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ORIGINAL ARTICLE

Associations between sensorimotor gating mechanisms and athletic performance in a variety of physical conditioning tests

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Abstract
Purpose The elite athlete is fine-tuned all around to deliver favorable results in sporting events. In this study, we address the question of whether basic movements—such as reflexes—and heterogeneous attentional modulation components—such as sensorimotor gating mechanisms—are also tuned up to maximize the results of middle-distance runners in physical conditioning tests.
Methods We selected an array of professional middle-distance runners and healthy counterparts that were submitted to measurement of (1) physical conditioning parameters, including somatotype, jump, strength, and flexibility tests; and (2) sensorimotor gating mechanisms, including acoustic startle reflex, prepulse inhibition, and habituation.
Results Our results showed athletes scored better on the athletic tests compared to controls, as expected. They also exhibited a lower startle amplitude, while maintaining higher prepulse inhibition values. They reacted faster to the acoustic stimuli, and sex-related differences—found in controls—were not present in athletes. Our data also pointed out to substantial correlations between sensorimotor gating and physical conditioning parameters.
Conclusions All in all, these data may point to physical conditioning-driven neural plasticity of brain sensorimotor gating circuits in charge of triggering involuntary movements to harness control and efficiency over reflexed muscle activity.

Keywords Anthropometric measurement · Biological adaptations · Bosco jump test · Fitness · Habituation · Humans · Prepulse inhibition · Startle reflex

Abbreviations

ASR	Acoustic startle reflex
BMI	Body mass index
CMJ	Counter-movement jump
DJ	Drop jump
EMG	Electromyography
PPI	Prepulse inhibition
SJ	Squat jump

Introduction

There is a growing interest in sports science and applied physiology about the nature of the biological processes that underlie the elite athlete (Dawes et al. 2016; Donnelly et al. 2016; Helms et al. 2016; Molina et al. 2016). Their practical preparation develops functional and physiological processes that improve performance during competition. The integration of multiple fields of science is required to elucidate

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these precise adaptations that occur in the neurophysiology of athletes and in their somatosensory system specifically.

Reflexes are the simplest form of movement. They are involuntary and unchangeable once they are elicited. They can be used as standards to evaluate certain sport skills (Kaltsatou et al. 2011; Taube et al. 2007), and even reflex-based tools have been proposed as cheap, easy, and efficient methods to identify and classify athletes (Judge and Burke 2015). In contrast, non-selective attentional modulation is a heterogeneous process that accompanies executive functions as well as alertness, arousal, and vigilance (Parasuraman 1998). The startle reaction is an example of a non-selective attentional process (Bakker et al. 2006) and could potentially be a good candidate to be evaluated in athletes for its simplicity. Specifically, the acoustic startle reflex (ASR) is a short and intense motor reaction that involves the contraction of a large number of muscle groups throughout the body in response to a loud and unexpected acoustic stimulus.

When the sound or noise that normally causes the ASR is shortly preceded (between 30 and 500 ms) by a weak sensory stimulus (visual, sound, or touch), the startle response is less pronounced or even abolished (Braff et al. 2001; Valls-Solé 2003). This prepulse inhibition (PPI) is directly related to sensorimotor gating mechanisms, which are adaptive operations to prevent overstimulation, helping the brain to focus on a specific stimulus among a host of other distracters (Valls-Solé 2012). The sensorimotor gating mechanisms involve feed-forward and feed-back inhibition of the stimulus perceived. Usually, athletes need to narrow down their attention on a single stimulus to perform in a sporting event; hence, developing a fine-tuned somatosensory system might be advantageous to deliver favorable results.

In this study, we are interested in finding out whether specific physical conditioning/training in a group of middle-distance runners could be related to specific adaptations of sensorimotor gating circuits. Further development of the somatosensory system by training may allow greater control over all the muscles of the body. This control may enable refined reactions to incoming stimuli, and these reflexes could be modified by specific training to deliver optimum athletic performance (Granacher et al. 2006).

As seen above, prior research works have studied reflexes as a mean to evaluate skill or classify athletes based on spinal stretch reflexes, which are directly related to motor control in response to somatosensory, as opposed to audiosensory, input. The plasticity of that monosynaptic spinal reflex is very specific: stretch reflex gain can either be up- or down-regulated in the specific muscles used for the task in response to the demands of the training or skills performed (skilled/intricate movement vs. gross explosive movement). Here, we used an auditory-based (versus proprioceptive) brainstem (versus spinal) reflex in a population of athletes who seldom experience auditory stimuli in their training.

With this purpose, we will evaluate both athletes and healthy counterparts in a series of physical tests to explore a broad range of aspects in their fitness level, as well as startle reflex measurements including PPI and habituation to examine the state of sensorimotor gating neural processing. Specifically, in this study we aim to find out (1) whether the sensorimotor gating mechanisms are fine-tuned in athletes compared to controls, and (2) whether these possible fine-tuned processes could specifically be correlated to better scores in a broad range of fitness parameters.

Materials and methods

Participants

Before we collected the data, we calculated an approximate sample size taking into account $p < 0.05$ as acceptable and a study with 80% power; considering a 5% dropout rate we would need to complete ~ 150 participants. Thus, we selected 80 (39 males, 41 females) Spanish professional middle-distance (800 and/or 1500 m dash) running athletes (≥ 20 h of physical conditioning/training per week during a minimum of 2 years) and 76 (39 males, 37 females) healthy controls (≤ 6 h of training/week) of virtually the same age (23.8 ± 4.7 vs. 22.6 ± 4.1 years old) out of the School of Nursing and Physical Therapy of the University of Salamanca, following exhaustive standard medical anamnesis to assess suitability for participating in the study. Smoking and/or abuse of pharmacological substances were used as exclusion criteria. Data from four athletes and three controls were discarded from analysis following exclusion criteria. All measurements were conducted in the afternoon to minimize the effect of intra-/inter-subject circadian rhythms. In addition, women were tested during the luteal phase of the menstrual cycle (based on the date of their last menstruation, its duration, and periodicity) since hormonal changes in the cycle may give variations in the results of the startle tests. This study meets the ethical standards laid down in the 1964 Declaration of Helsinki, and the University of Salamanca Ethics Committee approved it. Informed consent was obtained from all individual participants included in the study.

Athletic parameter assessment

Anthropometric measurements

Using standard clinical equipment and following the ISAK guidelines (Marfell-Jones et al. 2006), we measured each participant for weight, height, eight skinfolds (tricipital, subscapular, pectoral, ileocrestal, supraspinal, abdominal, mid-thigh, and mid-leg), three breadths (humeral biepicondylar, wrist bistyloid, and femoral bicondylar), and four girths (upper arm in maximum contraction, waist, hip, mid-thigh, and mid-leg). Height was measured to the nearest 0.1 cm using a stadiometer (GPM, Seritex, Inc., Carlstadt, NJ). Body mass was measured to the nearest 0.1 kg using a portable scale (model 707, Seca Corporation, Columbia, MD). Skinfold thickness was recorded to the nearest 0.2 mm at a constant pressure of 10 g/mm using a Holtain skinfold caliper (Holtain Ltd., Crymych, UK). Girths were determined to the nearest 0.1 cm using a flexible anthropometric steel tape measure (Holtain Ltd., Crymych, UK). Skinfolds were measured three times at each site in a rotation system, as described by Heyward (Heyward 1977), and the mean of the three measurements was used in the analysis. Breadths and girths were measured once at each site. Somatotype was determined according to the Carter and Heath method (Carter 1982). Body composition was estimated following the four-component model and in accordance with the ISAK recommendations (Heyward 1977). Body fat was assessed by applying the following formula for males (Carter and Health 1990): Fat% = (Σ6skinfolds × 0.1051) + 2.58; and for females, the following formula was used (Carter and Health 1990): Fat% = (Σ6skinfolds × 0.1548) + 3.58, where the six skinfolds were triceps, subscapular, supraspinal, abdomen, thigh, and medial calf expressed in millimeters. Body muscle mass corresponded to the following equation (Würch 1974): Muscle (kg) = total body mass − (fat + bone + (total body mass × C/100)), where C was 24.1 in males and was 20.9 in females. All variables are expressed in kilograms. Finally, body bone mass was calculated with the following formula for both males and females (Rocha 1975): Bone (kg) = 3.02 (Height2 × Wrist*B* × Femur*B* × 400) 0.712, where *B* means breadth and the three variables were expressed in meters. All these data determined the body mass index (BMI) and somatotype: morphological body conformation related to three interrelated components: endomorphy, as the tendency of accumulating fat mass; mesomorphy, as the degree of musculoskeletal development associated with size; and ectomorphy, as the linearity of the body (Sheldon 1950).

Bosco jump tests

A commercial jump tester (ERGO-JUMP Plus BOSCO SYSTEM® Byomedic, S.C.P., Barcelona, Spain) was used to assess neuromuscular jump capacity of the participants. This system consists of several sensors fixed in a base on which jumps are performed. Data captured from take off to landing are sent to a computer which processes different parameters. These parameters are flight time (ms), jump height (cm), and potency output (W/Kg). We used three tests to evaluate different neuromuscular components: squat jump (or SJ, to evaluate the explosive power of the lower limbs), counter-movement jump (or CMJ, involves elastic elements and subsequent reuse of elastic energy in the jump), and drop jump (or DJ, entails an eccentric contraction to cushion a 40-cm fall in which elastic energy is stored and reused in the subsequent concentric contraction for the jump) (Bosco and Komi 1979; Bosco et al. 1983a, b).

Strength and flexibility tests

Grip strength test A calibrated manual dynamometer (Sammons Preston Rolyan, Bolingbrook, IL, USA) was used to test the grip strength (Kg) of the hand during a maximum contraction maintained for 5 s. Participants performed the test with the dominant hand first and then with the non-dominant hand. They repeated it three times, and we calculated the mean value.

Posterior muscle chain flexibility measurement: the "sit-and-reach" test Participants sat on the floor and maintained the knees blocked in extension with the popliteal cavity in contact with the floor. Then they had to stretch the posterior muscle chain while simultaneously moving both hands forward along a calibrated box in mm, as seen elsewhere (Mier 2011). They repeated this test three times, and we calculated the mean value.

Startle reflex parameter assessment

Setup

A commercial human startle response monitoring system (EMG Human Startle-SR Lab, San Diego, CA, USA) was used to deliver acoustic startle stimuli and record electromyographic (EMG) activity. The stimuli were presented to the participants binaurally through Sony MDR-V6 headphones (SONY Electronics Inc., San Diego, CA, USA) while sitting in a moderately lit soundproof room. The eye blink component of the startle response was indexed by recording EMG activity of the *orbicularis oculi* muscle by positioning two miniature silver/silver chloride electrodes filled with electrolyte paste directly beneath the right eye. The ground electrode was attached to the mastoid muscle behind the right ear. The EMG signal amplification gain control was kept constant for all participants, and the recorded EMG activity was band-pass filtered to eliminate interference (50 Hz as recommended by SR Lab). EMG data were scored off-line using the analytic program of the system to assess the response amplitude (mV), and the latency (ms) of the response peak, which was determined as the point of maximal amplitude that occurred within 120 ms from the onset of the stimulus.

In the *orbicularis oculi* muscle, both the blink reflex (a brainstem reflex to protect the eye that is not part of the startle reflex) and the ASR response overlap. An off-line analysis of the recording was performed to prevent errors in calculations of the startle parameters. Most of the recordings presented two peaks of maximum amplitude after the acoustic stimulus: the first one corresponds to the blink reflex itself and the second one to the palpebral component of the ASR (Meincke et al. 2002).

Experimental session

The pulse-alone stimulus was a 40-ms presentation of 110 dB SPL white noise, and the prepulse stimulus was a 20-ms presentation of 85 dB SPL white noise. The session began with a 5-min acclimatization period consisting of 70 dB SPL continuous white noise, which was maintained along the session. Participants received 80 startle stimuli in three blocks: the initial pulse-alone trial block (block 1), the eliciting PPI trial block (block 2), and the final pulse-alone trial block (block 3). The period of prepulse onset to pulse onset intervals, also known as inter-stimulus interval (ISI) to elicit PPI, was 30, 60, and 120 ms. Trials were presented in a pseudorandom order with an inter-trial interval ranging 8–25 s. The percentage of inhibition was calculated for each respective ISI according to the following formula: %PPI = [(startle amplitude on pulse-alone trial − startle amplitude on prepulse-to-pulse trial)/startle amplitude on pulse-alone trial] × 100. We also calculated habituation as a percentage comparing the ASR amplitude in block 3 vs. block 1. The session lasted approximately 25 min and participants were not given any specific instructions. This session was designed following that elsewhere (Swerdlow et al. 2007, 2005).

Data analysis

In total, we studied 22 variables divided in 2 categories:

1. Athletic parameters (to assess fitness level): body mass index (kg/m^2), endomorph, mesomorph, and ectomorph indexes (arbitrary units); flight time (ms) and jump height (cm) for the three Bosco jump tests, and potency output (W/kg) for the drop jump test; hand grip strength (kg) and posterior muscle chain flexibility (cm).
2. Startle reflex (to assess sensorimotor gating): startle amplitude (mV), latency (ms), and habituation (%). Also, percentage of prepulse inhibition (PPI) when the ISI = 30 ms, 60 ms, and 120 ms, and their specific latencies.

Data are reported as means ± SD. Experimental conditions were compared by either a Student's *t* test (athlete vs. control groups) or an analysis of variance, ANOVA (male and female in athlete and control groups), and a Bonferroni test was used for post hoc comparisons. A Pearson's Chi-squared test (χ^2) was used to find correlations among independent variables of the two datasets studied (sensorimotor gating mechanisms and fitness level tests among either athlete or control groups). Data are reported grouping gender when no significant differences were found between males and females. The statistical package employed was SPSS-PASW Statistics 18.0.0 (SPSS Inc., Chicago, IL, USA). Differences were regarded as statistically significant when $^*p < 0.05$.

Results

Athletes scored better results in a broad range of physical tests

The first of the athletic parameters we were interested in studying was the participant's somatotype. We found that our control group exhibited a higher endomorph index compared to that from athletes ($p < 0.05$; Table 1A and Fig. 1a). On the other hand, athletes exhibited higher mesomorph index compared to controls ($p < 0.05$; Fig. 1a). However, there was no significant difference found between both groups on the ectomorph index (n.s., Fig. 1a).

Athletes scored better results on the Bosco jump tests. Their flight time and jump height were higher compared to those from the control group across the three different tests, plus athletes also developed higher potency output during the jumps ($p < 0.05$; Table 1A and Fig. 1b–d).

We found significant differences between groups on the grip strength and flexibility tests, with athletes scoring higher results when compared to controls. There were also notable inter-sex differences, with males exhibiting higher grip strength than females, whereas females reached higher flexibility values than males ($p < 0.05$; Table 1A).

Athletes exhibited fine-tuned sensorimotor gating processes

Regarding startle reflex parameters, athletes exhibited lower amplitude than controls; or in other words, athletes startled less intensely than their counterparts ($p < 0.05$; Table 1B and Fig. 2a). Control males showed a small habituation at the end of the session ($p < 0.05$; Fig. 2b). On the other hand, control females habituated to the startling stimulus more than males did ($p < 0.05$; Fig. 2b). Interestingly, this fact did not occur in the athlete group, both males and females exhibited a medium-range habituation to the startling stimulus with no gender-related divergences (n.s., Fig. 2b).

We found significant differences in the prepulse inhibition values: athletes exhibited higher grade of inhibition to the 3 ISI presented compared to those from controls, 60 ms being the best interval to elicit stronger inhibitions ($p < 0.05$; Table 1B and Fig. 2c).

Table 1 (A) Physical conditioning test results grouped by sex, (B) startle reflex and sensorimotor gating parameters results grouped by sex

	Control		Athlete	
	Male	Female	Male	Female
(A)				
Anthropometric index				
BMI (kg/m^2)	24.8 (3.8)	21.4 (4.4)	25.5 (3.5)	23.1 (3.8)
Endo (a.u.)	4.6 (2.4)	4.3 (3.)	2.7 (1.9)	2.8 (2.6)
Meso (a.u.)	3.7 (1.8)	3.9 (1.9)	5.2 (0.9)	5.1 (1.4)
Ecto (a.u.)	2.1 (0.9)	2.0 (0.8)	2.1 (0.3)	2.1 (0.4)
Flight time				
SJ (ms)	435.5 (75.4)	398.2 (84.1)	512.3 (48.2)	472.9 (39.8)
CMJ (ms)	447.6 (68.2)	402.7 (81.4)	534.3 (48.2)	507.9 (41.7)
DJ (ms)	437.1 (91.4)	418.5 (78.4)	512.5 (38.0)	496.4 (45.1)
Jump height				
SJ (cm)	23.6 (5.3)	19.7 (5.9)	31.6 (6.1)	28.8 (8.8)
CMJ (cm)	23.1 (4.3)	21.6 (5.1)	34.5 (6.7)	30.5 (5.89)
DJ (cm)	23.4 (6.1)	22.1 (5.9)	31.8 (4.8)	30.4 (5.8)
Potency (W/kg)	23.1 (6.2)	19.7 (6.4)	32.4 (8.1)	28.1 (5.9)
Strength (kg)	41.4 (9.7)	26.3 (3.3)	55.9 (8.5)	37.9 (6.8)
Flexibility (cm)	11.7 (2.1)	15.8 (2.8)	18.8 (3.1)	19. 5 (3.9)
(B)				
ASR amplitude	49.1 (12.1)	43.5 (16.2)	27.3 (8.1)	24.1 (10.7)
Habituation (%)	14.1 (15.3)	58.1 (8.6)	37.1 (10.8)	37.9 (4.5)
PPI (%)				
ISI 30	41.2 (15.1)	45.5 (17.3)	60.3 (21.2)	63.2 (10.2)
ISI 60	57.6 (18.4)	59.4 (19.8)	83.6 (18.6)	81.4 (14.6)
ISI 120	44.1 (13.1)	42.4 (17.1)	65.7 (15.4)	69.2 (16.5)
Latency (ms)				
ASR	62.1 (5.6)	67.8 (7.4)	55.4 (5.9)	58.4 (7.3)
ISI 30	50.1 (8.3)	53.1 (6.8)	51.7 (7.6)	53.1 (7.1)
ISI 60	59.8 (9.6)	57.6 (6.7)	51.8 (6.3)	52.9 (7.1)
ISI 120	61.7 (5.5)	64.2 (6.8)	54.9 (5.6)	55.1 (5.1)

Data are reported as means (SD)

In general, athletes also showed a shorter startle reaction time, or latency, when compared to that from controls ($p < 0.05$; Table 1B and Fig. 2d). Except for the prepulse-to-pulse interval of 30 ms, it took less time for athletes to develop a startle reaction than it did for controls.

Sensorimotor gating mechanisms are correlated to scores in physical tests

We found a strong positive correlation between the endomorph index and the amplitude of the startle reflex ($p < 0.01$; Table 2A), meaning the higher the fat mass in a participant's body composition, the more likely to elicit higher startle reflex amplitude. We also found a positive correlation between the habituation percentage and the ectomorph index ($p < 0.01$; Table 2A; Fig. 3b), or in other words, the higher the amplitude of the reflex at the end of the session (block 3 vs. block 1), the less linear the body composition is. Our results showed control males keep on averaging high startle amplitude during the session.

In the same line, we found strong correlations between both the hand grip strength and the flexibility tests and the amplitude of the startle reflex ($p < 0.01$; Table 2A; Fig. 3d). Participants scoring better results in both physical tests were more likely to peak lower startle amplitude. Supporting the same idea, we also found correlations between the strength and flexibility tests and the percentage of inhibition of the startle reflex at all ISIs ($p < 0.01$; Table 2B; Fig. 3a). Athletes exhibiting higher PPI values compared to their counterparts (indirect attention driven on a specific stimulus among distracters) performed better than controls during the strength and flexibility tests, whereas scoring lower in those physical tests was related to lower inhibition values.

We also found noteworthy correlations between all the latencies for the startle reflex and the values of the Bosco jump tests ($p < 0.01$; Table 2C; Fig. 3c). The shorter the

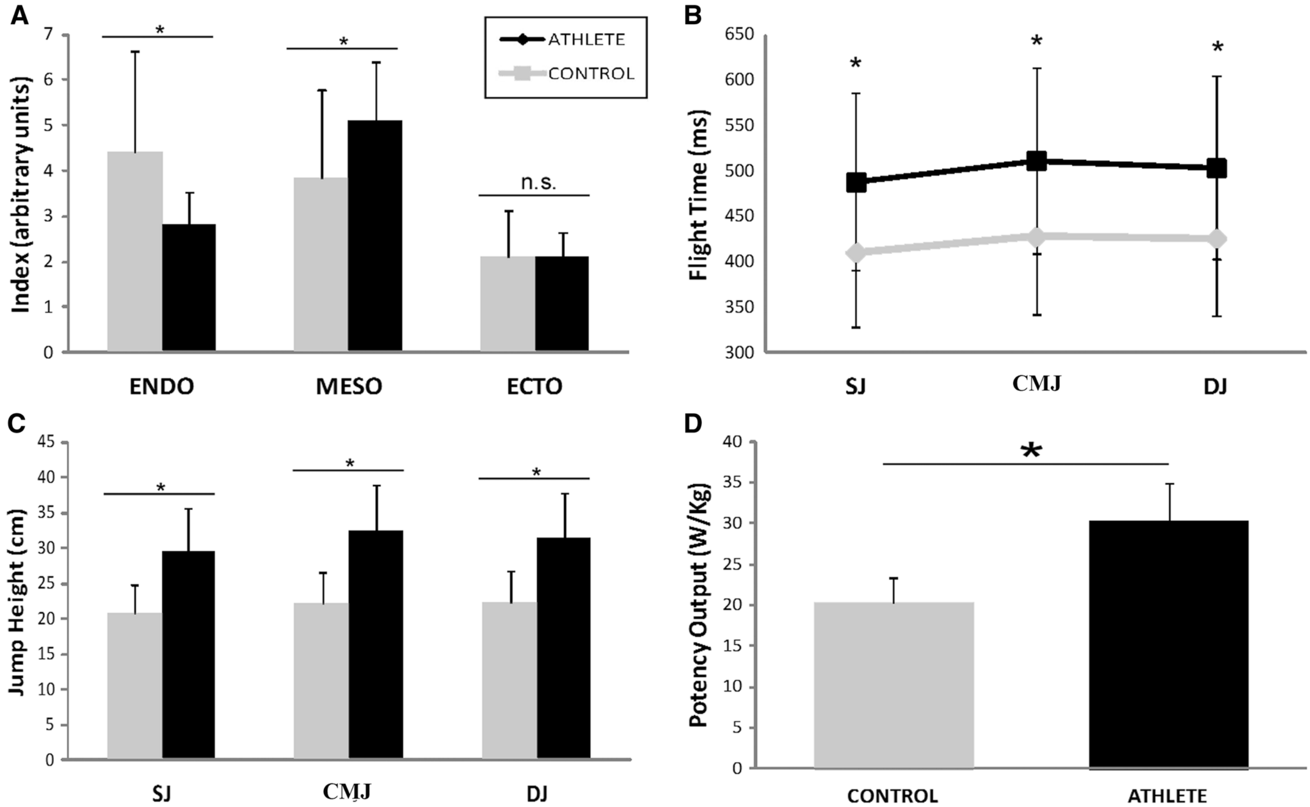

Fig. 1 Results of physical conditioning tests by experimental groups. **a** Somatotype. Notice how athletes tended to show higher mesomorph index while lower endomorph index compared to controls. **b** Flight time of the three Bosco jump tests. Notice how athletes averaged higher values on all the tests compared to controls. **c** Jump height of the three Bosco jump tests. Notice how athletes averaged higher values on all the tests compared to controls. **d** Potency output of the drop jump test. Notice how athletes averaged higher values on all the tests compared to controls as well. *SJ* squat jump, *CMJ* counter-movement jump, *DJ* drop jump. $^*p < 0.05$

reaction time to the acoustic stimuli (whether pulse-alone or prepulse-to-pulse when ISI = 30, 60, or 120 ms) the more likely it is to exhibit higher scores for flight time, jump height and potency output during the jump tests. In other words, participants exhibiting higher jump results also reacted faster to the acoustic stimuli, and this did not occur in the control group.

Taking into account all the data, not only did athletes perform better than controls during the physical tests but they also exhibited better results during the startle reflex/sensorimotor gating session, suggesting higher degree of neurological processes for filtering out redundant or unnecessary stimuli in the brain from all possible environmental stimuli, and they also had a more efficient muscle control of their bodies as well.

Discussion

Athletes scored better results on the physical tests compared to controls, as expected. They also exhibited lower startle amplitude, while maintaining higher prepulse inhibition values compared to those from controls. They reacted faster to the acoustic stimuli, and sex-related differences were erased. Even though reflexes are involuntary basic movements, athletic conditioning could have potentially modified them to be triggered in a faster fashion.

One possible interpretation of these results may be that improved startle reflex and attentional modulation of PPI do not drive or lead to better scores in physical conditioning tests, but rather athletes possessed better reflexes per se to begin with. This interpretation is plausible, although this study was not conceived to give full answer to this question; otherwise a longitudinal (rather than a cross-sectional) study should have been employed. Another interpretation may be that physical conditioning through daily training sessions for years could be driving these plastic changes in the sensorimotor gating circuitry. Our data may show the first evidence in this line, although this study should be taken as an exploratory one to stimulate research in the field in any case. Several questions were indeed derived and further experiments should be carried out, such as a longitudinal study to find out whether

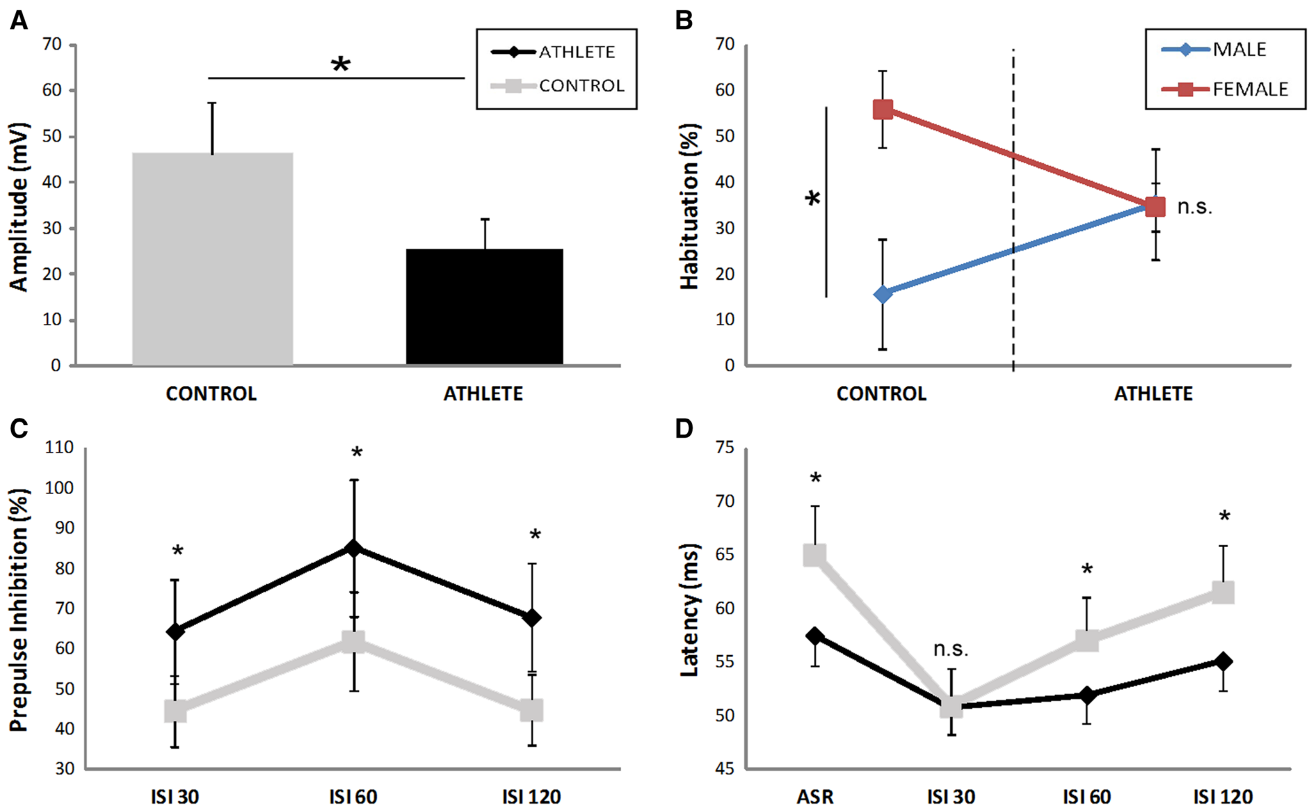

Fig. 2 Results of the startle reflex parameters by experimental groups. **a** Amplitude of the acoustic startle reflex. Notice how athletes showed a lower startle amplitude compared to controls. **b** Percentage of habituation inter-gender. In the control group, we found a significant difference between males and females, but in the athlete group, interestingly, that difference disappeared, with males and females showing similar values. **c** Percentage of prepulse inhibition when inter-stimulus interval (ISI) is 30, 60, or 120 ms. Notice how athletes averaged higher inhibition values compared to controls. **d** Latency of the responses. Notice how, in general, athletes reacted faster to the acoustic stimuli compared to controls. *ASR* acoustic startle reflex. *$p<0.05$

correlations between improved reflexes/attentional processes and physical conditioning scores are causative.

A reflex is an involuntary muscle reaction to certain types of stimulation; certain sensations or movements produce specific muscular responses. Reflexes can be learned but require many years of experience and practice to form part of the response repertoire of an athlete (Taube et al. 2007). Practice sessions to improve the ability of the performer to develop a reflex behavior could be organized on a daily basis, even in the elderly (Granacher et al. 2006).

The startle reflex and PPI are being increasingly studied to understand the neurobiology of information processing in psychiatric patients compared with healthy subjects (Powell et al. 2012), but nothing similar had been done in athletes yet. Structures involved in the PPI include inferior and superior colliculi, pedunculopontine tegmental and laterodorsal nuclei, reticulated portion of the substantia nigra, and the caudal pontine reticular nucleus (Swerdlow et al. 2005; Davis and Gendelman 1977). This provides an anatomical reference in which plasticity and re-structuring mechanisms may take place, highlighting these circuits as good targets in which permanent biological adaptations during regular training may occur (Costa et al. 2004; Luft et al. 2008; Roche et al. 2003).

Athletes in this study exhibited lower startle amplitude, shorter latencies and higher prepulse inhibition levels. This could suggest that athletes focused their attention more efficiently to a given stimulus, blocking away other distracters in a more effectively fashion. This could be explained by plasticity in the sensorimotor gating circuits specifically. In professional competition, separating the internal environment from external stimuli (distracters) is a crucial action for athletes to reach success. Thus, attenuation (or inhibition) of the startle response may be a good biological adaptation to deliver favorable results.

We found a positive correlation between the endomorph index and the amplitude of the startle reflex meaning the higher the fat mass in a participant's body composition, the more likely to peak a higher startle amplitude. This could suggest that there is a less effective motor control when the percentage of body fat is higher, even for the nature of involuntary movement, like a reflex. These findings, along

Table 2 Correlations by group between results of physical conditioning tests and startle reflex parameters

(A)	ASR		
	Amplitude	Latency	Habituation
Anthropometric index			
Endo			
Pearson	0.792		
p value (bil)	0.01		
n	149		
Meso			
Pearson			
p value (bil)			
n			
Ecto			
Pearson			0.746
Sig. (bil.)			0.01
n			149
Flight time			
SJ			
Pearson		−0.877	
p value (bil)		0.01	
n		149	
CMJ			
Pearson		−0.724	
p value (bil)		0.001	
n		149	
DJ			
Pearson		−0.642	
p value (bil)		0.001	
n		149	
Jump height			
SJ			
Pearson		−0.809	
p value (bil)		0.001	
n		149	
CMJ			
Pearson		−0.887	
p value (bil)		0.01	
n		149	
DJ			
Pearson		−0.636	
p value (bil)		0.001	
n		149	
Potency			
Pearson		−0.602	
p value (bil)		0.001	
n		149	
Strength			
Pearson	−0.724		
p value (bil)	0.001		
n	149		

Table 2 (continued)

(A)	ASR		
	Amplitude	Latency	Habituation
Flexibility			
Pearson	−0.802		
p value (bil)	0.001		
n	149		

(B)	PPI		
	ISI 30	ISI 60	ISI 120
Strength			
Pearson	0.715	0.641	0.711
p value (bil)	0.001	0.001	0.001
n	149	149	149
Flexibility			
Pearson	0.523	0.763	0.628
p value (bil)	0.001	0.001	0.001
n	149	149	149

(C)	Latency		
	ISI 30	ISI 60	ISI 120
Flight time			
SJ			
Pearson	−0.614	−0.649	−0.71
p value (bil)	0.01	0.01	0.001
n	149	149	149
CMJ			
Pearson	−0.598	−0.692	−0.519
p value (bil)	0.05	0.01	0.001
n	149	149	149
DJ			
Pearson	−0.678	−0.703	−0.777
p value (bil)	0.001	0.001	0.01
n	149	149	149
Jump height			
SJ			
Pearson	−0.795	−0.631	−0.772
p value (bil)	0.01	0.001	0.01
n	149	149	149
CMJ			
Pearson	−0.694	−0.419	−0.681
p value (bil)	0.01	0.05	0.01
n	149	149	149
DJ			
Pearson	−0.571	−0.688	−0.914
p value (bil)	0.05	0.01	0.01
n	149	149	149
Potency			
Pearson	−0.71	−0.815	−0.649
p value (bil)	0.01	0.01	0.01
n	149	149	149

Only statistically significant values are shown

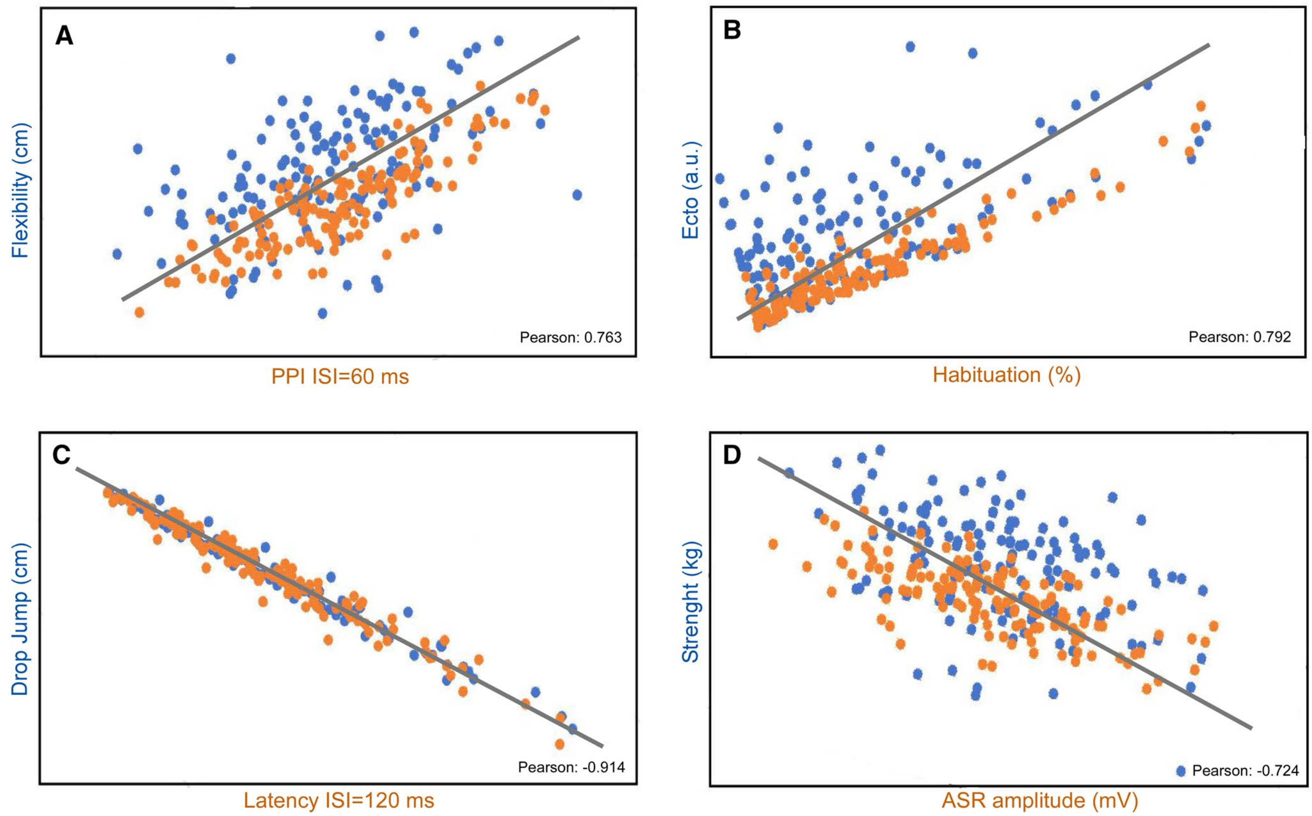

Fig. 3 Representative examples of correlations between the startle reflex parameters and the physical conditioning tests. **a** Scatter plot representation of the flexibility sit-and-reach test and the percentage of prepulse inhibition when ISI = 60 ms. **b** Scatter plot representation of the ectomorph index and the percentage of habituation. **c** Scatter plot representation of the drop jump test height and the latency of prepulse inhibition when ISI = 120 ms. **d** Scatter plot representation of the grip strength test and the amplitude of the acoustic startle reflex

with those of previous studies, may suggest that athletes have a more effective motor control compared to untrained counterparts. The ASR improves (shortens) reaction time of a planned movement without perturbing the planned motion, such as would be desired during the start of a race since runners know the gun is about to fire and they plan on running (Valls-Solé 2012). Habituation is one of the fundamental aspects of information processing that serves to focus attentional mechanisms on relevant environmental cues, as well as being the simplest form of learning (Geyer and Braff 1982). We found that among controls, females displayed significantly higher habituation than males; however, in athletes, habituation tended to converge not showing any significant sex-related difference. In other words, control females had lower responses at the end of the startle measurement session compared to those from the beginning, whereas control males tended to have the same amplitude at the beginning and at the end of the session. However, at the end of the session, both male and female athletes responded with nearly half of the amplitude compared to the initial response. These two facts suggest that there may be a sexual dimorphism that allowed females to adapt better than males or males to keep on responding to the stimulus in an intense way (attentional modulation of PPI off the stimulus in females vs. on the stimulus for males). Neural plasticity could be causing these adaptations following athletic purpose as well.

There is a controversy in the literature about sex-related startle amplitude; some have pointed out males peak a significantly smaller amplitude when compared to females (Kofler et al. 2001), whereas others found no differences (Ludewig et al. 2003). Nonetheless, varying results of the startle magnitudes could be explained by divergent estrogen concentration in the blood throughout the menstrual cycle due to modulation of the dopaminergic system (Jovanovic et al. 2004). These differences were not observed in our study in females since we carried out the measurements during the same cycle phase.

Startle reflex measurement in athletes is a relatively unexplored field. It would be of potential interest to study whether habituation and PPI are disrupted in selective attention tests or during orienting responses. In addition, expanding the number of parameters studied and the number and nature of the participants in different sport disciplines would be important to assess the extent of the brain plastic changes in sensorimotor gating circuitry due to the regular practice of a sport modality. Furthermore, measurement of the startle reflex/PPI/habituation may be an objective test to evaluate the neurophysiological profile of an athlete, as well as their evolution when submitted to specific modes of training such as strength, endurance, or speed.

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Compliance with ethical standards

Conflict of interest The authors declare no competing conflicts of interest, financial or otherwise.

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