Effects of Repeated-Sprint Training in Hypoxia on Tennis-Specific Performance in Well-Trained Players

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ABSTRACT

This study examined the physiological, physical and technical responses to repeated-sprint training in normobaric hypoxia [RSH, inspired fraction of oxygen (FiO_2) 14.5 %] vs. normoxia (RSN, FiO_2 20.9 %). Within 12 days, eighteen well-trained tennis players (RSH, n = 9 vs. RSN, n = 9) completed five specific repeated-sprint sessions that consisted of four sets of 5 maximal shuttle-run sprints. Testing sessions included repeated-sprint ability and Test to Exhaustion Specific to Tennis (TEST). TEST's maximal duration to exhaustion and time to attain the 'onset of blood lactate accumulation' at $4\,mMol.L^{-1}$ (OBLA) improvements were significantly higher in RSH compared to RSN. Change in time to attain OBLA was concomitant with observations similar in time to the second ventilatory threshold. Significant interaction (P = 0.003) was found for ball accuracy with greater increase in RSH (+ 13.8 %, P = 0.013) vs. RSN (–4.6 %, P = 0.15). A correlation (r = 0.59, P < 0.001) was observed between change in ball accuracy and TEST's time to exhaustion. Greater improvement in some tennis-specific physical and technical parameters was observed after only 5 sessions of RSH vs. RSN in well-trained tennis players.

Introduction

In tennis, players must possess well-developed technical and tactical skills and high fitness in order to cope with the physical demands of the game in competition [23, 38]. It has been suggested that competitive tennis players need a mixture of fitness qualities such as speed, agility, repeated-sprint ability (RSA), and power, combined with well-developed aerobic fitness to achieve high levels of performance [19]. Tennis competition has average points lasting less than 10 s, with rest periods of approximately 20 s between points and 90 s after every second game [37]. Thus, the training of competitive tennis players should focus on improving their ability to repeatedly perform high-intensity efforts and to recover rapidly between them [45]. For these reasons, physical exercise aiming to enhance both aerobic and anaerobic performance should be part of any tennis

training program. Because training time optimization is paramount due to intensive competition calendars, providing an ideal conditioning design is a significant challenge.

Improvement in fitness such as sprinting speed is generally thought to be training-specific, with specially designed speed programs shown to improve neuromuscular qualities [11, 50], whereas repeated-sprint training programs have shown higher impact on single and repeated shuttle sprint performance [10, 20]. Different studies have explored the effects of repeated-sprint training in hypoxia (RSH) on high-intensity intermittent sport performance [7, 22, 27] and its putative benefits compared with similar training in normoxia (RSN) [17], but none specifically investigated tennis-related performance. RSH appears as a promising training strategy in racquet sports to improve match-related performance [16]. With RSH, enhanced blood perfusion levels due to the compensatory vasodilation in response to the decreased oxygen content and improved behavior of fast-twitch fibers are expected compared with RSN [13, 17, 18]. Furthermore, exercise prescription theory dictates that exercise training prescription should be as specific as possible to facilitate appropriate physiological adaptations [47]. Therefore, repeated-sprint training protocols should be based on work-to-rest ratios of actual RSA while playing the sport (adding hypoxia to this training serves to induce a larger metabolic stimulus resulting in greater adaptation). RSA describes the aptitude of an athlete to recover and maintain maximal effort during subsequent sprints. Although debated [48], this attribute is considered important to various intermittent activities (e. g., rugby, soccer, Australian football, ice/field hockey, tennis) [2].

RSH to improve endurance performance has also resulted in conflicting results. Galvin et al. [21] found significantly improved endurance performance whereas Hamlin et al. [28] did not using the same test (i. e., Yo-Yo intermittent recovery test level 1) after RSH in rugby players. More recently, Jones et al. [33] reported significantly faster final running velocities in female field-hockey players during a 30–15 intermittent field test after RSH compared to control conditions, whereas others have found little effect on 20 m shuttle run performance post-RSH in Australian football athletes [26]. The effect of a repeat-sprint training on subsequent specific test to exhaustion has not been researched in tennis to date. Although racket sports can potentially benefit from physiological improvements by using RSH, there is a paucity of research that has identified its impact on tennis-specific performance.

Using a double-blind controlled design, this study aimed to investigate the effects of a tennis-specific RSH vs. RSN in well-trained players. Based on the effect of RSH studies [17, 21, 22], we hypothesized that RSH would provide greater gains on RSA-related parameters than RSN. We also assumed that RSH would induce better resistance to fatigue in tennis-specific intermittent tasks, observable mainly near exhaustion.

Methods

Participants

The sample size was estimated gauging acceptable precision or confidence intervals using the approach developed for magnitude-based inferences [30]. Based on the assumption that a between-group difference in mean RSA time of $1.2 \pm 1.1\%$ is meaningful [9, 12] and considering a within-subject SD (typical error) of 0.8 % [32], a sample size of > 7 participants per group would provide maximal chances of 0.5 and 25 % of type I and type II errors, respectively. Thus, 20 competitive tennis players (16 males and 4 females) volunteered to participate in the study. They were all well-trained [i. e., international tennis number (ITN): 1 (elite) to 2 (advanced player)]. Participants were first contacted by email to inform them of the project. The information was disseminated to a list of players with the help of tennis coaches living in Paris and the surrounding region. The study was approved by the local ethical committees (French National Conference of Research Ethics Committees; Dijon), performed in accordance with the ethical standards reported [29], and conformed to the recommendations of the Declaration of Helsinki. Participants gave their written informed consent after having been fully informed about the experimental procedure. Inclusion criteria were (i) age between 18 and 35 years old; (ii) a ranking allowing participation in a national team championship; and (iii) no previous experience of any exposure to normobaric hypoxia. Exclusion criteria were any history of altitude-related sickness or health risks that would have compromised the participant's safety during the experiment. The athletes' availability for an adapted 12-day microcycle had been considered to make their participation feasible.
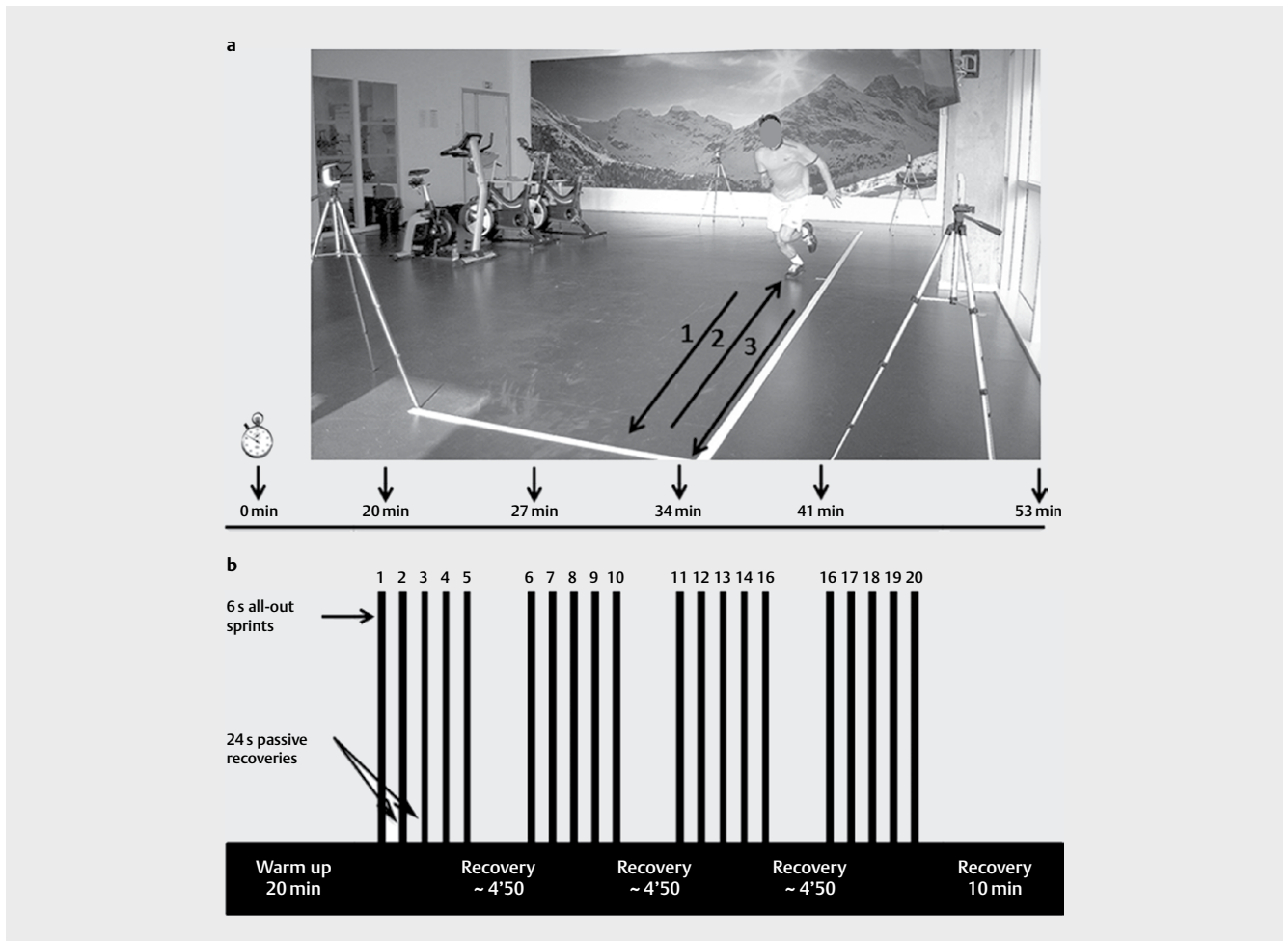
Experimental design

Group assignments were blinded both to the participants and all investigators (except the principal investigator). Participants were told that they were all training in normobaric hypoxia but had no accurate information about the simulated altitude levels set in the hypoxic room. According to their competitive tennis level (known from their national ranking), they were matched into pairs and then randomly assigned into the following training groups: RSH (n = 10; 8 males and 2 females; age 24.8 ± 5.1 years; weight 68.4 ± 11.2 kg; height 1.79 ± 0.07 m) or RSN (n = 10; 8 males and 2 females; age 22.8 ± 4.1 years; weight 77.5 ± 10.7 kg; height 1.85 ± 0.07 m). During the study, 2 female participants (1 from each group) were withdrawn due to injury. To determine the efficacy of the blinding process, participants were requested to indicate on a Likert scale (100 m marks from 0 to 4000 m) the expected altitude level after each training session.

The experimental protocol included one testing session performed in normoxia before (Pre-) and after (Post-) a 12-day RSH/RSN training period (5 sessions respectively). Days 1, 3, 5, 9 and 11 concerned RSH; days 2, 4, 8, 10 and 12 concerned RSN. The time of day for testing was controlled and matched both within and between groups.

Specific training sessions

All specific training sessions were performed in an air-conditioned (21 °C, ~55 % relative humidity) normobaric hypoxic room (size 15.04 m × 8.54 m; b-Cat®, Tiel, Netherlands) (▶ **Fig. 1**). For RSH, the inspired fraction of oxygen (FiO$_2$) was set at 14.5 %, equivalent to ~3000 m, shown to not reduce peak power output during repeated-sprint efforts [27]. For careful blinding purpose, the hypox-

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▶ **Fig. 1** Hypoxic room fitted for repeated shuttle-run maximal sprint training **a** and description of a typical training session **b**.

ic system was also switched on during RSN sessions (FiO_2 20.9 % equivalent to ~200 m) in order to create similar background noise.

Specific aerobic capacity

Participants' physical performance was assessed using a testing battery performed in normoxia in a well-ventilated room at a constant temperature of ~21 °C and ~55 % relative humidity. Pre- and Post-testing sessions were completed in the exact same sequence: (i) 20 min of standardized warm-up including athletic and acceleration drills; (ii), RSA test; and (iii) after 40 min of rest, an incremental field test up to exhaustion [i. e., the so-called 'test to exhaustion specific to tennis' (TEST)] [4]. Participants were asked to arrive at the testing sessions in a rested and hydrated state (at least 3 h after a meal and having avoided strenuous training in the preceding 24 h).

TEST [4, 5] was selected to assess participants' high-intensity intermittent performance. Briefly, TEST consisted of hitting balls thrown by a 'HighTOF' ball machine (Echouboulains, France) at constant velocity [6], alternating forehand and backhand strokes. TEST has been previously reported to be relevant for tennis field testing and training purposes [4]. The TEST started with a 2-min 'habituation'/warm-up phase where a ball frequency (BF) of 16 shots.min^{-1} with balls thrown to the central area of the court (minimal lateral displacement) was adopted. After 1 min of passive rest (quiet

standing), the first TEST stage began with a BF of 10 shots.min^{-1}, thereafter increased by + 2 shots.min^{-1} every min until the stage corresponding to a BF of 22 shots.min^{-1}. Thereafter, the increment in BF was set at + 1 shots.min^{-1} until exhaustion [4]. After each 1-min stage, a 30-s passive recovery break (quiet standing) was implemented.

Participants had to hit balls cross-court in a prescribed pattern. Slice strokes were not allowed because of their potential influence on ball positioning and therefore on TEST performance and associated physiological responses. Participants were asked to perform TEST just as they would during official competitions. While they can visualize the areas in which they were aiming to play, they were told to "hit the ball with the best possible speed/accuracy ratio". Further, stroke involvement was motivated by 'live' (immediate) feedback. Based on previous results reporting range of ball velocities (BV) between 86 and 120 km.h^{-1} (sub-maximum to maximum strokes), BV < 80 km.h^{-1} was chosen as the criteria for unsuccessful BV and ball accuracy (BA) [i. e., 50 % of balls landing outside the target zone], in accordance with the results obtained with elite players [5] at the end of each stage completed.

TEST ended with participants' voluntary exhaustion or was stopped by the investigators if: (i) participants felt exhausted or failed to reach and hit the ball twice in a row, or (ii) they were no longer able to per-

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form strokes with an acceptable execution technique and BV/BA declined, as determined by one experienced tennis national coach. Specifically, participants were given a warning the first time they disrespected the rules, and were stopped on the second warning. TEST's performance was measured as total time to exhaustion (TTE).

Evaluation of groundstroke performance

During TEST, groundstroke production was assessed via two main variables: BV and BA. BV ($km.h^{-1}$) was measured with the Play-Sight® system (PlaySight Interactive, Ltd., Kokhav Ya'ir, Israel) which was approved by the International Tennis Federation (ITF) as a tennis player analysis technology for all ITF-sanctioned tournaments. For instance, correlations were reported between competitive level and BA (r = 0.61) [1] or stroke ratings (i. e., a surrogate of BA) (r = 0.94) [49]. BV and BA data were averaged for each TEST stage. Finally, because BV and BA better reflect the overall stroke precision in tennis when combined, the tennis performance (TP index) [5] was calculated as the product of these two variables. Consequently, if one factor was unchanged (e. g., BV) and the other one increased (e. g., BA), TP followed the pattern of BA. To determine the mean of each parameter measured over the entire TEST, calculation was based on the values obtained for each TEST stage.

Physiological measurements

During TEST, expired air was analyzed (breath-by-breath measurements) for oxygen consumption ($\dot{V}O_2$) using a portable gas analyzer (Metamax II CPX system, Cortex®, Leipzig, Germany). Gas and volume calibration of the measurement device was performed before each test according to manufacturer's instructions. Heart rate (HR) was checked continuously (Suunto Ambit2®, Vantaa, Finland). Furthermore, 25 μL capillary blood samples were collected from fingertip and analyzed for blood lactate concentration (LT-1730; Arkray®, Kyoto, Japan) at the baseline, during TEST (i. e., during the 30-s recovery periods after every stage until a value of 4 mMol.L^{-1} was obtained and thereafter every 2 stages), and 15 s after TEST exhaustion to assess maximal blood lactate concentration ($[La]_{max}$).

Detection of the second ventilatory threshold (VT2) was done by analyzing the points of change in slope (breaks in linearity) of ventilatory parameters [24, 52]. VT2 was determined using the criteria of an increase in both $\dot{V}E/\dot{V}O_2$ and $\dot{V}E/\dot{V}CO_2$[15]. VT2 assessment was made by visual inspection of graphs of time plotted against each relevant respiratory variable measured during testing. All visual inspections were carried out by two experienced exercise physiologists. The results were then compared and averaged. The difference in the individual determinations of VT2 was < 3 %.

The onset of blood lactate accumulation (OBLA), defined as the exercise intensity corresponding to 4 mMol.L^{-1} blood lactate concentration was also determined. By plotting each subject's blood lactate concentration against time of TEST completion and visually connecting the data points, we estimated the time to attain OBLA. This physiological variable has been shown to be a good predictor of endurance performance [36].

Repeated-sprint ability

The RSA test consisted of ten 20-m sprints departing every 20 s performed in a back and forth format. Participants had to complete the distance in a straight line as fast as possible. Sprint times were measured to the nearest 0.01 s using photocells connected to an electronic timer (Witty, Microgate, Bolzano, Italy). During the first sprint, they were required to achieve at least 95 % of their criterion score (i. e., defined as the best of three single 20-m sprints interspersed with 2 min of recovery) as a check of any pacing strategy. All of the athletes satisfied this criterion score. Three scores were calculated during the RSA test: best sprint time (RSA_{best}), cumulated sprint time (RSA_{TT}) and percentage of sprint decrement calculated as follows (S_{dec}) [25]: $[(RSA_{TT})/(RSA_{best} \times 10) - 1] \times 100$ [25].

Statistical analysis

All data are expressed as the mean ± SD. Mean difference for change between Pre- and Post-training (in %), and 95 % confidence interval (95 % CI) were reported when appropriate. Changes in performance and physiological variables were compared between Pre- and Post-training using paired sample t-test. For each t-test, effect sizes were calculated with Cohen's d (d) with the following criteria: a d of < 0.2 is classified as a trivial, 0.2 to 0.4 as a small, 0.5 to 0.7 as a moderate and > 0.8 as a large effect. Mixed ANOVA with repeated measures [Time (Pre- vs. Post-) × Condition (RSH vs. RSN)] analysis was applied to compare performance and physiological variables. Pairwise differences were identified using the Tukey post hoc analysis procedure adjusted for multiple comparisons. ANOVA assumptions were verified before all statistical analyses. For each mixed ANOVA, partial eta squared (η^2) was calculated as measures of effect size. Values of 0.01, 0.06, and above 0.14 were considered as small, medium, and large, respectively. Pearson's product moment correlation analysis was employed to determine the relationships between technical parameters and TTE-relative changes. The following criteria were adopted to interpret the magnitude of r: < 0.1, trivial; 0.1–0.3, small; 0.3–0.5, moderate; 0.5–0.7, large; 0.7–0.9, very large; and 0.9–1.0, almost perfect. The null hypothesis was rejected at P < 0.05. Statistical analysis was performed using Sigmaplot 3.5 software (Systat Software, San Jose, CA, USA).

Results

Efficacy of the blinding procedure

Participants were not able to identify the group they were assigned to [i. e., they indicated similar simulated altitude: 2663 m (95 % CI: 2316 to 3010 m) and 2422 m (95 % CI: 1849 to 2995 m) for RSH and RSN, respectively].

Aerobic capacity

The physiological responses to the on-court endurance test are summarized in ▶ Table 1. TTE and time to VT2 increased from Pre- to Post-training for RSH (+ 14.6 %, P < 0.01, d = 1.04 and + 23.6 %, P < 0.01, d = 1.16 respectively) and RSN (+ 7.9 %, P < 0.01, d = 0.55 and + 10.9 %, P < 0.01, d = 1.01). Significant interactions between time and condition were found for TTE (P < 0.01, η^2 = 0.01) and time to VT2 (P = 0.02, η^2 = 0.03) (▶ Table 1). No significant interactions were found for the rest of outcome variables analyzed.

Change in time to attain OBLA after the training period was significantly higher in RSH (+ 40.1 %, P = 0.03, d = 1.15) than in RSN (+ 12.3 %, P = 0.24, d = 0.57).

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▶ **Table 1** Comparison of performance (TTE) and physiological ($\dot{V}O_{2max}$, HR_{max}, $\dot{V}E_{max}$, $[La^-]_{max}$, time to OBLA, time to VT2) variables between RSH and RSN groups.

	RSH			RSN			ANOVA (η^2)		
	Pre-	Post-	Difference (%)	Pre-	Post-	Difference (%)	Time	Condition	Interaction (Time-Condition)
TTE (s)	592 [533-650]	679 [609-749]	**14.6 [11.8-17.4]** ***	581 [521-641]	627 [559-695]	7.9 [4.0-11.8] **	**<0.001 (0.14)**	0.425 (0.03)	**0.007 (0.01)**
$\dot{V}O_{2max}$ (mL·min⁻¹·kg⁻¹)	58.1 [53.2-63.0]	59.0 [54.6-63.4]	1.6 [-1.4-4.6]	52.9 [50.1-55.7]	52.1 [48.1-56.1]	-1.7 [-2.4-5.8]	0.994 (0.0)	**0.002 (0.15)**	0.636 (0.003)
HR_{max} (beats·min⁻¹)	195 [188-202]	193 [185-201]	-0.8 [-2.0-0.4]	196 [191-201]	194 [188-200]	-1.1 [-2.4-0.2]	0.528 (0.002)	0.803 (0.014)	0.924 (0.04)
$\dot{V}E_{max}$ (L·min⁻¹)	134 [118-150]	132 [117-147]	-1.3 [-2.9-5.5]	144 [133-155]	146 [134-158]	1.4 [-3.3-6.1]	0.977 (0.0)	**0.037 (0.13)**	0.739 (0.0)
$[La]_{max}$ (mMoles·L⁻¹)	12.0 [8.7-15.3]	11.8 [7.6-16.0]	-0.8 [-23.7-22.1]	11.0 [8.8-13.2]	10.2 [8.9-11.5]	-3.4 [-25.7-18.9]	0.682 (0.003)	0.318 (0.016)	0.785 (0.001)
Time to OBLA (s)	345 [271-419]	479 [375-583]	**40.1 [25.6-54.6]** *	374 [303-445]	428 [410-446]	15.6 [7.8-23.4]	0.012 (0.05)	0.755 (0.0)	0.269 (0.01)
Time to VT2 (s)	373 [323-422]	460 [395-525]	**23.6 [14.9-32.3]** ***	386 [359-419]	426 [408-463]	10.9 [4.4-17.4] **	**<0.001 (0.21)**	0.718 (0.05)	**0.018 (0.03)**

Values are mean [95% CI]. Significant differences between Pre- and Post- absolute data (* p<0.05, ** p<0.01, *** p<0.001) are in bold. Statistical analysis is based on absolute values. Partial eta-squared (η^2) was calculated as measures of effect size for mixed ANOVA; TTE=total time to exhaustion; $\dot{V}O_{2max}$=maximal oxygen uptake; HR_{max}=maximal oxygen uptake; $\dot{V}E_{max}$=maximal ventilation; $[La^-]_{max}$=maximal lactate concentration; OBLA=onset of blood lactate accumulation, at 4 mMoles.L⁻¹; VT2=second ventilatory threshold..

Technical parameters

In reference to Pre-, BV did not significantly improve (+ 0.2 %, 95 % CI: −3.3 to 3.7 %, P = 0.99, d = 0 for RSH, and + 2.3 %, 95 % CI: 0.5 to 4.1 %, P = 0.2, d = 0.27 for RSN, respectively) throughout the whole test (▶ **Fig. 2b**) and at 100 % $\dot{V}O_{2max}$ (−4.6 %, 95 % CI: −11.9 to 2.7 %, P = 0.16, d = 0.41 vs. −0.6 %, 95 % CI: −4.8 to 3.6 %, P = 0.65, d = 0.08).

Significant interactions were found for BA (P < 0.01, η^2 = 0.08) and TP (P = 0.02, η^2 = 0.04) (▶ **Fig. 2a**, **2c**). Although no changes were observed in RSN (−4.6 %, 95 % CI: −11.6 to 2.4 %, P = 0.15, d = 0.34 and −2.1 %, 95 % CI: −10.2 to 6 %, P = 0.44, d = 0.19 for BA and TP, respectively), BA and TP significantly increased from Pre- to Post- in RSH (+ 13.8 %, 95 % CI: 4.0 to 23.6 %, P = 0.01, d = 0.87, and + 13.8 %, 95 % CI: 2.7 to 24.9 %, P = 0.03, d = 0.56). Similarly, BA_{max} and TP_{max} at 100 % $\dot{V}O_{2max}$ were further increased in RSH (+ 33.6 %, 95 % CI: 4.9 to 62.3 %, P = 0.01, d = 1.00 and + 28.0 %, 95 % CI: −41.0 to 60.1 %, P = 0.04, d = 0.65) vs. RSN (+ 5.1 %, 95 % CI: −13.2 to −23.4 %, P = 0.59, d = 0.19 and + 3.7 %, 95 % CI: −13.5 to 20.9 %, P = 0.70, d = 0.13).

Significant small to moderate correlations were found between TP and TTE (r = 0.48, P = 0.04) (▶ **Fig. 3a**), and between changes in BA throughout the whole test and TTE (r = 0.59, P = 0.01) (▶ **Fig. 3b**).
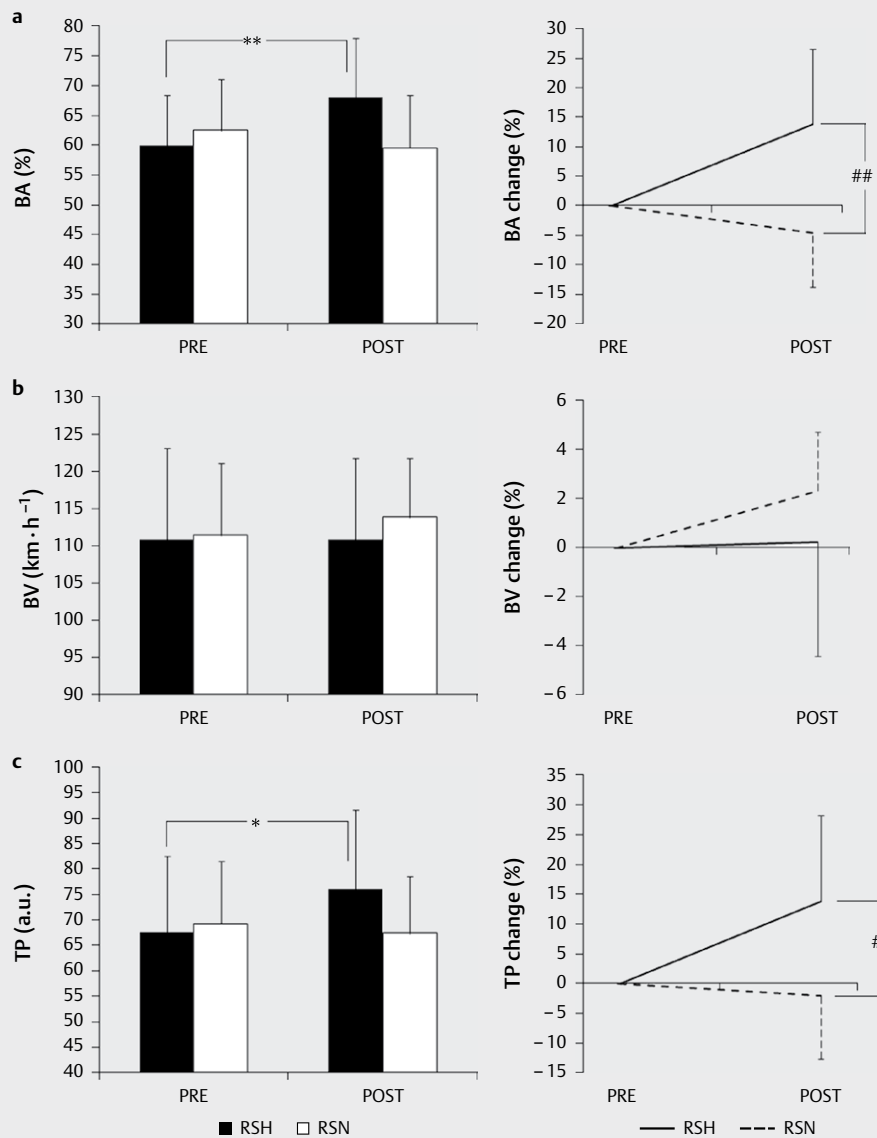
Sprint-performance parameters

RSA_{Best} and RSA_{TT} were significantly different between groups (condition effect). Pre- and Post-test performance results are summarized in ▶ **Table 2**. Concerning the effect of training, evolution in RSA performance remained unchanged after intervention in both RSH and RSN (interaction in ▶ **Table 2**).

Discussion

To the best of our knowledge, this is the first study involving well-trained to elite tennis players in hypoxic training. In partial agreement with our initial hypothesis, the main finding of this study is that a 12-day RSH period induced larger benefits in tennis-specific physical/physiological and technical parameters than RSN. Collectively, these findings indicate that RSH is an effective intervention to develop tennis-specific capabilities in well-trained tennis players.

Physiological measurements

In the present study, we found that RSH delayed fatigue during TEST and increased TTE with a two-fold higher improvement compared with RSN. This finding is comparable to some previous RSH studies [17, 18]. For instance, Galvin et al. [21] recently showed a 19 % additional benefit of RSH compared with RSN in rugby players' high-intensity intermittent running performance (i. e., Yo-Yo intermittent recovery test level 1). Substantially higher performance improvement was shown as practically relevant because Yo-Yo intermittent recovery tests correlate with physical performance and the amount of high-intensity running in several intermittent sports [21]. RSH also induced a significant increase in TTE during an ergocycle test, whereas no significant change was observed in RSN [34]. Fatigue development was also delayed after RSH during a repeated-cycling sprint test performed until exhaustion [17]. Of interest is that this beneficial effect of RSH on TTE was larger in upper-body exercise (i. e., double-poling sprint training in hypoxia) [18]. Likewise, improved specific test with ball hitting per-

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▶ **Fig. 2** Comparison within and between type of intervention (RSH vs. RSN) and changes in ball velocity (BV) **a**, ball accuracy (BA) **b** and tennis performance index (TP) **c**. * P<0.05, significantly different from Pre-. * * P<0.01, significantly different from Pre-. * * * P<0.001, significantly different from Pre-. #P<0.05, significant time×condition interaction. ##P<0.01, significant time×condition interaction. .

formance is transferable to tennis performance [2]. However, small changes were observed when using a continuous incremental test, indirect estimated $\dot{V}O_{2max}$ and TTE as recently mentioned [8], thereby indicating that sport-specific aerobic field-based protocol may be preferred over laboratory-based continuous protocols due to an increase in ecological validity for performance measurement. For example, Brocherie et al. (2015) [7] reported similar improvement in maximal aerobic velocity for either RSH or RSN using a modified version of the University of Montreal track test.

The increase in time to attain OBLA was higher in RSH than in RSN. This finding is concomitant with a larger improvement in time of VT2 occurrence in RSH compared with RSN. These variables have been shown to correlate with endurance performance, have been used to prescribe exercise training loads, and are useful to monitor
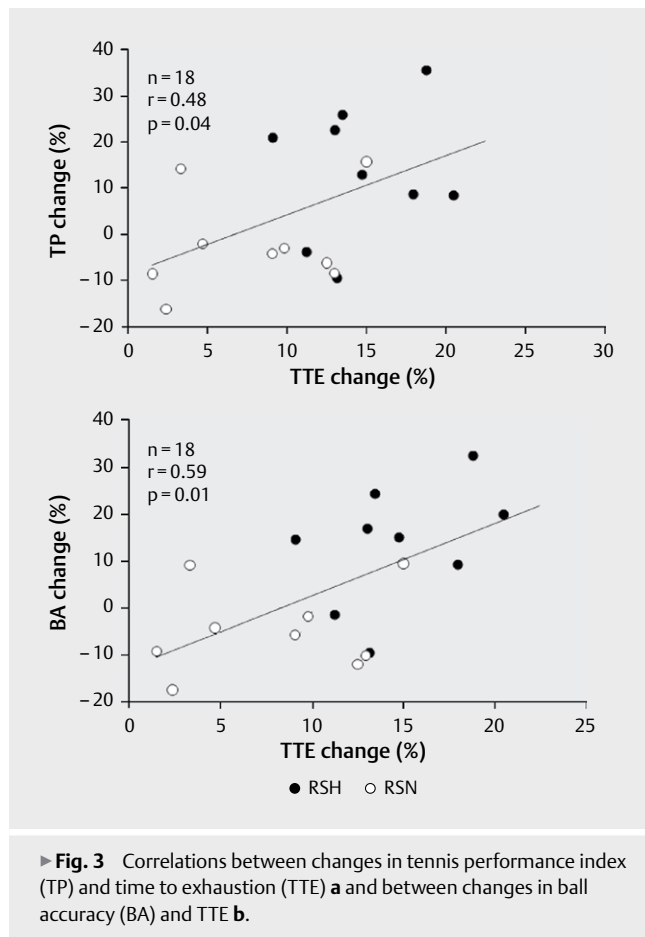
adaptation to training [3]. It has been previously demonstrated that cycling power output corresponding to OBLA improved by + 7 % during an incremental test after RSH only [44]. This is in line with the enhanced buffer capacity or upregulation of genes involved in pH control previously reported after RSH [17, 44]. Potential underlying mechanisms might arise from upregulation of genes previously associated to RSH as phosphofructokinase, monocarboxylate transporter-1 protein (MCT-1) [44], carbonic anhydrase III or lactate dehydrogenase [17]. This improvement in VT2 is of practical importance because it has been deemed to be a better marker of submaximal endurance performance than $\dot{V}O_{2max}$ and because VT2 was correlated with competitive levels in male tennis players (r = 0.55; P = 0.001) [1].

Based on our overall present results, i. e., because neither $\dot{V}O_{2max}$ nor RSA_{TT} improved post-training in the RSH group, we can assume some physiological adaptations to explain the improvements in time to attain OBLA and TTE. We hypothesized that RSH would induce beneficial adaptations mainly due to the improved blood perfusion level inducing enhanced oxygen utilization. With maximal effort intensities, specific skeletal muscle adaptations (molecular level) may arise through the oxygen-sensing pathway (i. e., capillary-to-fiber ratio, fiber cross-sectional area, myoglobin content and oxidative enzyme activity such as citrate synthase) that either do not occur in normoxic conditions or, if they do, they do so to a lesser degree [16, 31, 51, 53]. Additionally, exercising in hypoxia is known to trigger a compensatory vasodilatation to match an increased oxygen demand at the muscular level [13].

Technical performance measurements

Changes in TP during TEST were mainly caused by the improved BA and cannot be explained by a lack of involvement in ball hitting in favor of lower energy consumption. We did not find significant differences in BV between RSH and RSN from Pre- to Post-test as nor for 100 % $\dot{V}O_{2max}$. Moreover, the level of engagement in strokes is also confirmed by the exhaustion criteria (i. e., VE_{max}, HR_{max}, $[La]_{max}$) that were similar in both groups.

BA significantly increased in RSH, whereas it decreased in RSN. While we cannot rule out a potential learning effect in both groups, it seems that RSH favored some fatigue resistance-related adapta-

▶**Fig. 3** Correlations between changes in tennis performance index (TP) and time to exhaustion (TTE) **a** and between changes in ball accuracy (BA) and TTE **b**.

▲**Table 2** RSA performance before (Pre-) and after (Post-) 12 days of repeated-sprint training in hypoxia (RSH) vs. normoxia (RSN).

| | RSH | | | RSN | | | ANOVA (η²) | | |
	Pre-	Post-	Differences (%)	Pre-	Post-	Differences (%)	Time	Condition	Interaction (Time-Condition)
RSA_{Best} (s)	3.30 [3.18-3.42]	3.27 [3.18-3.36]	−1.1 [−2.8-0.6]	3.21 [3.15-3.27]	3.17 [3.09-3.25]	−1.3 [−2.8-0.2]	0.308 (0.02)	**0.018 (0.09)**	0.954 (0.0)
RSA_{TT} (s)	34.2 [33.2-35.2]	33.8 [32.8-34.8]	−1.1 [−2.5-0.3]	33.3 [32.6-34.0]	33.0 [32.5-33.5]	−0.8 [−2.2-0.6]	0.349 (0.01)	**0.029 (0.07)**	0.888 (0.0)
S_{dec} (%)	3.6 [2.4-4.8]	3.5 [2.3-4.7]	0.0 [−2.1-2.1]	3.9 [1.7-6.1]	4.4 [2.6-6.2]	0.5 [−1.1-2.1]	0.758 (0.001)	0.433 (0.009)	0.714 (0.002)

Values are mean [95 % CI]. Significant differences between Pre- and Post- absolute data (* p<0.05, ** p<0.01, *** p<0.001) are in bold. Statistical analysis is based on absolute values. Partial eta-squared (η²) was calculated as measures of effect size for mixed ANOVA; Best sprint during RSA (RSA_{Best}), total time of the 10 sprints (RSA_{TT}), sprint decrement during RSA (S_{dec}).

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tions, potentially transferable to technical performance. However, few investigations conducted on the effects on cognitive skills (e. g., visual search and decision-making) in the hypoxic condition have demonstrated their effects on attention, perception, executive functioning and short-term memory [39]. Although it is accepted that hypoxia adversely affects cognitive function (i. e., reaction time, short-term memory, complex attention, executive function and cognitive flexibility), hypoxia acclimatization might influence decision-making in a positive way [43]. Can we presume some direct influence of RSH on central nervous system or peripheral resistance to fatigue improvements? On the one hand, during acute hypoxic fatiguing exercise such as RSA, performance decrements could be explained by a reduced neural drive to the musculature, arising secondary to a stronger reflex inhibition due to brain hypoxia [35]. On the other hand, frontal lobe oxygenation has been recently assessed under hypoxic stress and remained unchanged whatever the exercise intensity following regulation of cerebral blood flow during sprint exercise on a cycle ergometer [14]. Studies on cerebral oxygenation kinetics during RSH would be of interest to measure this effect over time and to explain why the RSH group remained more accurate near exhaustion in tennis-specific patterns.

No RSH-induced putative changes in RSA$_{best}$ and RSA$_{TT}$

The results observed during RSA tests partly concur with some previous team-sport RSH studies, which found that RSH equally improved RSA performance compared with RSN [7, 21, 26, 42]. In contrast, Brocherie et al. [8] indicated that meta-analysis' aggregated findings show a greater beneficial effect of RSH vs. RSN for improving mean RSA outcomes. Although the present findings add to the debate [40], they question the type of drills used (more or less specific motor skills) during training and testing sessions, as well as the optimal combination of training variables (e. g., exercise-recovery ratio, session frequency). In addition, we cannot ignore that the present study includes a moderate hypoxic dose while the mean of the RSH studies recently meta-analyzed [8] was 9.4 ± 3.1 RSH sessions including 1216 ± 527 s sprinting duration over a 27.3 ± 8.4 days period.

Practical applications

With the modern tennis game becoming increasingly dynamic and tournament schedules more demanding, the importance of adapted strategy to physical fitness is well accepted [46]. Further adaptations by using upper body (e. g., with ball hitting) during RSH with its positive influence on RSA and muscle blood perfusion [18] appear more suitable than extending the length of the protocol. We suppose that this intervention can be programmed 2-3 times per season in order to develop or maintain the athletes' aerobic capacity and BA.

From a practical point of view, this study seems useful for tennis players preparing for competition. Details on a periodized RSH microcycle for a 12-day "in-season" period were provided and can be used by staff involved in highly trained athletes.

The RSH method can be performed with new hypoxic technologies (e. g., normobaric hypoxic room to reduce the inspired oxygen

fraction via nitrogen dilution or oxygen filtration). In a recent meta-analysis, the mean simulated altitude used in the RSH studies included ranged from 2900–3500 m [8]. Although it seems that "higher may not be better" because a simulated altitude of 4000 m may potentially blunt absolute training quality [27], it is recommended that a simulated altitude of ~3000 m must be employed when implementing RSH in intermittent-sport athletes. Even if no research has yet compared RSH under normobaric vs. hypobaric conditions, mounting evidence indicates that hypobaric hypoxia likely induces more severe physiological responses (oxygen saturation and heart rate) than normobaric hypoxia [41]. This would suggest that performance, as well as physiological and biomechanical alterations, may be different when sprinting repeatedly at terrestrial altitude. Consequently, altitude between 2000 m and 2500 m would probably be relevant in this condition.

Limitations and perspectives

Tennis performance is multifactorial and there are basic performance skills like psychological, tactical or strategic capabilities that are not even evaluated. Relating to the extra weight of the portable analyzer and the impact of the mask for gas analysis, it is possible that it may have slightly affected technical performance in both training groups and during Pre- and Post- Tests sessions.

The constitution of both groups by favoring the balance of the levels of play created differences in values in sprints and $\dot{V}O_{2max}$, and possible misunderstandings. However we stayed focused on the analysis of the effects of training and their comparison between conditions.

To investigate the mechanisms underlying the RSH-induced improvement in BA, studies on oxygenation (muscle and brain), as done by Curtelin et al. [14] during sprints on a cycle ergometer in hypoxia, would be worthwhile. Adding cognitive tests would also be valuable for understanding psychological/cognitive function.

With the methodological constraints encountered when conducting study with "near" elite athletes, it was impossible – due to different individualized schedules (compared with team sports) – to plan other Post-testing sessions to investigate the delayed effects of RSH as Hamlin et al. did recently [28]; the inclusion of a control group would have also been beneficial to determine its effect.

Conclusion

With a low hypoxic dose (5 sessions) over a 12-day period, repeated-sprint training in hypoxia improved total time to exhaustion in a tennis-specific aerobic test. Larger and concomitant improvements in time to attain the 'onset of blood lactate' at 4 mMol.L^{-1} and time of the second ventilatory threshold occurrence were observed in RSH compared with RSN. Such innovative training also contributed to improved technical performance, particularly the ball accuracy near exhaustion (100 % $\dot{V}O_{2max}$). The gains in repeated-sprint ability were of a similar extent following both training interventions.

Repeated-sprint training in hypoxia could provide an effective strategy as compared with similar training in normoxia to improve performance and to delay technical impairments near exhaustion in tennis players.

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Conflict of interest

The authors declare that they have no conflict of interest.

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