Monitoring technical tennis performance under increasing physical intensity by the PTTF-test

Supervisión del desempeño técnico en tenis cuando la intensidad física es cada vez mayor mediante la prueba PTTF

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Abstract

Monitoring technical skills under increasing physical intensity is important for determining a player's performance level in tennis. Therefore, the aim of this study was to determine to what extent the new Physical Technical Tennis-specific Field test (PTTF-test) was able to capture fluctuations in technical skill under increasing physical intensity in adolescent talented tennis players. Forty adolescent players (21 males, 19 females, mean age = 15.4 yrs) performed the PTTF-test until exhaustion (i.e., when they were not able to hit two subsequent oncoming balls with an adequate technique). Technical skills (stroke velocity, stroke accuracy, VA-index and percentage errors) were compared between physical intensity levels, age categories and genders. For all age categories and genders, physical intensity (heart rate) increased between the 'BASELINE'-situation and the 'FINAL'-situation (p<.001). All technical skills, i.e. stroke velocity, stroke accuracy, VA-index and percentage errors, decreased when comparing the FINAL intensity level to the BASELINE intensity level (p<.001). Players in older age categories (16+) reached a higher PTTFlevel and exhibited lower mean heart rates than players in the youngest age category (U14) in both the 'BASELINE'-situation and the 'FINAL'-situation depending on the level players reached (p<.010). These findings show that the PTTF-test is able to analyse and monitor the performance of technical skills under increasing physical intensity in adolescent talented tennis players.

Keywords: *Racket sports, field test, physical fitness, technical skills, tennis players, youth sports.*

Resumen

Supervisar las habilidades técnicas cuando la intensidad física es cada vez mayor es importante para determinar el nivel de desempeño de un jugador en tenis. Por lo tanto, el objetivo de este estudio fue determinar hasta qué punto la nueva prueba de campo físico-técnica específica para el tenis (prueba PTTF) puede capturar las variaciones en la habilidad técnica en jugadores talentosos de tenis adolescentes cuando la intensidad física es cada vez mayor. Cuarenta jugadores adolescentes (21 hombres, 19 mujeres, edad media = 15,4 años) completaron la prueba PTTF hasta el fallo (cuando en recepción no eran capaces de golpear dos pelotas sucesivas con una técnica adecuada). Las habilidades técnicas (velocidad del golpe, precisión del golpe, velocidad y precisión de la pelota y el porcentaje de error) fueron comparadas entre los niveles de intensidad física, las categorías por edad y el sexo. Para todas las categorías de edad y sexos, la intensidad física (frecuencia cardíaca) aumentó entre la situación BASE y la situación FINAL (p<.001). Todas las habilidades técnicas, i.e. velocidad del golpe, precisión del golpe, velocidad y precisión de la pelota y porcentaje de error, disminuyeron al comparar el nivel de intensidad FINAL con el nivel de intensidad de BASE (p<.001). Los jugadores en las categorías de mayor edad (16+) alcanzaron

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un nivel PTTF más alto y mostraron frecuencias cardíacas menores que los jugadores en la categoría más joven (U14) tanto en la situación BASE como en la FINAL dependiendo del nivel que los jugadores alcanzaban (p<.010). Estos hallazgos muestran que la prueba PTTF es capaz de analizar y supervisar el desempeño de las habilidades técnicas cuando la intensidad física es cada vez mayor en jugadores adolescentes de tenis talentosos.

Palabras clave: *deporte de raqueta, prueba de campo, estado físico, habilidad técnica, jugadores de tenis, deporte juvenil.*

INTRODUCTION

"You need to be constantly playing well throughout five hours if you want to win a match like this. I guess there is an endurance part." (Novak Djokovic about his win in 2019 over Roger Federer in the longest Wimbledon final in history (Amako, 2019)). This quote reflects the importance of maintaining high performance in tennis up to the end of every match. Even more, it reflects the importance of maintaining high performance under physically demanding situations, in which decrements of performance might be expected. Tennis performance is directly related to a player's technical skills. They are crucial for discriminating tennis players of various performance level (Baiget, Fernandez-Fernandez, Iglesias, Vallejo, & Rodriguez, 2014; Baiget, Iglesias, & Rodriguez, 2016; Del Villar, Garcia Gonzalez, Iglesias, Perla Moreno, & Cervello, 2007; Kolman, Huijgen, Kramer, Elferink-Gemser, & Visscher, 2017; Lyons, Al-Nakeeb, Hankey, & Nevill, 2013; Vergauwen, Spaepen, Lefevre, & Hespel, 1998; Vergauwen, Madou, & Behets, 2004). Though the importance of technical skills is undisputed, it seems especially important to persevere technical performance throughout the match. Also, under the prolonged physical demands towards the end of matches players need to retain their technical skills at a high level (Kovacs, 2004; Kovacs, 2007). Measuring technical skills under increasing physical intensity is difficult and no tests so far captured all relevant components.

Tennis is a sport with an intermittent profile (Kovacs, 2006). The aerobic and anaerobic energy demands are high throughout these intermittent profiled matches (Bangsbo, 1994; Kovacs, 2007). During long and high-intensity rallies, heart rates of 70-80% of the maximum heart rate and peak heart rates of 100% of the maximum heart rate are elicited (Baiget et al., 2014). The aerobic and anaerobic capacity of a tennis player may therefore highly influence individual performance and match outcome. Consequently, the monitoring of technical and physical skills under increasing physical intensity in a tennis-specific setting is valuable for determining a tennis player's performance level.

Technical skills may be evaluated based on stroke analysis (which captures the mechanical aspects of strokes), as well as based on stroke outcomes (such as stroke accuracy and stroke velocity). Further on, we continue using the term technical skills to describe the stroke outcomes. Technical tennis skills that are most often studied are stroke velocity and stroke accuracy. Stroke velocity (Kolman et al., 2017; Landlinger, Stöggl, Lindinger, Wagner, & Müller, 2012; Vergauwen et al., 1998; Vergauwen et al., 2004) and stroke accuracy (Baiget et al., 2014; Baiget et al., 2016; Del Villar et al., 2007; Kolman et al., 2017; Lyons et al., 2013; Vergauwen et al., 1998; Vergauwen et al., 2004) discriminate between players of different performance levels with better players reaching higher stroke velocities and being more accurate. Not surprisingly, a combination of stroke velocity and stroke accuracy, the VA-index also distinguishes tennis players of different performance levels (Kolman et al., 2017; Vergauwen et al., 1998). Moreover, higher ranked tennis players make fewer stroke errors than their lower ranked counterparts (Kolman et al., 2017; Vergauwen et al, 1998). Therefore, the proposed set of technical skills should contain stroke velocity, stroke accuracy, the VA-index and percentage of errors (PE).

The development of a player's tennis performance is influenced by individual, environmental and task constraints (Newell, 1986). Over time these constraints may change and therefore influence tennis performance. Especially within youth athletes, in which individual constraints change rapidly due to changes in biological development and training (Malina, Rogol, Cumming, Coelho e Silva, & Figueiredo, 2015), improvements but also stagnation in tennis performance are quite common. For instance, physical fitness has a uniform rapid development for male youth tennis players, whereas the development flattens out at the age of 14-15 years old for female youth tennis players (Faff, Ladyga, & Starczewska-Czapowska, 2000; Kramer, Huijgen, Elferink-Gemser, & Visscher, 2016). Although studies measuring technical skills over age are scarce, it has been established that forehand stroke velocity and backhand stroke velocity are positively correlated with age for male youth tennis players (González-González, Rodríguez-Rosell, & Clavero-Martin, 2018). Still, the lack of information regarding the development of the remaining technical skills over age shows the need for new studies. Therefore, capturing the differences of physical and technical skills between male and female tennis players over age will be an important topic within this study.

The interaction between a tennis player and its opponent makes individual tennis performance difficult to determine in matches, as the opponent influences a player's performance as well. Therefore, to capture a player's performance at a certain moment or to monitor progress over time, fixed field test protocols are valuable to measure tennis skills (Kolman et al., 2017; Landlinger et al., 2012; Lyons et al., 2013; Vergauwen et al., 1998; Vergauwen et al., 2004). Fixed field test protocols are essential to compare a player to another player or with performance benchmarks for performance discrimination purposes. Monitoring technical skills under increasing physical intensity is important for determining a tennis player's performance level in tennis. Test protocols including a tennis-specific execution of strokes in incremental stages to induce higher intensities and fatigue have been developed, such as the modified specific endurance field test and the TEST-protocol (Baiget et al., 2014; Brechbuhl, Girard, Millet, & Schmitt, 2016; Smekal et al., 2000). Yet, this specific endurance field test protocol lacks rest intervals given the intermittent character of tennis (Baiget et al., 2014) and the technical performance of strokes is no outcome measure of interest in the TEST protocol (Brechbuhl et al., 2016). Additionally, in these test protocols oncoming ball direction was alternately between the forehand and backhand side of the participant, leading up to a back-and-forth running protocol between the sidelines of the court. Such a back-and-forth running protocol is neglecting the importance of tennis-specific footwork between the strokes. Randomization of oncoming ball direction could solve this problem.

In order to successfully monitor technical tennis skills under increasing physical intensity in a maximized tennis-specific setting, a suitable field test protocol is required. Therefore, the TEST-protocol and specific endurance field test protocol (Baiget et al., 2014; Brechbuhl et al., 2016) will form the basis, and will be modified with respect to abovementioned required adjustments. The current study introduces the new Physical Technical Tennis-specific Field test (PTTF-test) protocol and aims to determine to what extent the PTTF-test is able to capture fluctuations in technical skill under increasing physical intensity in adolescent talented tennis players. The study aims to capture decreasing technical performance under increasing physical intensity. In addition, we will compare performance in the PTTF-test between age categories and between boys and girls. We hypothesize that the PTTF-test succeeds in capturing decreasing technical performance under increasing physical intensity for adolescent talented tennis players.

MATERIALS AND METHODOLOGY

Participants

The minimum age for participation was 12 years old. Participants were excluded in case of a health condition or injury that would make them unable to perform a physical test, or if they were not allowed by the trainer or medical staff. A total of 21 male tennis players (age 15.5 ± 2.5 yrs) and 19 female tennis players (age 15.2 ± 2.2 yrs) from the Netherlands participated in this study. They were considered elite players, as they were the nationally highest ranked performers within their age categories: U14, U16 and 16+ (see also Table 1).

Before the measurements, participants and their parents were fully instructed on the objective, design, method and risks of the test by an information letter. Both the participants and parents (if the participant was under the age of 16) provided written informed consent prior to inclusion within the study. The local ethical committee of the psychology department of the University of Groningen approved the study (PSY-1819-S-0262) that was performed consonantly to the ethical standards derived from the Declaration of Helsinki.

PTTF-test set-up

The measurements for this study took place on a hardcourt indoor tennis court. This court has a Playsight Smartcourt for video-review and analytics and as such is equipped with 10 on-court cameras. The system allows for the valid registration of stroke velocity and ball placement and the registration of session video material. To measure stroke accuracy, target areas were presented on-court to which participants were instructed to direct their strokes. Two target area's (squared plastic of 100.6 x 68.7 cm) were placed near the intersections of the baseline with both singles sidelines, precisely 100.6 cm from the baseline and 68.7 cm from the sidelines, as presented in Figure 1. Set-up of the target area's was based on the D4T test (Kolman et al., 2017), but exact dimensions were slightly adjusted to the pre-specified dimensions of the line system that is available in the Playsight Smartcourt software. During the PTTF-test protocol the participants were fed with regular tennis balls (Dunlop Fort Max TP) by a manually programmed ball machine (Promatch SmartShot Xtra). The ball machine was located in the middle of the court between the singles sidelines and 100.6 cm behind the baseline, as shown in Figure 1. Participants used their own tennis racket during the test protocol and wore a pulse monitoring belt (Polar Team² Pro) for heart rate registration.

PTTF-test protocol

Prior to the PTTF-test protocol, the participants performed a 5-min specific warming-up session, including running, arm rotations, lunges, squat jumps, sprints and 30 practice strokes fed by the ball machine. This warming-up session was created by and performed under the supervision of physical staff members. In the PTTF-test protocol the participants were fed with oncoming balls by the ball machine and instructed to hit both forehand and backhand strokes crosscourt towards the presented targets in an incremental physical intensity level design.

Participants were instructed to hit balls with "the best possible velocity-accuracy ratio", whereby slice strokes were not permitted. Physical intensity levels consist of 60 s activity, which are alternated with 30 s rest, as adopted from the TEST protocol (Brechbuhl et al., 2016). This rest period closely approaches the 25 s intervals between points in a tennis match. Oncoming ball frequency at the first intensity level is 12 strokes. min^{-1}. Physical intensity increases for every new level of 60 s. Oncoming ball frequency increases with 2 strokes. min^{-1} up to 18 strokes.min^{-1} at level 4. From level 5 and on, oncoming ball frequency increases with 1 stroke. min^{-1} per level. Oncoming ball direction, velocity and height are randomised within the intensity levels for the participants to evoke tennis-specific footwork between the strokes. Oncoming ball velocity was based on the D4T test and further adjusted during trials to induce more variability (Kolman et al., 2017). Eventually, oncoming ball velocity in the PTTF-test is randomised within the range of 60 and 80 kph .The randomised pattern varies per intensity level as well, to prevent for habituation of the pattern by the participant. The same standardized pattern of oncoming balls is presented to all par-ticipants to secure a standardized test protocol. The PTTF-test protocol ends with a participant's voluntary exhaustion or when the participant is not able to hit two subsequent oncoming balls with an adequate technique as determined by experienced coaches (hit the ball with the racket snares instead of the racket frame and hit the ball in a controlled manner in the direction of the net) or when the participant fails in striking three oncoming balls in total within a given intensity level.

Outcome variables PTTF-test

The determination of physical responses by Polar heart rate measurements has been commonly used throughout activity (Baiget et al., 2014; Baiget, Fernandez-Fernandez, Iglesias, Vallejo, & Rodriguez, 2015). This method for the determination of physical responses is a valuable tool in order to secure the ideal rest interval of tennis through the absence of any additional measurements during the rest intervals. The Polar pulse monitoring belts allow for the registration of participants' heart rate during the PTTF-test as a measure for physical intensity. The continuous registered heart rate data are used to calculate mean heart rate for every intensity level that the participant performed. PTTFlevel is the outcome measure of step-out moment from the test protocol.

For technical performance measurements, Playsight Smartcourt allows for the registration of stroke velocity and ball placement for every performed stroke within the PTTF-test. For stroke accuracy, strokes are awarded with a score of 1, 3, 6 or 9 points based on ball placement location as presented in Figure 1. Balls that landed outside of these point awarding zones, but inside the singles tennis field are awarded with a score of 0 points. Finally, strokes that landed outside the singles tennis field or strokes that ended up in the net were given a score of -1 points. With all data it was possible to calculate the outcome variables stroke velocity, stroke accuracy, the VA-index, PE for every intensity level that was performed by the participant. The VA-index is a validated combination score of stroke accuracy and stroke velocity in which stroke velocity is squared and therefore more rewarded due to the harder increment on higher scores (Kolman et al., 2017; Vergauwen et al., 1998). The VA-index is calculated by the following formula whereby stroke velocity is expressed in kph:

$$VA\text{ - }index = \frac{kph^2}{100} \times \frac{\text{sum of achieved points for ball accuracy}}{\text{number of strokes} \times (9)}$$

PE is expressed by the number of errors as a percentage of the total strokes within a level. Strokes in the net, off-court or sliced strokes are counted as errors.

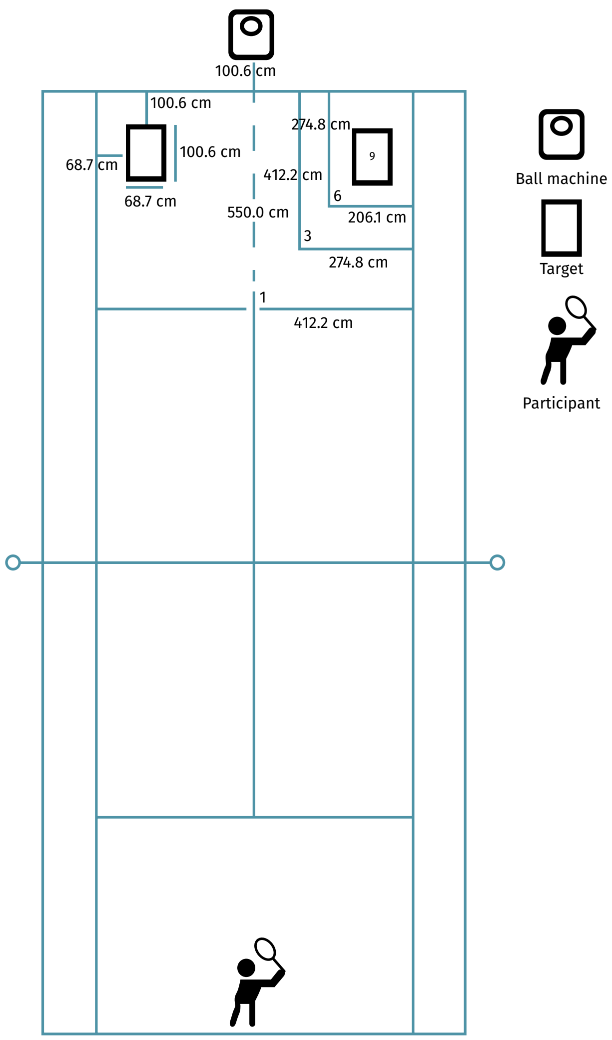

Figure 1. PTTF-test protocol set-up including the dimensions and location of the targets and the point awarding for stroke accuracy based on ball bounce location.

Statistical Analysis

Outcome variables are compared between situations with low physical intensity (LOW-Phys. Int.) and with higher physical intensity (HIGH-Phys. Int.). The 'BASELINE'-situation (LOW-Phys.Int.) is represented by the mean value of the outcome variables from intensity level 2 and intensity level 3 for every participant. Intensity level 1 is not included within the 'BASELINE'-situation, as it is a way for the participants to conform with the test protocol. The 'FINAL'-situation (HIGH-Phys.Int.) is participant-dependant and represented by the mean value of the outcome variables from the final two intensity levels that the participant performed during the PTTF-test.

The statistical analysis was executed with the software IBM SPSS statistics 23.0. The accuracy scores inter-rater reliability was determined with Cohen's kappa and by the examining of four full test protocols by two observers. Cohen's kappa for inter-rater reliability showed an excellent consensus between two observers for accuracy score determination based on ball bounce location, $\kappa = .85$ ($p<.001$).

At first, Analysis 1 was performed to compare the mean heart rates, PTTFlevel and the technical skills in both intensity situations between age categories and genders. A MANOVA analysis with age category and gender as grouping factors and with heart rate, stroke velocity, stroke accuracy, VA-index and percentage errors of both intensity situations and PTTFlevel all as dependant variables was performed as a basic comparison between groups. Analysis 2 assessed the increase in physical intensity between these situations by mean heart rate applying a repeated measures ANOVA with grouping factors age category and gender, and with the 'BASELINE'-situation and the 'FINAL'-situation as repeated measures. Analysis 3, a repeated measures MANOVA with grouping factors age category and gender, and with the 'BASELINE'-situation and the 'FINAL'-situation as repeated measures, was used to assess the effect of physical intensity on the set of outcome variables mean stroke velocity, mean stroke accuracy, the VA-index, and percentage errors. Follow-up univariate analyses are performed to check for the effect of physical intensity on the outcome variables separately. The combination of analysis 2 and analysis 3 will be used to determine the criterion validity of the PTTF-test for capturing decreasing technical performance under increasing physical intensity.

Checks for the normality of distribution, independence of measures, the homogeneity of covariance matrices and sphericity are performed. Sphericity is checked by Mauchly's test. In the case that sphericity assumption is violated, a Greenhouse-Geisser correction is used to adjust. The Bonferroni correction is performed for all post-hoc testing. Effect sizes in the data analysis are classified as large ($\eta^2>0.14$), medium ($0.06<\eta^2<0.14$) or small ($0.01<\eta^2<0.06$) (Cohen, 1988). For all data analysis the level of significance is set at an alpha of 5%.

RESULTS

Participants characteristics, and the PTTFlevel ('FINAL'-situation) for each age category and divided by gender, are presented within Table 1.

Table 1.
Participants characteristics (mean ± SD) and their final reached intensity level (PTTFlevel) per age category group, divided by males ($\male$, n=21) in 1a. and females ($\female$, n=19) in 1b.

1a. $\male$	**U14 (n=7)**	**U16 (n=7)**	**16+ (n=7)**	**Total (n=21)**
Age (yrs)	13.2 ± 0.4	15.0 ± 0.5	18.3 ± 2.2	15.5 ± 2.5
Height (m)	159.8 ± 6.0	179.5 ± 6.0	189.4 ± 6.8	176.2 ± 13.9
Body Mass (kg)	43.1 ± 4.1	64.6 ± 7.5	81.3 ± 5.6	63.0 ± 16.9
Training background (y)	7.7 ± 1.0	7.9 ± 1.7	12.4 ± 1.8	9.3 ± 2.7
Tennis volume ($h*week^{-1}$)	11.0 ± 1.4	12.6 ± 3.2	16.3 ± 4.3	13.3 ± 3.8
Physical volume ($h*week^{-1}$)	4.3 ± 1.1	3.6 ± 0.6	5.0 ± 0.6	4.3 ± 1.0
PTTFlevel	7.8 ± 0.7	8.6 ± 1.2	10.0 ± 1.0	8.8 ± 1.3

1b. $\female$	**U14 (n=7)**	**U16 (n=7)**	**16+ (n=5)**	**Total (n=19)**
Age (yrs)	13.2 ± 0.5	15.1 ± 0.6	18.3 ± 1.0	15.2 ± 2.2
Height (cm)	162.1 ± 4.9	171.1 ± 7.2	170.2 ± 7.2	167.5 ± 7.5
Body Mass (kg)	47.0 ± 6.1	61.1 ± 6.7	64.2 ± 4.0	56.7 ± 9.5
Training background (y)	7.3 ± 1.6	9.6 ± 1.7	11.4 ± 2.1	9.2 ± 2.4
Tennis volume ($h*week^{-1}$)	9.9 ± 2.0	12.1 ± 1.4	16.6 ± 3.5	12.5 ± 3.5
Physical volume ($h*week^{-1}$)	3.4 ± 0.9	4.5 ± 1.7	6.6 ± 1.1	4.6 ± 1.8
PTTFlevel	8.4 ± 1.3	8.4 ± 0.8	8.6 ± 1.5	8.4 ± 1.1

Analysis 1: comparison of the PTTF outcome variables in BASELINE and FINAL intensity situations between age categories and gender

The mean heart rates, mean stroke velocity, mean stroke accuracy, VA-index and PE in the 'BASELINE' and 'FINAL' situation and PTTFlevel are presented in Table 2, divided by age category and gender. The MANOVA found a multivariate Age category effect (F(22,48) =3.328, p=.000; Wilks' Lambda = 0.157, partial η^2 = 0.604). Univariate testing showed that the Age category effect was apparent for PTTFlevel (F(2,34) = 4.341, p=.021; partial η^2 = 0.203), mean heart rate in the 'BASELINE'-situation (F(2,34) =5.468, p=.009; partial η^2 = 0.243), mean stroke velocity in the 'BASELINE'-situation (F(2,34) =8.139, p=.001; partial η^2 = 0.324), VA-index in the 'BASELINE'-situation (F(2,34) =10.700,

p=.000; partial η^2 = 0.386), mean heart rate in the 'FINAL'-situation (F(2,34) =6.958, p=.003; partial η^2 = 0.290), mean stroke velocity in the 'FINAL'-situation (F(2,34) =7.311, p=.002; partial η^2 = 0.301) and PE in the 'FINAL'-situation (F(2,34) =7.538, p=.002; partial η^2 = 0.307). The results derived from the subsequent Bonferroni post-hoc testing described the differences between the groups as illustrated in Table 2. No Gender effect or Age category x Gender interaction effect was revealed.

Analysis 2: The increase of physical intensity in the PTTF-test

The Repeated Measures ANOVA results regarding heart rate are presented in Table 3. Mean heart rate was significantly higher in the 'FINAL'-situation (190.5 ± 8.1) than in the 'BASELINE'-situation (174.1 ± 11.5); F(1,34) = 140.269, p=.000; Wilks' Lambda = 0.195, partial η^2 = 0.805. Furthermore, no significant interaction effects were found (Table 3). The mean heart rates in both intensity situations are illustrated in Table 2 for all age categories and divided by gender.

Analysis 3: The effect of physical intensity on technical performance

The repeated measures MANOVA found a significant effect of Intensity situation (F(4,31) = 75.931, p=.000; Wilks' Lambda = 0.093, partial η^2 = 0.907) and Intensity situation x Age category interaction effect (F(8,62) = 2.441, p=.023; Wilks' Lambda = 0.578, partial η^2 = 0.240).

Further univariate analyses are presented in Table 4 and illustrate that mean stroke velocity was significantly lower in the 'FINAL'-situation (94.3 ± 7.9) than in the 'BASELINE'-situation (101.6 ± 8.1); F(1,34) = 100.310, p=.000; partial η^2 = 0.747. Secondly, mean stroke accuracy was significantly lower in the 'FINAL'-situation (1.6 ± 0.6) than in the 'BASELINE'-situation (2,6 ± 0,5); F(1,34) = 144.388, p=.000; partial η^2 = 0.809. Furthermore, VA-index was significantly lower in the 'FINAL'-situation (16.1 ± 6.4) than in the 'BASELINE'-situation (30.5 ± 7.4); F(1,34) = 278.325, p=.000; partial η^2 = 0.891. Finally, PE was significantly higher in the 'FINAL'-situation (28.9 ± 9.4) than in the 'BASELINE'-situation (19.2 ± 9.3); F(1,34) = 32.353, p=.000; partial η^2 = 0.488.

Table 2.
Outcome variables for both intensity situations of the PTTF-test divided by age category and gender

	N	PTTFlevel	Heart rate (beats.min-1)	Stroke velocity (kph)	Stroke accuracy (points)	VA-index	PE(%)
			'BASELINE'- SITUATION				
♂ U14	7	n/a	181.8 ± 10.2	95.8 ± 6.5	2.7 ± 0.3	27.8 ± 5.4	12.4 ± 7.9
♀ U14	7	n/a	176.5 ± 10.6	95.4 ± 5.8	2.2 ± 0.4	22.2 ± 4.0	21.5 ± 11.9
Total U14	14	n/a	179.1 ± 10.4	95.6 ± 5.9	2.5 ± 0.5	25.0 ± 5.4	17.0 ± 10.8
♂ U16	7	n/a	179.6 ± 4.9	105.3 ± 5.5	2.6 ± 0.6	31.3 ± 5.6	21.0 ± 5.0
♀ U16	7	n/a	173.1 ± 11.4	101.5 ± 6.8	2.8 ± 0.4	31.8 ± 5.7	18.8 ± 8.9
Total U16	14	n/a	176.3 ± 9.1	103.4 ± 6.2*	2.7 ± 0.5	31.6 ± 5.5**	19.9 ± 7.0
♂ 16+	7	n/a	161.8 ± 12.6	107.7 ± 10.7	3.1 ± 0.6	39.3 ± 7.3	20.5 ± 11.8
♀ 16+	5	n/a	171.2 ± 7.7	104.8 ± 4.0	2.5 ± 0.1	30.2 ± 3.1	22.1 ± 7.6
Total 16+	12	n/a	165.7 ± 11.5** #	106.5 ± 8.4***	2.8 ± 0.5	35.5 ± 7.4***	21.2 ± 9.9
			'FINAL'-SITUATION				
♂ U14	7	7.8 ± 0.7	197.6 ± 9.9	90.3 ± 7.9	2.1 ± 0.8	19.7 ± 8.2	18.1 ± 8.5
♀ U14	7	8.4 ± 1.3	192.7 ± 5.9	87.6 ± 7.5	1.2 ± 0.3	10.3 ± 3.2	28.8 ± 3.1
Total U14	14	8.1 ± 1.0	195.1 ± 8.2	89.0 ± 7.5	1.7 ± 0.8	15.0 ± 7.7	23.5 ± 8.3
♂ U16	7	8.6 ± 1.2	191.4 ± 8.0	98.6 ± 3.6	1.4 ± 0.5	14.5 ± 5.6	31.9 ± 10.3
♀ U16	7	8.4 ± 0.8	190.2 ± 8.2	92.4 ± 6.7	1.7 ± 0.6	16.0 ± 6.4	26.0 ± 10.3
Total U16	14	8.5 ± 1.0	190.8 ± 7.8	95.5 ± 6.1*	1.6 ± 0.5	15.3 ± 5.9	28.9 ± 10.4
♂ 16+	7	10.0 ± 1.0	185.5 ± 4.0	98.9 ± 8.6	1.8 ± 0.4	19.7 ± 6.2	35.2 ± 6.3
♀ 16+	5	8.6 ± 1.5	183.7 ± 3.7	99.3 ± 4.4	1.5 ± 0.2	16.5 ± 1.8	35.5 ± 2.1
Total 16+	12	9.4 ± 1.4**	184.8 ± 3.8**	99.0 ± 6.9**	1.7 ± 0.4	18.3 ± 5.0	35.3 ± 4.8***

n/a. non applicable variable in the 'BASELINE'-situation;
In comparison with the Total U14 group: *. effect significant at the α=0.050 level; **. effect significant at the α=0.010 level; ***. effect significant at the α=0.001 level. In comparison with the Total U16 group: #. effect significant at the α=0.050 level.

Table 3.
Repeated Measures ANOVA Test of Within-Subjects Effects for Heart Rate in the PTTF-test.

Effect	MS**	df***	F	p	Partial Eta squared
IS*	5168.306	1	140.269	0.000#	0.805
IS* x Age category	20.744	2	0.563	0.575	0.032
IS* x Gender	16.543	1	0.449	0.507	0.013
IS* x Age category x Gender	112.236	2	3.046	0.061	0.152
Error	36.846	34			

*. Intensity Situation; **. mean square; ***. degrees of freedom;
#. effect significant at the α=0.001 level.

With regard to the Intensity situation x Age category interaction, a significant effect was found on VA-index; ($F(2,34) = 6.432$, p=.004; partial η^2 = 0.274). However, the effect was not apparent for the remaining technical outcome variables. Table 2 shows the mean stroke velocity, mean stroke accuracy, VA-index and PE in both the intensity situations for all age categories and per gender.

DISCUSSION

The current study successfully introduced the new Physical Technical Tennis-specific Field test (PTTF-test) protocol which captures the fluctuations in technical skills under increasing physical intensity in adolescent talented tennis players. This study first compared performance in the PTTF-test between age categories and gender. Hereafter, we captured decreasing technical performance under increasing physical intensity.

At first, the mean heart rates, PTTFlevel and technical skills were compared in both the 'BASELINE' and 'FINAL' intensity situation between age categories and gender. Results from this analysis revealed that the 16+ group reached a higher PTTFlevel in the PTTF-test protocol and exhibited lower mean heart rates in both intensity situations than the U14 group. These results were not surprising, given the rapid development of physical fitness during this period of youth hood (Faff et al., 2000; Kramer et al., 2016). Faff and colleagues demonstrated that body mass, maximal oxygen uptake, maximal running speed, blood lactate concentration, and, to a lesser extent, speed of running at anaerobic threshold, increase with age in male and female tennis players from 12 to 24 years old (Faff et al., 2000). In addition, Kramer and colleagues showed that male as well as female junior elite tennis players improved on upper and lower body-power, speed and agility during U14-U16 (Kramer et al., 2016). Furthermore, we found that the U16 and 16+ groups performed higher mean stroke velocity values in the 'BASELINE'-situation and in the 'FINAL'-situation than the U14 group, which is in accordance with earlier research demonstrating that forehand stroke velocity and backhand stroke velocity are positively correlated with age for male youth tennis players (González-González et al., 2018).

Table 4.
Repeated Measures MANOVA Test of Within-Subjects Effects for technical performance in the PTTF-test.

Effect	Variable	MS**	df***	F	p	Partial Eta squared
IS*	Velocity	1037.817	1	100.310	0.000#	0.747
	Accuracy	19.923	1	144.388	0.000#	0.809
	VA-index	4042.995	1	278.325	0.000#	0.891
	Percentage Errors	1919.228	1	32.353	0.000#	0.488
IS* x Age category	Velocity	2.716	2	0.263	0.771	0.015
	Accuracy	0.255	2	1.849	0.173	0.098
	VA-index	93.430	2	6.432	0.004##	0.274
	Percentage Errors	92.122	2	1.553	0.226	0.084
IS* x Gender	Velocity	0.953	1	0.092	0.763	0.003
	Accuracy	0.003	1	0.023	0.881	0.001
	VA-index	5.543	1	0.382	0.541	0.011
	Percentage Errors	6.796	1	0.115	0.737	0.003
IS* x Age category x Gender	Velocity	16.736	2	1.618	0.213	0.087
	Accuracy	0.227	2	1.646	0.208	0.088
	VA-index	37.434	2	2.577	0.091	0.132
	Percentage Errors	11.626	2	0.196	0.823	0.011
Error	Velocity	10.346	34			
	Accuracy	0.138	34			
	VA-index	14.526	34			
	Percentage Errors	59.321	34			

* . Intensity Situation; ** . mean square; ***. degrees of freedom;
#. effect significant at the α=0.001 level; ##. effect significant at the α=0.010 level.

Second, the increase in physical intensity between the 'BASELINE'-situation and the 'FINAL'-situation of the PTTF-test protocol was assessed. The results showed that participants' mean heart rate was significantly higher in the 'FINAL'-situation than in the 'BASELINE'-situation. This confirms our hypothesis that the PTTF-test is able to analyse technical skills under increasing physical intensity, contributing to the criterion validity of the PTTF-test. The absence of interaction effects (intensity situation x gender, intensity situation x age category and intensity situation x age category x gender) confirms that this result is apparent for both male and female tennis players, as well as for the U14, U16 and 16+ age groups.

Third, the technical skill variables between the 'BASELINE'-situation and the 'FINAL'-situation were compared to analyse the effect of increasing physical intensity. The results revealed that intensity level influenced all technical skill variables. Scores for stroke velocity, stroke accuracy and VA-index were lower and PE were higher at the 'FINAL'-situation compared with the 'BASELINE'-situation, indicating that all technical skills decreased as physical intensity increased. Only an Intensity situation x Age category interaction effect for VA-index was found, the decrease of VA-index was more severe in the older age groups. The U16 and 16+ groups performed significantly better than the U14 group in the 'BASELINE'-situation; however, a difference in performance that was not apparent in the 'FINAL'-situation anymore. The absence of any further interaction effects suggests that the decrease of the technical skills stroke velocity, stroke accuracy and PE by increased physical intensity holds for all age categories and gender. These results contribute to confirmation of the criterion validity of the PTTF-test for capturing decreasing technical performance under increasing physical intensity.

The current study has established a test protocol which captures the decrease in technical skills under increasing physical intensity in adolescent talented tennis players. The technical skills stroke velocity, stroke accuracy, VA-index and PE are yet well studied. Regarding their discriminative value for performance level, stroke velocity (Kolman et al., 2017; Landlinger et al., 2012; Vergauwen et al., 1998; Vergauwen et al., 2004), stroke accuracy (Baiget et al., 2014; Baiget et al., 2016; Del Villar et al., 2007; Kolman et al., 2017; Lyons et al., 2013; Vergauwen et al., 1998; Vergauwen et al., 2004), VA-index (Kolman et al., 2017; Vergauwen et al., 1998) and PE (Kolman et al., 2017; Vergauwen et al, 1998) have all been able to discriminate between tennis players of different performance levels. However, the discriminative value of their decrease under increased physical intensity has yet to be determined. In the current study, only elite performers per age category have been included. As such, it remains interesting to investigate how technical skills fluctuate under increasing physical intensity for sub-elite and novice tennis players to be able to monitor their performance as well. Therefore, future research is needed in tennis players of different performance levels. Even more to further support the criterion validity of the PTTF-test.

Regarding the method, no measures for test-retest reliability were part of this study, which can be considered a limitation. However, from multiple cited on-court tennis tests we know that test-retest reliability is often very good (Baiget, et al., 2014; Kolman et al., 2017; Smekal et al., 2000). Still, we recommend test-retest reliability measures for future research with the PTTF-test. The results for inter-rater reliability showed an excellent consensus between two observers for accuracy score determination based on ball bounce location. The use of Playsight Smartcourt for video review of ball bounce location has contributed to this result and is an advantage of the PTTF-test protocol. Additionally, the sample size in this study might be considered as a limitation. In terms of feasibility, one has to realize that the test takes quite some time to administer. In addition, not all tennis courts are equipped with high-tech video review systems and ball machines with adjustable programs which can be considered as limitations of the PTTF-test, which challenge reproducibility of this study.

The PTTF-test provides a new method for capturing decreasing technical skills under increasing physical intensity for well-trained boys and girls of different age categories. Future research should investigate whether the PTTF-test is applicable for coaches to discriminate between players' performance levels even further. Implications for coaches and tennis players so far might be to implement the PTTF-test at the beginning and the end of a determined time period in order to monitor tennis players' progress. The PTTF-test might be used for the monitoring of baseline technical skills, the decrease of technical skills under physical intensity or physical fitness in a tennis-specific setting by monitoring the reached final intensity level of the PTTF-test.

CONCLUSIONS

In this study the PTTF-test protocol was successfully introduced as a new method for capturing decreasing technical performance under increasing physical intensity. At first, results showed that the older age group (16+) reached a higher PTTFlevel in the PTTF-test protocol and exhibited lower mean heart rates in both intensity situations (BASELINE versus FINAL) than the youngest age group (U14). The results showed an increase in physical intensity (heart rate) between the 'BASELINE'-situation and the 'FINAL'-situation of the PTTF-test protocol for all age categories and both genders. The results revealed that all technical skills decreased when comparing the FINAL intensity level to the BASELINE intensity level. The current test PTTF protocol is a promising test for coaches and players to analyse and monitor the performance of technical skills under increasing physical intensity.

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