Self-Regulation training improves stress resilience in Elite Pre-Pubescent Female Gymnasts

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Abstract

The importance of managing stress load in young female athletes, particularly those at the highest level in sports such as gymnastics, has gained significant attention in recent times. Effective stress management strategies can help these athletes perform better, reduce the risk of injury and improve their overall well-being. The aim of the current work is to investigate the effect of training self-regulation ability through biofeedback on pre-pubescent female elite gymnasts’ stress management. 8 elite young female athletes from a top-flight French national league club took part in the study. We implemented a within-subject, cross-over design; during the experimental condition athletes involved in biofeedback training in rest and stress scenarios, while in the control condition the participants watched motivational videos. Our results show that biofeedback training of elite athletes increased self-regulatory ability and psychological resilience under stressful conditions and it seemingly decreased sensitivity to gymnastics-specific stress. The main result of this study is to have demonstrated that individual's ability to self-regulate stress-related psychophysiological phenomena is trainable.

Introduction

The world of high-level sports is characterized by intensive practice, demanding competition, public display of skills, and evaluation by judges. These experiences can become overwhelming for the athletes and there is evidence indicating negative long-term influence of the stress on the sports performance across different age groups (Arnold & Fletcher, 2021). Thus, a growing number of studies about the nature, the determinants, and the effects of stress (and anxiety) on the competitors does not come as a surprise. In parallel, researchers are exploring different intervention modalities aimed at stress-regulation, leveraging both on psychological (Balk & Englert, 2020; Jones, 2003) and technological (Dupee & Werthner, 2011) advances to help athletes achieve ever more. Research has shown that the stress-related phenomena are experienced by athletes in a variety of competitive environments, ranging from non- and sub-elite to elite and professional competitions (Dugdale et al., 2002; Fletcher & Hanton, 2003; Greenspan & Feltz, 1989; Morgan, 1974). Moreover, there is a widespread agreement that the excessive stress and tension before and/or during competition represent major threats to the athlete's ability to meet or exceed their performance goals (Davis & Sime, 2005), resulting in a greater likelihood of injuries (Nippert & Smith, 2008), attentional difficulties (Cañal-Bruland et al., 2010; Oudejans et al., 2011; Vine et al., 2016), decreased enjoyment and higher dropout rates (Dupee et al., 2016; Smith & Pollak, 2020).

Optimal internal state is maintained through an efficient mind-body regulation, underlined by an adaptive interplay of the sympathetic and parasympathetic subsystems (Benarroch et al., 1995; Porges, 2007; Thayer & Lane, 2009). However, excessive and sustained psychophysiological tension and overarousal caused by the chronic stress can alter the systems’ flexibility, and lead to the suboptimal individual functioning (Marin et al., 2011; Mariotti, 2015; Yaribeygi et al., 2017) with reduced degrees-of-freedom in the interactions with the environment (Damasio, 1998). The ability to adapt and maintain or regain the
state of purposeful internal equilibrium in different environmental conditions is termed psychophysiological self-regulation (Inzlicht et al., 2021; Porges, 2007; Prinzel III et al., 2001).

Recently, some authors have associated this capacity with the concept of psychological resilience: an indicator of the ability to cope and deal with possible adverse situations (Fletcher & Hanton, 2003; Iodice et al., 2022). Given the pervasiveness of the stress response and its documented negative influences on both short- and long-term health outcomes, as well as a multitude of individual abilities (O’Connor et al., 2021; Thoits, 2010) and performances (Anderson et al., 2019; Lochbaum et al., 2022) including the negative phenomenological cost (Arnold & Fletcher, 2021), an efficient stress management through self-regulation represents a highly desirable ability.

One of the most promising techniques to this purpose is biofeedback, a mind–body intervention that has the benefit of being unobtrusive, passive, and continuous (Bar-Eli et al., 2002; Brown, 1977; Dupee & Werthner, 2011; Sandweiss & Wolf, 1985; Strack et al., 2011; Zaichkowsky & Fuchs, 1988). Unlike many mind–body interventions addressing stress (for a review see (Lehrer et al., 2000; Rumbold et al., 2012) biofeedback externalizes an individual’s physiological state, allowing the user to monitor changes in real time (Blumenstein & Hung, 2014; Kennedy & Parker, 2019; Schwartz & Andrasik, 2017). While many attempts to define biofeedback can be found in the scientific literature (for a review, see (Peper & Shaffer, 2010; Schwartz et al., 2017; Schwartz & Andrasik, 2017), its core underlying idea is simple – feedback is crucial for any sort of learning. Analog to dancers practicing their craft in front of the mirror, biofeedback can be conceived as “a psycho-physiological mirror” (Peper & Schmid, 1983), which helps to practice and to improve self-regulation (Dupee et al., 2016). Biofeedback instrumentation provides the information about physiological processes that normally occur outside awareness (such as cardiac rhythm, muscle or brain activity) in form of auditory, visual or sensory signals (Peek, 2017). This information (i.e., feedback) helps to learn psychoregulatory control “for the purposes of improving health and performance” (Peek, 2017) (p. 17). Therefore, we can say that individuals use biofeedback to help create awareness of internal processes that are not typically consciously controlled (Blumenstein & Weinstein, 2011; Landers, 1985; Zaichkowsky & Fuchs, 1988). When provided with feedback regarding physiological processes (e.g., in the form of heart rate or respiration rate), an individual can begin to formulate strategies for self-regulation. Also, biofeedback-based interventions usually begin with the identification of suboptimal physiological functioning and learned situational responses.

Recently, Codonhato and colleagues (Codonhato et al., 2018) investigated the relationship between resilience and stress tolerance in elite-level gymnasts. The authors show that resilience, the ability to self-regulate, has a direct impact on stress management and injury prevention. Moreover, a series of recent studies provided empirical support for the idea that this capacity for self-regulation and/or resilience can indeed be trained via biofeedback training, in both athletic (Rusciano et al., 2017) and non-athletic (Iodice et al., 2022) populations.

The aforementioned study of Codonhato et al. (Codonhato et al., 2018), along with previous ones of Duda and Gano-Overway (Duda & Gano-Overway, 1996a, 1996b), shed light on the stress experienced by
young elite gymnasts, but, to the best of our knowledge, the usefulness of biofeedback-based interventions in this particular age group hasn’t been explored yet. Considering the growing professionalization of the sport and the ever-lowering age of access to professional competitions, the exposure to stress in the early stages of the development trajectory could potentially have snowballing effects later, both in terms of sport performance and life experiences (Caine & Nassar, 2005; Jurimae & Jurimae, 2001; Smith & Pollak, 2020; White & Bennie, 2015). The current study aims to investigate the effect of one month biofeedback training on very young elite gymnasts. The results of our study will allow to help clarify the mechanisms underlying the training of self-regulatory and thus resilience skills in young women. We will highlight the possibilities of using this training methodology in elite sportswomen to help prevent physical injuries and early talent drop-out in emotionally demanding sports. Furthermore, to the best of our knowledge, our study for the first time investigates this research topic in prepubescent young women.

Materials and Methods

Participants

Prospective inclusion of athletes from a top-flight French national league club involved a screening process wherein a female investigator (GP) assessed the attainment of menarche by querying both the subjects and their respective parents or guardians. Athletes who had not yet reached menarche were considered pre-pubescent (Gillen et al., 2021; Granados et al., 2015). Finally, a sample including 8 elite young female athletes was enrolled for the study (table 1). They were recruited in January 2020. The data collection started on February 17th and lasted until June of the same year. The participants compete in the high-level national tournaments and spend an average of 24 hours of training per week. None of them had any experiences with stress management interventions or mental preparation practices including meditation or yoga. Furthermore, none of the participants had musculoskeletal injuries during the study and were taking any anti-inflammatory drugs or corticosteroids. Afterwards, the personal information of the participants were removed and thus the data analyses were completely anonymous.

Study design

We implemented a within-subject, cross-over design (Laborde et al., 2017; Quintana & Heathers, 2014). This choice was dictated by the exceptional nature of the study population (i.e., elite gymnasts), since it proved difficult to access this population for a continuous period in the same facility. Moreover, it was crucial to avoid any confound in the interpretation of results that all gymnasts performed the same number of training sessions with the same instructor.

The study design therefore comprised two phases (hereafter conditions): (i) Control condition (CTRL) which comprised 8 sessions, two per week, for a duration of 4 weeks and (ii) Experimental condition (with Biofeedback treatment - BF) which comprised 8 sessions, two per week, for a duration of 4 weeks.
A two-week break (from the date of the CTRL condition post-test assessment) was provided between the two conditions.

All participants were evaluated in four laboratory sessions, one week before the start and at the end of each condition. Assessments sessions were conducted at week 1 (Assessment procedure – T0 CTRL condition), week 6 (Assessment procedure – T1 CTRL condition), week 9 (Assessment procedure – T0 BF condition) and week 14 (Assessment procedure – T1 BF condition) for all the participants (Figure 1). Before the start of assessments, sessions were held with the goal of introducing the participants to the aims and the methods of the study, and later to the biofeedback’s functioning and use.

Both the psychological and the physiological tests were conducted in the same room located at the Club headquarters. Room temperature and humidity were monitored during the evaluations. All the sessions were conducted with the same artificial light to avoid possible influences due to seasonal changes, both on the participants mood as well as on the quality of the physiological recordings. The chosen experimental room was never used by the participants, before or during the experiment, as a personal office or meeting room, in order to avoid a bias or influence due to familiarity with the setting. To a feasible extent, every physiological recording was scheduled on an empty stomach.

All assessment sessions, each lasting about 60 min, were structured as follows: after being welcomed by the experimenter, participants were invited for a psychological evaluation via the self-administered Multidimensional Assessment of Interoceptive Awareness (MAIA) questionnaire (Mehling et al., 2012). After a 5-minute break, participants were asked to get themselves comfortable in an ergonomic chair and relax for 6 minutes, while the operator positioned the sensors. The physiological assessment was carried out by practicing the Sue Wilson profile “Optimizing performance and health suite” (Wilson, 2007), on a 15-inch computer monitor. This standardized evaluation method consists of a baseline of 2 minutes with eyes closed, followed by 2-min baseline with eyes open, in which the participant is required to observe a fixed point in front of her. Subsequently, participant faces six cognitive stress tasks, lasting between 1 and 2 minutes, intermitted by recovery phases lasting 1.30 minutes after each stress task. The physiological parameters were measured across all phases. The experimenter was always present, providing guidance and instructions for each task.

**Psychological assessment.** To evaluate the effects of biofeedback training on the perceived individual self-regulatory capabilities, was used the validated French version (Willem et al., 2022) of The Multidimensional Assessment of Interoceptive Awareness (MAIA) test. It is a self-report psychological instrument, aimed at measuring the efficacy of mind-body therapies and “capture the potential changes in body awareness over time as people learn and practice therapies that claim to enhance body awareness” (Mehling et al., 2012)(p. 19), such as meditation and biofeedback. It is composed of 32 items unfolding over 8 scales: *Noticing* (the ability to be aware of body sensations), *Not Distracting* (the tendency not to use distraction to cope with discomfort), *Not Worrying* (the tendency not to experience emotional distress), *Attention regulation* (the capacity to maintain and focus attention to body sensations), *Emotional Awareness* (the ability to attribute specific physical sensations to physiological
manifestations of emotions), Self-regulation (assessing the ability to regulate distress by attention to body sensations), Body Listening (the tendency to actively listen to the body for insight) and Trusting (body perception as safe and trustworthy place) (idem, p.10). It encompasses different aspects of interoceptive body awareness, a key precursor of self-regulation capabilities. Furthermore, it presents satisfactory psychometric properties (Willem et al., 2022).

Biofeedback assessment. BF assessment sessions were carried out using a Sue Wilson profile “Optimizing performance and health suite” (Wilson, 2007) via ProComp Infiniti™ T7500M Biofeedback System manufactured by Thought Technology (Montreal, Quebec, Canada), with a BioGraph Infiniti™ software (version 6.0). The recorded signals included peripheral temperature (a sensor placed on the middle finger of the non-dominant hand) (Shaffer et al., 2016), skin conductance level (two separate sensors, placed on the index and pinky fingers of the non-dominant hand) (Boucsein, 2012; Peek, 2017), muscle activity (EMG electrode positioned on the right trapezius) (Arena et al., 1995), blood volume pressure (BVP, via a sensor placed on the index finger of the non-dominant hand) (Peper et al., 2006) and respiration rate (RR, strain-gauged belt, placed around the midsection of the abdomen and installed in an upright position during a maximal inhalation) (Ferguson et al., 2020).

The Wilson test suite comprises multiple stress and recovery phases, spread across 14 activities, of which 6 stress tasks (Stroop Colour test, Math test, ReachTrack Game, Dual Tracking Game, Anticipation and Brief Stressor), preceded by two baselines (eyes closed and eyes open). Each stress task is followed by a recovery phase.

Training Program

Procedure. The entire experimental protocol was carried out at the Club Elan Gymnique Rouennais (Rouen, France) in a quiet and isolated office in the club’s facilities. Both study conditions included 8 sessions (two per week) each lasting 40 minutes.

In the control condition (CTRL), subjects were exposed to 40-minute motivational videos featuring exceptional artistic gymnastics performances from the recent Olympic games and World Championships, accompanied by music (the videos were taken from the 2016 Olympic Games in Rio de Janeiro, 2018 Word Championship in Doha and 2019 World Championships in Stuttgart). The experimenter (GP) followed each individual session via videoconference.

The experimental condition (BF) involved biofeedback training. Training sessions lasted around 40 minutes and included an initial 5-minute relaxation phase followed by 20 minutes of biofeedback training. Each session was concluded with a brief follow-up on the subjective experience of the participant. Participants set in an ergonomic chair and the training procedures was administered via a 15-inch computer monitor. The experimenter carefully provided detailed descriptions of each variable shown on the biofeedback training screen (i.e., skin conductance level and peripheral temperature). The control of the respiration rate and the diaphragmatic breathing were introduced as potential means of establishing control over physiological functions (Blumenstein et al., 1995; Ely et al., 2020; Nelson
Ferguson et al., 2020; Perry et al., 2011). In the first session visual feedback was set in the form of a respiration pacer for each participant (e.g., 6 breaths/min) (Lehrer et al., 2000) and participants were instructed for natural and shallow abdominal breathing in accordance to their resonance frequency. The idea of balloon imagery (i.e., trying to fill the balloon with each inhale and deflate the balloon with each exhale) was introduced to participants to facilitate abdominal breathing and learn diaphragmatic breathing as well as minimizing thoracic movement, skills considered important in the quest to maintain control over physiological functions (Khazan, 2013; Perry et al., 2011).

From the second session onwards, five biofeedback activities followed with a decreasing presence of feedback – skin conductance level training with visual and audio feedback, peripheral temperature training with visual and audio feedback, skin conductance level training with only visual feedback, peripheral temperature training with only visual feedback, skin conductance level training with only audio feedback, peripheral temperature training with only audio feedback (Iodice et al., 2022), and both with only visual feedback (in a form of value graph). Visual feedback was presented via a dynamic on-screen animation, while the audio feedback was provided as a sound which would become harmonious in proportion to the subject's ability to follow the instructions. Participants were trained to decrease the skin conductance level or increase the peripheral temperature alternatively, using the provided feedback (Rusciano et al., 2017). The sessions included the equivalent, 10-minute parts of thermal and electrodermal feedback, presented in a randomized order. At the end of each session, the data and the training progress was shown to the participant and briefly discussed, along with addressing any potential questions.

**Data processing**

*Psychological data.* The analysis was carried out considering the within-subject variation. Averages were calculated of the results of the questionnaires submitted before and after each condition (CTRL and BF).

*BF data.* Data analysis was carried out considering intra-individual variations of physiological parameters (i.e., metabolism level) and within the same evaluation session (i.e., hydration), in the stress and recovery phases (Time). First, normalization of all dependent variables was conducted. Subsequently, baseline amplitude was calculated over 2 min rest data recording to provide an indication of the ongoing rest activity (Iodice et al., 2022). The main metric used for presenting the efficacy of self-regulation is Delta calculated between the mean of the baseline and peak values of physiological parameters during both stress tasks and recovery periods during the assessment.

**Statistical analysis**

The Shapiro–Wilk test was conducted to verify that all data were normally distributed.

In the case of psychological data (MAIA), a paired t-test was used to ascertain the effects of treatment. The BF data was analyzed via 2 (Condition, CTRL and BF) x 2 (Time, stress and recovery) repeated measures analysis of variance (ANOVA). Furthermore, potential interactions (Time x Condition) for each
dependent variable were assessed. Post-hoc tests compared averages between treatments, separately for each phase (stress and recovery). Moreover, planned contrasts were used to verify the differential effects of BF on self-regulation index and compared whether it changed after the BF compared to CTRL condition. The significance level was set to 0.05. To decrease Type I errors, we only tested interactions involving treatment and session in the main ANOVAs. The results were adjusted for multiple comparisons by controlling the pool of all p values using the false discovery rate (FDR) procedure (Benarroch et al., 1995). For each analysis, we report the F or t statistic, the p value, and the effect size (Cohen's d), measured via partial eta squared (\(\eta^2_p\)). Effect sizes was assessed using G*Power statistical software, in agreement with Cohen's norms (Cohen, 1988). Obtained values have been deemed as small when \(\geq 0.01\), medium when \(\geq 0.06\), and large when \(\geq 0.14\). In the analysis of physiological data, Bonferroni correction was applied to probability values to account for potential biases due to multiple comparisons.

**Results**

*Psychological data.* As shown in the Table 1, analysis revealed significant differences between conditions (CTRL vs. BF) on Total scores \((t(7) = -4.255, p = 0.004)\), as well as on Not Distracting \((t(7) = -4.664, p = 0.002)\), Attention regulation \((t(7) = -3.895, p = 0.006)\), Emotional awareness \((t(7) = -2.779, p = 0.027)\) and Self-regulation subscales \((t(7) = -3.074, p = 0.018)\). In order to show the statistical power of the study, a post hoc test on the sample size was realized with G*Power. A high effect size in Total Score \((d = 1.603)\), in Not Distracting \((d = 1.779)\), in Attention Regulation \((d = 1.457)\), Emotional Regulation \((d = 1.061)\), and in Self-Regulation \((d = 1.151)\) were observed. A moderate effect size was determined in Noticing \((d = 0.531)\) and Trusting \((d = 0.561)\).

Results also indicate that the BF was followed by significantly higher test scores.

*Biofeedback data.* Repeated measures ANOVA 2 (Conditions: CTRL vs. BF) × 2 (Time: stress and recovery; within-subjects) was performed to assess the effect of treatment on their self-regulatory ability (Fig. 3).

Repeated measures ANOVA showed significant effects of condition (CTRL vs. BF) for the parameter Temperature \((F_{(1,7)} = 17.449, p = 0.004, \eta^2 = 0.708, \eta^2_p = 0.714, \omega^2 = 0.456)\). While the difference for the Skin Conductance Level (SCL) has not reached statistical significance, the direction and the amplitude of change indicate positive effects of BF \((F_{(1,7)} = 2.88, p = 0.133, \eta^2 = 0.198, \eta^2_p = 0.292, \omega^2 = 0.151)\), as it is in the case of level of muscular activation, *i.e.*, EMG \((F_{(1,7)} = 1.882, p = 0.212, \eta^2 = 0.164, \eta^2_p = 0.212, \omega^2 = 0.04)\). Additionally, significant effects for Time were recognized in parameter Skin Conductance Level (SCL) \((F_{(1,7)} = 20.396, p = 0.003, \eta^2 = 0.163, \eta^2_p = 0.744, \omega^2 = 0.391)\). We observed significant interaction between Condition and Time for parameter Temperature \((F_{(1,7)} = 10.157, p = 0.015, \eta^2 = 0.003, \eta^2_p = 0.592, \omega^2 = 0.005)\). Post-hoc analysis revealed that the temperature was significantly higher after the treatment (BF) in both stress \((t(7) = 3.917, d = -1.767, p_{bonf} = 0.034, p_{holm} = 0.018)\) and recovery periods.
(t(7) = -4.412, d = -1.991, p_{bonf} = 0.018, p_{holm} = 0.018). We didn't observe any significant differences for other parameters (Table 2). A high effect size was estimated in Temperature (d = 1.58) and Blood Volume Pressure (d = 1.467), a moderate effect size in Skin Conductance Level (d = 0.642) and in level of muscular activation (d = 0.518) was observed.

Discussion

In the present study, we explored for the first time whether training self-regulatory skills through BF can influence resilience to stressful conditions in prepubescent female elite athletes. Our results show that BF training of elite athletes (1) increased self-regulatory ability and psychological resilience under stressful conditions and (2) it seemingly decreased sensitivity to gymnastics-specific stress. These two findings taken together support the idea that psychophysiological self-regulation is trainable.

The protocol of this study was based on the previous research revealing the efficacy of thermal and electrodermal (Iodice et al., 2022; Peper & Schmid, 1983; Rusciano et al., 2017) biofeedback in the case of self-regulation training for the gymnasts. Namely, psychophysiological self-regulation refers to a person's ability to regulate affective and cognitive states and adapt to various environmental conditions, thus enabling flexible behaviour that preserves homeostasis in response to different situational demands (Porges, 2007; Prinzel III et al., 2001). The efficiency of self-regulation largely depends on resilience, a key psychobiological capacity for maintaining normal functioning and health that involves adaptability to adversity (Russo et al., 2012). This theoretical framework is based on the neurovisceral integration model that integrates extensive evidence linking the autonomic and central nervous systems in a functional and structural network involved in the emotional regulation of behavior (Dworkin et al., 1994; Iodice et al., 2019; Pezzulo et al., 2018; Porges, 2007; Thayer & Lane, 2009; Yu et al., 2021). Indeed, our results suggest a positive influence of BF training on both psychological and physiological dimensions of self-regulatory capabilities. Particularly, the former was assessed via the MAIA test, which has been used extensively in studies on both healthy and clinical populations (Park et al., 2021; Phillipou et al., 2022) and for the evaluation of training induced changes in the cases of mind-body interventions such as meditation (Bornemann et al., 2015)) and biofeedback (Iodice et al., 2022). In fact, while all the factors have shown improvements after the BF training, statistical significance was detected on more sophisticated interoceptive awareness sub-abilities such as not distracting (the tendency not to use distraction to cope with discomfort), attention regulation (the ability to sustain and control attention to body sensations), emotion awareness (the ability to attribute specific physical sensations to physiological manifestations of emotions) and self-regulation (the ability to regulate distress by attention to body sensations). On the contrary, sub-abilities that can be considered as precursors to these more sophisticated ones (such as noticing or the ability to be aware of body sensations, or body listening, that is, the tendency to actively listen to the body for insights) were not significantly increased after training. This is partially in contrast with Bornermann and colleagues (Bornemann et al., 2015) which reported a significant increase in all the sub-abilities after a three-months contemplative training. A possible explanation for this difference may lay on intrinsic differences between the two employed training procedures. While Bornemann et al. (Bornemann et al., 2015) required participants to complete
structured modules based on meditation techniques during which no objective feedback were provided (thus stimulating participants’ subjective ability to predict their physiological state), our training was based on objectification of internal physiological state (thus avoiding participants’ to firstly focus on “recognizing” phase (e.g., noticing and body listening), concentrating their resources on training their ability to modify physiological signals, thus skipping faster to the “regulating phase”).

Likewise, Lima-Araujo and colleagues (Lima-Araujo et al., 2022) reported a significant increase in five of the eight MAIA sub-abilities (i.e., Body Listening, Trusting, Self-Regulation, Attention Regulation and Emotional Awareness) after a brief mindfulness training strongly focused on body scan abilities and learning of breathing patterns. While the participants in their training didn’t receive any objective feedbacks on their performance, this protocol nonetheless presents many similarities to the one we employed, which could account for the greater overlap between our respective results.

Moreover, our results may contribute to the ongoing debate on the components of interoception—accuracy, sensibility and awareness—and their relationships as recently pointed out by, among others, Garfinkel and colleagues (Garfinkel et al., 2015). Namely, the authors suggest that the aforementioned categorization could be reconceptualized in terms of distinction between objective interoceptive processes (i.e., accuracy: the ability to correctly monitor changes in internal body state), subjective (sensibility: the tendency to focus on internal body state), and metacognitive ones (awareness or error awareness: quantifiable difference between self-reported judgement about one’s interoceptive accuracy and objectively assessed interoceptive accuracy). This idea is seemingly supported also by recent results suggesting differences in the neural underpinning of distinct interoceptive components (Du et al., 2023), feedback-based trainings ground their effectiveness (at least in part) in their potential to highlight errors in the interception monitoring process, enabling the subject to immediately compare the real state with the perceived one and thus allowing for continuous adjustments of the predicted state. This focus on the metacognitive component of interoception is the peculiar feature that distinguishes neuro- and biofeedback procedures from other methods usually employed to train the ability to deliberately manage psychophysiological states. Subsequently, our results contribute to the scarcely documented literature on interoceptive processes and feedback-based training in the young athletic population. Indeed, while effectiveness of the BF-based procedures has been widely studied in clinical contexts (e.g., ADHD, (Kuznetsova et al., 2022)), and their usefulness was recently confirmed in a systematic review on the effects of biofeedback training in children and adolescents (Dormal et al., 2021), their potential application in the case of young athletes is still relatively unexplored (see (Zadkhosh et al., 2018)). The recorded physiological parameters show a main effect interaction of condition (CTRL vs BF, p<0.004) for the peripheral temperature parameter. Particularly, our data suggests a lower sensitivity to the stress stimuli after BF training. We also note that in the control condition, before training with BF, prepubescent female athletes had no ability to regain the homeostatic balance, once perturbed by the stress stimuli.

On the other hand, while the overall trend manifests expected behavior, the observed changes in skin conductance level parameter haven’t reached statistical difference, neither did the interaction between the experimental conditions. Our best a posteriori hypothesis regarding such data concerns the mere
nature of the physiological signals investigated. Namely, while temperature of the body is relatively easy to understand as idea, conductance is a more abstract concept, which might be more difficult for prepubescent females to grasp and perceive. The human being's difficulty in perceiving abstract concepts has been the subject of much research in the fields of psychology and neuroscience. Our best a posteriori hypothesis regarding such data concerns the mere nature of the physiological signals investigated and the age of participants. Indeed, while the concept of body temperature is relatively straightforward to grasp, conductance represents a more abstract notion. Referring to classical theories of child development (Piaget 1952), it appears that, from this point of view, the participants in this study are at the end of the concrete operations stage (or at the very beginning of the formal stage). At this stage, the ability to use abstract notions is not yet fully acquired.

Therefore, our findings firstly corroborate those of previous studies, which suggest that when the subjects have the opportunity to receive interoceptive feedback of their neurovisceral state during targeted training, this allows for the adaptation of self-regulatory control mechanisms (e.g., (Meyerholz et al., 2019; Mirifar et al., 2017)). Furthermore, our study extends the findings on the influence of self-regulatory capacity on the stress management process to prepubertal athletes, as well as contributing to the understanding of the relationship between stress, psychophysiological reactions and training capacity. Finally, we suggest that our approach introduces a new procedure to train young high-level athletes to protect their psychophysical balance during the long hours of training (24h a week in our sample), which could, as suggested by some authors (Rusciano et al., 2017), be crucial in injury prevention.

**Declarations**

The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report. We certify that the submission is original work and is not under review at any other publication.

**Acknowledgement**

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**CRediT author statement**

Data availability statement. The data that support the findings of this study are available on request from the corresponding author, PI. The data are not publicly available due to restrictions: they contain information on minors that could compromise their privacy.

Compliance with Ethical Standards

Conflicts of interest The authors do not have any potential conflict of interest to disclose. All authors therefore declare that they do not have any conflict of interests.

Ethical Approval The study was carried out according to the ethical principles put forward in the Declaration of Helsinki and its subsequent amendments and it was approved by the Ethical Committee of the University of Rouen (n. 2020-04-A).

Informed Consent All participants provided verbal and written informed consent obtained from the parents/tutors.

Open Access We followed all necessary protocols and procedures to maintain the integrity of the study and safeguard the rights and privacy of our participants. As part of our commitment to transparency, we will make our data and materials openly and anonymously available to facilitate replication and verification of our findings. It is important to note that this study was not preregistered in an independent, institutional registry.

References


Table 1
Anthropometric and athletic characteristics of elite gymnasts.

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Gymnastics experience (years)</th>
<th>Height (cm)</th>
<th>Body weight (kg)</th>
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</table>

Table 2
Results of the repeated measures ANOVAs conducted on all physiological parameters: T, peripheral temperature; SCL, skin conductance level; EMG, muscle activity; BVP, blood volume pressure and heart rate; RR, respiration rate using the condition (CTRL vs. BF) and time (stress and recovery) as factors.

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<th>p</th>
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<th>η²p</th>
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Figures
Figure 1

Weekly (W) timeline of the study setup. W0 and W8: Familiarisation; W1 and W6 Assessment of the control condition. W9 and W14 Evaluation of the Biofeedback condition; W7 rest.

Figure 2

MAIA questionary data. Image shows results after BF treatment (black) and Control (red) conditions. The results are presented for (a) Total Score and (b) Questionnaire’s subscales: Noticing (N) Not Distracting (ND) Not Worrying (NW) Attention Regulation (AR) Emotional Awareness (EA) Self-regulation (SR) Body Listening (BL) Trusting (T). ** p<.001; * p<.05 Significant differences.
Figure 3

Effects of treatment. Images shows effects of treatment in peripheral temperature (A) and skin conductance level (B) in BF (black) and CTRL (red) conditions. during baseline, stress, and recovery phase. Vertical bars measure standard error.