Effects of Playing Surface (Hard and Clay Courts) on Heart Rate and Blood Lactate During Tennis Matches Played by High-Level Players

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Abstract

Martin, C, Thevenet, D, Zouhal, H, Mornet, Y, Delès, R, Crestel, T, Ben Abderrahman, A, and Prioux, J. Effects of playing surface (hard and clay courts) on heart rate and blood lactate during tennis matches played by high level players. *J Strength Cond Res* 24(x): 000–000, 2010—The aim of this study was to compare tennis matches played on clay (CL) and resin (R) courts. Six matches were played (3 on CL courts and 3 on R courts) by 6 high-level players. Heart rate (HR) was monitored continuously while running time (4.66 m), and blood lactate concentration ([La]) were measured every 4 games. Mean duration of points and effective playing time (EPT) were measured for each match. Mean HR (154 ± 12 vs. 141 ± 9 $b \cdot min^{-1}$) and [La] values (5.7 ± 1.8 vs. 3.6 ± 1.2 $mmol \cdot L^{-1}$) were significantly higher on CL ($p < 0.05$). The [La] increased significantly during the match on CL court. Mean duration of rallies (8.5 ± 0.2 vs. 5.9 ± 0.5 seconds) and EPT (26.2 ± 1.9 vs. $19.5 \pm 2.0\%$) were significantly longer ($p < 0.05$) on CL. Running time values in speed tests were not significantly different between CL and R. Running time performance was not significantly decreased during the match, whatever the playing surface. This study shows that the court surface influences the characteristics of the match and the player's physiological responses. The court surface should be a key factor for consideration when coaches determine specific training programs for high-level tennis players.

Key Words racquet sports, court surface, speed tests

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Introduction

Competitive tennis players are used to playing multiple tournaments on different court surfaces. The International Tennis Federation (22) classifies court surfaces into 5 categories according to court pace: slow, medium–slow, medium, medium–fast, and fast. It is well known that the court surface influences the tennis ball rebound and as a consequence the ball speed (18). Court pace depends on the friction between the ball and the court surface (coefficient of friction) and somewhat on the AU4 coefficient of restitution. Slower surfaces, such as clay (CL) courts, are characterized by higher friction and restitution coefficients than faster surfaces. This results in a high and relative gentle bounce and slows down the ball on CL (3). Court surface influences the friction and the restitution coefficients, which can both have an impact on the match's technical characteristics, that is, its effective playing time (EPT), total match duration (MD), and mean rally duration.

Some studies have evaluated the influence of court surfaces on game plan (33) and on injuries generated (31), but only AU5 few studies have analyzed the effect of court surfaces on the match's technical characteristics and/or the player's phys- AU6 iological responses. Ferrauti et al. (9), O'Donoghue and Liddle (31) have shown that the EPT, defined as the duration AU7 during which the ball is really in play, is, on average significantly longer on CL (20–30% of total MD) than on faster surfaces, such as hard courts (10–15% of total MD). In a study by Paruit-Portes (34), mean duration of rallies (MDRs) and percentage of EPT significantly influenced the energy expenditure of tennis players. Reilly and Palmer (37) have investigated exercise intensity in men's single tennis on hard courts. They showed that the greater the EPT and the distance run in tennis, the higher the values of heart rate (HR) and blood lactate concentration [La]. Furthermore, Murias et al. (30) and Girard and Millet (16) have compared the technical characteristics and the physiological responses of the same subjects playing tennis matches on different surfaces. They reported that the mean HR and match characteristics (MDRs and mean distance run by point) were significantly higher on CL than on hard courts. However, these studies (16,30) did not report similar [La] results. Indeed, Girard and Millet (16) found that [La] was not significantly different between CL and hard courts, whereas Murias et al. (30) reported that [La] was significantly higher on CL courts.

The literature shows that HR and [La] were not only measured to test the influence of court surface on a player's physiological responses but also as indices to evaluate the fatigue effects on tennis performance (20). According to Hornery et al. (20), fatigue can be defined as an acute impairment of exercise performance, which ultimately leads AU8 to the incapacity to produce maximal force output and/or control motor function. In tennis, fatigue may be related to a prolonged or high-intensity physical exertion (20). The literature shows that fatigue impairs the running movement efficiency. Indeed, Ferrauti et al. (10) evaluated the effect of the resting duration in intermittent tennis training drills on running speed. They noticed that players who had only benefited from 10-second rest between every trial ran significantly slower and were more strained than the players having benefited from 15-second rest. It seems therefore that the fatigue caused by a reduced resting duration decreases the running movement speed. Consequently, we can suppose that the fatigue effects could be more important on CL because this court surface may cause longer rallies, intense and prolonged matches, and lower effective resting time (ERT) percentage. Consequently, the player's running movement performance on CL could be hindered because of fatigue. The purpose of this study was to compare tennis matches played by high-level players on CL and resin (R) courts. It was hypothesized that tennis matches played on AU9 CL are more physically demanding than those played on R. Consequently, one may speculate that the fatigue induced by a more intense physical strain on CL may hinder the sprint performance.

Methods

Experimental Approach to the Problem

The purpose of this study was to compare tennis matches played by high-level players on CL and R courts. To address this issue, HR, [La], running time of speed tests, MD, EPT, ERT, and MDRs were measured during 16 game matches on CL courts and on R courts by high-level tennis players (Figure 1). In addition, to measure more accurately the fatigue effects on the running movements, players were asked to perform speed tests every 4 games (Figure 1). It was hypothesized that matches played on CL are more physically demanding than on R, because this court surface generates greater EPT and MDR. Consequently, increases in mean HR, [La], and running time were expected to be found on CL courts compared with on R courts.

Subjects

Six right-handed tennis players (4 men and 2 women, age: 22 ± 2.9 years, height: 175.6 ± 0.05 cm, body mass: 67 ± 8.2 kg, practice: 8.8 ± 3.1 $h \cdot wk^{-1}$, years of practice: 16.2 ± 2.9 years), with an International Tennis Number ranging from 1 to 3 (23), volunteered to participate in this study. They were AU10 involved in ITF Pro competitions. The subjects were AU11 nonsmokers and very fit, which allowed them to be involved in these evaluations without additional effort. Before participation, they gave their written consent to participate in the study after a thorough explanation of the experimental procedure. The study respected all local laws for studies involving human subjects and was approved by the Ethics Board of the University of Rennes 2.

Procedures

Every subject completed a total of 2 randomized matches on each surface (CL and R indoor courts) in December after the physical training period. The matches were limited to a total of 16 games. The CL courts were composed of unbound mineral aggregate and R courts were made up of synthetic, pigmented R pavement (Figure 2). Each match was played by F2 2 subjects of equal playing ability. The players of a given pair played each other on both surfaces. As a consequence, 3 matches have been played on each surface. There was a 7-day resting duration that separated the 2 matches played by the same subjects. Each match was preceded by a standardized warm-up lasting approximately 15 minutes: submaximal run, proprioception and stretching exercises (10 minutes), and specific tennis warm-up with balls and racket (5 minutes). Each match was divided into 4 sequences of 4 games. After each sequence, 1 blood taking and 2 speed AU12 tests were executed. During the match, the HR was recorded

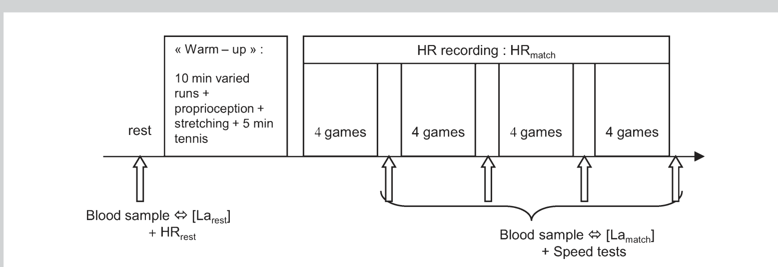

Figure1. Experimental protocol.

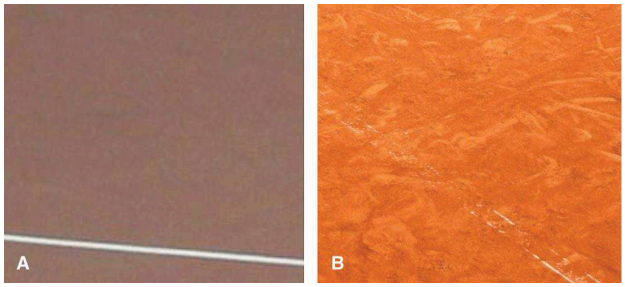

Figure 2. Example of court surface used for the study: resin (A) and clay (B).

AU13 (Figure 1). With the exception of the blood samples and the speed tests to measure, respectively [La], and running time every 4 games, the matches were played according to the rules of the International Tennis Federation (21). The resting times allowed were 20 seconds between points, 90 seconds between change-overs, and 120 seconds between sets (21). The subjects were asked to play at their best level as in an official tournament. Four new balls were provided for each match.

Heart Rate. The HR was registered every 5 seconds during the matches using a Polar (S810 TM, Kempele, Finland). Rest HR (HR_{rest}) corresponded to mean HR values registered during the last minute before the warm-up started. Match HR (HR_{match}) corresponded to mean HR values registered during the match including resting times (between points, games, and sets).

Blood Taking and Lactate Concentration Measurement. Arterialized blood samples (10 μl) were taken with a micropipette from the forefinger of the hand that does not hold the racket
AU14 (13). After blood was taken from the players, the samples were immediately tested using an electrolyte portable
AU15 analyzer (Doctor Lange, microphotometer LP20, Germany) (24). Immediately before the warm-up started, the blood lactate concentration rest ($[La]_{rest}$) of each player was measured. During the matches, these blood takings were used to measure the [La] of each player 1 minute after the 4th ($[La]_4$), 8th ($[La]_8$), 12th ($[La]_{12}$), and 16th ($[La]_{16}$) games of the match. Mean [La] ($[La_{match}]$) corresponded to the mean of these 4 values.

Speed Tests. We have used an original protocol. During the match, after each blood taking, players performed 2 speed tests: the first one on their forehand side, then the other one on their backhand side. For sprinting, players were asked to run a 4.66-m sprint as fast as possible between the center of
F3 the baseline and the first line of double plays (Figure 3). They
AU16 were placed in the starting position facing the net with the feet spread out. The subjects executed a maximal run without a signal to avoid the effects of reaction time. The time trials were measured using photocells (height: 40 cm, Globus, Italy) placed at the starting and AU17
finishing lines. Eight maximal runs were executed by each player during this study. The results of these tests were used to measure the running time after the 4th ($[T_4]$), 8th ($[T_8]$), 12th ($[T_{12}]$), and 16th ($[T_{16}]$) games of the match for every subject.

Match's Technical Characteristics. Technical characteristics (MD, EPT, number of rallies played) were measured to calculate MDRs and ERT. The MD was measured from the beginning of the first rally until the end of the last rally. The evaluator used the following method to measure the duration of each rally: He started the stopwatch when the player released the ball during the serve and stopped it when the rally was finished (fault or winner shot). The EPT was calculated by dividing the sum of the single rally duration by the MD
(40). The EPT was expressed as the percentage of the MD. AU18
The MDR was determined by dividing the sum of rally duration by the number of rallies played during the match. The MDR was calculated to the hundredths of a second.

Statistical Analyses

Lactate concentration (Figure 4) was analyzed as follows: 1 2- F4
way analysis of variance with repeated measures (surface [CL AU19
vs. R] × time [rest, 4th, 8th, 12th, and 16th games]) was used to examine the court surface effect on [La].

Speed tests (Figures 5 and 6) were analyzed as follows: 1 3- F5, F6
way analysis of variance with repeated measures (surface [CL vs. R] × stroke [forehand vs. backhand] × time [4th, 8th,

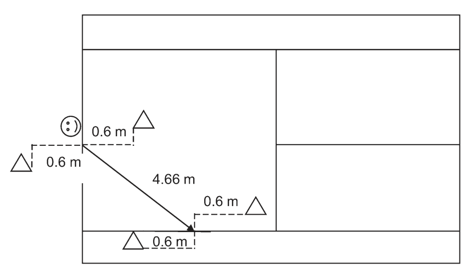

Figure 3. Experimental design of a speed test (forehand side) on the court with the position of photocells (Δ).

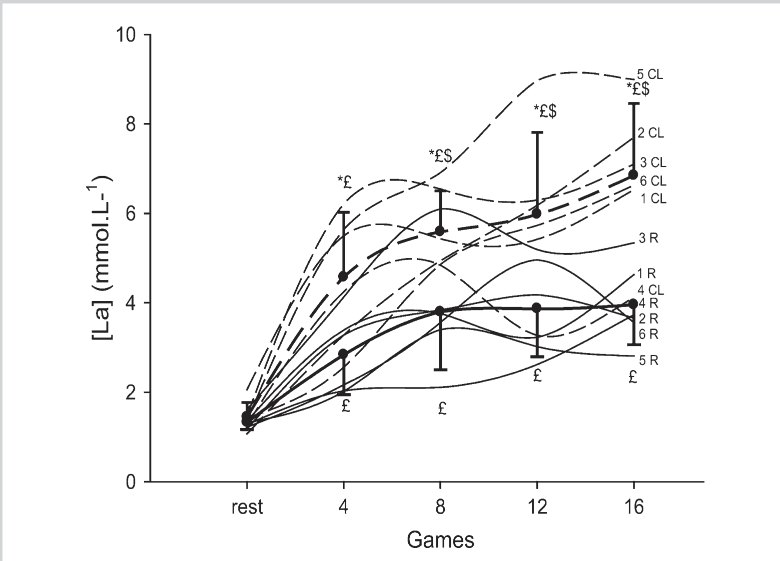

Figure 4. Mean evolution of the blood [La] concentration during tennis matches played on clay (CL) (——) and on resin (R) (–––). Values are mean ± *SD* (*N* = 6). *Significantly different between CL and R ($p < 0.05$). £Significantly different from rest. $Significantly different from game 4 ($p < 0.05$). 1–CL corresponds to the [La] values of the player no. 1 on clay. 1–R corresponds to the [La] values of the player no. 1 on resin.

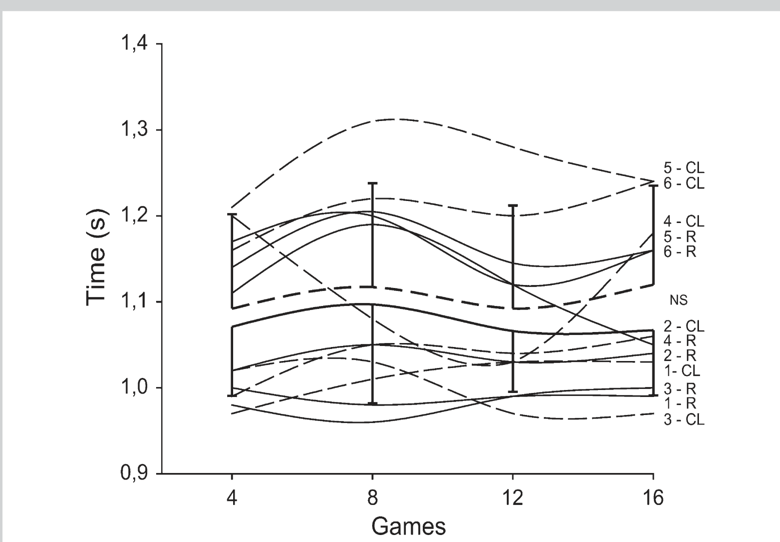

Figure 5. Running time evolution in sprint tests performed on the backhand side on clay (CL) (——) and on resin (R) (–––). Values are mean ± *SD*. NS = nonsignificant. 1–CL corresponds to the running time values of the player no. 1 on clay. 1–R corresponds to the time values of the player no. 1 on resin.

12th, and 16th games]) was used to examine the court surface effect on running time.

Lactate concentration, HR, and match characteristics (Table 1) were analyzed as follows: paired *t*-test determined the significance between CL and R for HR_{match}, $[La]_{match}$ and match characteristics values.

The p value ≤ 0.05 was accepted as the level of statistical significance. If a difference was not statistically significant at the chosen alpha level, the beta risk of an erroneous conclusion of equivalence was chosen as a p value ≤ 0.2.

The speed tests reliability on CL and R courts was determined by the intraclass correlation coefficient (ICC) (1). The ICC coefficient, based on a random effect 2-way analysis of variance (surface × sequence) model, is a measure of variance between the repeated measures (4th, 8th, 12th, and 16th games for speed tests) according to the equation $ICC(2.1) = (BMS - EMS)/(BMS + (k - 1)\,EMS + k(JMS - EMS)/n)$ where BMS is the between-subject mean square, EMS the residual mean square, JMS the treatments mean square, k the number of repeated measures for the speed tests ($n = 4$), and n is the number of subjects ($n = 6$).

Results

No significant difference ($p > 0.05$) for HR_{rest} (74 ± 8 vs. 79 ± 10 b·min^{-1}) and $[La]_{rest}$ (1.44 ± 0.3 vs. 1.33 ± 0.2 mmol·L^{-1}) was noticed between CL and R ($p > 0.2$). The HR_{match} (154 ± 12 vs. 141 ± 9 b·min^{-1}) and $[La]_{match}$ (5.7 ± 1.8 vs. 3.6 ± 1.2 mmol·L^{-1}) were significantly higher ($p < 0.05$) on CL than on R (Table 1). Mean match characteristics–EPT and MDR–were significantly higher ($p < 0.05$) on CL than on R, and ERT

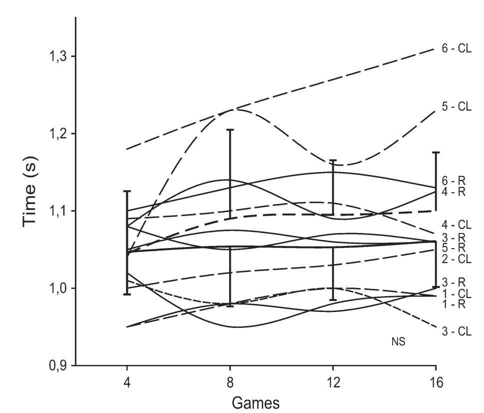

Figure 6. Running time evolution in sprint tests performed on the forehand side on clay (CL) (——) and on resin (R) (– – –). Values are mean ± *SD*. NS = nonsignificant. 1–CL corresponds to the running time values of the player no. 1 on clay. 1–R corresponds to the running time values of the player no. 1 on resin.

was significantly higher ($p < 0.05$) on R than on CL (Table 1).

Figure 4 shows that [La] increased significantly during the match only on CL. The statistical analysis showed a main effect of the surface ($p < 0.05$, $p > 0.8$) and of the time ($p < 0.001$, $p > 0.8$). The [La] was significantly higher ($p < 0.05$) on CL than on R, from the fourth game of the match.

The values of the ICC coefficient for the speed tests on CL and R courts were 0.998 and 0.999, respectively.

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Table 1. Mean values (±*SD*) of match characteristics, HR and [La], measured on CL and R.*

	CL	R	*p*
MD (min)	56.9 ± 5	56.0 ± 10.1	0.832
EPT (%)	26.2 ± 1.9†	19.5 ± 2.0	0.049
ERT (%)	73.8 ± 1.9†	80.5 ± 2.0	0.049
MDR (s)	8.5 ± 0.2†	5.9 ± 0.5	0.017
HR_{match} ($b\cdot min^{-1}$)	154 ±12†	141 ± 9	0.031
$[La]_{match}$ ($mmol\cdot L^{-1}$)	5.7 ± 1.8†	3.6 ± 1.2	0.031

*CL = clay; R = resin; MD = match duration; EPT = effective playing time; ERT = effective resting time; MDR = mean duration of rallies; $[La]_{match}$ = mean blood lactate concentration of the match; FC_{match} = mean HR during the match.

†$p < 0.05$: significant difference between CL and R.

The mean running time values in speed tests also revealed no significant main surface, stroke, and time effects ($p > 0.2$) (Figures 5 and 6).

Discussion

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The purpose of this study was to compare tennis matches played by high-level players on CL and R courts. It was hypothesized that tennis matches played on CL are more physically demanding than those on R. As a consequence, one may speculate that the fatigue induced by a more intense physical strain on CL may hinder the sprint performance. In agreement with our hypothesis, results from this study show that HR and [La] values are significantly higher on CL courts than on R courts, suggesting an overall higher physiological demand on CL. However, no significant difference between surfaces was observed for running time values.

Like other studies (25,40), we have tried to assess the tennis match intensity by measuring [La]. Our results show that mean $[La]_{match}$ values are significantly lower on R than on CL ($p < 0.05$). These results are in agreement with those reported by Murias et al. (30). However, they are not in line with the results of Girard and Millet (16) that did not report significant difference of [La] values between CL and hard courts. These discrepancies are probably the results of differences in the characteristics of the subjects (number of subjects, playing ability, age, height, and body mass) and the experimental design (total MD and blood taking). Indeed, in the study by Girard and Millet (16), the matches were limited to a total time of 30 minutes. In addition, these authors have analyzed only 1 postexercise blood sample for each player. This postexercise blood taking only measures the glycolytic system activity during the last moments of the match. As previously reported by Murias et al. (30) in tennis and by Delamarche et al. (6) in handball, we have collected blood samples every 4 games to evaluate more accurately the evolution of [La] concentration during the match.

In our study, the highest values of [La] were over 8 $mmol\cdot L^{-1}$ for 2 players on CL. These peak values are in accordance with those reported by other authors (7). They suggest a higher anaerobic system request (37) on CL. They coincide most likely with crucial points of the match (game point, set point, and match point) (7,40). In addition, our results show that mean $[La]_{match}$ values are significantly lower on R than on CL ($p < 0.05$). Match characteristics values (MDR, ERT) influenced by the court surface may probably explain this phenomenon. The fact that, on R courts, the rallies are less long (Table 1) and less intense than on CL courts (HR_{match} was significantly lower on R, Table 1) could be an important factor responsible for higher [La] values on CL courts. However, it is possible that the request of anaerobic metabolism was underestimated on CL and R courts. Indeed, the periods of rest during match are sufficient to allow players to reduce the metabolism products (2). This underestimation is probably more important on R because ERT measured on this surface is significantly higher than on

CL. As a consequence, on fast surface, lactate is probably more metabolized, eliminated and reused during rest periods. This can explain why our [La] values were significantly lower on R. Care should be taken when looking at the results because [La] values only reflect the level of activity during the few minutes before sampling.

Most of the studies simulating tennis matches show that mean HR values vary between 140 and 150 b·min^{-1} (2,7,40). In this study, the mean HR values averaged 154 $\pm$ 12 b·min^{-1} on CL courts and 141 $\pm$ 9 b·min^{-1} on R courts. As previously reported by Murias et al. (30), HR_{match} is significantly higher on CL than on R ($p < 0.05$) in this study. This significant difference could be the result of the match characteristics (MDR, EPT, and ERT), which are influenced by the playing surface. Indeed, Girard and Millet (16) found high correlations between % HR_{max}, duration of rallies (R: $r = 0.91$; $p < 0.01$–CL: $r = 0.76$; $p < 0.05$) and shots played consecutively (R: $r = 0.92$; $p < 0.01$–CL: $r = 0.79$; $p < 0.05$) on CL and hard courts. HR increases when subjects hit more consecutive shots and play longer rallies (i.e., higher MDR). In this study, it seems logical that HR_{match} is significantly higher on CL than on R because MDR is significantly longer on CL ($p < 0.005$). In addition, EPT is significantly lower ($p < 0.05$) and ERT significantly higher on R than on CL ($p < 0.05$). These results suggest that the overall physical strain is reduced on fast surfaces, and this factor could be responsible for lower HR_{match} values on R courts (25). However, our results about resting time are not in line with those reported by AU21 O'Donoghue and Ingram (32). According to these authors, the court surface has no significant influence on the mean rest time between rallies. These discrepancies are probably the results of differences in the procedure used to evaluate resting time.

In the literature, Illinois agility run (4,19) and 10-, 20-, and 40-m forward sprint tests (12) are generally used to evaluate running performances of team sport players. In tennis, baseline sprint tests (10), 5-, 10-, and 15-m forward sprints (16) and lateral sprints (39) tests are often used to test the AU22 player's physical attributes. However, we have chosen a short diagonal sprint because tennis players need to be not only exceptional movers in a linear direction but they must also have exceptional lateral movements for short distances (26). Moreover, it is well known that approximately 95% of all strokes are played within $<$5 m, with the player in a standing position (38). The reliability of the speed test has been tested with ICC coefficients. The ICC coefficients confirm that this speed test is appropriate for the purpose of this research.

In this study, the range of the running time values is in agreement with the literature. Indeed, Ferrauti et al. (10) reported running time values of 1.022 $\pm$ 0.044 and 0.999 $\pm$ 0.045 seconds for baseline sprint tests (with a measurement point at 4.12 m) completed by 2 groups of nationally ranked tennis players. The results of our study show that the mean running time values reveal no significant main surface and stroke effects. In addition, the mean running time does not increase significantly during the match. These results could be explained by [La] values. Indeed, Ferrauti et al. (10) showed that the maximum running performance measured in the baseline speed test did not decrease significantly after a tennis training session despite the high values of [La] (around 9 mmol·L^{-1}) measured at the end of the session. This suggests that [La] values in this study are too low to influence significantly the running time in the speed tests. Nevertheless, Ferrauti et al. (10) showed that the players performed better sprint performances with a 15-second recovery between each trial than with a 10-second recovery. These authors concluded that the running speed in tennis depends on the recovery time. In this study, the players benefited from 20-second rest between points. This duration seems to be sufficient for allowing players to sustain their running performance in sprint tests. The stability of the running time values in speed tests could also be explained by the numerous rest intervals between points, games, and sets (i.e., ERT values reaching 80.5% of MD on R and 73.8% on CL). This amount of rest was probably sufficient for supplying the ATP and phosphocreatine reserves (17) and AU23 consequently for maintaining the running time during the match. Moreover, the low MD in this study (56.9 $\pm$ 5.1 minutes on CL and 56.0 $\pm$ 10.1 minutes on R) could explain the non significant time effect on [La]. Indeed, Girard et al. (14) showed that decreases in force capability contraction and indices of fatigue were significant only after 150 minutes AU24 of a 3-hour tennis match play. In addition, peak power in vertical jumps was kept constant during the tennis match simulated in their study. Vergauwen et al. (42) attempted to identify the fatigue effects in tennis. They showed that decreased sprint performance (70 m) only appeared after 2 hours of an experimental intense tennis training. Moreover, we can suppose that the low distance of the sprint tests (4.66 m) and the number of games played (only 16) in this study were not sufficient to cause a level of fatigue that would have decreased running performance during the matches.

In conclusion, this study shows that the court surface influences tennis match characteristics. On CL courts, EPT and MDR are increased, whereas ERT is decreased. On R, EPT, and MDR are reduced, whereas ERT is increased. These changes are probably responsible for the higher mean HR and [La] values measured on CL, suggesting an overall higher physiological demand on that surface. In addition, our results show that the running time performance was not significantly decreased during the match, whatever the playing surface. The court surface does not influence significantly the running time values in speed tests.

Practical Applications

Elite tennis players and coaches need some knowledge about the nature of physiological requirements of tennis matches. Indeed, according to the specificity principle of training, training programs must be both physiologically and mechanically specific to the demands of the tennis (5). In this way, the court surface should be a key factor for consideration when coaches determine specific training programs for high level tennis players (27). If players train on the same type of court AU25 as the incoming competition's, they will be used to its the AU26 physiological and mechanical requirements. Consequently, they will be more efficient. Because CL courts induce longer AU27 points, higher EPT, HR, and [La], training in preparation for the CL court season needs to focus on developing muscular and cardiovascular endurance. According to Maes (28), in addition to the "off-season" endurance training period in mid-November, professional players should participate in a second endurance training phase in preparation for the CL court season. The conditioning phase should focus on tennis-specific endurance training using on-court drills, such as "cross rallies" or "baseline competitions without service and return" recommended by Ferrauti et al. (11). Moreover, Reid et al. (36) have determined the physiological responses (HR, [La], rate of perceived exertion) of on-court drills (Star, Box, Suicide, Big X) commonly used in the endurance training of professional players (29). The physiological responses to "Star" and "Box" (6×30 seconds) were comparable to normal tennis match play demands, measured usually on hard court (7). "Suicide" and "Big X" drills (6×60 seconds) were physically more demanding with physiological responses similar to maximum in game values, measured usually on CL court (7,40). Consequently, it appears that coaches should use "Suicide and Box drills" for preparing players for the more intensive physiological demands induced by matches played on CL court. Using this type of on court-specific drills on CL permits the players to work aerobic efficiency and capacity (8) and maximize on-court movement patterns, such as baseline rallies and lateral slides that are very common on CL courts (32,38). Indeed, it is well known that the court surface influences on-court movement. On hard court, professional players are under increased time pressure of 45% of time, whereas it is only 29% on CL (35). To prepare matches on hard courts that cause shorter points and more strokes hit under time pressure, training should include more anaerobic sessions (28), agility, coordination, and speed activities (reaction time, frequency of body movement).

Acknowledgments

The authors declare that they have no conflict of interest. The results of this study do not constitute endorsement of the AU28 product by the authors or the NSCA.

References

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1. Bartko, JJ. On various intraclass correlation reliability coefficients. *Psychol Bull* 83: 762–765, 1976.
2. Bergeron, MF, Maresh, CM, Kraemer, WJ, Abraham, A, Conroy, B, and Garabee, C. Tennis: A physiological profile during match play. *Int J Sports Med* 12: 474–479, 1991.
3. Brody, H. *Tennis Science for Tennis Players*. University of Pennsylvania Press, Philadelphia, PA: 1987.
4. Caldwell, BP and Peters, DM. Seasonal variation in physiological fitness of a semiprofessional soccer team. *J Strength Cond Res* 23: 1370–1377, 2009.
5. Chandler, J and Chandler, WB. Training principles. In: *Strength and Conditioning for Tennis*. Reid, M, Quinn, A, and Crespo, M, eds. London, United Kingdom: International Tennis Federation, 2003. pp. 59–65.
6. Delamarche, P, Gratas, A, Beillot, J, Dassonville, J, Rochcongar, P, and Lessard, Y. Extent of lactic anaerobic metabolism in handballers. *Int J Sports Med* 8: 55–59, 1987.
7. Fernandez, J, Mendez-Villanueva, A, and Pluim, BM. Intensity of tennis match play. *Br J Sports Med* 40: 387–391, 2006.
8. Fernandez-Fernandez, J, Sanz-Rivas, D, and Mendez-Villanueva, A. A review of the activity profile and physiological demands of tennis match play. *Strength Cond J* 31: 15–26, 2009.
9. Ferrauti, A, Bergeron, MF, Pluim, BM, and Weber, K. Physiological responses in tennis and running with similar oxygen uptake. *Eur J Appl Physiol* 85: 27–33, 2001.
10. Ferrauti, A, Pluim, BM, and Weber, K. The effect of recovery duration on running speed and stroke quality during intermittent training drills in elite tennis players. *J Sports Sci* 19: 235–242, 2001.
11. Ferrauti, A, Weber, K, and Wright, PR. Endurance: Basic, semi-specific and specific. In: *Strength and Conditioning for Tennis*. Reid, M, Quinn, A, and Crespo, M, eds. London, United Kingdom: International Tennis Federation, 2003. pp. 93–111.
12. Gabbett, TJ. Physiological characteristics of junior and senior rugby league players. *Br J Sports Med* 36: 334–339, 2002.
13. Girard, O, Chevalier, R, Leveque, F, Micallef, JP, and Millet, GP. Specific incremental field test for aerobic fitness in tennis. *Br J Sports Med* 40: 791–796, 2006.
14. Girard, O, Lattier, G, Micallef, JP, and Millet, GP. Changes in exercise characteristics, maximal voluntary contraction, and explosive strength during prolonged tennis playing. *Br J Sports Med* 40: 521–526, 2006.
15. Girard, O and Millet, GP. Effects of the ground surface on the physiological and technical responses in young tennis players. In: *Science and Racket Sports III*. Reilly, T, Hughes, M, and Lees, A, eds. London, United Kingdom: EFN Spon, 2004. pp. 43–48.
16. Girard, O and Millet, GP. Physical determinants of tennis performance in competitive teenage players. *J Strength Cond Res* 23: 1867–1872, 2009.
17. Glaister, M. Multiple sprint work: Physiological responses, mechanisms of fatigue, and the influence of the aerobic fitness. *Sports Med* 35: 757–777, 2005.
18. Groppel, JL and Roetert, EP. Applied physiology of tennis. *Sports Med* 14: 260–268, 1992.
19. Hastad, DN and Lacy, AC. *Measurement and Evaluation in Physical Education and Exercise Science* (2nd ed.). Scottsdale, AZ: Gorsuch Scarisbrick Publishers, 1994.
20. Hornery, DJ, Farrow, D, Mujika, I, and Young, W. Fatigue in tennis: Mechanisms of fatigue and effect on performance. *Sports Med* 37: 199–212, 2007.
21. International Tennis Federation. The rules of tennis. Available at: http://www.itftennis.com/shared/medialibrary/pdf/original/IO_38810_original.PDF. Accessed September 12, 2006.
22. International Tennis Federation. 2009 ITF Approved Tennis Balls & Classified Court Surfaces–a guide to products and test methods. Available at: http://www.itftennis.com/shared/medialibrary/pdf/original/IO_33562_original.PDF. Accessed June 13, 2008.
23. International Tennis Federation. ITN on court assessment. Available at: http://www.itftennis.com/shared/medialibrary/pdf/original/IO_43630_original.PDF. Accessed August 10, 2009.
24. Kamber, M. Lactate measurements in sports medicine comparison of measurements methods. *Schweizerische Zeitschrift für Sportsmedizin* 40: 77–86, 1992.

25. König, D, Hounker, M, and Schmid, A. Cardiovascular, metabolic, and hormonal parameters in professional tennis players. *Med Sci Sports Exerc* 33: 654–658, 2001.
26. Kovacs, MS. Applied physiology of tennis performance. *Br J Sports Med* 40: 381–385, 2006.
27. Kovacs, MS. Tennis physiology: Training the competitive athlete. *Sports Med* 37: 189–198, 2007.
28. Maes, C. Planning physical conditioning with professional players. In: *Strength and Conditioning for Tennis*. Reid, M, Quinn, A, and Crespo, M, eds. London, United Kingdom: International Tennis Federation, 2003. pp. 217–225.
29. Maeso, M. Physical training for top professional players. In: *Tennis Player Development. 12th ITF Worldwide Coaches Workshop*. Crespo, M, Reid, M, and Miley, D, eds. London, United Kingdom: International Tennis Federation, 2001. pp. 107–109.
30. Murias, JM, Lanatta, D, Arcuri, CR, and Laino, FA. Metabolic and functional responses playing tennis on different surfaces. *J Strength Cond Res* 21: 112–117, 2007.
31. Nigg, BM and Segesser, B. The influence of playing surfaces on the load on the locomotor system and on football and tennis injuries. *Sports Med* 5: 375–385, 1988.
32. O'Donoghue, P and Ingram, B. A notational analysis of elite tennis strategy. *J Sports Sci* 19: 107–115, 2001.
33. O'Donoghue, P and Liddle, D. A notational analysis of time factors of elite men's and ladies single tennis on clay and grass surfaces. In: *Science and Racket Sports II*. Reilly, T, Hughes, M, and Lees, A, eds. London, United Kingdom: EFN Spon, 1998. pp. 241–246.
34. Paruit-Portes, MC. Etude télémétrique de la fréquence cardiaque du joueur de tennis (entraînements et matchs). *Méd Sport* 56: 35–40, 1982.
35. Pieper, S, Exler, T, and Weber, K. Running speed loads on clay and hard courts in world class tennis. *Med Sci Tennis* 12: 14–17, 2007.
36. Reid, M, Duffield, R, Dawson, B, Baker, J, and Crespo, M. Quantification of the physiological and performance characteristics of on-court tennis drills. *Br J Sports Med* 42: 146–151, 2008.
37. Reilly, T and Palmer, J. Investigation of exercise intensity in males singles lawn tennis. In: *Science and Racket Sports*. Reilly, T, Hughes, M, and Lees, A, eds. London, United Kingdom: EFN Spon, 1994. pp. 10–13.
38. Roetert, P, Ellenbecker, T, and Chu, D. Movement mechanics. In: *Strength and Conditioning for Tennis*. Reid, M, Quinn, A, and Crespo, M, eds. London, United Kingdom: International Tennis Federation, 2003. pp. 165–173.
39. Salonikidis, K and Zafeiridis, A. The effects of plyometric, tennis drills, and combined training on reaction, lateral and linear speed, power and strength in novice tennis players. *J Strength Cond Res* 22: 182–191, 2008.
40. Smekal, G, Von Duvillard, SP, Rihacek, C, Pokan, R, Hofmann, P, Baron, R, Tschan, H, and Bachl, N. A physiological profile of tennis match play. *Med Sci Sports Exerc* 33: 999–1005, 2001.
41. Therminarias, A, Dansou, P, Chirpaz-Oddou, MF, Gharib, C, and Quirion, A. Hormonal and metabolic changes during a strenuous tennis match: Effect of ageing. *Int J Sports Med* 12: 10–16, 1991.
42. Vergauwen, L, Spaepen, AJ, Lefevre, J, and Hespel, P. Evaluation of stroke performance in tennis. *Med Sci Sports Exerc* 30: 1281–1288, 1998.