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RESEARCH

Quantitative EEG in sports: performance level estimation of professional female soccer players

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Abstract

Purpose: Measuring the peak performance of athletes remains a challenge in movement science and sports psychology. Non-invasive quantitative electroencephalography (QEEG) recordings can be used to analyze various factors in sports psychology.

Method: In this context, sports-related psychological factors were used to estimate the performance of Thai professional female soccer players before a competition. The QEEG recordings of thirty-two players were recorded three times: twice before a competition (once a week) and a week after a competition. Four factors of sports psychology were estimated and observed: anxiety, perceptual response to an acute bout of brain activity, assertiveness, and brain central fatigue. A brain topographic map (absolute power) and brain connectivity (coherence and amplitude asymmetry) data were used to analyze sports-related psychological factors. These factors were measurable based on the brain activity of the athletes and could be used to evaluate their performance during competitions by using QEEG values.

Results: Sports-related psychological performance was estimated by Pearson's correlation coefficients, which revealed that a quick perceptual response to an acute bout of brain activity could predict an athlete's performance during competition ($r = .584$, $p = .000$). Additionally, Spearman's correlation coefficients were used to estimate athletes performance. The results revealed a strong relationship ($r_s = .634$, $p = .000$), which was derived from the summation of anxiety and perceptual response to an acute bout of brain activity.

Conclusion: Consequently, the results of the present study can provide information to help staff coaches to choose the best performing players, representing an alternative method for accurately selecting key players in the competitive sports community.

Keywords: Quantitative electroencephalogram (QEEG), Brain topographic map (absolute power), Brain connectivity (coherence and amplitude asymmetry), Sports psychology, Peak performance

Introduction

For several decades, assumptions have been made about peak performance, and investigating the empirical evidence pertaining to the relation between peak performance and age has been an area of focus [1]. The International Association of Athletics Federations (IAAF) reported that the mean peak age in world-class athletic contestants was typically 25–27 years. Improvements in athletic performance were related to athlete performance level, sex and discipline, and women improved more than men in all events except for sprints [2]. However, peak performance is the highest level or quality of an athlete's performance during competition. There are three ways in which peak performance is used: to subjectively reflect maximum experience, to physiologically represent the time point at which the difference between fitness

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and fatigue is maximized, and to cognitively reflect skill level, which typically can be observed only after extensive training [3]. The inverted-U theory defines a model that can be used to describe the arousal-performance relationship in terms of sports psychology. Athletes should obtain optimal arousal to exhibit their highest performance [4].

An important factor for achieving peak performance during the Olympic Games is a complex and delicate process influenced by a variety of psychological factors that was observed in Atalanta US teams [5]. Psychological preparation is the most important part of athletic performance. The significant statistical link with Olympic rankings reveals that mental readiness or psychological factors such as stress, anxiety, tension, and aggression affect sports performance [6]. Moreover, peak performance in Australian elite athletes was characterized by the automatic execution of performance. A model of optimal psychological state assisted athletes in transitioning from experiencing diverse psychological factors during competition to an automatic psychological state of peak performance. This optimal psychological state identifies self-regulation, control, and trust as processes [7], as well as emotion [8]. In particular, an optimal psychological state may be useful for athletes to perform well or succeed under the pressure of the game, which is often referred to as clutch performance in sports [9]. Furthermore, psychological factors are important and influential in sports, and three key elements are associated with psychological readiness [10]. Psychological readiness is associated with athletes perceived likelihood of a successful return to their sport following injury [11].

In the refinement of research on psychological factors, athletes performance was found to be a key component in achievements in sports. Factors such as intrinsic motivation [12], selective attention [13, 14], goal setting [15], working memory [16], decision making [17], positive self-concept [18], and self-control [19, 20] have been determined by using brain dynamics. Additionally, advanced electroencephalography (EEG) technologies have been used to gain insight into human brain function during whole-body movement and understanding the cortical processes that underlie performance in the sporting domain [21, 22]. Interventions such as mental coaching programs could lead to better performance-related outcomes. These programs could be combined with either heart rate variability (HRV) or EEG alpha power feedback [23, 24]. Furthermore, the results of neurofeedback in the study by Thompson and Thompson (2007) revealed stress management as a tool for optimizing the performance of athletes by using EEG assessments [25]. Indeed, athlete performance is affected by several mechanisms of the human body, among which sports psychology is a main mechanism that can be understood and interpreted via QEEG.

The purpose of this study was to use non-invasive QEEG recordings of Thai professional female soccer players to observe sports-related psychological factors to estimate their performance. According to previous studies, there were the evidences that anxiety [24, 26], perceptual response to an acute bout of brain activity [27], assertiveness [28], and brain central fatigue [29, 30] could potentially be observed from QEEG patterns (among time, frequency, and spatial domains). Therefore, we picked up these four sports-related psychological factors for estimating the performance compared with the real score form the staff coaches. These methods may be used as an alternative way for staff coaches to select the players who may have the best performance in an upcoming competition.

Materials and methods

The procedures of this study were developed to predict the performance of athletes during competition by using the factors of sports psychology to examine athletes brain activity in terms of QEEG values. The study volunteers participated in the 2014 AFC Women's Asian Cup. Thirty-two athletes from the Thai professional female soccer team took part in this study. The athletes consisted of three goalkeepers (GKs), eight center defenders (DCs) and full backs (DLs/DRs), 11 defensive center midfielders (DMCs) and center midfielders (MCs), and seven forwards (FCs) and strikers (STs). The thirty-two participants had a meanSD age of 23.882.721 years with an age range of 19–29 years, a meanSD height of 161.55.535 cm with a height range of 153.0–173.0 cm, and a meanSD weight of 54.525.848 kg with a weight range of 44–69 kg. Twenty-eight participants were right leg and right arm dominant, and four participants were left leg and left arm dominant. All experimental procedures were performed under the rules and regulations of the Center of Ethical Reinforcement for Human Research, Mahidol University (COA No. MU-CIRB 2015/143.2411). All participants signed an informed consent form after the study was explained to them by a researcher. The collected data were treated confidentially.

The participants were familiarized with QEEG measurements by a demonstration and explanation of the instruments, tasks and procedures before the recordings. In the current study, QEEGs of Thai professional female soccer players were seated in a chair in a relaxed position and were instructed not to move; data was recorded for 5 min while the participants eyes remained open. The participants were recorded three times, with recordings sessions occurring 2 weeks and 1 week before the competition and 1 week after the competition. These three time points of QEEG recordings were conducive to changes in sports psychology factors. A recording was performed 2 weeks before the competition to establish the individual's QEEG baseline. According to the literature, competitive anxiety has been reported to affect athletes 1 week before an important sport competition [31]. Hence, the 1 week before competition recording time was selected. There were the evidences that the athletes have been affected by competitive anxiety and basic emotions 3 days after a competition [32, 33]. However, according to the team management plan of the staff coaches for the national players, we were only allowed to get back to the camp and performed the EEG recording 1 week after the competition. It should be noted that the previous studies [32, 33] were the exploratory researches and have not shown the effectiveness of selecting to perform the EEG recording 1 week after the competition, so this was one of our limitations.

The Discovery 24E instrument is a 24-channel EEG and DC amplifier, that is standardized and available for field testing. The instrument consists of 19 channels at the recording of positions Fp_1, F_3, C_3, P_3, O_1, F_7, T_3, T_5, F_z, Fp_2, F_4, C_4, P_4, O_2, F_8, T_4, T_6, C_z, and P_z. The collected data were analyzed using NeuroGuide software. All results are presented as the mean and standard deviation. In addition, the QEEG values of all the results were verified using the Kolmogorov–Smirnov (K–S) test. Four sports-related psychological factors and the average performance scores (APSs) (in Table 1) were drawn as the scatter plots (Fig. 1) to preliminary investigate whether they were the possible factors to estimate the APSs. Two variables of Fig. 1b and d revealed the linear relationship to the APSs, while two other variables of Fig. 1a and c revealed the non-linear relationship to the APSs (which later we found that this preliminary investigation supported the Pearson's correlation coefficients in Table 2). The preliminary investigation suggests that, the perceptual response to an acute bout of brain activity and the brain central fatigue were likely to be able to estimate the APSs. However, according to the literatures, anxiety [24, 26] and assertiveness [28] also revealed the possible relationships to the APSs. Therefore, these two factors would still be employed as the alternative ranking to further investigate their nonlinear relationships in our statistical analysis. To estimate athletes performance, the correlations between the rankings of sports-related psychological factors and APSs were further analyzed using Spearman's correlation coefficient.

The reliability percentages of the QEEG data were assessed using the split half and test–retest methods, for which the values were expected to be greater than 90%. The portion of the QEEG data that contained no artifacts was selected before analysis in NeuroGuide software.

a COB Pre2A and PostA is the QEEG value changes observed between (COB) 1 week before the competition (Pre2A) and 1 week after the competition (PostA) which indicated anxiety.

b COB Pre1P and Pre2P is the QEEG value changes observed between (COB) 2 weeks before the competition (Pre1P) and 1 week before the competition (Pre2P) which indicated perceptual response to an acute bout of brain activity.

c COB Pre2Asrt and PostAsrt is the QEEG value changes observed between (COB) 1 week before the competition (Pre2Asrt) and 1 week after the competition (PostAsrt) which indicated assertiveness.

d COB Pre2F and PostF is the QEEG value changes observed between (COB) 1 week before the competition (Pre2F) and 1 week after the competition (PostF) which indicated brain central fatigue.

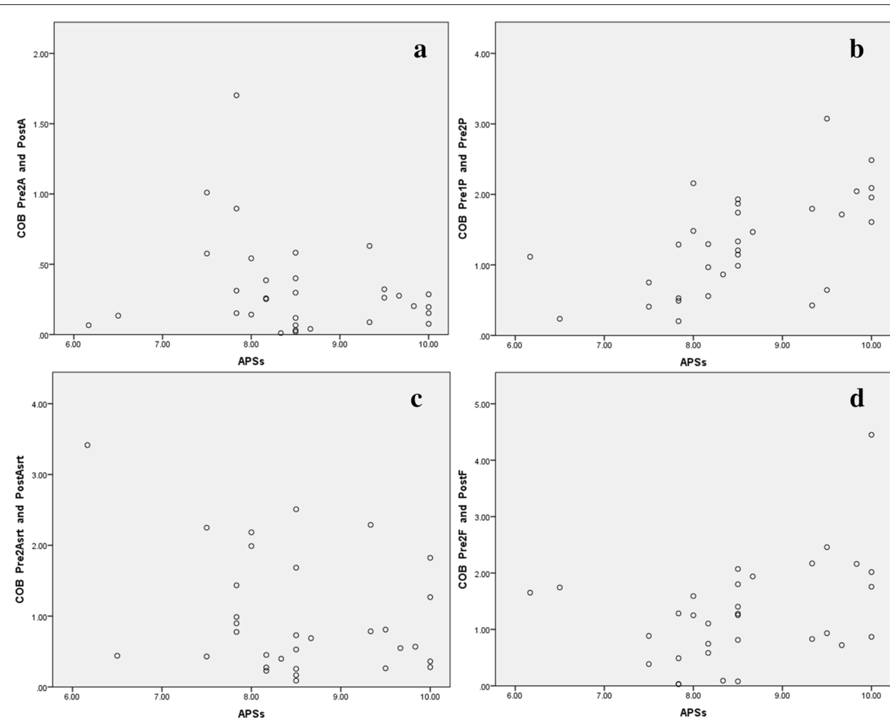

Fig. 1 Scatter plot of four sports-related psychological factors and average performance scores (APSs)

Table 1 Athletes average performance scores (APSs) according to staff coaches ($n = 32$)

N	Average points	N	Average points	N	Average points	N	Average points
S_1	6.167	S_9	10.00	S_{17}	8.000	S_{25}	8.000
S_2	8.500	S_{10}	8.500	S_{18}	10.00	S_{26}	8.167
S_3	8.667	S_{11}	6.500	S_{19}	8.167	S_{27}	7.833
S_4	7.500	S_{12}	8.500	S_{20}	9.500	S_{28}	7.500
S_5	9.333	S_{13}	9.833	S_{21}	9.667	S_{29}	9.333
S_6	10.00	S_{14}	8.500	S_{22}	8.500	S_{30}	9.500
S_7	8.500	S_{15}	7.833	S_{23}	7.833	S_{31}	7.833
S_8	8.500	S_{16}	8.333	S_{24}	10.00	S_{32}	8.167

S_n represents the subject number n

The QEEG data were analyzed via Z scores using the FFT method, as described by Eq. (1), which represented the absolute power, coherence, and amplitude asymmetry. The mathematical Gaussian curve, i.e., bell curve, was applied via the estimation of probabilities using the auto-spectrum and cross-spectrum of the EEGs, which was defined as the Z scored FFT method [34]. This method was used to identify the brain regions that were deregulated and departed from the expected values.

$$Z_{FFT} = \frac{X_i - \overline{X}}{SD_S} \tag{1}$$

where X_i is the recorded EEG of the selected frequency band, SD_S is the standard deviation of the normative database [35, 36], and $\overline{X}$ is the mean of the normative database [35, 36]. The normative database is the QEEG data acquired from 564 normal people with different ages, sex, dominant limb collected from a global population [36]. According to Thatcher (1998), the subjects were instructed to sit in the relax position to obtain this normative database [36]. In this study, four sports-related psychological factors that affect athletes performance were evaluated. These factors were demonstrated in brain phenomena, which depended on the Z scored FFT analysis via brain topographic maps and brain connectivity, as follows.

Brain topographic maps: In this study, the results are displayed as topographic maps that were calculated by the absolute power of each EEG frequency band compared with the normative database.

Brain connectivity: The objective of evaluating brain connectivity is to gather knowledge related to computational neuroscience, neuroscience methodology and experimental neuroscience. Understanding the tripartite relationship among anatomical connectivity, brain dynamics and cognitive function is of particular interest. In this study, brain connectivity was calculated based on coherence and amplitude asymmetry. The colored lines represent the strength of the communication level between positions. Coherence analyses measured the similarity of frequency contents between two channels regardless of amplitude and phase [37]. This approach can be described by Eq. (2) as a spectral morphology comparison, as follows:

$$Coh(f) = \left(\frac{\left(\sum_f |F_1(f)|.|F_2(f)| \right)^2}{\left(\sum_f |F_1(f)|^2 \right) \cdot \left(\sum_f |F_2(f)|^2 \right)} \right) \tag{2}$$

where $Coh(f)$ is a coherence function, f is EEG frequency band, and $F_1(f)$ and $F_2(f)$ are Fourier transforms of EEG signals in two different channels.

Moreover, amplitude asymmetry introduces the distinction between hemispheric specialization and activation. Specialization refers to the preparedness of a hemisphere to process information of a specific type (verbal or spatial) or in a particular manner. Activation refers to the degree to which a particular hemisphere is working or engaged [38]. Amplitude asymmetry (Asy) can be described by Eq. (3), as follows:

$$Asy = \frac{AF_1 - AF_2}{AF_1 + AF_2} \tag{3}$$

where AF_1 and AF_2 are the amplitudes in the frequency bands of two different channels from symmetric location of left and right sides of the brain.

Pearson's correlation coefficient (r) describes the linear relationship between two interval variables, two ratio variables, or one interval and one ratio variable [39, 40]. In this study, Pearson's correlation coefficient was used to report the relationship between the APSs and sports-related psychological factors. These two data are plotted the relationship by a dots as shown in Fig. 1. The sports-related psychological factors were presented in terms of EEG phenomena, for which the Z score FFT of QEEG values was employed to calculate the relationship. Four factors of sports psychology were considered: anxiety, perceptual response to an acute bout of brain activity, assertiveness, and brain central fatigue. Anxiety factors were demonstrated by the difference in QEEG value changes between 1 week before the competition (Pre2A) and 1 week after the competition (PostA). Perceptual responses to an acute bout of brain activity were demonstrated by the difference in QEEG value changes between 2 weeks before the competition (Pre1P) and 1 week before the competition (Pre2P). Assertiveness was evaluated by QEEG value changes between 1 week before the competition (Pre2Asrt) and 1 week after the competition (PostAsrt). Brain central fatigue was evaluated by QEEG value changes between 1 week before the competition (Pre2F) and 1 week after the competition (PostF). Furthermore, Spearman's correlation coefficient (r_s) is a nonparametric analog of Pearson's correlation. Spearman's correlation examines the disparity between two or more sets of rankings by evaluating the difference [39, 40]. In this study, Spearman's correlation coefficient was used to evaluate the association between APSs and sports-related psychological factor rankings. There were four factors of sports-related psychological rankings that were ranked among sets of four, three, and two factors. The ranking of sports-related psychological factors was determined by using low anxiety (A), quick perceptual response to an acute bout of brain activity (P), high assertiveness (Asrt), and high brain central fatigue (B).

Results

QEEG data were analyzed according to four psychological factors that seemed to affect the sport performance of Thai professional female soccer players. The performance scores of Thai professional female soccer players during the competition were rated according to feedback from their staff coaches, as shown in Table 1. Consequently, Thai professional female soccer players were classified according to their overall performance level via the average of their performance scores and QEEG values.

According to the APSs from Table 1, from 2 week until 4 days before the competition, all 32 players would have chances to play in 3 friendly matches. Hence, all 32 players would have the score rated from staff coaches. After that 18 out of 32 players were selected to play in the 4-match in the 2014 AFC Women's Asian Cup. It should be noted that the performance of these selected 18 players were rated based on 3 friendly and 4 real matches from the staff coaches. After the competition, all 32 players will be evaluated via QEEG. It should also be mentioned that, 4 weeks after this competition, there will be another international competition and all 32 players will still have chances to be selected by the staff coaches to be in the final 18. In depth analysis of how these two groups (selected and not selected) performed will need further investigation.

Anxiety phenomenon in QEEG estimations

Anxiety results of brain activity were demonstrated in the form of topographic maps (Z score FFT: absolute power) of the alpha frequency band (8–12 Hz) in the posterior head region. Brain activity was analyzed at five sites (P_3, O_1, P_4, O_2, and P_z), which revealed a lower amount of brain processing than the normal brain state. The anxiety phenomenon was investigated according to QEEG values that differed from the normal brain state before competition [41], as shown in Fig. 2. In addition, the average QEEG values of the 32 Thai professional female soccer players (Z score FFT: absolute power) were revealed at the three time points, as shown in Fig. 3. The light blue bar shows the data that were recorded 2 weeks before a competition and represents the athlete's brain activity confounded with the anxiety (arousal and excitement) phenomenon. The blue bar shows the data that were recorded 1 week before the competition and represents the anxiety (arousal and excitement) state of brain activity. The green bar shows the data that were recorded 1

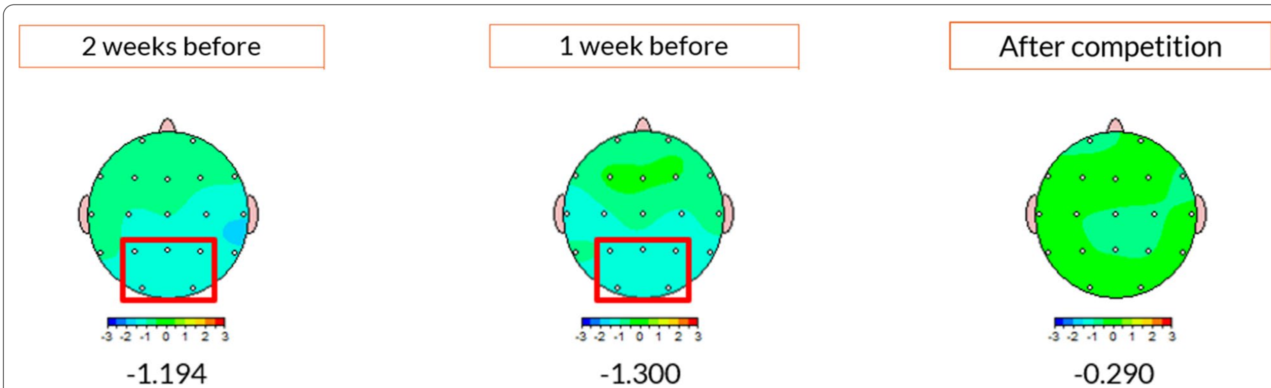

Fig. 2 Anxiety results at the three time points according to QEEG values in the alpha frequency band (Z score FFT: absolute power)

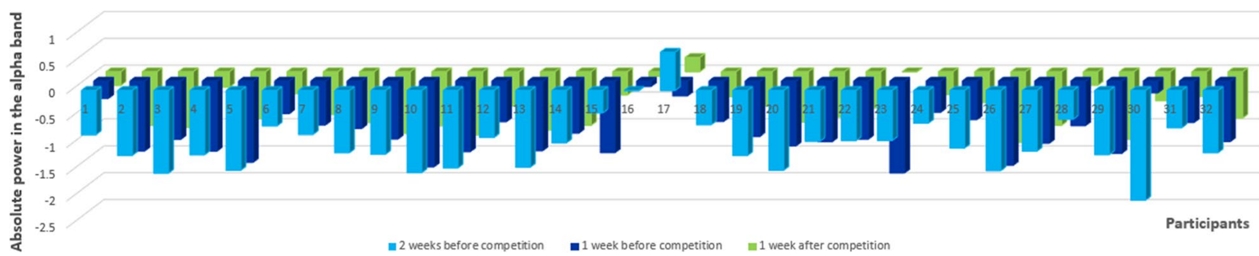

Fig. 3 Brain activity of Thai professional female soccer players presented as QEEG values (Z score FFT: absolute power) in the alpha frequency band

week after the competition, which indicates the return of brain activity to a normal state. The trends in QEEG values (Z score FFT: absolute power) of the Thai professional female soccer players were examined 2 weeks and 1 week before the competition and were compared with the values measured 1 week after the competition, as shown in Fig. 4.

Perceptual response to an acute bout of brain activity phenomena in QEEG estimations

The results of a perceptual response to an acute bout of brain activity were demonstrated in the form of brain connectivity (Z score FFT: coherence) in the delta frequency band (0.1–3 Hz) across all positions of the brain (64 pairs of channels: Fp_1–F_3, Fp_1–C_3, Fp_1–P_3, Fp_1–O_1, Fp_1–F_7, Fp_1–T_3, Fp_1–T_5, F_3–C_3, F_3–P_3, F_3–O_1, F_3–F_7, F_3–T_3, F_3–T_5, C_3–P_3, C_3–O_1, C_3–F_7, C_3–T_3, C_3–T_5, P_3–O_1, P_3–F_7, P_3–T_3, P_3–T_5, O_1–F_7, O_1–T_3, O_1–T_5, F_7–T_3, F_7–T_5, T_3–T_5, Fp_2–F_4, Fp_2–C_4, Fp_2–P_4, Fp_2–O_2, Fp_2–F_8, Fp_2–T_4, Fp_2–T_6, F_4–C_4, F_4–P_4, F_4–O_2, F_4–F_8, F_4–T_4, F_4–T_6, C_4–P_4, C_4–O_2, C_4–F_8, C_4–T_4, C_4–T_6, P_4–O_2, P_4–F_8, P_4–T_4, P_4–T_6, O_2–F_8, O_2–T_4, O_2–T_6, F_8–T_4, F_8–T_6, T_4–T_6, Fp_1–Fp_2, C_3–C_4, O_1–O_2, T_3–T_4, F_3–F_4, P_3–P_4, F_7–F_8, and T_5–T_6). Brain connectivity analysis revealed higher connectivity compared with the normal brain state (no line, or a blue line changed to a red line), indicating that there were more affective and perceptual responses to acute bouts during a competition. This phenomenon increased when the competition approached, and it returned to a normal state when the competition was finished [41], as shown in Fig. 5. Moreover, the average QEEG values of the 32 Thai professional female soccer players (Z score FFT: coherence) for the three time points are shown in Fig. 6. The green bar shows the data that were recorded 2 weeks before the competition and represents the normal state of brain activity. The red bar shows the data that were

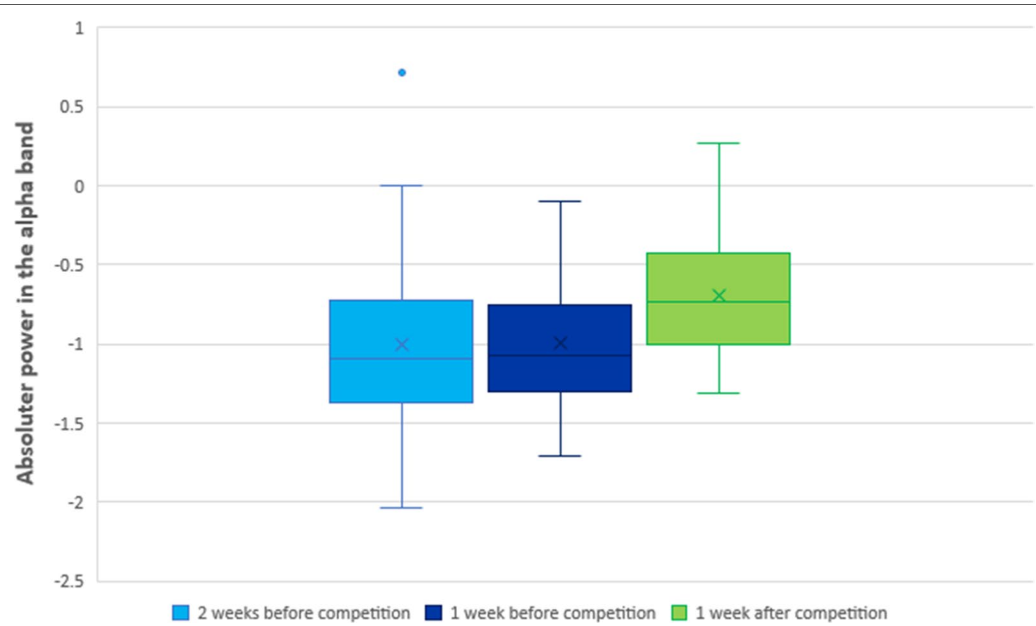

Fig. 4 The trends of the brain activity of 32 Thai professional female soccer players presented as QEEG values (Z score FFT: absolute power) in the alpha frequency band

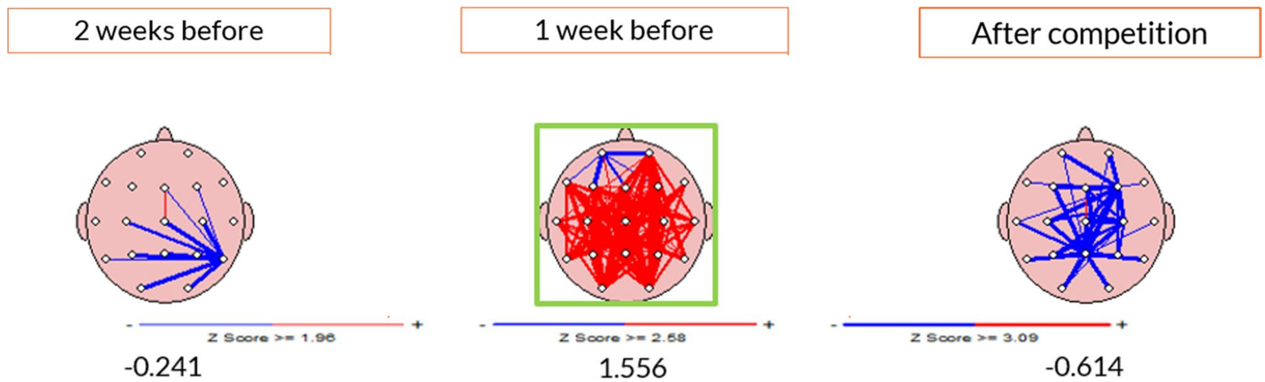

Fig. 5 The results of perceptual responses at the three time points to an acute bout of brain activity based on QEEG values (Z score FFT: coherence) in the delta frequency band

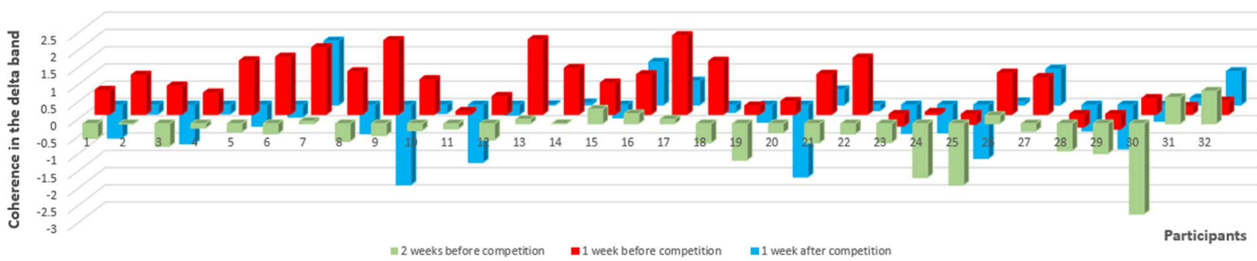

Fig. 6 Brain activity of Thai professional female soccer players presented as QEEG values (Z score FFT: coherence) in the delta frequency band

recorded 1 week before the competition and represents the perceptual response to an acute bout of brain activity (good decision-making, alertness, attentiveness, and awareness) of brain activity. The blue bar shows the data that were recorded 1 week after the competition. Normally, 1 week after a competition, brain activity returns to a normal state; however, some Thai professional female soccer players exhibited a confounded brain central fatigue phenomenon, which is discussed in the next section. The trends of QEEG values (Z score FFT: coherence) of Thai professional female soccer players were examined 1 week before the competition and were compared with the values measured 2 weeks before and 1 week after the competition, as shown in Fig. 7.

Assertiveness phenomenon in QEEG estimations

Assertiveness was observed according to brain activity recordings of Thai professional female soccer players who were assigned to different positions. A distinctly greater response was found in the defensive player group than in the offensive player group. Therefore, the nature of the Thai professional female soccer team may be to play with a defensive style. The assertiveness phenomenon was found in the beta frequency band (12–25 Hz) at the frontal area of the brain. This phenomenon was analyzed in two ways: by brain topographic maps (Z score FFT: absolute power) and brain connectivity (Z score FFT: amplitude asymmetry). The brain topographic maps revealed a higher level of brain processing than that observed in the normal brain state. This analysis included 4 channels: Fp_1, F_7, Fp_2, and F_8. Additionally, brain connectivity revealed higher differences in amplitude at each of the EEG channels between hemispheres than during the normal brain state. This analysis included 28 pairs of channels corresponding to Fp_1–F_3, Fp_1–C_3, Fp_1–P_3, Fp_1–O_1, Fp_1–F_7, Fp_1–T_3, Fp_1–T_5, F_7–F_3, F_7–C_3, F_7–P_3, F_7–O_1, F_7–T_3, F_7–T_5, F_7–F_8, Fp_1–Fp_2, Fp_2–F_4, Fp_2–C_4, Fp_2–P_4, Fp_2–O_2, Fp_2–F_8, Fp_2–T_4, Fp_2–T_6, F_8–F_4, F_8–C_4, F_8–P_4, F_8–O_2, F_8– T_4, and F_8–T_6.The results of the brain topographic maps and brain connectivity were demonstrated 1 week before the competition, for which an orange color was used to display the data and tended to be more highly increased than at other time points [42], as shown in Figs. 8 and 9. Furthermore, the average QEEG values in the 32 Thai professional female soccer players (Z score FFT: absolute power and amplitude asymmetry) were measured at the three time points, as shown in Figs. 10 and 11. The light green bar corresponds to results recorded 2 weeks before the competition, which represents the normal state of brain activity. The orange bar corresponds to results recorded

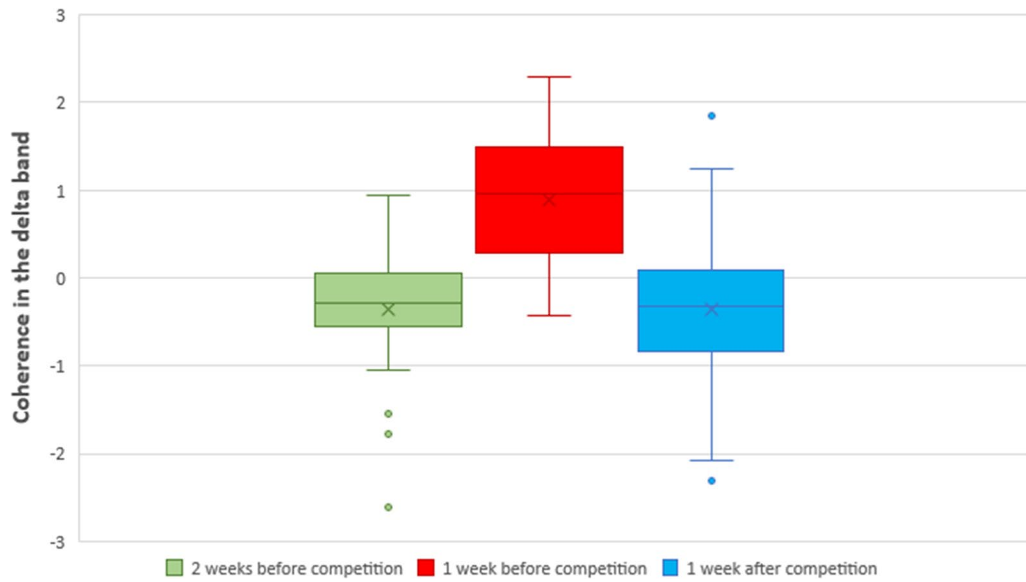

Fig. 7 The trends of the brain activity of 32 Thai professional female soccer players presented as QEEG values (Z score FFT: coherence) in the delta frequency band

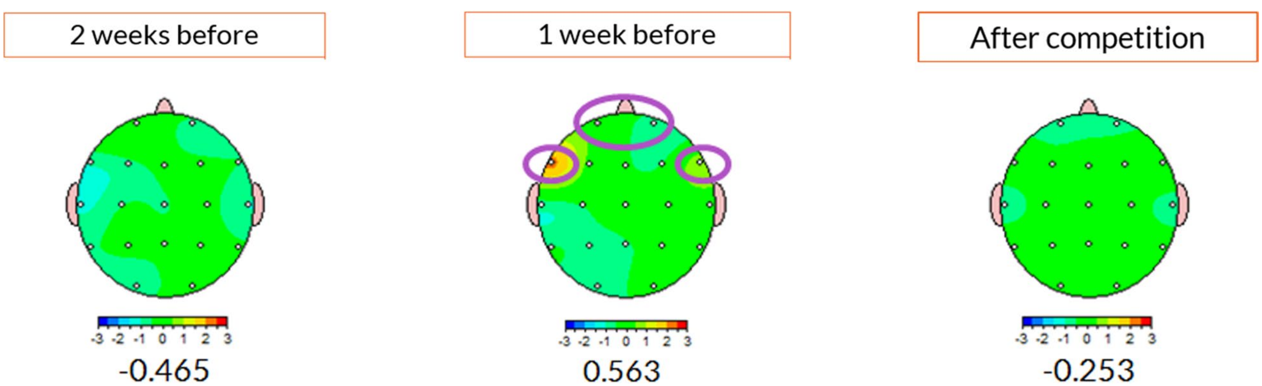

Fig. 8 Assertiveness results at the three time points according to QEEG values (Z score FFT: absolute power) in the beta frequency band

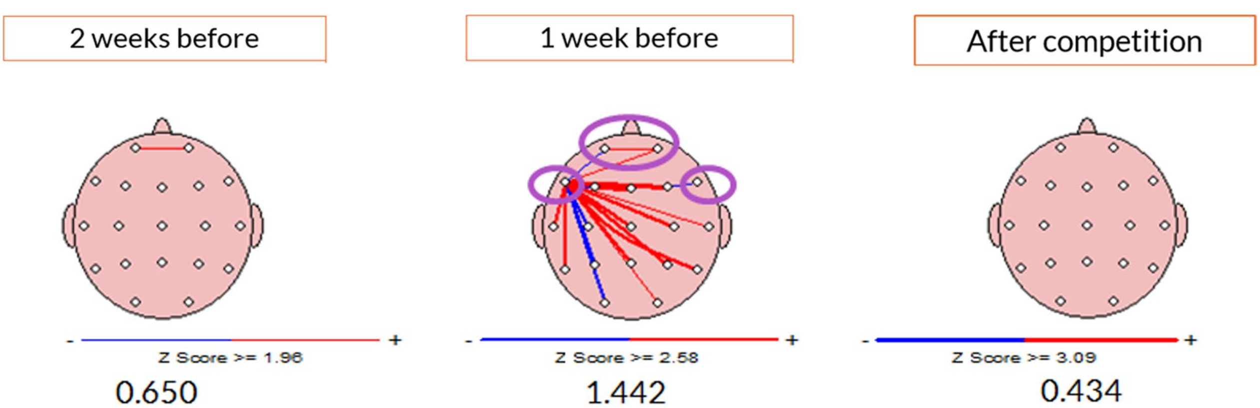

Fig. 9 Assertiveness results at the three time points according to QEEG values (Z score FFT: amplitude asymmetry) in the beta frequency band

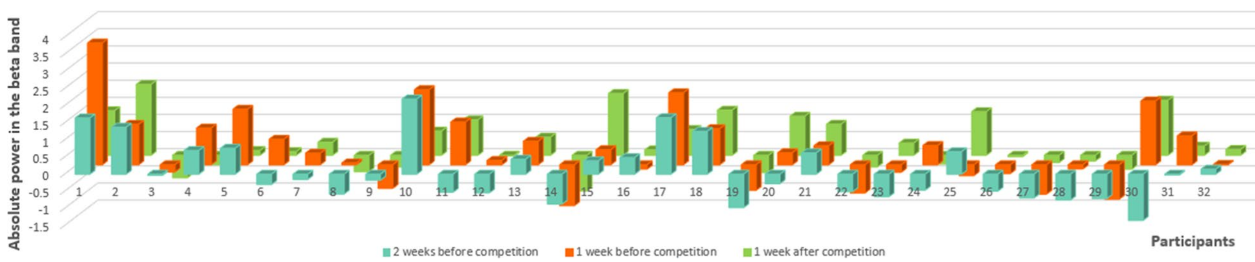

Fig. 10 Brain activity of Thai professional female soccer players presented as QEEG values (Z score FFT: absolute power) in the beta frequency band

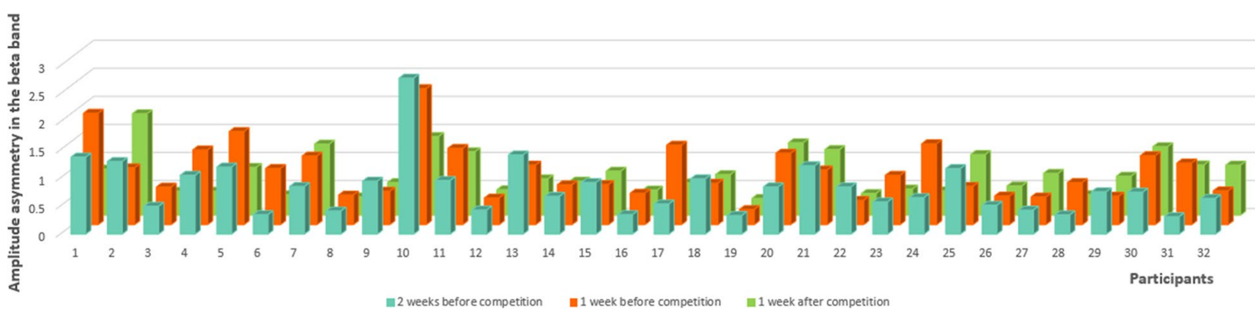

Fig. 11 Brain activity of Thai professional female soccer players presented as QEEG values (Z score FFT: amplitude asymmetry) in the beta frequency band

1 week before the competition, which represents higher QEEG values in both analyses compared with other time points. The green bar corresponds to results recorded 1 week after the competition, at which time the brain activity had returned to the normal state. The trends in QEEG values (Z score FFT: absolute power and amplitude asymmetry) of the Thai professional female soccer players were examined 1 week before competition and were compared with data acquired 2 weeks before and 1 week after competition; absolute power and amplitude asymmetry data are shown in Figs. 12 and 13, respectively.

Brain central fatigue phenomenon in QEEG estimations

The effects of brain central fatigue were clearly observed in brain connectivity (Z score FFT: coherence) in the delta frequency band (0.1–3 Hz). This phenomenon was revealed by the low interaction level at all positions of the brain after competition, as shown by the blue lines in the brain connectivity map. Normally, the brain activity of athletes returns to a normal state, which appears similar to their brain connectivity 2 weeks before competition. Additionally, a much more distinct pattern of brain central fatigue appeared in the key players (the players on the field) than in the substitute players of the team [43], as shown in Fig. 14. The average QEEG values of the 32 Thai professional female soccer players (Z score FFT: coherence) at the three time points are displayed in Fig. 6. The blue bar reflects the QEEG values of the athletes 1 week after the competition, which differed from the values 2 weeks before the competition and indicated that the athletes experienced a brain central fatigue effect. The trends of the QEEG values (Z score FFT: coherence) of the Thai professional female soccer players at the three time points were examined 1 week after the competition and were compared with the data obtained 2 weeks and 1 week before the competition, as shown in Fig. 7.

Sports-related psychological performance

Pearson's correlation coefficient (*r*) was used to examine the relationship between the APSs and the change observed between (COB) two time points regarding athletes brain activity, as shown in Table 2. There were two factors of sports psychology that were used to evaluate the performance of athletes. First, the effect of an athlete's brain activity is a perceptual response to an acute bout of brain activity phenomena. A strong correlation indicates a quick perceptual response to an acute bout of brain activity that can predict the athlete's performance during a competition ($r = .584$, $p = .000$). Second, the athlete's brain activity as it relates to brain central fatigue was evaluated. The results moderately indicated that athletes who experienced brain central fatigue after the competition may have exhibited good performance during the competition ($r = .368$, $p = .019$). On the other

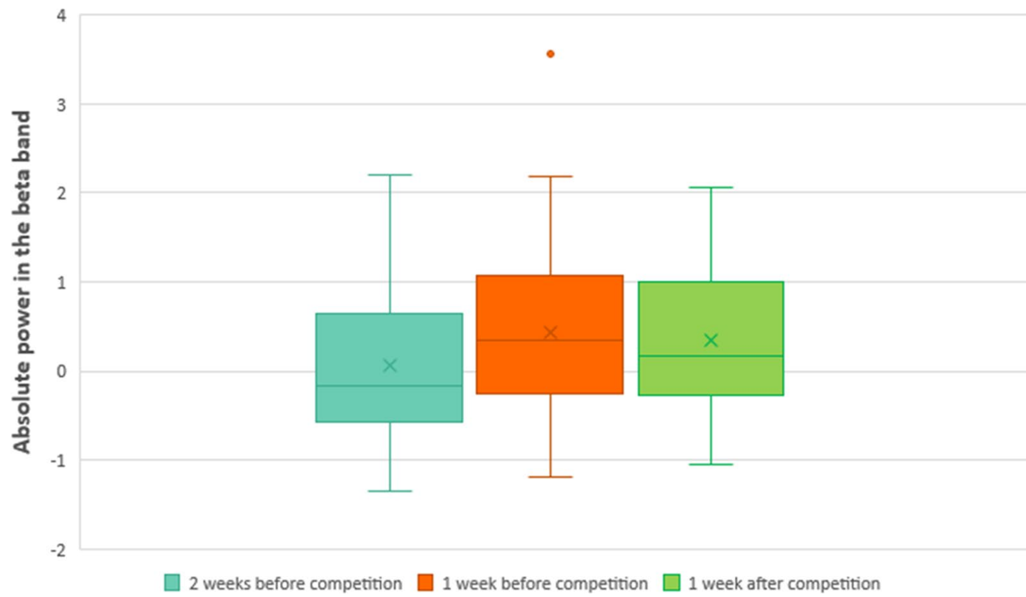

Fig. 12 The trends of the brain activity of 32 Thai professional female soccer players presented as QEEG values (Z score FFT: absolute power) in the beta frequency band

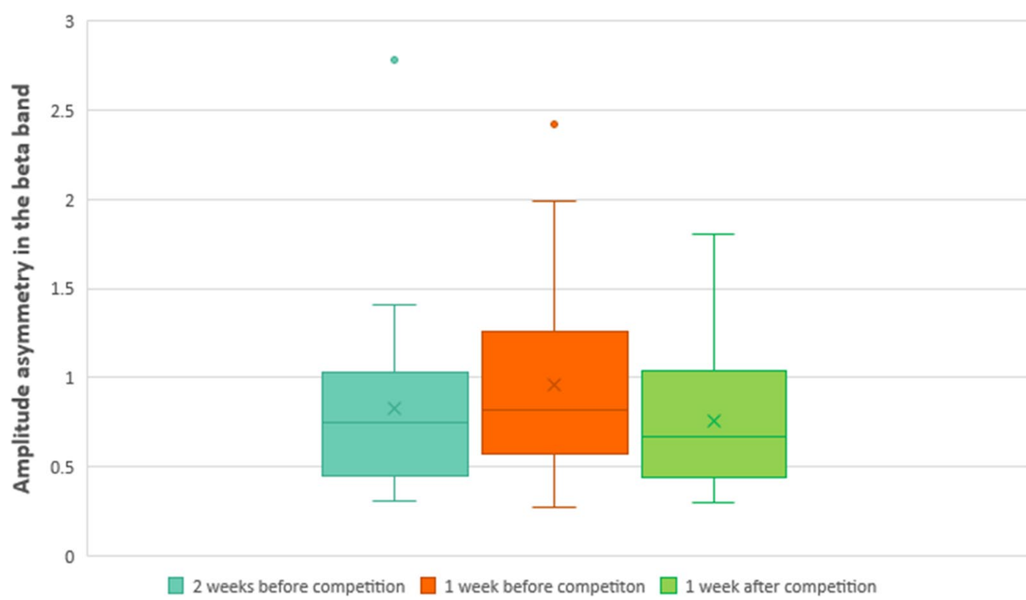

Fig. 13 The tends of the brain activity of 32 Thai professional female soccer players presented as QEEG values (Z score FFT: amplitude asymmetry) in the beta frequency band

hand, the anxiety and assertiveness factors of athletes brain activity could not predict their performance during the competition. These factors might be effective in predicting performance when combined with other sports-related psychological factors.

Furthermore, Spearman's correlation coefficient (r_s) was used to evaluate the association between the APSs and the sports-related psychological factor ranking (SPFR), as shown in Table 3. Four effects of athletes brain activity were related to performance, namely, anxiety (A), perceptual response to an acute bout of brain activity (P), assertiveness (Asrt), and brain central fatigue (F). These factors were used to rate QEEG values with low anxiety, quick perceptual response to an acute bout of brain

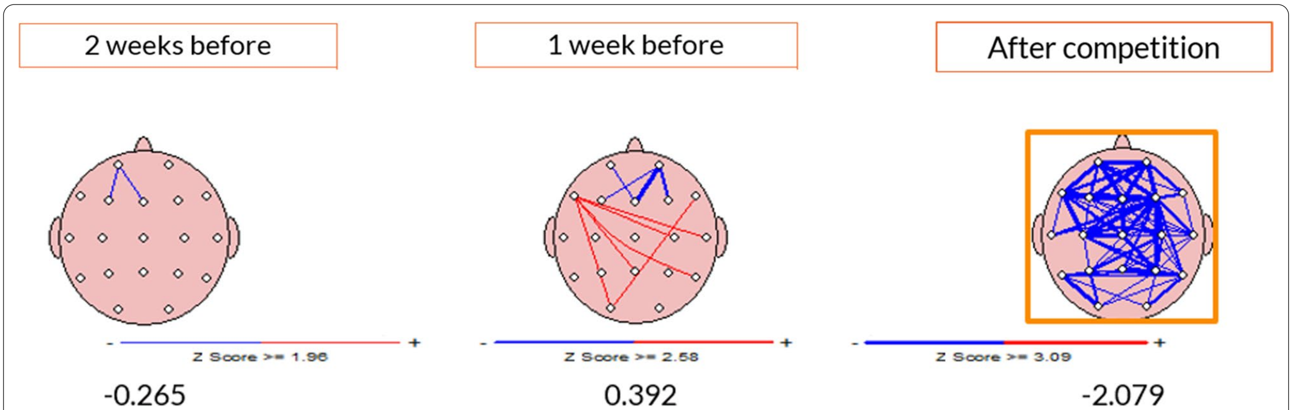

Fig. 14 The brain central fatigue results at the three time points according to QEEG values (Z score FFT: coherence) in the delta frequency band

Table 2 Results of Pearson's correlation coefficient (*r*) between the APSs and the change in athlete brain activity between two time points ($n = 32$)

Time points	*r*	Sig.
APS and COB Pre2A and PostA	− .211	.124
APS and COB Pre1P and Pre2P	.584**	.000*
APS and COB Pre2Asrt and PostAsrt	− .280	.061
APS and COB Pre2F and PostF	.368**	.019*

*The lower bound of true significance.

**Significant correlation

Table 3 Results of Spearman's correlation coefficient (r_S) between the APSs and SPFR ($n = 32$)

SPFR conditions	r_S	Sig.
APSs and SPFR among A, P, Asrt, and F	.478**	.003*
APSs and SPFR among A, P, and Asrt	.423**	.008*
APSs and SPFR among A, P, and F	.622**	.000*
APSs and SPFR among A, Asrt, and F	.228	.055
APSs and SPFR among P, Asrt, and F	.384**	.015*
APSs and SPFR between A and P	.634**	.000*
APSs and SPFR between A and Asrt	.066	.359
APSs and SPFR between A and F	.486**	.002*
APSs and SPFR between P and Asrt	.309**	.042*
APSs and SPFR between P and F	.628**	.000*
APSs and SPFR between Asrt and F	.127	.245

*A lower bound of the true significance.

**Significant correlation

activity, high assertiveness, and high brain central fatigue. Notably, the results revealed a moderate relationship($r_s = .478$, $p = .003$) of the rating derived from the summation of the anxiety, perceptual response to an acute bout of brain activity, assertiveness, and brain central fatigue factors. This rating might not predict performance for players of all positions of the team. Moreover, the results demonstrated a strong relationship ($r_s = .622$, $p = .000$) among the rating derived from the summation of anxiety, perceptual response to an acute bout of brain activity, and brain central fatigue factors. The highest relationship was revealed between the APSs and these three factors of sports psychology. Last, two factors of sports psychology seemed to predict the peak performance of all player positions of the team. The results revealed a strong relationship ($r_s = .634$, $p = .000$) between the rating derived from the summation of the anxiety and perceptual response to an acute bout of brain activity factors.

Discussion

In the present study, we investigated the performance related to EEG activity among Thai professional female soccer team members before and after a competition. The sports-related psychological factors of the athletes QEEG activity were used to estimate their performance during the competition. Two analyses were performed (1) to estimate the relationship between the APSs and the COB athletes brain activity at two time points and (2) to determine the association between the APSs and SPFR. First, the relationship between the APSs and the COB athletes brain activity at two time points was used to examine the athletes performances by using Pearson's correlation coefficient (*r*), which was used to assess anxiety, perceptual response to an acute bout of brain activity, assertiveness, and brain central fatigue. The relationship between the APSs and the COB conditions of anxiety did not predict performance. Statistical analysis showed no significant relationship ($r = -.211$, $p = .124$). A previous study showed the existence of a negative correlation between cognitive anxiety and performance in 101 basketball players; low cognitive anxiety levels were very important for high sports performance [44]. In particular, the official statistics of basketball players of the Spanish Basketball Federation showed a correlation between anxiety and skill performance of athletes [45]. Moreover, anxiety seems to individually reveal the optimal zone of the athlete's peak performance. The inverted-U theory explains that an athlete's performance level relies on his or her optimal arousal level. Performance level depends on interpersonal variables, as well as specific personality, expected outcome, and the sport itself [3]. The development of a catastrophic model provided a theoretical framework for better understanding the relationship between cognitive anxiety and somatic anxiety and their effects on performance [46, 47].

The statistical analysis of the APSs and the COB conditions of perceptual response to an acute bout of brain activity showed that the perceptual response to an acute bout of brain activity could be used to evaluate athletes performance ($r = .584$, $p = .000$). The strong correlation indicated that a quick perceptual response to an acute bout of brain activity might be a considerable component of the success of athletes in a sport. This phenomenon seems to indicate that the athlete exhibits good decision-making skills during competition. Decision-making and action planning play important roles in elite athletes contributes to their success in sports. These factors can be demonstrated by neurophysiological data recorded from brain waves [48]. Athletes must engage in continuous judgment and decision making (JDM) among alternative actions that can be taken during a competition, and these actions play a major role in the success or failure of a sports-related activity [49]. Furthermore, JDM has been used to provide a rudimentary introduction in endurance sports [50]. The development of skilled decision-making was used to examine other factors associated with tactical creativity, such as age and expertise levels, training, or motivation. Unexpected decisions made by teammates seemed to increase the number of shots on goal in soccer [51]. Furthermore, human electrical brain signals demonstrated the motor stages of perceptual decision-making and cognitive processes such as decision-making and attention, which were shown in delta oscillations [52, 53].

Statistical analysis of the APSs and the COB conditions of assertiveness showed that the assertiveness level could not be used to evaluate athletes performance ($r = -.280$, $p = .061$). This result might not explain the relationship between assertiveness and athletes performance, which depends on the style of team play. The Thai professional female soccer team appears to have a defensive style of play. Collectively, assertiveness distinctly appeared in the defensive player group more than in the offensive player group. A study of association football athletes in the 2010 World Cup indicated that the results of aggression and performance varied across all 32 counties depending on position [54]. Two features of aggressive or violent behavior could be defined from an individualistic perspective in the field of sporting activities [55]. Statistical analysis was used to estimate the variation in the scoring of all matches in the 1st division of the Spanish football league for the 2007/2008 and 2008/2009 seasons. The variables related to the type of aggression could be distinguished between home and away teams [56]. However, aggression and achievement motivation contributed significantly to performance in three different levels of soccer players [57]. The aggressive behavior of athletes was measured and appeared to be able to be controlled by training, which could have contributed to winning the gold medal in the London Olympics in 2012 [58].

The relationship between APSs and the COB conditions of brain central fatigue seems to be an indicator of performance. Statistical analysis moderately indicated that the athletes who had brain central fatigue after the competition were those who exhibited good performance during the competition ($r = .368$, $p = .019$). These were Thai professional female soccer players who remained in the field for the full match and for every match of the tournament. Vetter and Symonds (2010) analyzed the effect of competition season on the mental exhaustion of athletes [59]. Mental fatigue was induced in athletes who performed for prolonged periods of time and exerted maximal effort during the match [60, 61]. Athletes need to recover between matches. The recovery period might be potentially influenced by the magnitude of soccer match-induced fatigue, which may consist of extrinsic and/or intrinsic factors [62]. Consequently, the recovery period from neuromuscular fatigue and biochemical changes might be a considerable factor for the performance of an elite female soccer player and may contribute to the unstable performance of athletes [63]. Due to differences in technical and physical performance between the first and second halves of official soccer matches, the results are useful for classifying soccer players who have the most relevant technical and specific skills. This approach could be an effective tool for player selection and could lead to more successful matches [64]. However, a study of 26 male soccer players from local soccer teams or universities who regularly participate in training and competition confirmed that mental fatigue impairs both physical and technical performance in soccer players [65].

Last, the association between the APSs and SPFR revealed Thai professional female soccer players who exhibited high performance during the competition; therefore, the ranking score could be estimated from psychological factors. These results were separated into three conditions (rankings based on sets of four, three, or two sports-related psychological factors) derived from summations of anxiety (A), the perceptual response to an acute bout of brain activity (P), assertiveness (Asrt), and brain central fatigue factors (F). Statistical analysis of the APSs and SPFR revealed a moderate relationship among the four factors (r_s = .478, p = .003). This result seems to accurately reveal a lower relationship between the APSs and SPFR than that in the other conditions. Thus, some Thai professional female soccer players have unique individual characteristics, such as brain activity, daily skill training programs, speed of rehabilitation after an injury, mental health, determination, and activities of daily life. These characteristics might affect their psychological factors, which may cause them to show different performances. Personality factors affect sports performance; therefore, it may be possible to predict the success of an athlete based on the unique blend of his or her personality characteristics and psychological characteristics [66, 67]. Additionally, the statistical analysis of the APSs and SPFR revealed a strong relationship for rankings based on three (r_s = .622, p = .000) and two (r_s = .634, p = .000) sports-related psychological factors. These results indicated that Thai professional female soccer players who had high performance during competition exhibited low anxiety and a quick perceptual response to an acute bout of brain activity before the competition but high brain central fatigue after the competition. In terms of cognitive performance, athletes should ideally exhibit low stress and modulated anxiety, high speed and accuracy of decision-making, and cognitive fatigue after prolonged continuous performance [68–70]. On the other hand, some of the statistical analysis results might not explain the relationship between psychological factors and Thai professional female soccer players performance during competition. The psychological factors based on player position, which could possibly be related to psychological skills [71–74], various psychological attributes [75] and physical skills and fitness [76, 77], should be separately analyzed. Nevertheless, Hodge and Hermansson (2007) proposed the psychological preparation of athletes for the Olympic Games. The authors suggested that mental skills developed with the help of a trainer/sports psychologist are very beneficial for supporting the challenges of performance [78]. Abdullah et al. (2016) revealed that there is a strong relationship between psychological factors and the performance of elite soccer players, although psychological factors alone cannot determine performance in a soccer game [79]. In future studies, this finding regarding psychological factors could be used to provide neurofeedback as treatment; to develop a brain warm-up exercise device; to train visual attention, promote self-confidence, assist in recovery from injury; and to optimize aspects of each specific type of sport to achieve peak performance.

Conclusion

This study investigated the effects of sports-related psycho-logical factors based on QEEG data. These factors were presented as QEEG values (Z score FFT: absolute power, coherence, and amplitude asymmetry), and we demonstrated their relationships with athlete performance. The present study revealed that Thai professional female soccer players who exhibited high performance during competition had low anxiety with quick perceptual responses to an acute bout of brain activity. Moreover, assertiveness and brain central fatigue appeared to affect performance and could be estimated based on player position and distinguished between key and substitute players. The results from the present study could allow staff coaches to choose players with the best performance, providing an alternative method for accurately selecting the key players for competitive sports. Therefore, a sports-related psychological factor ranking (SPFR) can be used to predict an athlete's performance during a competition.

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Declarations

Conflict of interest

The authors reported no potential conflicts of interest.

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