enter Run-on– > motor cortex.

(*continued on next page*)

Table 1 (*continued*)

Study	Subjects	Task	Behavioral performance	EEG measures	Difference between athletes and controls
	Controls: N = 15 Age = 19.0				
Cooke et al. (2015),[21]	Athletes: N = 10 Age = 20.9 Controls: N = 10 Age = 19.0	Participants completed 120 golf putts.	Not reported	Alpha	Golfers indicated greater reduction in high alpha power after a missed putt than novices.
Wang et al. (2015),[28]	Athletes: N = 12 Age = 20.6 Controls: N = 13 Age = 19.1	Participants conducted two cognitive tasks involving working memory and attention.	Badminton players showed similar response accuracy to non-athletes, but significantly faster response than non-athletes.	Theta Alpha Beta	Athletes showed significant increase in theta power and decrease in beta power, which contributed to enhanced working memory and attentional performance, respectively.
Duru and Assem. (2018),[29]	Athletes: N = 10 Age = 22.9 Controls: N = 10 Age = 22.9	Participants performed 2 blocks of arithmetical tasks.	No significant difference was found between the groups.	Delta Theta Alpha Beta	Karate players indicated higher posterior alpha power than non-athletes.
Del Percio et al. (2019),[23]	Athletes: N = 13 Age = 25.1 Controls: N = 8 Age = 25.6	Participants assessed the distance between football players presented in a video.	No significant difference was found between the groups.	Alpha	Football players indicated greater bilateral parietal alpha ERD than non-athletes during the cognitive task.

3.2. EEG measures employed by the included studies

3.2.1. Theta (4–7 Hz)

Attentional processes activate frontal cortical areas which are responsible for generation of theta oscillations.[31–33] Therefore, frontal theta activity has been considered an indicator of attention. Previous research identified greater frontal theta power associated with increased task complexity.[34] When a task becomes challenging, increased attention paid to the task causes stronger theta activity in the frontal lobe.

The included studies reported higher frontal theta power in athletes performing both motor and cognitive tasks.[16,21,24,30] In addition, the enhanced theta oscillation is associated with favorable performance. Considering the cortical activation pattern and behavioral performance, researchers proposed that, compared with non-athletes, athletes have developed adequate abilities and efficient strategies of allocating more attentional resources to support performance in a complex task.[24]

3.2.2. Alpha (8–12 Hz)

As a dominant EEG oscillation in human brain activity, alpha band reflects an inhibitory function.[35] Alpha event-related desynchronization (ERD) indicates a functional correlate of brain activation, suggesting increased cortical activation in response to a stimulus. On the other hand, alpha event-related synchronization (ERS) represents a functional correlate of inhibition, which is often seen in an idling state.[36] Cortical activation is characterized by 'focal ERD/surround ERS', which indicates increased cortical activation in the event-related area accompanied by inhibition of surrounding areas.[37]

The primary finding on alpha oscillation is the lower ERD in athletes, suggesting lower cortical activation associated with task performance.[9,22] Recruiting fewer neural resources without compromising performance is consistent with the neural efficiency hypothesis. Therefore, the lower alpha ERD associated with a comparable or better performance was interpreted as a feature for superior brain function.

3.2.3. Beta (13–30 Hz)

Cortical oscillations in the beta frequency band reflect motor-related processing.[38,39] Beta ERD (lower beta power) indicates increased excitability of motor cortex neurons, which is associated with faster motor responses in simple self-paced movement tasks.[30,40,41] Recent neuroimaging studies have shown that beta ERD also occurs when imagining or observing a movement, suggesting increased mental engagement in processing motor-related information.[42,43]

The included studies reported greater beta ERD (reduced beta power) in athletes than controls.[16,25,30] The increased excitability of the motor cortex produced beneficial effects on behavioral performance including improved accuracy in golf putting and shooting,[16,26] and shorter reaction time in cognitive tests.[30] Based on the findings of beta oscillation and corresponding behavioral performance, beta ERD implies favorable brain functioning.[30,40,41]

3.3. Research findings on behavioral performance

3.3.1. Meta-analysis on behavioral performance

There were 14 articles comparing athletes with controls in behavioral performance. The meta-analytic effect indicated favorable result for athletes, suggesting that athletes outperformed controls in behavioral tasks, *Hedges'g* $= 0.42$, $p = 0.02$. Heterogeneity test identified a moderate variance across the studies, $Q_{13} = 36.61$, $p = 0.004$, $I^2 = 57.53\%$. Publication bias assessed by Egger's regression was non-significant, $t_{12} = 1.73$, $p = 0.11$. The result of meta-analysis on behavioral performance was displayed in Fig. 2.

3.3.2. Moderator analyses on behavioral performance

Moderator analyses were conducted on general tasks and sport-related tasks. Six studies examined motor or cognitive performance in general tasks. The result indicated a small, non-significant effect size, *Hedges'g* $= 0.14$, $p = 0.44$, suggesting comparable performance between athletes and controls in the general tasks.

Sport-related tasks were applied to 9 studies, involving shooting

(N = 4), golf putting (N = 2), and cognitive tasks simulating sport environment (N = 3). A large, positive effect size was identified, *Hedges'g* = 0.90, $p = 0.01$, presenting robust evidence that athletes outperformed controls in sport-related tasks. Moderator analysis on the two tasks identified moderate heterogeneity across the included studies and low risks of publication bias. Fig. 3 presented the meta-analytic results of general tasks and sport-related tasks.

3.4. Research findings on brain function

3.4.1. Meta-analysis on brain function

An important step of conducting the meta-analysis on brain function is to determine effect direction of individual studies. However, interpretations of neuroimaging measures in the studies are not always straightforward.[44] Therefore, authors' interpretations on EEG measures as well as performance outcomes were both considered in determining the effect direction.[11] A positive result displays the brain function in favor of athletes, while a negative result suggests favorable brain function to controls.

A total of 16 studies compared athletes with controls in brain function. Meta-analysis indicated a moderate effect size which favored athletes over controls, *Hedges'g* = 0.49, $p = 0.03$. The result provided empirical evidence for athletes' significant advantage at the neural level. The test for heterogeneity indicated a large variance across the studies, $I^2 = 91.65\%$, with the p-value indicating a significant result $p = 0.001$. Egger's regression test was non-significant ($t_{14} = 0.25$, $p = 0.80$), suggesting low publication bias. The meta-analysis comparing athletes with controls in brain function was presented in Fig. 4.

3.4.2. Neural advantages in athletes

Athletes showed significant advantages in neural functioning over controls when performing motor and cognitive tasks. Specifically, the neural advantages are characterized with neural efficiency, increased cortical asymmetry, greater cognitive flexibility, and precise timing of cortical activation.

Neural efficiency is one of the prominent neural processing features identified in athletes, suggesting less energy expenditure spent during task performance. The neural efficiency hypothesis was initially developed based on the research evidence that brighter individuals indicated lower brain activation when performing cognitive tasks.[45,46] Findings of the reviewed studies expanded the neural efficiency hypothesis to the field of sport performance. Compared with novices or non-athletes, athletes recruited fewer neural resources while conducting comparable performance in the general tasks and superior performance in the sport-specific tasks.[7–9,22,24]

In the study involving skilled rifle-shooters and novices, experts showed significant hemispheric asymmetry during the preparatory period of shooting, whereas novices indicated comparable activation between the two hemispheres.[20] Specifically, experts were characterized by increased beta power in the left hemisphere and reduced beta power in the right hemisphere. Motor skill acquisition leads to cortical activation changes from broad neural connections to functional specialization, suggesting better neural control over the task-irrelevant cortical regions.[47] The prominent hemispheric asymmetry in expert shooters was attributed to the longitudinal training which caused optimal reorganizations in brain function to support high-level performance.

Another feature of superior neural functioning is attributed to the greater neural flexibility and precise timing of cortical activation in athletes, which was identified in the preparatory period of golf putting.[25] Athletes initially indicated lower cortical activation (higher alpha power) than novices 2s−3s prior to the movement, suggesting more relaxation in athletes during the early phase of preparation. But in the last 2s preceding the movement, the trend was reversed due to a prominent reduction of alpha power in athletes, indicating increased cortical activation prior to initiating the putting movement.[25] In this experiment, athletes' mental state changed from relaxation to concentration at the exact time point before the movement execution. The precise control over the timing of cortical activation displayed a prominent advantage in athletes' neural function which was not observed in novices or non-athletes.

4. Discussion

4.1. Summary of the primary findings

The current review included 16 studies which investigated cortical activities of athletes and controls while performing behavioral tasks. Meta-analysis indicated significant advantages in athletes over controls in overall behavioral performance. Moderator analyses suggest that the favorable performance observed in athletes is mainly attributed to the significant advantages in sport-related tasks. While comparable performance was identified between athletes and controls in general tasks, athletes outperformed controls in sport-related tasks as a result of intensive training over a long time.

Cortical activities were mainly measured by theta, alpha, and beta frequency bands. By synthesizing EEG findings of the included studies, we conducted a meta-analysis on brain functioning. Athletes indicated significant advantages at the neural level, which were embodied as neural efficiency, increased cortical asymmetry, greater cognitive flexibility, and precise timing of cortical activation. Therefore, the current review provided empirical evidence for superior brain function and behavioral performance associated with sport training.

4.2. Interpretations of the findings

Athletes' advantages over their non-athlete counterparts suggest positive impacts of sport experience on neural functioning and behavioral performance. In a study comparing fencing athletes with non-athletes in cognitive tasks, superior performance associated with athletes was attributed to the training-induced facilitation in inhibitory control and task switching.[48] Sport competition requires athletes to make decisions and take actions within a constrained time window.[49] Longitudinal training plays the role as affordances to develop motor and cognitive abilities as well as stimulate athletes' brain functioning in information processing.[30] Indeed, previous studies have identified modulations of brain functioning which suggest the underlying mechanisms of improved behavioral performance. Progressive reduction in alpha ERD has been found along with acquisition and refinement of motor skills.[8,29] Additional finding also shows modulations of theta and beta rhythms as indicators of better attention and working memory performance in badminton athletes.[30]

Meta-analysis regarding behavioral performance found that athletes indicated favorable performance over non-athletes only in sport-related tasks instead of general tasks. This finding suggests behavioral changes as a result of sport experience. More importantly, the favorable performance in sport specific tasks strengthens the implication with respect to the neural factors underpinning the development of expertise as a function of intensive training.[4] However, the current finding of sport-related superiority do not fully support the hypothesis that the training-induced advantage may transfer to fundamental tasks.[38,50,51] Despite accumulating evidence for the generalizability of sport experience

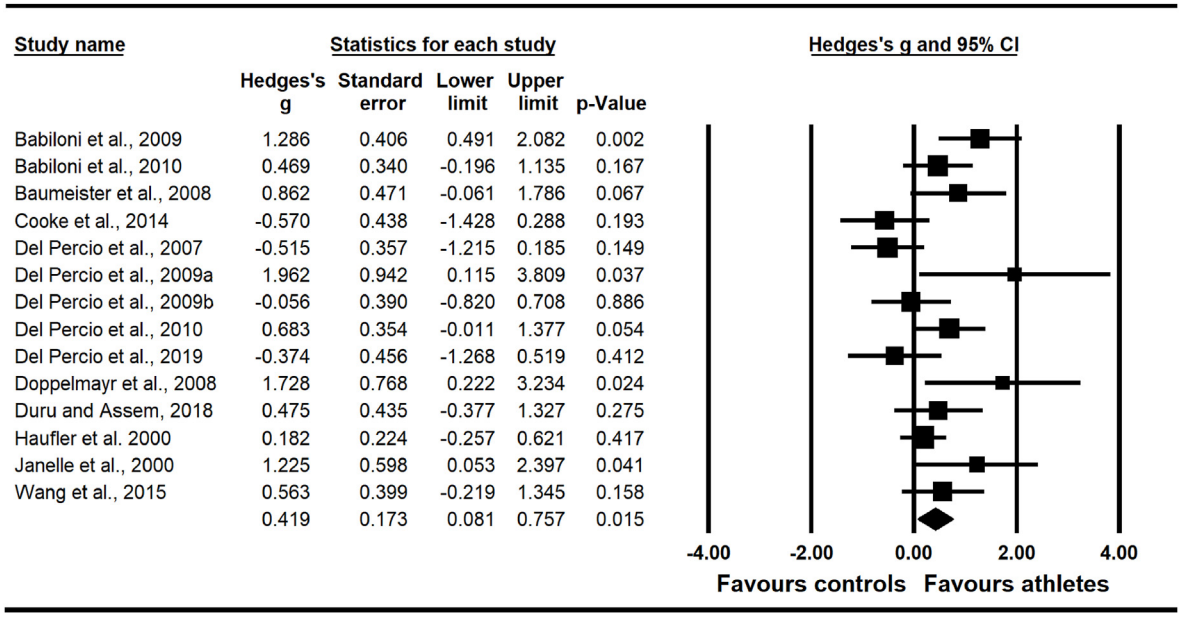

Fig. 2. Forest plot for behavioral performance.

to fundamental cognitive functions,[17,28,30] the mixed results of the included studies led to a non-significant effect size. A possible reason is attributed to the limited number of studies (N = 6) in general task performance and variety of the behavioral assessments across the included studies. As further evidence is needed in future studies, the existing evidence is still inadequate to reach a solid conclusion.

4.3. Implications of the findings

The primary findings of the current review imply promising applications of EEG to practice. The EEG-based research on sport performance is thought to provide neural evidence for developing effective training methods.[4] By voluntarily regulating brain activity to the desired patterns, athletes can achieve an optimal state before an important event. EEG parameters, such as theta and alpha waves, are the targets that athletes practice to control in the neurofeedback training.[52,53] A meta-analysis on existing neurofeedback studies indicated a significant effect of improving sport performance.[54]

Another application of the neural findings is to scout young athletes with talents.[1] Traditional talent identification is primarily based on physiological measures and performance displayed at a specific time point. However, current research has shown limitations of the traditional approach, given the fact that an athlete's career success cannot be predicted by early performance.[55,56] The neural approach may provide a valuable addition to scouting. With the increasing knowledge on the connection between desirable profiles of brain function and performance development, neural information should be valued equally important as the commonly used physiological measures in evaluating potentials of young athletes.

4.4. Limitations

The primary limitation lies in the fact that all the included studies are cross-sectional design, which is insufficient to make causal inferences between sport training and neural adaptations.[57] A nature-nurture debate may exist as to whether sport training enhances brain function or advantage at the neural level is a prerequisite for individuals to become athletes.[11] Research findings based on the cross-sectional design cannot exclude the possibility that genetic, anatomical, physiological, or psychological factors between athletes and non-athletes contribute to the distinct EEG profiles.[4] Therefore, subsequent research based on robust experimental design should be developed to answer this question.

Heterogeneity is another concern with the current review. Considerable variances across the studies have been identified in meta-analysis on both behavioral performance and brain function. The large heterogeneity is considered a reflection of non-randomized studies, which is a limitation of the cross-sectional design.[58] In addition, a variety of sports involved in the included studies may also contribute to the large heterogeneity. Distinct cortical activation patterns have been reported in different sports. For example, neural efficiency is a prominent profile in expert shooters,[22] but recruiting more neural resources appears to be helpful in enhancing golfers' putting performance.[25] Considering the heterogeneity across the included studies, we should interpret the current findings with caution.

5. Conclusions

The scoping review and meta-analysis identified significant advantages in athletes over non-athletes at both behavioral and neural levels. The superior performance in athletes was largely attributed to the sport-related tasks instead of the general tasks. In addition, the favorable brain function in athletes can be summarized as neural efficiency, increased cortical asymmetry, greater cognitive flexibility, and precise timing of cortical activation. The findings of the review implied promising directions of integrating EEG technique into training and scouting. EEG-based research in future will add significant value to promote current understandings of neural mechanisms underlying sport performance.

Study name	Subgroup within study	Hedges's g	Standard error	Lower limit	Upper limit	p-Value
Wang et al., 2015	General task	0.563	0.399	-0.219	1.345	0.158
Haufler et al. 2000	General task	-0.069	0.234	-0.528	0.390	0.768
Duru and Assem, 2018	General task	0.475	0.435	-0.377	1.327	0.275
Del Percio et al., 2010	General task	0.683	0.354	-0.011	1.377	0.054
Del Percio et al., 2009b	General task	-0.056	0.390	-0.820	0.708	0.886
Del Percio et al., 2007	General task	-0.515	0.357	-1.215	0.185	0.149
	General task	0.144	0.186	-0.221	0.509	0.439
Janelle et al., 2000	Sport task	1.225	0.598	0.053	2.397	0.041
Haufler et al. 2000	Sport task	2.885	0.768	1.379	4.391	0.000
Doppelmayr et al., 2008	Sport task	1.728	0.768	0.222	3.234	0.024
Del Percio et al., 2019	Sport task	-0.374	0.456	-1.268	0.519	0.412
Del Percio et al., 2009a	Sport task	1.962	0.942	0.115	3.809	0.037
Cooke et al., 2014	Sport task	-0.570	0.438	-1.428	0.288	0.193
Baumeister et al., 2008	Sport task	0.862	0.471	-0.061	1.786	0.067
Babiloni et al., 2010	Sport task	0.469	0.340	-0.196	1.135	0.167
Babiloni et al., 2009	Sport task	1.286	0.406	0.491	2.082	0.002
	Sport task	0.895	0.332	0.243	1.546	0.007

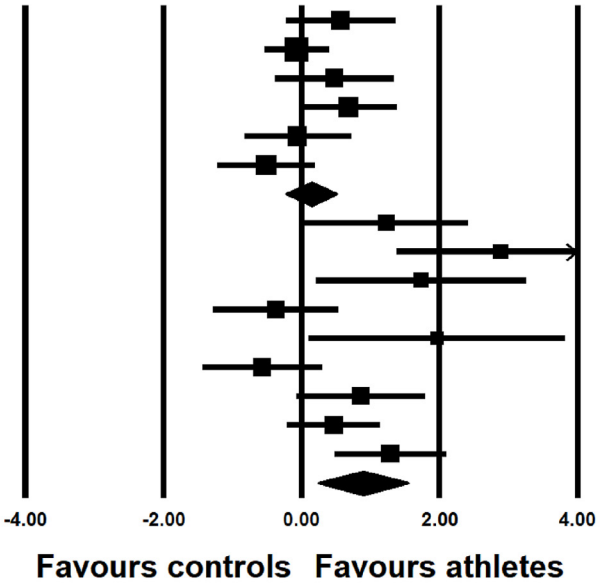

Fig. 3. Forest plot for moderator analyses of behavioral performance.

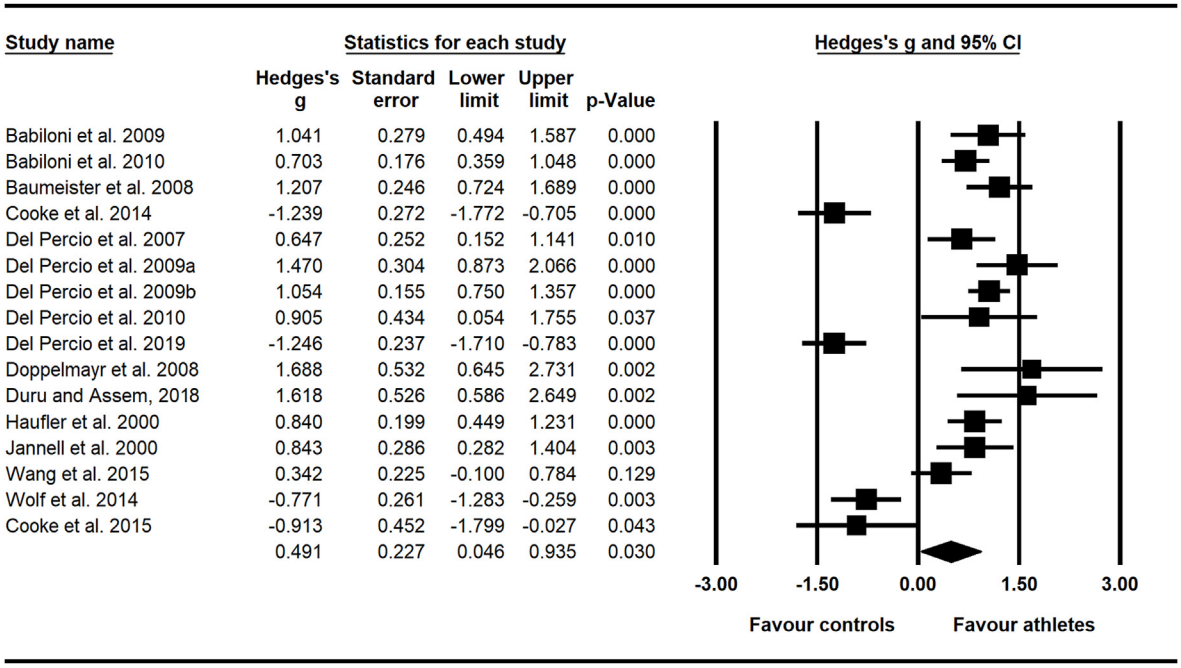

Fig. 4. Forest plot for comparison between athletes and controls in brain function.

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Declaration of competing interest

The authors declare no conflict of interest.

References

1. Scharfen HE, Memmert D. Measurement of cognitive functions in experts and elite athletes: a meta-analytic review. *Appl Cognit Psychol*. 2019;33(5):843–860.
2. Nakata H, Yoshie M, Miura A, Kudo K. Characteristics of the athletes' brain: evidence from neurophysiology and neuroimaging. *Brain Res Rev*. 2010;62(2):197–211.
3. Nidal K, Malik AS. *EEG/ERP Analysis: Methods and Applications*. Crc Press; 2014.
4. Park JL, Fairweather MM, Donaldson DI. Making the case for mobile cognition: EEG and sports performance. *Neurosci Biobehav Rev*. 2015;52:117–130.
5. Crews DJ, Landers DM. Electroencephalographic measures of attentional patterns prior to the golf putt. *Med Sci Sports Exerc*. 1993;25(1):116–126.
6. Khanna A, Pascual-Leone A, Michel CM, Farzan F. Microstates in resting-state EEG: current status and future directions. *Neurosci Biobehav Rev*. 2015;49:105–113.
7. Babiloni C, Marzano N, Infarinato F, et al. "Neural efficiency" of experts' brain during judgment of actions: a high-resolution EEG study in elite and amateur karate athletes. *Behav Brain Res*. 2010;207(2):466–475.
8. Del Percio C, Babiloni C, Marzano N, et al. "Neural efficiency" of athletes' brain for upright standing: a high-resolution EEG study. *Brain Res Bull*. 2009;79(3-4):193–200.
9. Babiloni C, Del Percio C, Rossini PM, et al. Judgment of actions in experts: a high-resolution EEG study in elite athletes. *Neuroimage*. 2009;45(2):512–521.
10. Tricco AC, Lillie E, Zarin W, et al. PRISMA extension for scoping reviews (PRISMA-ScR): ehecklist and cxplanation. *Ann Intern Med*. 2018;169(7):467–473.
11. Meijer A, Königs M, Vermeulen GT, et al. The effects of physical activity on brain structure and neurophysiological functioning in children: a systematic review and meta-analysis. *Dev Cogn Neurosci*. 2020;45:100828.
12. Borenstein M, Hedges LV, Higgins JP, Rothstein HR. *Introduction to Meta-Analysis*. John Wiley & Sons; 2009.
13. Higgins JP, Thompson SG, Deeks JJ, Altman DG. Measuring inconsistency in meta-analyses. *BMJ*. 2003;327(7414):557–560.
14. Higgins JP, Thompson SG. Quantifying heterogeneity in a meta-analysis. *Stat Med*. 2002;21(11):1539–1558.
15. DerSimonian R, Kacker R. Random-effects model for meta-analysis of clinical trials: an update. *Contemp Clin Trials*. 2007;28(2):105–114.
16. Haufler AJ, Spalding TW, Santa Maria DL, Hatfield BD. Neuro-cognitive activity during a self-paced visuospatial task: comparative EEG profiles in marksmen and novice shooters. *Biol Psychol*. 2000;53(2-3):131–160.
17. Duru AD, Assem M. Investigating neural efficiency of elite karate athletes during a mental arithmetic task using EEG. *Cogn Neurodyn*. 2018;12(1):95–102.
18. Buzsaki G. *Rhythms of the Brain*. Oxford University Press; 2009. https://doi.org/10.1093/acprof:oso/9780195301069.001.0001.
19. Abhang PA, Gawali BW, Mehrotra SC. Chapter 2 - Technological tasics of EEG recording and bperation of opparatus. In: *Introduction to EEG- and Speech-Based Emotion Recognition*. Academic Press; 2016. https://doi.org/10.1016/B978-0-12-804490-2.00002-6.
20. Janelle CM, Hillman CH, Apparies RJ, et al. Expertise differences in cortical activation and gaze behavior during rifle shooting. *J Sport Exerc Psychol*. 2000;22(2):167–182.
21. Doppelmayr M, Finkenzeller T, Sauseng P. Frontal midline theta in the pre-shot phase of rifle shooting: differences between experts and novices. *Neuropsychologia*. 2008;46(5):1463–1467.
22. Del Percio C, Babiloni C, Bertollo M, et al. Visuo-attentional and sensorimotor alpha rhythms are related to visuo-motor performance in athletes. *Hum Brain Mapp*. 2009;30(11):3527–3540.
23. Babiloni C, Del Percio C, Iacoboni M, et al. Golf putt outcomes are predicted by sensorimotor cerebral EEG rhythms. *J Physiol*. 2008;586(1):131–139.
24. Baumeister J, Reinecke K, Liesen H, Weiss M. Cortical activity of skilled performance in a complex sports related motor task. *Eur J Appl Physiol*. 2008;104(4):625–631.
25. Cooke A, Kavussanu M, Gallicchio G, et al. Preparation for action: psychophysiological activity preceding a motor skill as a function of expertise, performance outcome, and psychological pressure. *Psychophysiology*. 2014;51(4):374–384.
26. Cooke A, Gallicchio G, Kavussanu M, et al. Premovement high-alpha power is modulated by previous movement errors: Indirect evidence to endorse high-alpha power as a marker of resource allocation during motor programming. *Psychophysiology*. 2015;52(7):977–981.
27. Del Percio C, Franzetti M, De Matti AJ, et al. Football players do not show "neural efficiency" in cortical activity related to visuospatial information processing during iootball fcenes: an EEG mapping study. *Front Psychol*. 2019;10:890.
28. Del Percio C, Infarinato F, Iacoboni M, et al. Movement-related desynchronization of alpha rhythms is lower in athletes than non-athletes: a high-resolution EEG study. *Clin Neurophysiol*. 2010;121(4):482–491.
29. Del Percio C, Brancucci A, Bergami F, et al. Cortical alpha rhythms are correlated with body sway during quiet open-eyes standing in athletes: a high-resolution EEG study. *Neuroimage*. 2007;36(3):822–829.

30. Wang CH, Tsai CL, Tu KC, et al. Modulation of brain oscillations during fundamental visuo-spatial processing: a comparison between female collegiate badminton players and sedentary controls. *Psychol Sport Exerc*. 2015;16:121–129.
31. Gevins A, Smith ME, McEvoy L, Yu D. High-resolution EEG mapping of cortical activation related to working memory: effects of task difficulty, type of processing, and practice. *Cereb Cortex*. 1997;7(4):374–385.
32. Smith EE, Jonides J. Storage and executive processes in the frontal lobes. *Science*. 1999;283(5408):1657–1661.
33. Klimesch W. EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Cerebr Cortex*. 1999;29(2-3):169–195.
34. Smith ME, McEvoy LK, Gevins A. Neurophysiological indices of strategy development and skill acquisition. Brain research. *Cogn Brain Res*. 1999;7(3):389–404.
35. Klimesch W. α-band oscillations, attention, and controlled access to stored information. *Cognit Brain Res*. 2012;16(12):606–617.
36. Klimesch W, Sauseng P, Hanslmayr S. EEG alpha oscillations: the inhibition-timing hypothesis. *Brain Res Rev*. 2007;53(1):63–88.
37. Neuper C, Pfurtscheller G. Event-related dynamics of cortical rhythms: frequency-specific features and functional correlates. *Int J Psychophysiol*. 2001;43(1):41–58.
38. Chaddock L, Neider MB, Voss MW, et al. Do athletes excel at everyday tasks? *Med Sci Sports Exerc*. 2011;43(10):1920–1926.
39. Voss MW, Kramer AF, Basak C, et al. Are expert athletes 'expert' in the cognitive laboratory? A meta-analytic review of cognition and sport expertise. *Appl Cognit Psychol*. 2010;24(6):812–826.
40. Chen R, Yaseen Z, Cohen LG, Hallett M. Time course of corticospinal excitability in reaction time and self-paced movements. *Ann Neurol*. 1998;44(3):317–325.
41. Senkowski D, Molholm S, Gomez-Ramirez M, Foxe JJ. Oscillatory beta activity predicts response speed during a multisensory audiovisual reaction time task: a high-density electrical mapping study. *Cereb Cortex*. 2006;16(11):1556–1565.
42. Pfurtscheller G, Solis-Escalante T, Barry RJ, et al. Brisk heart rate and EEG changes during execution and withholding of cue-paced foot motor imagery. *Front Hum Neurosci*. 2013;7:379.
43. Babiloni C, Del Percio C, Vecchio F, et al. Alpha, beta and gamma electrocorticographic rhythms in somatosensory, motor, premotor and prefrontal cortical areas differ in movement execution and observation in humans. *Clin Neurophysiol*. 2016;127(1):641–654.
44. de-Wit L, Alexander D, Ekroll V, Wagemans J. Is neuroimaging measuring information in the brain? *Psychon Bull Rev*. 2016;23(5):1415–1428.
45. Neubauer AC, Grabner RH, Freudenthaler HH, et al. Intelligence and individual differences in becoming neurally efficient. *Acta Psychol (Amst)*. 2004;116(1):55–74.
46. Neubauer AC, Fink A. Intelligence and neural efficiency. *Neurosci Biobehav Rev*. 2009;33(7):1004–1023.
47. Park DC, Reuter-Lorenz P. The adaptive brain: aging and neurocognitive scaffolding. *Annu Rev Psychol*. 2009;60:173–196.
48. Di Russo F, Taddei F, Apnile T, Spinelli D. Neural correlates of fast stimulus discrimination and response selection in top-level fencers. *Neurosci Lett*. 2006;408(2):113–118.
49. Wright MJ, Bishop DT, Jackson RC, Abernethy B. Cortical fMRI activation to opponents' body kinematics in sport-related anticipation: expert-novice differences with normal and point-light video. *Neurosci Lett*. 2011;500(3):216–221.
50. Voss MW, Kramer AF, Basak C, et al. Are expert athletes 'expert' in the cognitive laboratory? A meta-analytic review of cognition and sport expertise. *Appl Cognit Psychol*. 2010;24(6):812–826.
51. Vestberg T, Gustafson R, Maurex L, Ingvar M, Petrovic P. Executive functions predict the success of top-soccer players. *PLoS One*. 2012;7(4), e34731.
52. Gruzelier JH, Thompson T, Redding E, et al. Application of alpha/theta neurofeedback and heart rate variability training to young contemporary dancers: state anxiety and creativity. *Int J Psychophysiol*. 2014;93(1):105–111.
53. Cheng MY, Huang CJ, Chang YK, et al. Sensorimotor rhythm neurofeedback enhances golf putting performance. *J Sport Exerc Psychol*. 2015;37(6):626–636.
54. Xiang MQ, Hou XH, Liao BG, et al. The effect of neurofeedback training for sport performance in athletes: a meta-analysis. *Psychol Sport Exerc*. 2018;36:114–122.
55. Boccia G, Brustio PR, Moisè P, et al. Elite national athletes reach their peak performance later than non-elite in sprints and throwing events. *J Sci Med Sport*. 2019;22(3):342–347.
56. Boccia G, Cardinale M, Brustio PR. Performance progression of elite jumpers: early performances do not predict later success. *Scand J Med Sci Sports*. 2021;31(1):132–139.
57. Kesmodel US. Cross-sectional studies - what are they good for? *Acta Obstet Gynecol Scand*. 2018;97(4):388–393.
58. Carter B, Rees P, Hale L, et al. Association between portable screen-based media device access or use and sleep outcomes: a systematic review and meta-analysis. *JAMA Pediatr*. 2016;170(12):1202–1208.