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Alpha Neurofeedback Training in Elite Soccer Players Trained in Groups

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Abstract
Neurofeedback training is applied in the world of sports as a means to improve athletes' performance. Training sessions are usually organized on an individual basis, one at a time. Here we investigated if the training could also be organized in groups. Forty-one national-level football (soccer) players (26 females, 15 males) carried out training sessions simultaneously in groups of up to 13, using a wearable device with Bluetooth connection, during their regular training hours at the club. It was possible to obtain good EEG measurements using this setup, albeit with a somewhat higher data loss than usual in standard laboratory sessions. The brain's alpha activity was trained using music-based neurofeedback in a crossover design. A training session consisted of alternating periods of neurofeedback and execution of cognitive tasks. EEG alpha (8–12 Hz) activity was higher in the neurofeedback periods compared to the cognitive task periods, and the reverse was true for beta (13–30 Hz) activity. The training program resulted in an increase of 34% in alpha activity associated with the training, and improved the athletes' performance on task switching and mental rotation tasks. In addition, self-reported sleep duration, as well as scores on the Being in Shape questionnaire (Feeling of Control and Flow) also improved. This study shows that neurofeedback training is feasible in groups of athletes, which can stimulate its application in team sports.

Keywords Alpha activity · Neurofeedback training · Soccer · Cognitive performance · Wearable EEG

Introduction

Elite athletes try to control every single aspect of their performance to reach the highest level possible. The concept of "marginal gains" (e.g., Hall et al., 2012) concerns the idea that even small improvements on a particular detail such as attention, speed of action, processing speed, can mean the difference between a gold and silver medal. It is therefore no surprise that a considerable amount of research is devoted to optimizing sports performance. In addition to control over physical aspects of the sport, it is also important for top athletes to gain control over the mental aspects that play a role in optimal sports performance. Sports psychology is a rapidly expanding branch within sports science, and a number of positive (e.g., mindfulness, mental practice, neurofeedback) as well as negative (anxiety, anger, depression) influences on sports performance have been identified (Lochbaum et al., 2022).

In addition to behavioral assessment and intervention tools, psychophysiological measures are increasingly being used in the field of sports performance. These measurements are non-intrusive, easy to apply, have a good time resolution, and allow the estimation of both central and autonomic nervous system activity. Many autonomic measures cardiovascular activity can nowadays be measured quite easily using standard wearable devices. However, if the aim is to monitor or influence mental aspects of sports performance, it would be more obvious to look at central nervous system activity instead of autonomic nervous system activity as they are measured by standard wearable devices. Unsupervised measurement of central nervous system activity is much more difficult though, and therefore much less being used at the moment compared to autonomic measures.

The electroencephalogram (EEG), first discovered around 100 years ago, could for a long time only be recorded under

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laboratory conditions in an electrically shielded room from participants sitting as still as possible wearing head caps containing conductive gel. Movement, electrical interference, or bad electrode contacts would make the EEG very hard to interpret. This made EEG applications during sports performance virtually impossible, and applications around sports events cumbersome. Nevertheless, EEG technology has been used for some time in a variety of sports, mostly in individual sports such as golf and archery, and the general findings are that a decrease in brain activation is related to an increase in sports performance. This "neural efficiency hypothesis", developed in the context of general intelligence (Haier et al., 1988), states that experts perform more effectively than beginners by only recruiting the brain areas needed to perform the task at hand, while at the same time inhibiting other brain areas that are not required.

Rhythmic EEG activity can be classified into several frequency bands: delta (< 4 Hz), theta (4–7 Hz), alpha (8–12 Hz), beta (13–30 Hz), and gamma (> 30 Hz). Fast EEG rhythms are indicative of brain activation, as in intense mental activity; slow rhythms with brain inactivation, as in sleep. The intermediate alpha rhythm appears to reflect a special state of "relaxed wakefulness". Its maximum can be seen over the posterior parts of the brain, and in resting state conditions it is almost always greater when participants have closed compared to open eyes. Klimesch et al. (2007) developed an "inhibition-timing" hypothesis about alpha EEG activity, which entails that alpha power is inversely proportional to the activity of the underlying brain tissue. This hypothesis makes alpha activity extremely suitable for application in the field of sports, where sports performance is linked to neural efficiency, as argued above. If sports performance is linked to reduced brain activity, then this could be accompanied by an increase in EEG activity in the alpha band.

There is a lot of evidence supporting the positive relationship between sports performance and alpha activity, reviewed by several authors (e.g., Del Percio et al., 2011; Park et al., 2015). In much of this research, alpha activity is the dependent variable used as an index of the active inhibition of brain areas that are not required for the execution of a particular motor skill required for optimal sports performance. However, alpha activity has also been used as an independent variable. In this case, the goal is to teach athletes to gain control over alpha activity so that they can activate or inhibit it as the situation requires. Besides improving sports performance, alpha activity has long been associated with positive effects on relaxation, sleep, and well-being (e.g., Gruzelier, 2002).

In neurofeedback training (NFT), operant conditioning procedures are used to change brain rhythms, and it is then investigated how these changes relate to changes in performance. Landers et al. (1991) are usually credited as being the first to apply NFT for enhancing sports performance. They up-trained slow brain potentials over the left ("correct feedback") and right ("incorrect feedback") temporal cortex in archers and found that performance increased in the correct feedback group and decreased in the incorrect feedback group. Since then, there have been more applications of NFT research in sports. The reviews of Mirifar et al. (2017), and Rydzyk et al. (2023) indicate that NFT effectively improves the athletes' performance in a specific sports task and/or in relevant underlying aspects of cognition and affect (Mirifar et al., 2017, p. 429).

There might be several reasons why NFT is slow to be adopted in the field of sports, despite the mostly positive effects on performance, relaxation, and well-being. One reason is that the traditional EEG setup with wired, gel-based electrodes does not fit well with the sporting environment. Secondly, NFT studies can take considerable time to complete. There are usually 10–20 training sessions to complete for each participant, there are training and control groups, so many NFT studies take half a year or more to complete. We (Van Boxtel et al., 2012) have initiated a program in an attempt to improve these drawbacks. A recording system was used in which the electrodes were moistened with tap water. The system was easier and quicker to set up than a standard laboratory recording system, but still needed supervision from a trained experimenter. With this system we trained alpha activity up in groups of five participants simultaneously. The feedback consisted of adapting music quality depending on the level of the brain rhythm to train. Using a double-blind between-subjects design, there were three conditions; alpha up (8–12 Hz), random beta up (different 4 Hz bands in the 13–30 Hz range), and no feedback (music only). The alpha up group showed a greater increase in alpha activity than either of the other two groups after the training, and especially on a follow-up measurement 6 weeks later, and that group also reported feeling more relaxed and comfortable compared to the other groups. In a subsequent study, we (Dekket et al., 2014) found that this approach was feasible in elite gymnasts. We found that alpha activity increased, and that this increase also resulted in an improvement of "being in shape".

The goal of the present study is to take this approach a step further, and thereby to stimulate the adoption of NFT applications in elite sports. Recent technological advances have made EEG recordings much easier, and commercial, wireless, 'dry' EEG systems are now readily available. Because we wanted to work simultaneously in groups of people outside of a laboratory cabin, we asked two football (soccer) teams to participate. In this way, we also created a natural environment in which players can participate simultaneously during normal training hours at the club. In addition, elite clubs have already realized for a long time that success does not only depend on physical fitness and

development of game tactics, but also on cognitive and psychological skills, such as attention, working memory, and executive functions. For this type of function, it is likely that NFT will be beneficial based on the neural efficiency hypothesis, in addition to having positive effects on relaxation, sleep, and well-being.

The participating clubs did not want to withhold a possible beneficial effect of NFT from any of their players. We therefore used a crossover design, in which there were three sessions intended to assess the effect of the NFT (assessment sessions A1–A3). Half of the group (A) received the NFT between A1 and A2, while the other half (B) received treatment as usual (TAU). After A2, the second group (B) received the NFT and the first group (A) received TAU.

The first question we wanted to address was whether simultaneous recordings were possible in groups, using a wireless EEG device connected to a smartphone. With many wireless devices connecting to smartphones, Bluetooth and WiFi interference is more than likely. We therefore started every assessment session with a resting state measurement of eyes open and eyes closed. For a good EEG measurement, we expected EEG spectra with decreasing power as a function of frequency, and a clear alpha peak superimposed on it around 10 Hz, which is greater under eyes closed than eyes open conditions.

Secondly, we expected alpha power to show alternating increases and decreases, as a function of the epoch within a training session. The approach in our previous work, as in the present study, was to alternate NFT epochs with cognitive tasks. This had two purposes. On the one hand, the participants were kept alert in this way without their attention flagging during the NFT periods in which they did nothing but listen to music. On the other hand, in this way we could immediately and easily collect data on cognitive processes. Keeping the order of alternating NFT and cognitive task epochs constant, we expected a 'saw-tooth' pattern of alpha activity with higher values in the NFT compared to the task periods.

Thirdly, we expected that alpha activity would increase as a result of the training. Given the cross-over design, this would result in an interaction between assessment session and group. Group A received the training between A1 and A2, and is therefore expected to show the largest increase in alpha activity between A1 and A2, not so much between A2 and A3. Group B received the training between A2 and A3, there is expected to show similar levels of alpha activity between A1 and A2, and an increase between A2 and A3. At A3, both groups are expected to show comparable levels of alpha activity.

Our fourth expectation was that the NFT resulted in a concomitant change in the performance on cognitive tasks and subjective questionnaires. The cognitive tasks that were used in the training to bring about alternation between NFT and cognitive epochs were task switching (executive functions), psychomotor vigilance (sustained attention), and mental rotation (mental representations). In the assessment sessions, the participants also performed a stop-signal task (response inhibition), attentional network task (alerting, orienting and executive attention), and N-back task (working memory). Taken together, these tasks were thought to provide a good overview of basic cognitive functions important for various aspects of the sports performance. In addition, we also collected subjective data about workload, mood, stress, sleep, and "being in shape". Just like for the EEG data, we expected interactions between assessment sessions and groups with group A showing effects between A1 and A2 not between A2 and A3, and group B between A2 and A3 not between A1 and A2.

Methods

Participants

Two Dutch professional soccer teams participated in the study. The teams were from different clubs and were tested at different locations. One team consisted of 29 women competing at the highest national level, and the other team consisted of 19 males competing at the second national level. Most players were in their twenties, and 90% were right-handed. Ethical and legal considerations prevented us from collecting individual demographic data, motivated by the fact that some of them enjoyed national exposure and because the results of the study could not be shared with the club management at the individual level because this might have consequences for their future. Therefore we did not collect data which might allow them to be traced back to the individual.

Participation was voluntary and the participants were not paid. The study took place during their regular training hours. The data of 7 participants were discarded; 4 because they dropped out of the study or left the club, and 3 because there were technical issues, either in the assessment sessions or in a number of training sessions. The resulting group consisted of 26 females and 15 males, which for the present purposes were treated as a single group of 41 participants.

The study was approved by the Ethics Review Board of the Tilburg School of Social and Behavioral Sciences, ref. EC_TSB_RP770_2301_9306. Data storage and handling conformed to EU privacy regulations (GDPR).

Apparatus

All EEG signals were collected with a BrainBit device (BrainBit Inc., Rancho Santa Margarita, CA, USA), It has the form of a flexible extension band with dry electrodes,

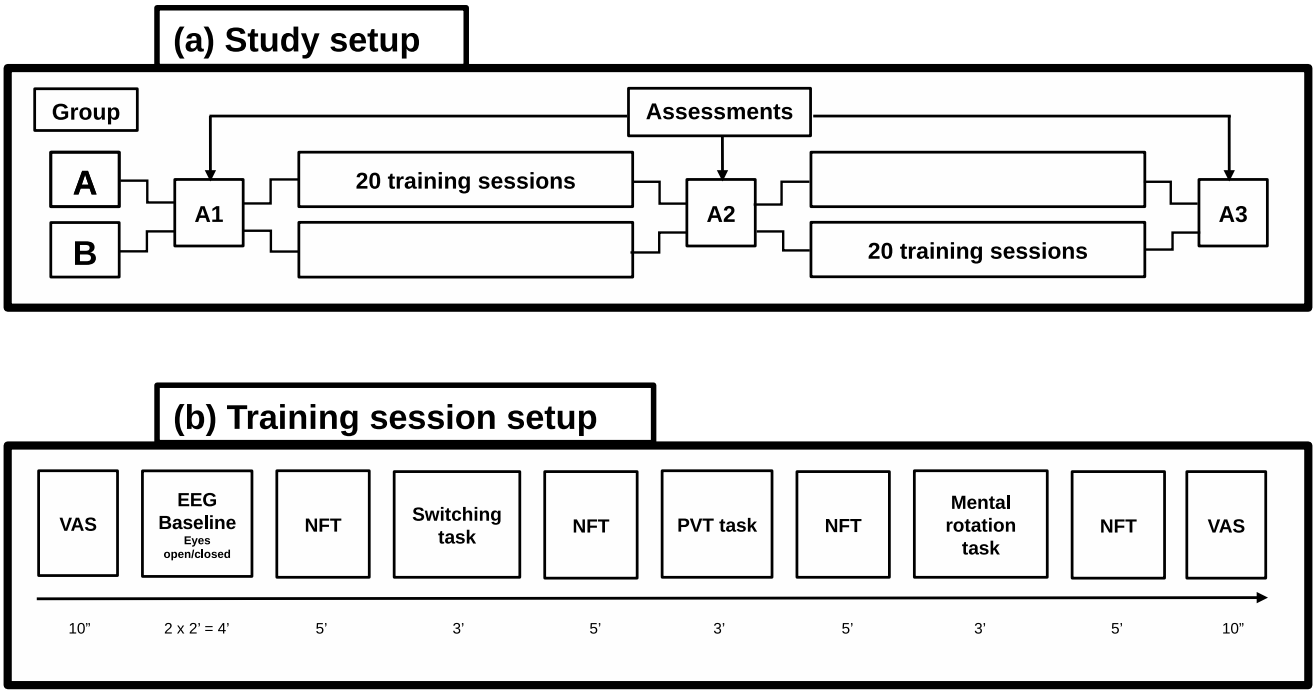

Fig. 1 Study design and setup of a single training session

an integrated electronic module and removable battery. The band is placed horizontally around the head above the ears, so that the electrodes are roughly located above 10–20 positions T3, T4, O1 and O2, all referred to the ground located on the forehead (roughly Fpz). Signals from these electrodes are sampled at a rate of 250 Hz and transmitted via Bluetooth LE to the receiving device (either a laptop or an iPhone—see below). We tested whether the device allowed us to record alpha activity in a similar way to a standard laboratory-style gel-based EEG recording system (Nexus-32F), and found it to be the case.

Design

The study consisted of 20 training sessions for each participant, preferably one session per workday, thus spanning 4 weeks in total. Because of various commitments of the players, in practice the training sessions were spread over a period of about 6 weeks. The training sessions took place in a room at the clubs, in which up to 13 players were present at the same time, right before their field training started. If a player could not be present on a certain day, that training session was not repeated but skipped. Players with less than 15 training sessions were dropped from the study. On average, the players received 19.03 training sessions.

To assess the progress of the training, there were 3 assessment sessions, referred to as A1 to A3. Because the clubs wanted to offer the alpha neurofeedback training to all the players, we used a crossover design. A1 was always organized before the intervention started. In each team, half of the players received the intervention between A1 and A2 (group A), the other half between A2 and A3 (group B). A visual representation of the study design is presented in Fig. 1a.

Assessment Sessions

The assessment sessions took place in a room at the club, containing a big table with a chair for each participant, making it possible to record the session for all participants at the same time. They received a standard 15'' laptop with a screen refresh rate of 60 Hz, and an iPhone, also with a screen refresh rate of 60 Hz. The laptop contained home made software developed in Python to present three cognitive tasks: an N-back task, a stop-signal task, and an Attention Network Task (ANT), always in this order. In addition, the participants also performed one training session with the iPhone app (see below). The total duration of an assessment session was about one hour.

N-back Task (working memory). One out of a set of eight letters (B, F, K, H, M, Q, R, X) was presented centrally on the laptop screen for 500 ms, after which a fixation cross was presented for 1500 ms on average (1250–1750, rectangular distribution). On 50 out of 150 trials (33.3%), a letter was identical to the letter presented two letters before in the sequence. In that case, the participant had to press the 'C' button with their left hand. On the remaining 100 trials,

this was not the case, and the participants had to press the 'M' button with their right hand. On 12.5% of the trials ('lure'), the same letter was presented as the letter 1 or 3 letters before. In case of a correct response, the fixation cross turned green until the start of the next trial. On errors, the cross turned red.

Stop-Signal Task (response inhibition). A green arrow pointing left or right (50/50%) was presented at the center of the laptop screen for 800 ms. The participants were instructed to respond as quickly as possible with the index finger of the hand corresponding to the direction of the arrow by pressing either the 'C' or the 'M' key. On 50 of the 150 trials (33.3%), the arrow turned red for 100 ms, signaling the participants to withhold their response. The interval between the onset of the green arrow and the instant at which it turned red on a stop trial, was determined by a staircase tracking algorithm that started at 250 ms and increased or decreased by 50 ms depending on whether the response was withheld. After the response, a fixation cross was presented at the screen for an average duration of 1200 ms (950–1450 ms, rectangular distribution). Feedback was given when RT on a trial (excluding the first 5) exceeded the 75% percentile over the last 12 trials by showing the word "faster" on the screen. There was also feedback when the participant failed to stop at a stop signal: "STOP at red signal".

ANT Task (attention). The target stimulus in this task was an array of five arrows pointing left or right (50/50%), which remained on the screen for 1700 ms. The participants were instructed to press the button 'C' or 'M' with their left or right hand, respectively, depending on the direction of the central arrow. The arrows flanking the central arrow could either point to the same direction as the central arrow (congruent, 33.3%) to the opposite direction (incongruent, 33.3%), or consist of a simple dash without arrowhead (neutral, 33.3%). The array of arrows was either presented above or below a central fixation cross (50/50%). At 400 ms before the target stimulus, a cue was presented for 100 ms in one of 4 conditions: no cue (cue equaled the fixation cross), central cue (fixation cross replaced by an asterisk), double cue (asterisks above and below the fixation cross), spatial cue (asterisk above or below the fixation cross, depending on where the target stimulus was going to be presented. In total, there were 4 cue types * 3 targets * 2 directions* 2 locations = 48 trial types repeated twice, totaling to 96 trials. The total trial length was 2200 ms, and the inter trial interval was 925 ms on average (325–1525 ms, rectangular distribution), during which the white fixation cross was presented, or a red cross in case of any error.

Questionnaires. The following subjective data were collected using visual-analog sliders on the laptop screen: Workload (NASA-TLX, Hart & Staveland, 1988), Mood (Profile of Mood States, POMS—short version, Shacham, 1983), Stress (Perceived Stress Scale, PSS-10, Cohen et al., 1983), Sleep (Athlete Sleep Screening Questionnaire, ASSQ, Driller et al., 2018), Being in shape (Dekker et al., 2014). The questionnaires were always presented in the same order.

Training Sessions

A visual representation of the contents of a training session is shown in Fig. 1b. The participants used an iPhone with a specially designed app that guided them through the session. An iPhone was given to them in case they did not have a personal one. Each training session started and ended with a visual-analog slider by which the participants indicated their level of drowsiness, relaxation, and boredom (fixed order) on a scale from 0 to 100. The app then continued with the collection of 2 periods of 2 min resting-state EEG, in which the participants were sitting still with eyes open and eyes closed, respectively. This was followed by 4 NFT periods of 5 min each, which were alternated with 3 gamified cognitive tasks that lasted 3 min each; a switching task, a psychomotor vigilance task (PVT), and a mental rotation task, always in the same order. A single training session lasted about 45 min in total. The instructions for the alpha NFT periods was to just "sit back, relax, and listen to the music". For the task periods, the participants were asked to execute the tasks as quickly as accurately as possible. It was possible that the players interacted during the training session, but a test leader was present who intervened when the players did not focus on the session.

EEG alpha training (NFT). The participants listened to their own favorite music that they selected before the start of the study, using earplugs or headphones. The music was passed through a high-pass filter that removed the low frequencies in the music based on the EEG alpha level of the brain signals. The lower the level of alpha activity, the more low frequencies were filtered out. This made the music sound distant and superficial if the alpha level was low, versus and full and rich when the alpha level was high, thus providing an intuitive feedback on the EEG alpha level based on the quality of the music. The procedure was similar to that described in our previous work (Van Boxtel et al., 2012). More specifically, five times per second (each 200 ms) a segment of the preceding 4 s of EEG data was filtered by fifth-order Butterworth filters at 1 Hz high-pass and 65 Hz low-pass, and a second-order notch filter at 50 Hz. To be usable for a feedback update, this segment should fulfil three criteria: (i) no clipping or overflow of the amplifier; (ii) peak-to-peak of at most 200 µV; (iii) the ratio between the line noise (49–51 Hz) and EEG power (4–30 Hz) should be smaller than 1.0.for each electrode. The relative alpha power was then calculated as the sum of the power in the alpha band (7.7–12.3 Hz), divided by the sum of the power in the beta

band total power (14.7–25.3 Hz). If both electrodes showed a good epoch of 4 s, then the average of the two electrodes was used. If only one electrode yielded a good epoch, then only that channel was used. If neither electrode resulted in a good epoch, then no feedback update was given. The relative alpha measure was filtered by a first-order IIR filter with a time constant of 4 s. In this way, the speed of the changes in the feedback was smoothed somewhat, and did not go back and forth too quickly. The feedback measure was used to drive the cut-off frequency of a first-order high-pass filter built into the audio path of the music played through the headphones. This cut-off frequency equaled 2 Hz if the current alpha level was greater than the maximum alpha level for the previous part, and 1500 Hz if the current alpha level was lower than the minimum alpha level for the previous part. For intermediate levels, a linear interpolation was done in such a way that the cut-off frequency was high for low current alpha levels and low for high alpha levels.

Switching Task. The gamified switching task, called "deluge of dice" is played on the iPhone. A die containing 1 to 6 dots is displayed either at the top or at the bottom of the screen (50/50%, 30% switches, 15% top–bottom and 15% bottom-top). The die could appear outlined or solid (50/50%). If it appeared on the top, the participants had to ignore the number of dots and respond with the left or the right hand, according to whether the die was outlined or filled, respectively. If it appeared on the bottom, they had to ignore the form and respond to the number of dots; left for 1 to 3 dots, right for 4 to 6 dots. A die was presented every 2000 ms on average (1750–2250 ms, rectangular distribution), and stayed on the screen during the whole trial period. When a response was given, the color of the dice turned green or red, depending on whether the response was correct or not. The task was stopped after 3 min, during which approximately ninety trials were administered on average.

PVT Task. The gamified psychomotor vigilance task, called "react-o-matic", was a simple reaction time task focused on response speed. A white outline of a circle filled with black (background) was shown on the screen, which required to be responded to as soon as its center became filled with white. At that same instant a black outlined circle started to grow from the inside out, on the now white background, which stopped as soon as a button at the bottom of the screen was pressed. This gave intuitive feedback about response speed. The actual reaction time value in milliseconds was also displayed on the screen as soon the response was given, or the words "too early" or "too slow" on premature reactions and timeouts, respectively. Half of the trials were presented with a short interval (2–5 s, rectangular distribution); the other half with a long interval (5–10 s, linearly descending distribution). Again, this task lasted 3 min, during which an average total of 30 trials were administered.

Mental Rotation. The gamified mental rotation task was called "typo trap", and involved the display of one out of four numbers, 2, 4, 5, or 7, for a duration of 300 ms. The numbers were randomly rotated around the Y-axis of a coordinate system, in steps of 30 degrees. On half of the trials, the letter was mirrored, and this was integrated with the rotation. The task of the participants was to indicate whether the number was mirrored (press left button) or not (press right button). The degree of rotation was to be ignored. If a correct response was given, the number reappeared in the color green, otherwise it reappeared in red. In the 3 min task period, an average total of 96 trials were administered at a pace of 1875 ms (1625–2125 ms, rectangular distribution).

Data Processing

EEG data. The EEG data were subjected to extensive data preprocessing. This was needed because of the large between- and within-subject variability caused by the field conditions under which the experiment was carried out. We used a Welch spectrum with segments of 4 s and 75% overlap. Before the transformation into the frequency domain, we first computed, for each segment and electrode montage, the difference between the maximum and minimum EEG amplitude in that segment. All segments for a specific task in each assessment session and for each electrode montage were then modeled by an exponential distribution, and only those segments within the 95% confidence interval were selected for further processing and transformation into the frequency domain.

This procedure resulted in loss of data, ranging across participants from 12 to 68%. On average, there was 32% data loss (median 31%), slightly more in the left electrode montage T3–O1 then in the right T4–O2, 33% vs 31%. The data loss consisted of lost data packages in the Bluetooth transmission between the EEG device and the app or laptop, as well as discarded segments because of movement-related or other artifacts detected.

The accepted 4-s segments were band-pass filtered using a first-order Butterworth filter, tapered using a Hamming window, and then transformed into the frequency domain by FFT. The transformed segments were then averaged to obtain the Welch spectrum. The average power (log10 transformed squared magnitude) in the alpha band (7.7–12.3 Hz) was normalized by the power in the beta band (14.7–25.3 Hz) to obtain more stable spectra. This was done because we wanted to remain as close as possible to the way the neurofeedback training was administered. We refer to this activity as 'normalized alpha'. To disentangle alpha from beta activity, we used Principal Components Analysis (PCA) on the frequency spectra using the covariance matrix and Varimax rotation to simple structure. The Scree plot was used to determine how many components to extract, and the

component scores for those components were then analyzed in the same way as the raw power values. PCA was used instead of further analyses of raw alpha and beta power, because it indicates which frequency bands are best used based on the variance in the experimental data, rather than using predefined bands, and has the additional advantage of normalizing the power.

Cognitive tasks. An exGaussian model was used to fit reaction times to the cognitive tasks. It consists of a Gaussian distribution with parameters μ and σ, representing the mean and standard-deviation of a normal distribution, overlapped with an exponential distribution with parameter τ, which models the variability in the right-hand tail of the RT distribution.

Statistical Analysis

All analyses were done by linear mixed-effects models with restricted maximum likelihood estimation, using the Satterthwaite method to estimate the degrees of freedom needed for calculating p-values. Focus was on the interaction between Assessment Session and Group. In case of statistically reliable interactions, simple effects were calculated for further exploration.

Results

EEG Data

Resting state. Averaged spectra in eyes open and eyes closed resting state conditions in the assessment session A1, are presented in Fig. 2, separately for the two montages T3–O1 and T4–O2. As can be seen in Fig. 2, the spectra have the characteristic property that power diminishes with increasing frequency (1 / f ratio). A prominent alpha power peak is also clearly present in the 8–12 Hz range, which is also characteristic for EEG power spectra. As expected, normalized alpha power was greater in eyes closed compared to eyes open conditions ($F(1, 111.22) = 160.91$, $p < 0.001$), and did not differ between the montages ($F(1, 110.50) = 0.01$). The Scree plot of the PCA on these spectra suggested extracting and rotating 3 components, explaining 92% of the variance. The second extracted component, which explained 20% of the variance, showed loading with a maximum around 10 Hz, and its scores showed that it was greater in the eyes closed compared to the eyes open situation ($F(1, 113.05) = 8.93$, $p < 0.01$). It could therefore be identified as an "alpha" component. The other two rotated components did not show any effects. The results of the PCA thus corroborated the analyses on the raw data.

Taken together, these results show that it is possible to reliably record EEG using a wireless device with a Bluetooth connection, from up to 13 participants at the same time. The normalized alpha power in the eyes closed resting state condition was greater than the alpha power recorded during eyes open.

Neurofeedback and task periods. Normalized alpha power in the periods of neurofeedback and cognitive tasks, averaged over the two montages and the three assessment sessions, are depicted in Fig. 3. It can be seen that it was greater in the neurofeedback periods compared to the task periods ($F(1, 1344.3) = 124.54$, $p < 0.001$). The PCA on the raw spectra resulted in the extraction of separable alpha and beta components, explaining 21% and 52% of the total variance, respectively (see Fig. 5). Analyses of the scores of these extracted components revealed that beta power was greater in the task periods compared to the neurofeedback periods ($F(1, 1343.6) = 130.77$, $p < 0.001$), but alpha power was not statistically separable between neurofeedback and task

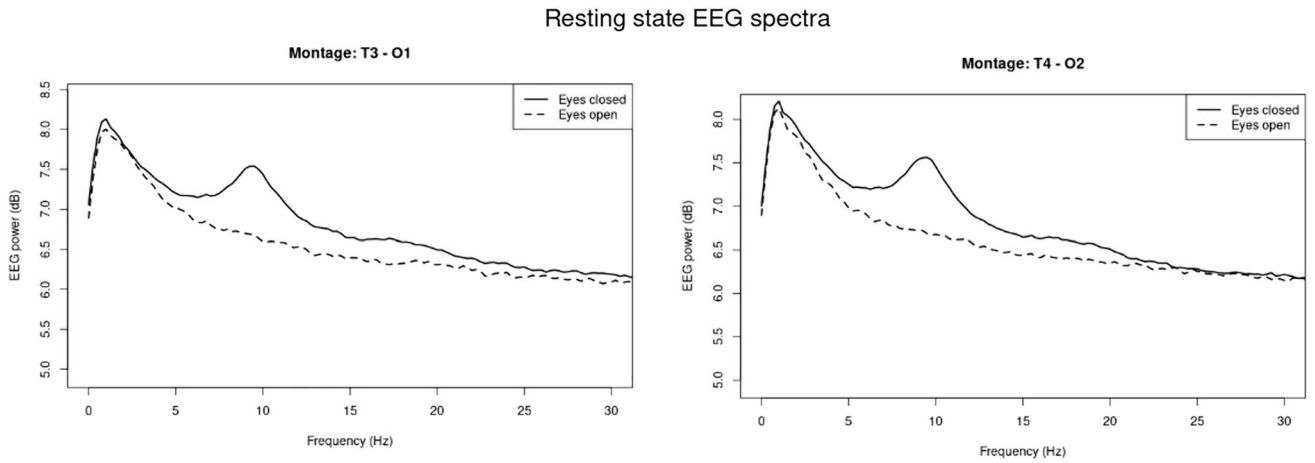

Fig. 2 Spectra of eyes open and closed resting state epochs at session A1

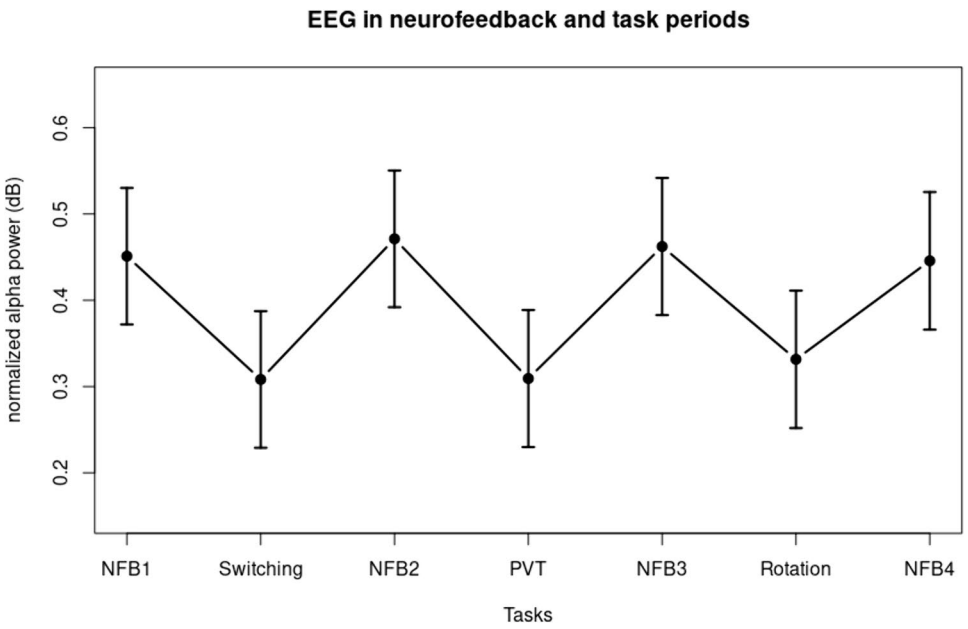

Fig. 3 EEG in neurofeedback and task periods, averaged over assessment sessions and montages

periods ((1, 1344.4) = 0.15, n.s.). In other words, the effect observed in Fig. 3 was due to beta power, not alpha power.

Turning now to the changes of EEG power over the three assessment sessions, we found that normalized alpha power increased over the sessions by 34.3%, from 0.35 in A1 to 0.47 in A3 ($F(2, 1349.77) = 22.84$, $p < 0.001$). Although there was no overall difference between the two groups ($F(1, 39.17) = 0.03$, n.s.), there was an interaction between assessment sessions and groups ($F(2, 1349.77) = 15.88$, $p < 0.001$). The estimated marginal means of this interaction are displayed in Fig. 4. Simple effects confirmed the pattern that can be observed in the figure that normalized alpha power increased as a result of the neurofeedback training, that is, for group A between A1 and A2 ($F(1, 503.99) = 27.16$, $p < 0.001$) not between A2 and A3 ($F(1, 451.42) = 0.46$, n.s.), and for group B between A2 and A3 ($F(1, 426.32) = 48.45$, $p < 0.001$) not between A1 and A2 ($F(1, 467.36) = 1.63$, n.s.).

The results of the PCA (Fig. 5) confirmed these findings. The Scree plot suggested extracting 3 components, together explaining 92% of the variance. For the alpha component (21% of variance), there was an overall increase over assessment sessions ($F(2, 1348.17) = 25.33$, $p < 0.001$). The increase occurred between A1 and A2 for group A, and between A2 and A3 for group B ($F(2, 1348.17) = 22.34$, $p < 0.001$). The beta component (52% of variance) decreased over assessment sessions

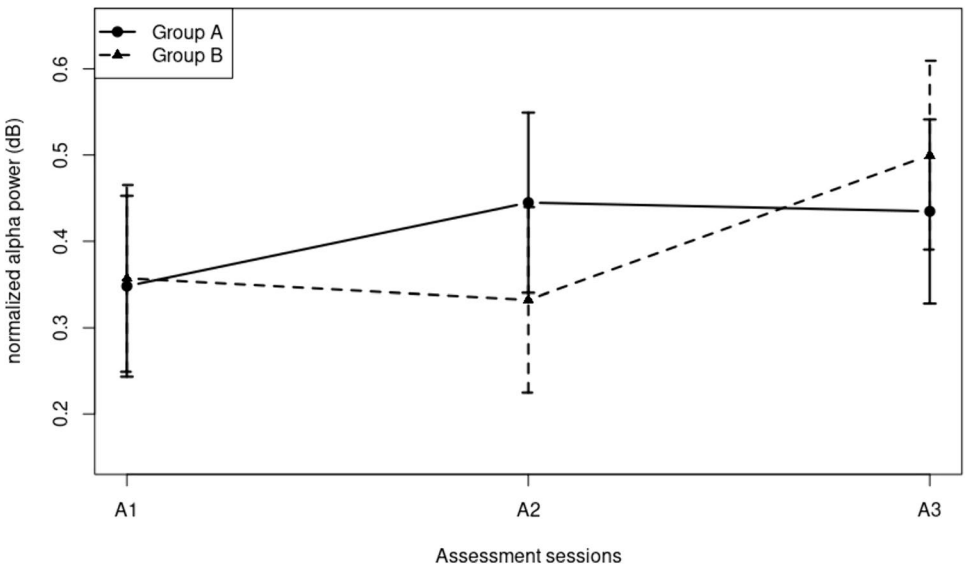

Fig. 4 Alpha power averaged over montages, by assessment sessions, separately for the groups

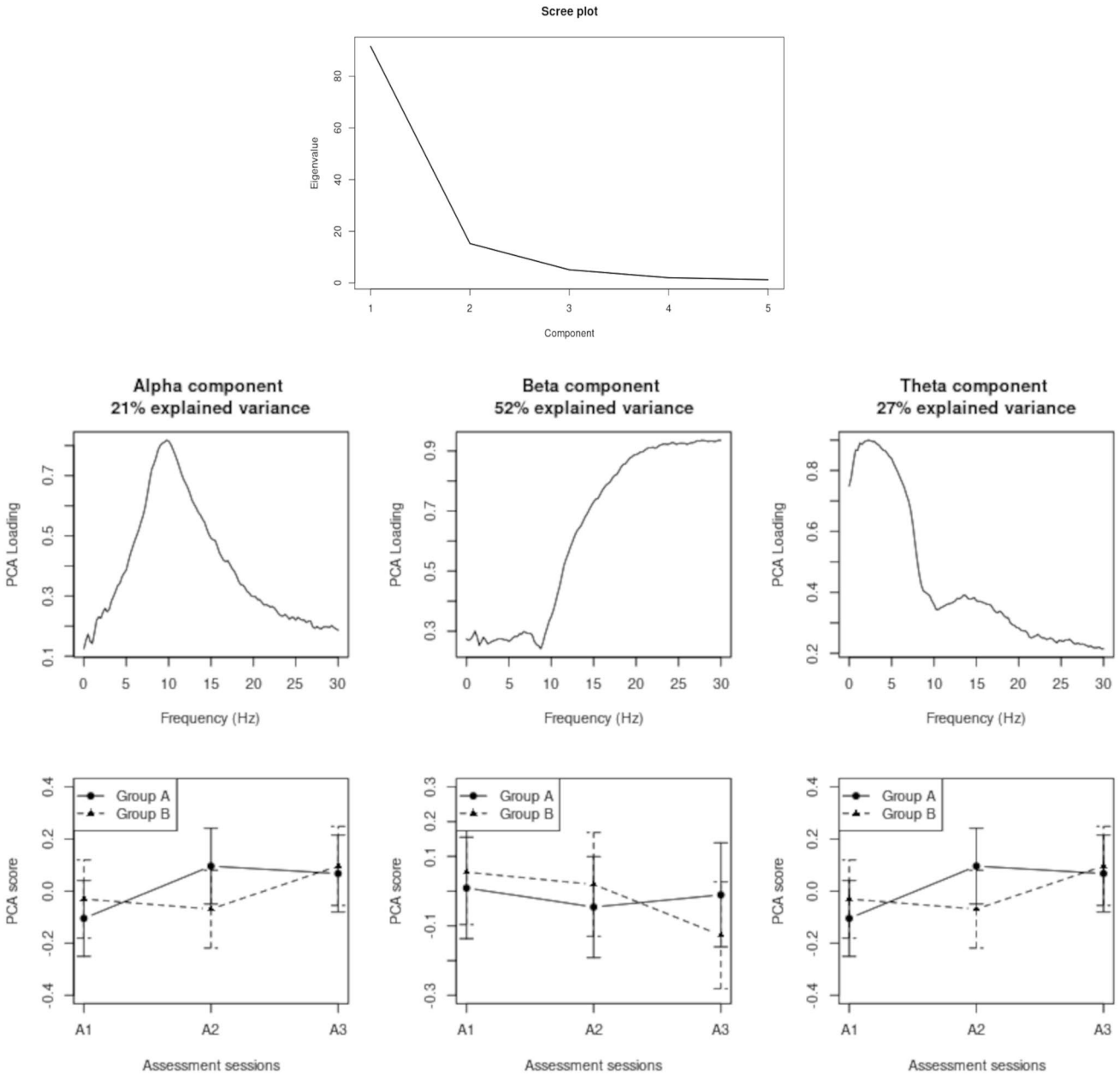

Fig. 5 PCA component loadings for alpha, beta, and theta activity, and their effect on the component scores

(F(2, 1352.76) = 6.13, p < 0.01); the decrease occurred between A2 and A3 for group B not for group A (F(2, 1352.76) = 5.80, p < 0.01). The PCA also resulted in component with high loading in the theta range, explaining 27% of the variance. The analysis of the scores of this component resembled that of the alpha component, with an overall increase over assessment sessions (F(2, 1353,92) = 25.66, p < 0.001), which occurred between A1 and A2 for group A and between A2 and A3 for group B (F(2, 1353.92) = 4.45, p < 0.05).

Behavioral Data

Cognitive tasks. An overview of the results obtained from the cognitive tasks is presented in Table 1. The most important effect for all tasks was the interaction between Group and Assessment Session, which is highlighted in the table. Plots of the estimated marginal means involved in this interaction is presented as supplementary information S1. It can be seen in the table that performance was fast and accurate, and that there were clear learning effects (main effects of

Table 1 Results of performance on cognitive tasks

(a) N-back task

	RT μ		RT σ		RT τ		Prop. correct	
	df	*F*	*df*	*F*	*df*	*F*	*df*	*F*
Session	2, 62.700	4.6592*	2, 65.414	6.2222**	2, 63.108	3.7897*	2, 54.811	7.6989**
Group	1, 37.684	1.6834	1, 38.088	0.6081	1, 35.826	0.0918	1, 29.830	1.1845
Session* Group	2, 62.700	1.0550	2, 65.414	1.9360	2, 63.108	0.1677	2, 54.811	1.2767

(b) Stop-signal task

	Go RT μ		Go RT σ		Go RT τ		SSRT	
	df	*F*	*df*	*F*	*df*	*F*	*df*	*F*
Session	2, 64.496	5.8137***	2, 66.803	7.8580***	2, 60.490	12.8062***	2, 55.436	33.710*
Group	1, 38.791	20.5501***	1, 39.495	7.0759*	1, 30.024	6.2112*	1, 28.389	0.0216
Session* Group	2, 64.496	0.7594	2, 66.803	1.0272	2, 60.490	0.1884	2, 55.436	2.5278

(c) ANT task

	RT μ		RT σ		RT τ		Prop. correct	
	df	F	df	F	df	F	df	F
Session	2, 294.497	4.9744**	2, 294.080	0.3649	2, 295.200	0.6383	2, 294.799	10.3960***
Group	1, 37.267	0.8580	1, 36.106	0.0041	1, 36.221	0.0078	1, 39.152	3.3395
Target	2, 289.198	21.5396***	2, 287.946	0.8071	2, 288.149	0.6444	2, 291.107	258.5536***
Session * Group	2, 294.497	1.0648	2, 294.080	0.6253	2, 295.200	1.2586	2, 294.799	1.5902
Session * Target	2, 289.198	0.2653	4, 287.946	0.1573	4, 288.149	0.3788	4, 291.107	5.0692***
Group * Target	2, 289.198	0.0622	2, 287.946	0.2568	2, 288.149	0.2055	2, 291.107	7.0791***
Session * Group * Target	4, 289.198	0.9478	4, 287.946	0.3217	4, 288.149	0.7813	4, 291.107	0.4749

(d) Switching task

	RT μ		RT σ		RT τ		Prop. correct		Swiching costs	
	df	*F*	*df*	*F*	*df*	*F*	*df*	*F*	*df*	*F*
Session	2, 370.62	66.0476***	2, 373.43	45.9709***	2, 376.81	37.5947***	2, 375.43	11.6701***	2, 380.63	2.5636
Group	1, 34.14	1.2220	1, 34.21	0.8484	1, 35.02	6.1285*	1, 35.51	3.8943	1, 32.91	1.2846
	1, 368.10	331.4338***	1, 368.20	33.1599***	1, 369.13	12.0706***	1, 369.53	21.2978***		
Session * Group	2, 370.62	12.0847***	2, 373.43	8.2721***	2, 376.81	15.2115***	2, 375.43	34.5260***	2, 380.63	1.0431
Session * Switch	2, 368.10	0.6908	2, 368.20	1.9718	2, 369.13	0.9582	2, 369.53	3.4716		
Group * Switch	1, 368.10	1.2405	1, 368.20	5.1042*	1, 369.13	0.1743	1, 369.53	0.3480		
Session * Group * Switch	2, 368.10	0.4775	2, 368.20	2.5510	2, 369.13	0.3317	2, 369.53	0.5079		

(e) Psychomotor vigilance task

	RT μ		RT σ		RT τ		Prop. correct	
	df	*F*	*df*	*F*	*df*	*F*	*df*	*F*
Session	2, 301.550	0.3517	2, 314.857	3.1880*	2, 317.95	2.6845	2, 65.606	3.7857*
Group	1, 38.939	1.2413	1, 27.305	4.6336*	1, 33.49	8.1684**	1, 33.945	1.1632
Session* Group	2, 301.550	0.8615	2, 314.857	1.1405	2, 317.95	1.2703	2, 65.606	1.9489

(f) Mental rotation task

	RT μ		RT σ		RT τ		Prop. correct	
	df	*F*	*df*	*F*	*df*	*F*	*df*	*F*
Session	2, 176.842	2.3181	2, 173.606	5.8988**	2, 175.51	4.1685*	2, 64.949	15.6035***
Group	1, 36.684	0.8826	1, 29.839	3.7076	1, 29.51	8.5135**	1, 34.862	2.9488

Table 1 (continued)

(f) Mental rotation task

	RT μ		RT σ		RT τ		Prop. correct	
	df	*F*	*df*	*F*	*df*	*F*	*df*	*F*
Session* Group	2, 176.842	2.6557	2, 173.606	2.1072	2, 175.51	2.2231	2, 64.949	9.5638***

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

assessment sessions). The interactions between groups and assessment sessions were observed for the switching and the mental rotation tasks, and the means involved in these effects showed that learning was indeed enhanced between A1 and A2 for group A, and between A2 and A3 for group B. Importantly, the estimated marginal means involved in these effects (S1) showed a similar pattern as normalized alpha activity (Fig. 4) and the PCA alpha component, not the PCA beta component (Fig. 5).

Questionnaires. An overview of the results obtained from the subjective questionnaires is presented in Table 2. The most important effect for all questionnaires was the interaction between Group and Assessment Session, which is highlighted in the table. Plots of the estimated marginal means involved in this interaction is presented in the supplementary information S2. There were no main effects of assessment sessions and groups. Interactions between these two factors were observed for the sleep duration question from the ASSQ, and for the 'feeling on control' and 'flow' variables of the Being in Shape questionnaire.

Discussion

The aim of this study was to investigate if EEG alpha activity could be increased in elite athletes who, in a groups of participants simultaneously received neurofeedback training with a modern wireless EEG recording device. In addition, we wanted to investigate if the increase in EEG alpha activity would improve cognitive performance as well as subjective experience of well-being, such as mood and sleep.

The first question was whether it was possible to reliably record EEG alpha activity simultaneously in groups of participants using a wireless device. This turned out to be possible. We also showed that it was possible to do so in groups of up to 13 people at the same time. There was approximately 30% data loss due to the simultaneous recordings (lost data packages) and the field conditions outside of a standard EEG laboratory. This was higher than normally observed in a standard laboratory using gel-based wired EEG equipment, where 10–15% data loss is usually expected. It is good to realize that these types of experiments will result in a higher than expected data loss, but otherwise excluding data segments with lost data packages and other artifacts did result in EEG power spectra as they can usually be observed. The spectra had the characteristic feature that power decreases with increasing frequency. The spectra also exhibited a clear alpha power peak in the 8–12 Hz range, which was greater with eyes closed compared to eyes open. These two phenomena together are the defining characteristics of EEG spectra, and it is therefore safe to conclude that our setup with simultaneous recordings using a wireless device was successful. In addition, the result of the PCA, corroborated and strengthened this conclusion.

We used a specific device for our study, but it can be expected that similar devices on the market will produce similar results. Websites of companies that sell those products often do show EEG spectra similar to what we reported here, but to our knowledge, we are the first to demonstrate the use of such equipment simultaneously in larger groups. This makes it possible to do this type of research in teams, which is advantageous for team spirit, and also reduces research time considerably, because the recordings do not need to be done serially.

The second question concerned the nature of our training setup with alternating epochs of neurofeedback training and cognitive tasks. The setup was chosen to keep the participants alert by not using too long periods of sitting still and listening to music, while at the same time collecting data about cognitive performance during various tasks. We predicted that neurofeedback training periods would show greater alpha activity compared to epochs during which the participants performed cognitive tasks. In addition, due to the fixed alternating order, we predicted that a 'saw-tooth' pattern would be visible. The first impression was that this indeed seemed to be the case, based on our definition of alpha activity. Both the saw-tooth pattern was found, and alpha activity in the average of all neurofeedback training epochs, compared to the average of the cognitive task epochs, was also different in a statistically reliable way.

However, our definition of alpha activity was based on alpha power normalized by beta power. This was done to make the spectra more comparable between participants and sessions, but also begged the question whether the saw-tooth pattern was the result of changes in alpha activity or of mirrored changes in beta activity. Alpha activity was expected to be high in neurofeedback epochs and low in task epochs, but the reverse could be expected for beta activity. Taking

Table 2 Result of subjective questionnaires

	Session		Group		Session * Group	
	df	*F*	*df*	*F*	*df*	*F*
(a) Workload (NASA-TLX)						
Mental Demand	2, 73.053	0.4609	1, 39.787	0.5268	2, 73.053	0.4552
Physical Demand	2, 71.559	2.4707	1, 38.524	1.4259	2, 71.559	1.6325
Temporal Demand	2, 72.562	0.6899	1, 39.293	0.0023	2, 72.562	0.4053
Performance	2, 75.191	0.3407	1, 40.346	1.5761	2, 75.191	1.2586
Effort	2, 74.016	4.0898*	1,40.288	3.3624	2, 74.016	0.0299
Frustration	2, 72.331	0.5586	1, 39.174	0.1406	2, 72.331	0.3071
(b) Mood (POMS)						
Tension/Anxiety	2, 73.286	0.6755	1, 39.683	0.7638	2, 73.286	0.3560
Anger/Hostility	2, 74.056	0.2580	1, 40.251	0.2284	2, 74.056	0.0992
Vigor/Activity	2, 72.425	2.7084	1, 38.525	0.2140	2, 72.425	1.3437
Fatigue/Inertia	2, 74.090	5.8872**	1, 39.227	1.9509	2, 74.090	1.8551
Depression/Dejection	2, 73.008	0.2216	1, 39.283	0.1671	2, 73.008	1.2117
(c) Stress (PSS-10)						
Perceived helpnessness	2, 72.436	0.5195	1, 39.607	0.0050	2, 72.436	0.8018
Lack of self-efficacy	2, 72.510	1.0156	1, 39.200	0.4261	2, 72.510	0.5153
(d) Sleep (ASSQ)						
Sleep duration	2, 72.733	1.1716	1, 39.617	0.0005	2, 72.733	4.7522*
Time to fall asleep	2, 71.703	1.6051	1, 39.259	0.1931	2, 71.703	2.0861
Sleep satisfaction	2, 73.903	1.4633	1, 39.869	0.3940	2, 73.903	0.0705
(f) Being in shape						
Physical shape	2, 74.058	0.0633	1, 39.519	0.3661	2, 74.058	1.5271
Ability to recover	2, 73.230	0.3892	1, 39.569	1.1374	2, 73.230	1.6739
Feeling of control	2, 72.052	1.2522	1, 38.721	0.0014	2, 72.052	3.3413*
Mental balance	2, 74.270	2.5148	1, 39.831	0.1535	2, 74.270	1.4458
Confidence	2, 71.821	0.4413	1, 39.016	0.0168	2, 71.821	1.2661
Committment	2, 71.765	1.6611	1, 37.745	0.0002	2, 71.765	0.1929
Focus	2, 71.549	4.2797*	1, 37.676	0.1074	2, 71.549	0.0958
I rritation	2, 73.887	0.1098	1, 39.553	1.3433	2, 73.887	0.8397
External factors affecting performance	2, 74.335	0.4917	1, 39.987	0.6506	2, 74.335	0.0991
Mental shape	2, 74.139	0.7572	1, 40.065	0.6730	2, 74.139	1.4998
Ability to suppress distraction	2, 73.898	1.2805	1, 38.826	0.2433	2, 73.898	0.4439
Flow	2, 73.506	0.6051	1, 40.094	1.1303	2, 73.506	4.1830*
Resilience to stress	2, 72.016	1.8746	1, 38.514	0.1901	2, 72.016	0.0047
Ability to follow instructions	2, 71.865	3.8924*	1, 38.625	3.9460	2, 71.865	0.9186
Ability to collaborate with others	2, 70.367	0.5452	1, 36.667	0.3671	2, 70.367	0.1238
(f) Visual-analog scale, post-pre						
Drowsiness	2, 72.695	0.8315	1, 39.969	3.7039	2, 72.695	1.6026
Relaxation	2, 68.082	0.4965	1, 37.735	0.7611	2, 68.082	0.8710
Boredom	2, 72.337	1.5537	1, 39.716	0.4127	2, 72.337	0.5316

the alpha / beta ratio could then be the result of changes in alpha, changes in beta, or a combination of the two. We tried to disentangle the two using PCA, and found a clear saw-tooth pattern for the component reflecting beta activity, and a much less clear pattern for the component interpreted as reflecting alpha activity. The scores associated with the extracted component with loading in the beta range were greater for the task periods compared to the neurofeedback training periods, whereas the alpha component's scores did not differ between epochs. Therefore, the conclusion seems warranted that the saw-tooth pattern was mainly the result of changes in beta not alpha activity.

The third hypothesis concerned the question whether alpha activity would increase as a result of the training. Given the cross-over design that was used, this would imply that alpha activity would always increase between

the assessment sessions during which the training was administered, not between the assessment sessions during which there was no training (treatment as usual). This was exactly what we found. For the group that received the training between the first and second assessment sessions, the increase in alpha activity occurred between those two sessions not between the second and third session. For the group that received the training between the second and third assessment sessions, there was no increase between the first and second sessions, but between the second and third. Both groups reached the same level of alpha activity at the third assessment session. The results of the PCA alpha component exactly showed the same pattern of results. Using two different methods of analysis that arrive at the same conclusions enhances the validity of those conclusions. Interestingly, the PCA beta component showed decreases in the same training periods in which the alpha component increased. Together these components produce the results found in global alpha activity scores as defined. In addition, it can also be concluded that the neurofeedback training increased alpha activity while at the same time decreasing beta activity.

The increase in alpha activity was approximately one-third of baseline levels. Given the present design, it is unsure whether this increase resulted from the neurofeedback training itself, from sitting still and listening to music during the training, from both, or from other aspects of the study. The reason is that we did not include control conditions in the study setup, because the clubs wanted to offer the training to all players without making a group who received no training or another intervention. However, in our previous work (Van Boxtel et al., 2012) we used three groups. One group received genuine alpha activity training, much the same as in the present work. Another group received beta activity training in 4 Hz bands that were different in every training session, and, interestingly, a third group just sat still and listened to their favorite music. The increase in alpha activity in the real alpha training group was very similar to what we found in the present work (33%), but the increase in the music only group was quite small, about 5%. This shows that the increase was at least partly due to the neurofeedback training.

It is difficult to compare the present findings to other studies, because of the many differences between studies in electrode location, training protocol, control groups, etc. Several studies suggest that our findings are reasonably comparable to what others have found, though. For instance, Cho et al (2008) reported an increase of up to 50% in alpha activity level over 11 training sessions of 17.5 min each. More recently, Su et al. (2021) reported an increase of about 40% over 12 sessions of 6 min each, and Shen et al. (2023) found an increase of 13% over 5 sessions of 25 min each. All in all, it seems safe to conclude that the present setup using simultaneous auditory neurofeedback training in groups of elite athletes using a wireless EEG device, was successful in increasing EEG alpha activity.

The next question then is if the increase in EEG alpha activity has effects on the cognitive behavior and sense of well-being of the athletes. Judging from the subjective data as measured by the questionnaires and slider scales, these effects are limited, if they exist at all. Self-reported sleep duration and fatigue increased slightly, and the amount of effort invested in the tasks decreased, but none of these effects could be related to the phases of the training. Therefore these were just overall effects of the training program as a whole. A possibly interesting effect that was specific for the groups and the assessment session, were the questions about "feeling in control" and "being in a flow" of the Being in Shape questionnaire, but these interactions were not entirely consistent and the psychometric properties of that questionnaire are unknown. The visual sliders used before and after each individual training session resulted in more consistent findings. It appeared that the athletes found the training to be relaxing, but also not very challenging, perhaps reflecting the fact that the training sessions were organized just before their regular training when the players were eager to go out onto the pitch. Moreover, relating subjective data to neurofeedback training is often found to be very difficult because of the fact that people interpret questions in different ways and there is little standardization.

As to the cognitive tasks, performance improved over the assessment sessions. For most tasks, mean and variability of response times decreased and accuracy increased as a result of training. For the relatively basic cognitive processes, such as working memory, psychomotor vigilance, response inhibition, and attention, the training effects did not depend on the instant at which the intervention was given. By contrast, the higher cognitive processes of task switching and mental rotation did show those effects. It is striking that these more difficult tasks show effects of neurofeedback training in this group, because these are preeminently cognitive processes that are necessary to achieve good performance on the field in a team sport. It is quite difficult to interpret the current results in terms of the existing literature in this area, especially specifically for sports, because there are large differences in the tasks used, the brain rhythms trained, the electrode positions, etc. It is very well possible that neurofeedback training outside of the alpha range works well for improving response speed on relatively simple cognitive tasks (e.g., Brito et al., 2022), and that higher cognitive processes mostly benefit from enhancing alpha rhythms, as suggested by the present work (see also Takabatake et al., 2021). Here we did find that the effects in the switching and mental rotation tasks resembled the effects of alpha activity more than beta activity, but perhaps the relationship is too uncertain to draw definitive conclusions. This is an interesting line of research for future work, in which individual differences in trainability of both brain rhythms and cognitive tasks can be taken into account.

Taken together, the results of this study show that it is feasible to conduct neurofeedback training in groups as opposed to individually, using a wireless device which is easy to set up. This implies that neurofeedback studies can be made much more (cost) efficient compared to individual training sessions, which is likely to stimulate the application of this type of research for team sports.

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Author Contributions G.B. wrote the main manuscript text. All authors contributed to the study design, the data collection, and the analyses of the results. All authors reviewed the manuscript.

Data Availability The participants of this study did not give written consent for their data to be shared publicly, so due to the sensitive nature of the research supporting data is not available..

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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ARTICLES FOR FACULTY MEMBERS

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RESEARCH

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Counteracting mental fatigue for athletes: a systematic review of the interventions

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Abstract

The deleterious effects of mental fatigue (MF) on athletes have been carefully studied in various sports, such as soccer, badminton, and swimming. Even though many researchers have sought ways to ameliorate the negative impact of MF, there is still a lack of studies that review the interventions used to counteract MF among athletes. This review aims to report the current evidence exploring the effects of interventions on MF and sport-specific performance, including sport-specific motor performance and perceptual-cognitive skills. Web of Science, Scopus, PubMed, and SPORTDicus (EBSCOhost) were combed through to find relevant publications. Additionally, the references and Google Scholar were searched for any grey literature. For the current review, we included only randomized controlled trials that involved athletes, a primary task to induce MF, interventions to counter MF with comparable protocols, and the outcomes of sport-specific motor performance and perceptual-cognitive skill. The selection criteria resulted in the inclusion of 10 articles. The manipulations of autonomous self-control exertion, person-fit, nature exposure, mindfulness, and transactional direct current stimulation showed that positive interventions counteract MF and improve sport-specific performance in different domains, including strength, speed, skill, stamina, and perceptual-cognitive skills. The selected interventions could significantly counteract MF and improve subsequent sport-specific performance. Moreover, self-regulation and attention resources showed the importance of the potential mechanisms behind the relevant interventions.

Keywords Motor performance, Perceptual-cognitive skill, Attention resources, Self-regulation, Intervention

Introduction

In recent years, MF has emerged as a factor affecting sport-specific performance, distinct from the more conventional phenomenon of "physical fatigue" [1, 2]. A psychobiological syndrome caused by extended cognitive effort, MF is characterized by sensations of "fatigue" and "loss of energy" [3, 4]. One of the initial studies found MF to have negative effects on endurance [4]. Since then, the impairment of a variety of motor performance skills has been detected in athletes, such as intermittent endurance [5] and passing skill in soccer [5, 6]; visuomotor skill in basketball [7]; goal kicking skill in Australian football [8]; and 1500-m swimming performance [9]. MF specifically impairs athletes' capacity to sustain performance during high-intensity periods, which is critical in scenarios requiring intermittent endurance, as demonstrated by the Yo-Yo Intermittent Recovery Test [5]. This form of fatigue causes a subjective amplification of perceived exertion, making physical tasks appear more difficult than they are [5, 9, 10]. Consequently, players

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may experience significant difficulties exerting effort during sprints. Moreover, MF has a detrimental effect on a player's cognitive functions, prominently reflected in prolonged reaction times and reduced decision-making efficiency [10, 11]. Such cognitive impairments can lead to decreased accuracy in both passes and shoots [6], consequently affecting the overall performance and strategic implementation within the game context.

Besides motor performance, some studies such as Fortes, Lima-Junior [12], Fortes, Lima-Junior [13], Gantois, Ferreira [14] have argued that the perceptual-cognitive skill (e.g., decision-making) is significantly influenced in MF. Specifically, perceptual-cognitive skill is the capacity to extract relevant clues and combine them with available knowledge to respond properly [15]. Accordingly, any deviation from an optimal perceptual-cognitive skill could have significant consequences for game outcomes [16].

Notably, MF induces an abnormal increase in rating perception of effort (RPE) proposed in the psychological model of exercise [17]. It indicates that MF influences the concentration of adenosine with the activation of the anterior cingulate cortex (ACC) and a corresponding decrease in dopamine [3, 18]. This proposition has been confirmed in an experiment related to sport-specific performance (e.g., intermittent stamina) [19]. Conversely, the application of transcranial direct current stimulation (tDCS) has been shown to have the ability to hinder the advancement of RPE during performance tasks (e.g., endurance) [20]. Therefore, tDCS has received scholarly attention as a potential method for reducing MF effects and improving performance in the sports context [21–23]. However, the existing literature portrays a varied array of results regarding this issue. Penna, Filho [23] found no statistically significant changes in completion time during an 800 m swimming trial after administering tDCS, whereas Nikooharf Salehi, Jaydari Fard [21] observed positive results in mitigating the negative effects of MF in a 50 m swimming task. Given the contrasting viewpoints, there is a need to conduct a comprehensive review that aims to clarify and integrate the available information regarding the effectiveness of these interventions.

In addition, a potential extension for the model is proposed by a recent study [24]. Due to the different mechanisms of the components of sport-specific performance, Sun and colleagues suggested adding a third factor of directed attention into the model to explain the impairment of perceptual-cognitive skill (e.g., decision-making). Apart from explaining the adverse effects of MF, these theories have also been used to form potential strategies to counteract MF, especially in athletes. Therefore, Sun, Soh [25] conducted a study involving an intervention utilizing virtual nature stimuli, positing that mentally fatigued athletes who engaged in a 12.50-min exposure within natural scenes exhibited a diminished decline in soccer decision-making, potentially attributable to increased attention resources (e.g., directed attention). Consequently, a particular question arises regarding the interaction between directed attention and self-regulatory resources, considering their acknowledged conceptual similarity [26]. Could manipulation of self-regulation, in effect, also serve as a strategy to mitigate the impact of MF? Is it possible that professional athletes, due to their presumably higher levels of self-regulatory resources [27], demonstrate better performance in sport-specific tasks compared to athletes at lower competitive levels?

It is important to highlight that the existing body of literature lacks a comprehensive review, resulting in an unclear understanding of the mechanism of counteractive interventions, such as the involvement of attention and self-regulatory resources. Despite the presence of specific investigations that have provided empirical evidence supporting the effectiveness of manipulations for self-regulation such as autonomy [28] and person-fit [27], this gap continues to exist.

In the most recent year, some investigations have begun to get promising results from analysing the interventions in this field. For example, Oliver, Sullivan [29] analysed nutritional interventions counteracting MF in three populations, including sporting, military, and aerospace. The result showed positive effects for MF and improvement of cognitive skills (e.g., reaction time). Consistent with the psychobiological model, Azevedo, Silva-Cavalcante [30], Franco-Alvarenga, Brietzke [31] demonstrated that caffeine intake led to a decrease in RPE under mentally fatiguing conditions and improved subsequent athletic performance (e.g., cycling endurance). However, some supplements such as caffeine could have excessive effects, such as abnormal nervousness, irritability, insomnia, and sensory disturbances [32]. Furthermore, the effects of MF are lessened only after using caffeine or a carbohydrate mouth rinse for 40 min or 15 min, respectively, and only occur after several days, such as creatine [33].

Another most recent review conducted by Proost, Habay [34] examined some strategies to counteract MF. However, only the potential countermeasures were emphasized. More importantly, they did not focus on sport-specific performance in athletes.

Therefore, the current review aims to investigate all the evidence on different interventions for reducing the impact of MF and improving subsequent sport-specific performance, including motor performance and perceptual-cognitive skill in athletes.

Methods

The review complies with the Preferred Reporting Items Checklist (PRISMA) requirements for reporting [35]. Four major databases (Web of Science, SPORTDicus through EBSCOhost, PubMed, and Scopus) were used to conduct a thorough search of published works from the time they were published until December 2022 (Supplementary Table S1). In addition, citations and reference lists were combed to identify more studies.

Eligibility criteria

The PICOS method was used to look for literature (Table 1). Articles were considered if they met certain requirements: (a) considered a variety of levels of athletes (e.g., amateur, semi-professional, and professional) without any injury; (b) included one of five components of sport-specific motor performance (strength, speed, stamina, flexibility, and skill) or perceptual-cognitive skill; (c) investigate interventions aimed at mitigating MF within the intervention group and use various controls—whether passive, placebo, or wait-list—in the control group) execute any intervention to minimise MF. When employing a placebo control, the study must clearly specify the type of placebo implemented; (d) recruited a task for prior mental exertion to induce MF condition; (e) published the results with a randomized controlled trial; and (f) peer-reviewed articles in English.

Notably, in the current review, skill is defined as the capacity to perform tasks at a high level while also being effective and efficient [36]. It is alternatively known as technical performance or skilful sports execution [2, 37]. In ball games like basketball and soccer, skill refers to the player's ability to control the ball. This includes shooting, passing, tackling, and dribbling the ball in a way that helps the team.

The incorporation of perceptual-cognitive skills in the current analysis holds significant practical significance, as it enables athletes to perceive and understand complex patterns within the competitive environment (e.g., opponents' actions and behaviours). Consequently, perceptual-cognitive skill acts as a catalyst for prompt reactions, resulting in the implementation of motor execution aimed at achieving optimal performance [38].

Literature search and selection

The databases were searched using the keywords, truncation, and Boolean operators shown in Supplementary Table S1. Additional material was searched through references and Google Scholar. Two independent reviewers examined the article abstracts, titles, and search results to find articles that satisfied the requirements. A full-text evaluation of 256 papers followed the screening (Fig. 1). In addition, a third reviewer was consulted when disagreements arose.

Protocol and registration

The protocol used for methodology and planned analysis was recorded in OSF Registries (https://osf.io/9nz26). Thus far, no protocols have examined the impact of non-supplement interventions on sport-specific motor performance and perceptual-cognitive competence simultaneously. Therefore, the suggested protocol's originality is ensured.

Risk of bias assessment

The risk of bias in various studies was evaluated using the Revised Cochrane Risk of Bias instrument for randomized trials (RoB 2.0). "Low risk of bias," "high risk of bias," or "some worries of bias" were assigned to each of the following five categories based on signalling questions. Reviewers followed the guidelines set by Cochrane.

Results

Literature selection

The initial phase of searching yielded a total of 1255 unique studies. After carefully removing any duplicates, a collection of 1007 research papers were selected for further examination. After conducting a thorough examination of the titles and abstracts, a total of 751 studies were found to be inconsistent with the research objectives and were subsequently eliminated from further evaluation. The third phase involved a comprehensive

Table 1 PICOS criteria

PICOS	Criteria
Participation	Athlete, with no restrictions on their sport activity, gender, or age
Intervention	Manipulations to counteract MF whilst measuring subsequent sport-specific performance without any supplements
Comparison	Intervention vs. non-intervention groups (e.g., passive, placebo, or wait-list control group)
Outcome	Sport-specific motor performance and perceptual-cognitive skill
Study Design	Randomized Controlled Trial

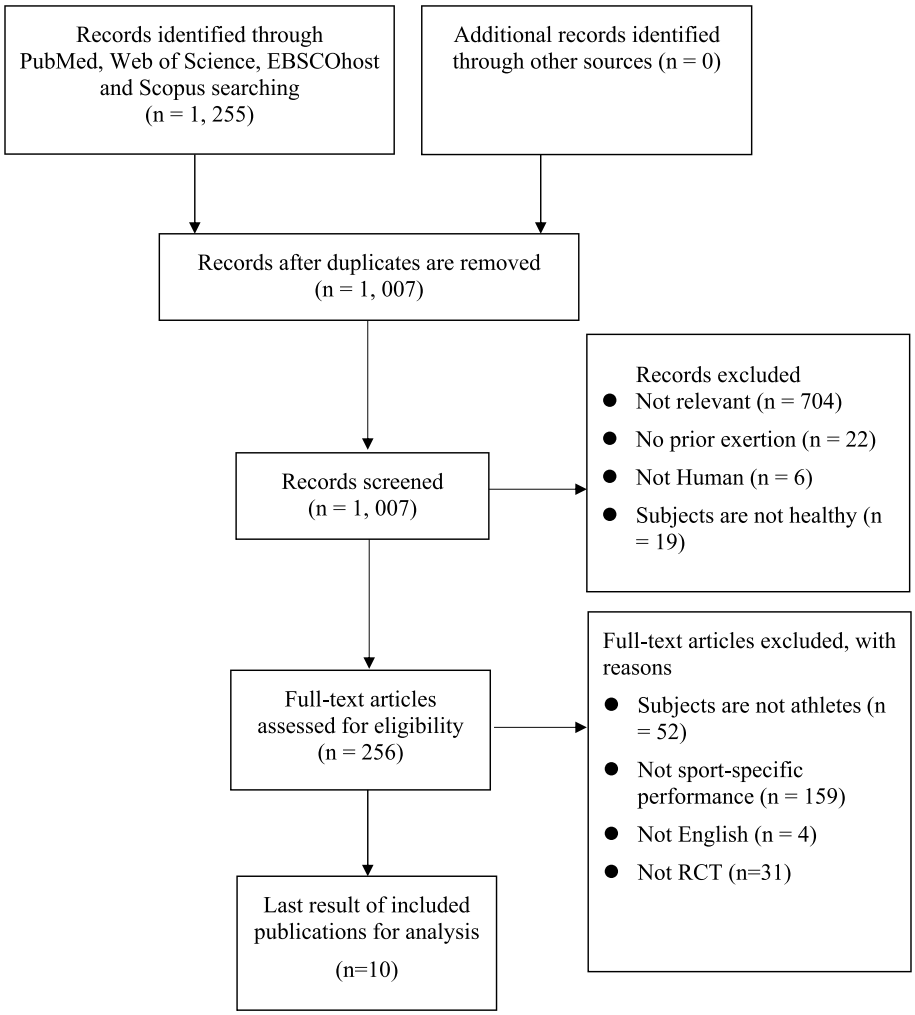

Fig. 1 PRISMA summary of selection procedure

assessment of 256 full-text papers conducted by two independent reviewers, both of whom agreed on the eligibility of the included studies. After a thorough and meticulous evaluation, there were 10 research studies that met all the specified qualifying criteria. Therefore, these 10 research studies were included in the current review. The visual representation of the selection process is illustrated in Fig. 1.

Risk of bias

One study [21] had a high-risk bias in the outcome due to unblinding of the assessors. The other four studies were considered to have an "unclear risk of bias" for unclear evidence. Three studies [23, 25, 28] were rated as having some concerns about bias due to no information on allocation concealment. The details are shown in Figs. 2 and 3.

Population characteristics

A total of 316 participants were included (Table 2). The ratio of female to male participants was 279:37. The average age was 19.4 [39] to 30.0 years [23]. The professional level of athletes comprised the primary population.

Since the perceptual-cognitive skill is especially challenging in open-skill sports [16], we divided all sports into two categories: open-skill sports, such as tennis [28], basketball [40–42], and soccer [25]; and closed-skill sports, such as cycling [27], shooting [39], and swimming [21–23].

The counteractive effects of the investigated interventions on sport-specific performance

The intervention of autonomy-supportive environment

The autonomy-supportive environment refers to a situation that enables athletes to satisfy their basic needs for autonomous acting and decision-making to lead to

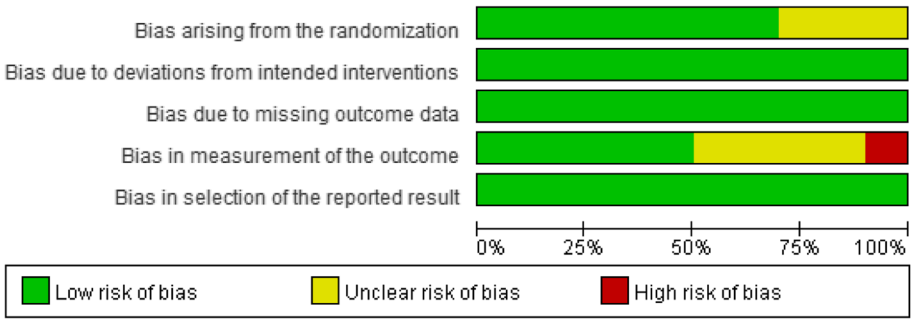

Fig. 2 Risk of bias for all included studies

Fig. 3 Risk of bias summary for each included study

better performance in sports [28, 43]. Englert and Bertrams [28] initially investigated a particular intervention that focused on the creation of an autonomy-supportive environment. This environment was designed to aid participants in making decisions regarding whether or not to cease their efforts in a preceding MF task. Specifically, they examined the negative impact on tennis serve skill under conditions of high pressure. The results showed that the autonomy-supportive group significantly outperformed the control group (no autonomy-supportive manipulation) in serving accuracy (M = 17.10, SD = 6.43 vs. M = 13.05, SD = 3.99; $p = 0.04$) with a prior transcription task.

The intervention of person-fit

Two separate investigations have been conducted to examine the intervention of person-fit. Martin, Staiano [27] examined the strength of cycling performance and revealed that professional athletes with better person-fit could resist MF and maintain power generated on a cycle ergometer. Specifically, professional cyclists had no significant main impacts on the condition (mental fatigue vs. non-MF: $p = 0.675$, $\eta_p^2 = 0.020$), and recreational athletes' power dropped significantly ($p = 0.017$, $\eta_p^2 = 0.530$) [27]. Similarly, in the sport of shooting, shooting accuracy did not significantly drop in elite-level (better person-fit) athletes after a MF task compared with the non-MF group ($p > 0.05$) [39]. Moreover, Martin, Staiano [27] also found that professional cyclists could maintain average speeds well. In other words, the average speed was not considerably different (44.1 ± 2.2 vs. 44.3 ± 1.8, $p = 0.261$, $\eta_p^2 = 0.138$) in the time trial.

The intervention of nature exposure and mindfulness

Exposure to nature and the practice of mindfulness have been examined as effective interventions to counter MF and enhance subsequent sport-specific performance. Specifically, Sun, Soh [25] examined the effect of virtual nature as an intervention and found that a 12.50 min intervention could significantly improve soccer decision-making skills in reaction time (M = 5.01, SD = 1.46 vs. M = 7.21, SD = 1.65; $p < 0.01$; $\eta^2 = 0.08$), whereas there

Table 2 Overview of included publication details

NO.	Reference	Population Characteristics	Intervention	Prior Mental Exertion	Duration of the Prior Mental Exertion	Main Outcome	Psychophysiological Outcome	The domain of the Outcome	Sports
1	Englert and Bertrams [28]	57 semi-professionals Sex: 29 ♂; 28 ♀ Age: 24.7 ± 4.5	Autonomous self-control exertion	Transcription task	5 min	Serve accuracy↑	Sports anxiety ↔	Skill	tennis 
2	Martin, Staiano [27]	11 professionals; 9 recreational cyclists Sex: 20♂ Age: 23.4 ± 6.4	Person-fit	Stroop task	30 min	Cycling Power in professionals↑	RPE ↔ HR ↔ Blood lactate ↔	Strength Speed	cycling 
3	Shaabani, Naderi [40]	72 well-trained athletes Sex: 72 ♂ Age: 28.6 ± 4.0	Mindfulness	Stroop task	15 min	Shooting accuracy↑	Sport anxiety ↔ Depletion sensitivity ↔ Positive and negative affective states ↔	Skill	basketball 
4	Englert, Dziuba [39]	23 elites Sex: 12♂; 11♀ Age: 19.4 ± 4.1	Person-fit	Transcription task	5 min	Shooting accuracy↑	perceived self-control strength ↔	Skill	shooting 
5	Penna, Filho [23]	10 elites Sex: 10♂; Age: 30.0 ± 6.0	tDCS	Stroop task	45 min	800 m swimming trial ↔	Motivation ↔ RPE ↔	Stamina	swimming 

Table 2 (continued)

NO.	Reference	Population Characteristics	Intervention	Prior Mental Exertion	Duration of the Prior Mental Exertion	Main Outcome	Psychophysiological Outcome	The domain of the Outcome	Sports
6	Sun, Soh [25]	90 university athletes Sex: 90 ♂ Age: 20.7 ± 2.0	Nature exposure	Stroop task	30 min	Soccer decision-making↑	Motivation ↔ RPE ↔	Perceptual-cognitive skill	soccer 
7	Nikooharf Salehi, Jaydari Fard [21]	15 professionals Sex: 15♀ Age: 23.0 ± 1.0	tDCS	Stroop task	60 min	50 m swimming trial↑		Speed	swimming 
8	Fortes, Ferreira [41]	20 professionals Sex: 20♂ Age: 24.8 ± 4.2	tDCS	Sport-based videogame	60 min	Basketball decision-making↑ Visuomotor skill↑	Eyeblink duration ↔ Pupil diameter ↔ Subjective MF ↓ Motivation ↔	Perceptual-cognitive skill	basketball 
9	Moreira, Moscaleski [42]	9 professionals Sex: 9♀ Age: 25.0 ± 8.0	tDCS	Stroop task	30 min	Shooting accuracy ↔	RPE ↔ Success motivation ↔ Intrinsic motivation ↔ Subjective workload ↔	Skill	basketball 
10	Fortes, Faro [22]	19 amateur athletes Sex: 19 ♀ Age: 20.2 ± 1.5	tDCS	Stroop task	30 min	Tethered swimming↑	Subjective MF ↓ Motivation ↔	Strength	swimming 

RPE Rating perception of effort, *HR* Heart rate, *tDCS* Transcranial direct current stimulation, *MF* Mental fatigue

was no significant difference in accuracy (M = 69.13 SD = 4.78 vs. M = 66.87 SD = 4.81; $p = 0.91$; $\eta^2 = 0.02$).

Shaabani, Naderi [40] performed a study that implemented a brief mindfulness intervention consisting of a 15-min breath and body mindfulness audio exercise. In contrast, the control group participants (no mindfulness) listened to an audiobook. The results showed that basketball shooting accuracy across 30 free throws was significantly higher in the depleted group following the brief mindfulness exercise, as compared to the no-intervention group (M = 49.39, SD = 8.32 vs. M = 40.73, SD = 8.72; $p < 0.05$) [40].

The intervention of transcranial direct current stimulation

The majority of investigations (five out of ten studies) have converged on the use of transcranial direct current stimulation (tDCS). This is likely due to its characteristics as a non-invasive form of brain stimulation that can increase cortical excitability [44, 45]. However, different studies have produced varying results.

Specifically, Fortes, Faro [22] applied tDCS to the orbital prefrontal cortex and detected a significant main effect of condition on the fatigue index ($F = 6.51$; $p = 0.04$; d = 0.34). This resulted in the maintenance of mean force and critical force in the tDCS group, while a significant drop was observed in the sham simulation group. Similarly, when applied to the midtemporal area, tDCS was found to be effective in decreasing MF ($P < 0.05$) compared with the sham group. The improved condition was associated with enhanced basketball visuomotor and decision-making skills as measured by reaction time and accuracy [41]. Nikooharf Salehi, Jaydari Fard [21] found that tDCS could significantly reduce the negative effect of MF and improve swimming speed at 50 m compared with the sham stimulation group (25.93 ± 1.32 s vs. 27.27 ± 1.68 s; $p \leq 0.01$).

However, Moreira, Moscaleski [42] did not detect the effects of tDCS on basketball shooting accuracy among female athletes after a 30-min Stroop task. That is, the number of shots to achieve 10 hits in undefended (M = 23.4, SD = 9.1 vs. M = 22.5, SD = 7.6; $p = 0.651$) and defended tests (M = 22.2, SD = 6.1 vs. M = 21.8, SD = 9.0; $p = 0.681$) were similar in two conditions (tDCS vs. sham – tDCS) [42]. Finally, Penna, Filho [23] showed similar performance of stamina in the comparison of the tDCS group and control group (692 ± 50 s vs. 692 ± 42 s, $p > 0.05$) during an 800 m swimming trial.

Psychophysiological outcome

Remarkably, the psychophysiological outcomes were consistent (Table 2). The indicators of MF, such as eye blink duration, pupil diameter [41], RPE [23, 25, 27, 42], and sports anxiety [28, 40], showed no significant difference between groups following the interventions. While subjective reports of MF significantly increased after the MF task, a notable decrease was observed in the tDCS intervention group [22, 41]. This decline can be attributed to the efficacy of tDCS in countering MF.

Discussion

We evaluated the existing literature on interventions that mitigate MF and subsequently enhance sport-specific performance, including sport-specific motor performance and perceptual-cognitive skill. Given the detrimental effects of MF, the present findings offer insights into potential interventions that can alleviate MF and improve sport-specific performance.

Sports characteristics

The academic study of MF in sports was initiated by Smith, Marcora [19]. The authors first reported on the impairment of intermittent endurance among various types of athletes (e.g., team sports). Since then, the effect of MF has been examined comprehensively in many sports in recent years. However, studies on interventions for MF have been limited to six sports (Table 2). As MF affects sport-specific performance, more studies in other sports are required in the future, such as boxing [11], table tennis [46], cricket [47], and Australian football [8].

Notably, some specific characteristics of the sports make them relevant subjects for such studies. For example, sports like tennis, basketball, and soccer involve a lot of tactical awareness, making decisions under pressure, and team coordination [48, 49]. MF directly impacts these cognitive aspects. In addition, MF influences pacing [19] and self-selected power output [50] in endurance sports like swimming and cycling. Finally, shooting is a sport that demands extreme concentration and precision. Even minor lapses due to mental fatigue in attention can significantly affect performance [51].

Moreover, there are only two studies that examined perceptual-cognitive skills in soccer and basketball. The skills refer to the abilities that allow athletes to process and interpret visuals rapidly and accurately. These skills are crucial for recognizing patterns, making quick decisions, anticipating opponents' actions, and more. In the context of sports, these skills enable athletes to respond effectively to dynamic and often unpredictable game situations [52]. In the current review, the visuomotor [41] and decision-making skills [25, 41] were examined. On one level, it is the main determining factor as to whether athletes will function well at superior levels (more rapid and accurate) [53]; on another level, it could determine competition results [16]. Future studies should examine these skills in more detail, especially in open-skill

sports due to the dynamic and complex competitive environment.

Interventions characteristics

In the current review, a variety of intervention types have been found to have a counteractive effect on MF and improve the subsequent sport-specific performance, including sport-specific motor and perceptual-cognitive skills. These interventions are discussed in the sections below.

The counteractive effect of autonomy-supportive environment

The autonomy-supportive environment is one in which coaches cultivate a milieu that positively encourages athletes to exhibit initiative and engage in self-directed decision-making processes [54, 55]. This approach contrasts with a controlled environment in which decision-making is mostly centralised in coaches, severely limiting athletes' sense of autonomy. Empirical evidence has demonstrated a role of autonomy support. Specifically, athletes experiencing a greater degree of autonomy are more likely to persevere, nurture creative ideas within their sporting disciplines, and accomplish significant advances in skill development [56, 57].

In such an environment, athletes demonstrate a tendency for increased active participation in training sessions and competitive events [58, 59]. This enhanced involvement is characterized by a propensity to independently initiate personal development, actively seek out challenges, and demonstrate a higher level of commitment in both practice and competitive settings. Moreover, the environment could be conducive to the development of more positive relationships between coaches and athletes, characterized by mutual respect and a deeper mutual understanding [60].

In the study encompassed within this review, Englert and Bertrams [28] found that the autonomy-supportive environment (e.g., athletes have the right to determine whether or not to exert self-regulation) could attenuate the detrimental effects of MF on second serve in tennis under high-pressure conditions.

The effect could be explained by two theories, namely, the self-determination theory and the resources model of self-regulation. Specifically, the resources model indicates that self-regulation is a limited "reservoir". It is seen as limited over time, along with physical and cognitive performance that requires self-regulation [61, 62]. On the other hand, it can also be exercised and increased significantly [63]. In a recent extensive analysis conducted by Sun, Soh [64], it was found that training programmes incorporating self-regulatory strength have a beneficial impact on MF and subsequent physical and cognitive performance. This finding aligns with the resources model of self-regulation, as posited by the resources model of self-regulation. To date, only one study has been undertaken on athletes [28], indicating a promising area for future research.

Moreover, the self-determination theory provides a framework to comprehend how these states of autonomy (or a rather widespread effect sensation of being compelled to act) lead to varied practical results [65, 66]. At its foundation, the self-determination theory proposes two types of motivation: intrinsic motivation refers to doing something out of interest or delight, whereas extrinsic motivation refers to doing something for instrumental purposes. Notably, situations with autonomy-supportive encouragement could increase levels of intrinsic motivation among athletes. Therefore, athletes with an autonomy-supportive environment can be inspired to put forth greater effort using more resources in the "reservoir" and show higher performance even under MF (e.g., [28]: tennis serving skill).

Given that Englert and his colleague also conducted their study under conditions of high pressure, such environments may be instrumental in reducing stress among athletes, fostering a sense of control pressure in their sporting activities [67].

The counteractive effect of person-fit

Person-fit in the sports context is explained as the compatibility between an athlete's characteristics and those of a specific sport-specific task [68]. Undoubtedly, athletes who have higher competitive levels, such as professionals and elites, possess better person-fit [69]. With regards to lifestyle, high-level athletes (e.g., professional and elite) are more likely to be in situations that require self-regulation and inhibition control more often than low-level athletes (e.g., recreational and non-elite) [70, 71]. High-level athletes must regulate their nutrition and alcohol consumption, refrain from smoking, ensure adequate rest, and adhere to a rigorous physical training regimen. This persistent self-regulation of behaviour may increase inhibitory control throughout the physical and cognitive domains [27, 72]. For example, a recent systematic review reported that individuals who spent several weeks doing self-regulatory exercises (posture regulation, financial monitoring, and non-dominant hand use) performed better in physical and cognitive tasks following prior MF task [64].

In the current review, better person-fit or high-level athletes (e.g., professional or elite) showed a superior ability to attenuate the negative impact of MF and maintain other sport-specific performance such as cycling strength and speed [27] and shooting accuracy [39], compared with their counterparts (e.g., recreational and non-elite).

High-level athletes might nonetheless experience MF. For example, professional athletes showed worse soccer decision-making after a 30-min use of social networks on smartphones or playing video games [73]. Future studies can investigate this discrepancy by using the same mentally fatiguing task with the same duration.

The counteractive effect of nature exposure and mindfulness

Nature exposure and mindfulness meditation are two promising interventions. Long-time (e.g., 12.50 min) exposure to nature scenes significantly improved soccer decision-making skills due to directed attention as well as self-regulation restoration [24, 25]. Since there is an overlap between directed attention and self-regulation [26], Sun and colleagues further proposed a conceptual framework to show the mechanism of the improvement regarding self-regulatory capability and perceptual-cognitive skills such as decision-making [24]. However, the proposition of the conceptual model should be tested through more empirical studies in the sport context. For example, competitive state anxiety and heart rate variability can be tested directly after the intervention of nature exposure, since they could be indicators of self-regulation [74, 75].

Self-regulation and mindfulness are linked by research [76, 77] as they share some common mechanisms. Notably, Friese, Messner [78] indicated that mindfulness meditation attenuates the depleted effect through the restoration of attention. Moreover, Bishop, Lau [79] emphasized the importance of self-control of attention as a component of mindfulness. Several questions were prompted. For example, could attention be a common resource for self-regulation and mindfulness? Perhaps, mindfulness meditation also could be manipulated for attention and integrated into the conceptual framework [24]. Moreover, since there was a threshold for the intervention of nature exposure to counteract mental fatigue and improve soccer decision-making [25], is there also a threshold for the intervention of mindfulness to restore attention resources? Nevertheless, it is necessary to examine this more deeply in future studies.

The counteractive effect of transcranial direct current stimulation

In recent years, five research studies have examined tDCS as an ergogenic aid to combat mental tiredness in the athlete population (see Table 2). The technique, which involves delivering a small electrical current to the scalp to raise (anodal tDCS: a-tDCS) or decrease (cathodal tDCS: c-tDCS) neuronal excitability for sustained durations [80], has been demonstrated to reduce the aberrant rise in RPE [81, 82], a phenomenon linked to the impairment of sport-specific performance as per the psychobiological model [47, 83]. The potential mechanism underlying the ergogenic effect of preventing MF may be the increased cortical excitability in certain brain regions targeted by anodal stimulation, such as the left temporal cortex [23], the middle temporal area [41], the dorsolateral prefrontal cortex [21, 42], and the orbital prefrontal cortex [22].

Although tDCS was anticipated to have a widespread effect [84], it did not improve cognitive performance in MF and subsequent swimming stamina (800 m swimming) in a study by Penna, Filho [23] (e.g., Stroop task). Thus, more research investigating the unique high-definition tDCS approach is required [85].

Consistent with the person-fit intervention, Penna et al. [23] demonstrated that the competitive state of the athletes nullified any potential favourable benefits of tDCS. Specifically, temporal brain activity is linked to the regulation of cardiac autonomic function [20, 86], and RPE is involved in this relationship [87]. However, this modulation may not have been significant enough to indicate improved performance among elite athletes (e.g., professionals). Penna and colleagues chose a group of athletes with 14 years of consistent training, and these athletes may have had enhanced temporal cortex function as a result of regular exercise.

In contrast, the other four studies that investigated tDCS showed significant improvement in the condition of MF. It increased cognitive performance (e.g., reaction time) in the mentally fatiguing task (e.g., Stroop task or video game) and in subsequent sport-specific performance such as 50 m swimming trial [21], basketball decision-making and visuomotor skill [41], basketball shooting accuracy [42], tethered swimming measured as a critical force, aerobic impulse, and mean force [22].

Notably, tDCS emerges as a potentially promising intervention for practical application. The intervention has the potential to ameliorate MF, subsequently enhancing various domains of sport-specific performance, including speed, skill, strength, and perceptual-cognitive skill, as delineated in Table 2. Perhaps more importantly, it can be applied after a mentally fatiguing task. That means there is a large possibility of applying the intervention before athletic competitions. However, more studies are required to examine different sports, such as Australian football, cricket, and table tennis, especially because their sport-specific performance is also influenced by MF [8, 46, 47].

The potential mechanism of applied interventions

In the current review, the potential mechanism of applied interventions could be explained through the psychophysiological outcomes in Table 2. MF was significantly improved, measured as subjective and physiological indicators after the tDCS [22, 41]. The

intervention probably improved attention resources and thus reduced MF as proposed by the most recent study [24]. It has been suggested by Andrew McKinley [88] that the characteristics of tDCS, such as electrode montage, duration, and intensity, are equivalent to enhancing focus and decreasing mental weariness. Both processes may share the same underlying mechanism.

Moreover, according to the resource model of self-regulation shown in the Discussion section, all the interventions investigated in the current review are related to self-regulatory capabilities among athletes. Some included studies manipulated attention resources through the intervention and showed significant results [21, 22, 25]. The resources of self-regulation and top-down attention (e.g., directed attention) are overlapping [26]. Therefore, as shown by Sun, Soh [24], the intermediate mechanisms to counteract MF and improve subsequent sport-specific performance might be self-regulation and directed attention.

In line with the psychobiological model, the traditional indicators of fatigue (e.g., heart rate and blood lactate) were not significantly different between the intervention and the control conditions [27]. Additionally, RPE as a primary component in the model was at a similar level between groups after the intervention [23, 25, 42]. This suggests that subsequent research on the intervention could be guided by the psychobiological model of exercise performance.

Limitations

Despite being carefully conducted, the current review has a few limitations. First, a meta-analysis was not conducted due to the heterogeneity across the measurement and interventions. Second, regarding the intervention of tDCS, only a-tDCS was investigated. The effects of different types of tDCS (a-tDCS vs. c-tDCS) were not evaluated due to the limited investigations of c-tDCS, as only one study examined c-tDCS [42]. Additionally, although this review implies that high-level athletes, whether professional or elite, may exhibit heightened self-regulation capabilities that enable them to sustain their sports performance, it is important to note that they are not immune to MF. For instance, elite cricketers' performances have been observed to deteriorate due to MF [47, 89]. However, this review could not identify interventions other than tDCS, given the constraints in recruiting professional athletes for the studies reviewed. Finally, only publications written in English were selected, which may have limited the results.

Conclusion

A careful selection of interventions could significantly counteract MF and improve the subsequent sport-specific performance in different domains. Self-regulation and attention resources appear to be important mechanisms behind this counteractive effect. Athletes who are in an environment that encourages autonomy may feel motivated to put in extra effort by utilizing additional resources. Therefore, it is probable that they will exhibit higher levels of performance even when the MF condition is present. Another promising intervention is tDCS; however, different types of tDCS, such as a-tDCS and c-tDCS, should be further investigated in future studies.

Supplementary Information

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Additional file 1: Supplementary Table S1. Detailed search strategy.

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Authors' contributions
HS, KGS, AM and ZT conceptualised the review, created aims and established inclusion criteria. HS, LZ and CD conducted the database searches and all screenings in accordance with the inclusion criteria. HS performed the assessment for risk of bias with AM and KGS, and wrote the initial draft. KGS supervised the study and contributed to analysis. ZT, LZ and XJG contributed to reviewing and editing. JT contributed to the data analysis and interpretation. All authors were involved in interpreting the data, critically revising the manuscript, and approved the final version for publication.

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ARTICLES FOR FACULTY MEMBERS

ADVANCING MENTAL PERFORMANCE IN COMPETITIVE AQUATIC ATHLETES THROUGH THE DEVELOPMENT AND VALIDATION OF A REAL-TIME BIOFEEDBACK SYSTEM FOR PSYCHOLOGICAL SKILLS TRAINING

Effects of real-time EEG neurofeedback training on cognitive, mental, and motor performance in elite athletes: a systematic review and meta-analysis. / Skalski, D., Łosińska, K., Prończuk, M., Tyrała, F., Trybek, G., Cięszczyk, P., Kuliś, S., Maszczyk, A., & Pietraszewski, P.

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Effects of real-time EEG neurofeedback training on cognitive, mental, and motor performance in elite athletes: a systematic review and meta-analysis

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Abstract

Study aim: Real-time EEG neurofeedback (NFB) training is gaining popularity as a cognitive-motor enhancement tool in elite sports. However, its protocol-specific effectiveness across disciplines and outcome domains remains unclear. This systematic review and meta-analysis examined the effects of real-time EEG NFB in elite athletes, focusing on protocol characteristics, targeted outcomes, and effect sizes.

Material and methods: A search of six databases (2000–2025) identified 24 studies involving national- or international-level athletes. Protocols were categorized by frequency band (e.g., SMR, beta, theta), sport discipline, and performance domain (cognitive, motor, psychological). Risk of bias was assessed using RoB 2 and ROBINS-I; GRADE was applied to evaluate evidence certainty. Eleven studies provided quantitative data for meta-analysis using standardized mean differences (SMD).

Results: Most studies involved individual sports, with judo, archery, and shooting most common. SMR and beta protocols dominated in precision sports; theta protocols were prevalent in combat sports. Meta-analysis showed a large pooled effect (SMD = 1.26; 95% CI: 1.05–1.45), with high heterogeneity (I^2 = 94.1%). GRADE indicated moderate certainty for cognitive and psychological outcomes.

Conclusion: EEG NFB appears effective in enhancing attention, motor control, and anxiety regulation in elite athletes. However, methodological variability highlights the need for standardized protocols and further replication.

Keywords: Cognitive enhancement – Psychomotor regulation – Attentional control – Performance optimization – Brain-computer interface

Introduction

In high-performance sport, marginal gains in attention, decision-making, and motor control can profoundly influence competitive success. Recent advancements in sport neuroscience have introduced real-time electroencephalographic (EEG) neurofeedback as a promising intervention to optimize performance-relevant brain activity. EEG neurofeedback enables athletes to self-regulate specific frequency bands—such as SMR (12–15 Hz), beta (13–30 Hz), and theta (4–8 Hz)—each associated with distinct neurophysiological functions. SMR protocols aim to enhance sensorimotor inhibition and postural stability by increasing activity over central sensorimotor areas (usually Cz), facilitating relaxed alertness and reduced motor excitability. Beta protocols are linked to active concentration, attentional focus, and cognitive control, particularly involving frontal and central regions. In contrast, theta training—often in the context of theta/beta ratios—targets deeper attentional states, working memory, and internalized focus, typically modulating midline frontal areas. These mechanisms are considered especially relevant for optimizing performance in high-cognitive or psychomotor-demand sports (Gruzelier, 2013; Gong et al., 2021; Hammond, 2007;

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Zoefel et al., 2011; Escolano et al., 2014). Recent systematic and narrative reviews (Tosti et al., 2024; Diotaiuti et al., 2024a; Diotaiuti et al., 2024b) have highlighted the efficacy of neurofeedback approaches in both performance regulation and clinical or cognitive contexts, emphasizing the growing importance of protocol personalization and integration with biofeedback techniques.

The mechanisms underlying EEG neurofeedback rely on operant conditioning, wherein athletes receive real-time feedback on their brain activity and adjust it toward targeted states. This approach has been associated with enhancements in focus, emotional regulation, reaction speed, and sensorimotor integration, making it especially relevant in sports requiring high cognitive and psychomotor demands (Da Silva & De Souza 2021; Gołaś et al., 2024). These demands are particularly pronounced in disciplines involving coordinated segmental movement and postural control, such as sport dance or precision sports (Kuliś & Gajewski, 2022).

Previous studies across sport disciplines, particularly in precision sports such as archery, shooting, and golf, report that beta and sensorimotor rhythm (SMR) protocols enhance attentional focus and reduce competition anxiety (Landers et al., 1991; Cheng et al., 2015; van Boxtel et al., 2024). In contrast, theta/beta protocols are frequently used in combat and power sports, aiming to improve complex motor control, balance, and visual reaction times (Maszczyk et al., 2020; Prończuk et al., 2023a). Despite these findings, heterogeneity in protocol parameters—such as session duration (ranging from 4 to 45 minutes), number and frequency of sessions, targeted EEG frequency bands (e.g., SMR vs. theta/beta), and type of feedback provided (visual, auditory, or combined)—as well as in study designs and outcome assessments, limits cross-study comparability.

Furthermore, the literature remains skewed toward individual sports, with few studies addressing team-based or open-skill contexts (van Boxtel et al., 2024). Given that team sports involve unique demands such as interpersonal coordination, tactical adaptation, and rapid decision-making under pressure, future research should explore how neurofeedback protocols can be tailored to enhance collective performance and cognitive functioning in team-based environments. Although immediate post-intervention effects appear consistently positive, particularly in domains such as attention and anxiety, evidence regarding long-term or transferable benefits remains limited (Toolis et al., 2023; Skalski et al., 2024). Additionally, the impact of environmental moderators (training frequency, hypoxia) and individual athlete characteristics is rarely addressed systematically. To address these gaps, the present work offers a systematic review and meta-analysis of studies evaluating the effects of real-time EEG neurofeedback training on cognitive, mental, and motor performance in elite athletes.

This review aims to systematically summarize and categorize existing empirical evidence on real-time EEG neurofeedback training in elite athletes, with particular emphasis on how outcomes vary by protocol type, sport discipline, and performance domain. Furthermore, it seeks to quantify the magnitude of intervention effects, where data allow, through meta-analytic techniques. Finally, this review intends to critically appraise the methodological quality of included studies and identify key limitations in the current literature, thereby offering clear recommendations for future research and practical implementation in high-performance sport contexts.

Material and methods

Protocol and registration

This systematic review and meta-analysis was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. The review protocol was prospectively registered in the PROSPERO database under the title "Real-Time EEG Neurofeedback and Athletic Performance: A Systematic Review of Cognitive and Motor Outcomes in Elite Sport" (registration number: CRD4201020923).

Eligibility criteria

Studies were included if they met the following criteria:

- Population: elite or high-performance athletes competing at national or international levels;
- Intervention: real-time EEG-based neurofeedback targeting specific frequency bands (SMR, beta, alpha, theta);
- Comparator: control group, sham neurofeedback, or pre-post comparison;
- Outcomes: at least one performance-related outcome, including cognitive (attention, decision-making), motor (reaction time, coordination), or psychological (anxiety, imagery);
- Study design: randomized controlled trials, quasi-experimental studies, or controlled before-and-after trials;
- Language: English or Spanish;
- Other: minimum 3 sessions of neurofeedback and a sample size of ≥ 5 participants.

Studies were excluded if they:

(a) focused solely on clinical or rehabilitation populations (e.g., ADHD, stroke);
(b) did not use real-time feedback (e.g., post-session or offline neuroimaging analysis);
(c) employed non-EEG-based feedback modalities such as fMRI, near-infrared spectroscopy (NIRS), or heart rate variability (HRV). These methods were excluded due to their fundamentally different neurophysiological targets, lack of millisecond-level temporal resolution, and limited suitability for dynamic sport-specific training;

(d) involved fewer than three neurofeedback sessions;
(e) lacked a performance-related outcome; or
(f) had insufficient methodological detail for quality assessment.

Information sources and search strategy

We performed comprehensive searches in the following databases: PubMed, Scopus, Web of Science, SPORTDiscus, and EMBASE (2000–March 2025). The search strategy combined free-text terms and controlled vocabulary where available. Keywords included variations and Boolean combinations such as:

("neurofeedback" OR "neurofeedback training") AND ("EEG" OR "electroencephalography") AND ("elite athlete" OR "high-performance athlete") AND ("cognitive" OR "motor" OR "performance").

No restrictions were placed on the specific sporting discipline or neurofeedback protocol during the initial search phase. The search was limited to studies published in English or Spanish and involving human participants. Reference lists of eligible articles were also manually screened to identify additional studies.

The search strategy was designed to ensure maximal sensitivity in identifying studies suitable for both qualitative synthesis and quantitative meta-analysis.

Study selection and screening

The initial database search yielded a total of 497 records. After the removal of duplicate records (n = 110), studies excluded by automation tools (n = 177), and records removed for other reasons (n = 20), a total of 190 titles and abstracts were screened for potential eligibility. Figure 1 summarizes the screening process in accordance with the PRISMA 2020 flow diagram.

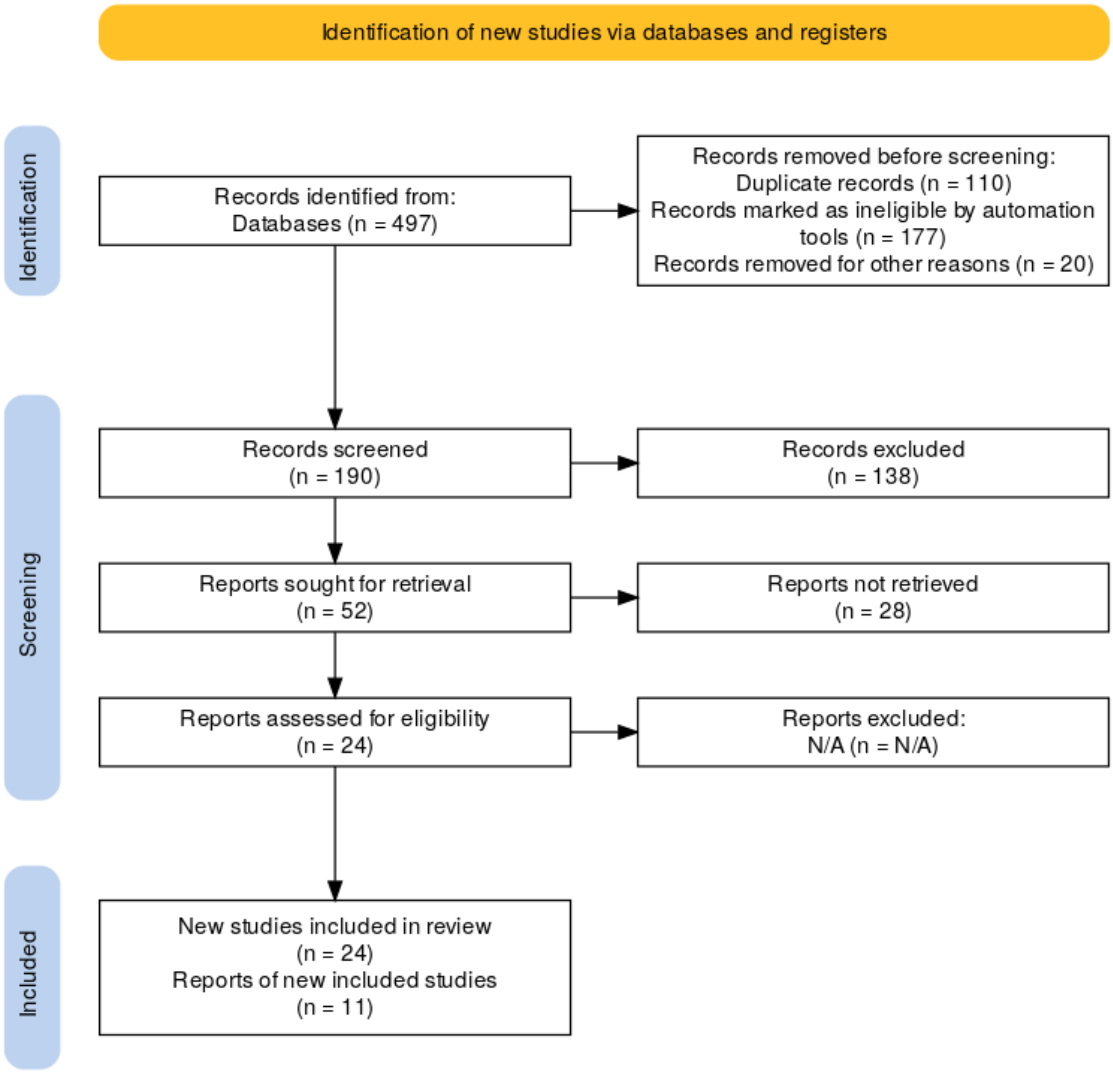

Figure 1. PRISMA flow diagram

Following this screening phase, 52 full-text articles were retrieved for detailed evaluation. Of these, 24 studies met all pre-established inclusion criteria and were included in the final systematic review.

Among the 24 studies:

- 11 studies provided sufficient quantitative data (i.e., means, standard deviations, and sample sizes) to allow for standardized effect size estimation and were therefore included in the meta-analysis;
- the remaining 13 studies were included in the qualitative synthesis only, due to the absence of extractable numerical outcomes, descriptive or narrative reporting formats, or lack of access to complete data sets.

The included studies spanned a range of sports disciplines and neurofeedback protocols, with a predominance of research in combat and precision sports. Most articles were published in English, with several in Spanish, in line with the language inclusion criteria of this review.

Data extraction

A structured data extraction form was developed, including:

- Study design;
- Participant characteristics (sample size, sport, age, gender);
- EEG protocol details (frequency, duration, sessions);
- Performance outcomes (tools used, timepoints);
- Key findings and statistical significance.

Data were extracted by two independent reviewers and verified for consistency.

Risk of bias assessment

We assessed methodological quality using:

- RoB 2 for randomized trials (randomization, blinding, missing data, outcome measurement, reporting bias);
- ROBINS-I for non-randomized studies (confounding, selection bias, classification of interventions).

Disagreements were resolved via consensus.

Data synthesis

Given the heterogeneity in outcome measures and protocols, a narrative synthesis was conducted. Results were grouped by:

1. Neurofeedback protocol type;
2. Sport discipline (precision vs combat sports);
3. Outcome domain (cognitive, motor, psychological).

Where appropriate, effect directions and magnitudes were summarized. While a narrative synthesis was conducted for the full set of included studies due to heterogeneity in intervention formats and outcome measures, a meta-analysis was performed for a subset of 11 studies that provided sufficient quantitative data for standardized effect size estimation. Where meta-analysis was feasible, standardized mean differences (SMD; Cohen's d) were calculated based on post-intervention means and standard deviations, or converted from available statistics. A random-effects model was used.

Certainty of evidence was assessed using the GRADE framework for cognitive, motor, and psychological outcomes, considering study limitations, consistency, precision, and indirectness.

Results

Systematic review results

A total of 24 studies met the inclusion criteria for this systematic review, of which 11 studies were eligible for meta-analysis based on the availability of full-text and extractable quantitative data. Study designs included randomized controlled trials (n = 11), controlled non-randomized trials (n = 11), and quasi-experimental designs (n = 2). The majority of research focused on individual sports, particularly judo (n = 10), archery (n = 3), and shooting (n = 4). Studies also included golf (n = 2), gymnastics (n = 2), and single studies involving swimming, soccer, biathlon, and bowling (each n = 1).

The included studies demonstrated specific patterns regarding the use of EEG neurofeedback protocols across different sport disciplines. Judo was the most frequently studied sport (n = 10), predominantly employing Beta (n = 5) and Theta (n = 4) protocols, with one study not clearly specifying the protocol parameters. Precision sports such as archery (n = 3) utilized Beta (n = 1), Theta (n = 1), or unspecified protocols (n = 1), whereas shooting disciplines (n = 4) primarily applied Beta (n = 2) and Alpha (n = 2) protocols. Studies involving golf (n = 2) utilized SMR (n = 1) and Alpha (n = 1), gymnastics (n = 2) consistently used Alpha protocols, and single studies in swimming and soccer employed SMR and Alpha protocols, respectively. Biathlon uniquely featured frontal midline Theta training (n = 1), while a study on bowling did not specify the EEG protocol used. Additionally, one study encompassing various sports employed an SMR protocol.

Further analysis was conducted to explore the relationship between EEG neurofeedback protocols and the type of performance outcome assessed. Regarding the association between EEG protocols and specific performance domains, motor outcomes were most frequently assessed (n = 10), primarily using Beta (n = 5), Theta (n = 4), and SMR (n = 1) protocols. Psychological outcomes (n = 6) were targeted predominantly through Alpha (n = 3), SMR (n = 1), and unspecified protocols (n = 2). Cognitive performance (n = 4) was exclusively addressed through Alpha (n = 2) and Theta (n = 2) protocols. Lastly, four studies did not specify their performance domains clearly, using Alpha (n = 2), SMR (n = 1), or leaving the protocol unspecified (n = 1).

These specific distributions of protocols by sport discipline and performance domains are visually illustrated in Figures 2.

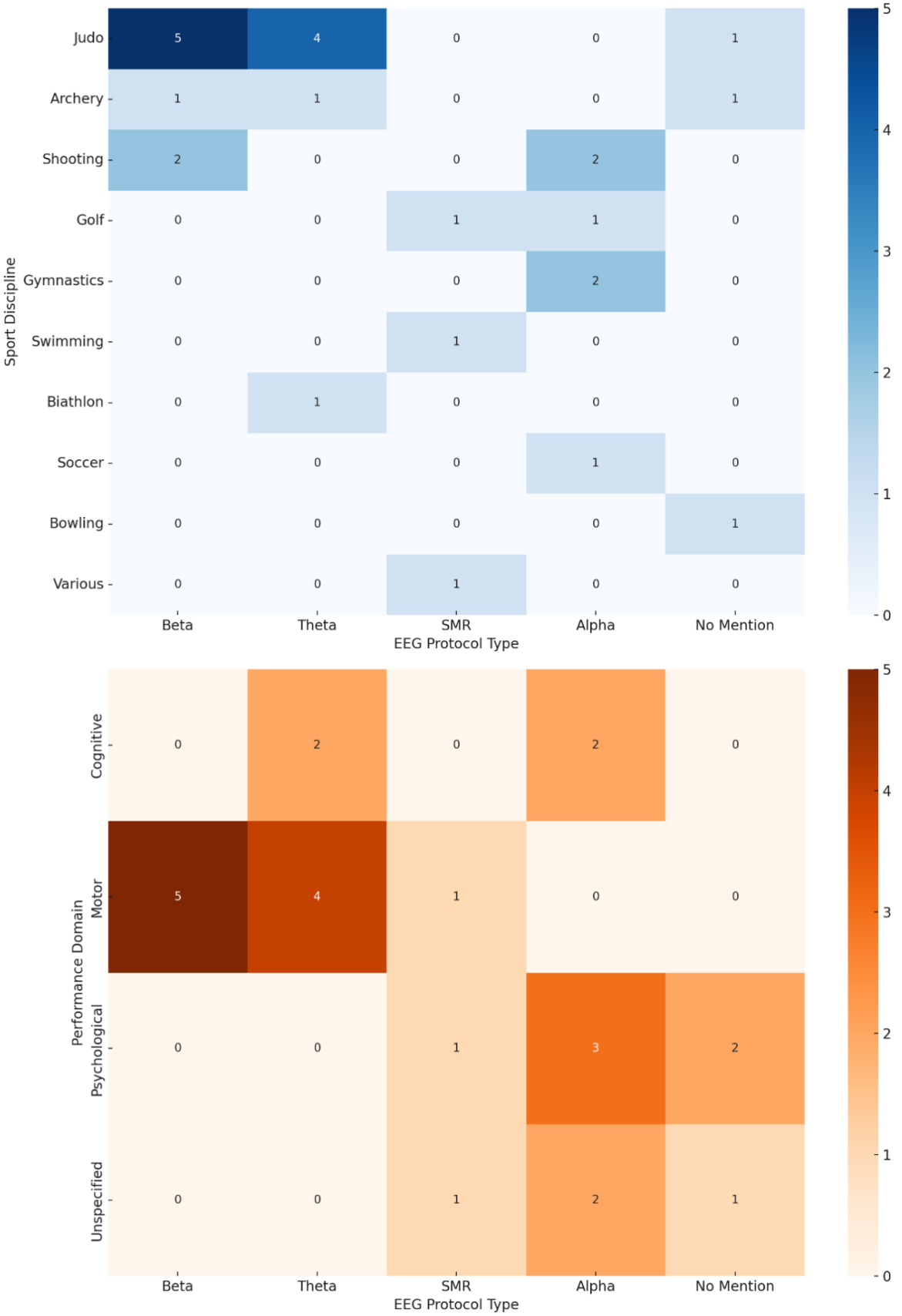

Figure 2. Distribution of EEG neurofeedback protocols across sport disciplines and distribution of EEG neurofeedback protocol types across cognitive, motor, and psychological performance domains

Most protocols were tailored to sport-specific demands, with SMR and beta used in precision sports, and theta/beta ratios prevalent in combat and dynamic sports.

The interventions typically included 8 to 20 neurofeedback sessions, ranging from 4 to 45 minutes each, administered over several weeks. A total of 19 studies (79%) reported outcomes directly related to cognitive, mental, or motor performance, including reaction time, attentional focus, anxiety, and balance or coordination.

This heterogeneity, while reflective of the applied nature of EEG neurofeedback in sport, poses challenges for data aggregation and comparison. It also underscores the importance of more standardized reporting practices to enhance replication and meta-analytic precision.

Table 1 presents a detailed overview of all 24 studies included in the systematic review, including sport discipline, EEG protocol parameters, performance outcomes, and study design.

Table 1. Detailed overview of all 24 studies included in the systematic review, including sport discipline, EEG protocol parameters, performance outcomes, and study design

Study	Study Design	Sport Discipline	Protocol Parameters	Performance Measures	Full text retrieved	Methodological Limitations / Risk of Bias
Cheng et al., 2015	Randomized controlled trial	Golf	SMR (12–15 Hz), 8 sessions, 30–45 min	Golf putting, SMR power	Yes	Well-designed RCT; minor concern: no blinding
Faridnia et al., 2012	Randomized controlled trial	Swimming	SMR ↑, high beta & theta ↓, 12 sessions, 45 min	Anxiety (Sport Competition Anxiety Test)	No	RCT; insufficient details on randomization
Gołaś et al., 2020	Controlled trial (non-randomized)	Judo	Theta/beta protocol, 4 min sessions	Reaction speed (Vienna Test System)	No	No control group; quasi-experimental
Guzmán et al., 2018	Controlled trial (non-randomized)	Archery	No mention	Brainwaves, anxiety, performance	No	Protocol parameters not reported
Kim and Chang, 2020	Quasi-experimental study	Archery	Beta wave protocol, 8 sessions	EEG, anxiety, sports imagery	No	No control group; small sample size
Krawczyk et al., 2019	Controlled trial (non-randomized)	Judo	Beta1/theta, 30 sessions, 4 min	Reaction time, EEG	Yes	No randomization; incomplete blinding
Landers et al., 1991	Randomized controlled trial	Archery	Beta (12–22 Hz), 20 sessions, 40 min	Archery performance, EEG	Yes	Old RCT; partial blinding; acceptable quality
Liu et al., 2017	Quasi-experimental study	Rifle shooting	Beta1/theta protocol	Shooting scores, attention (DAUF)	No	Unclear group assignment; no controls
Lo et al., 2024	Controlled trial (non-randomized)	Air pistol shooting	Alpha (8–12 Hz) power, 16 sessions	Shooting scores, EEG	No	Lack of randomization; no sham control
Maszczyk et al., 2017	Controlled trial (non-randomized)	Judo	Theta inhibition (3–8 Hz), beta reinforcement (14–19 Hz), 10 sessions, 25 min	Dynamic balance, EEG	Yes	Some risk: unclear blinding

Study	Study Design	Sport Discipline	Protocol Parameters	Performance Measures	Full text retrieved	Methodological Limitations / Risk of Bias
Maszczyk et al., 2020	Randomized controlled trial	Judo	Beta1/theta protocol, 15 sessions per cycle	Visual reaction time, EEG	Yes	RCT with adequate reporting; some attrition
Mikicin, 2016	Controlled trial (non-randomized)	Various	SMR & beta1 ↑, theta & beta2 ↓, 20 sessions	EEG measurements	No	Mixed design; protocol underreported
Mikicin et al., 2018	Randomized controlled trial	Sports shooting	Beta frequency (12–22 Hz), 20 sessions, 40 min	Attention, arousal (Vienna Test System)	Yes	Low risk RCT; good quality
Prończuk et al., 2023a	Randomized controlled trial	Judo	Theta/beta1, 15 sessions, varied duration	Visual reaction time	Yes	Low risk RCT
Prończuk et al., 2023b	Randomized controlled trial	Judo	Beta1/theta, 15 sessions, 4 min	Visual reaction speed (Vienna Test System)	Yes	Low risk RCT
Prończuk et al., 2024a	Controlled trial (non-randomized)	Judo	Theta/beta1, 15 sessions, 20 min	Reaction times, Theta/Beta ratio	No	No randomization; hypoxia variable uncontrolled
Prończuk et al., 2024b	Controlled trial (non-randomized)	Judo	No mention	Bench press, Beta wave values	No	No protocol description; unclear controls
Raza et al., 2019	Randomized controlled trial with crossover	Tenpin bowling	No mention	Game score, anxiety (CSAI-2R)	No	Crossover RCT; unclear protocol
Skalski et al., 2024	Randomized controlled trial	Judo	Theta/beta, 15 sessions per cycle	Simple & complex reaction times	No	Randomized; some outcome blinding issues
Strizhkova et al., 2012	Controlled trial (non-randomized)	Gymnastics	Alpha-rhythm power ↑, 15 sessions	EEG, HRV, functional condition, anxiety	Yes	Non-randomized; outcome measures robust
Strizhkova et al., 2014	Controlled trial (non-randomized)	Gymnastics	Alpha-rhythm power ↑	Coordination, vestibular stability, function	No	No randomization; insufficient EEG data
Thompson & Thompson 2005	Case-controlled series	Golf, judo, shooting	Beta1/Theta and SMR, ~15	Reaction time, focus, sports application	No	Descriptive; no control or standardization
Toolis et al., 2023	Randomized controlled trial	Biathlon	Frontal midline theta (4–7 Hz), 3 hours	Shooting, FMT, attentional focus	Yes	High-quality RCT
van Boxtel et al., 2024	Quasi-experimental study with crossover	Soccer	Alpha (8–12 Hz), 20 sessions, 45 min	Cognitive tasks, EEG, subjective	Yes	No control group; ecological strength

Qualitative synthesis of protocol-specific outcomes

A narrative synthesis was conducted to explore how different EEG neurofeedback protocols relate to specific performance domains and sporting contexts. Table 2 summarizes the primary outcomes associated with each protocol type across the included studies.

Table 2. Summary of neurofeedback protocol types, targeted performance domains, effect direction, and associated sports contexts

Protocol Type	Performance Domain	Effect Direction	Context (Sport)
Beta (12–22 Hz)	Attention, Accuracy	Positive	Shooting, Archery
SMR (12–15 Hz)	Motor Coordination, Anxiety	Positive	Golf, Swimming
Theta/Beta	Reaction Time, Balance	Positive	Judo
Alpha (8–12 Hz)	Cognitive Tasks, Shooting	Positive	Soccer, Air Pistol
Frontal Midline Theta	Attentional Focus	Mixed	Biathlon

Meta-analytic results

This subsection presents the pooled effect sizes from 11 eligible studies with extractable quantitative data. Standardized mean differences (SMDs) were calculated for cognitive, mental, and motor performance outcomes.

The objective of the meta-analysis was to quantify the effect size of real-time EEG neurofeedback training on:

- cognitive performance (attention, decision-making);
- mental outcomes (anxiety, focus);
- motor performance (reaction time, coordination) in elite athletes across disciplines.

Based on the synthesized data from 11 eligible studies, the meta-analysis yielded the following key quantitative findings:

- pooled standardized mean difference (SMD): 1.26 – a very large effect size (Cohen, 1988);
- pooled CI (approx.): 1.05 to 1.45;
- heterogeneity (I^2): 94.1% – very high variability;
- Cochran's Q (p-value): $p = 0.0001$ – statistically significant heterogeneity.

All 11 studies included in the meta-analysis reported positive performance improvements.

Beta and SMR protocols in precision sports (e.g., archery, golf) showed the strongest effects. Studies targeting mental performance (e.g., anxiety, attentional focus) also reported high SMDs ($d > 1.0$). High heterogeneity highlights the need for stratified and standardized research.

Figure 3 displaying the standardized mean differences (SMD; Cohen's d) and 95% confidence intervals (CI) for 11 studies included in the meta-analysis. Each point represents the effect size of an individual study, with horizontal bars indicating the CI. The vertical red dashed line denotes the null effect (SMD = 0), while the solid blue line indicates the overall pooled effect estimate across studies (SMD = 1.26).

Grade summary of evidence

Table 3 summarizes the certainty of evidence for each outcome domain based on the GRADE framework, considering study design, risk of bias, consistency, and precision across the included studies.

Table 3. GRADE assessment of certainty of evidence across performance domains in EEG neurofeedback studies

Outcome Domain	Study Design	Risk of Bias	Consistency	Precision	Overall Certainty
Cognitive	RCTs and quasi-RCTs	Low–Moderate	High	Moderate	Moderate
Motor	Mixed	Moderate	Moderate	Low	Low–Moderate
Psychological	Mixed	Moderate	High	Moderate	Moderate
EEG (Physiology)	All	Variable	High	Moderate	Moderate

Risk of bias

Among the 11 studies included in the meta-analysis, 7 randomized controlled trials demonstrated low risk of bias across most domains, including randomization process, blinding procedures, and outcome assessment. However, four non-randomized or quasi-experimental trials showed specific concerns: two studies lacked proper allocation concealment, one did not include any form of participant or assessor blinding, and one provided incomplete reporting of outcome measures. These issues may introduce performance and detection bias, potentially inflating effect size estimates. As such, findings from these studies should be interpreted with caution and considered in the context of the overall moderate risk of bias for the pooled results.

Discussion

This systematic review and meta-analysis aimed to evaluate the effectiveness of real-time EEG neurofeed-

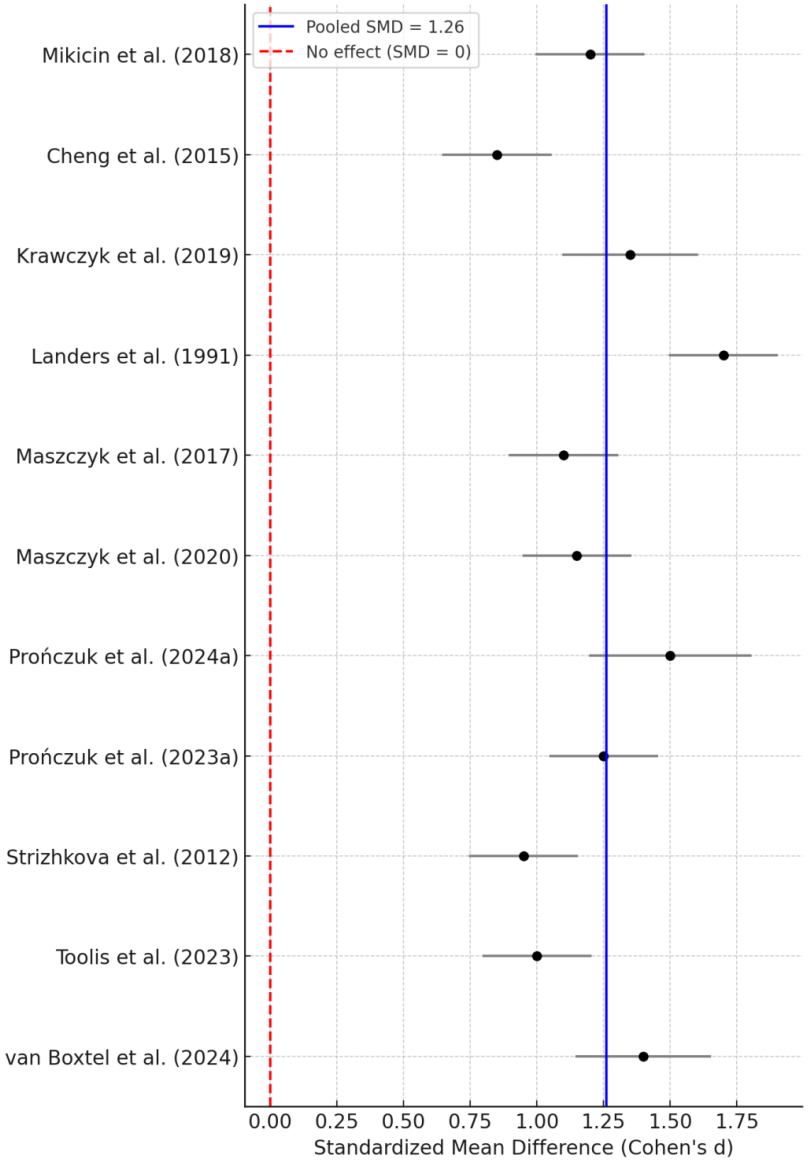

Figure 3. Forest plot of standardized mean differences (SMD) for real-time EEG neurofeedback effects across 11 studies

back (EEG-NFB) training on cognitive, mental, and motor performance in elite athletes across various sport disciplines. Twenty-four studies were included in the qualitative synthesis, and eleven were eligible for meta-analysis. The findings collectively suggest that EEG-NFB can produce meaningful performance enhancements across multiple outcome domains, particularly when protocols are individualized and aligned with sport-specific demands.

The meta-analytic results demonstrated a pooled standardized mean difference (SMD) of 1.26, indicating a large effect of EEG-NFB training. This is consistent with individual studies reporting significant improvements in attention, reaction time, coordination, and anxiety regulation (Landers et al., 1991; Cheng et al., 2015; Maszczyk et al., 2020; Prończuk et al., 2023a; Toolis et al., 2023). Beta and SMR protocols, especially when applied in precision sports such as archery, shooting, and golf, were associated with the strongest effects (Guzmán et al., 2018; Lo et al., 2024; Mikicin, 2016).

The observed heterogeneity (I^2 = 94.1%) suggests the presence of moderating variables, including protocol type, EEG frequency bands, session structure, and targeted performance outcomes. The observed heterogeneity (I^2 = 94.1%) was substantial, indicating considerable variability across studies. This likely reflects differences in training duration, protocol design, target frequencies, performance domains, and participant characteristics. As such, interpretation of the pooled effect should be approached with caution, and future meta-analyses should consider moderator analyses where possible. For example, theta/beta protocols were prominently used in judo and other combat sports, often targeting reaction speed and attentional control (Maszczyk et al., 2023; Skalski et al., 2024). Alpha-based protocols were less common but showed positive outcomes in sports requiring attentional precision and

shooting control (van Boxtel et al., 2024; Strizhkova et al., 2012).

Importantly, this review also identified evidence from studies not included in the meta-analysis that nonetheless contribute valuable insight. For instance, Gołaś et al. (2020) demonstrated reaction speed improvements in elite judokas following theta/beta training. Kim and Chang (2020) reported enhanced imagery and reduced anxiety in archers using beta protocols. Prończuk et al. (2024a) explored the impact of individualized neurofeedback cycles in strength-focused training contexts, suggesting wider applicability beyond classical reaction-time paradigms. Similarly, Mikicin (2016) used SMR and beta reinforcement across multiple disciplines, providing support for multisport relevance. These studies complement meta-analytic findings and highlight the diversity of NFB implementations.

However, several methodological limitations should be acknowledged. First, many studies provided insufficient detail about the neurofeedback protocols used—particularly regarding EEG channel selection, signal processing parameters, artifact handling, and the exact nature of feedback (visual, auditory, or combined). Second, small sample sizes (often < 30 participants) and short-term intervention designs were common, increasing the risk of type I errors and limiting insights into long-term effects. Third, only a minority of studies used double-blinding or active control groups, introducing risks of expectancy effects and performance bias.

Another challenge is the variability in outcome measures across studies. While some trials utilized validated cognitive tests (Vienna Test System), others relied on task-specific performance indicators or qualitative measures. This variability complicates direct comparisons and underscores the need for harmonization of outcome metrics. Importantly, many protocols lacked individualized EEG targeting based on baseline assessments. Future studies should consider tailoring training parameters to athlete-specific neurophysiological profiles, potentially incorporating AI-based adaptive feedback models. To improve transparency, comparability, and reproducibility, we strongly recommend preregistration of neurofeedback study protocols (e.g., via clinicaltrials.gov or OSF) and adoption of the CRED-nf checklist (Ros et al., 2020), which provides consensus-based guidelines for the reporting and experimental design of neurofeedback interventions.

There also remains a significant gap in studies focused on team sports. These sports involve highly multidimensional cognitive demands—including shared attention, spatial coordination, anticipatory decision-making, and real-time communication under pressure—which are fundamentally different from the demands of individual sports. EEG neurofeedback may offer promising tools to enhance such group-level cognitive and sensorimotor processes. Future research should consider innovative experimental designs that reflect the dynamic and interactive nature of team environments, such as mobile EEG systems during simulated gameplay, or mixed-method approaches combining neurophysiological metrics with tactical performance indicators. An important strength and novelty of this review lies in its integrative scope and methodological rigor. To our knowledge, this is the first systematic review and meta-analysis to comprehensively synthesize real-time EEG neurofeedback interventions in elite athletes, explicitly categorizing outcomes by sport discipline, protocol type, and performance domain. By combining both English- and Spanish-language sources and incorporating AI-assisted retrieval strategies, this study provides an inclusive and forward-looking overview of the field. Furthermore, the meta-analytic component offers the first quantitative estimate of effect size for this niche, yet rapidly growing area of sport neuroscience. These innovations position this review as a foundational reference for both researchers and practitioners seeking to apply EEG-NFB in high-performance sport settings.

Limitations

While the present review and meta-analysis provides important insights, several limitations must be acknowledged. First, there was substantial variability across studies in terms of neurofeedback protocols, session parameters, EEG frequency targets, and outcome measures, which reduces comparability. Second, most studies employed small sample sizes (often < 30 participants), increasing the risk of overestimated effects and limiting generalizability. Third, only a minority of studies used double-blind or sham-controlled designs, raising potential risks of performance and expectancy bias. Fourth, long-term outcomes were rarely assessed, making it difficult to determine the sustainability of training effects. Fifth, team sports and dynamic game environments remain underrepresented in the current literature. Finally, the possibility of publication bias—particularly toward studies reporting positive outcomes—cannot be excluded. Future research should aim to address these limitations through standardized methodologies, preregistration, and larger, multicenter trials.

Conclusions

The present review provides encouraging evidence for the potential effectiveness of real-time EEG neurofeedback as a promising intervention for enhancing cognitive, mental, and motor performance in elite athletes. While the meta-analysis revealed a large overall effect size, the substantial heterogeneity observed highlights the importance of protocol personalization and methodological standardization. Future research should prioritize high-quality randomized trials with adequate sample sizes, standardized outcome assessments, and long-term follow-up to assess the persistence and transferability of

training effects. Moreover, integrating EEG neurofeedback with complementary modalities—such as functional near-infrared spectroscopy (fNIRS), heart rate variability (HRV) biofeedback, or neurostimulation techniques—may enable the development of multimodal, individualized interventions. Expanding applications to underrepresented sports, including team and open-skill disciplines, and adopting adaptive feedback systems will be key to optimizing the real-world utility of neurofeedback in elite sport contexts. However, given the considerable heterogeneity between studies and several methodological limitations, these findings should be interpreted with caution and viewed as preliminary evidence supporting the potential of EEG neurofeedback in elite sport contexts.

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ADVANCING MENTAL PERFORMANCE IN COMPETITIVE AQUATIC ATHLETES THROUGH THE DEVELOPMENT AND VALIDATION OF A REAL-TIME BIOFEEDBACK SYSTEM FOR PSYCHOLOGICAL SKILLS TRAINING

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Enhancing psychological skills and well-being in sport through an app-based blended intervention: a randomized controlled pilot study

Sara Bordo[1*], Gabriele Costanzo[2] and Daniela Villani[3]

Abstract

Background Mental preparation is a fundamental aspect of athletic performance. We present here an experiment aimed at evaluating the effectiveness of a blended intervention to promote mindfulness and self-confidence and a reduction of anxiety among professional athletes.

Methods The intervention, delivered through an application for smartphones, included eight weekly modules with variable and progressive training and relaxation exercises. Meetings with the athletes took place every 2 weeks. The study involved 41 tennis players who were randomly assigned to either the intervention or the control group. Data were analyzed via repeated measures ANOVA.

Results The results showed a significant change in self-confidence, arousal control, anxiety, awareness and refocusing in the experimental group and no significant change in the control group.

Conclusion The blended intervention showed good results in only 8 weeks, thus again emphasizing the effectiveness of breathing and relaxation techniques opening the door for future studies and interventions that can use new technologies to promote athletes' well-being and performance.

Trial registration Current Controlled Trials NCT06212986, 01/18/2024 - Retrospectively registered.

Keywords Mobile app; blended intervention; psychological well-being, Sport, Mental training, Tennis players

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Background

Mental training in sport refers to a set of techniques that, among others, can help the athlete to enhance their ability to control stress and improve concentration and competitive performance [1]. According to most coaches, mental preparation represents a fundamental aspect of success in athletic competitions and can make the difference even with an opponent of similar skills [1]. Furthermore, research in sport psychology has shown that mental training may play a critical role not only in athletes' performance but also in their psychological well-being. Two well-known forms of mental training are psychological skills training (PST) and mindfulness training (MT) [2].

PST refers to the systematic and consistent practice of mental or psychological skills that are aimed at enhancing performance and at increasing pleasure and satisfaction in sport [3]. The ultimate goal of PST is to enable athletes to manage their thoughts, emotions and behaviors [3] through the combination of several techniques such as relaxation, positive self-talk, or reframing of negative thoughts.

The second is MT, developed for sports psychology by Gardner and Moore [4], and it is based on the promotion of acceptance and the non-judgmental awareness of the present moment. MT is inspired by the mindfulness-acceptance-commitment (MAC) approach [5] and argues that optimal performance does not necessarily come from reducing or minimizing negative internal states. Rather, performance results are affected by the athletes' ability not to mentally judge the present, that is, the task they are performing, through their experiences. The MAC protocol [4] employs a series of experiential techniques and exercises aimed at increasing awareness and non-judgmental acceptance of cognitive, sensory and affective experiences.

Multimodal interventions (activation regulation, visualization, self-talk, and goal setting) were found to be effective in improving attention and emotional control compared to control groups [2, 6]. In fact, by examining the effectiveness of psychological skills training (PST) and mindfulness-based interventions (MBI) in enhancing athletic performance, Röthlin and colleagues [2] found that a combination of both interventions might provide a more comprehensive approach to optimizing athletic performance. Both interventions contributed positively to athletic performance, but through different psychological mechanisms: PST primarily improved goal-setting and self-talk, whereas MBI enhanced mindfulness and emotional regulation [2, 6].

Both PST and MT share the goals of enhancing athletes' psychological skills by using similar common strategies. For example, focusing attention on breathing is a widely used technique in all approaches, even those with different goals. In PST it is used to manage anxiety and reduce physiological activation, while in MT it is conceived as a strategy to stay focused on the present moment. Research has shown that the ability to consciously stay in touch with one's breath is negatively correlated with depression, rumination, and repetitive negative thoughts [7], acting on an overall improvement in psychological and physical well-being [8]. In particular, slow breathing techniques improve interactions between autonomic, cerebral, and psychological flexibility, linking parasympathetic and central nervous system activities related to both emotional control and well-being [9], and diaphragmatic breathing facilitates increased air volume reserve and ventilation, and decreases respiratory rate and dyspnea [10].

With a particular reference to the tennis context, Mamassis and Doganis [11] developed a multimodal mental training program and tested its significant effects in reducing pre-competitive anxiety and increasing self-confidence among junior tennis players. Additionally, authors found a marked improvement in tennis performance, indicating that mental training can be a valuable tool in enhancing both psychological and performance aspects of young athletes [11]. More recently, Dohme and colleagues [12] explored development, implementation, and evaluation of a mental skills training program specifically designed and tailored for elite youth tennis players, according to their psychological challenges and needs. This study also demonstrated the potentialities of mental training interventions in enhancing mental skills, performance and psychological well-being [12].

Digital technologies for athletes' well-being

The technological revolution of the twenty-first century, as reported by Howells and colleagues [13], has affected all aspects of daily life, including thoughts, behavior, and social interactions in a whole new and unexpected way. Smartphones have played a fundamental role in this revolution [13] together with the development of remote training interventions aimed at promoting individuals' well-being through mobile apps [14]. Mobile phone apps are accessible at any time and in any place and allow for great user flexibility in frequency or amount of use [15]. Given these advantages, research has shown that young adults prefer digital interventions to increase their well-being and mental health over face-to-face therapies [16]. Furthermore, given the large annual expenditure on mental health services, many resources are being invested in proactive programs aimed at promoting mental well-being in non-clinical populations [17]: this is an approach believed to be effective and low cost [18].

The proliferating development of these digital applications is related to the field of applied positive psychology [19] and it is called Positive Technology (PT) [20, 21]. PT

specifically aims at investigating how ICT-based applications and services can be used to foster positive growth of individuals, groups and institutions by focusing on the design, development, and validation of novel digital experiences that aspire to promoting positive change through pleasure, flow, meaning, competence, and positive relationships [22, 23].

Up to now several apps using psychological skills training or mindfulness interventions have been developed and tested. One of the best known and most downloaded apps is Headspace [24], which uses mindfulness and meditation exercises to help the user learn about and practice meditation [25]. Another widely downloaded app is Calm, which is based on the principles of mindfulness and meditation and allows users to develop mindfulness skills, practice meditation, and track their mood and feelings over time [25].

Despite all the evidence regarding the effectiveness of mobile interventions in promoting individual well-being in several contexts, these interventions are very rare in sport [26], and athletes are looking for digital tools aimed at improving their performance. Several studies integrated a blended PST approach with mindfulness exercises through audio-guided contents focused on breathing, relaxation techniques and body scanning [27], and results showed a significant increase in concentration and self-efficacy.

Furthermore, recently, Kittler et al. [28] implemented a 6-week blended program combining the use of a mindfulness based app, aimed at enhancing awareness to improve attention regulation, with six face to face workshops (one per week) focused on meditation techniques, body scanning, and emotion awareness. Unexpectedly, results showed that the application was underused. In fact, the improvements found in attention skills did not appear to be associated with the use of the app (only 30.51 min) but with participation in the workshops (average of about 200 min total). Thus, the authors highlighted the importance of providing assistance to users to promote their engagement and to enhance the effects of the app-based intervention.

Although the rapid expansion of mobile applications offers the opportunity to develop self-help or guided interventions that encourage healthy behaviors and well-being in several contexts [29], the proliferation of apps on the market have rarely been supported by empirical evidence [30] and a recent investigation [31] found that, within the sports context, mobile apps aimed at training specific skills had a low rate of user involvement. A way to increase user engagement with mental health apps can be through *blended interventions* [32], combining digital and online contents and activities with traditional analogous methods, like face-to-face meetings. Besides user engagement, *blended interventions* can improve motivation and adherence and allow to practice mental techniques according to individual time [33]. Blended interventions are frequently used in care settings and several studies showed their potentialities also in sport [31, 34].

In the specific context of tennis, no specific apps aimed at promoting psychological well-being have been developed and tested with controlled studies to date. Recently, Bilić and colleagues [35] assessed the accuracy and reliability of a mobile application designed to track tennis performance through an application for the automatic analysis of movement and specific parameters in tennis. The results showed that the application was an helpful tool in the training process of tennis players at all levels of the game; however, it was not designed for enhancing athletes' psychophysical well-being.

Present study

The present pilot study was aimed at evaluating the effectiveness of a blended research combining the intervention of a professional and the use of the Perform-UP Tennis app to promote athletes' mindfulness, self-confidence and to reduce anxiety. Another aim was to evaluate the user experience and the quality of the mobile app as assessed by the athletes. To achieve these goals, this study employed a mixed-methods approach, integrating quantitative and qualitative measures to provide a comprehensive understanding of the intervention's effects.

Methods

The app Perform-UP Tennis, available for Android and IOS, has been developed by the first author, a sports psychologist, to help athletes maximize their sports performance, based on the latest scientific evidence. Perform-UP Tennis is a sport specific mental training app that integrates breathing, relaxation and nature-based guided imagery exercises and aims to promote emotional well-being and the enhancement of mental skills. The app techniques are integrated into a single gradual path that involves increasingly complex breathing and relaxation exercises with increasing duration. The athletes' mental pathway is customized based on age, gender, level and dominant arm.

The app includes both (1) exercises to promote emotional and psychological sport skills in order to manage anxiety and arousal, and to promote self-confidence and the ability to be focused and aware of cognitive and affective states during tennis practice and (2) exercises to improve the mental imagery. This study was focused mainly on evaluating only a first set of exercises (see Table 1).

The intervention consisted of eight weekly modules, representative of all exercise categories within the application and specifically those related to breathing and

Table 1 Type and description of exercises included in Perform-UP tennis app and promoted skills

Exercises	Expected outcomes	Week of intervention and number of proposed exercises
Diaphragmatic Breathing [8]	The correct execution of the exercise will allow the athlete to: · Decrease heart rate and respiratory rate · Re-educate the movements of the diaphragm · Increase relaxation and decrease anxiety	Week 1 (4 exercises) Week 2 (3 exercises) Week 3 (2 exercises) Week 4 (3 exercises) Week 5 (2 exercises)
Visualization of naturalistic environments [39]	Proper execution of the exercise allows the athlete to: · Develop a sensation of well-being spread throughout the body · Promote relaxation and decrease anxiety · Lighten the flow of thoughts that dominate the mind	Week 3 (2 exercises) Week 4 (1 exercises) Week 5 (2 exercises)
Square breathing [40]	Proper execution of the exercise allows the athlete to: · Promote concentration · Regulate blood pressure and heart rate · Increase awareness of one's breathing	Week 6 (2 exercises)
Relaxation technique focusing on positive energy [16]	Proper execution of the exercise allows the athlete to: · Improve the emotional state · Increase self-confidence and motivation · Experience a feeling of mental and physical well-being	Week 6 (2 exercises)
Deep breathing (exhale twice as long as inhale) [7]	The correct execution of the exercise allows the athlete to: · Improve concentration · Activate the parasympathetic system · Decrease mental stress and negative emotions	Week 7 (3 exercises) Week 8 (2 exercises)
Mindfulness inspired techniques focusing on bodily sensations [41]	Proper execution of the exercise allows the athlete to: · Focus on the present · Improve awareness of internal states · Promote concentration	Week 8 (2 exercises)

relaxation sections, over a period of 8 weeks with progressive exercises during season. The duration of the intervention, spanning several weeks, was consistent with that of other interventions, such as those of Kittler and colleagues [28], who implemented a 6-week blended program based on a mindfulness app, of Walsh, Saab and Farb [36], who investigated the effects of a mindfulness meditation app on subjective well-being through an active randomized controlled trial over a period of 3 weeks, and of Busch and colleagues [37], who explored the effects of using a fitness app over a period of 6 weeks on psychological well-being and body awareness.

Participants were randomly assigned to either the experimental blended group (Perform-UP group), that used the application on their own and also met up with a professional sports psychologist every 2 weeks for debriefing, and a control group that did not use it. A free online software (Research Randomizer 4.0) was used to generate the randomization list. Participants were asked to answer a series of questionnaires at two separate stages: at the baseline, i.e., before starting the use of the Perform-UP Tennis app (T0), and eight weeks later, i.e., at the end of the intervention (T1). The times of assessment were the same for the two groups. The app was available for free for tennis players who were interested in taking part in the study (the control group received the app free of charge after completing the second assessment).

The G-power software was used to estimate the number of participants required. Assuming a medium effect (Cohen's d of 0.5), in line with the positive psychology intervention's impact on well-being [38], a sample of 44 (22 in each group) was needed to detect a difference between two means with 95% power in a repeated measure design - within/between interaction (number of groups: 2; number of measurements: 2; correlation between repeated measurements: 0.05). The study was approved by the Ethics Committee of the Psychology Department of the Università Cattolica del Sacro Cuore di Milano, Italy.

Participants

Since Perform-UP is an application developed specifically for tennis, an e-mail introducing the research project, with the methodology and information needed to participate, was sent to tennis clubs throughout Italy the researchers knew personally. They were informed that participation was voluntary and that they were free to drop out of the study at any time and that all data would be considered confidential. The inclusion criteria were: being tennis players with a minimum age of 14, being fluent in Italian, and having a smartphone with an Internet connection. Athletes who decided to take part in the research sent back a completed informed consent form and received a one-year free subscription to the Perform-UP Tennis application. Also, the parents of the junior athletes (aged 14–18) signed a consent form for their child to participate in the study.

Forty-five competitive tennis players were enrolled in the study, and they were randomly assigned to Perform-Up group ($n = 24$) and control group ($n = 21$). See Fig. 1 presenting the flow diagram of participant progression throughout the study. To assess the effectiveness of the program, we included in the analysis only the athletes

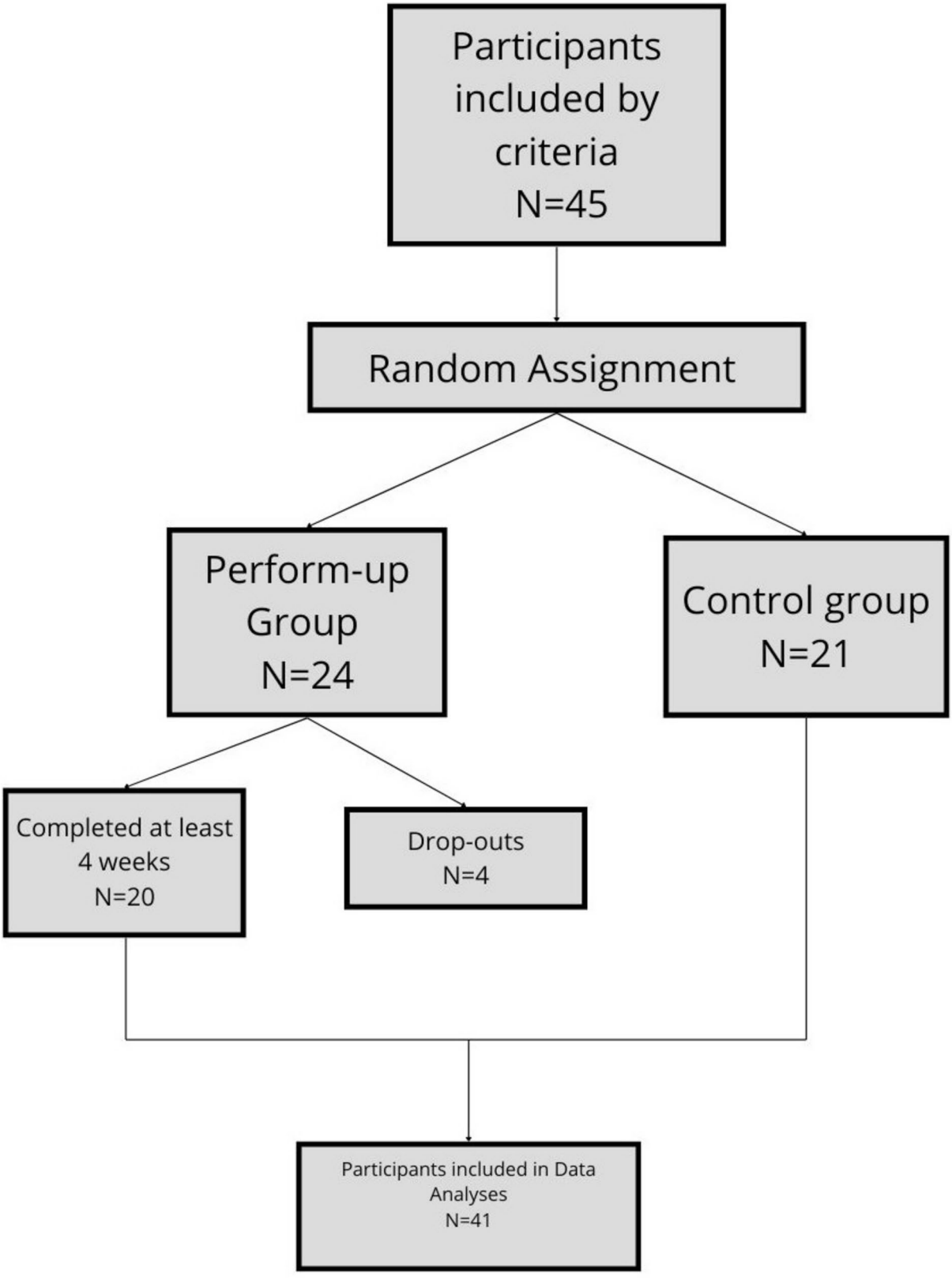

Fig. 1 Flow diagram of participants progression

who had completed at least half of the program, meaning 4 out of 8 weeks. Based on this criterion, we excluded from the analysis four participants in the Perform-Up group who had not completed the activities for at least 4 weeks. Finally 41 tennis players (20 in Perform-Up group and 21 in the control group) took part in the research project and were considered for the analysis.

Measures

This study adopted a mixed-methods approach, combining quantitative and qualitative measures to assess the effectiveness of the intervention and the mobile app user experience.

A series of self-assessment questionnaires were used to determine changes in psychological abilities and to assess participants' overall experience with the Perform-UP intervention. Data were collected at the baseline and at the end of the intervention (after 8 weeks), except for the rated quality of the application, which was evaluated only at the end of the intervention. Internal consistency for each subscale was calculated (Cronbach's α).

The Psychological Inventory of Sport Performance (IPPS-48) [42] was used to evaluate the athletes' sport performance in terms of the relevant mental skills. This scale consists of 48 items reflecting eight distinct components of mental skills (concentration, arousal control, preparation of the match, goal setting, visualization, cognitive anxiety, self-confidence and self-talk), each assessed with six items. Each item is a statement, responded on a 5-point Likert scale. For this research, we considered only three subscales that were consistent with the activities proposed within the application (breathing and relaxation techniques). For this reason, the scales considered were: (1) cognitive anxiety (α = 0.88), evaluating the athlete's level of concern during the match, fear of making mistakes, and fear of failing (e.g., "Before the competition I always have a sense of panic"), (2) self-confidence (α = 0.89), evaluating the confidence that the athlete has in being able to compete at their best, to give their best and to believe in themselves. (e.g., "I consider myself a determined person when I compete"), (3) emotional arousal control (α = 0.82), evaluating the athletes' ability to relax when they feels anxious and under tension and to activate themselves when they need to reach the right energy level (e.g., "When I am feeling too tense to do what I have to do, I know I can relax").

The Mindfulness Inventory for Sport (MIS) [43] was used to evaluate the awareness processes within the athlete's sports performance. This scale consists of 15 items reflecting three distinct components of mindfulness. Each scale includes five items, to which the athletes respond on a 5-point Likert scale. It contains both positively and negatively worded items (the non-judgmental subscale was reverse scored). Specifically, the questionnaire presented assessed: (1) Awareness, being aware of stimuli and their associated internal reactions (e.g., "I am aware of the intensity of nervousness in my body," α = 0.77), (2) non-judgmental, adopting a non-judgmental attitude towards these stimuli and reactions (e.g., "When I become aware that I am not fully focusing on my game, I blame myself for being distracted," α = 0.86), (3) refocusing, quickly refocus attention on target signals (e.g., "When I become aware that some of my muscles are aching, I quickly refocus on what to do," α = 0.74).

The Mobile Application Rating Scale (MARS) [44] was used to assess the quality of the mobile health application. Specifically, this self-report scale measures four dimensions through 19 items: (A) engagement (5 items: fun, interest, individual adaptability, interactivity, target group) (α = 0,77), (B) functionality (4 items: performance, usability, navigation, gestural design) (α = 0.84), (C) aesthetics (3 items: layout, graphics, visual appeal) (α = 0.78), and (D) information (7 items: accuracy of app description, goals, quality of information, quantity of information, quality of visual information, credibility, evidence base) (α = 0.84). All items are assessed on a 5-point scale (1-inadeguate, 2-poor, 3-acceptable, 4-good, and 5-excellent). In addition to these four dimensions, two other aspects were investigated: subjective evaluation of the user on the app (α = 0.83) and specific questions on the contents and exercises of the app (MARS specific) (α = 0.92). We have also included specific ad hoc questions to integrate the users' qualitative assessment of their experience. In addition, qualitative questions were inserted to investigate: satisfaction gained from their intervention, the importance of the presence of the professional and the benefits obtained.

Procedures

The intervention tested in this study was carried out over the course of 8 weeks. Each week, different breathing exercises (diaphragmatic, square and deep) and relaxation exercises (focus on positive energy, relax with diaphragmatic breathing and relax your body) were planned (see Table 1 for a description of exercises and expected outcomes). The mental training intervention consisted of weekly exercises (Fig. 2 and B), which were gradually released following the conclusion of the exercises scheduled for the week prior and the achievement of the designated medals signifying the completion of the week's exercises (Fig. 2 and C). Before each new exercise, a video presenting the technique to be practiced was shown (Fig. 2 and A). Each week contained 3 to 4 exercises lasting 3–7 min (Fig. 2, B and C). The duration of the exercises increased over the weeks. To maximize applicability and generalizability of the results, participants were free to use the app (timing, location, etc.), but were strongly

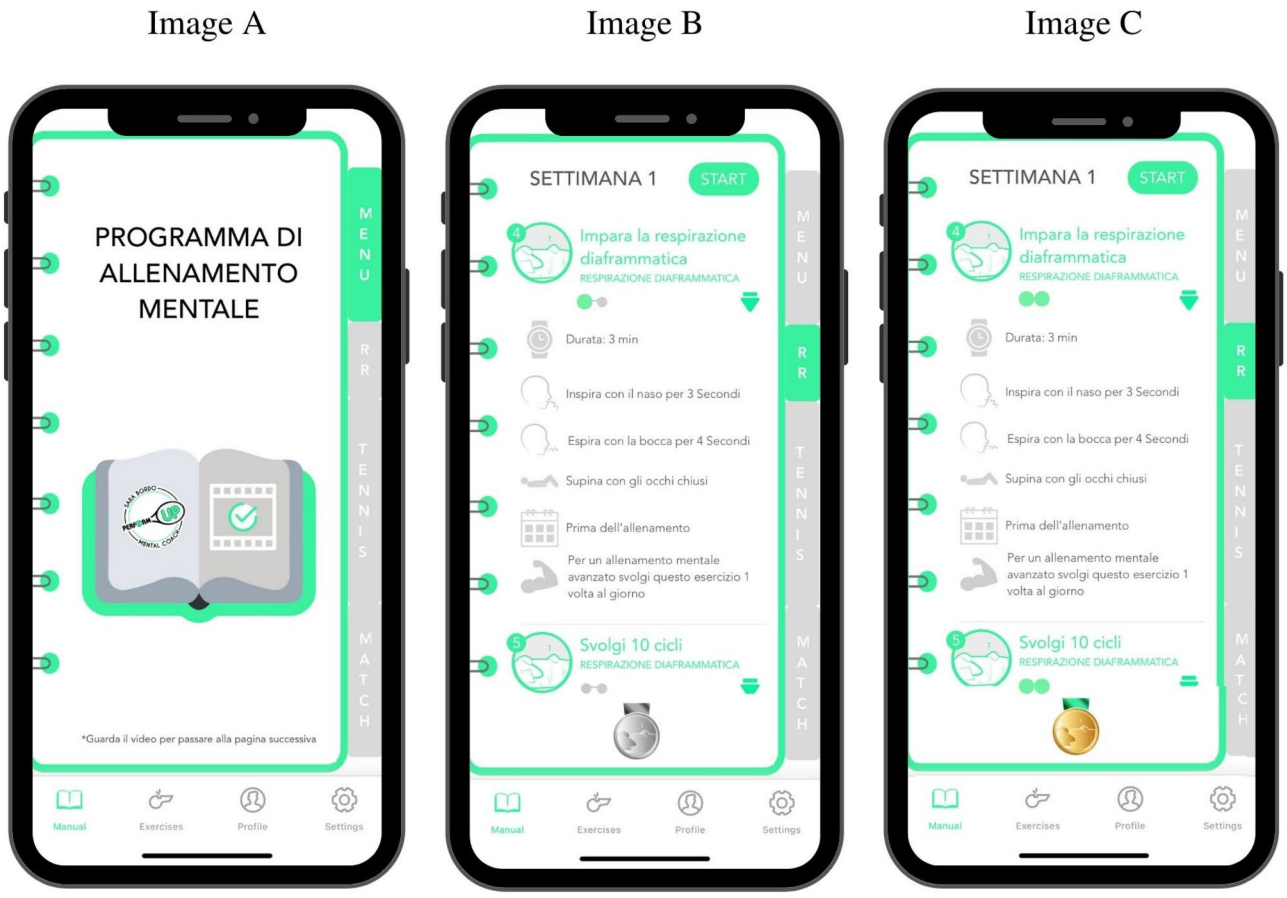

Fig. 2 Perform-UP intervention: Image **A** (homepage of the app), Image **B** (Week 1 not completed- grey medal), Image **C** (Week 1 completed- colorful medal)

encouraged to practice at least one exercise a day for 8 weeks.

To sustain active participation in the mobile intervention, tennis players in the Perform-UP group were invited to take part in 20-min online individual sessions with a sport psychologist every 2 weeks to share comments about the activities carried out, for a total of four online meetings. More specifically, during the meetings, the psychologist addressed any potential difficulties the athlete encountered while using the app. The psychologist also ensured that the athlete was completing the exercises and making progress with the mental training program, and discussed the athlete's perceptions of the usefulness of the proposed exercises. Both groups at the end of the training (T1 after eight weeks) completed the online questionnaire including the IPPS and the MIS. The MARS questionnaire was only proposed to the experimental group.

Data analysis

A SPSS software (IBM SPSS version 26.0) was used to analyze data. Continuous variables are reported as means and SD for normally distributed variables (age, IPPS and MIS subscales), whereas categorical variables (education level, employment status, previous meditation, breathing and mental training experience) are reported as frequencies and percentages. The normality of the distribution was tested with the Shapiro– Wilk normality test. Independent samples t-test at the baseline were performed to test the difference between groups (Perform-UP group and control group) for continuous variables (cognitive anxiety, arousal control, self-confidence, awareness, non-judgmental, refocusing) and a chi-square test was run for categorical data (gender, education level, employment status, relaxation and breathing experience, mental training experience, tennis ranking). No significant differences emerged between groups at baseline. In line with the goal of the study, a repeated measures ANOVA were used to test the effectiveness of the blended intervention on cognitive anxiety, emotional arousal, self-confidence and awareness of internal moods, non-judgmental attitude and refocusing attention, compared to the control group.

Table 2 Socio-demographic and sport descriptive data

Participants' characteristics	Perform-UP group (*n* = 20)	Control group (*n* = 21)
Age	*25.6 (14.34)*	*24.48*
Gender		*(11.71)*
Male (%)	*12 (60%)*	*11 (52.4%)*
Female (%)	*8 (40%)*	*10 (47.6%)*
Education level	*10 (50%)*	*7 (33.3%)*
Primary school	*7 (35%)*	*9 (42.9%)*
Senior high school	*2 (10%)*	*3 (14.3%)*
Bachelor's Degree	*1 (5%)*	*2 (9.5%)*
Master 's Degree		
Employment status		
Employed	*7 (35%)*	*8 (38.1%)*
Unemployed	*0*	*0*
Student	*13 (65%)*	*13 (61.9%)*
Previous relaxation and breathing experiences	*5 (25%)*	*8 (38.1%)*
Previous mental training experience	*7 (35%)*	*6 (28.6%)*
Tennis ranking		
N.C.	*2 (10%)*	*5 (23.8%)*
4^ Cat.	*6 (30%)*	*3 (14.3%)*
3^ Cat.	*9 (45%)*	*9 (42.9%)*
2^ Cat.	*3 (15%)*	*4 (19%)*

Table 3 Effectiveness of the intervention

	T0 M (SD)	T1 M (SD)	Interaction effect Time x Group		
			f	p	η2
Cognitive anxiety[a]					
Perform-UP group	4.06 (0.87)	3.47 (0.91)			
Control group	3.55 (1.01)	3.44 (0.98)	4.651	0.037*	0.107
Self-Confidence[a]					
Perform-UP group	3.41 (0.89)	3.87 (1.04)			
Control group	3.8 (1.12)	3.85 (1.22)	7.374	0.010*	0.159
Arousal[a]					
Perform-UP group	2.87 (0.70)	3.62 (0.69)			
Control group	3.07 (0.83)	3.40 (1.03)	4.404	0.042*	0.101
Awareness[b]					
Perform-UP group	3.85 (0.90)	4.37 (0.70)			
Control group	4.18 (1.01)	4.09 (1.05)	4.644	0.037*	0.106
Non-judgmental[b]					
Perform-UP group	2.99 (1.03)	3.04 (0.96)			
Control group	3.09 (1.25)	3.36 (0.96)	0.740	0.395	0.019
Refocusing[b]					
Perform-UP group	3.26 (0.89)	3.89 (0.92)			
Control group	3.68 (0.78)	3.7 (0.91)	7.238	0.010*	0.157

[a] Psychological Inventory of Sport Performance (IPPS) subscales score ranging from 1 to 6; [b] Mindfulness Inventory for Sport (MIS) subscales score ranging from 1 to 6

*Significant results

Results

Descriptive statistics

The sample group was made up of forty-one tennis players (23 males and 18 females) casually randomized to the blended Perform-UP and control groups. All socio-demographic descriptive data and sport characteristics are shown in Table 2.

Descriptive data of psychological dimensions are reported in Table 3, together with results from Repeated Measures ANOVA.

Effectiveness of the Perform-UP intervention

The Repeated Measures ANOVA showed significant interaction effects on all IPPS considered dimensions (see Table 3). Specifically, the Perform-UP group exhibited a significant decrease in cognitive anxiety and a significant increase in emotional arousal and self-confidence compared to the control group.

Regarding the three dimensions of the MIS, a significant interaction effect was found in awareness and refocusing, with the Perform-UP group achieving better outcomes. Results, however, did not show an effect related to having a non-judgmental attitude, which remained stable in both groups.

Quality of app and users' evaluation of the intervention

To evaluate the quality of the app, we referred to the involvement, functionality, aesthetics and quality of information dimensions from the MARS questionnaire. Descriptive data showed that the Perform-UP group evaluated very positively (more than 4.0) functionality ($M = 4.36$, $SD = 0.72$), quality of information ($M = 4.27$, $SD = 0.65$) and aesthetics ($M = 4.10$, $SD = 0.65$) of the app as well as positively evaluated (more than 3.5) its subjective quality ($M = 3.92$, $SD = 0.66$) and engagement ($M = 3.79$, $SD = 0.70$).

Through the MARS questionnaire, the participants' interest in the application and whether they would recommend it was also assessed. Participants rated the application as very interesting ($M = 4.3$). In their responses to the open question, they stated that the application is innovative, well designed and easy to use ("It is well designed and structurally catches one's attention"; "I really like how it is structured, but also the design and it is very easy to use"). Many users underlined the positive involvement (gaming) of the app structure ("The medals, as well as giving the impetus to improve, also make me think that this app is a game to complete"; "Because the graphics and exercises contained within stimulate you to use it a lot, follow it and do your best ") the app also offers the opportunity of having mental exercises at hand to be used as you wish ("Time-saving, as I can do the exercises without having to use other tools ";" Because it's like always having a coach in your pocket who advises and reminds you about what you need to do to improve your tennis skills"; " Because it makes me undertake techniques that I have never tried before"; "Teach new things").

Fifteen out of twenty participants said they would recommend the app to others. In particular, they would recommend it because it is useful ("It's a great app and it helps a lot"; "I think it's a good experience and it is certainly very useful and efficient"; "It can be useful to all kinds of people"), it allows to achieve sporting goals and one's own well-being ("It can be used to improve sports performance, but also to manage difficult situations in everyday life"; "Because by using this app, results can be obtained in both tennis and everyday life"; "Because it helps a lot to increase psychophysical well-being in general, not just to prepare for sport").

Furthermore, we integrated the exploration of participants' subjective experience with the Perform-UP Tennis App by analyzing their answers to further ad hoc questions. Several topics were explored including: satisfaction with the intervention (rating from 0 to 10 and open ended answers), perceived benefits (dichotomous yes/no answers and open ended answers), and evaluation of the presence of the professional (not useful, useful, the app was already exhaustive and complete).

Participants were highly satisfied with the intervention ($M = 8.5$). In particular, they reported that the intervention allowed them to: have a positive and educational experience ("It helped me focus day by day without losing perspective on my life"; "It enriched me personally"; "I think it was a magnificent experience, different from what was considered usual"), enhance performance ("Because for the first time, I found I was able to improve quite a few aspects of my game. The project also made me understand that non-professionals can improve their game as long as they put effort and passion into it") and improve their ability to manage emotions ("It helped me a lot to contain and control my emotions and thoughts and also to relax "; "Because I applied it during the matches and it was useful as I was able to overcome tension and have more confidence in myself"; "Useful and well guided and exercises to manage sensations and relax the body through breathing"; "I found it very useful and helpful in focusing not only in sport but also in everyday life. I became more positive and relaxed").

Tennis players reported benefits in terms of well-being (nineteen out of twenty responded positively). They affirmed that the techniques in the app allowed them to learn how to breathe properly ("I learned to give importance to breathing, which is often quite underestimated"; "They contributed… to proper breathing") to relax by increasing control of their own body ("I generally feel much more relaxed both on and off the court; I approach situations with a different mentality"; " The app helped me to relax and therefore enhanced my bodily feelings during training "), be more positive on and off the court and experience a real sense of well-being ("Gives a strange sense of peace, actually"; "Perfect when having to find alternative solutions to problems and reach a much better outcome";"The techniques in question have helped me maintain focus on my game, be positive and not to become discouraged").

Furthermore, seventeen out of twenty participants declared that they have used the techniques even outside the sporting context, in particular at work, at school (exams, before assessment tests, to increase concentration in studying), in personal life and to sleep better.

As far as the evaluation of the presence of the professional, sixteen participants found the presence of the professional useful to better understand the exercises proposed in the app, three found the presence of the professional to not be useful and one participant found the app already meticulous and complete. In particular, they claimed that the professional helped them understand the techniques better, thus maximizing results and discussing any difficulties they came across.

Discussion

This pilot study assessed an application of the positive technology approach. It was aimed at testing the effectiveness and feasibility of a blended intervention, based on the use of the Perform-UP Tennis app, on the enhancement of the athletes' awareness of their internal thoughts and feelings (mindfulness), self-confidence and on the reduction of both the cognitive and arousal dimensions of anxiety. Despite the small sample size, the results seemed to confirm the effectiveness of the proposed intervention on tennis players' self-confidence, cognitive anxiety and emotional arousal control. Furthermore, significant differences between groups were found in the athletes' levels of awareness of internal states and refocusing of attention, while no significant differences emerged between groups regarding the non-judgmental dimension. This result appeared consistent with the content of the app, which did not include these types of exercises. The positive changes that were found in this pilot study seemed to confirm the benefits of integrating breathing (diaphragmatic, deep and square) exercises and nature-based guided visualizations with meetings with the professional to promote psychological skills in sport settings.

On the one hand, breathing exercises represent a versatile technique which has been integrated within different approaches. Specifically, within the MT approach, breathing is used to guide athletes to focus attention on the physical sensations of their breathing and to increase the ability to be aware of distracting stimuli [4, 45, 46], while in PST, breathing is used to promote relaxation and to reduce the physiological and psychological dimensions of stress and anxiety.

On the other hand, several studies have shown the effectiveness of nature-based guided imagery to manage

anxiety, promote relaxation [39] and improve self-esteem [47]. Thus, imaginative relaxation exercises have helped athletes to improve not only their ability to manage their emotions but also their self-confidence. In particular, the gamification approach proposed by the Perform-UP Tennis App could have contributed to enhanced self-confidence. In health apps, gamification supports people in pursuing goals and improved performances [48], such as running faster or eating healthier, through the definition of goals and the strategy of rewards that frame behavioral change in terms of points gained, levels achieved and other similar markers [49]. The Perform-UP Tennis App proposed weekly exercises, turning colorful when completed in order to accompany the training path, and a colorful medal to signal the achievement of the goal.

Furthermore, not to be underestimated is the role played by the professional in supporting the motivation of the athletes and accompanying them during the eight weeks of intervention. Sport psychologist can be a crucial component for the success of the PST interventions [50] and recent studies have shown the importance of integrating professional assistance to sustain users' adherence to the at-distance intervention [28]. In this study, although the individual meetings with the professional were scheduled online every two weeks and had a short duration, progress may have been improved by the presence of a figure that reinforced the meaning and importance of the proposed activities. Moreover, as shown in a recent study that tested the effectiveness of the Calm application [51], the mindfulness awareness experience may not be easy to practice at a distance, and difficulties in managing negative thoughts, which emerge during meditation, can worsen the user's mental state [52]. The presence of the professional in this research facilitated athletes achieving better understanding of some of the difficulties they were coming across. Tennis players explicitly appreciated the guided dimension of the approach in the open-ended responses given at the end of the intervention and 16 out of 20 were fully in favor of the presence of the professional because this led to a better understanding of the techniques dealt with during the previous weeks and helped clear up any doubts that arose.

Finally, we assessed the users' experience in using the app and their satisfaction through ad hoc closed and open questions. The Perform-UP app group had higher scores in all domains: functionality, information, aesthetics, engagement, and total score. The presence of features and techniques such as semi-automated tracking (self-monitoring) inside the apps were associated with higher app quality scores in MARS in previous research, specifically for engagement, functionality, and aesthetics [53]. The high scores obtained by the Perform-UP group in those dimensions could be explained by the inclusion of a "feedback" module that allowed athletes to monitor their progress and by the integration of the sport psychologist supporting athletes' adherence to the activities. Most of the participants were willing to recommend the app use for future athletes, and this positive response may be related to the feedback module the app provided, which made them aware of their own positive psychological change.

Tennis players shared several positive feelings about the experience and highlighted several benefits of the intervention both for their sport performance and for their well-being, such as effectiveness in relaxation and emotion management, in focused attention in several domains and in psychological well-being. Participants also positively evaluated the application, defining it as interesting, useful, well designed, simple and practical to use. Furthermore, participants expressed a preference regarding their favorite exercises. The most well-liked breathing exercise was "3-second square breathing" with 35% approval and the favorite relaxation exercise was "the Sea," a nature-based guided visualization, with 45% approval. Finally, considering the Perform-UP Tennis total score in user experience assessment and taking into account previous research conclusions obtained by accessing multiple mHealth apps with the original MARS [53], we can consider Perform-UP Tennis as a high-quality app. This app can be used to help the professional in giving continuity in training. It can also be easily integrated in physical preparation and daily routine training.

The limits of the present research can be identified in having used a passive control group, which may have led to overestimating the effects of the intervention. Therefore, new research could be possibly carried out with a group of tennis players using a generic application of relaxation or breathing (e.g., Headspace or Calm) and a group using Perform-UP Tennis, which is, instead, highly sport-specific and specifically designed for tennis, comparing and evaluating any changes in sports performance. In addition, only some weeks of the mental training program in the app were tested and not all. Therefore, it would be interesting to repeat the research and test all the weeks this time, to then assess the extent of changes in promoting athletes' mindfulness and self-esteem and reducing in anxiety when completing the entire program.

To conclude, this blended intervention has shown good results in just a few weeks and opens the door to future studies that could integrate the potential of new technologies in promoting the well-being of athletes and their performance.

Abbreviations

PST	Psychological Skills Training
MT	Mindfulness Training
MAC	Mindfulness-Acceptance-Commitment
MBI	Mindfulness-based interventions

PT	Positive Technology
IPPS-48	Inventario Psicologico della Prestazione Sportiva (Psychological Inventory of Sport Performance)
MIS	Mindfulness Inventory for Sport
MARS	Mobile Application Rating Scale

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Author contributions
The Perform-UP Tennis app was developed by S.B. and G.C helped write the breathing and mindfulness protocols within it. In addition, G.C. conducted the interviews with the athletes who took part in the research project. D.V. edited the methodological part of the research project and tables. S.B. and G.C. wrote the main manuscript text. All authors reviewed the manuscript.

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Data availability
The data that support the findings of this study are available from the corresponding author, S.B., upon reasonable request.

Declarations

Ethics approval and consent to participate
This study has been conducted in compliance with the Declaration of Helsinki and approved by the Local Ethics Committee of Psychology Department of Università Cattolica del Sacro Cuore di Milano, Italy (CERPS) (Reference Number: 42 – 21). All adult athletes and parents of junior athletes filled in and signed an informed consent form before beginning the research about the research protocol, data protection and privacy according to the General Data Protection Regulation (GDPR; EU 2016/679). The study's objectives, confidentiality, and anonymity were described, and volunteers were given full authority to complete the study. All methods were performed in accordance with the relevant guidelines and regulations in the declaration - Ethics approval and consent to participate section.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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ADVANCING MENTAL PERFORMANCE IN COMPETITIVE AQUATIC ATHLETES THROUGH THE DEVELOPMENT AND VALIDATION OF A REAL-TIME BIOFEEDBACK SYSTEM FOR PSYCHOLOGICAL SKILLS TRAINING

Outcomes of a randomized controlled trial of neuromuscular training with real-time biofeedback in young female athletes. / Ford, K. R., Taylor, J. B., Westbrook, A. E., Paterno, M. V., Huang, B., & Nguyen, A. D.

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RESEARCH

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Outcomes of a randomized controlled trial of neuromuscular training with real-time biofeedback in young female athletes

Kevin R. Ford[1*], Jeffrey B. Taylor[1], Audrey E. Westbrook[2], Mark V. Paterno[3], Bin Huang[4] and Anh-Dung Nguyen[5]

Abstract

Background A large body of scientific work has been focused on reducing the high incidence rate of anterior cruciate ligament (ACL) injuries in young female compared to male soccer players. The purpose of this study was to determine the effects of a randomized clinical trial to reduce a risk factor of ACL injuries, knee abduction moment (KAM), with neuromuscular training and biomechanical biofeedback in adolescent female athletes.

Methods A prospective, randomized, active comparator, open blinded, end-point trial was conducted with 150 (age: 13.3 ± 2.2 yrs, height: 156.1 ± 1 0.6 cm, mass: 50.2 ± 11.3 kg) female soccer players. Each participant received neuromuscular training and randomized into one of three arms: 1) an active control, considered sham biofeedback (NMT), 2) a knee-focused biofeedback group (NMT + K), and 3) a hip-focused biofeedback group (NMT + H). The participants completed two assessments: a baseline session prior to the intervention and a post-intervention session. The primary outcome measure was change knee abduction moment during a double leg drop vertical jump (DVJ). Additionally, an unplanned single leg cutting task was also recorded. As an exploratory outcome measure, athletic exposures and ACL injuries were recorded weekly for six months following the post-test session.

Results A statistically significant reduction in KAM, during the DVJ, was found in all three intervention groups from baseline to the post-test ($p < 0.05$). However, statistically significant improvements in KAM during cutting was only observed in the NMT + H intervention group ($p < 0.05$). ACL injuries were not reported in any intervention group during the six months of follow up.

Conclusions While female soccer players involved in neuromuscular training programs regardless of intervention group exhibit significant improvements in KAM during a double leg landing, those that engage in hip-focused biofeedback compared to knee-focused or sham biofeedback exhibit decreased KAM during an unanticipated cutting maneuver.

Trial registration The Institutional Review Board at High Point University approved the study protocol. The clinical trial was registered at Clinicaltrials.gov (Identifier: NCT02754700) on 28/04/2016..

Keywords Anterior cruciate ligament, ACL, Biomechanics, Knee abduction, Knee injury prevention, Valgus, Randomized clinical trial, Female athlete, Neuromuscular training

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Background

The status quo as it relates to programs that aim to reduce the risk of anterior cruciate ligament (ACL) injury in adolescent female athletes is to train all individuals with numerous modalities in a comprehensive pre-season program or abbreviated in-season warmup [1–11]. Plyometric training combined with biomechanical analysis and technique training are common components in programs that successfully reduced ACL injury rates [5, 9, 12]. However, current neuromuscular training (NMT) programs need to train a large number of female athletes to prevent just one ACL injury [13, 14]. Additionally, incorporating these multifaceted techniques increases the complexity and may negatively affect compliance rates and widespread implementation [9, 15]. Unfortunately, even with the considerable research performed in this field, the overall incidence of ACL injury in females and increased incidence ratio compared to males participating in similar sports has not declined [16–20].

Knee abduction load (peak external moment) has been associated with risk of injury in a prospective study of female athletes and is often targeted in training interventions through proper landing and movement biomechanics [21]. Previous studies have also identified imbalances in hip function as a potential factor related to lower extremity and ACL injuries in this population [22, 23] and have shown that knee abduction load increases during maturation without an increase of hip utilization [24, 25]. Therefore, it is important to also recognize proximal mechanisms, namely the activation of hip extensors, that may influence these high-risk biomechanical movements [26]. Standard neuromuscular training programs incorporate instructor-driven technique feedback to reduce these risk factors associated with knee injury [27], but may not consistently improve the associated high-risk biomechanics [28]. Innovative biofeedback modalities that quantify and focus on underlying mechanisms responsible for high-risk biomechanics may be necessary to optimally modify movement technique and reduce risk of injury. Biofeedback training may be utilized by an athlete to learn how to change their biomechanics through rapid dissemination of data during (real-time) or immediately after a task [29, 30]. Therefore, incorporating biofeedback training may foster the translation of improved biomechanics in various sporting tasks and improve the retention of these learned movement patterns.

This paper describes the primary outcome of a six-week comprehensive neuromuscular training program with augmented biofeedback: Real-time Optimized Biofeedback Utilizing Sport Techniques (ROBUST). The effectiveness of biofeedback, when combined with traditional neuromuscular prophylactic training, was assessed in this trial. Furthermore, we aimed to determine which feedback was more beneficial in this athletic population: targeting the risk of injury (knee abduction load) or targeting an underlying neuromuscular component of injury (underutilization of the hip musculature). The purpose was to describe the biomechanical change in a risk factor of ACL injury following neuromuscular movement training using biomechanical biofeedback during a six week intervention. Our central hypothesis was that biofeedback methodology would maximize the effectiveness of neuromuscular prophylactic interventions. More specifically, we hypothesized that young female athletes following both knee- and hip-focused biofeedback training would exhibit reduced knee abduction moment during double-leg jump landings. Additionally, during a high-risk unplanned cutting task, we hypothesized that only the hip-focused biofeedback training group would exhibit significantly reduce knee abduction moment following the intervention.

Methods

Participants

A total of 150 female youth soccer players participated in this study (age:13.3 ± 2.2 yrs; height: 156.1 ± 10.6 cm; mass:50.2 ± 11.3 kg). Participants were enrolled in a prospective, randomized, active comparator, open blinded, end-point trial of a six-week comprehensive neuromuscular training program. This study adheres to CONSORT guidelines. Active controls were utilized for ethical reasons based on the effectiveness of NMT on reducing risk of knee injury [8, 9, 31, 32]. An a priori power analysis was conducted that showed a minimum of 40 participants in each group were required to achieve 80% power (alpha level 0.05)[33]. An equal sample size of $N = 50$ ($N = 150$ total) was randomized in computer-generated blocks to three study arms described below. We assumed 20% of loss to follow up, expecting a sample size of 40 to remain in each group. Participants were randomized into the three study arms using a random sequence of numbers stored in a spreadsheet only accessible to unblinded study staff and assigned in the randomization scheme according to the order they were enrolled in the study. The three study arms were as follows: 1) NMT: active control group of neuromuscular training with sham biofeedback, 2) NMT +K: intervention group of neuromuscular training with knee-focused biofeedback, and 3) NMT +H: intervention group of neuromuscular training with hip-focused biofeedback. The inclusion criteria consisted of 1) female between the ages of 9 and 19 ys, 2) participating on a competitive soccer team at the time of enrollment, 3) not currently injured or unable to participate in sport due to injury, and 4) able to commit to participating in the 6-week intervention. A written

participant consent, and/or parental consent and participant assent as appropriate based on age was obtained.

The Institutional Review Board at High Point University approved the study protocol. The clinical trial was registered at Clinicaltrials.gov (Identifier: NCT02754700) on 28/04/2016.

Intervention

Testing and training occurred at the High Point University Human Biomechanics and Physiology Laboratory. The participants were not given the knowledge that they were receiving specific arms of biofeedback that could be different than their fellow participants. Interventionists responsible for delivering the neuromuscular training and all other investigators were blinded to the group status during data collection (baseline, post), management and analysis. The neuromuscular training program was performed three times per week, with augmented biofeedback (according to group assignment) one time per week [33]. This resulted in 18 total sessions over 6 consecutive weeks. Each session lasted 90 min with a 9–10 min active warm-up, and 3 separate 27–30 min sessions of each of the following: resistance training, technique/plyometric training, and core strength training. Training was overseen by a licensed athletic trainer with expertise in ACL injury risk screening and training.

The neuromuscular training program [33] was designed from recommended guidelines and modified from a number of studies that have been scientifically developed to reduce knee injuries in female athletes and specifically applied with techniques for an external focus of attention [4, 9, 27, 30, 34, 35]. Please see Taylor et al. [33] for a detailed description of the intervention.

The biofeedback portion (10 min) was provided once weekly with a three-dimensional motion analysis system, consisting of fifteen digital high-resolution cameras (Kestrel, Motion Analysis Corporation, Rohnert Park, CA), and two time-synchronized, embedded, oversized force platforms (AMTI, Watertown, MA) (See Supplemental Materials). Specifically, the participants were withdrawn from the typical neuromuscular intervention at various times once a week. Participants were instrumented with retroreflective markers as previously described [33] by the same interventionist. A real-time skeleton avatar was displayed with a participant-specific model on a large screen during the session (Visual3D, C-Motion, Inc. Germantown, MD). In addition, a line graph showing real-time internal hip extensor moment (NMT + H), or external knee abduction moment (NMT + K) was displayed with a highlighted goal region that they were encouraged to attain that was progressively adjusted each week. The active control group (NMT) had a sham biofeedback session (line graph representing sagittal plane knee range of motion) to match volume, though their "goal region" to attain did not encourage alteration of their current squatting pattern. Members of the hip-focused group were instructed to watch the real-time graph and activate posterior-chain muscles throughout the movements to increase the hip extensor moment feedback with the hypothesis that an underlying mechanism of injury might relate to underutilization of the hip musculature. Individuals in the knee-focused group were instructed to maintain knees over toes and to push laterally through their feet. The active control group was instructed to perform the same movements with a sham biofeedback avatar. During biofeedback for each group, a series of 10 repetitions of three exercises (double-leg squat, single-leg squat, and single-leg jump landing) were performed through the six-weeks [33].

Data collection

Independent of the biofeedback intervention group, each participant completed a pre-testing baseline session and a post-testing session. During the pre-test, participants completed an electronic REDCap (Research Electronic Data Capture) [36] with the following data collected: demographic information, sport participation history, lower extremity injury history, parents' height for calculation of pubertal stage, and a menstrual history. Lower extremity biomechanics during double leg landing and unplanned single leg cutting were collected during pre- and post-testing sessions. Participants performed these tasks on a synthetic turf surface, while wearing standardized cleats (adidas ×15.2; Beaverton, Oregon, USA). As described in detail [33], each participant had 43 retroreflective markers secured at anatomical landmarks with double-sided tape for for 3-dimensional biomechanical analysis by the same researcher throughout the study. Three-dimensional motion capture was sampled at 200 Hz and kinetic data sampled at 1200 Hz with Cortex software (version 7; Motion Analysis Corp, Santa Rosa, California, USA).

Each participant performed three trials of a drop vertical jump (DVJ) (Fig. 1). Participants stood on top of a 31-cm box and positioned their feet 35-cm apart and arms at their side. They were instructed to drop down directly off the box and immediately jump vertically towards an overhead target that was placed at their previously determined maximal vertical countermovement jump reach [37]. Participants also performed an approach run with unanticipated cue to either perform a plant with a of 90° sideways cut (CUT) (Fig. 1) or a plant with a 180° backpedal [38]. The purpose of the backpedal was to provide an additional movement so the participant could not preplan the cut while approaching. Three trials of each movement were randomized and performed on each leg.

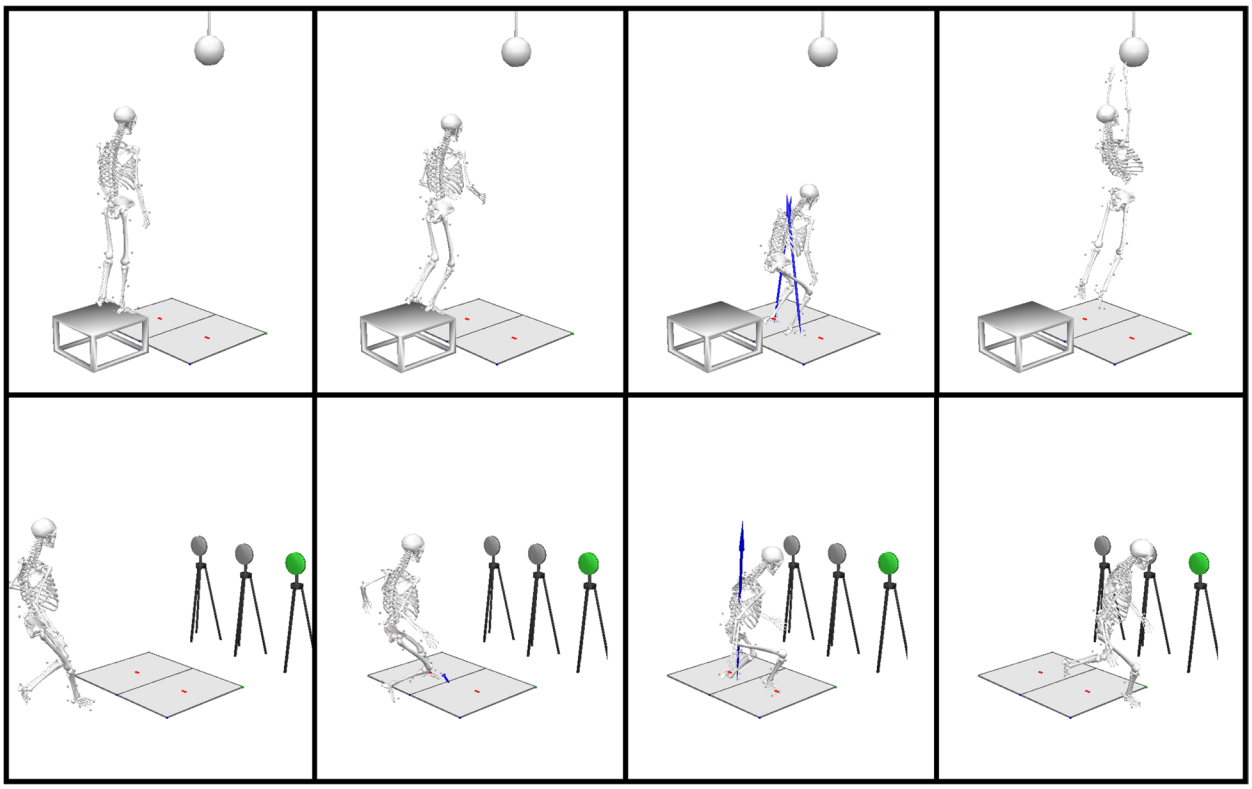

Fig. 1 Top row illustrates the drop vertical jump (DVJ) task. Bottom row illustrates the unanticipated cutting (CUT) task

Participants ran at 75% of their maximal speed from a distance of 5 m away from the force platforms. A light disc positioned in front of the participants (FITLIGHT trainers™, FITLIGHT Sports Corp., Aurora, Ontario, Canada) would illuminate when they passed 2 m in front of the force platforms indicating whether they were to plant and cut sideways at 90° or plant and backpedal to the starting point. Timing gates (TracTronix, Lenexa, Kansas, USA) were positioned 2.5 m apart so that the approach velocity of each trial could be calculated. Approach velocities were not statistically different ($p > 0.05$) among groups or between sessions (NMT: baseline 2.93 ± 0.36 m/s, post 2.97 ± 0.26 m/s; NMT + K: baseline 2.92 ± 0.34 m/s, post 2.86 ± 0.29 m/s; NMT + H: baseline 2.95 ± 0.36 m/s, post 2.95 ± 0.34 m/s). Trials were repeated if the participant did not land cleanly on the force platform. Cutting and backpedas were randomly ordered. Backpedals were not analyzed for this study, only the DVJ and CUT. Instructions of all tasks were provided by the same member of the research team at pre-test and post-testing sessions who was blinded to group membership.

Athletic exposures and ACL injuries were recorded each week for six months following the post-test session using a monthly electronic survey (REDCap) [36] using previous methodology described by Paterno et al. [39]. Participants were asked to report any knee injury and athletic exposures. Athletic exposures were defined as any participation in a soccer game or practice. Individual mean imputation was utilized to account for missing survey data in the instance a participant did not complete one of their surveys (31.3%) [40].

Data and statistical analysis

Kinematic marker data and ground reaction forces (GRF) were lowpass filtered at 12 Hz and used to calculate joint moments through inverse dynamics in Visual 3D (v6, C-Motion Inc.) [24, 41]. Joint moments were analyzed during the landing phase for each task, defined from initial contact on the force platform (GRF > 10 N) until toe off from the force platform (vertical GRF < 10 N) [24]. Net external abduction moment was calculated and represents the abduction external load on the joint, with negative values representing knee abduction based on the analysis convention. The primary outcome variable was peak knee abduction moment during the DVJ and CUT for each group during baseline and post-testing [33].

An intention-to-treat analysis approach was used in all student participants ($N = 150$, 50 in each group) with multiple imputation for participants with missing outcomes using PROC MI (SAS v9.4) for each testing

session. Five sets of imputation were generated, with final results analyzed using PROC MIANLYSIS (SAS v9.4). The secondary analysis took a per-protocol approach. To assess intervention effects on post-test outcomes while controlling for potential baseline differences, an analysis of covariance (ANCOVA) was conducted with post-test measures as the dependent variable, baseline measures as the covariate, and group (three levels: NMT, NMT + K, NMT + H) as the between-subjects factor. To confirm that groups were equivalent at baseline, a one-way analysis of variance (ANOVA) was performed on baseline measures. Paired t-test were used to determine baseline to post-test differences in peak knee abduction moment in each group. One-tailed tests of significance were utilized to support the directional hypothesis of reduced knee abduction following the intervention ($p < 0.05$).

The open-source statistical parametric mapping (SPM) package [42] was utilized to statistically compare knee abduction moment time series data in MATLAB ($p < 0.05$). A SPM paired t-test model was utilized to identify significant differences between baseline and post-test for each group at specific time points during the stance phase of landing and cutting [43].

Results

One hundred and fifty female participants were block (age) randomized into NMT groups ($N = 50$; age:13.3 ± 2.1 yrs; height:157.0 ± 10.6 cm; mass:50.2 ± 11.2 kg), NMT + K ($N = 50$; age:13.3 ± 2.3 yrs; height: 155.3 ± 9.8 cm; mass:49.8 ± 10.9 kg), and NMT + H ($N = 50$; age:13.2 ± 2.1 yrs; height: 156.1 ± 11.5 cm; mass:50.6 ± 11.9 kg) and completed initial baseline testing. Of these, 140 participants (93.3%) completed the 6-week intervention and post-test (Fig. 2). Of the 10 participants that did not complete the intervention, 9 participants completed pre-test and several training sessions, however elected to withdraw from the study due to time commitment issues and 1 participant elected to withdraw following an ankle injury unrelated to the study. Each group completed comparable sessions of NMT and biofeedback sessions during the 6-week period (Training: NMT 15.1 ± 2.5 sessions, NMT + K 15.5 ± 2.0 sessions, NMT + H 15.6 ± 2.1 sessions; Biofeedback: NMT 5.7 ± 0.7 sessions, NMT + K 5.7 ± 0.5 sessions, NMT + H 5.9 ± 0.3 sessions). Of the 140 participants that completed the intervention and post-test, thirteen did not complete testing for the CUT due to equipment malfunction (NMT: $n = 4$, NMT + K: $n = 5$, NMT + H: $n = 4$). These missing observations were imputed for the intention-to-treat analyses.

Following the post-test session, surveys reporting athletic exposures for a total of six months were collected from each participant (Fig. 2). Weekly athletic exposures for cutting and pivoting sports were not statistically different ($p > 0.05$) among groups (NMT 4.89 ± 1.25 exposures, NMT + K 4.96 ± 1.82 exposures, NMT + H 4.80 ± 1.41 exposures). There were no ACL injuries reported during the six-month period among any of the intervention groups.

Discrete variables

An ANCOVA was performed on post-test peak knee abduction moment during the drop vertical jump, with baseline measures entered as a covariate and intervention group as the between-subjects factor (Table 1). Baseline knee abduction was a significant covariate ($t(136) = 9.83$, $p < 0.001$). Neither the NMT + K ($t(136) = 0.59$, $p = 0.28$) nor the NMT + H group ($t(136) = -0.31$, $p = 0.38$) differed significantly from the reference group (NMT) after adjusting for baseline. A one-way ANOVA on baseline knee abduction during the drop vertical jump revealed no significant differences between groups, $F(2,137) = 0.528$, $p = 0.591$, indicating that the groups were comparable at baseline. However, paired t-tests identified statistically significant baseline to post-test improvement during the drop vertical jump for the primary outcome variable of peak knee abduction moment (Fig. 3) in all three groups during (Table 1; NMT: $p = 0.001$, $d = -0.48$; NMT + K: $p = 0.003$, $d = -0.42$; NMT + H: $p = 0.002$, $d = -0.45$). The intention-to-treat analysis confirmed these results with significant improvement in each group (NMT: $p < 0.001$, $d = -0.58$, NMT + K: $p = 0.010$, $d = -0.38$, NMT + H: $p = 0.001$, $d = -0.46$). A 22.7% mean improvement peak knee abduction moment, the primary outcome in this RCT ($p > 0.05$).

For the unanticipated cut, the ANCOVA (Table 1). revealed that baseline knee abduction was a significant covariate in the post-test measure ($t(123) = 8.66$, $p < 0.001$). The NMT + H showed decreased knee abduction moment during cutting compared to the reference group (NMT) ($t(123) = 1.68$, $p = 0.048$), whereas the NMT + K did not differ statistically ($t(123) = 0.53$, $p = 0.298$). A one-way ANOVA on baseline unanticipated cutting knee abduction moments revealed no significant differences between groups ($F(2,124) = 1.32$, $p = 0.271$), indicating that the groups were comparable at baseline. The NMT + H intervention group was the only group that exhibited statistically significant differences in peak knee abduction moment (Fig. 4) during the unanticipated cutting task with paired t-test (Table 1; NMT: $p = 0.49$, $d = 004$; NMT + K: $p = 0.377$, $d = -0.05$; NMT + H: $p = 0.003$, $d = -0.44$). This was confirmed with the intention-to-treat analysis that showed statistically significant reduction in peak knee abduction moment in the NMT + H group from baseline to post-test during the CUT (NMT: $p = 0.417$, $d = 0.04$, NMT + K: $p = 0.17$, $d = -0.15$, NMT + H: $p = 0.01$, $d = -0.35$). The improvement in peak knee

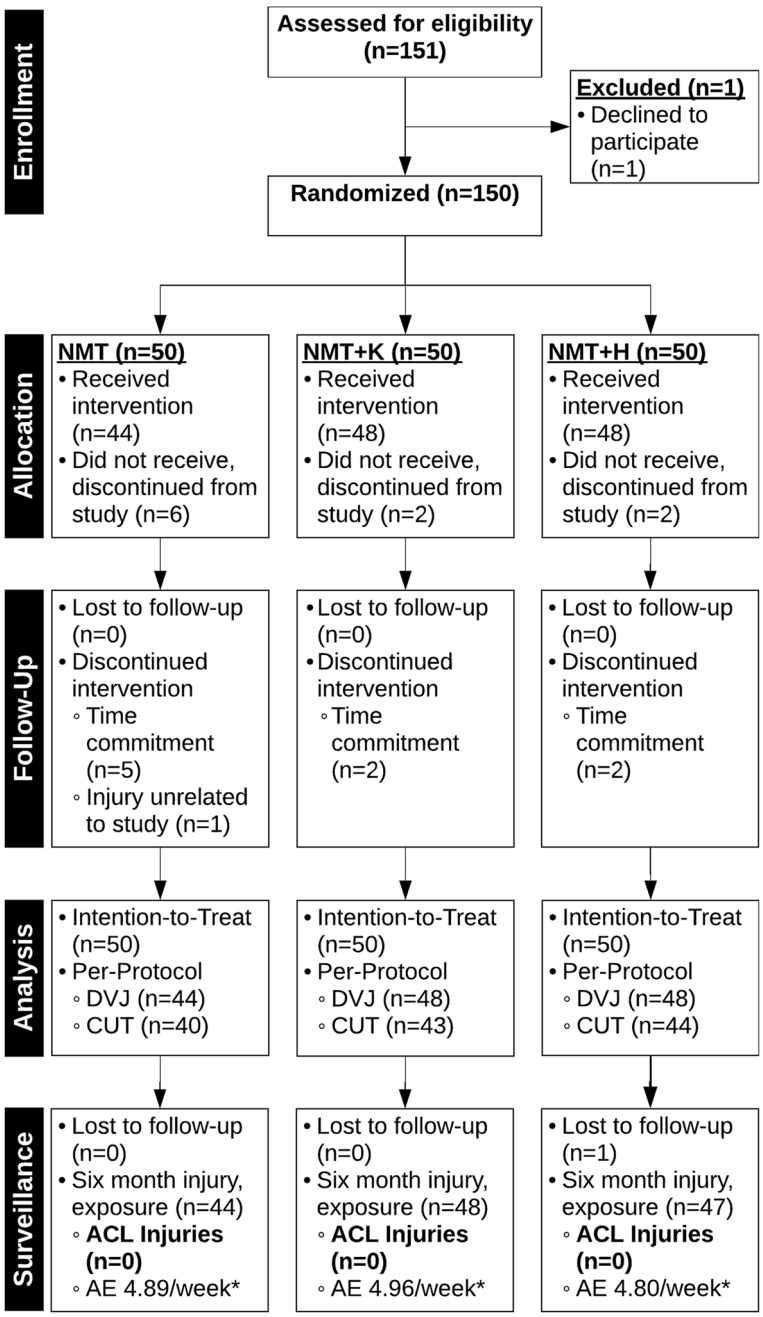

Fig. 2 CONSORT Flow Diagram. *Athletic Exposures (AE) calculated over the 6-month surveillance period, presented as the average weekly exposure during cutting/pivoting activities

abduction in the NMT + H intervention group was 22.5% during the cutting task. The improvement (post-test minus baseline) in NMT + H was significantly greater compared to NMT ($p = 0.02$).

Curve analysis

During the DVJ, all three groups significantly reduced ($p < 0.001$) the magnitude of knee abduction moment when examining the time series data through statistical parametric mapping (Fig. 5). The statistical differences between baseline and post testing emerged at approximately 30% of stance in each group (NMT 30.2%, NMT + K 30.8%, and NMT + H 31.1%). Statistical differences between baseline and post-testing remained different through 77.2% of stance in NMT + H, 65.8% of stance in NMT + K, and 58.2% of stance in NMT. Like the discrete

Table 1 Knee abduction moment during drop vertical jump and unanticipated cut testing at baseline and post-test

	Baseline (Nm)	Post-Test (Nm)	ANCOVA	Paired T-Test, Cohen's Effect Size
	Mean [95% CI]	Mean [95% CI]		
Drop vertical jump[a]				
NMT	− 21.4 [− 25.4, − 17.4]	− 16.6 [− 19.7, − 13.5]		*$p = 0.001$, $d = -0.48$
NMT + K	− 19.5 [− 23.2, − 15.8]	− 14.6 [− 17.6, − 11.7]	$p = 0.28$ (vs NMT)	*$p = 0.003$, $d = -0.42$
NMT + H	− 22.2 [− 26.9, − 17.8]	− 17.6 [− 21.1, − 14.1]	$p = 0.38$ (vs NMT)	*$p = 0.002$, $d = -0.45$
Unanticipated cutting[b]				
NMT	− 25.0 [− 30.4, − 19.6]	− 25.0 [− 29.6, − 20.5]		$p = 0.49$, $d = 004$
NMT + K	− 23.6 [− 28.9, − 18.3]	− 22.8 [− 28.0, − 17.6]	$p = 0.30$ (vs NMT)	$p = 0.377$, $d = -0.05$
NMT + H	− 29.5 [− 35.3, − 23.8]	− 22.9 [− 27.8, − 18.0]	*$p = 0.048$ (vs NMT)	*$p = 0.003$, $d = -0.44$

[a] Baseline knee abduction was a significant covariate during drop vertical jump ($t(136) = 9.83$, $p < .001$)

[b] Baseline knee abduction was a significant covariate during unanticipated cutting ($t(123) = 8.66$, $p < .001$)

* statistically significant difference ($p < 0.05$)

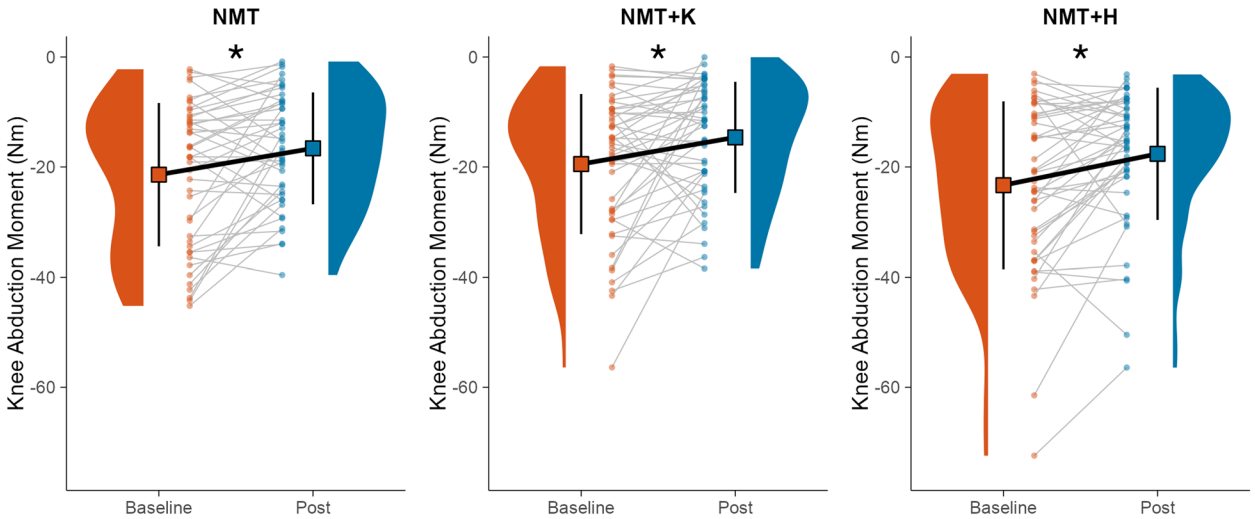

Fig. 3 Square box indicates the group mean (± 1 standard deviation) during baseline and post-testing during drop vertical jump trials for neuromuscular training (NMT), neuromuscular training plus knee focused biofeedback (NMT + K), and neuromuscular training plus hip focused biofeedback (NMT + H). Each individual participant mean of three trials is also indicated by the small circle for each time point with thin line connecting baseline to post-test. Truncated violin plots show the density of the data distribution. (*$p < 0.05$ difference from baseline to post)

analysis of cutting, only the NMT + H group had significant differences ($p < 0.001$) from baseline to post testing with statistical parametric mapping of the time series data (Fig. 6). Participants in NMT + H group reduced knee abduction moment following 6 weeks of training (20.6% to 53.2% stance, $p < 0.001$).

Discussion

High incidence rates of ACL injuries in female athletes outline the necessity of training programs that can modify the high-risk biomechanics associated with injury and decrease the prevalence in this population [27]. These data support the idea that these programs can facilitate neuromuscular adaptations that focus on safe movement patterns, thereby allowing these athletes to adopt muscular recruitment strategies that decrease joint torque and protect the ACL from high impulse loading [44, 45]. Therefore, the question of whether targeting knee abduction moment or targeting hip extensor moment during training can most optimally improve active knee stabilization during sport related tasks was postulated. The salient finding in this study, and in support of our hypothesis, was that knee abduction moment was improved during unanticipated single leg side-step cutting in the hip focused biofeedback group. This was supported in both discrete (peak moment) and continuous time series analysis during early to midstance of the cutting task. Additionally, knee abduction moment (peak and time

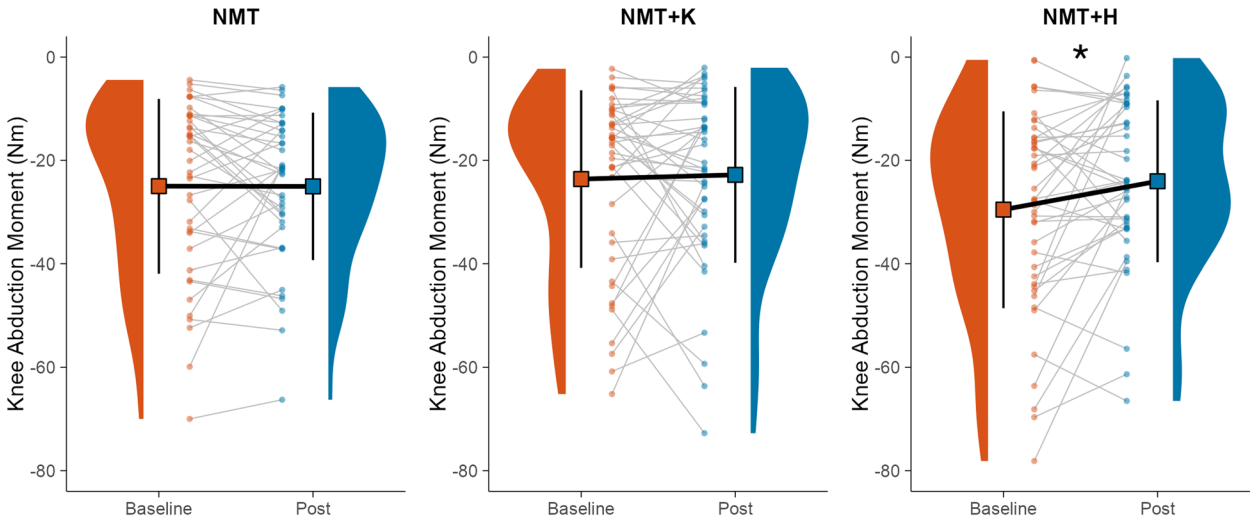

Fig. 4 Square box indicates the group mean (± 1 standard deviation) during baseline and post-testing during unanticipated side-step cut trials for neuromuscular training (NMT), neuromuscular training plus knee focused biofeedback (NMT + K), and neuromuscular training plus hip focused biofeedback (NMT + H). Each individual participant mean of three trials is also indicated by the small circle for each time point with thin line connecting baseline to post-test. Truncated violin plots show the density of the data distribution. (*$p < 0.05$ difference from baseline to post)

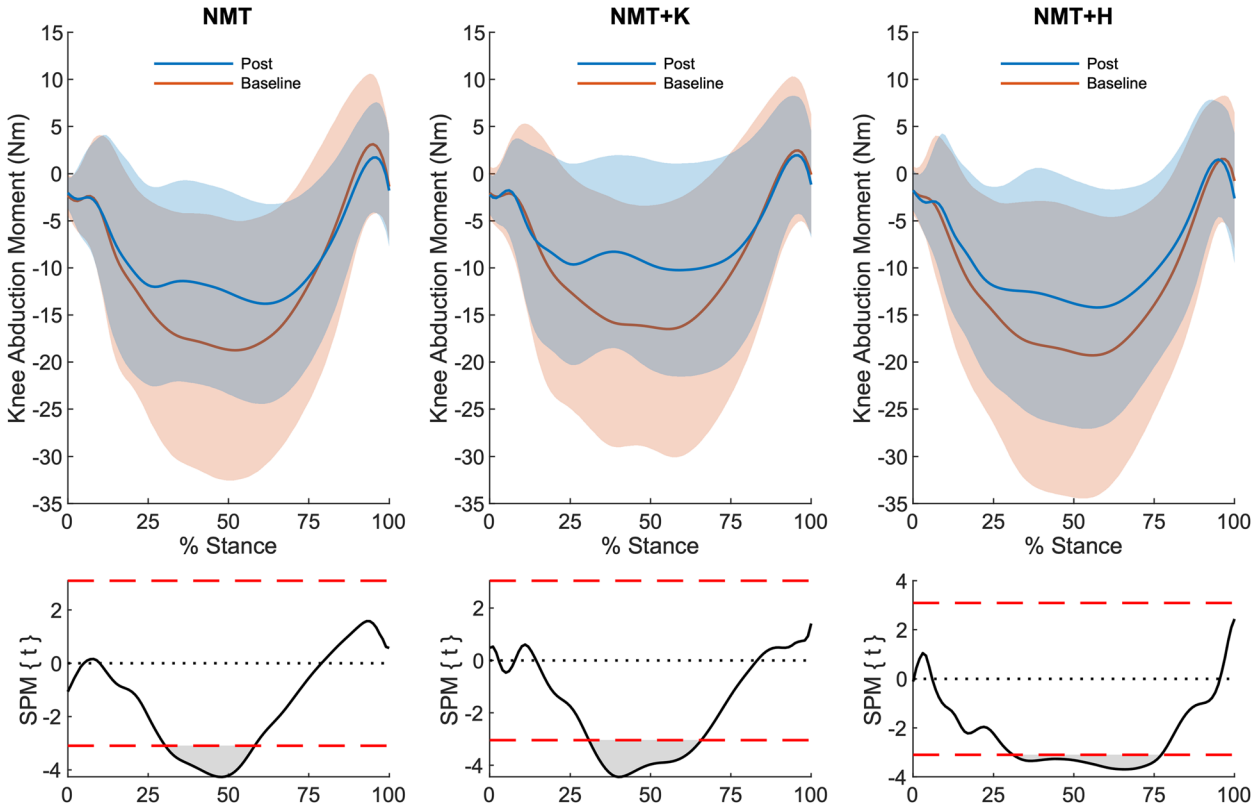

Fig. 5 Top row shows drop vertical jump of each group (mean ± 1 standard deviation shaded) during baseline and post testing. Bottom row shows the corresponding statistical parametric mapping (SPM) analysis to determine baseline to post testing differences between time series data from each group. Red dashed line indicates critical t threshold for significance (shaded region indicates significant differences $p < 0.001$)

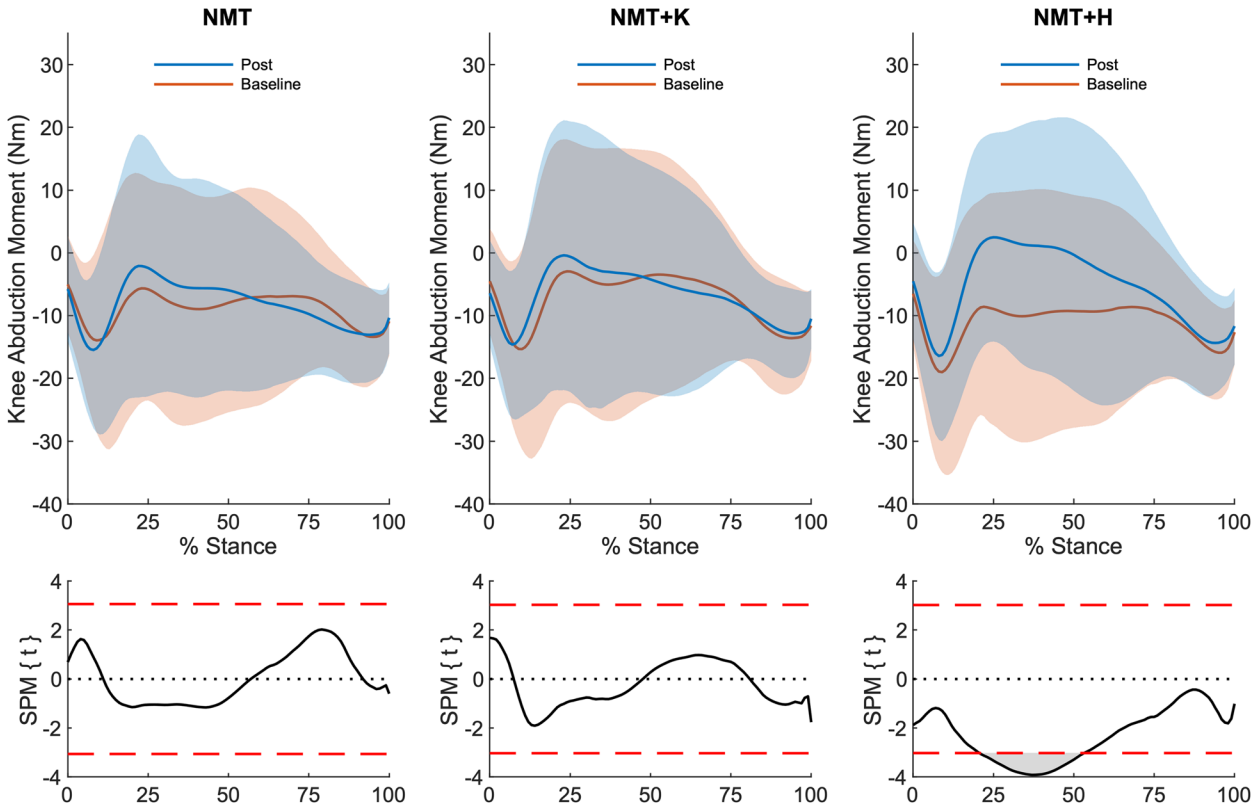

Fig. 6 Top row shows unanticipated cut of each group (mean ± 1 standard deviation shaded) during baseline and post testing. Bottom row shows the corresponding statistical parametric mapping (SPM) analysis to determine baseline to post testing differences between time series data from each group. Red dashed line indicates critical t threshold for significance (shaded region indicates significant differences $p < 0.001$)

series analysis) was improved in the drop vertical jump task in all three groups. Taken together, this would support comprehensive neuromuscular training combined with innovative biofeedback modalities to target underlying hip focused mechanisms which may translate to more dynamic sport related movements. Furthermore, as an exploratory outcome, we systematically included a prospective 6-month injury surveillance period to record both injury and athletic exposures. None of the study participants sustained an ACL injury during this follow-up period.

The baseline measures during both the drop vertical jump and unanticipated cutting significantly predict the post-test measures based on the results of the ANCOVA. During the drop vertical jump, significant improvements across the three groups in knee abduction moment were found. However, given the relationship between baseline and post-test measures, some participants likely still exhibit high levels of knee abduction moment, which may need additional follow-up. Previous studies have identified that female athletes with high levels of knee abduction moment at baseline are potentially more responsive to neuromuscular training than those athletes who do not exhibit the same movement pattern [46, 47]. Furthermore, during the cutting task, the baseline knee abduction moment may be indicative of which athletes may be more likely to need and benefit from an intervention. Additional studies should examine the impact that baseline magnitude of risk may have on those who respond and those who do not respond to neuromuscular training with biofeedback.

While there are many neuromuscular strategies that can influence high-risk loading during dynamic tasks, incorporating kinetic biofeedback during squatting into neuromuscular training programs has been shown to transfer to dynamic drop landings [29]. In this study, we identified improvements in a drop landing across all groups, indicating that neither knee nor hip focused biofeedback significantly influenced the effects of neuromuscular training in such a task. The biofeedback provided a visual of each participant's real-time extensor torque in attempt to promote increased musculature torque rather than consistent verbal instruction during the neuromuscular training, therefore participants may have employed different strategies that did not carry over to a drop landing task. However, with a transfer task that

is more demanding and unanticipated (cutting), only the hip focused biofeedback group significantly reduced knee abduction load following training. Therefore, focusing attention on the underlying mechanism (proximal hip) that controls knee loading may be the most effective strategy, as it could be considered a more feasible external focus of control compared to knee extensors. Furthermore, rehabilitation programs that target deficits associated with secondary ACL injuries also identify enhancement of hip strength as an optimal method to improve dynamic knee control. The targeting of such proximal mechanisms, notably hip extension, may therefore transfer motor learning to dynamic unanticipated tasks and potentially result in a greater reduction in the risk of ACL injury in young female athletes. While the technologies utilized in this study might be difficult implement on a wide-scale at present, the future of makerless motion capture and augmented reality is rapidly developing. We aimed to determine if the variables of interest in the biofeedback modality could potentially be utilized in addition to neuromuscular training. The continued development and practical use of such technologies should be further investigated.

The prospective and randomized aspects are strengths of this study. An additional strength was our ability to retain 93.3% of the participants through 6-weeks of a training intervention and biomechanical post-test session. Higher compliance rates of NMT sessions are associated with low rates of ACL injury [15]. Therefore, the strategies used to maintain adherence to our program (i.e. regular correspondence with parents/guardians as well as participants) seem to be an efficient method to promote continued attendance. While the current study is limited to the immediate effects following the intervention, additional analyses will examine the effects of retention on the improvements we identified in knee abduction moments. Furthermore, a variety of secondary kinetic and kinematic biomechanical variables will be analyzed across additional joints and planes of movement during landing and cutting tasks.

The knee abduction moment waveform comparison should be cautiously interpreted for both the drop vertical jump and unanticipated cutting task. Specific noncontact ACL injuries from landing and cutting would typically occur earlier in the stance phase compared to a laboratory-controlled risk screening assessment. However, the greater magnitude of knee abduction moment throughout the stance phases of landing and cutting should be further evaluated to determine relevance to future risk of ACL injury. Additionally, the nature of the prompts and specific exercise progressions during biofeedback should be further investigated. For instance, the instruction in the knee-focused group of "push laterally through their feet" could have induced hip-focused results. However, the intent was to focus on the external biofeedback that was provided on the screen for each of the intervention groups.

Conclusions

The implications from this study highlight the potential transferrable effects that hip-focused biofeedback may have on cutting biomechanics when augmented with neuromuscular training. It is also important to realize that each training group exhibited significant improvements knee abduction moments during a double leg landing task regardless of biofeedback designation. These data, combined with previous literature, signify the importance of neuromuscular training programs that aim to modify the high-risk biomechanics associated with ACL injury.

Abbreviations

ACL	Anterior cruciate ligament
KAM	Knee abduction moment
NMT	Neuromuscular training with sham biofeedback group
NMT + K	Neuromuscular training with knee-focused (external knee abduction moment) biofeedback group
NMT + H	Neuromuscular training with hip-focused (internal hip extension moment) biofeedback group
DVJ	Drop vertical jump
ROBUST	Real-time Optimized Biofeedback Utilizing Sport Techniques
CUT	Unanticipated single leg 90° sideways
GRF	Ground reaction force
SPM	Statistical parametric mapping

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12891-025-08647-3.

Supplementary Material 1: Supplementary video of methods.

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Authors' contributions

KRF, JBT, MVP, AND, and BH conceptualized and designed the study. KRF, JBT, AND, and AEW collected and analyzed the data. All authors were involved in drafting the manuscript. All authors read and approved the final version of the manuscript.

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Data availability

The datasets used during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Participants were fully informed of the risks and benefits associated with this study and provided written participant informed consent, and/or parental informed consent and participant assent as appropriate. The study protocol was approved by the Institutional Review Board at High Point University and registered as a clinical trial (Clinicaltrials.gov Identifier: NCT02754700, Date Registered 28/04/2016).

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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Short-Term Effects of Heart Rate Variability Biofeedback on Working Memory

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Abstract

Drawing upon the well-documented impact of long-term heart rate variability biofeedback (HRVB) on psychophysiological responses, this study seeks to explore the short-term effects arising from a single HRVB session during and after paced breathing exercise. The research aligns with the neurovisceral integration model, emphasizing the link between heart rate variability (HRV) levels and cognitive performance. Therefore, a randomized controlled trial employing a between-subjects design was conducted with 38 participants. Each participant was assigned to either the paced breathing intervention group or the spontaneous breathing control group. The study assessed various parameters such as cardiac vagal tone, evaluated through vagally mediated HRV measures, and working memory, measured using the N-back task. Additionally, participants' affective states were assessed through self-reported questionnaires, specifically targeting attentiveness, fatigue, and serenity. The results notably reveal enhancements in the working memory task and an elevated state of relaxation and attention following the HRVB session, as evidenced by higher averages of correct responses, serenity and attentiveness scores. However, the findings suggest that this observed improvement is not influenced by changes in cardiac vagal tone, as assessed using a simple mediation analysis. In conclusion, this study presents promising insights into the impact of a single HRVB session, laying the foundation for future research advancements in this domain.

Keywords Heart rate variability · Biofeedback · Vagal tone · Working memory · Cognitive performance

Abbreviations

RMSSD	Root mean square of successive differences
HRV	Heart rate variability
HRVB	Heart rate variability biofeedback
HF	High frequency
ANS	Autonomic nervous system
DASS	Depression anxiety stress scale
PANAS	Positive and negative affect schedule
PSQI	Pittsburgh sleep quality index
IPAQ	International physical activity questionnaire
SDNN	Standard deviation of all normal to normal (R-R) intervals

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Introduction

Within the intricate interplay of cardiac and cognitive domains, heart rate variability (HRV) emerges as a captivating physiological measure that offers valuable insights into the relationship between autonomic nervous system (ANS) and cognitive performance (Berntson et al., 1997; Thayer & Lane, 2000; Thayer et al., 2009). Reflecting the dynamic balance between sympathetic and parasympathetic influences on the heart, HRV encompasses the variation in time intervals between successive heartbeats (Berntson et al., 2009; Malik et al., 1996). This measure serves as an indicator of autonomic flexibility and regulatory capacity, with higher HRV suggesting a healthier and more adaptive ANS functioning (Ernst, 2017).

Six major domains of cognitive function have been postulated by the American Psychiatric Association: namely, complex attention, executive function, language, learning and memory, perceptual-motor function, and social cognition (Sachdev et al., 2014). Studies on executive function represent a growing field due to its direct association with activities of daily living (Chan et al., 2008; Starcke et al.,

2016). Executive function refers to the higher cognitive skills underpinning self-control and goal-directed behaviour, including decision-making, problem-solving, and self-regulation. It comprises three primary areas: inhibitory control, working memory, and cognitive flexibility (Diamond, 2013). Inhibitory control involves the capacity to self-regulate one's attention, actions, and emotions. Working memory involves the retention of information for a limited amount of time as it is being mentally processed. Cognitive flexibility refers to the mental ability to adapt to new situations or changes, and it is based on inhibitory control and working memory. From a neuroscientific perspective, the executive function processes are predominantly located in the prefrontal cortex of the frontal lobe and supported by connected brain structures (Blair, 2017).

Historically, the exploration of afferent cardiovascular activity towards the brain has been closely examined, particularly in relation to cognitive function (Porges, 1995). Notably, the seminal work by Lacey and Lacey (1970) established a link between heart rate deceleration and improved cognitive performance in sensory-intake tasks, as evidenced by faster reaction times (Lacey et al., 1974). Recognizing the complexity of the heat-brain connection, Wölk & Velden highlighted the significance of the pattern and stability of heart afferent input in influencing cognitive function on a micro-scale level, spanning 3–4 cardiac cycles (Wölk & Velden, 1987, 1989). More recently, this investigative approach has been expanded to explore the relationship between cardiovascular afferent activity and cognitive function on a macro-scale temporal pattern with longer time periods (McCraty et al., 2009; McCraty & Shaffer, 2015). Taking a theoretical approach, various models have emerged to elucidate the heart-brain interaction, revealing its profound impact on psychological responses and cognitive performance (Shaffer et al., 2014). Prominent examples include the polyvagal theory (Porges, 2011), the cardiac coherence model (McCraty & Childre, 2010), and the neurovisceral integration model (Thayer & Lane, 2000; Thayer et al., 2009). The latter model demonstrates the link between the prefrontal cortex and cardiac vagal tone, thus delineating the association between HRV and emotion, cognition, and mental well-being. An association between higher resting HRV measures and better emotion recognition was demonstrated by Quintana et al. (2012), indicating a relationship between the ANS and cognitive processes. One of the critical domains of the neurovisceral integration model is the relationship between cognitive function and HRV, particularly the root mean square of successive differences (RMSSD) and high frequency (HF) power (Thayer & Lane, 2000; Thayer et al., 2009). Forte et al. (2019) identified the major cognitive areas used in HRV studies by conducting a systematic review of the literature and concluded that, in general, higher resting HRV measures were associated with improved cognitive functioning, as examined in tasks assessing attention (Williams et al., 2016), global cognition (Frewen et al., 2013), and memory (Hansen et al., 2003, 2004).

While exploring ways to improve HRV, biofeedback through paced breathing exercises under slow respiratory rates emerged as a promising approach for enabling an individual to increase vagally-mediated HRV measures by activating the parasympathetic response (Lehrer et al., 2000; Khazan, 2013). The maximum HRV level, in which heart rate rhythms and breathing patterns are synchronised, is commonly referred to as the resonant frequency. Normal resonant frequency rates for adults range between 4.5 and 6.5 breaths/min (Lehrer, 2007). Further, heart rate variability biofeedback (HRVB) is an effective technique for building resilience and improving mental health and well-being in the long term (Lehrer & Gevirtz, 2014; Gevirtz, 2013; Laborde et al., 2019a). In a recent meta-analytic study, Lehrer et al. (2020) reported a significant and small-to-medium effect size regarding the efficacy of multiple-session HRVB in improving a wide variety of physical (e.g., asthma) and psychological symptoms (e.g., anxiety, depression). Moreover, preliminary evidence suggests that HRVB stimulates activity in the vagus nerve, which is a major parasympathetic nerve associated with relaxation and reduced stress levels (Gerritsen & Band, 2018). Initially, Lehrer et al. (2000) proposed a 10-session resonance breathing protocol to train individuals on HRVB techniques. Researchers have applied this protocol widely to investigate the long-term impact of HRVB on physical health, mental health, and cognitive performance. Nevertheless, Lehrer et al. (2013) simplified the training protocol and reduced the number of sessions to five for research and clinical purposes. Although it is advantageous to determine the resonant frequency for each individual, studies conducted in the past few years have indicated consistent physiological responses when breathing at a rate of 6 breaths/min (bpm; Van Diest et al., 2014; Zaccaro et al., 2018). However, further investigations are needed to understand the psychological responses with respect to the resonant frequency (see section "Cardiac Vagal Tone").

To date, only a few studies have attempted to examine the short-term effects of a single HRVB session on the psychophysiological responses and cognitive performance (Laborde et al., 2019b, 2022b; Lin et al., 2020; Prinsloo et al., 2011, 2013; Schuman & Killian, 2019; Steffen et al., 2017; Wells et al., 2012; You et al., 2021a). Moreover, there is still controversy over the extent of HRVB influence on cognitive function, as discussed in a recent systematic literature review by Tinello et al. (2022). While there was a generally positive relationship between HRVB intervention and cognitive performance in the reviewed studies, there was a lack of evidence supporting that cognitive improvement can be directly attributed to an increase in HRV measures.

This uncertainty stems from the fact that half of the studies examined (8 out of 16) did not present physiological data following the intervention. Therefore, the present study aimed to investigate the influence of HRVB on a range of affective states (attentiveness, fatigue, and serenity), executive function (cognitive performance in a working memory task), and cardiac vagal tone as a physiological measure during and after the intervention. In assessing cardiac vagal tone, RMSSD was selected as the primary measure due to its reduced sensitivity to respiration compared to HF power (Shaffer & Ginsberg, 2017). The hypotheses for this study are as follows, where the HRVB intervention was conducted as a short-term single paced-breathing session:

H1 HRVB improves the affective states associated with attentiveness, fatigue, and serenity during and after the paced-breathing session.

H2 HRVB improves the working memory after the paced-breathing session.

H3 HRVB improves cardiac vagal tone during and after the HRVB activity.

H4 The improvement of cognitive performance after the HRVB activity is mediated by changes in the cardiac vagal tone.

Materials and Methods

Participants

The study aimed to recruit a total of 34 participants based on a priori power analysis for a repeated measures ANOVA with a between-subjects factor design using G*power. The analysis considered a statistical power $(1 - \beta)$ of 80%, a significance level (α) of .05, a correlation among repeated measures of .50, and the ability to detect a large effect size (f) of .40.

In total, 44 healthy adults aged 23–62 years were recruited to participate in the study. These individuals were randomly assigned to either the intervention or control group. Recruitment efforts targeted individuals from Hamad Bin Khalifa University (HBKU) in Qatar, as well as the general community through email advertisements and personal invitations. To ensure the validity of the findings, exclusion criteria were applied, which included physical health conditions associated with cardiovascular or respiratory diseases, diagnosed psychiatric conditions, and an age outside the range of 18–65 years at the time of recruitment. Additionally, participants were instructed to avoid consuming caffeine, smoking, and eating heavy meals for 2 h prior to the study. They were also advised against engaging in intense physical workouts for 24 h to minimize any potential confounding effects on the physiological responses (Laborde et al., 2017; Quintana et al., 2016). The study protocol was approved by the Institutional Review Board at Qatar Biomedical Research Institute at HBKU (QBRI-IRB-2021-03-088). Before participating in the study, all participants were provided with detailed information about the nature of the experiment and provided their informed consent by signing the form digitally. Following data collection, the HRV recordings were visually inspected and filtered to remove noise and artifacts. As a result, data from six participants were excluded due to poor signal quality, where the noise level exceeded 5% of the recording. The remaining dataset consisted of 38 participants, of which 20 were women (mean age: 35.5 ± 11) and 18 were men (mean age: 34.4 ± 9.86).

Experiment Design

A randomized controlled trial was conducted to investigate the impact of HRVB through paced breathing on various affective states, executive function, and physiological measures in healthy individuals. The study employed a mixed-factorial design with two independent variables: group (between-subjects) and time (within-subjects). Participants were randomly assigned to one of two groups: (1) the HRVB group, which received paced breathing as a biofeedback intervention, and (2) the control group, which engaged in normal breathing without any intervention.

Data collection included HRV measurements and affective state questionnaires at four time points throughout the study: (1) baseline, (2) pre-intervention (during the first cognitive task), (3) mid-intervention, and (4) post-intervention (during the second cognitive task). HRV data were collected using a photoplethysmography (PPG)-based sensor attached to the non-dominant hand, while blood pressure was measured using an upper arm cuff device. Figure 1 illustrates the experimental protocol.

Questionnaires

All participants filled out the HRV-related questionnaire developed by Quintana et al. (2016) as a screening survey to assess their eligibility. Furthermore, participants completed a set of questionnaires during baseline, including questions related to demographics; Positive and Negative Affect Schedule (PANAS) to assess emotional state (Watson & Clark, 1994); Depression, Anxiety, and Stress Scale (DASS-21) to assess depression, anxiety, and stress (Lovibond & Lovibond, 1995); International Physical Activity Questionnaire-Short Form (IPAQ-SF) to measure physical

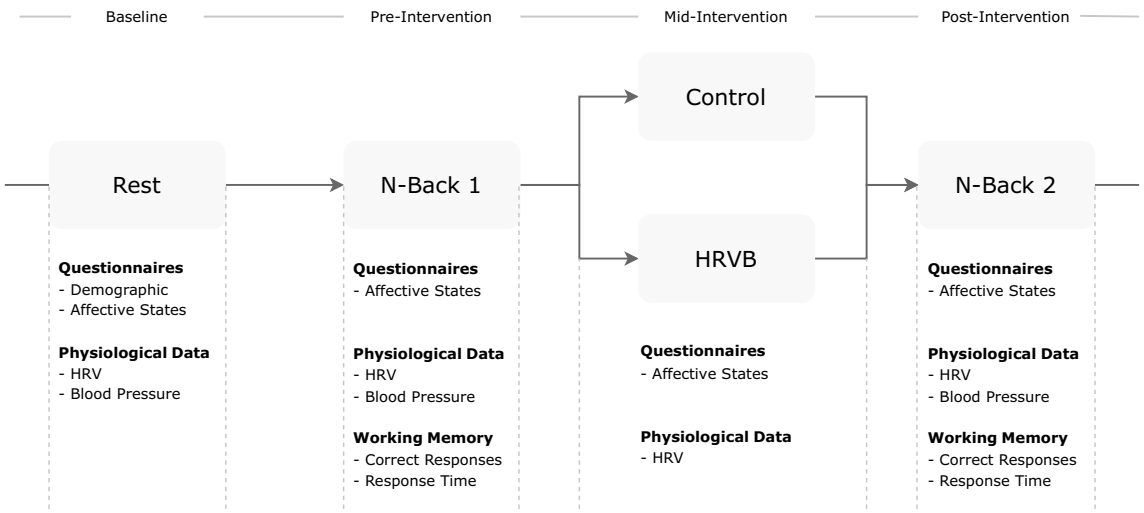

Fig. 1 A flowchart for the experimental protocol

activity (Craig et al., 2003); and Pittsburgh Sleep Quality Index (PSQI) to assess sleep quality (Buysse et al., 1989).

In addition, affective states were measured during the experiment via self-reported questionnaires on attentiveness, fatigue, and serenity using the PANAS-Expanded Form (PANAS-X), which is based on a multiple-item Likert scale. Each component of the PANAS-X consisted of multiple terms measuring affective states at that moment, and these terms had to be rated 1 for "not at all" to 5 for "extremely". All questionnaires used were presented in the English and Arabic languages as most of the participants were non-native English speakers. The Arabic versions of the questionnaires were obtained as follows: PANAS (Davis et al., 2020), DASS (Ali et al., 2017), PSQI (Suleiman et al., 2010), and IPAQ (Helou et al., 2017). The remaining demographic and HRV-related questionnaires were translated by the first author.

Working Memory

Executive function was assessed using the N-back task, a computer-based cognitive test for evaluating the working memory capacity (Kirchner, 1958). It involved presenting a series of random alphabetical letters on a laptop screen. Participants were required to determine if the current letter matched the one presented in the previous N trials. The N-back task was implemented using the PsyToolkit web-based platform, with N set to 2 (Stoet, 2010, 2017). Each letter was displayed for 1800 ms, followed by a 500-ms blank screen period. Participants were instructed to press the "M" key on the keyboard if there was a match, and no response was required otherwise.

The cognitive task yielded three possible responses: correct responses, missed responses, and false alarms. Additionally, the reaction time was measured as the duration it took for participants to correctly press the "M" key after the letter appearance, indicating a match response. The N-back task consisted of two blocks, each comprising 50 trials. Randomization of letters was performed to eliminate potential biases. Participants underwent a training session with 25 trials to familiarize themselves with the task before completing it. To assess cognitive performance improvement, participants completed the N-back task at two time-points: pre-intervention and post-intervention. Hence, correct responses and reaction time were used to evaluate working memory capacity performance.

Physiological Data

HRV was recorded using the CorSense device by Elite HRV[1], which could be conveniently attached to the finger and had a sampling rate of 500 Hz. Prior to each measurement, a 20-s stabilization period was allowed to ensure the heart rate had leveled out. In the case of any technical issues, HRV was recorded for 6 min to ensure a minimum recording length of 5 min. Participants were instructed to minimize hand movements to maintain a high-quality signal. For the HRV analysis, the Systole Python package was used to compute the time-domain and frequency-domain measures (Legrand & Allen, 2022). All signals were visually inspected and filtered using the adaptive threshold artefact detection and moving window average correction methods (Lipponen & Tarvainen, 2019). Moreover, blood pressure was measured for all participants following each cognitive task using

[1] https://elitehrv.com/corsense.

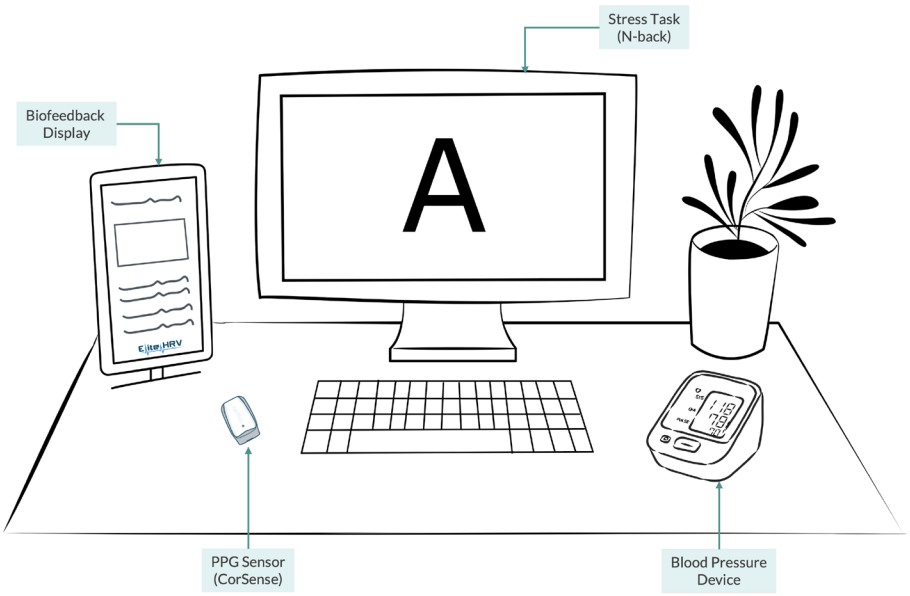

Fig. 2 The experiment setup includes the CorSense sensor, blood pressure device, biofeedback interface, and cognitive task screen

an OMRON M7 Intelli IT[2] cuff wrapped around the upper arm.

Procedure

The experimental sessions were conducted during the daytime (9:00 am to 2:00 pm) in the human-computer interaction (HCI) lab at HBKU, with each session lasting 45 min. The HCI lab is a quiet small room specifically designed for in-person experimental studies. A schematic diagram of the overall experimental setup is shown in Fig. 2. The experiment protocol involved collecting psychophysiological data at four time points: (1) baseline, (2) pre-intervention, (3) mid-intervention, and (4) post-intervention.

Upon arrival at the lab, participants were requested to sign the consent form and complete baseline questionnaires concerning demographic information, anxiety, depression, stress, emotional state, physical fitness, and sleep quality. Subsequently, a 6-min HRV recording was taken while the participants were at rest, followed by a blood pressure measurement. After the baseline measurements, participants began the first cognitive task presented on a laptop screen, with HRV data also recorded during this phase. Participants were left alone in the room to complete the cognitive tasks, while the researcher remained present between phases to address any concerns and ensure there were no technical issues. Following that, participants received a randomly generated message on the screen indicating their group assignment to either Group 1 or Group 2 (i.e., control or HRVB, respectively).

In the HRVB group, participants engaged in a paced breathing exercise for 6 min by following a breathing guide displayed on an iPad screen using the Elite HRV deep breathing feature. The visualization of the sinusoidal wave of the HRV signal during breathing, along with instructional audio guiding inhalation and exhalation, provided the biofeedback element to the participants. A brief explanation of the relationship between HRV and breathing was provided to make participants aware of any deviations from the expected sinusoidal pattern. Participants were instructed that, visually, HRV should exhibit an increase during inhalation and a decrease during exhalation, forming a wave-like pattern. Prior to the paced breathing activity, a 2-min training session was conducted to ensure participants could correctly perform the breathing exercise. The paced breathing activity utilized a prolonged exhalation period with a ratio of 4 s of inhalation and 6 s of exhalation (6 bpm; Khazan, 2013). Longer exhalations have been shown to be a stimulating protocol for notable improvements in cardiac vagal tone (Van Diest et al., 2014). Participants in the control group were instructed to sit quietly for 6 min and breathe normally, similar to the baseline phase. Finally, all participants completed the second cognitive task and proceeded to a debriefing session.

Analysis Plan

In this experimental study, we analyzed the statistical mean differences between groups to investigate the impact of the intervention on affective states (H1) using a two-way mixed analysis of variance (ANOVA), followed by planned contrasts. The independent variables were defined by the group factor (HRVB vs. control; between-subjects) and the time

[2] https://omron-healthcare.com/products/m7-intelli-it/.

factor (pre-, mid-, post-intervention; within-subjects), while the dependent variables included scores for attentiveness, fatigue, and serenity. To assess the effects of the intervention on cognitive performance (H2), we employed independent sample t-tests to compare the difference between post and pre scores of the correct responses and reaction time between both groups. Additionally, we analyzed the statistical mean differences between groups to investigate the impact of the intervention on RMSSD (H3) using two-way mixed ANOVAs, followed by planned contrasts for post-hoc analysis. The statistical analyses for H1–H3 were conducted using JASP software (JASP Team, 2023). Finally, a simple mediation model analysis was performed using the PROCESS package in R, developed by Hayes (2022) to examine the mediating role of cardiac vagal tone in the association between the HRVB intervention and the improvement in cognitive performance (H4).

As a measure of effect size, the omega squared (ω^2) was reported for the ANOVA, with values of .01, .06, and .14, indicating small, medium, and large effect sizes, respectively. Moreover, Hedges' g was reported for all pairwise comparisons, with the values of .20, .50, and .80, indicating small, medium, and large effect sizes, respectively (Cohen, 1988). The confidence interval (95% CI) was reported in the statistical analyses, as appropriate.

Results

Descriptive Statistics

A descriptive statistical overview of demographic characteristics and baseline psychophysiological measures based on the group are shown in Supplementary Table A1. At baseline, there were no significant differences between the groups in terms of age; blood pressure; body mass index; depression, anxiety, and stress (DASS-21); experience with deep breathing; experience with meditation; HRV measures; physical activity level (PSQI); positive and negative affective states (PANAS-X); or sleep quality (PSQI; see Table A1). Gender was balanced, with 10 women and nine men in each group. The effect of gender on the baseline HRV measures was also examined, and the independent t-test revealed no significant mean differences (p-values > .32 for all).

At baseline, the correlations among variables presented in Supplementary Table A1 were calculated using the Pearson's correlation coefficient. There were significant positive relationships between the negative affective states measured by the PANAS and DASS-21 (depression: r = .69, anxiety: r = .72, stress: r = .71, all $p < .05$) and sleep quality measured by the PSQI (r = .39, $p < .05$). There was a significant inverse relationship between age and the baseline SDNN measure. However, there were no significant relationships between age and the remaining HRV measures. Additionally, the correlation coefficients between RMSSD and self-reported affective states at baseline were found to be non significant (attentiveness: r = .08, fatigue: r = − .19, serenity: r = .22, all $p > .05$; refer to Supplementary Table A2 for additional HRV metrics).

Affective States

The first hypothesis posed that a single session of HRVB would have positive effects on levels of perceived attentiveness, fatigue, and serenity. A two-way mixed ANOVA was performed to assess the impact of the group (HRVB vs. control; between-subjects) and time (pre-, mid- and post-intervention; within-subjects) on the affective states reported from the PANAS-X questionnaire. The Greenhouse–Geisser correction was applied when the sphericity assumption was violated. All scores at the pre-, mid-, and post-intervention time points were normalised by subtracting the scores reported at baseline. Shapiro–Wilk test was conducted to ensure normality ($p > .05$ for all) and homogeneity of variances was found for all PANAS-X components, as assessed by Levene's test ($p > .36$ for all).

Attentiveness There was a statistically significant interaction between group and time on the attentiveness scores, $F(2, 72) = 3.6$, $p = .032$, $\omega^2 = .014$. Planned contrasts revealed that attentiveness score was significantly greater in the HRVB group compared to the control group at mid-intervention ($M_{diff} = 1.79$, $SE = 0.73$, $p = .018$, Hedges' $g = 0.81$) and post-intervention ($M_{diff} = 2$, $SE = 0.73$, $p = .008$, Hedges' $g = 0.91$).

Fatigue There was no statistically significant interaction between group and time on the fatigue scores, $F(2, 72) = 1.02$, $p = .37$, $\omega^2 = .00$. The main effect of time showed a statistically significant difference in mean fatigue score at the different time points, $F(2, 72) = 7.38$, $p = .001$, $\omega^2 = .035$. Planned contrasts revealed a significant increase in the fatigue score of the HRVB group at mid-intervention compared to the pre-intervention ($M_{diff} = 1.95$, $SE = .56$, $p < .05$, Hedges' $g = 0.53$).

Serenity There was a statistically significant interaction between group and time on the serenity scores, $F(1.48, 53.1) = 15.6$, $p < .001$, $\omega^2 = .08$. Planned contrasts revealed that

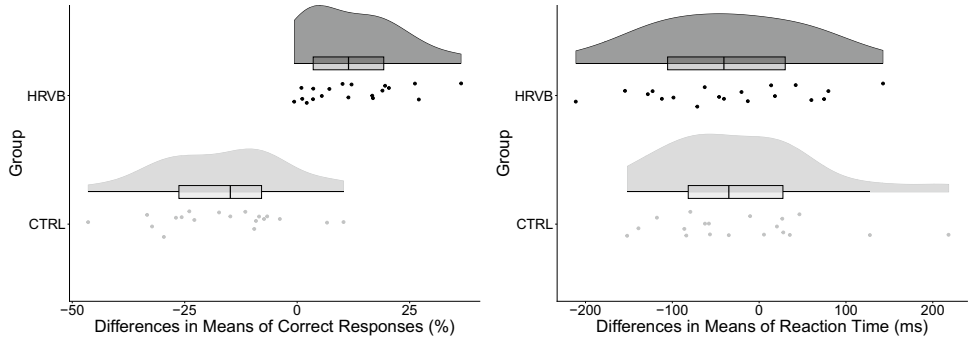

Fig. 3 Results of the difference in cognitive performance (post–pre)

serenity score was significantly greater in the HRVB group compared to the control group at mid-intervention (M_{diff} = 3.84, SE = 0.82, $p < .001$, Hedges' g = 1.7) and post-intervention (M_{diff} = 3.42, SE = 0.82, $p = .002$, Hedges' g = 1.4).

Working Memory

The second hypothesis stated that a single session of HRVB would improve the cognitive performance of the working memory task. An independent-samples t-test was performed to assess the differences in correct responses and reaction time between control and HRVB. The correct responses and reaction time were computed as the change in scores between post-intervention and pre-intervention. The Shapiro–Wilk test was conducted to ensure normality on the correct responses and reaction time for each group. The results were non-significant, indicating that both metrics were approximately normally distributed ($p > .11$ for all). The variance was homogeneous between the groups for both metrics, as assessed by Levene's test ($p > .56$ for all). The results revealed that the correct responses score was higher in the HRVB group compared to the control group, a statistically significant difference of 29.2% (95% CI 20.8–37%), t(36) = 7.2, $p < .001$, Hedges' g = 2.2. In contrast, there was no significant difference between both groups in reaction time t(36) = .49, $p = .63$, Hedges' g = .16. Figure 3 shows raincloud plots for the differences in correct responses and reaction time (Allen et al., 2021).

Cardiac Vagal Tone

The third hypothesis stated that a single HRVB session would improve the cardiac vagal tone as indexed by the RMSSD measure. A two-way mixed ANOVA was performed to assess the impact of the group (HRVB vs. control; between-subjects) and time (pre-, mid- and post-intervention; within-subjects) on the RMSSD while considering age and baseline measurements as covariates. Following ANOVA computation, planned contrasts was carried out to discern any significant pairwise differences. To ensure normality, the Shapiro–Wilk test was calculated for the log-transformed HRV values of each experimental condition. The results across all conditions were non-significant, indicating that the RMSSD measures were approximately normally distributed ($p > .05$ for all). Mauchly's test of sphericity indicated that the assumption of sphericity was met for the two-way interaction, ($\chi^2(2) = .29$, $p = .86$). Moreover, we conducted an exploratory and supplementary analysis to examine the impact of the biofeedback session on additional HRV measures including MeanRR, SDNN, and HF power, using two-way mixed ANOVAs. The mean differences of the HRV measures are presented in their non-transformed form (i.e., absolute values) for simplicity and ease of interpretation, while the statistical analyses were performed on the log-transformed data. To assess participants' adherence to the instructed slow-breathing protocol (6 bpm), the respiration rate (RESP) was estimated using Kubios HRV standard software based on the observed peak frequency in the spectral analysis of the HRV signal (Bailón et al., 2007; Shaffer & Meehan, 2020). Table 1 shows the descriptive statistics for all examined HRV measures and the estimated respiration rate.

RMSSD There was no statistically significant interaction between group and time on the RMSSD measure, F(2, 68) = 1.42, $p = .25$, $\omega^2 = .006$. Likewise, there were no significant main effects of either time F(2,68) = 0.29, $p = .75$ $\omega^2 = .00$ or group F(1, 34) = 4.15, $p = .05$, $\omega^2 = .04$. The mean differences in RMSSD between the HRVB and control groups were observed at mid-intervention (Adjusted M_{diff} = 22.95 ms, SE = 12.17 ms, Hedges' g = .38), and post-intervention (Adjusted M_{diff} = 19.81 ms, SE = 12.17 ms, Hedges' g = .23).

MeanRR There was no statistically significant interaction between group and time on the MeanRR measure, F(2, 68) = 2.25, $p = .11$, $\omega^2 = .013$.

Table 1 Descriptive statistics for the physiological measures

	Pre		Mid		Post	
Measure	HRVB	Control	HRVB	Control	HRVB	Control
RMSSD						
ms	54.4 (43.1)	48.1 (18.9)	58.5 (40.5)	44.6 (31.1)	69.6 (64.6)	53.5 (35.8)
log	3.73 (0.75)	3.8 (0.38)	3.86 (0.66)	3.6 (0.64)	3.89 (0.85)	3.79 (0.63)
MeanRR						
ms	743.1 (105.6)	723.3 (77)	748.53 (104)	738.2 (79.8)	778.7 (104)	731.4 (78.6)
log	6.60 (0.15)	6.58 (0.1)	6.66 (0.13)	6.6 (0.1)	6.65 (0.13)	6.59 (0.11)
SDNN						
ms	66.9 (47.4)	51.7 (25)	106 (47.9)	52.8 (21.2)	79.2 (64)	56 (34)
log	3.99 (0.66)	3.86 (0.42)	4.56 (0.49)	3.90 (0.39)	4.07 (0.8)	3.88 (0.54)
HF power						
ms	1755 (2763)	1187 (2201)	1674 (2048)	1120 (1185)	3323 (5286)	1256 (1934)
log	6.28 (1.67)	6.15 (1.41)	6.54 (1.55)	6.54 (1.09)	6.62 (1.99)	6.19 (1.5)
RESP						
bpm	9.45 (1.26)	9.98 (1.25)	6.08 (0.28)	9.54 (1.12)	8.54 (1.10)	9.53 (1.2)

Note Data is represented by the format of Mean (SD)

Similarly, there were no significant main effect of group, $F(1,34) = 1.08$, $p = .31$, $\omega^2 = .00$. However, there was a significant main effect of time, $F(2, 68) = 8.65$, $p < .001$ $\omega^2 = .08$. Planned contrasts revealed than MeanRR for the HRVB group was greater at mid-intervention (Adjusted $M_{diff} = 40.2$ ms, SE = 10.7 ms, $t(68) = 3.76$, $p < .001$) and post-intervention (Adjusted $M_{diff} = 34.82$, SE = 10.7, $t(68) = 3.25$, $p = .002$) compared to pre-intervention.

SDNN There was a statistically significant interaction between group and time on the SDNN measure, $F(2,68) = 4.21$, $p = .019$, $\omega^2 = .038$. Planned contrasts revealed that SDNN at mid-intervention was greater in the HRVB group compared to the control group (Adjusted M_{diff}=.695, SE = .173, t = 4.01, $p = .002$). Furthermore, SDNN for the HRVB group was significantly elevated at the mid-intervention compared to both pre- and post-intervention ($p < .001$).

HF Power There was no statistically significant interaction between group and time on the HF power measure, $F(2, 68) = 0.24$, $p = .79$, $\omega^2 = .00$. Similarly, there were no significant main effects of either time, $F(2, 68) = 0.12$, $p = .89$ $\omega^2 = .00$, or group $F(1, 34) = 0.66$, $p = .42$, $\omega^2 = .00$.

The final hypothesis (H4) suggested that the improvement in cognitive performance following the HRVB session is mediated by the cardiac vagal tone. A simple mediation model analysis was performed using the bootsrapping method of the 95% CI with a bootstrapping sample of 10,000. The outcome variable for the analysis was the correct responses, the predictor variable was the HRVB intervention as represented by the group assignment (i.e., control coded as 0 and HRVB coded as 1), and the mediator variable was the RMSSD measure. The findings indicate a statistically significant total effect (c = 8, $p = .01$, 95% CI [1.62, 14.38]), and similarly, the direct effect is also statistically significant (c = 7.7, $p = .02$, 95% CI [1.09, 14.47]). Notably, the indirect effect of the HRVB intervention on cognitive performance was not statistically significant (95% CI [−1.33, 1.73]).

Discussion

Affective States

Several self-reported affective states were investigated in this study, including attentiveness, fatigue, and serenity. The findings partially support H1 because only attentiveness and serenity components of the PANAS-X questionnaire revealed positive results for the levels in attention and relaxation during and after the HRVB intervention. These results are in line with those reported in previous studies focused on attention control (de Bruin et al., 2016) and relaxation (Clamor et al., 2016; Lin et al., 2020; Prinsloo et al., 2013; Van Diest et al., 2014; Zaccaro et al., 2018). The present study extended these findings by examining participants' subjective perception of their own attentiveness and relaxation following the cognitive task and HRVB session.

Regarding serenity levels, Lehrer and Gevirtz (2014) stipulated that the mechanisms underlying HRVB induce a relaxation response by stimulating parasympathetic activity mediated by vagal tone. The attentiveness score outcomes in this study suggest a link to improved performance in the cognitive task after the biofeedback intervention. During the debriefing session, one participant in the HRVB group commented: "The deep breathing practice helped me think clearly about strategies to solve the cognitive task".

Although there was no statistically significant interaction observed in terms of the impact of paced breathing on perceived fatigue between the two groups, the HRVB group reported a significant higher average score immediately after the intervention compared to pre-intervention representing a medium effect size. This finding could be due to the participants' lack of familiarity with paced breathing exercises, which resulted in a dyspnoeic or uncomfortable experience. In the same vein, You et al. (2021b) noted an elevation in perceived stress following a series of three 5-min paced breathing exercises in their study. This increase in stress levels was attributed to the discomfort experienced during paced breathing, which is a common occurrence among individuals unfamiliar with the practice.

Working Memory

For the cognitive performance aspect of this study, the findings partially support H2 because the HRVB group performed better in the cognitive task compared to the control group, as assessed by the correct responses. However, no differences were found with respect to reaction time. More specifically, the HRVB group performed better than the control in the second N-back task, which assessed participants' working memory capacity. These results are consistent with Prinsloo et al.'s (2011) findings regarding improvement in cognitive performance (i.e., inhibitory control measured using a Stroop task) after a single HRVB session. This observed significant increase in correct responses could be theoretically attributed to the HRVB intervention, which stimulated the vagus nerve. In particular, previous studies have linked the activation of parasympathetic activity with improvement in the working memory and attention-based tasks (Forte et al., 2019; Hansen et al., 2003, 2004). However, there was no significant difference in reaction time between the two groups post-intervention in the present study, which is in direct contrast to Prinsloo et al. (2011). This rather contradictory result may be due to the experimental protocol as the previous study advised participants to consider speed when responding, whereas participants were not similarly advised in this study. Another possible explanation may be that this study looked at reaction time for correct responses to accurately quantify processing speed (Ratcliff, 1993). Mahinrad et al. (2016) found that poor processing speed and long reaction time in cognitive functioning evaluated by a Stroop task were associated with low HRV measures. However, the authors analysed HRV signals using a 10-s segment, while the present study analysed HRV signals using a 5-min segment. There is a well-established trade-off between accuracy and reaction time in cognitive activities: individuals compromise accuracy for speed, or vice versa (Donkin et al., 2014; Franzon & Hugdahl, 1987; Wylie et al., 2009). Further, Mahinrad et al. (2016) focused on a specific age group (i.e., older participants), thus limiting the generalisability of their findings to younger age groups.

Cardiac Vagal Tone

At a physiological level, the findings do not support H3 due to insufficient evidence indicating improvements in cardiac vagal tone during and after the HRVB intervention. Although statistical analysis did not show a significant difference in vagal tone, measured by RMSSD, between the two groups at various time points, the HRVB group exhibited higher RMSSD values compared to the control group at mid-intervention and post-intervention, with small effect sizes. However, there was no significant association between vagal tone and improved working memory, as evidenced by the non-significant results of the mediation analysis, thereby not supporting H4. These findings are in agreement with prior research demonstrating that a single-paced breathing session does not sufficiently improve RMSSD after the session (Laborde et al., 2019b; You et al., 2021a) and the improvement in cognitive performance is not mediated by RMSSD (Laborde et al., 2022a). Consequently, the present study obtained a similar conclusion regarding post-intervention RMSSD and vagal tone, despite the previous studies not including a biofeedback component in their design. However, exploring variations in the patterns and amplitude of cardiovascular vagal afferent input during the paced breathing activity could provide valuable insights into the mechanisms underlying the study outcomes (McCraty & Childre, 2010). This can potentially offer a more nuanced understanding of how HRVB influenced cognitive performance and changes in affective states.

Contrary to the results reported in You et al. (2021a), the present study did not find significant group differences in RMSSD during the intervention; however, these results are in line with those of Laborde et al. (2019b). While this study implemented a paced breathing rate similar to that in You et al. (2021a), the discrepancy in results could be due to the number and duration of paced breathing exercises (e.g., three 5-min sessions), type of participant (e.g., athletes), or type of control (e.g., watching television).

Limitations

There are a number of limitations in the present study related to the biofeedback protocol. First, the lack of participants' familiarity with paced breathing exercises may have posed challenges in correctly performing the activity. Although the exercise duration was intentionally selected to be short (6 min) to minimise discomfort in participants unfamiliar with the exercise, a better strategy may be to adopt multiple consecutive short sessions with breaks in between, as in Laborde et al. (2022b) and You et al. (2021a). Furthermore, real-time respiratory monitoring using a respirometer during the intervention could have provided stronger evidence of participant compliance to the instructed slow-breathing protocol (6 bpm), potentially boosting the interpretability of the study's findings (Shaffer & Meehan, 2020). Second, all participants performed the breathing exercise at the same rate of 6 breaths/min rather than determining the resonant frequency for each participant. Although several studies have indicated similar physiological behaviour with 6 breaths/min during the exercise, Steffen et al. (2017) observed differences in self-reported mood between breathing at resonant frequency and one breath per minute higher than the determined resonant frequency. Consequently, future studies could investigate the distinctions between resonant frequency and breathing at a fixed rate after the paced breathing exercise at a psychological level.

Conclusions

In summary, this study explores the impact of HRVB on psychophysiological measures, specifically focusing on self-reported affective states, cardiac vagal tone, and cognitive performance related to working memory. Despite the absence of an associated increase in vagal tone, as indicated by RMSSD, cognitive performance displayed promising improvement following the biofeedback intervention, evident in correct responses and attentiveness scores. The lack of increase in vagal tone could be explained by several factors, such as the biofeedback protocol, duration of the biofeedback session, or participants' lack of familiarity with paced breathing. An additional prominent finding is the improvement in relaxation levels measured via self-reported serenity scores after the biofeedback intervention. For a more comprehensive understanding of vagal tone within the neurovisceral integration model, future studies could incorporate alternative cognitive stress tasks that impose a higher mental workload, such as the dual N-back task involving auditory and visual stimuli. With respect to the effects of paced breathing on vagal tone, the biofeedback protocol can be similarly improved by determining the resonant frequency for each participant or incorporating a longer paced breathing session.

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Author Contributions MB and TS conceptualized and designed the study. MB collected the data and performed the data analyses. MB wrote the main manuscript. TS reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

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Data Availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

Ethical Approval The study was approved by the Institutional Review Board at Qatar Biomedical Research Institute at HBKU (Protocol Code QBRI-IRB-2021-03-088 and date of 8th of March 2021).

Consent to Participate Informed consent was obtained from all participants involved in the study.

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ARTICLES FOR FACULTY MEMBERS

ADVANCING MENTAL PERFORMANCE IN COMPETITIVE AQUATIC ATHLETES THROUGH THE DEVELOPMENT AND VALIDATION OF A REAL-TIME BIOFEEDBACK SYSTEM FOR PSYCHOLOGICAL SKILLS TRAINING

The effects of biofeedback training on athletes' mental health and performance: a systematic review and Bayesian meta-analysis. / Zhang, X., Chang, Z., Zhao, S., & Ning, Z.

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The effects of biofeedback training on athletes' mental health and performance: a systematic review and Bayesian meta-analysis

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Background: Biofeedback and neurofeedback are increasingly used in sports psychology, yet their overall effectiveness for athletes' mental health, athletic performance, and cognitive performance remains unclear.
Methods: We conducted a systematic review of randomized controlled trials across eight databases and performed Bayesian random-effects meta-analyses. Study selection used ASReview with the SAFE rule; full-text screening was done in Covidence; risk of bias followed Cochrane guidance; certainty of evidence was appraised with GRADE.
Results: Forty-one studies met inclusion. Pooled effects were statistically significant across domains: mental health μ(SMD)=0.76 (95% CrI 0.44–1.09), athletic performance μ(SMD)=0.88 (0.69–1.05), and cognitive performance μ(SMD)=0.81 (0.48–1.14).
Conclusion: Biofeedback and neurofeedback benefit athletes across mental, athletic, and cognitive outcomes. Given heterogeneity and sample sizes, further rigorous trials are warranted to refine the estimates.
Systematic review registration: PROSPERO registration CRD420251015094.

KEYWORDS

biofeedback, neurofeedback, mental health, athletic performance, Bayesian meta-analysis

Introduction

As an interdisciplinary technique that integrates physiology, psychology, and neuroscience, biofeedback training is increasingly recognized as an effective intervention for enhancing athletes' mental health and performance (Kloudova, 2021). Research has demonstrated a significant positive correlation between optimal mental states and athletic performance, wherein effective regulation of emotional reactivity and anxiety enhances decision making and attentional control-key determinants of athletic success (Raglin, 2001; Rice et al., 2016). Therefore, an in-depth investigation into the application value of biofeedback in enhancing athletes' mental health and performance represents a meaningful and timely direction in contemporary sports science research (Blumenstein et al., 2014).

Biofeedback can be defined as a technique that uses instruments to monitor an individual's physiological activities in real time and provides feedback through visual or auditory means (Egner and Gruzelier, 2004; Giggins et al., 2013; Schwartz, 2010). Herbert Benson's "relaxation response" theory suggests that by regulating the autonomic nervous system, biofeedback can effectively reduce the levels of stress hormones such as cortisol in the body, thereby alleviating the stress response (Lehrer et al., 2020). Furthermore, the core theoretical mechanism

underlying biofeedback interventions lies in enhancing individuals' ability to regulate autonomic nervous system activity particularly heart rate variability (HRV) through training. This process relies on the plasticity of vagal tone, whereby repeated practice improves the ability to identify and control the resonance frequency per week between heart rate and resonant frequency, thereby increasing parasympathetic activation (Lehrer et al., 2003; Pagani et al., 2009). Additionally, from the perspective of operant conditioning, biofeedback is a learning process where individuals achieve intentional control over their body states through awareness and regulation of physiological signals (Basmajian, 1983). This process reflects the fundamental view of the mind body interaction theory that psychological processes can have regulatory effects on physiological functions through the central nervous system (Blanchard and Young, 1979). Although these theories provide important theoretical support for the application of biofeedback training, current empirical research on it is still insufficient, and its true effectiveness remains controversial in multiple fields (Rydzik et al., 2023).

Recent research suggests that biofeedback training has a positive effect on improving athletes' mental health (Saha et al., 2013), with statistically significant benefits observed in shooting athletes (Donghai et al., 2024a), and football players (Rusciano et al., 2017). Biofeedback training can effectively attenuate the stress response by modulating autonomic nervous system activity, thereby enhancing emotional regulation and cognitive function (Dehghani et al., 2023). Notably, the enhancement of physiological self-regulation through biofeedback not only contributes to improved self-efficacy but may also indirectly reduce anxiety (Goessl et al., 2017; Teufel et al., 2013). Taken together, these findings highlight that biofeedback training not only alleviates stress and anxiety through enhanced emotional and physiological self-regulation, but also builds a solid psychological foundation that may benefit athletic performance.

In addition to its positive impact on mental health, research also shows that biofeedback training has a direct promoting effect on athletic performance itself. It is also applicable to swimming (Bar-Eli, 2004), golf (Cheng et al., 2015), judo (Pronczuk et al., 2023), winter sports athletes (Toolis et al., 2024), and basketball players (Paul and Garg, 2012). Furthermore, improving the regulatory ability of the autonomic nervous system through biofeedback also helps enhance an individual's cognitive performance (Pronczuk et al., 2023), such as attention control, working memory, and decision making ability. These cognitive factors play significant roles in complex and high speed competitive environments (Rusciano et al., 2017; Paul and Garg, 2012; Dana et al., 2019; Mikicin et al., 2015). Therefore, biofeedback training can not only enhance the self-regulation ability of physiology and emotion, but also support the improvement of cognitive efficiency, thereby comprehensively promoting the improvement of athletic performance (Brito et al., 2022; Tosti et al., 2024).

Although existing studies have to some extent verified the positive effects of biofeedback training on improving athletes' mental health and performance, research in this field is still relatively scarce. Existing studies mostly focus on a specific sport or small sample experiments, lacking extensive coverage and in depth exploration across different sports (Paul and Garg, 2012; Bar-Eli et al., 2002; Wilson and Bird, 1981; Yılmaz et al., 2025). Most existing meta-analyses have primarily examined the effects of heart rate variability biofeedback on depression and general performance, often without specifically focusing on athlete populations or encompassing the full range of biofeedback modalities (Lehrer et al., 2020; Pizzoli et al., 2021). Consequently, there is a pressing need for more diverse and representative large-scale studies-particularly systematic empirical investigations across various sports-to comprehensively assess the applicability, developmental potential, and actual efficacy of biofeedback interventions in athletic settings (Lehrer et al., 2020).

Furthermore, although the majority of studies support the effectiveness of biofeedback training in improving mental health and enhancing both motor and cognitive performance, notable exceptions have also been reported. For instance, no significant differences in attentional performance were found between the experimental and control groups following neurofeedback training (Mirifar et al., 2019). Similarly, physical flexibility significantly improved across all three experimental groups after biofeedback training; however, the magnitude of improvement did not differ significantly between groups, suggesting that the specific type of training administered had no distinct effect on flexibility outcomes (Wilson and Bird, 1981). Moreover, the interaction between group type and training outcome was not statistically significant, indicating that group assignment did not moderate the training's impact on flexibility gains (Wilson and Bird, 1981). Therefore, these differences suggest that the effects of biofeedback or neurofeedback training may not be universally applicable, and its benefits may depend on a variety of factors, including the specific sport participated in, the training program adopted, as well as the individual's sports background and psychological characteristics, etc. (Tosti et al., 2024).

Building upon findings from prior studies, the present research incorporates a dose–response and moderation analysis to explore how variations in intervention dosage-defined by intervention time (weeks), frequency per week, and frequency per week-impact outcomes related to mental health, athletic performance, and cognitive performance. Using a Bayesian meta-analytic framework, this study systematically evaluates the overall effectiveness of biofeedback training among athletes, with the hypothesis-grounded in prior empirical evidence and dose-effect patterns-that such training yields significant positive effects across all three domains.

Methods

This study was registered on the PROSPERO platform (registration number: CRD420251015094) and conducted in accordance with the PRISMA guidelines for systematic reviews and meta-analyses (Haddaway et al., 2022). During literature screening and data analysis, we used R (version 4.5.1), the Python-based ASReview tool, the Covidence platform, and GRADEprofiler to support screening and evaluation procedures.

Inclusion criteria for screening

Literature screening followed the PICOS framework. Participants in the included studies were athletes of any age and health status. Only randomized controlled trials (RCTs) that used biofeedback or neurofeedback training as the intervention were eligible. The control group could include participants who received no psychological or physiological training, or those who underwent alternative skill training that did not involve biofeedback or neurofeedback.

Eligible studies were required to report outcome measures related to mental health, athletic performance, or cognitive performance. Publications in both English and Chinese were considered. Studies were excluded if they met any of the following criteria: (1) master's or

doctoral theses and conference abstracts, which were excluded to ensure methodological consistency and reliable data extraction; (2) non-original articles such as letters, editorials, or commentaries; (3) studies lacking extractable data; or (4) studies in which the experimental and control groups received different types of biofeedback or neurofeedback interventions.

Information retrieval

A comprehensive search strategy was developed on February 17, 2025, using both Medical Subject Headings (MeSH) and free-text terms. Systematic searches were performed across eight databases: Ovid, Web of Science, Scopus, PubMed, Embase, PsycINFO, SPORTDiscus, and CNKI (China National Knowledge Infrastructure). The keywords and MeSH terms were discussed and finalized by four authors (XZ, ZC, SZ, and ZN). Detailed search strings for each database are provided in Supplementary File S1. Screening was conducted using the Covidence online platform and ASReview, a Python-based machine learning tool for literature prioritization (van de Schoot et al., 2021). A total of 5,527 studies were identified for further evaluation.

Screening process

All titles and abstracts were first evaluated with ASReview, a machine learning based screening tool. ASReview predicts study relevance by training a classification model on labeled abstracts and continuously reprioritizes the remaining records according to their likelihood of inclusion (Holzinger, 2016; Van de Schoot et al., 2021; Wang et al., 2020). This approach markedly reduces manual workload by presenting the most likely relevant records first.

During this phase we applied the conservative SAFE rule, which stops screening only after 200 consecutive records have been judged irrelevant (Boetje and Van De Schoot, 2024). Full-text screening was then conducted independently by two reviewers (XZ and ZC) on the Covidence platform, as recommended in PRISMA guidelines. Eligible articles were recorded with the Extraction 1.0 form, and any disagreements were resolved by a third and fourth reviewer (SZ and NZ) (Boetje and Van De Schoot, 2024).

Extract data information

For each study, the extracted features include the author, publication year, country, intervention, study design, biofeedback training or neurofeedback training, practice period, sample size, gender, athlete type, age, training years and outcome. The outcomes of mental health include anxiety, stress, anger, fatigue and depression. The results of athletic performance include golf performance, speed, swimming performance, balance, shooting performance, endurance, coordination, basketball performance, bowling performance, football performance, strength, running performance, rowing performance and flexibility. Cognitive performance results include attentional control, attentional focus, selective attention, task performance metrics and working-memory performance.

The data were extracted by two authors (XZ and ZC) respectively, and the differences were resolved through consultation with the third and fourth authors (SZ and ZN). The results are presented in the form of mean ± standard deviation (M ± SD). For the data that were not initially provided in M ± SD format, we used an online tool called Meta Analysis Accelerator for conversion (Abbas et al., 2024). Since none of the included studies reported correlation coefficients, a correlation coefficient of 0.5 was assumed for all analyses, following the recommendation of Follmann et al. (1992). When data were not provided in numerical form, we used GetData Graph Digitizer to extract the corresponding values from the figures (Digitizer, 2020).

Risk bias assessment

The risk of bias in all included studies was independently evaluated according to the criteria in the Cochrane Handbook of Systematic Reviews of Interventions (Higgins et al., 2011). Two authors (XZ and ZC) evaluated the studies in randomized controlled trials (RCTs) through the Covidence tool in accordance with the Cochrane Risk of bias Assessment Criteria (ROB2), covering seven areas of bias: (1) Random sequence generation; (2) Allocation concealment (3) Blinding of participants and staff; (4) Blinding of outcome assessment; (5) incompleted data; (6) Selective Reporting (7) Other biases. The risk of bias is classified as low, unclear or high. All the assessment results were agreed upon through discussion and recorded in the Excel template. Subsequently, the data were input into the R software, and the bias risk summary graph was generated using the robvis package (McGuinness and Higgins, 2021).

GRADE evidence grade evaluation

In the field of athletic performance research, this study adopts the GRADE method to systematically assess the quality of evidence from four core dimensions (Higgins et al., 2011). Firstly, the potential risk of bias in the included studies was assessed-specifically, the systematic errors that may arise during research design, implementation, or result reporting, which could compromise the validity of the conclusions. Secondly, heterogeneity across studies was evaluated using the I^2 statistic to assess the degree of inconsistency in the results. Thirdly, the indirectness of the evidence was evaluated-specifically, whether the interventions, study populations, and outcome measures included in the reviewed studies directly addressed the core questions of this analysis. Finally, the imprecision of the effect estimates was assessed. The robustness and reliability of the conclusions were primarily evaluated based on the width of the confidence intervals around the effect sizes and the sample sizes of the included studies.

According to the GRADE standard, the quality of evidence is divided into four grades: "high," "medium," "low" and "very low," reflecting the gradient level of evidence credibility from highly certain to highly uncertain.

Data analysis

This study conducted a meta-analysis within the framework of Bayesian statistics to integrate prior information more comprehensively and quantify the uncertainty of the estimated values.

The overall meta-analysis was conducted using the bmeta package (version 4.5.1) in R software (Higgins et al., 2009). Firstly, with the help of the escalc() function of the meta forpackage, calculate the standardized mean difference (SMD) and its variance (vi) of each study, and then calculate the Standardized error (sei) and accuracy (1/vi). After establishing the data object, the bmeta() function is used to fit the random effects model (type = "ran"), and the model type is specified as the standard normal variance structure (model = "std.mv"). The total number of sampling iterations of MCMC is set at 50,000 times, and the burn in period is set to 20,000 iterations. The model output includes the estimation of the posterior mean of the effect size, the 95% Credible interval (CrI), and the heterogeneity parameter (tau). The heterogeneity level was supplemented and evaluated simultaneously by calculating the I^2 value through the rma() function in the metafor package.

Subgroup analysis was accomplished using the bayesmeta (Röver, 2020) package (version 4.5.1). In addition, subgroup analyses were performed by athlete competitive level (elite vs. amateur) to examine potential differences in mental health, athletic performance, and cognitive performance outcomes. Furthermore, subgroup analyses were also performed according to blinding procedures (open-label vs. adequate blinding) to examine whether trial design characteristics influenced the observed effects.

Furthermore, Bayesian meta-regression models were fitted using the brms package to evaluate potential moderators of heterogeneity, including gender (percentage of female participants) and age (mean age of participants) (Bürkner, 2017; Carpenter et al., 2017). The model specification was yi | se(sei) ~ 1 + Moderator + (1 | Study), where yi denotes the standardized mean difference and see the corresponding standard error. Weakly informative priors (Normal(0,2) for intercepts, Cauchy(0,1) for random-effect SDs) were applied. Models were run with 8 chains, 4,000 iterations each (2000 warm-up), with adapt_delta set to 0.999 and max_treedepth set to 15. Model performance was assessed using Bayesian R^2 with 95% credible intervals to quantify the proportion of variance explained.

The input includes the effect size (yi) and the standardized error (sei). The prior of the overall effect size is set as a normal distribution with a mean of 0 and a Standardized deviation of 5 (mu.prior. mean = 0,mu.prior.sd = 5) (Röver, 2020; Röver and Friede, 2023), and the heterogeneity parameter τ is set as a non-information uniform distribution (tau.prior = "uniform"). The bayesmeta() function was used to fit the model, and the prior and posterior images of the overall effect, heterogeneity, predicted distribution and their combined distribution were plotted to comprehensively present the uncertainty structure. All analyses were completed in R software (version 4.5.1). The 95% confidence interval (CrI) is interpreted as the probability that the true value of the parameter falls within this interval under the given data and model being 95%. The overall analysis process considers model transparency, estimation accuracy and bias test, providing solid statistical support for the research conclusion. The Bayesian meta-analysis used the Bmeta and Metafor escalc R packages to calculate effect size (SMD) and variance reciprocal in each study. The Bayesian approach is considered suitable for meta analyses including few studies, providing evidence for both null and alternative hypotheses, and offering complete information about credible parameter values and the probability of any given value (Higgins et al., 2009; Röver, 2020; Harrer et al., 2021; Kruschke and Liddell, 2018).

Publication bias

To assess whether there was publication bias in the included studies, this study used the bmeta package and the bayesmeta package for the visualization analysis of funnel plots. Specifically, in the bmeta analysis, the funnel.plot() function is used to draw the funnel plot with the effect size as the horizontal axis and the Standardized error as the vertical axis, and the symmetry is visually checked to determine whether there is bias. In Bayesmeta analysis, the funnel.bayesmeta() function is used to further verify the existence of the small sample effect or potential bias within the Bayesian framework. Through visual examination of the symmetry of the funnel plot, if significant asymmetry is observed, it may suggest the existence of publication bias.

Furthermore, Egger's regression test was performed, and both contour-enhanced funnel plots and sunset (power-enhanced) funnel plots were applied as complementary approaches. These methods enabled visualization of significance contours and study-level statistical power, thereby providing a more comprehensive assessment of potential publication bias (Duval and Tweedie, 2000). Specifically using the trimfill() function in the metafor package of the R language, combined with iterative operations, the number of missing studies is estimated, and the effect size is corrected accordingly, thereby enhancing the robustness of the research results and further improving the scientific nature of the conclusion.

Results

The results of this study consist of six parts: literature screening process, summary of research characteristics, Risk of bias assessment, results of meta-analysis, publication bias test and GRADE evidence classification.

Literature screening process

Through systematic retrieval of eight databases (Ovid, CNKI, Scopus, Pubmed, Embase, PsycINFO, SPORTDiscus and Web of Science), 5,527 related literatures were initially obtained. EndNote X9 software was used to remove duplicates. 756 duplicate literatures were eliminated, and the remaining 4,771 entered the initial screening. The initial screening adopted ASReview for title and abstract screening. The machine learning model automatically evaluated 1,256 literatures, and finally 197 entered the full text screening stage. After reading the full text, 164 studies that did not meet the inclusion criteria were excluded, and 32 qualified studies were initially retained. To further ensure the completeness of the literature, an additional 9 related studies were included through citation retrospective supplementary search. Ultimately, 41 studies met the inclusion criteria of the meta analysis. The research screening process is detailed in Figure 1 (PRISMA flowchart).

Characteristics included in the study

A total of 41 randomized controlled trials were included in this study, involving 1,230 athletes, including 905 males and 282 females. Additionally, gender data were missing for 43 participants (3.50% of

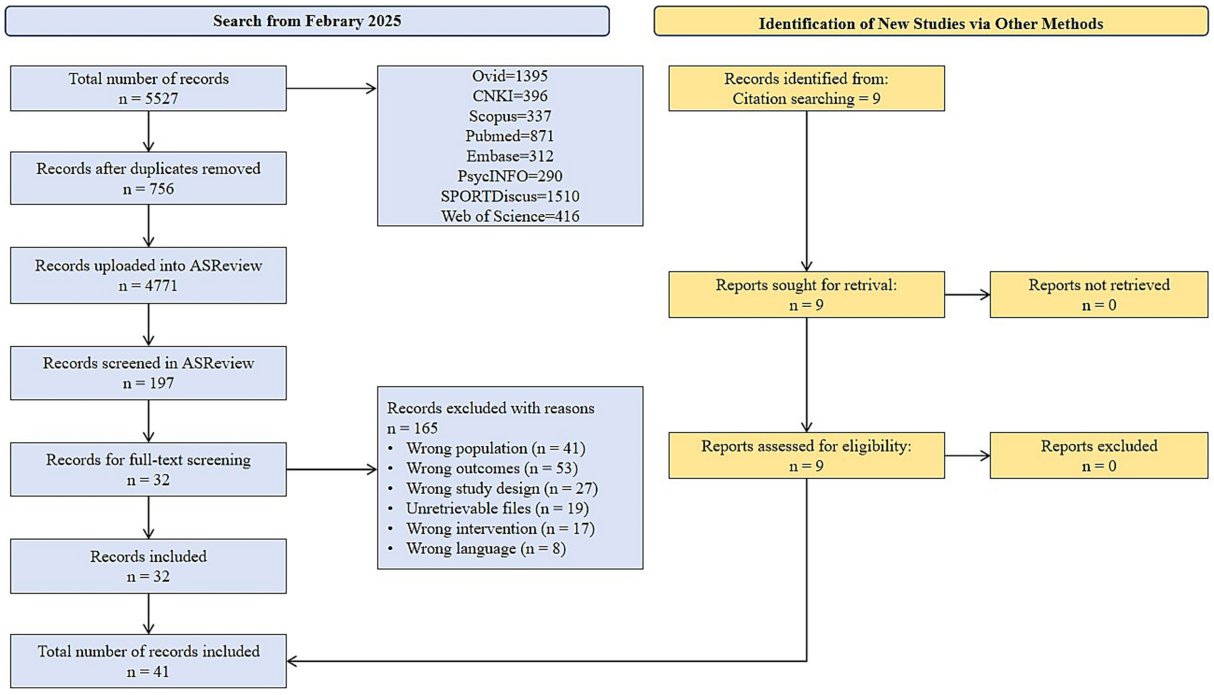

FIGURE 1
PRISMA flowchart of study selection.

the total sample), as reported in two of the included studies (Mikicin et al., 2015; Maszczyk et al., 2020). Among all the studies, 29 used biofeedback training as an intervention, and 12 used neurofeedback training. In terms of the geographical distribution of the studies, 22 studies were from Asia (accounting for 53.66%), 14 from Europe (accounting for 34.15%), 4 from North America (accounting for 9.76%), and 1 from Oceania (accounting for 2.44%). It should be noted that the age information of the subjects was not reported in 12 studies, accounting for 29.27% of the total included trials. For detailed characteristics of each study, please refer to the Supplementary Material S2.

Risk of bias

As shown in Figure 2, the risk of bias was evaluated across key methodological domains. In Sequence Generation, a small proportion (7.1%) of studies were rated as having some concerns due to insufficient detail about the randomization process; no study was considered high risk. In the field of allocation concealment, most studies were rated as high concern, with 85.4% rated as some concerns and 2.4% as high risk, mainly because concealment methods were not reported or were clearly inadequate. In the field of Blinding of Participants and Personnel, 65.9% of studies had some concerns and 4.9% were at high risk, often due to a lack of reported blinding in trials involving subjective outcomes. Similarly, in the field of Blinding of Outcome Assessors, 56.1% had some concerns and 4.9% were rated as high risk due to insufficient reporting on whether blinding was performed or absent when outcome evaluation could be influenced. For Incomplete Outcome Data and Selective Reporting, all studies were at low risk, reflecting proper data handling and transparent reporting. Overall, more than 45% of studies had at least some risk of bias, primarily due to missing or insufficient reporting on allocation and blinding procedures.

Meta-analysis

The meta-analysis included 41 studies and focused on three primary outcomes: mental health, athletic performance, and cognitive performance in athletes. Specifically, 15 studies with 394 athletes examined the effects on mental health, 24 studies involving 2,320 athletes focused on athletic performance, and 11 studies with 348 athletes assessed cognitive performance. The results indicate that biofeedback and neurofeedback training have positive effects across all three domains, effectively improving athletes' mental health, enhancing athletic performance, and strengthening cognitive performance.

Mental health

The results analysis revealed that the biofeedback intervention had a significant moderate effect on improving the mental health of athletes [μ(SMD) = 0.76; 95% CrI: 0.44 to 1.09; τ(tau) = 0.99; Rhat = 1.001], indicating an overall positive impact on psychological well-being (Figure 3).

Athletic performance

The analysis demonstrated that the biofeedback intervention was found a statistical significance on enhancing athletic performance [μ(SMD) = 0.88; 95% CrI: 0.69 to 1.05; τ(tau) = 2.24; Rhat = 1.001], indicating strong evidence of improved Athletic performance among athletes (Figure 4).

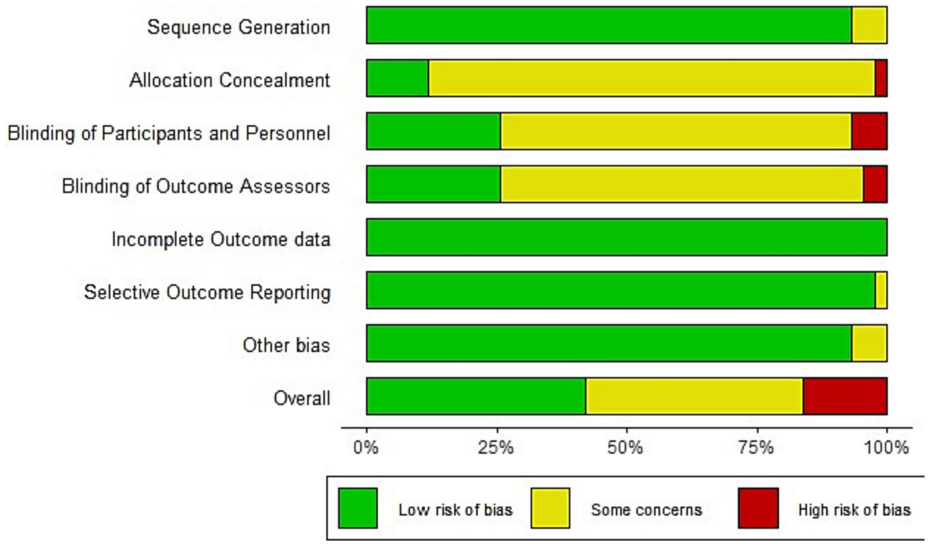

FIGURE 2
Risk of bias summary.

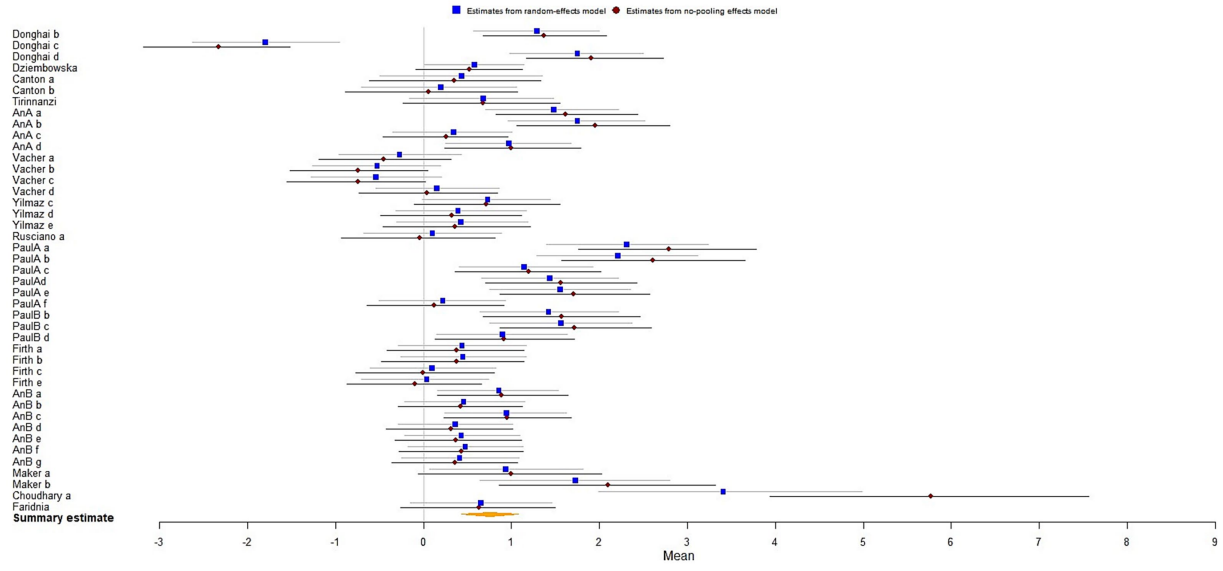

FIGURE 3
The forest plot in mental health.

Cognitive performance

The results indicated statistically significant effects of biofeedback and neurofeedback training on cognitive performance [μ(SMD) = 0.81; 95% CrI: 0.48 to 1.14; τ(tau) = 1.42; Rhat = 1.001], demonstrating overall enhancements in cognitive performance (Figure 5).

Subgroup analysis based on intervention type (biofeedback vs. neurofeedback)

Mental health (biofeedback and neurofeedback)

In terms of mental health, biofeedback interventions demonstrated a statistically significant effect [μ(SMD) = 0.76; 95% CrI: 0.42 to 1.10; τ(tau) = 1.01], indicating robust improvements in athletes' psychological well-being. Neurofeedback, however, was represented by a single study only, yielding an effect estimate of [μ(SMD) = 0.61; 95% CrI: −0.28 to 1.51; τ(tau) not estimable]. The forest plots for each subgroup are provided in Supplementary Document S4.

Athletic performance (biofeedback and neurofeedback)

In terms of athletic performance, both biofeedback and neurofeedback interventions demonstrated statistically significant effects, with biofeedback yielding an effect size of [μ(SMD) = 0.85; 95% CrI: 0.46 to 1.26; τ(tau) = 0.89] and neurofeedback training

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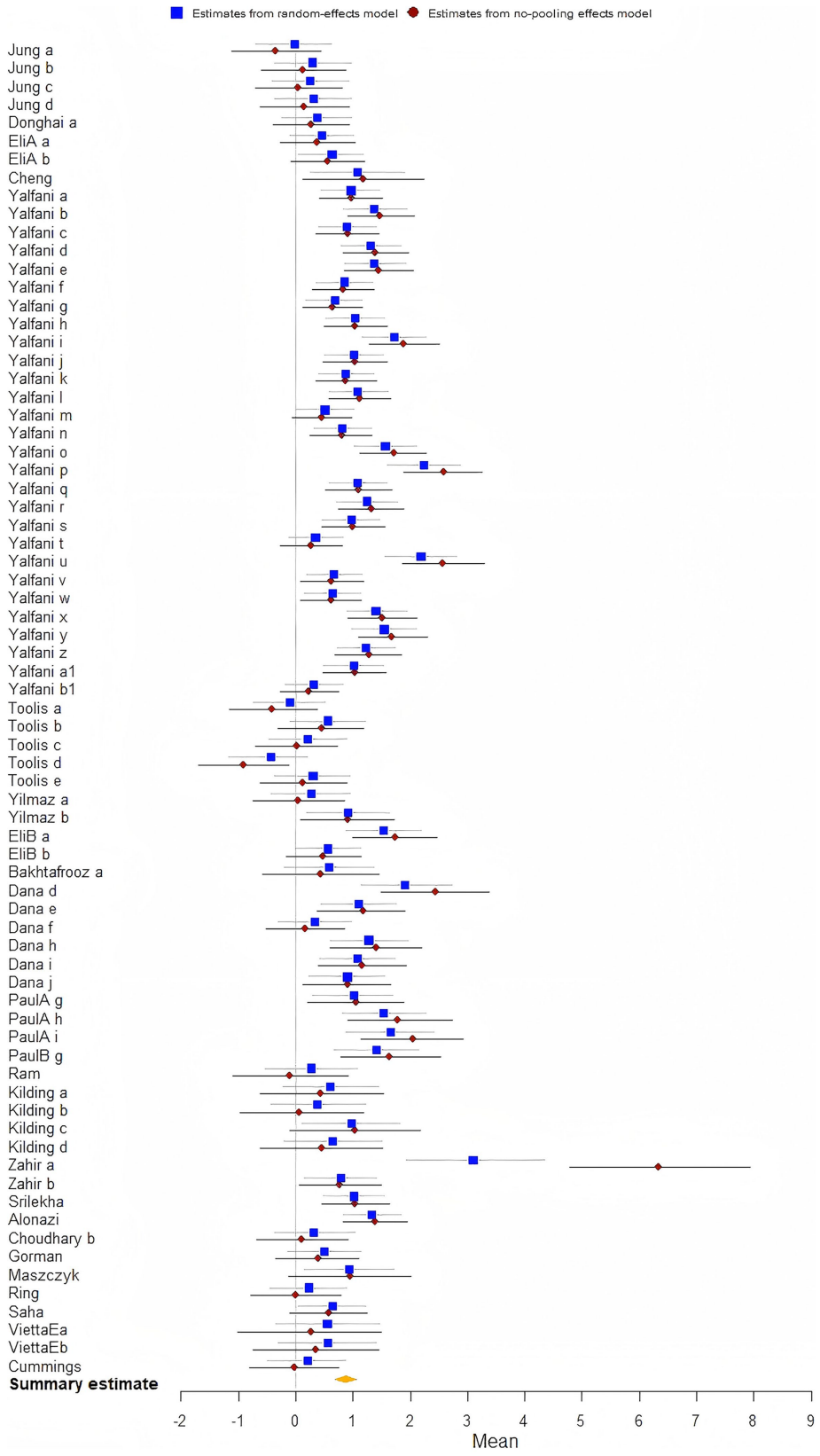

FIGURE 4
The forest plot in athletic performance.

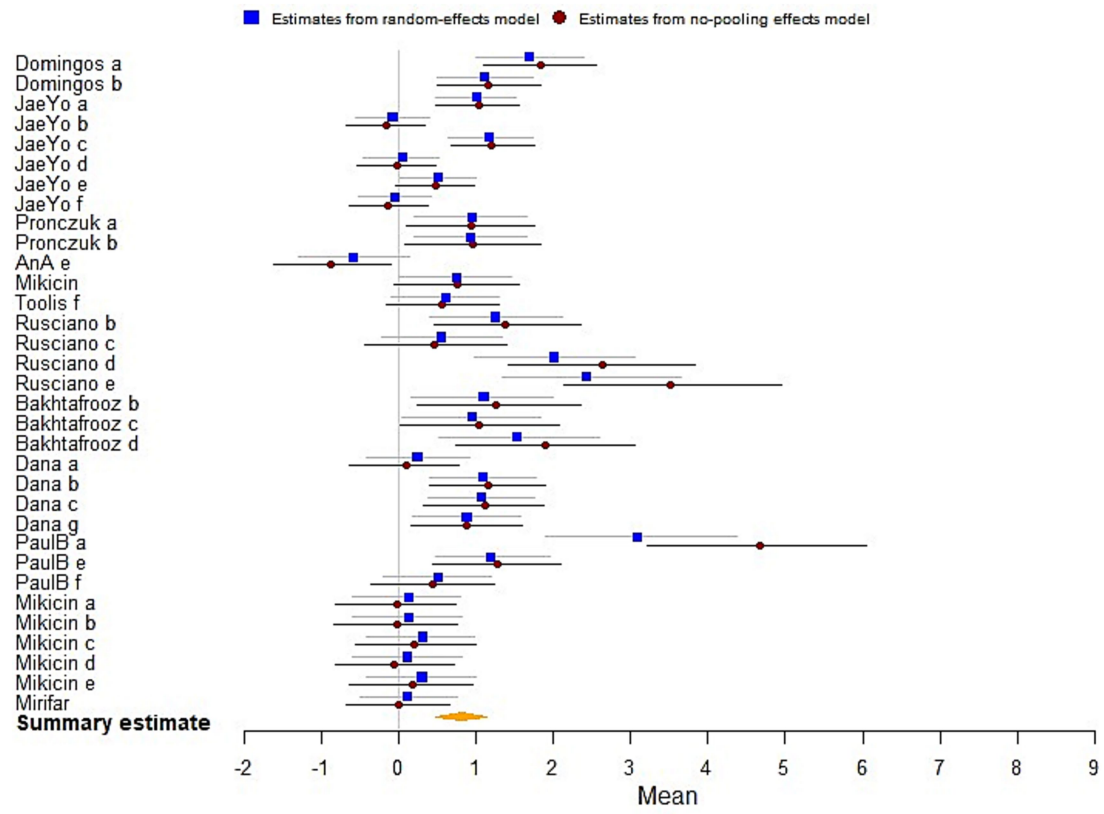

FIGURE 5
The forest plot in cognitive performance.

[μ(SMD) = 0.89; 95% CrI: 0.68 to 1.09; τ(tau) = 0.64]. The forest plots for each subgroup are provided in Supplementary Document S4.

Cognitive performance (biofeedback and neurofeedback)

In terms of cognitive performance, both biofeedback [μ(SMD) = 0.97; 95% CrI: 0.40 to 1.54; τ(tau) = 1.44] and neurofeedback [μ(SMD) = 0.81; 95% CrI: 0.50 to 1.12; τ(tau) = 0.58] demonstrated Statistical significance. Forest plots for each subgroup are presented in Supplementary Document S4.

Subgroup analysis based on specific psychological and performance outcomes

Biofeedback training

A total of 10 outcome domains were included in the subgroup analysis of biofeedback training. Statistically significant effects were observed in basketball performance [μ(SMD) = 1.59; 95% CrI: 0.61–2.59; τ(tau) = 0.66], pressure reduction [μ(SMD) = 0.72; 95% CrI: 0.35–1.10; τ(tau) = 0.89] and anxiety reduction [μ(SMD) = 1.02; 95% CrI: 0–2.04; τ(tau) = 1.56]. No statistical significance was found in other outcomes. Forest plots are presented in Supplementary Document S4.

Neurofeedback training

A total of six outcome domains were included in the neurofeedback analysis. Statistically significant effects were observed in both balance [μ(SMD) = 1.17; 95% CrI: 0.95 to 1.40; τ(tau) = 0.52] and attentional control [μ(SMD) = 0.68; 95% CrI: 0.03 to 1.39; τ(tau) = 0.69]. No statistically significant effects were found in the remaining athletic performance or cognitive performance domains. Forest plots are provided in Supplementary Document S4.

Subgroup analysis based on athlete competitive level

For mental health, elite athletes showed an estimated effect of μ = 0.86 (95% CrI: 0.46–1.25; τ = 1.11, 95% CrI: 0.78–1.46), while amateur athletes showed μ = 0.29 (95% CrI: −0.08–0.66; τ = 0.22, 95% CrI: 0.00–0.58).

For athletic performance, the effect for elite athletes was μ = 0.76 (95% CrI: 0.23–1.31; τ = 1.16, 95% CrI: 0.68–1.69), compared with μ = 0.94 (95% CrI: 0.76–1.12; τ = 0.56, 95% CrI: 0.40–0.72) for amateur athletes.

For cognitive performance, elite athletes showed μ = 1.01 (95% CrI: 0.47–1.58; τ = 1.15, 95% CrI: 0.69–1.66), whereas amateur athletes showed μ = 0.52 (95% CrI: 0.17–0.89; τ = 0.44, 95% CrI: 0.00–0.83).

Overall, these findings suggest some variation by competitive level, with elite athletes tending to show higher estimates in mental health and cognitive performance, and amateur athletes showing relatively higher estimates in athletic performance. Forest plots for these subgroups are provided in Supplementary Document S4.

Subgroup analysis based on blinding

Subgroup analyses based on blinding procedures revealed differential patterns across outcome domains. For mental health, open-label studies indicated a moderate effect with greater uncertainty [μ(SMD) = 0.63; 95% CrI: −0.16 to 1.43; τ(tau) = 1.58], whereas adequately blinded trials demonstrated a more precise and significant effect [μ(SMD) = 0.83; 95% CrI: 0.46 to 1.21; τ(tau) = 0.99].

For athletic performance, open-label studies showed negligible effects [μ(SMD) = 0.01; 95% CrI: −2.17 to 2.18; τ(tau) = 1.45], while adequately blinded trials yielded significant improvements [μ(SMD) = 0.86; 95% CrI: 0.48 to 1.25; τ(tau) = 0.97].

Regarding cognitive performance, adequately blinded studies showed statistically significant benefits [μ(SMD) = 0.86; 95% CrI: 0.44–1.29; τ = 1.00].

Overall, adequately blinded trials consistently yielded statistically significant effects, whereas open-label trials did not show significant results. Forest plots for these subgroups are provided in Supplementary Document S4.

Subgroup analysis based on biofeedback dose

This section presents exploratory analyses of the relationship between different intervention dosages, categorized by intervention time (weeks), session length (minutes), and weekly frequency (sessions/week), and their effects on mental health, athletic performance, and cognitive performance outcomes. In the subgroup analyses across these outcome domains, interventions were consistently classified according to three dimensions to allow for systematic comparison. Based on intervention time (weeks), interventions were divided into three groups: less than 5 weeks, 6 to 10 weeks, and more than 10 weeks. In terms of session length, they were categorized as sessions lasting less than 20 min, 21 to 40 min, or 41 to 60 min. Regarding weekly frequency, interventions were classified as occurring 3 or fewer times per week, 4 to 5 times per week, or 6 to 7 times per week. These consistent classification criteria provided a comprehensive basis for evaluating the effectiveness of interventions across varying time frames and intensities. These analyses are exploratory and are not intended as dosage recommendations.

Mental health

Statistically significant effects were observed for duration <5 weeks [μ(SMD) = 0.76; 95% CrI: 0.48–1.04], weekly frequency 4–5 sessions/week [μ(SMD) = 1.06; 95% CrI: 0.73–1.41], and session length 21–40 min [μ(SMD) = 1.06; 95% CrI: 0.58–1.55]. Other bins did not consistently reach statistical significance. Detailed results and corresponding forest plots are presented in Supplementary Documents S4, S5.

Athletic performance

Statistically significant effects were observed for duration 6–10 weeks [μ(SMD) = 1.11; 95% CrI: 0.89–1.34], weekly frequency 4–5 sessions/week [μ(SMD) = 1.25; 95% CrI: 0.62–1.83], and session length 21–40 min [μ(SMD) = 0.81; 95% CrI: 0.25–1.37]. Other bins did not consistently reach statistical significance. Detailed results and corresponding forest plots are presented in Supplementary Documents S4, S5.

Cognitive performance

Statistically significant effects were observed for duration <5 weeks [μ(SMD) = 0.98; 95% CrI: 0.34–1.64], weekly frequency 3 sessions/week [μ(SMD) = 0.91; 95% CrI: 0.58–1.27], and session length <20 min [μ(SMD) = 0.53; 95% CrI: 0.05–1.02] and 41–60 min [μ(SMD) = 1.03; 95% CrI: 0.41–1.63]. Other bins did not consistently reach statistical significance. Detailed results and corresponding forest plots are presented in Supplementary Documents S4, S5.

Moderator analyses

Using Bayesian meta-regressions, we examined demographic moderators. In these models, R^2 denotes the proportion of between-study variance explained by the moderator, with higher values indicating that more of the heterogeneity across studies is accounted for.

For gender (percentage female), the estimated associations were: mental health, 0.48 (95% CrI: −0.91 to 1.92; R^2 = 0.74, 95% CrI: 0.55–0.88); athletic performance, −1.08 (−1.87 to 0.31; R^2 = 0.59, 0.42–0.76); cognitive performance, −0.97 (−2.47 to 0.56; R^2 = 0.72, 0.46–0.89). None of these associations reached statistical significance, although negative trends were observed for athletic performance and cognitive performance.

For age (mean years), estimates were close to zero across domains-mental health, 0.00 (−0.08 to 0.09; R^2 = 0.83, 0.65–0.94); athletic performance, 0.01 (−0.07 to 0.08; R^2 = 0.61, 0.42–0.78); cognitive performance, 0.05 (−0.07 to 0.16; R^2 = 0.74, 0.40–0.93). Moderator effect plots are provided in Supplementary Document S6.

Publication bias

In this meta-analysis, we assessed potential publication bias across the three outcome domains (mental health, athletic performance, and cognitive performance).

Mental health: The funnel plot showed clear asymmetry, and Egger's regression confirmed statistical significance (intercept = −2.48, 95% CI [−3.33, −1.62], $p < 0.001$). However, the trim-and-fill method did not impute additional studies, and the adjusted pooled effect size remained significant (SMD = 0.75, $p < 0.001$), suggesting that the main conclusions were not driven by publication bias.

Athletic performance: Egger's test did not detect evidence of asymmetry (intercept = 0.89, 95% CI [0.53, 1.25], $p = 0.98$), and visual inspection of the funnel plot also suggested a symmetrical distribution of effect sizes, supporting the robustness of findings in this domain.

Cognitive performance: The funnel plot appeared asymmetric, and Egger's regression provided evidence of small-study effects (intercept = −1.15, 95% CI [−1.66, −0.65], $p < 0.001$). Nonetheless, the trim-and-fill method did not impute additional studies, and the adjusted effect remained statistically significant ($p < 0.001$) (Figures 6–8).

Beyond these conventional approaches, complementary analyses using contour-enhanced and sunset (power-enhanced) funnel plots also indicated potential small-study effects in mental health and

cognitive performance, whereas results for athletic performance remained symmetrical. All extended funnel plot analyses are provided in Supplementary Figure S7.

GRADE evidence grade evaluation

The GRADE assessment of the evidence regarding the effects of biofeedback and neurofeedback training on mental health, athletic performance, and cognitive performance indicated that the overall certainty of evidence was low to very low. Specifically, the quality of evidence for mental health outcomes was rated as low, while the evidence for athletic performance and cognitive performance was rated as very low. This downgrading was primarily due to moderate risk of bias in most studies, high heterogeneity, and insufficient sample sizes (Figure 9). The subgroup GRADE assessment charts are provided in Supplementary Document S8.

Discussion

This study is the first to employ the Bayesian meta-analysis to explore the effects of biofeedback training on the mental health and performance of athletes. This systematic review and meta-analysis synthesize information about the impact of (1) biofeedback or neurofeedback on mental health, (2) athletic performance (3) and cognitive performance.

Research findings

The results of this meta-analysis demonstrate that both biofeedback and neurofeedback training have statistically significant effects on athletes' mental health, athletic performance, and cognitive performance. Subgroup analyses further elucidated the specific effectiveness of these interventions across different outcome domains.

Biofeedback training demonstrated statistically significant effects in improving mental health and enhancing athletic performance. These effects were most pronounced in improvements in anxiety reduction and basketball performance. Other outcome domains did not exhibit statistical significance under biofeedback interventions.

Neurofeedback training produced statistical significance in cognitive performance, particularly in enhancing attentional control. No other outcome domains reached statistical significance in the neurofeedback subgroup.

In the main analysis, the heterogeneity for cognitive performance was high ($\tau = 1.4$). However, subgroup analysis further revealed that biofeedback contributed a higher heterogeneity ($\tau = 1.44$) compared to neurofeedback ($\tau = 0.58$), indicating that most of the heterogeneity in cognitive performance outcomes stemmed from biofeedback interventions.

Exploratory analyses suggested that some intervention dosage ranges may be associated with larger improvements. For mental health, effects appeared greater when interventions lasted 5 weeks or less, were delivered 4–5 times per week, and each session lasted 21–40 min. For athletic performance, relatively larger effects were observed with interventions lasting 6–10 weeks, conducted 4–5 times per week, with sessions of 41–60 min. For cognitive performance,

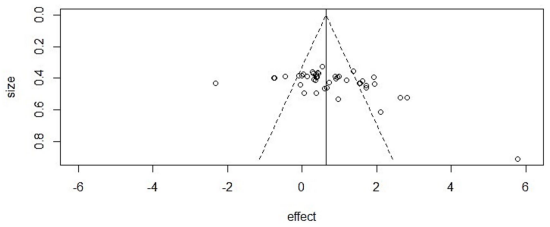

FIGURE 6
Funnel plot in mental health.

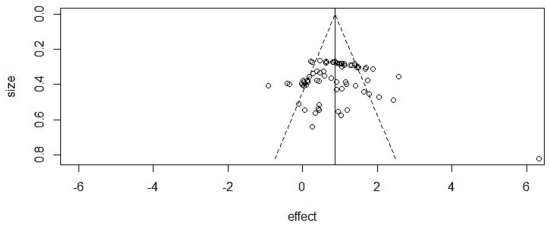

FIGURE 7
Funnel plot in athletic performance.

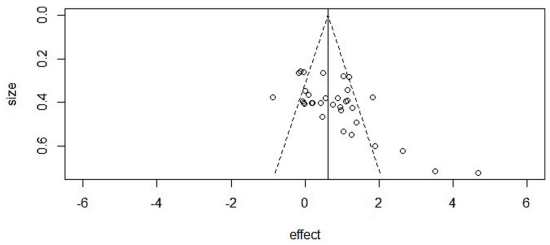

FIGURE 8
Funnel plot in cognitive performance.

improvements were observed in subgroups with interventions lasting 5 weeks or less, performed 3 times per week, and with sessions of either 20 min or less or 41–60 min. However, these patterns were not consistent across outcomes and the certainty of evidence was low; thus, they should be interpreted as exploratory findings and do not constitute dosage recommendations. Subgroup analyses based on athlete competitive level indicated that elite athletes benefited more in mental health and cognitive outcomes, while amateur athletes showed greater improvements in athletic performance. These findings suggest that the competitive background of athletes may moderate the effectiveness of biofeedback and neurofeedback interventions.

Moderator analyses revealed that gender did not significantly influence the effectiveness of biofeedback and neurofeedback interventions, while age accounted for a comparatively larger share of variance in athletic performance outcomes, although its effect was not statistically significant. According to the R^2 values, part of the heterogeneity across studies may be explained by demographic factors such as age and gender. These findings suggest that demographic characteristics should be considered as potential contributors to heterogeneity in future research. In addition, the subgroup analysis by

Biofeedback & Neurofeedback for Mental health and performance

Patient or population: patients with Mental health and performance
Settings:
Intervention: Biofeedback & Neurofeedback

Outcomes	Illustrative comparative risks* (95% CI) Assumed risk Control	Corresponding risk Biofeedback & Neurofeedback	Relative effect (95% CI)	No of Participants (studies)	Quality of the evidence (GRADE)	Comments
Mental health (Biofeedback & Neurofeedback)		The mean mental health (biofeedback & neurofeedback) in the intervention groups was **0.76 standard deviations higher** (0.44 to 1.09 higher)		1176 (15 studies)	⊕⊕⊖⊖ low[1,2,3]	
Athletic performance (Biofeedback & Neurofeedback)		The mean athletic performance (biofeedback & neurofeedback) in the intervention groups was **0.88 standard deviations higher** (0.09 to 0.69 higher)		2847 (70 studies)	⊕⊖⊖⊖ very low[1,2]	
Cognitive performance (Biofeedback & Neurofeedback)		The mean cognitive performance (biofeedback & neurofeedback) in the intervention groups was **0.81 standard deviations higher** (0 to 1.15 higher)		1152 (36 studies)	⊕⊖⊖⊖ very low[1,2,3]	

*The basis for the **assumed risk** (e.g. the median control group risk across studies) is provided in footnotes. The **corresponding risk** (and its 95% confidence interval) is based on the assumed risk in the comparison group and the **relative effect** of the intervention (and its 95% CI).

CI: Confidence interval;

GRADE Working Group grades of evidence
High quality: Further research is very unlikely to change our confidence in the estimate of effect.
Moderate quality: Further research is likely to have an important impact on our confidence in the estimate of effect and may change the estimate.
Low quality: Further research is very likely to have an important impact on our confidence in the estimate of effect and is likely to change the estimate.
Very low quality: We are very uncertain about the estimate.

[1] Most information comes from medium bias
[2] High heterogeneity (I square>75%)
[3] Small sample size

FIGURE 9
The GRADE summary in mental health, athletic performance and cognitive ability.

blinding suggested that adequately blinded trials tended to produce more consistent and reliable estimates with lower heterogeneity, underscoring the importance of rigorous blinding procedures in minimizing bias.

The observed domain-specific effects may be explained by underlying neurophysiological mechanisms. Biofeedback interventions, particularly heart rate variability and stress-regulation protocols, primarily target autonomic nervous system activity. By enhancing vagal tone and promoting parasympathetic dominance, biofeedback improves emotional regulation and stress recovery, which are especially relevant for psychological outcomes such as anxiety reduction and for sports like basketball where mental resilience and decision-making under pressure are crucial (Lehrer et al., 2003; Goessl et al., 2017; Paul and Garg, 2012). In contrast, neurofeedback protocols directly modulate cortical activity patterns, particularly within EEG frequency per bands associated with attentional control and sensorimotor integration. By reinforcing adaptive brain states-such as increasing SMR or frontal midline theta power while reducing maladaptive theta activity neurofeedback strengthens attentional focus and postural control, which may explain its stronger effects on cognitive outcomes and balance-related performance (Cheng et al., 2015; Dana et al., 2019; Gong et al., 2021; Yalfani et al., 2024; Enriquez-Geppert et al., 2017; Ros et al., 2020). Together, these mechanistic differences suggest that biofeedback and neurofeedback optimize complementary domains of athletic functioning, with biofeedback more closely aligned to stress resilience and psychological regulation, and neurofeedback more directly enhancing neural efficiency in attention and balance.

These findings suggest domain specific strengths for different types of biofeedback-based interventions.

The impact of biofeedback training on mental health and performance

The results of this meta-analysis confirm that biofeedback training significantly enhances athletes' mental health. Specifically, it helps reduce anxiety and alleviate stress. Biofeedback is not merely a tool for physiological regulation; it also plays a critical role in managing psychological stress. Existing studies support these findings, showing that biofeedback can effectively help athletes cope with anxiety and stress (Donghai et al., 2024a; Dziembowska, 2015; Tirinnanzi, 2022), By fostering greater interoceptive awareness and top down control over stress reactivity, Biofeedback helps athletes shift from reactive to proactive coping strategies by enhancing self-regulation and physiological awareness, thereby improving their mental toughness in high pressure environments (Donghai et al., 2024a). Notably, biofeedback induced improvements in autonomic regulation are closely linked to enhanced emotional regulation and cognitive control, both of which are critical in moderating anxiety responses during performance situations (Goessl et al., 2017; Teufel et al., 2013). These mechanisms offer a compelling explanation for the expanding role of biofeedback in sports psychology and athlete preparation.

Recent studies increasingly support the psychological and performance benefits of biofeedback training in athletic contexts (Yılmaz et al., 2025; Makaracı et al., 2023). This paragraph reviews key meta-analytic findings that validate its effectiveness, particularly in cognitively demanding sports (Tosti et al., 2024). Biofeedback training has demonstrated clear benefits across various sports, including basketball, football, swimming, and endurance disciplines (Saha et al., 2013; Paul and Garg, 2012). A recent systematic review (Pagaduan et al., 2022) highlight the positive effects of heart rate variability biofeedback on improving physiological regulation and performance

outcomes in athletes particularly in basketball, shooting, and long distance running by enhancing respiratory mechanics, improving autonomic regulation, and reducing psychophysiological stress. Through the application of this technique, athletes can adjust their breathing frequency per week and enhance parasympathetic nervous system activity, optimizing both physiological responses and mental states. The importance of emotional regulation in improving performance is also underscored, especially under interventions that promote optimal heart rate variability and autonomic regulation. Therefore, the foundational concept proposed by Bar-Eli (2004) and later echoed by Yılmaz et al. (2025) which posits that biofeedback enhances athletic performance by simultaneously optimizing psychological and physiological states (Bar-Eli, 2004; Yılmaz et al., 2025; Pagaduan et al., 2022).

Biofeedback, particularly heart rate variability and biomechanical biofeedback, plays a critical role in enhancing both cognitive and athletic performance in athletes. This has been supported by multiple studies, including those by Gorman et al. (2021), Paul et al. (2012), and Saha et al. (2013), which collectively underscore the effectiveness of real-time physiological feedback in improving reaction time, concentration, and overall athletic execution. These findings highlight biofeedback as a valuable tool for athletes-not only for enhancing physical performance but also for sharpening cognitive functions under pressure. By training individuals to regulate both physiological responses and emotional states, biofeedback helps athletes achieve a state of optimal performance, particularly in high-stress, cognitively demanding sports contexts (Saha et al., 2013; Gorman et al., 2021; Paul et al., 2012).

In summary, current evidence highlights biofeedback as an effective intervention for improving both mental health and performance in athletes (Donghai et al., 2024b). By supporting physiological regulation and emotional control, it helps athletes manage stress, maintain focus, and perform more effectively under pressure (Goessl et al., 2017). These findings suggest that biofeedback holds strong potential for integration into athlete training and performance enhancement programs (Pagaduan et al., 2020).

The impact of neurofeedback training on performance

Compared with the scarcity of research in the field of mental health, the promoting effect of neurofeedback training on athletic performance has received broader empirical support. Multiple studies have shown that neurofeedback training has significant effects in a series of sports that have high requirements for fine motor control, sensory and perceptual integration, and attention regulation, especially in golf, shooting, sprinting, static and dynamic balance events (Toolis et al., 2024; Dana et al., 2019; Yalfani et al., 2024; Bakhtafrooz et al., 2025; Chen et al., 2022). These sports usually require athletes to have a high degree of sensorimotor coordination, continuous concentration and moderate muscle relaxation to achieve precise and stable movement performance (Tosti et al., 2024). Neurofeedback training can improve these key neural mechanisms by regulating the characteristics of electroencephalogram (EEG) activities, thereby optimizing motor performance (Gong et al., 2021). Consistent with our subgroup findings, recent studies have demonstrated that neurofeedback training significantly improves balance-related athletic performance, particularly in sports requiring postural control and stability (Dana et al., 2019; Yalfani et al., 2024).

In athlete populations, neurofeedback training has shown notable efficacy in enhancing core cognitive performance that are closely tied to athletic performance, such as attention. Cognitive performance are crucial for optimizing decision making under pressure, maintaining performance consistency, and adapting rapidly to dynamic competitive environments (Tosti et al., 2024). Beyond motor performance, neurofeedback training has also been shown to significantly enhance attentional functioning, which is a key cognitive factor influencing athletic success. In sports settings, attention is critical for maintaining situational awareness, making rapid decisions, and sustaining consistent performance under pressure (Rydzik et al., 2023). Empirical studies have found that neurofeedback training protocols targeting the modulation of specific EEG bands such as enhancing sensorimotor rhythm (SMR) and beta activity while suppressing theta waves can lead to measurable improvements in various aspects of attention, including alertness, orienting efficiency, and conflict monitoring (Dana et al., 2019; Mikicin et al., 2015; Bakhtafrooz et al., 2025). These improvements reflect neurofeedback training capacity to promote adaptive cortical arousal states, reduce cognitive interference, and strengthen athletes' ability to maintain task relevant focus (Cheng et al., 2024). Collectively, this evidence suggests that neurofeedback training serves as a dual function intervention, meanwhile, optimize the performance of the athlete population (Tosti et al., 2024).

Therefore, neurofeedback training may enhance performance through a dual mechanism: by optimizing sensorimotor control essential for precise physical execution, and by reinforcing attentional regulation that supports consistency and adaptability in high-pressure environments (Cheng et al., 2024). This convergence of motor and cognitive improvements reinforces neurofeedback's unique value in sports contexts where both physical precision and mental toughness are critical for success (Tosti et al., 2024).

Dose reporting

While the majority of studies in our meta-analysis support the effectiveness of biofeedback and neurofeedback in improving psychological self-regulation and athletic performance, significant variability was observed across intervention duration (weeks), weekly frequency (sessions/week), and session length (minutes). This variation underscores the need for a more standardized approach to biofeedback intervention protocols and reporting. These subgroup findings are exploratory and do not constitute dosage recommendations.

Furthermore, Onagawa et al. (2023) highlighted the importance of intervention duration, noting that programs extending beyond 10 weeks may yield reduced incremental benefits (Onagawa et al., 2023) Our findings are consistent with this possibility in some subgroups; however, the evidence is limited. These ranges need to be tested in preregistered randomized trials that systematically manipulate duration, session length, and weekly frequency.

Taken together, the results suggest that intervention duration, weekly frequency, and session length may influence the effectiveness of biofeedback. To ensure consistent evaluation and replication, future studies should adopt standardized dose reporting [e.g., the Consensus

on the Reporting and Experimental Design of Neurofeedback studies, CRED-nf checklist (Ros et al., 2020; Onagawa et al., 2023; Yu et al., 2025; Schulz et al., 2010; Hassan et al., 2022), and preregister trial protocols, specifying planned dose ranges and analyses to enable robust assessment of long-term impact].

Strengths and limitations

This study adopted the Bayesian meta-analysis for the first time to systematically evaluate the effects of biofeedback and neurofeedback training on athletes' mental health, athletic performance and cognitive performance. Compared with the traditional Frequentist statistical methods, Bayesian analysis can provide more robust effect estimation and allow for the direct calculation of the probability distribution of the intervention effect, thereby enhancing the interpretability of the research conclusion (Van De Schoot et al., 2021). To ensure high data quality and reliability of the results, a rigorous literature screening process was implemented using the PICOS framework, comprehensive subgroup analyses, and a transparent inclusion protocol. In particular, this study employed ASReview, a machine learning–assisted systematic review tool, to improve efficiency and objectivity in the screening process. ASReview significantly reduces reviewer bias and enhances reproducibility by prioritizing relevant studies based on active learning algorithms, making the screening both faster and more evidence driven compared to traditional manual methods.

Although biofeedback training demonstrated statistically significant improvements in anxiety reduction, basketball performance, and pressure management, the benefits did not generalize across all measured domains. Among the 10 outcome indicators analyzed under biofeedback, only three reached statistical significance, suggesting domain specificity in its effectiveness. Additionally, this study did not systematically compare the differential effects of various types of biofeedback, such as heart rate variability feedback and electromyography feedback, limiting our ability to identify which modalities are most effective.

Interpretation of the findings is complicated by high between-study heterogeneity across all three primary outcomes ($\tau = 0.99$ for mental health; 2.24 for athletic performance; 1.42 for cognitive performance). Subgroup analyses by intervention type, dose, blinding, and competitive level, as well as moderator analyses (age, gender), reduced-but did not eliminate this variability. Inconsistencies in blinding procedures and variability in study quality may also have contributed to the instability of the results, underscoring the need for future high-quality, rigorously blinded trials. Trim-and-fill adjustments did not materially alter the pooled estimates, whereas contour- and power-enhanced funnel plots indicated small study effects in the mental health and cognitive domains; findings for these outcomes should therefore be interpreted with caution. Given the diversity of study designs, intervention protocols, participant characteristics, and outcome measures across the included RCTs, residual heterogeneity remained despite these analytic controls. In addition, a few studies reported extremely small variances, which disproportionately increased their statistical weights and led to unstable estimates of between-study heterogeneity (τ) in some subgroups. These cases should therefore be interpreted with caution (Pronczuk et al., 2023; Dziembowska, 2015; Bakhtafrooz et al., 2025). Future studies should adopt more consistent protocols and standardized outcome definitions to improve comparability and precision.

The number of studies using neurofeedback training as an intervention was relatively limited, and their sample sizes were generally small. Among the outcome domains analyzed, only attentional control and balance reached statistical significance, whereas other domains did not demonstrate consistent effects. In the domain of mental health, only one study on neurofeedback training (Faridnia et al., 2012) was available, which limited the reliability of subgroup findings. Although an effect size could be estimated, the scarcity of evidence precludes firm conclusions, thereby restricting the generalizability of neurofeedback's effects on mental health. Future research with larger samples and more rigorous designs is necessary to better understand the effectiveness of neurofeedback across various domains.

While the dose–response analysis indicated statistically significant effects for certain categories of intervention time (weeks), frequency per week, and time per session, most other subgroups did not reach significance, reflecting variability in the impact of intervention doses. In addition, only six trials included any form of follow up, and none extended beyond 6 months, which limited the ability to evaluate the long-term sustainability of intervention effects. Furthermore, the certainty of evidence assessed by the GRADE framework was rated as low for mental health outcomes and very low for both athletic and cognitive performance outcomes. These ratings underscore that, despite statistically significant pooled effects, the strength of evidence remains limited due to factors such as risk of bias, heterogeneity, small sample sizes, and potential publication bias. Consequently, the findings should be interpreted with caution and future high-quality trials are warranted to strengthen the evidence base.

Future research should address several limitations identified in this study. First, more detailed comparisons of different biofeedback modalities (e.g., heart rate variability vs. electromyography) are needed to determine which are most effective for various outcomes. Larger sample sizes and more neurofeedback studies, especially in mental health, would increase the reliability of findings. Standardizing outcome measures and reducing study heterogeneity through subgroup analyses could improve consistency across studies. Long-term follow-ups should be incorporated to assess the sustainability of intervention effects, as most current studies only track short-term outcomes. Additionally, more robust dose–response analyses are needed to identify the optimal intervention time (weeks), frequency per week, and frequency per week of interventions. Addressing these gaps will help refine the understanding of biofeedback and neurofeedback training's effects on athletes. Future studies should also adopt standardized methodological frameworks such as the BEST toolbox and the CONSORT guidelines, in addition to the CRED-nf checklist, to further improve methodological consistency, reduce heterogeneity, and enhance the reproducibility of findings in this field (Ros et al., 2020; Schulz et al., 2010; Hassan et al., 2022).

Conclusion

This meta-analysis provides evidence that biofeedback training has statistically significant effects on improving athletes' mental health, particularly through reductions in anxiety and improved pressure management. Significant improvements were also found in

athletic performance, especially in basketball. Meanwhile, neurofeedback training demonstrated statistically significant effects primarily in the domain of cognitive performance, with notable gains in attentional control and balance.

Exploratory subgroup analyses suggested that intervention dosage may influence the observed effects. Some dose ranges appeared to show larger improvements (e.g., mental health: intervention time <5 weeks, frequency 4–5 times per week, time per session 21–40 min; athletic performance: intervention time 6–10 weeks, frequency 4–5 times per week, time per session 41–60 min; cognitive performance: intervention time <5 weeks, frequency 3 times per week, time per session either <20 min or 41–60 min). These findings provide preliminary evidence of potential dosage effects, particularly for biofeedback on mental health. Future studies are needed to generate more robust and confirmatory evidence.

These findings support the use of biofeedback and neurofeedback as targeted interventions to improve specific psychological and performance outcomes in athletes. Further research is needed to explore the mental health effects of neurofeedback, standardize intervention protocols, and evaluate long-term outcomes. This study provides a comprehensive evaluation of the effects of biofeedback training on athletes' mental health and performance through systematic review and Bayesian meta-analysis, offering practical guidance and significant theoretical and practical value.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

XZ: Formal analysis, Data curation, Project administration, Writing – review & editing, Validation, Methodology, Investigation, Software, Writing – original draft. ZC: Writing – review & editing, Investigation, Supervision. SZ: Formal analysis, Methodology, Supervision, Software, Writing – review & editing. ZN: Resources, Project administration, Methodology, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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ARTICLES FOR FACULTY MEMBERS

ADVANCING MENTAL PERFORMANCE IN COMPETITIVE AQUATIC ATHLETES THROUGH THE DEVELOPMENT AND VALIDATION OF A REAL-TIME BIOFEEDBACK SYSTEM FOR PSYCHOLOGICAL SKILLS TRAINING

The relationship between mindfulness and athletes' mental skills may be explained by emotion regulation and self-regulation. / Rogowska, A. M., & Tataruch, R.

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The relationship between mindfulness and athletes' mental skills may be explained by emotion regulation and self-regulation

Aleksandra M. Rogowska[1*] and Rafał Tataruch[2]

Abstract

Background Although numerous psychological determinants of sports success have been identified in the scientific literature, research on the contribution of mindfulness and interoceptive awareness to sports achievements remains limited. This study investigates the relationship between self-reported mental skills determining sports success (i.e., flow state, attention, technique, sensitivity to error, commitment, and achievement), state mindfulness for physical activity (of the mind and the body), and interoceptive awareness (including scales of noticing, not distracting, not worrying, attention regulation, emotional awareness, self-regulation, body listening, and trusting).

Methods A cross-sectional online survey was conducted on a sample of elite athletes in speed skating ($n=54$) and university students of physical education ($n=102$) representing various sports disciplines and competitive levels. The Sports Success Scale (SSS), the State Mindfulness Scale for Physical Activity (SMS-PA), and the Multidimensional Assessment of Interoceptive Awareness (MAIA-2) were used to assess psychological determinants of athletic achievements, state mindfulness, and interoceptive sensitivity, respectively.

Results Our findings indicate some small-to-moderate differences in particular dimensions of psychological traits related to sports success, mindfulness, and interoceptive awareness between athletes of different genders, groups, and competitive levels. A chain mediation model showed that the relationship between body mindfulness and psychological variables determining sports success is fully explained by two dimensions of interoception: self-regulation and attention regulation.

Conclusions Cultivating the mindfulness state of the body can improve self-regulation and attention regulation, which in turn may increase the mental skills required for successful sports participation. Therefore, mental training should focus primarily on body mindfulness, attention regulation, and self-regulation to improve the mental skills responsible for athletes' sports achievements. In addition, individual differences in athletes' gender, sports discipline, and level of sports competition should be considered during mental training.

Keywords Elite athletes, Interoceptive awareness, Speed skating, Sports success, State mindfulness for physical activity

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Background

Sports performance refers to an individual's or team's proficiency in competitive sports and athletic pursuits. Sports success results from the interplay of various internal and external factors that influence the development of sports skills and lead to optimal performance levels during long-term sports training. It is a multifaceted concept involving various physical, mental, and strategic factors that contribute to sports success [1–4]. Factors affecting sports performance include physical abilities (e.g., strength or speed), technical skills (e.g., technical and tactical), mental skills (e.g., concentration, confidence, anxiety control, and stress management), and achievement motivation (e.g., task and ego involvement, and mastery orientation) [1–4]. The present study will examine associations between mental skills and successful participation in sports.

The Sports Success Scale (SSS), a multidimensional measurement tool for crucial factors determining sports achievements in the psychological field, was developed by Mousavi and Vaez Mousavi [5] through an extensive review of the sports science literature and expert opinions. Factor analysis of the SSS revealed five psychological factors of high sports performance: flow state (an optimal level of arousal and mental state of maximum efficiency), attention (the ability to focus attention on a limited range of stimuli or events), technique (an appropriate practice that improves speed, technique, and tactical principles; advanced level of sports skills, accuracy, and coordination in performance; and the ability to repeat the action), sensitivity to error (ability to identify and correct errors during a performance), commitment (a sense of dependence and belonging to specific sport activity, perseverance, and stability in continuing this behavior), and achievement motivation (the need to master difficult tasks, strive for perfection, overcome difficulties and obstacles, be better than others, and a proud sense of success).

Another psychological factor important to sports performance is mindfulness. Research indicates mindfulness can enhance physical activity and sports performance [6–9]. Mindfulness is a mental state achieved by focusing on the present moment and accepting one's feelings, thoughts, and bodily sensations without judgment or evaluation [10, 11]. It encourages the recognition of physical sensations and their relation to emotional states, increases self-awareness and concentration abilities, and improves athletes' attention and emotional regulation. Furthermore, mindfulness practice has been found to reduce stress and anxiety and improve overall well-being [7, 12–14]. Mindfulness emphasizes the connection between the mind and body, increasing interoceptive awareness – the ability to perceive internal bodily sensations, such as hunger, thirst, temperature, heart rate, breathing patterns, muscle tension, fatigue, and overall physical discomfort [15–23]. Interoceptive awareness can be assessed using behavioral observations during stressful situations, interoceptive accuracy tasks (e.g., monitoring internal bodily sensations, such as counting heartbeats or detecting changes in breathing rate), psychophysiological assessments (of heart rate variability, skin conductance, or respiratory rate), experimental techniques, clinical interviews, and self-report questionnaires [24–35]. The Multidimensional Assessment of Interoceptive Awareness (MAIA-2) is a self-report tool designed to assess interoceptive awareness on eight dimensions: noticing (the awareness of internal bodily sensations, such as heartbeat, breathing, and muscle tension), not-distracting (the ability to stay focused on bodily sensations without being easily distracted by external stimuli), not-worrying (the tendency to worry or become anxious about bodily sensations), attention regulation (the ability to regulate attention towards bodily sensations, including shifting attention away from them when necessary), emotional awareness (the awareness of how bodily sensations correlate with emotional states, such as recognizing how one's heart rate increases during moments of stress), self-regulation (the ability to regulate emotions and bodily sensations effectively), body listening (the ability to listen to and interpret bodily sensations as meaningful information), and trusting (the extent to which individuals trust their bodily sensations as accurate indicators of their internal state) [36].

Interoceptive awareness and mindfulness are interconnected concepts that involve paying attention to internal bodily sensations and the present moment [37, 38]. Both phenomena, mindfulness, and interoceptive awareness, involve self-reflection on the body and promote awareness of bodily sensations. While mindfulness does not differentiate between attention directed towards exteroception, interoception, or thoughts, interoceptive awareness specifically focuses on somatic experiences, but does not differentiate between different attention styles towards internal stimuli, whether mindful or anxiety-driven [37]. Developing interoceptive awareness can enhance mindfulness practice, while mindfulness can improve awareness of bodily sensations and emotions, leading to improved well-being and emotional regulation [15–17, 19–23, 30, 37–42]. To cultivate interoceptive awareness, athletes should engage in mindfulness practices, such as body scans, meditation, and yoga [43]. These practices can help individuals become more in tune with their bodily sensations and can be integrated into their training routines.

Interoception has recently gained recognition in physical activity and sports performance research as a means of improving physical and mental resilience (understood as a cognitive process focused on coping with difficult

events and situations and recovering from them) by monitoring one's inner bodily sensations and making appropriate adjustments [43–48]. It plays a crucial role in shaping athletes' emotional experiences, decision-making processes, and well-being [43, 47, 49, 50]. Developing interoceptive awareness can enhance an athlete's body confidence, resulting in better self-esteem and more positive body image, ultimately contributing to improved performance [50, 51]. Interoceptive awareness increases self-regulation and enables athletes to better manage their attention and emotions during competitions [50]. By being attuned to their physiological responses, such as increased heart rate and muscle tension, athletes can recognize signs of anxiety or stress and employ strategies, such as deep breathing or relaxation techniques, to remain calm and focus on high-pressure competitive situations [51]. Furthermore, athletes with a strong interoceptive awareness can better gauge their pain threshold and identify early signs of fatigue, overtraining, injury, or overuse, thereby preventing more severe injuries [52–57]. Lastly, athletes with strong interoceptive awareness can optimize their training load and use appropriate recovery strategies, such as proper rest, sleep, or nutrition, to ensure they are adequately prepared for their next training session or competition [43]. Overall, interoception has the potential to enhance athlete performance, well-being, and resilience significantly.

The current study

Although extensive research has been conducted on athletic success for several decades, the interplay between psychological factors that significantly contribute to becoming a successful or elite athlete remains largely unknown. This lack of knowledge can have significant implications for the inappropriate selection process of various sports disciplines and the insufficient development of sports talent. Specifically, there is limited understanding of the configuration of mental skills crucial for successful participation in sports activities. In this study, we aimed to examine the complexity of perceived psychological traits, abilities and competencies, including multiple components of mental skills determining sports success (i.e., flow state, attention, technique, sensitivity to error, commitment, and achievement), as well as two multidimensional interrelated variables: interoceptive awareness (including such scales as noticing, non-distracting, not-worrying, attention regulation, emotional awareness, self-regulation, body listening, and trusting subscales) and state mindfulness in physical activity (comprising state mindfulness of the mind and body).

Elite athletes in speed skating (EASS) will be compared with university students in physical education (USPA). We will explore whether the EASS demonstrates specific self-reported psychological skills than the USPA sample. Additionally, we will examine gender (women vs. men) and competitive level (international vs. national or lower) differences. Another objective of this study is to identify the most critical psychological variables for sports achievement. Therefore, we will explore the associations between the mental dimensions of sports success, state mindfulness for physical activity, and interoceptive awareness. We are interested in the extent to which self-reported state mindfulness and interoception can explain the variance in mental athletic skills. To the best of our knowledge, these analyses have never been performed previously. Therefore, the present study has exploratory characteristics, and we do not assume any direct hypotheses.

Materials and methods

Participants and procedure

Initially, an *a priori* power analysis was conducted using G*Power 3.1 software [58] to determine the appropriate sample size for the study. It was determined that 51 participants per group were necessary for an independent sample Student's *t*-test to detect an effect size of Cohen's $d=0.50$ with 80% power ($\alpha=0.05$). For correlation analysis, a minimal sample size of 84 people was expected, taking into account an effect size of $\rho=0.30$ and 80% power ($\alpha=0.05$, two-tailed). To demonstrate an effect size of $f2=0.15$ with 80% power ($\alpha=0.05$) for a linear multiple regression model with 13 predictors (when R^2 increases), a minimum of 118 participants was required. Since 156 people participated in the present study, the sample size is adequate, and the post-hoc analysis showed a power of 0.91 for the *t*-test, 0.99 for the Spearman's correlation, and 0.89 for the linear regression test.

Following approval from the IRB, recruitment of participants commenced. The cross-sectional online study was conducted in Poland between 3 August and 30 November, 2020. The survey, which included informed consent and standardized psychological questionnaires, was disseminated via e-mail to elite athletes (all members of the Polish Speed Skating Association) and physical education students from the FPEP at one university. The criterion for inclusion in both the EASS and USPA samples was a minimum age of 16 years old.

A total of 156 athletes participated in the study, including 54 EASS (25 women) and 102 USPA (40 women). The participants ranged in age from 16 to 34 years ($M=21.57$, $SD=3.58$), with 41.67% females. The EASS group included athletes from short-track ($n=15$), sprint on long-track ($n=15$), intermediate runs, and all-around-event on long-track ($n=23$), and their average training experience was nine years ($M=9.11$, $SD=4.36$), ranging from 1 to 22 years. The group was divided into Junior ($n=28$), Youth ($n=11$), and Senior ($n=15$) categories, with 13 individuals representing the Master International

level, 18 at the Master class, 14 in the First Sports class, and 9 in the Second class. Among EASS, 17 participants were at the national competitive level, while 37 were at the international level. The USPA sample consisted of 69 undergraduates (Bachelor's degree) and 35 graduates (Master of Science degree) in their first ($n=9$), second ($n=79$), and third ($n=15$) year of study. The USPA group represented various sports disciplines, including athletics ($n=9$), badminton ($n=2$), basketball ($n=8$), bodybuilding ($n=4$), combat sports and martial arts ($n=8$), cross-fit ($n=2$), cycling ($n=1$), dancing ($n=4$), fitness ($n=7$), football ($n=31$), gymnastics ($n=2$), handball ($n=8$), swimming ($n=4$), table tennis ($n=2$), and volleyball ($n=10$). Participants competed at various levels, including local or recreational ($n=22$), regional ($n=34$), national ($n=29$), and international ($n=17$).

Measures

The survey consisted of a demographic part (including age, gender, sports discipline, training experience, sports class, and competition level) and three standardized questionnaires measuring mental skills, mindfulness, and interceptive awareness: the Sports Success Scale (SSS), the State Mindfulness Scale for Physical Activity (SMS-PA) and the Multidimensional Assessment of Interoceptive Awareness, version 2 (MAIA-2), respectively. All questionnaires were previously developed in English and validated (see references below). For this study, we translated all questionnaires from English into Polish by a bilingual specialist in sports psychology, and vice versa from Polish into English by a Polish specialist in English philology. Then, in a discussion, both experts agreed on the final Polish version of the items in the questionnaires.

Mental skills

The Sports Success Scale (SSS) is a self-report instrument designed to assess crucial psychological dimensions of high achievement in sports, as described by Mousavi and Vaez Mousavi [5]. The SSS comprises 29 items across six scales: Flow state (5 items), Attention (5 items), Technique (4 items), Sensitivity to error (5 items), Commitment (5 items), and Achievement (5 items). Participants rate their compliance with each item on a 6-point scale (1=*Strongly disagree* to 6=*Strongly agree*), with the total SSS score ranging from 29 to 174 (a higher score indicating a better personal predisposition for sports achievements). The internal consistency of the SSS, as assessed by Cronbach's alpha, was 0.89 in the present study, with scale-specific alpha coefficients ranging from 0.61 to 0.73 for Flow state, Attention, Technique, Sensitivity to error, Commitment, and Achievement, respectively.

Mindfulness

The State Mindfulness Scale for Physical Activity (SMS-PA) was created by Cox et al. [59] to evaluate physical and mental mindfulness states, as well as the fundamental characteristics of mindfulness, such as attention, awareness, and openness. The SMS-PA consists of 12 items across two scales: State mindfulness of the mind (SMM, 6 items) and State mindfulness of the body (SMB, 6 items). Participants rate their level of mindfulness on a scale from 0 to 4 (0=*Not at all* to 4=*Very much*), with higher scores indicating greater mindfulness. The Cronbach's alpha coefficients for the SMM and SMB scales were 0.84 and 0.89 in this study, respectively.

Interoceptive awareness

The Multidimensional Assessment of Interoceptive Awareness, Version 2 (MAIA-2) is a self-report questionnaire designed to assess various aspects of interoceptive awareness [36]. It evaluates an individual's ability to recognize and interpret bodily sensations and their awareness of these sensations on 37 items across eight scales: Noticing (NO, $n=4$), Not distracting (NT, $n=6$), Not worrying (NW, $n=5$), Attention regulation (AR, $n=7$), Emotional awareness (EA, $n=5$), Self-regulation (SR, $n=4$), Body listening (BL, $n=3$), and Trusting (TR, $n=3$). Participants are asked to rate their agreement or frequency of experiencing these sensations on a 6-point Likert scale (from 0=*Never* to 5=*Always*). High scores indicate a high interoceptive sensibility. The internal consistency of the particular MAIA-2 scales in the present study is 0.66, 0.68, 0.75, 0.83, 0.79, 0.78, 0.73, and 0.85 for Noticing, Not distracting, Not worrying, Attention regulation, Emotional awareness, Self-regulation, Body listening, and Trusting scales, respectively.

Statistical analysis

Descriptive statistical analyses were initially conducted to assess the normality assumption for parametric tests. As not all variables met the normality assumption (assessed using the Shapiro-Wilk test), we performed a non-parametric Mann-Whitney *U*-test to examine differences in SSS, SMS-PA, and MAIA-2 scales between genders (Women, Men), spots groups (EASS and USPA), and competitive levels (International, National or lower). Rank biserial correlation (RBC) was used to assess the effect size for *U*-test. Spearman's correlation was conducted to assess relationships between all scales of SSS, SMS-PA, and MAIA-2. Hierarchical linear multiple regression analysis was then performed for the total SSS as a dependent variable, as well as gender, group, competitive level, and all scales of the SMS-PA and MAIA-2 questionnaires. All assumptions for linear regression were met, including multicollinearity (variance inflation factor VIF < 3, ranging between 1.19 and 2.35 in the

present study; tolerance > 0.25, ranging between 0.43 and 0.84), multivariate normality (Shapiro-Wilk statistic = 0.99, $p = 0.397$), autocorrelation (Durbin-Watson statistic = 1.91, $p = 0.484$), and heteroscedasticity (Breush-Pagan statistic = 18.86, $p = 0.127$). The statistical analyses were performed using JAMOVI version 2.3.28 software for Windows.

Results

Intergroup differences in mental skills, mindfulness, and interoceptive awareness

The intergroup differences in mental skills, state mindfulness for physical activity, and interoceptive awareness scales were examined using the Mann-Whitney *U*-test. The results of the gender comparison showed that women scored significantly higher than men in commitment and emotional awareness. In contrast, men outperformed women in technique, not worrying, and trusting scales, although the effect size for these differences was small (Table 1). The USPA sample scored higher than the EASS group in state mindfulness for physical activity for both the mind and the body, with a moderate effect size. At the same time, EASS showed higher commitment than USPA, with a small effect size (Table 2). Athletes at the highest international competitive level (independent of sports discipline) scored higher in technique (SSS) and not worrying (MAIA-2) than those representing the national or lower competitive levels (regional, local, or recreational), but the effect size was small (Table 3). On the other hand, athletes at the international competitive level demonstrated lower scores in state mindfulness for physical activity for both the mind and the body, and the Not distracting scale of the MAIA-2, compared to those at the national or lower levels of competitions, with a small effect size.

Associations between mental skills, mindfulness, and interoceptive awareness

Initially, Spearman's correlation analyses were conducted to investigate how state mindfulness for physical activity and interoceptive awareness are related to mental skills responsible for sports success (Table 4). Mind mindfulness was unrelated to the SSS scales. Body mindfulness was positively related to FS, TE, and the total SSS score. Most of the interoceptive awareness scales were positively associated with the total SSS score. However, ND was negatively related to the SSS, while EA was unrelated. Considering associations between particular subscales of the SSS and dimensions of interoceptive awareness, FS was positively related to NO, NW, AR, SR, BL, and TR, and negatively to ND. The AT and SE scales of the SSS were positively correlated with the NO, AR, BL, and TR scales of interoceptive awareness. The technique scale (TE) was found to correlate positively with NW, AR, and TR, while negatively correlated with ND. Commitment (CM) positively correlated with most scales of interoception (excluding SR and NW), while negatively associated with ND. Finally, AC has a negative correlation with ND and a positive correlation with AR. All significant correlations were small in magnitude, ranging between 0.16 and 0.38.

A hierarchical linear multiple regression analysis was conducted to determine the extent to which each set of variables (mindfulness, interoceptive awareness)

Table 1 Gender differences in mental skills, mindfulness state, and interoceptive awareness

Variable	Scales	Women ($n = 65$)		Men ($n = 91$)		*U*	*p*	RBC
		M	*SD*	*M*	*SD*			
Mental skills	Flow state	21.00	3.50	21.73	4.03	2611.0	0.212	-0.117
	Attention	21.77	3.24	22.32	4.34	2652.5	0.272	-0.103
	Technique	16.05	3.35	17.69	3.43	2131.0	0.003	-0.279
	Sensitivity to error	21.12	2.37	21.78	3.76	2653.0	0.272	-0.103
	Commitment	26.02	2.79	24.48	4.21	3572.5	0.026	0.208
	Achievement	20.25	3.66	20.53	4.73	2722.5	0.398	-0.079
	Total sport success	126.20	12.17	128.53	19.63	2618.0	0.223	-0.115
State mindfulness	Mind mindfulness	20.31	4.59	19.85	4.69	3117.0	0.566	0.054
	Body mindfulness	20.42	5.85	20.63	5.83	2841.0	0.676	-0.039
Interoceptive awareness	Noticing	3.48	0.84	3.22	0.95	3484.0	0.058	0.178
	Not distracting	1.86	0.69	1.92	0.70	2828.5	0.643	-0.044
	Not worrying	2.20	0.98	2.69	0.72	1956.0	< 0.001	-0.339
	Attention regulation	3.17	0.76	3.29	0.79	2663.5	0.290	-0.099
	Emotional awareness	3.78	0.85	3.33	0.91	3838.0	0.002	0.298
	Self regulation	2.67	1.04	3.03	0.85	2457.5	0.071	-0.169
	Body listening	2.96	1.04	3.08	0.95	2774.5	0.509	-0.062
	Trusting	3.28	1.01	3.80	0.86	2079.5	0.001	-0.297

Note. For the Mann-Whitney *U*-test, effect size is given by the rank biserial correlation (RBC).

Table 2 Differences in mental skills, mindfulness state, and interoceptive awareness scales between university students of physical education (USPA) and elite athletes of speed skating (EASS)

Variable	Scales	USPA ($n=102$)		EASS ($n=54$)		*U*	*p*	BRC
		M	*SD*	*M*	*SD*			
Mental skills	Flow state	21.75	3.56	20.82	4.25	3067.0	0.242	0.114
	Attention	21.74	3.97	22.76	3.78	2268.5	0.070	-0.176
	Technique	17.04	3.40	16.94	3.67	2753.5	1.000	-22.16
	Sensitivity to error	21.44	3.38	21.63	3.06	2597.0	0.558	-0.057
	Commitment	24.43	3.92	26.43	3.04	1826.5	< 0.001	-0.337
	Achievement	20.47	4.22	20.30	4.51	2708.5	0.866	-0.017
	Total sport success	126.86	17.80	128.87	15.20	2592.5	0.549	-0.059
State mindfulness	Mind mindfulness	21.81	3.82	16.70	4.22	4629.0	< 0.001	0.681
	Body mindfulness	22.97	4.77	15.94	4.77	4736.5	< 0.001	0.720
Interoceptive awareness	Noticing	3.23	0.90	3.51	0.92	2327.5	0.111	-0.155
	Not distracting	1.95	0.65	1.79	0.76	3098.0	0.199	0.125
	Not worrying	2.45	0.72	2.56	1.10	2631.0	0.647	-0.045
	Attention regulation	3.21	0.70	3.28	0.92	2561.0	0.472	-0.070
	Emotional awareness	3.45	0.81	3.63	1.07	2359.0	0.140	-0.143
	Self regulation	2.99	0.86	2.67	1.07	3203.5	0.093	0.163
	Body listening	3.09	0.87	2.91	1.17	3000.5	0.356	0.090
	Trusting	3.55	0.94	3.64	1.00	2536.0	0.413	-0.079

Note. For the Mann-Whitney *U*-test, effect size is given by the rank biserial correlation (RBC).

Table 3 Differences in mental skills, mindfulness state, and interoceptive awareness scales between athletes at international and other competitive levels

Variable	Scales	National or lower ($n=102$)		International ($n=54$)		*U*	*p*	BRC
		M	*SD*	*M*	*SD*			
Mentals skills	Flow state	21.33	3.96	21.59	3.58	2628.0	0.639	-0.046
	Attention	21.81	4.01	22.61	3.72	2358.5	0.140	-0.144
	Technique	16.50	3.57	17.96	3.12	2108.0	0.016	-0.235
	Sensitivity to error	21.28	3.31	21.94	3.16	2437.5	0.237	-0.115
	Commitment	24.78	3.87	25.78	3.45	2310.5	0.097	-0.161
	Achievement	20.46	3.98	20.32	4.90	2712.0	0.877	-0.015
	Total sport success	126.16	17.64	130.20	15.28	2351.0	0.134	-0.146
State mindfulness	Mind mindfulness	20.80	4.52	18.61	4.57	3519.0	0.004	0.278
	Body mindfulness	21.48	5.53	18.76	5.98	3512.0	0.005	0.275
Interoceptive awareness	Noticing	3.31	0.87	3.36	1.00	2628.0	0.639	-0.046
	Not distracting	1.96	0.67	1.78	0.73	3238.0	0.071	0.176
	Not worrying	2.32	0.77	2.80	0.97	1916.5	0.002	-0.304
	Attention regulation	3.16	0.75	3.38	0.83	2338.0	0.121	-0.151
	Emotional awareness	3.53	0.85	3.49	1.02	2753.0	0.999	-40.310
	Self regulation	2.84	0.88	2.96	1.08	2445.0	0.248	-0.112
	Body listening	3.05	0.93	2.98	1.08	2833.5	0.767	0.029
	Trusting	3.53	0.90	3.68	1.05	2357.0	0.136	-0.144

Note. For the Mann-Whitney *U*-test, effect size is given by the rank biserial correlation (RBC).

contributes to the unique variance in mental skills determining sports success among athletes (Table 5). In the first step of the analysis, bi-categorical variables, including gender (coded Women=0, Men=1), group (USPA=0, EASS=1), and competitive level (National or lower=0, International=1), were entered into the model. The resulting regression model was found insignificant, with an R-value of 0.13, R^2 of 0.02, and an F value of 0.82 ($p>0.05$), explaining only 2% of the variance in psychological variables determining sports success. However, when two scales of state mindfulness for physical activity were added to the model in the second step, the regression results significantly improved, with an R-value of 0.29, R^2 of 0.08, and an F value of 2.63 ($p<0.05$),

Table 4 Spearman's correlations between the Sports Success Scale (SSS), State Mindfulness for Physical Activity (SMS-PA), and Multidimensional Assessment of Interoceptive Awareness (MAIA-2)

Variables		Sports Success Scales (SSS)						
		FS	AT	TE	SE	CM	AC	SSS
State mindfulness for PA								
	Mind mindfulness	0.05	-0.08	0.05	-0.01	-0.13	0.08	0.02
	Body mindfulness	0.29***	0.09	0.20*	0.13	-0.04	0.10	0.22**
Interoceptive awareness								
	Noticing (NO)	0.23**	0.21**	-0.01	0.28***	0.27***	0.05	0.24**
	Not distracting (ND)	-0.18*	-0.06	-0.18*	-0.14	-0.18*	-0.17*	-0.21*
	Not worrying (NW)	0.18*	0.15	0.16*	0.07	-0.04	0.13	0.18*
	Attention regulation (AR)	0.38***	0.30***	0.20*	0.29***	0.24**	0.19*	0.38***
	Emotional awareness (EA)	0.15	0.10	-0.03	0.13	0.35***	0.03	0.14
	Self-regulation (SR)	0.26**	0.12	0.08	0.11	0.10	0.07	0.18*
	Body listening (BL)	0.36***	0.25**	0.15	0.24**	0.27***	0.16	0.34***
	Trusting (TR)	0.29***	0.21**	0.22**	0.24**	0.18*	0.14	0.28***

Note. PA = physical activity, FS = Flow state, AT = Attention, TE = Technique, SE = Sensitivity to error, CM = Commitment, AC = Achievement, SSS = Total score of the Sports Success Scale. $N = 163$. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

explaining 8% of the variance in mental skills related to sport success. Body mindfulness was found to be a significant positive predictor of the total SSS score (β = 0.30, $p < 0.01$). In the third step of the regression analysis, all scales of the interoceptive awareness were included in the model, resulting in a significant increase in explained variance to 26%, with an R-value of 0.51, R^2 of 0.26, and an F value of 3.79 ($p < 0.001$). However, only two scales of the MAIA-2 (AR and SR) were found to be significant predictors of mental skills (β = 0.28, $p < 0.01$ and β = -0.22, $p < 0.05$, respectively), while the state mindfulness of the body was no longer significant. The present results suggest that both self-regulation and attention regulation may play a mediating role in the association between body mindfulness and psychological variables determining sports performance.

Undertaking a GLM mediation analysis, we sought to examine the mediating role of self-regulation and attention regulation in the relationship between body mindfulness and sports success (as depicted in Table 6; Fig. 1). Our analysis revealed a chain mediating effect of body mindfulness on sports success, whereby both self-regulation and attention regulation scales of interoceptive awareness were involved. The chain mediation model of regulation-based interoceptive abilities fully mediated the association between body mindfulness (as measured by the SMS-PA) and sports success (as assessed by the SSS). Specifically, self-regulation and attention regulation served as complete mediators in the relationship between body mindfulness and sports success (as illustrated in Fig. 1).

Discussion

The primary objective of this study was to investigate the most critical psychological factors that impact both objective measures of sports achievement, such as representing a national speed skating team and competing at international levels, and mental skills determining sports success. Our findings indicate that gender has a minimal relationship with the mental skills of sports success and interoceptive awareness, and no association with state mindfulness for physical activity. Women are more engaged in sports activities and are more emotionally aware of their interoceptive signals than men. However, men have improved women's sports techniques and are better at not worrying about and trusting their bodies. Our results align with previous studies [25, 60–63]. The observation that women often score higher than men in emotional awareness can be attributed to a combination of biological, social, and cultural factors [61–63]. Biological differences concern brain structure and function related to emotional processing [60]. The size and connectivity of brain regions involved in emotional regulation and empathy, such as the amygdala and prefrontal cortex, promote better emotional processing and higher emotional intelligence in women than men. Awareness of emotion-related body states depends on both internal physiological signals and external situational signals [61, 63]. Women differ from men in that they prefer to use different cues when defining their emotional state, namely, in a way consistent with cognitive appraisals. Gender differences may also result from biases in the interpretation of ambiguous internal body states, which are determined by gender-specific linguistic socialization. During the socialization process, girls may receive more encouragement to talk about their feelings, express empathy, and engage in emotionally expressive behaviors.

On the other hand, boys may be socialized to suppress emotions, leading to lower levels of emotional awareness and expression. Additionally, cultural norms and expectations regarding gender roles and expression may interact with gender-specific emotional socialization to

Table 5 Linear multiple regression for the total score of the Sport Success Scale ($N = 163$)

			95% CI									
Predictor	**b**	**SE b**	**Lower**	**Upper**	**t**	**p**	**β**	**ΔR^2**	**F**	**df_1**	**df_2**	**p**
Intercept	125.80	2.12	121.60	130.00	59.24	< 0.001		0.02	0.82	3	149	0.483
Gender (Men)	2.40	2.44	-2.42	7.22	0.98	0.327	0.16					
Group (EASS)	-0.19	3.01	-6.15	5.76	-0.06	0.950	-0.01					
Level (International)	3.11	2.98	-2.78	9.01	1.04	0.298	0.21					
Intercept	105.58	7.77	90.23	120.94	13.59	< 0.001		0.07	5.28	2	147	0.006
Gender (Men)	2.78	2.38	-1.94	7.49	1.16	0.246	0.19					
Group (EASS)	5.85	3.53	-1.13	12.82	1.66	0.100	0.40					
Level (International)	2.43	2.91	-3.32	8.17	0.84	0.405	0.16					
Mind mindfulness	0.10	0.34	-0.57	0.77	0.30	0.768	0.03					
Body mindfulness	0.78	0.28	0.23	1.34	2.79	0.006	0.30					
Intercept	92.83	10.69	71.71	113.96	8.69	< 0.0001		0.18	4.22	8	139	< 0.001
Gender (Men)	1.48	2.53	-3.52	6.49	0.59	0.559	0.10					
Group (EASS)	-0.34	3.48	-7.23	6.54	-0.10	0.922	-0.02					
Level (International)	1.84	2.87	-3.83	7.51	0.64	0.522	0.12					
Mind mindfulness	-0.27	0.33	-0.92	0.38	-0.82	0.415	-0.08					
Body mindfulness	0.43	0.28	-0.13	0.99	1.53	0.128	0.16					
Noticing	0.97	1.52	-2.03	3.98	0.64	0.523	0.06					
Not distracting	-1.68	1.75	-5.13	1.78	-0.96	0.338	-0.08					
Not worrying	1.75	1.49	-1.19	4.70	1.18	0.241	0.10					
Attention regulation	5.38	1.77	1.89	8.87	3.05	0.003	0.28					
Emotional awareness	0.65	1.69	-2.69	4.00	0.39	0.699	0.04					
Self regulation	-3.43	1.61	-6.61	-0.26	-2.14	0.034	-0.22					
Body listening	2.94	1.58	-0.19	6.06	1.86	0.065	0.19					
Trusting	2.05	1.40	-0.72	4.82	1.47	0.145	0.13					

Table 6 The mediating effect of Attention regulation (AR) for the association between mindfulness of the body (MB) and total score of the Sports Success Scale (SSS)

				BC 95% CI				
Type	**Effect**	**b**	**SE b**	**Lower**	**Upper**	**β**	**z**	**p**
Indirect	MB ⇒ SR ⇒ SSS	-0.02	0.08	-0.17	0.14	-0.01	-0.24	0.809
	MB ⇒ AR ⇒ SSS	0.13	0.11	-0.06	0.39	0.05	1.22	0.222
	MB ⇒ SR ⇒ AR ⇒ SSS	0.13	0.06	0.05	0.29	0.05	2.13	0.033
Component	MB ⇒ SR	0.06	0.01	0.03	0.09	0.36	4.27	< 0.001
	SR ⇒ SSS	-0.30	1.21	-2.45	2.24	-0.02	-0.25	0.804
	MB ⇒ AR	0.02	0.01	-0.01	0.04	0.13	1.34	0.181
	AR ⇒ SSS	7.50	1.69	4.18	10.77	0.39	4.44	< 0.001
	SR ⇒ AR	0.29	0.08	0.15	0.45	0.35	3.77	< 0.001
Direct	MB ⇒ SSS	0.25	0.24	-0.26	0.70	0.10	1.05	0.292
Total	MB ⇒ SSS	0.50	0.21	0.09	0.91	0.19	2.38	0.017

Note. Confidence intervals computed with Bias Corrected (BC) bootstrap method using 1000 replications. Betas are completely standardized effect sizes. CI = confidence interval

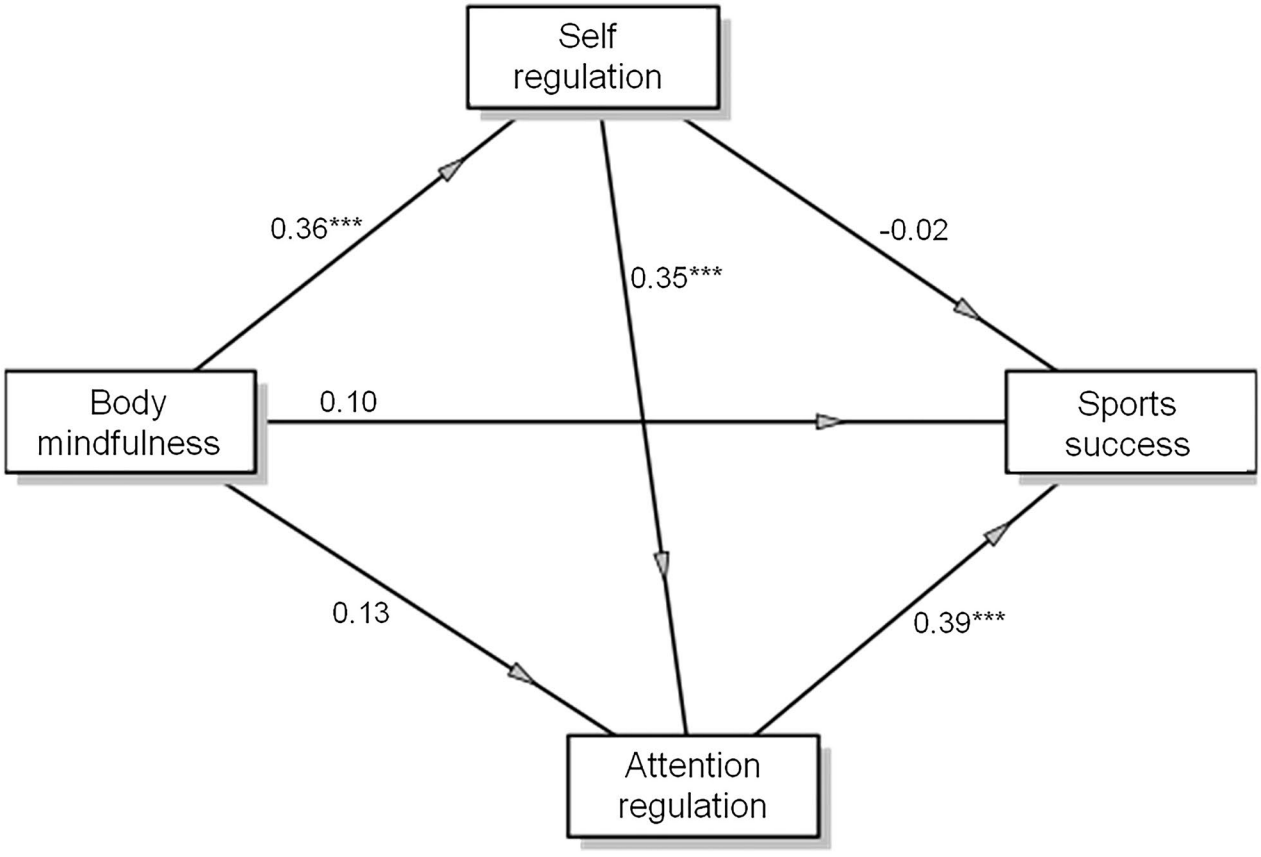

Fig. 1 A chain mediation model of the association between the state of mindfulness of the body and sports success via self-regulation and self-attention scales of interoception. ***$p < 0.001$

shape attitudes toward emotions and influence emotional awareness and expression. Women may experience different psychosocial factors and distinct stressors than men, and have different coping mechanisms compared to men, which can impact their emotional awareness and regulation.

In addition, we aimed to examine whether successful athletes differ significantly from those with lower levels of sports achievement. We addressed this question by comparing elite athletes with physical activity students and athletes representing international and lower competitive levels. The sample of elite athletes in speed skating (EASS, members of the Polish National Olympic

Representation) showed higher sports commitment than those representing various sports disciplines and competitive levels (university students of physical activity, USPA), but on a small effect size. On the other hand, the EASS sample scored significantly lower in both scales of state mindfulness for physical activity (of the mind and body) than the USPA group. A high competition level and pressure to win among EASS can reduce mindfulness skills, dwelling on past failures, or worrying about the future. Previous studies revealed that competitive anxiety related to high sports pressure (internal, e.g., perfectionism-related, and external pressure of other team members, coaches, family, and significant others) and uncertainty stress are negatively related to mindfulness [64–72]. In particular, mindfulness traits act as mediators and protective factors in the effects of impulsivity on anxiety among female athletes [69].

The differences between athletes competing at the international level and those at national or lower competitive levels may be attributed to superior sports techniques and the ability to remain focused amidst intense competition. It is plausible that extensive experience in competition fosters these skills. Unfortunately, athletes participating in international competitions scored lower in mind and body state mindfulness, which refers to the ability to remain present and focused during physical activity, than their counterparts at the national or lower level. Top athletes may face more challenges than lower-level athletes. Therefore, they should routinely practice mindfulness skills [73, 74]. Inadequate mindfulness skills can make individuals more susceptible to distractions, which can negatively affect concentration and sports performance [6–9].

On the other hand, mindfulness practice has been shown to enhance physical activity and sports performance. Therefore, it can be inferred that the EASS sample, as well as athletes at the highest international competitive level, would benefit from increased mindfulness training to enhance their sports performance. Indeed, research showed that systematic mindfulness practice and experiential acceptance approaches can significantly reduce competitive anxiety, rumination, experiential avoidance, and emotion regulation difficulties, and simultaneously increase positive emotions and self-efficacy, improving attentional control, mindfulness, flow, and performance in elite sports [6, 7, 75–79]. The mindfulness-based intervention also has beneficial effects on executive functions in athletes [8, 80, 81].

Interoceptive processes play a critical role in regulating physical exertion during physical activities and sports [43, 49]. Previous research has demonstrated that a co-designed exercise intervention can improve interoceptive awareness and mental health in non-athletes [44]. Additionally, a moderate-vigorous physical activity-based intervention can increase cardiac interoceptive accuracy, and individuals with a higher sports background tend to benefit more than those who are physically inactive [47]. Research further indicates that sprinters and distance runners outperform non-athletes in areas such as body trust, attention regulation, and self-regulation [50].

Our investigation uncovered a novel finding that body mindfulness for physical activity influences the psychological dimensions of sports success through a series of interoceptive regulatory skills, specifically self-regulation and attention regulation. A high degree of mindfulness in physical activity is a predictor of elevated self-regulation, which subsequently leads to enhanced attention regulation skills and greater mental skills in sports success among athletes. Previous research has indicated that mindfulness training can improve interoceptive awareness [22, 44, 47, 48, 82]. Thus, it is crucial to cultivate mindfulness practice alongside physical training to increase open awareness by consciously paying attention to the present moment, engaging in breath observation, and encouraging the recognition of internal physical sensations and their connection to emotional states without judgment [6–9]. Mindfulness may offer various benefits, including reduced stress, improved emotional regulation, increased enjoyment and fulfillment from physical activity, heightened self-awareness, concentration, and performance, which ultimately determine injury prevention, resilience, recovery, and overall well-being [7, 12–14].

Despite the clear evidence provided by this study regarding the existence of psychological factors determining athletic performance, certain limitations preclude generalization. First, the studies were cross-sectional, meaning that any cause-and-effect relationship presented in the regression and mediation analyses should be considered with caution. Future research should be longitudinally performed to examine the interplay and dynamic changes in mindfulness, interoceptive awareness, and psychological skills related to sports performance during the long-term process of sports activity and development. Although the sample size met the minimum requirements for power analysis, further research could replicate the current findings with a more representative sample for various individual and team sports. Second, all variables were self-reported, which is related to biases resulting from subjective assessments and cognitive distortions (e.g., defense mechanisms, false beliefs, such as about perfectionism, one's abilities, or self-efficacy). It is uncertain whether the same results would be obtained if interoceptive awareness and mental skills related to sports success could be assessed using more objective measurements. Therefore, future research should use more objective psychophysiological methods to assess mindfulness and interoceptive awareness, as well as external and more objective assessments by competent

judges (sports coaches, referees, and psychologists) in assessing psychological abilities. Additionally, an experimental study with mindfulness training among athletes would be more appropriate to examine the mediating effect of self-regulation and attention regulation on the association between mindfulness and the psychological dimensions of sports success. Therefore, future research should address these issues. Furthermore, different sports areas should be included in future studies to examine differences between various sports disciplines in mindfulness, interoceptive awareness, and psychological skills.

Conclusions

The present research unveiled disparities among athletes in terms of self-reported mindfulness, interoceptive awareness, and psychological dimensions of athletic success, which were influenced by factors such as gender, level of competition, and sports discipline (being a member of a prestigious team of elite athletes). Therefore, sports psychologists and coaches should be aware of these differences and adapt training to athletes' specific needs. Among all the psychological variables examined, body state mindfulness for physical activity, self-regulation, and attention regulation skills of interoceptive awareness were found to be the most crucial for sports success. Additionally, self-regulation and attention regulation were discovered to completely mediate the relationship between body mindfulness and sports success. These findings have significant implications for sports psychologists, who should incorporate mindfulness practices to enhance athletes' self-regulation and attention-regulation abilities, and subsequently improve sports performance among athletes.

Author contributions

AMR: Conceptualization, Methodology, Formal Analysis, Project administration, Resources, Validation, Visualization, Writing– original draft, Writing– review & editing; RT: Data curation, Conceptualization, Investigation, Methodology, Writing– review & editing.

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Data availability

The datasets generated for this study can be found in the Mendeley Data repository: Rogowska, A, Tataruch R. Comparison of interoceptive awareness, state mindfulness for physical activity, and sports success between elite speed skating athletes and college athletes (2023) Mendeley Data, V1. doi: 10.17632/vf5khf739w.1.

Declarations

Ethics approval and consent to participate

The studies involving humans were approved by the University of Opole Ethics Committee (Decision No. 6/2020). The studies were conducted in accordance with local legislation and institutional requirements. All participants provided their informed consent to participate in this study.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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