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The Hit & Turn Tennis Test: An acoustically controlled endurance test for tennis players

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Abstract
This study was conducted to validate and evaluate the "Hit & Turn Tennis Test", an acoustically progressive on-court endurance test for tennis players. Ninety-eight competitive tennis players (53 males, 45 females) of different age groups participated in the study. For validation, the adult male players completed three Hit & Turn tests, one on a clay court and two on a carpet surface, a tennis-specific ball machine test and an incremental treadmill run in a randomized order. A stronger correlation between maximal performance ($r = 0.81$, $P < 0.01$) and maximal oxygen uptake ($r = 0.96$, $P < 0.01$) was observed between the Hit & Turn test and the ball machine test, than between the Hit & Turn test and the treadmill test. For test–retest, we found a significant correlation between maximal performance on the same ($r = 0.83$, $P < 0.01$) and on different surfaces ($r = 0.74$, $P < 0.01$). During test evaluation, maximal performance was higher in males than in females ($P < 0.01$) and increased by consecutive age group in boys ($P < 0.01$) but not in girls ($P = 0.97$). In conclusion, Hit & Turn maximum test performance can be recommended as a valid and reliable indicator for tennis-specific endurance.

Keywords: *Tennis, test, specific endurance, oxygen consumption*

Introduction

Physical exertion during tennis involves high-intensity whole-body efforts including short-distance sprints with a maximal duration of 40–50 s interspersed with rest periods of variable duration, during which there are active periods of recovery (between points: 10–20 s) and sitting (during changeover break: 90 and 120 s) (Fernandez-Fernandez, Sanz-Rivas, & Mendez-Villanueva, 2009; Ferrauti, Weber, & Wright, 2003). Therefore, to be competitive and successful, tennis players require a mixture of speed, agility, and power combined with medium to high aerobic and anaerobic capacity. Thus, successful performance cannot be defined by one predominant physical attribute; tennis demands a complex interaction of several physical components and metabolic pathways (Ferrauti, Bergeron, Pluim, & Weber, 2001; Fernandez-Fernandez et al., 2009). However, it is recognized that aerobic fitness (i.e. maximal oxygen uptake, $\dot{V}O_{2max}$) is an important component of tennis performance and enables the player not only to repeatedly generate explosive actions (e.g. strokes and on-court movements), but also ensures fast recovery between rallies, especially during long matches (Girard, Chevalier, Leveque, Micallef, & Millet, 2006; König et al., 2001; Smekal et al., 2001).

From a physiological perspective, during long and fast rallies tennis elicits average heart rates of 70–80% of maximum, and peak values around 100% of maximum heart rate. Average oxygen uptake ($\dot{V}O_2$) values correspond to approximately 50–60% of maximum ($\dot{V}O_{2max}$). As with heart rate, during intensive rallies peak $\dot{V}O_2$ values can reach values above 80% of $\dot{V}O_{2max}$ (Fernandez-Fernandez et al., 2009; Kovacs, 2007). During match-play, demands alternate between energy provision for bouts of high-intensity work (via intramuscular phosphates and glycolysis) and replenishing energy sources and restoring homeostasis during the intervals in between (by oxidative metabolism) (Glaister, 2005; Spencer, Bishop, Dawson, & Goodman, 2005). Maximal oxygen uptakes above 60 $ml \cdot kg^{-1} \cdot min^{-1}$ reported in elite male players confirm the importance of possessing a medium to high aerobic capacity for

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tennis play (Fernandez-Fernandez et al., 2009; Kovacs, 2007).

The functional testing of tennis players' performance can involve evaluation through both laboratory and field tests. Incremental exercise tests in the laboratory (e.g. direct measurement of $\dot{V}O_{2max}$ while running to exhaustion on a treadmill) are commonly used for tennis players to provide useful markers to evaluate physical fitness, identify key training areas, and characterize training effects (Girard et al., 2006). However, during treadmill testing, the mode of exercise (continuous activity) cannot simulate the intermittent demands of tennis and does not reflect the specific intra- and inter-muscular activity of both upper and lower limbs with respect to hitting and footwork (e.g. accelerations, decelerations, and changes of direction) (Fernandez, 2005).

During the last decade, efforts have been made to develop field tests that can determine the exercise capacity and technical performance of athletes with acceptable accuracy under standardized conditions (Davey, Thorpe, & Williams, 2002; Girard et al., 2006; Smekal, et al., 2000; Vergauwen, Spaepen, Lefevre, & Hespel, 1998). However, because most of these tests require expensive equipment (i.e. a ball machine, video analyses or radar measurements) (Smekal et al., 2001; Vergauwen et al., 1998), or the underlying testing criteria are difficult to standardize (rhythm, direction, bounce, and velocity of the ball machine ball feed), they are not routinely used and no reliable and representative comparisons between tennis populations can be made. Thus, the aim of this study was to develop and evaluate a tennis-specific endurance test that is valid and accurate but easy to reproduce by coaches.

Methods

Participants

Ninety-eight competitive tennis players (53 males, 45 females) of different age groups participated in the study: 37 Under-14 (20 boys, 17 girls) and 32 Under-16 (19 boys, 13 girls) players, as well as 29 adults players (15 females, 14 males) (Table I). The classifications for the age groups were made according to the national tournament guidelines of the German Tennis Federation. All players were included in the national male or female junior or adult ranking lists. The participants were made familiar with all test procedures and measurements before testing began. They completed a health questionnaire and were free from cardiorespiratory and musculoskeletal disorders. Before participation, the experimental procedures and potential risks were explained fully to the participants and the parents of the junior players, all of whom provided written informed consent. The study was performed in accordance with the ethical standards reported by Harriss and Atkinson (2009), and conformed to the recommendations of the Declaration of Helsinki.

Table I. Participant characteristics (mean ± s).

Groups	n	Age (years)	Height (cm)	Body mass (kg)
Under-14 boys	20	13.5 ± 0.7	165 ± 9	50.9 ± 7.7
Under-16 boys	19	15.1 ± 0.6	176 ± 9	65.2 ± 7.8
Adult males	14	24.0 ± 5.0	184 ± 6	75.5 ± 9.8
Under-14 girls	17	13.2 ± 0.9	165 ± 9	52.3 ± 9.9
Under-16 girls	13	15.5 ± 0.8	168 ± 7	59.0 ± 6.8
Adult females	15	20.5 ± 4.1	169 ± 4	61.5 ± 5.4

Experimental design

The study consisted of the development and validation of the "Hit & Turn Tennis Test", and its evaluation with different age groups of both sexes.

During development, a literature- and data-based (Davey et al., 2002; Girard et al., 2006; Smekal et al., 2001; Vergauwen et al., 1998) consensus for the test protocol was found (e.g. running distance, footwork, running velocity, number, duration and height of the steps, stroke activity). In close discussion with high-level coaches, a test protocol was approved that (1) corresponds closely to the workload demands of tennis, (2) is suitable for an extensive range of age and performance player categories, (3) is reproducible in coaching practice without complex testing materials, and (4) is not primarily limited by speed and power capacities.

For validation, 14 adult male players completed three Hit & Turn tests, one on a clay court and two on a carpet surface, a tennis-specific ball machine test, and an incremental treadmill run in a randomized order and each separated by at least 72 h. The results of the ball machine test were used to determine the criterion-related validity. The three Hit & Turn tests were used to calculate the test–retest correlation and reproducibility in similar and different surroundings (Hopkins, 2000). All tests were performed in the morning between 10.00 h and 13.00 h. The two Hit & Turn carpet surface tests and the ball machine test were performed at the same indoor facility with a constant ambient temperature of ~19°C. The treadmill test was completed on a treadmill (Quasar med 4.0 treadmill, hp Cosmos, Nussdorf-Traunstein, Germany) in an indoor laboratory with similar ambient conditions to the tennis centre. The Hit & Turn test on clay was completed outdoors on two experimental days with a constant temperature of ~21°C. The participants were asked not to perform any strength or endurance training in the 48 h prior to the tests and to consume a carbohydrate-rich meal 2 h before testing.

Test evaluation was undertaken in the different national training centres where junior squad players and elite adult players train. Evaluation included the Hit & Turn test together with physiological (e.g. $\dot{V}O_2$, blood lactate concentration, and heart rate) measurements, and was undertaken during the players' respective training sessions at different times in the afternoon. The players and the parents of the juniors were informed of the test procedure and they were advised not to undertake any intensive training in the 24 h prior to the tests and to consume a carbohydrate-rich meal 2 h before testing.

Hit & Turn Tennis Test

The test was developed as an acoustically controlled progressive on-court fitness test that can be performed by one or more players simultaneously (Figure 1). The aim is to follow as long as possible the signals while performing the prescribed footwork and hitting pattern. The test involves specific movements along the baseline (i.e. sidesteps and running), combined with forehand and backhand stroke simulations at the doubles court corner (distance 11.0 m). At the beginning of each test level, the player stands with their racket in a frontal position in the middle of the baseline. Upon hearing a signal, the player turns sideways and runs to the prescribed (i.e. by the CD player) backhand or forehand corner. After making their shot, they return to the middle of the court using sidesteps or crossover steps (while looking at the net). When passing the middle of the baseline again, they turn sideways and continue to run to the opponent's opposite corner (Figure 1). Hitting can be done as a stroke simulation above the cones or against a ball pendulum (www.oncourtoffcourt.com). Stroke production should be simultaneous with the "beep" signals coming from the test CD, and the quality of strokes and footwork is controlled by the coach. The test ends when the player fails to reach the cones in time (i.e. a 1-m delay occurred) or is no longer able to fulfil the criteria of the test (i.e. unable to perform footwork or strokes with the prescribed technique). Coaches are recommended to use the maximal level completed as the indicator of performance during the test. Equations are determined and evaluated describing the relation between test level and $\dot{V}O_2$ for each sample group, which enables coaches to estimate the respective $\dot{V}O_{2max}$ (i.e. for adult male players, if the player finishes level 16 it is: $2.00 \times 16 + 30 = 62$ ml · min^{-1} · kg^{-1}) (see Table V).

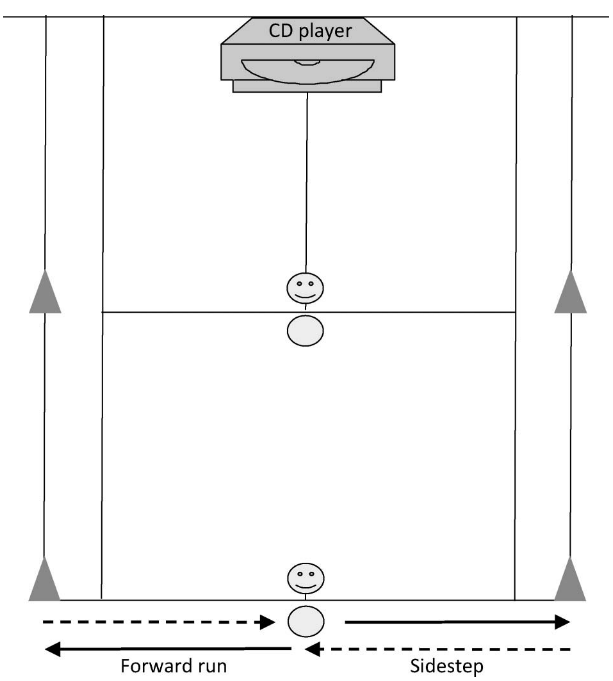

Figure 1. Running and hitting court positions during the Hit & Turn Tennis Test.

The test consists of 20 levels with a decreasing time span (0.1 s per level) between the forehand and backhand strokes starting from 4.9 s (level 1) and reducing to 3.0 s (level 20). The duration of each test level is about 47–50 s, including 12–16 strokes. Test levels are interspersed by a rest period of 10 s. After levels 4, 8, 12, and 16, a longer break of 20 s is taken for optional blood sampling (Figure 2).

For the purpose of evaluation, blood samples were taken from the earlobe after levels 4, 8, 12, and 16 as well as at the point of exhaustion. Oxygen uptake (MetaMax® II CPX, Cortex, Leipzig, Germany) and heart rate (Polar, Kempele, Finland) were measured continuously until exhaustion. As performance criteria we defined maximal performance (P_{max}) as the test level completed plus additional strokes at the point of exhaustion, and submaximal performance (P_{LA4}) as test level interpolated to a blood lactate concentration of 4 mmol · l^{-1}. Further measurements included $\dot{V}O_{2max}$ as the mean of the five highest $\dot{V}O_2$ values obtained during the test, maximal heart rate, and maximal blood lactate concentration.

Ball machine test

As the criterion of external validity, we used the ball machine test of Weber (1987), as modified by Smekal et al. (2000). This field test starts with 15 shots per minute (balls · min^{-1}), increasing by three shots per minute every 3 min until exhaustion. Two players performed the test at the same time, alternating four strokes in a row, resulting in a work-to-rest ratio of 1:1. Balls were projected by a ball machine to the right and the left corners of the

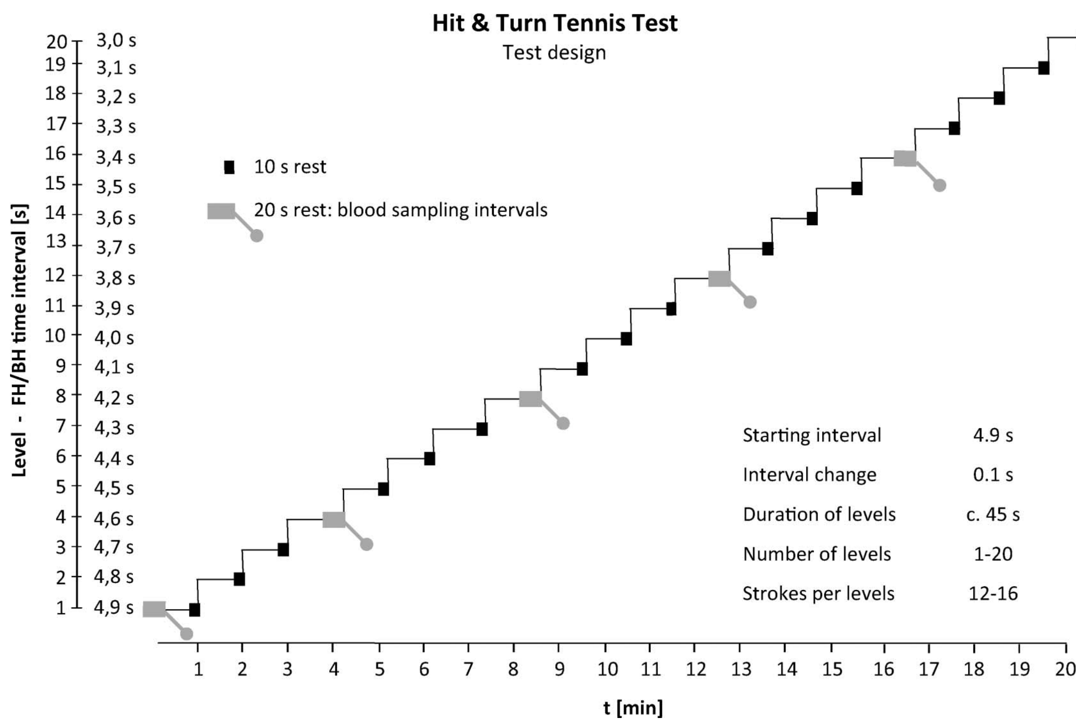

Figure 2. Progressive test design with time intervals from forehand (FH) to backhand (BH) corner.

baseline alternately. Participants had to hit alternate forehands and backhands cross court or down the line in a prescribed pattern. Direction and height of the flight of the ball, point of ball bouncing, ball velocity (70 km $\cdot$ h^{-1}), and quality of balls were kept constant during all experimental days. Blood samples were taken from the earlobe during a 30-s break after each step and at the point of exhaustion to determine blood lactate concentration. Oxygen uptake (MetaMax® II CPX, Cortex, Leipzig, Germany) and heart rate (Polar, Kempele, Finland) were measured continuously until exhaustion. As performance criteria, we used P_{max} and P_{LA4}. The mean of the five highest $\dot{V}O_2$ and heart rate values obtained during the test were regarded as $\dot{V}O_{2max}$ and maximal heart rate respectively.

Treadmill running test

The incremental laboratory treadmill run (Quasar med 4.0 treadmill, hp Cosmos, Nussdorf-Traunstein, Germany) started with an initial velocity of 2.4 m $\cdot$ s^{-1}, which was increased by 0.4 m $\cdot$ s^{-1} every 3 min until subjective exhaustion. Treadmill incline was set at 1%. Blood samples were taken from the earlobe during a 30-s break after each velocity and at the point of exhaustion to determine blood lactate concentration. Oxygen uptake (MetaMax® II CPX, Cortex, Leipzig, Germany) and heart rate (Polar, Kempele, Finland) were measured continuously until exhaustion. We report P_{max} (m $\cdot$ s^{-1}) as the point of exhaustion and P_{LA4} (m $\cdot$ s^{-1}) interpolated to a blood lactate concentration of 4 mmol $\cdot$ l^{-1}. The mean of the five highest $\dot{V}O_2$ and heart rate values obtained during the test were regarded as $\dot{V}O_{2max}$ and maximal heart rate respectively.

Physiological measurements

Oxygen uptake. Expired air was analysed continuously for gas volume (Triple digital-V® turbine), oxygen concentration (zirconium analyser), and carbon dioxide concentration (infrared analyser) using the MetaMax® II CPX system (Cortex, Leipzig, Germany). The portable measurement unit was carried by the player in the same way during all tests. The heart rate monitor (Polar, Kempele, Finland) was used alongside the MetaMax® system. Data were stored by the system and downloaded and sorted after each test by MetaSoft®. Gas and volume calibration of the measurement device was done in the morning of each test day. Room air calibration occurred before each test.

Blood lactate. Capillary blood samples (20 μl) were taken from the earlobe during the break immediately after finishing the respective test level. Local blood circulation was increased by Finalgon®. Blood samples were haemolysed in 2-ml microtest tubes. Blood lactate concentration was analysed enzymatic-amperometrically by the Biosen C-Line Sport (EKF-Diagnostik, Barleben, Germany) immediately after each test.

Statistical analysis

Data are presented as mean values and standard deviations (*s*). For test validation when testing on the same (carpet vs. carpet) or on different surfaces (carpet vs. clay), Bland and Altman analysis was performed and the mean bias ($\pm s$) and the lower and upper 95% limits of agreement were calculated (Bland & Altman, 1986). Since no positive relationship was observed between the individual bias and the size of the measurements, and thus there were no heteroscedastic errors, further transformations (e.g. calculating the ratio limits of agreement using log transformed measurements) were not necessary (Nevill & Atkinson, 1997). In addition, Pearson's product–moment correlation coefficients (*r*) were calculated between the respective test–retests as well as between the Hit & Turn maximum performance levels (P_{max}) and the players' ranking positions.

Data from test evaluation were analysed by a multi-factor analysis of variance (ANOVA) for repeated measurements after testing for sphericity using the Mauchly's test and when needed the Greenhouse-Geisser correction. The main factors were sex (male vs. female), age (Under-14, Under-16, adults), and measurement point (test levels). In the case of significance, interactions between these factors and simple effects (Newman-Keuls test) were verified. Statistical significance was set at $P < 0.05$(*) and $P < 0.01$(**).

Results

Test validation

Maximal values for $\dot{V}O_2$, heart rate, and blood lactate concentration were not significantly different between the Hit & Turn, ball machine, and treadmill tests. The treadmill test tended towards the highest values, and the ball machine test towards the lowest values. Maximal and submaximal performances, as well as all physiological measurements, were closely correlated between the Hit & Turn and ball machine tests ($P < 0.01$). The correlation coefficients tended to be lower when comparing the Hit & Turn and treadmill tests. Maximal test performance was not correlated between the treadmill and ball machine tests (Table II). A small negative but non-significant relationship was observed between the players' maximum test level (P_{max}) and their national ranking ($r = -0.475$).

The test–retest correlation of P_{max} during the Hit & Turn test was significant and tended to be higher when testing on the same ($r = 0.835$) than on different surfaces ($r = 0.745$). Maximal values for $\dot{V}O_2$, heart rate, and blood lactate concentration were also correlated significantly ($P < 0.01$) in both retests. Mean values of P_{max} tended to increase in both retests. The mean bias for the maximum test level reached during test repetition on the same (0.7 ± 1.6) and on different surfaces (1.3 ± 1.6) indicates a 5–10 % increase in test performance. The respective limits of agreement are shown in Table III. No heteroscedastic errors were found in the Bland-Altman analysis. No correlations between the individual bias and the size of the measurements were calculated ($r = -0.16$ for P_{max}; $r = -0.14$ for $\dot{V}O_{2max}$; $r = -0.36$ for maximal heart rate; and $r = -0.03$ for maximal blood lactate concentration).

Test evaluation

The results of the test evaluation in different age groups are shown in Table IV. Maximal Hit & Turn performance was significantly higher in males than females (ANOVA factor sex) and increased by consecutive age group in boys but not in girls (ANOVA factor age). Maximal oxygen uptake and P_{LA4} showed only a slight but significant increase from the youngest boys to adults but tended to decrease by consecutive age group in girls. Maximal heart rate (decrease) and maximal blood lactate concentration (increase) were clearly age-related in boys but not in girls (Table IV).

Maximal Hit & Turn performance was not correlated with body mass or height in any of the groups (Table V). Absolute $\dot{V}O_2$ [(ml · min^{-1}) was closely correlated with body mass but not P_{max}. In contrast, relative $\dot{V}O_2$ (ml · min^{-1} · kg^{-1}) was significantly correlated with P_{max} in all samples. A

Table II. Pearson's product–moment correlation coefficients (*r*) between the Hit & Turn Tennis Test, the tennis ball machine test, and the treadmill running test ($n = 14$ adult males).

	P_{max} (level)	P_{LA4} (level)	$\dot{V}O_{2max}$ (ml · min^{-1} · kg^{-1})	HR_{max} (beats · min^{-1})	LA_{max} (mmol · l^{-1})
Hit & Turn vs. treadmill	0.655*	0.605*	0.799**	0.662*	0.609*
Hit & Turn vs. ball machine	0.808**	0.820**	0.961**	0.951**	0.860**
Treadmill vs. ball machine	0.560	0.708*	0.789**	0.474	0.670*

Note: P_{max} = maximal test performance; P_{LA4} = submaximal test performance at a blood lactate concentration of 4 mmol · l^{-1}); $\dot{V}O_{2max}$ = maximal oxygen consumption; HR_{max} = maximal heart rate; LA_{max} = maximal blood lactate concentration. *$P < 0.05$; **$P < 0.01$.

Table III. Test–retest reliability of the Hit & Turn Tennis Test when testing on the same ($carpet_1$ vs. $carpet_2$) or on different surfaces ($carpet_{1,2}$ vs. clay) ($n = 14$ adult males).

	P_{max} (level)	$\dot{V}O_{2max}$ ($ml \cdot min^{-1} \cdot kg^{-1}$)	HR_{max} (beats $\cdot min^{-1}$)	LA_{max} ($mmol \cdot l^{-1}$)
$Carpet_1$ vs. $carpet_2$				
$Carpet_1$ (mean $\pm s$)	13.1 ± 2.7	54.2 ± 4.7	197 ± 12	10.2 ± 2.5
$Carpet_2$ (mean $\pm s$)	13.8 ± 2.6	52.1 ± 6.6	194 ± 10	9.5 ± 3.2
Bias (mean $\pm s$)	0.7 ± 1.6	-2.0 ± 2.9	-2.6 ± 7.2	-0.7 ± 2.1
Limits of agreement (lower/upper)	−2.4/3.9	−7.8/3.6	−16.7/11.4	−4.8/3.4
Correlation coefficient (*r*)	0.835**	0.925**	0.813**	0.905**
$Carpet_{1,2}$ vs. clay				
$Carpet_{1,2}$ (mean $\pm s$)	13.5 ± 2.5	53.3 ± 5.0	196 ± 7	9.8 ± 2.2
Clay (mean $\pm s$)	14.8 ± 1.8	53.7 ± 4.5	198 ± 7	9.9 ± 1.6
Bias (mean $\pm s$)	1.3 ± 1.6	0.54 ± 3.7	3.2 ± 9.4	0.1 ± 1.7
Limits of agreement (lower/upper)	−1.9/4.5	−6.8/7.9	−15.6/22.0	−3.3/3.5
Correlation coefficient (*r*)	0.745**	0.746**	0.887**	0.801**

Note: P_{max} = maximal test performance; $\dot{V}O_{2max}$ = maximal oxygen consumption; HR_{max} = maximal heart rate; LA_{max} = maximal blood lactate concentration. Limits of agreement = bias − 2*s* to bias + 2*s*. ***$P < 0.01$.

Table IV. Maximal and submaximal performance, and physiological measurements during the Hit & Turn Tennis Test in the different groups (ANOVA effects for sex and age groups are indicated) (mean $\pm s$).

Groups	P_{max} (level)	P_{LA4} (level)	$\dot{V}O_{2max}$ ($ml \cdot min^{-1} \cdot kg^{-1}$)	HR_{max} (beats $\cdot min^{-1}$)	LA_{max} ($mmol \cdot l^{-1}$)
Under-14 boys	13.1 ± 2.5	10.6 ± 1.6	55.0 ± 4.0	205 ± 7	6.0 ± 1.4
Under-16 boys	14.4 ± 2.2	10.2 ± 2.8	57.7 ± 6.4	201 ± 5	7.3 ± 1.7
Adult males	16.1 ± 2.3	11.6 ± 2.3	60.4 ± 5.3	198 ± 7	8.4 ± 1.3
Under-14 girls	$11.6 \pm 1{,}8$	7.6 ± 1.7	50.4 ± 7.4	206 ± 6	6.8 ± 1.3
Under-16 girls	11.7 ± 2.2	7.2 ± 3.4	49.0 ± 3.9	203 ± 4	7.9 ± 1.4
Adult females	11.8 ± 2.3	5.9 ± 3.0	47.3 ± 4.6	204 ± 3	7.7 ± 0.8
Sex (m_{U14}, f_{U14})	0.007**	0.005**	0.024*	0.401	0.097
Sex (m_{U16}, f_{U16})	0.002**	0.000**	0.000**	0.679	0.245
Sex (m, f)	0.000**	0.000**	0.000**	0.018*	0.029*
Age (m)	0.000**	0.024*	0.018*	0.000**	0.000**
Age (f)	0.971	0.041*	0.310	0.612	0.056

Note: P_{max} = maximal test performance; P_{LA4} = submaximal test performance at a blood lactate concentration of 4 $mmol \cdot l^{-1}$); $\dot{V}O_{2max}$ = maximal oxygen consumption; HR_{max} = maximal heart rate; LA_{max} = maximal blood lactate concentration. m = male, f = female. *$P < 0.05$; **$P < 0.01$.

Table V. Pearson's product–moment correlation coefficients (*r*) between maximal Hit & Turn Test performance and anthropometric characteristics as well as the $\dot{V}O_{2max}$ related to body mass by the use of different mass exponents.

Groups	$\dot{V}O_{2max}$ ($ml \cdot min^{-1}$)	$\dot{V}O_{2max}$ ($ml \cdot min^{-1} \cdot kg^{-0.7}$)	$\dot{V}O_{2max}$ ($ml \cdot min^{-1} \cdot kg^{-1}$)	Height (cm)	Body mass (kg)
Body mass (kg)					
Under-14 boys	0.880**	0.482*	−0.049	0.880**	
Under-16 boys	0.527*	0.108	−0.357	0.683**	
Adult males	0.821**	0.344	−0.084	0.826**	
Under-14 girls	0.756**	0.152	−0.272	0.873**	
Under-16 girls	0.753**	−0.020	−0.329	0.628*	
Adult females	0.630*	0.176	−0.093	0.381	
P_{max} (level)					
Under-14 boys	0.515*	0.504*	0.822**	0.342	0.422
Under-16 boys	0.598*	0.758**	0.783**	0.082	−0.087
Adult males	0.185	0.484	0.590*	−0.530	−0.180
Under-14 girls	0.415	0.721**	0.755**	−0.187	−0.530
Under-16 girls	0.283	0.674*	0.729**	0.099	−0.238
Adult females	0.347	0.592*	0.688**	−0.406	−0.233

Note: P_{max} = maximal test performance; $\dot{V}O_{2max}$ = maximal oxygen consumption. *$P < 0.05$; **$P < 0.01$.

less clear relationship was found when using a lower mass exponent ($ml \cdot min^{-1} \cdot kg^{-0.7}$).

During the Hit & Turn test, $\dot{V}O_2$ increased almost linearly with test levels in all groups (Figure 3). Oxygen uptake during several submaximal test levels was significantly higher in younger boys (levels 2, 3, 4, 5, 7, 8, 9) and girls (levels 5, 6). Functional equations for the relation between $\dot{V}O_2$ and Hit & Turn level for each group were calculated (Table VI). We compared the empirically measured $\dot{V}O_{2max}$ values with the estimated $\dot{V}O_{2max}$ values based on P_{max} in the different groups. While the individual absolute differences between both values (Δ) and the 95% confidence intervals are comparatively low, the correlation between empirical and estimated $\dot{V}O_{2max}$ values was not uniformly significant (Table VI).

Discussion

The main aim of the present study was to develop a specific, easily reproducible, and reliable endurance test for tennis players. A secondary aim was to design a test suitable for a wide range of age and performance groups. We found a close correlation between the Hit & Turn and the ball machine tests, which was the external criterion for validity (Table II), as well as significant test–retest correlations, even on different surfaces (Table III). Therefore, it seems that the Hit & Turn Tennis test can be recommended as a valid and sufficiently reproducible tool for the measurement of tennis-specific endurance.

Validation of the Hit & Turn test

Generally, it is well accepted that performance testing in intermittent sports should consider the specific workload demands. Determination of aerobic fitness is assumed to be highly dependent upon the mode of testing in continuous activities, which means that, for example, runners are generally tested on a treadmill and rowers on a rowing ergometer (Basset & Boulay, 2000; Girard et al., 2006). As a consequence, the main aim of the study was to design a test that mimics tennis-specific movement patterns by including stroke activities and specific footwork. Interestingly, we found that the correlation between the Hit & Turn maximal performance and treadmill tests was weaker than that between the Hit & Turn and ball machine tests, and no significant correlation was observed between the ball machine and treadmill tests (Table II). This is related to the involvement of the upper body muscles required for the ball stroke, as well as the involvement of additional muscles (e.g. bi-articulate leg muscles and hip adductors) that are active during running and sidestep movements (Jacobs, Bobbert, & Van Ingen Schenau, 1993, 1996). In this regard, Girard et al. (2006) reported that peak $\dot{V}O_2$ was higher during an intermittent racket test compared with an incremental test performed on a treadmill, probably due to the involvement of upper body muscles required for the simulated ball hitting action. Only a small negative but not significant correlation was found between players' Hit & Turn performance and their ranking position ($r = -0.475$), highlighting that tennis requires a complex interaction of different physical components (i.e. speed, agility, and power combined with medium to high aerobic capabilities) to achieve a good performance on the court.

During the test–retests, there was a strong correlation between maximal test performance and similar physiological demands, even when playing on different surfaces (Table III). In the present study, the players' activity profile (i.e. number of strokes, duration of exercise bouts) was controlled by the test CD, preventing the use of different tactical behaviour previously described between clay and hard court surfaces (Girard & Millet, 2004; Murias, Lanatta, Arcuri, & Laino, 2007). On the other hand, one may expect differences in the biomechanical efficiency (i.e. longer ground contact time on clay courts; higher rate of acceleration on faster surfaces) of

Table VI. Evaluation of empirically derived functional equations for the estimation of $\dot{V}O_{2max}$ based on maximal Hit & Turn Test performance level in different groups.

Groups	Equations	VO_{2max} ($ml \cdot min^{-1} \cdot kg^{-1}$)	$VO_{2max\text{-}est}$ ($ml \cdot min^{-1} \cdot kg^{-1}$)	Δ	95%CI	r
Under-14 boys	f(x) = 1.66x + 33.0 {6;14}	55.0 ± 4.0	54.3 ± 2.0	2.9 ± 2.6	−1.0/2.6	0.32
Under-16 boys	f(x) = 1.68x + 31.0 {6;12}	57.7 ± 6.4	56.2 ± 3.9	5.2 ± 4.5	−0.5/3.5	0.78**
Adult males	f(x) = 2.00x + 30.0 {8;16}	60.4 ± 5.3	62.1 ± 4.6	3.6 ± 3.0	−4.3/0.9	0.59*
Under-14 girls	f(x) = 1.21x + 35.0 {6;11}	50.4 ± 7.4	50.1 ± 2.3	4.4 ± 3.7	−2.7/3.3	0.76**
Under-16 girls	f(x) = 1.25x + 32.0 {6;11}	49.0 ± 3.9	47.9 ± 3.1	2.3 ± 1.6	−0.5/2.7	0.73**
Adult females	f(x) = 1.30x + 30.7 {6;11}	47.3 ± 4.6	46.1 ± 3.0	2.8 ± 2.1	−0.7/3.1	0.67**

Note: $\dot{V}O_{2max}$ = maximal oxygen consumption; $\dot{V}O_{2max\text{-}est}$ = estimated maximal oxygen consumption; Δ = absolute individual differences between empirical and estimated values; CI = confidence intervals for calculating the empirical value; r = Pearson's product–moment correlation coefficient. *$P < 0.05$; **$P < 0.01$.

playing surfaces (Girard, Eicher, Fourchet, Micallef, & Millet, 2007). However, the effect of the court surface appears to be balanced when the tactical impact is eliminated, with overall the same results on the two playing surfaces.

It should be noted that the mean bias for P_{max} showed an increase in performance during two test repetitions, independent of the court surface, and the interval between the limits of agreement is relatively high. These results, calculated by Bland-Altman analysis, are mainly due to two individuals showing an increase in P_{max} from levels 9 to 15 and from levels 10 to 14, respectively. We can speculate that, during a second test, some players were already adapted from a coordination point of view (e.g. footwork, stroke activity), leading to a more economical technical solution. Thus, $\dot{V}O_2$ on submaximal test levels was lower and a similar $\dot{V}O_{2max}$ at a higher maximal test level was achieved (Table III). In general, we discuss these effects as a typical consequence of an increase in test validity, which usually occurs with a decrease in test reproducibility (Hopkins, 2000). This leads to the practical recommendation of controlling the quality of movement properly, as well as to prepare the testing at least once to ensure sufficient reproducibility.

Evaluation of the Hit & Turn test

Clear statistical differences were observed for maximal performance and physiological demands when conducting the Hit & Turn test with different groups of tennis players (Table IV). In boys of different age groups, P_{max} increased uniformly with the adult players reaching the highest test levels. On the other hand, we found that the body mass related $\dot{V}O_{2max}$ only showed slight increases in older age groups (Table IV). It has previously been reported that the relative $\dot{V}O_{2max}$ in boys remained stable with increasing age from 5 to 16 years, while running performance (e.g. running time to complete one mile) improved significantly (Krahenbuhl & Pangrazi, 1983; Krahenbuhl, Skinner, & Kohrt, 1985; Morgan et al., 2004). This could be explained by a lower running economy in the children, caused by biomechanical limitations (i.e. force production and dysfunctional muscle co-contractions) (Rowland, 2007; Rowland, Staab, Unnithan, Rambusch, & Siconolfi, 1990). In the present study, $\dot{V}O_2$ during several submaximal Hit & Turn levels was significantly higher in younger boys (levels 2, 3, 4, 5, 7, 8, 9) (Figure 3), pointing to an impaired exercise economy in younger players even during a tennis-specific exercise. One could also speculate that the increase in height in older players might also impact Hit & Turn performance, since a wider range of the arms shortens the distance to be covered when running from the forehand to the backhand corner (Figure 1). However, no correlation was observed between maximal Hit & Turn performance and anthropometric characteristics (Table V).

Girls of different age groups achieved a lower P_{max} than the boys and no increase in P_{max} was found in older players when comparing the Under-14, Under-16, and adult female players. In addition, there was an age-dependent decrease in body weight related $\dot{V}O_{2max}$ (Table IV). This gender-specific relationship (older boys: higher performance than younger boys with similar $\dot{V}O_2$; older girls: similar performance with lower $\dot{V}O_2$) has previously been described in the literature for typical endurance exercises and has mainly been attributed to female-specific changes in body composition during maturation (Krahenbuhl et al., 1985). As already discussed for the boys, a lower exercise economy (i.e. higher $\dot{V}O_2$) was also found for the younger girls (levels 5, 6), explaining a similar P_{max} to the older players despite a lower $\dot{V}O_{2max}$ (Figure 3).

Regarding the practical value of the performance criteria obtained from the Hit & Turn test, besides P_{max} we calculated P_{LA4} and $\dot{V}O_{2max}$ (related to different mass exponents) (Table IV). These measurements are optional, providing additional information (e.g. $\dot{V}O_{2max}$ and interpolation of P_{LA4}), independent of the player's motivation to reach P_{max}. On the other hand, P_{LA4} only provides useful information in adult players since maximal blood

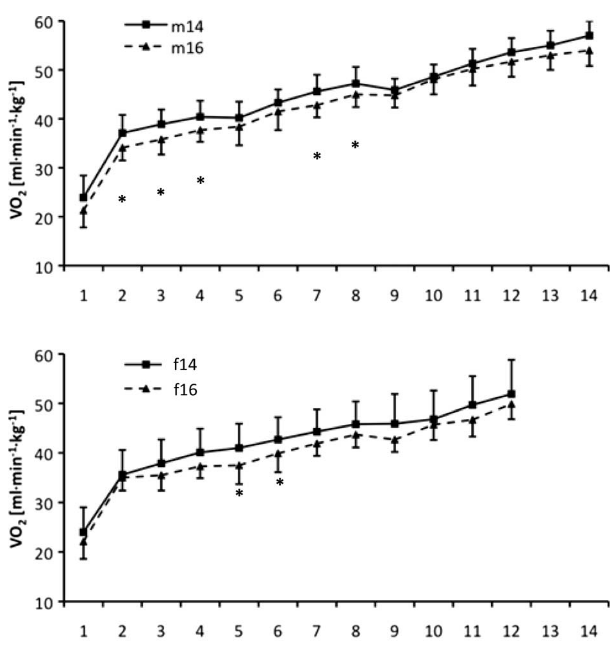

Figure 3. Oxygen consumption ($\dot{V}O_2$) of female (f) and male (m) junior tennis players of different age groups during the Hit & Turn Tennis Test. *Significant differences at each test level between Under-14 and Under-16 players ($P < 0.05$).

lactate concentrations were significantly lower in the younger age groups, especially in males (Table IV), pointing to a lower rate of blood lactate production, a well-known effect described previously (Ratel, Bedu, Hennegrave, Doré, & Duché, 2002; Ratel, Duche, Hennegrave, Van Praagh, & Bedu, 2002).

Although there is no consensus in the literature regarding the usefulness of different body mass related calculations of relative $\dot{V}O_{2max}$ in children, current suggestions for the respective mass exponents differ between 0.6 and 0.9 (Heymsfield & Pietrobelli, 2010; Svedenhag 1995). In our study, we found the closest relationship between $\dot{V}O_{2max}$ and P_{max} and the best elimination of the body mass impact on $\dot{V}O_2$ when using a mass exponent of 1.0 ($ml \cdot min^{-1} \cdot kg^{-1}$) in most age groups (Table V).

Maximal oxygen uptake is the most common parameter used to describe aerobic capacity in athletes (Bosquet, Léger, & Legros, 2002; Hammond & Froelicher, 1984). For practical reasons, several attempts have been made to estimate $\dot{V}O_{2max}$ from test performance using functional equations (Légér & Lambert, 1982; Ruiz et al., 2009; Wilkinson, Fallowfield, & Myers, 1999). In the present study, we developed and evaluated these respective equations for each group (Table VI). We found that the quality of the individual estimation was acceptable, but the correlation between the two $\dot{V}O_{2max}$ values was not uniformly significant. Nevertheless, we believe that estimated $\dot{V}O_{2max}$ could be a secondary performance criterion, assuming P_{max} to be the most meaningful value, especially if players of different age or maturation are to be compared.

In conclusion, the results of the present study show a close correlation between the Hit & Turn and ball machine tests, which was defined as the external criterion for validity, as well as significant test–retest correlations, even on different surfaces. Together with the differences in test performance found for the different groups by age and sex, we believe that the Hit & Turn test is a valid and reliable indicator for tennis-specific endurance, which is recommended as a practical tool for players of all ages and levels. Moreover, it would be interesting to use the submaximum and maximum Hit & Turn levels for training purposes. In this regard, the combining of different training strategies (i.e. high-intensity aerobic interval training) warrants further investigation.

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