Aerobic Fitness and Technical Efficiency at High Intensity Discriminate between Elite and Subelite Tennis Players

Authors
E. Baiget[1], **X. Iglesias**[2], **F. A. Rodríguez**[2]

Affiliations
[1] Universitat de Vic – Universitat Central de Catalunya, Sport Performance Research Group, Vic, Spain
[2] Universitat de Barcelona, Institut Nacional d'Educació Física de Catalunya, INEFC-Barcelona Research Group on Sport Sciences, Barcelona, Spain

Key words
- endurance tennis test
- technical effectiveness
- maximum oxygen uptake
- international tennis players

Abstract

The aim of this study was to determine whether selected physiological, performance and technical parameters derived from an on-court test are capable of discriminating between tennis players of national and international levels. 38 elite and subelite tennis players were divided into international level (INT, n = 8) and national level players (NAT, n = 30). They all performed a specific endurance field test, and selected physiological (maximum oxygen uptake [$\dot{V}O_{2max}$], and ventilatory thresholds [VT_1 and VT_2]), performance (test duration, final stage and hits per test) and technical (technical effectiveness [TE]) parameters were compared. INT showed greater $\dot{V}O_{2max}$, VO_2 at VT_2 ($ml \cdot kg^{-1} \cdot min^{-1}$), test duration (s), final stage (no.), hits per test (no.) and TE (% of successful hits), as compared with NAT ($p < 0.05$). At high exercise intensity (stages 5 and 6), the INT achieved better TE than NAT ($p = 0.001–0.004$), and the discriminant analyses showed that these technical parameters were the most discriminating factors. These results suggest that this specific endurance field test is capable of discriminating between tennis players at national and international levels, and that the better aerobic condition of the INT is associated with better technical efficiency at higher exercise intensities.

Introduction

High-level tennis players compete worldwide in international tennis circuits governed by the Association of Tennis Professionals (ATP) and the International Tennis Federation (ITF). The ATP comprises 62 ATP World Tour tournaments (i.e., ATP World Tour Masters 1000, 500 and 250 events) in 31 countries, and about 150 ATP Challengers events. The ITF Men's Circuit (Futures tournaments) offers more than 600 tournaments across 77 countries and provides the entry level to professional tournaments enabling players to eventually reach the ATP World Tour. The tournament structure is hierarchical and success is measured by player rankings; this structure is organized in different competitive levels according to the prize money and ranking points offered [27]. According to the ITF, a player with ATP ranking is an experienced professional world-class player that competes internationally and whose major source of income is the tournaments prize-money [ITF, International tennis number (ITN), 2012. http://www.tennisplayandstay.com/itn/about-the-itn/about-the-itn.aspx; accessed May 25, 2015]. A previous study reported that, on average, players earned their first ATP point at 16.9 ± 1.2 years, and then took 4.5 ± 2.1 years to transition to the top 100 at the age of 21.5 ± 2.6 years [27]. On the other hand, players at the minor competitive level who have not yet managed to obtain international classification (i.e., ATP ranking) focus their competitive activity on national category tournaments in their respective countries.

A competition tennis match play includes intermittent short-term periods (1–9 s) of moderate to maximum exercise intensity (i.e., strokes, starts and stops, direction changes and short accelerations) interspersed by rest intervals of short (maximum of 20 s between points) to medium duration (maximum of 90 s between change ends) [9,25]. The physiological exercise intensities are typically moderate, ranging from 70–90 % of HR_{max} and 50–60 % of maximum oxygen uptake ($\dot{V}O_{2max}$), although during long rallies intensity may be higher (i.e., 80 % of $\dot{V}O_{2max}$ and close to 100 % of HR_{max}) [8]. In recent years, the physical demands upon elite tennis players has increased significantly [3]. Although tennis con-

accepted after revision
February 15, 2016

Bibliography
DOI http://dx.doi.org/10.1055/s-0042-104201
Published online: 2016
Int J Sports Med

ISSN 0172-4622

Correspondence
Dr. Ernest Baiget
Universitat de Vic - Universitat Central de Catalunya
Sport Performance Analysis Research Group
Vic, Spain
Sagrada Família
7, Vic
Spain 08500
Tel.: +34/938/816 164
Fax: +34/938/891 063
ernest.baiget@uvic.cat

tinues to be a technical/tactical game, nowadays 210 km·h^{-1} serves are common and competitive performance depends largely on the player's physical ability [10]. Moreover, it has recently been shown that playing consecutive prolonged tennis matches implies reduction of match play performance (i. e., effective playing times), external load (i. e., 3D-movement load), and sprinting and jumping ability, as well as increased muscle damage markers and ratings of fatigue and soreness [14]. To reach the international level, tennis players also need to possess specific physiological attributes such as aerobic fitness [9,21], muscle strength and power [26], and sport-specific technical skills as predominant factors (e. g., racket and ball handling skills and stroke skills, such as service abilities) [30].

In recent years, there has been growing interest in the assessment of physiological and technical parameters using specific field tests [2,22,24,29,31,32]. Nowadays it is not possible to fully replicate in the laboratory the physiological demands, technical skills and muscle group involvement of tennis play, although specific field tests allow to partly reproduce the complex demands of tennis [11]. Technical performance tests have been suggested to assess the players' ability to aim the ball at a given place on the court and the accuracy, speed and power of hits [22,24,31,32], and incremental tests have been used to assess specific endurance [2,13,15,29]. On the other hand, a recently developed specific endurance field test (SET-Test) conducted with a tennis ball machine allows physiological and technical parameters to be assessed simultaneously [2,29]. Stemming from these tests, physiological (oxygen uptake [$\dot{V}O_2$], ventilatory thresholds [VTs] or blood lactate) and technical (percentage of correct hits) variables have been described [2,29], and their testing reliability and correlation with the competitive level established [2]. However, their discriminative ability between players of different competitive levels has not been tested.

Therefore, the aim of this study was to determine whether selected physiological, performance and technical parameters derived from a tennis-specific incremental field test are capable of discriminating between tennis players of different levels (national vs. international level).

Methods

Participants

38 competitive male tennis players were divided into 2 groups according to their level (**Table 1**). The subjects in the first group (INT, international level tennis players, n = 8) were involved in regular tennis competition at the international level (i. e., ITF Futures tournaments) with an ATP ranking (1 197 ± 330) and an International Tennis Number (ITN) of 1. The subjects in the second group (NAT, national level tennis players, n = 30) were involved in regular tennis competition at the national level (i. e., national tennis circuits) with an ITN ranging from 2 to 4 (advanced), but without ATP ranking points. The subjects were recruited using a convenience sampling procedure among volunteers belonging to 4 high-level tennis academies and training centres (see Acknowledgements). Sample size was calculated on the basis of mean values (± SD) for relative $\dot{V}O_{2max}$ obtained from a previous study [2] (63 and 56 ± 4.8 ml·kg^{-1}·min^{-1}), which estimated that a minimum of 8 subjects per group was required (α = 0.05; β = 0.80; two-tailed). The unequal sample size was due to the smaller population of players holding an ATP ranking. All players were focused on tennis-specific training (i. e., technical and tactical skills), aerobic and anaerobic training (i. e., on- and off-court exercises), and resistance training. One participant in each group was left-handed. The study was performed in accordance with the ethical standards of the International Journal of Sports Medicine [17], and conformed to the recommendations of the Declaration of Helsinki. All subjects voluntarily participated in the study after being informed about the scope and methods of the study, and delivered a written informed consent, with parental permission when needed. The study was approved by the university institutional review board for studies involving human subjects.

Table 1 Participant characteristics.

	INT (n = 8)	NAT (n = 30)	Difference (p-value) *
Age (years)	17.9 ± 1.0	18.3 ± 1.4	0.612
Height (cm)	180.1 ± 7.3	180.1 ± 8.3	0.986
Body mass (kg)	70.8 ± 5.5	73.2 ± 9.4	0.371
Training volume (h·week^{-1})	23 ± 4	23 ± 2	0.748
Training background (years)	6.7 ± 0.8	6.4 ± 1.3	0.576

Values are mean ± SD and p-value of the differences. INT, international level tennis players; NAT, national level tennis players; HR_{max}, maximum heart rate; * as determined by t-test or Welch's test according to equal or unequal variances, respectively, determined by Levene's test

Experimental design

Participants performed an incremental tennis-specific endurance field test recently shown to be reliable and valid for the determination of $\dot{V}O_{2max}$ and VTs [2]. Players were tested between February and April in noncompetition weeks. All tests were run in the morning (10–14 a.m.) of regular training days, and performed on an outdoor tennis court (GreenSet surface, GreenSet Worldwide S.L., Barcelona, Spain), at an ambient temperature ranging from 18 to 23 °C, with stable environmental and wind conditions (i. e., air velocity < 2 m·s^{-1}, relative humidity 54.4–61.0 % [Kestrel 4000 Pocket Weather Tracker, Nielsen Kellerman, Boothwyn, PA, USA]). Measurements began after an 18-min standardized warm-up including: 10 min of jogging around the court, dynamic flexibility, forward, sideways, and backwards running, and acceleration runs; 5 min of ground strokes (players were asked to hit the balls to the centre of the court); and 3 min of test familiarization, performing the test protocol at the lowest work load (frequency of balls ejected from the ball machine [$Ball_f$] = 9 shots·min^{-1}). To reduce interference from uncontrolled variables, all subjects were instructed to maintain their habitual lifestyle and normal dietary intake before and during the study. The subjects were instructed not to exercise the day before a test and to consume their last (caffeine-free) meal at least 3 h before the scheduled test time.

Specific endurance field test (SET-Test)

The test has been described in detail elsewhere [2]. In short, participants had to hit balls ejected by a ball machine (Pop-Lob Airmatic 104, France), starting on the right corner of the baseline (i. e., right-handed players start with a forehand and left-handed players start with a backhand). Subjects had to hit the balls alternating between forehand and backhand and they could choose between cross-court or down the line in a prescribed pattern (i. e., drive, topspin). The target landing point for the balls was about 2 m in front of the baseline, alternating balls to

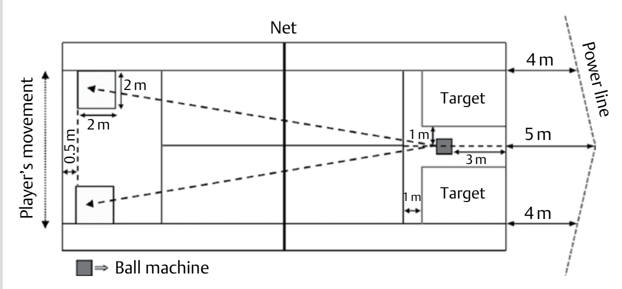

Fig. 1 Schematic setting for the specific endurance field test (SET-Test). (Reproduced with permission from *Baiget E, Fernández-Fernández J, Iglesias X, Vallejo L, Rodríguez FA*. J Strength Cond Res 2014; 28: 256–264) [2]).

the right and the left corners in a square of 4 m^2 (**Fig. 1**). Slice-strokes were not allowed because we assumed that they might influence the positioning of the ball and therefore physiological responses and test reliability [2]. The test began with a $Ball_f$ of 9 shots·min^{-1}, which was increased by 2 shots·min^{-1} every 2 min. The test ended at the player's request or was stopped by the researchers if the player was no longer able to fulfil the test criteria (i.e., to perform strokes with acceptable stroke technique and precision). Precision was determined as explained in "Technical measurements". Stroke technique (i.e., slice stroke avoidance) was judged by the experienced researchers through subjective observation, and technical scores (i.e., hits-errors) were registered by a single experienced coach. In this regard, we acknowledge that variability may exist with the testing protocol based on the coaches at hand. The ball machine was manually calibrated before each test, and the device's reliability was assessed by manual timing (mean CV of $Ball_f = 3.5 \pm 0.9\%$) and using a radar device (Stalker ATS 4.02, USA) (mean $Ball_v = 68.6 \pm 1.9$ km·h^{-1}; CV of 2.7%). A minimum of 40 new tennis balls (Babolat Team®) was used for each test.

Physiological measurements

Ventilatory gas exchange and heart rate (HR) were continuously recorded, beginning 2 min before the familiarization phase and finishing 5 min after the end of the test (recovery phase). Expired air was analyzed continuously for gas volume (triple digital-V1 turbine), oxygen concentration (zirconium analyzer), and carbon dioxide concentration (infrared analyzer) using a portable gas analyzer (K4 b^2, Cosmed, Italy). The portable measurement unit was carried on the trunk, with both the main sampling unit and the battery pack placed on the back of the player, and in the same way during all tests. HR monitoring (Polar, Kempele, Finland) was used alongside the portable gas analyzer unit. Gas and volume calibration of the measurement device was done on the morning of each test session. Room air calibration was conducted before each test.

VTs were detected by analysing the points of change in slope or breaks in linearity of ventilatory parameters [33]. 2 VTs were determined according to the model proposed by Skinner and MacLellan [28]: VT_1 or first ventilatory threshold, and VT_2 or second ventilatory threshold (Wasserman's respiratory compensation point). VT_1 was determined using the criteria of an increase in the ventilatory equivalent for oxygen ($\dot{V}_E/\dot{V}O_2$) with no increase in the ventilatory equivalent for carbon dioxide ($\dot{V}_E/\dot{V}CO_2$) and the departure from linearity of $\dot{V}_E$ caused by a more rapid increase in ventilation, whereas VT_2 corresponded to an increase in both $\dot{V}_E/\dot{V}O_2$, and$\dot{V}_E/\dot{V}CO_2$.$\dot{V}O_{2max}$ was determined by the observation of a "plateau" or levelling off in $\dot{V}O_2$ or when the increase in 2 successive periods was less than 150 ml·min^{-1} [33]. HR_{max} was considered as the highest heart rate value reached during the final minute of the test.

Performance measurements

The main performance measurements were (i) the test duration until the player felt exhausted or failed to hit the ball twice in a row, (ii) the final stage achieved with a precision of 0.5 periods (i.e., including the last completed min of exercise during the final stage), and (iii) the total number of hits per test. Additional performance variables were the duration and stage corresponding to $\dot{V}O_{2max}$, VT_1 and VT_2.

Technical measurements

In addition to the physiological and performance measurements, an objective evaluation of the players' technical effectiveness (TE) was carried out. TE was calculated based on the percentage of hits and errors, and 2 performance criteria were defined: (i) precision: the ball returned by the player had to bounce inside the target (i.e., 3.1 by 4.5 m square located 1 m from the service line and 1 m over the prolongation of the centre service line, and (ii) power: after bouncing inside the target, the ball had to go over the power line (located between 5 m from the centre of the baseline and 4 m from the side line) before bouncing a second time (**Fig. 1**) [2,29]. The spin level on the ball was disregarded. Hits and errors scores were recorded continuously at each stage by an experienced coach, and data were processed to derive the average technical effectiveness (TE, %) of the test, which was defined as the percentage of correct hits.

Statistical analysis

The Kolmogorov-Smirnov test was used to assess the Gaussian distribution of the data. Specified outcome measures in the 2 groups are presented as mean, standard deviation (±SD), mean difference (diff.), and 95% confidence interval (95% CI) when appropriate. After checking for equality of the variances (Levene's test), differences between the 2 groups' mean values of the variables measured during the test were assessed using the unpaired Student's t-test (equal variances) or by Welch's test (unequal variances). Stepwise discriminant analysis was used for selected physiological, performance and technical parameters derived from the on-court specific test, with competitive level as the dependent variable (national vs. international). Precise p-values are reported, and significance level was set at p (probability of type I error) $< \alpha = 0.05$. Data were analyzed using SPSS statistical software (version 13.0; SPSS Inc., Chicago, Ill).

Results

There were no significant differences in the biometric and training characteristics of both groups of participants (**Table 1**).

Physiological measurements

The physiological responses to the on-court endurance test in the 2 groups are summarized in **Table 2**. INT showed greater $\dot{V}O_{2max}$ (diff.: 8%; 95% CI: 1–17%; p = 0.037) and $\dot{V}O_2$ at VT_2 (diff.: 10%; 95% CI: 2–19%; p = 0.023), as compared with NAT. No differences were found for the rest of outcome variables analysed.

Table 2 Comparison of performance (duration and stage) and physiological ($\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}_E$, HR and R) variables corresponding to $\dot{V}O_{2max}$ and ventilatory thresholds (VT1 and VT2) in tennis players of international (INT) and national (NAT) level.

	VT_1		VT_2		$\dot{V}O_{2max}$	
	INT	NAT	INT	NAT	INT	NAT
Duration (s)	389 ± 87	342 ± 85	619 ± 85	568 ± 86	797 ± 83	763 ± 113
Stage (#)	3.0 ± 0.7	2.5 ± 0.6	4.9 ± 0.7	4.5 ± 0.8	6.4 ± 0.6	6.1 ± 1.0
$\dot{V}O_2$ (mL · kg^{-1} · min^{-1})	38.7 ± 3.4	36.0 ± 4.0	51.8 ± 3.8	46.9 ± 5.1 *	60.6 ± 5.1	55.7 ± 5.4 *
$\dot{V}O_2$ (mL · min^{-1})	2 732 ± 327	2 645 ± 456	3 665 ± 435	3 442 ± 548	4 286 ± 534	4 091 ± 616
$\dot{V}CO_2$ (mL · min^{-1})	2 433 ± 218	2312 ± 486	3 517 ± 308	3 371 ± 658	5 059 ± 736	4 555 ± 904
$\dot{V}_E$ (L · min^{-1})	66 ± 4	65 ± 9	93 ± 8	93 ± 12	133 ± 19	135 ± 18
HR (beats · min^{-1})	156 ± 9	155 ± 9	180 ± 9	178 ± 9	192 ± 12	190 ± 8
R	0.9 ± 0.1	0.9 ± 0.1	1.0 ± 0.1	0.9 ± 0.1	1.2 ± 0.2	1.1 ± 0.2

Values are mean ± SD and significant differences (* $p < 0.05$, Student's t-tests). VT_1, first ventilatory threshold; VT_2, second ventilatory threshold; $\dot{V}O_{2max}$, maximal oxygen uptake; INT, international level tennis players; NAT, national level tennis players; $\dot{V}O_2$, oxygen uptake; $\dot{V}O_2$, carbon dioxide production; V_E, ventilation; HR, heart rate; R, respiratory exchange ratio

Table 3 Comparison of performance (test duration, final stage, and hits per test) and technical effectiveness (TE) parameters obtained during the field test in players at the international (INT) and national level (NAT).

Variables	INT	NAT	p-value	Difference (%) (95 % CI)
Test duration (s)	862 ± 46	797 ± 80	0.005#	8.2 (2.8–13.5)
Final stage (stage no.)	7.1 ± 0.4	6.4 ± 0.7	0.010#	10.9 (3.2–16.5)
Hits per test (no.)	214 ± 21	192 ± 28	0.036 *	11.5 (1.2–21.4)
TE (% of successful hits)	70 ± 6	63 ± 9	0.021 *	11.1 (3.5–20.6)

Values are mean ± SD; p-value and significant group differences ($p < 0.05$) as assessed by Student's t-test (*) or Welch's test (#); Mean group differences (%) and their 95 % confidence interval are also shown

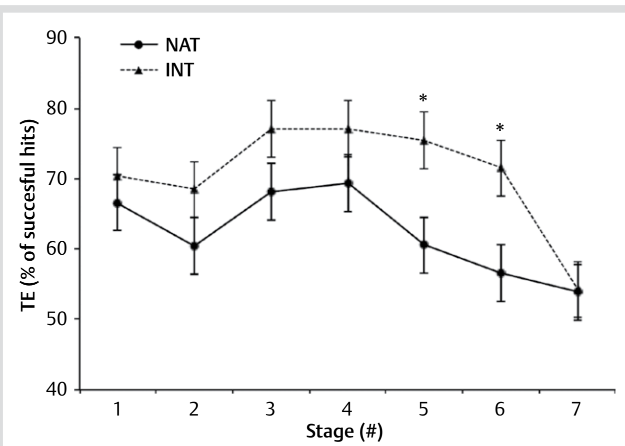

Fig. 2 Technical effectiveness (TE) at different stages of the tennis-specific incremental field test in tennis players of international (INT) and national level (NAT). Values are mean ± SD (significance: * $p < 0.05$).

Performance measurements

The main variables describing the performance measurements for both groups and percentage differences are shown in ▸ **Table 3**. INT achieved significantly longer test duration, higher final stage, and more hits per test than NAT.

Technical measurements

The technical performance results for both groups and percent differences are shown in ▸ **Table 3** and ▸ **Fig. 2**. INT showed greater TE (% of successful hits) than NAT. Similarly, if we consider technical efficiency at the different stages (▸ **Fig. 2**), INT achieved better TE than NAT during stages 5 and 6 (25 %; 95 % CI: 10–39 %; p = 0.001 and 25 %; 95 % CI: 12–37 %; p = 0.004, respectively).

Discriminant analysis

The results of the stepwise discriminant analysis are summarized in ▸ **Table 4**. The predictive model that best discriminated players by skill level included 3 technical efficiency factors (TE at stages 6, 5 and 4), and correctly classified 86 % of the players. The 2 most discriminating factors are the TE at higher exercise intensities (TE at stages 6 and 5) but not maximal; the TE at moderate exercise intensities (TE at stage 4) is the third most important factor. The physiological and performance variables did not appear in the predictive model.

Discussion

▼

To our knowledge, the present study is the first to investigate whether selected physiological, performance and technical parameters derived from an on-court test are capable of discriminating between tennis players of different levels (i. e., national vs. international level). The main finding was that INT players showed better aerobic fitness (on average, $\dot{V}O_{2max}$ and VT_2 were 8 % and 10 % greater, respectively) and better performance during the specific field test as compared with NAT. Similarly, INT were able to maintain significantly better levels of TE (11 % greater on average) through high exercise intensities, and the stepwise discriminant analyses suggest that the ability to maintain high levels of TE at high intensities may also be a factor that differentiates INT from NAT.

Physiological measurements

Elite-level tennis competition causes significant physiological and perceptual stress [16], and to be able to attend the technical, tactical and physiological demands the players have to possess high levels of physical fitness [10]. $\dot{V}O_{2max}$ is generally considered to be the best single marker for the functional capacity of the cardiorespiratory system. $\dot{V}O_{2max}$ values observed in the 2 groups (▸ **Table 2**) were within the ranges observed in competitive tennis players and meet recommended values for competing at a high level (> 50 ml · kg^{-1} · min^{-1}) [9, 20, 21]. Although the 2 groups carried out the same training volume (▸ **Table 1**) and showed the same $\dot{V}O_{2max}$ and VT_2 in absolute values (expressed

Step *	Entered	Wilks' lambda Statistic	df1	df2	df3	Statistic	p-value
1	TE at stage 6	0.591	1	1	23	15.914	0.001
2	TE at stages 6 and 5	0.498	2	1	23	11.094	<0.001
3	TE at stages 6, 5 and 4	0.397	3	1	23	10.627	<0.001

TE, Technical effectiveness (% of successful hits). * Maximum number of steps is 70; minimum partial F to enter is 3.84; maximum partial F to remove is 2.71

Table 4 Variables included in the stepwise discriminant analysis procedure: variables entered/removed *.

in $ml \cdot min^{-1}$), INT showed significantly higher level of aerobic fitness ($\dot{V}O_{2max}$ and VT_2 in $ml \cdot kg^{-1} \cdot min^{-1}$). However, the elevated aerobic fitness of INT may be due to the higher intensity of competition at the international level (i.e., ATP and ITF events). In other words, INT would need higher aerobic condition to deal with the intensity of high-level competition and, therefore, one of the components needed to play at the international level is a good level of aerobic fitness (i.e., $\dot{V}O_{2max}$~60 $ml \cdot kg^{-1} \cdot min^{-1}$) [3,20,21]. Although most of the important actions during the short-term periods of activity (i.e., strokes, accelerations or changes of direction) depend fundamentally on the anaerobic metabolism (intramuscular phosphates and glycolysis), the aerobic metabolism (oxidative phosphorylation) allows resynthesising the high-energy phosphates during recovery periods [10,30]. Adequate aerobic fitness promotes better physiological regeneration between points, matches and tournaments to maintain a high competitive level throughout the season [3]. In this sense, moderate significant relationships ($r = 0.55$, $p = 0.001$) have been found between competitive level (INT) and aerobic fitness (both $\dot{V}O_{2max}$ and VT_2), which greatly increases when these parameters are associated with TE, predicting over 50% of performance level variability [2]. In a 7-year prospective longitudinal single-case report on a world-class professional player, $\dot{V}O_{2max}$ was found to explain ~80% of an athlete's ATP ranking position in the following year ($r = 0.94$; $p < 0.001$) [3]. $\dot{V}O_{2max}$ and ATP entry ranking ranged from 55.0–67.4 $ml \cdot kg^{-1} \cdot min^{-1}$ and from 6–97 ATP ranking, respectively. Although a study case cannot be generalized and $\dot{V}O_{2max}$ is only one of a number of physiological variables, these values are in line with those observed in our previous study using the same tests and methodology [2] and those presented here, supporting the concept that professional players should have a cardiorespiratory capacity of ~55–70 $ml \cdot kg^{-1} \cdot min^{-1}$ to compete at the international level.

Performance measurements

Tennis performance is multifactorial in nature and depends on the adequate interaction of several elements (physiological, biomechanical, psychological, and perceptual capabilities) [18]. Although no differences were observed in the duration or stage corresponding to the $\dot{V}O_{2max}$ and VTs, INT showed better performance in terms of test duration and, as these 2 variables result in a product of one another, in the final stage achieved and the total number of hits per test. This, on the one hand, may be because of their better aerobic fitness. On the other hand, the performance outcome in the test would rely on each player's individual motor and technical efficiency (i.e., specific movements and strokes). Therefore, it is possible that the better technical level of INT allowed them to be more efficient during the test and, consequently, that 2 players with the same aerobic fitness could have achieved a different performance level (i.e., test duration). In this sense, it has been observed that the test used has a limited predictive validity of $\dot{V}O_{2max}$ based on maximal test performance, due to technical efficiency limitations [1].

Technical measurements

If we consider the overall TE (% of successful hits), there were clear technical differences between the 2 groups, with INT achieving 11% higher TE values on average. Consistent with this finding, TE has been identified as a good parameter to predict the competitive performance of tennis players [2,5,29,32,33]. If we consider the evolution of TE during the different stages (**Fig. 2**), no significant differences were observed when the intensity was low (stages 1 and 2), moderate (stages 3 and 4), or maximum (stage 7). However, at high intensity (stages 5 and 6) INT showed significantly better TE. This shows that INT players, in a closed situation during a tennis-specific incremental test, are able to maintain remarkably better levels of success (>70%) through high intensities ($Ball_f = 15$ and 17 $shots \cdot min^{-1}$). On one hand, this could be due to their better aerobic fitness, which allows them to attain a higher work rate during the test. On the other hand, the efficiency of tennis-specific movements patterns (i.e., strokes and displacements) depends largely on the physiological strain [20]. It is well known that as exercise intensity increases above a certain workload, glycolysis is activated and causes a significant increase of lactate in muscle and accumulates in blood [4]. In this sense, VT_2 was observed at stage ~4.9 (INT) and ~4.5 (NAT) (**Table 2**), and technical differences were observed from stage 5 onwards (**Fig. 2**), when the energy demands probably require glycolysis to be activated. Consistent with these results, investigations carried out with a ball machine at high intensity have shown that with increasing lactate levels the hit quota decreased [19]. In this same line, a previous study described 3 zones based on the evolution of TE throughout the test; following an adaptation period, the maximum effectiveness occurred at stages 3 and 4, and a steady decline was observed from stage 5 onwards, highlighting the appearance of premature fatigue and reduced accuracy [2]. However, at maximum intensity, the fact that no differences were observed may be because such intensities differ notably from those observed during singles match play [9]. In this respect it has been observed that when blood lactate concentrations exceed ~7–8 $mmol \cdot L^{-1}$, technical and tactical performance declines [7,21,23], and hitting accuracy significantly decreases (by ~81%) as the player reaches volitional fatigue [20].

Discriminant analyses

TE at stages 6 and 5 highlighted by the discriminant analyses suggests that the ability to maintain high levels of TE at high intensities may be a factor differentiating international from national players. These results are consistent with a previous study in which TE was identified as the best single predictive parameter of performance, capable of explaining 37% of the competitive level (i.e., ITN) [2]. This might be because the intensity of the displacements at international competitions (ATP and ITF events) is higher than at the national level, and INT are better adapted to high-intensity rallies.

Tennis coaches often prescribe on-court game-specific exercise drills to concurrently develop technical, tactical, and physiological factors [26]. Most of the training volume of the competitive tennis players has a technical-tactical character, in this sense, the ITF recommends about 15–20 $h \cdot week^{-1}$ of this kind of training to achieve elite levels [8]. According to the present results, technical efficiency at high intensities and aerobic fitness can be decisive factors for tennis players of national calibre who want to compete at the international level. Therefore, we suggest that part of their technical training should take place at high intensities, with a special focus in maintaining good technical efficiency (i. e., proper technique, efficient movements and displacements, and good stroke accuracy and precision). High-intensity interval training (HIT) has been proposed as a time-efficient training method to achieve physiological adaptations (e. g., cardiorespiratory and metabolic) and, as a consequence, to improve performance in intermittent sports [6]. Tennis is a sport based on unpredictability [20] and most of the training should be based on tactical situations. However, the inclusion of on-court HIT (i. e., repeated bouts of rather high but not maximal intensity exercise) can potentially improve both technical efficiency at higher exercise intensities and aerobic fitness. According to the present results and prior research, to concurrently develop both capabilities, competitive tennis players can use intensities around stage 5–6 (17–19 $shots \cdot min^{-1}$) or a $Ball_f$ at a level of 90–100% $\dot{V}O_{2max}$. Work and rest intervals can range from short (15 s) to long (4 min), with work-to-rest ratios of 1:1–4:1 [2, 12].

Study limitations

Concerning the testing protocol, we acknowledge that despite power being relatively controlled by requiring that the ball go over the power line after the hit (see "Methods"), the ball's speed after the hit was not actually measured. This might slightly influence the technical constraints (e. g., the ball's spin might vary among individuals and across exercise intensities) to a certain degree, thus introducing a potential bias in TE assessment. Relating to the extra weight of the portable analyser (475 g), it is possible that it may have slightly affected test performance, particularly at high intensities. A previous study did not detect such negative effects on physiological or technical parameters when the SET-Test was performed with the portable analyzer. Interestingly, wearing the instrument resulted in longer test duration and a higher final stage, possibly due to confounding factors (e. g., learning and/or Hawthorne effects) [2]. Finally, although this specific test allows discriminating between tennis players at NAT and INT levels, it is not intended to determine the competitive level of individual players but to assess their specific endurance capacities. Tennis performance is multifactorial and there are basic performance skills such as the psychological, tactical or strategic capabilities that are not evaluated.

Conclusions

The present results indicate that international level tennis players exhibit better aerobic fitness ($\dot{V}O_{2max}$ and VT_2) and better performance in a tennis-specific incremental field test compared with national level players. In addition, the results suggest that the ability to maintain high levels of technical efficiency at high intensities during the test may be a factor differentiating players at the international and national competitive level.

Acknowledgements

This study was supported by the Institut Nacional d'Educació Física de Catalunya (INEFC), Generalitat de Catalunya. The authors wish to thank Sánchez-Casal Academy, Bruguera Top Team Tennis Academy, Escola Balear de l'Esport, and Centre Internacional de Tennis of the Catalan Tennis Federation for their support and use of facilities, along with the players for their time and effort during the study. Finally, we also wish to thank Lisímaco Vallejo, Pedro Zierof and Valery Kryvaruchka for technical assistance during the experiments.

Conflict of interest: The authors have no conflict of interest to declare.

References

1 *Baiget E, Fernández-Fernández J, Iglesias X, Rodríguez FA.* Heart rate deflection point relates to second ventilatory threshold in a tennis test. J Strength Cond Res 2015; 29: 765–771
2 *Baiget E, Fernández-Fernández J, Iglesias X, Vallejo L, Rodríguez FA.* On-court endurance and performance testing in competitive male tennis players. J Strength Cond Res 2014; 28: 256–264
3 *Banzer W, Thiel C, Rosenhagen A, Vogt L.* Tennis ranking related to exercise capacity. Br J Sports Med 2008; 42: 152–154
4 *Beaver WL, Wasserman K, Whipp BJ.* A new method for detecting anaerobic threshold by gas exchange. J Appl Physiol 1986; 60: 2020–2027
5 *Birrer RB, Levine R, Gallippi L, Tischler H.* The correlation of performance variables in preadolescent tennis players. J Sports Med Phys Fitness 1986; 26: 137–139
6 *Buchheit M, Laursen PB.* High-Intensity interval training, solutions to the programming puzzle. Part II: Anaerobic energy, neuromuscular load and practical applications. Sports Med 2013; 43: 927–954
7 *Davey PR, Thorpe RD, Williams C.* Fatigue decreases skilled tennis performance. J Sports Sci 2002; 20: 311–318
8 *Fernández-Fernández J, Kinner V, Ferrauti A.* The physiological demands of hitting and running in tennis on different surfaces. J Strength Cond Res 2010; 24: 3255–3264
9 *Fernández J, Méndez-Villanueva A, Pluim BM.* Intensity of tennis match play. Br J Sports Med 2006; 40: 387–391
10 *Fernández-Fernández J, Sanz-Rivas D, Méndez-Villanueva A.* A review of the activity profile and physiological demands of tennis match play. Strength Cond J 2009; 31: 15–26
11 *Fernández-Fernández J, Ulbricht A, Ferrauti A.* Fitness testing of tennis players: How valuable is it? Br J Sports Med 2014; 48: 22–31
12 *Fernández-Fernández J, Zimek R, Wiewelhove T, Ferrauti A.* High-intensity interval training vs. repeated-sprint training in tennis. J Strength Cond Res 2011; 26: 53–62
13 *Ferrauti A, Kinner V, Fernández-Fernández J.* The Hit & Turn Tennis Test: an acoustically controlled endurance test for tennis players. J Sports Sci 2011; 29: 485–494
14 *Gescheit DT, Cormack SJ, Reid M, Duffield R.* Consecutive days of prolonged tennis match play: Performance, physical, and perceptual responses in trained players. Int J Sports Physiol Perform 2015; 10: 913–920
15 *Girard O, Chevalier R, Leveque F, Micallef JP, Millet GP.* Specific incremental field test for aerobic fitness in tennis. Br J Sports Med 2006; 40: 791–796
16 *Gomes RV, Coutts AJ, Viveiros L, Aoki MS.* Physiological demands of match-play in elite tennis: A case study. Eur J Sport Sci 2011; 11: 105–109
17 *Harriss DJ, Atkinson G.* Ethical standards in sport and exercise science research: 2016 update. Int J Sports Med 2015; 36: 1121–1124
18 *Hornery DJ, Farrow D, Mujika I, Young W.* An integrated physiological and performance profile of professional tennis. Br J Sports Med 2007; 41: 531–536
19 *König D, Huonker M, Schmid A, Halle M, Berg A, Keul J.* Cardiovascular, metabolic, and hormonal parameters in professional tennis players. Med Sci Sports Exerc 2001; 33: 654–658
20 *Kovacs MS.* Applied physiology of tennis performance. Br J Sports Med 2006; 40: 381–385
21 *Kovacs MS.* Tennis physiology: Training the competitive athlete. Sports Med 2007; 37: 189–198

22 *Landlinger J*, *Stöggl T*, *Lindinger S*, *Wagner H*, *Müller E*. Differences in ball speed and accuracy of tennis groundstrokes between elite and high-performance players. Eur J Sport Sci 2012; 12: 301–308
23 *Lees A*. Science and the major racket sports: a review. J Sports Sci 2003; 21: 707–732
24 *Lyons M*, *Al-Nakeeb Y*, *Hankey J*, *Nevill A*. The effect of moderate and high-intensity fatigue on groundstroke accuracy in expert and non-expert tennis players. J Sport Sci Med 2013; 12: 298–308
25 *Méndez-Villanueva A*, *Fernández-Fernández J*, *Bishop D*. Exercise-induced homeostatic perturbations provoked by singles tennis match play with reference to development of fatigue. Br J Sports Med 2007; 41: 717–722
26 *Méndez-Villanueva A*, *Fernández-Fernández J*, *Bishop D*, *Fernández-García B*, *Terrados N*. Activity patterns, blood lactate concentrations and ratings of perceived exertion during a professional singles tennis tournament. Br J Sports Med 2007; 41: 296–300
27 *Reid M*, *Morris C*. Ranking benchmarks of top 100 players in men's professional tennis. Eur J Sport Sci 2013; 13: 350–355
28 *Skinner JS*, *McLellan TM*. The transition from aerobic to anaerobic metabolism. Res Q Exerc Sport 1980; 51: 234–248
29 *Smekal G*, *Pokan R*, *von Duvillard SP*, *Baron R*, *Tschan H*, *Bachl N*. Comparison of laboratory and "on-court" endurance testing in tennis. Int J Sports Med 2000; 21: 242–249
30 *Smekal G*, *von Duvillard SP*, *Rihacek C*, *Pokan R*, *Hofmann P*, *Baron R*, *Tschan H*, *Bachl N*. A physiological profile of tennis match play. Med Sci Sports Exerc 2001; 33: 999–1005
31 *Vergauwen L*, *Madou B*, *Behets D*. Authentic evaluation of forehand groundstrokes in young low- to intermediate-level tennis players. Med Sci Sports Exerc 2004; 36: 2099–2106
32 *Vergauwen L*, *Spaepen AJ*, *Lefevre J*, *Hespel P*. Evaluation of stroke performance in tennis. Med Sci Sports Exerc 1998; 30: 1281–1288
33 *Wasserman K*, *Hansen JE*, *Sue DY*, *Stringer WW*, *Whipp B*. Principles of Exercise Testing and Interpretation: Including Pathophysiology and Clinical Applications. 4th ed. Philadelphia, Pa: Lippincott Williams & Wilkins; 2005