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Tennis Physiology

Training the Competitive Athlete

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Abstract

The game of tennis has evolved from the wooden-racket era of long, crafty points based on style and finesse, to the current fast paced, explosive sport based on power, strength and speed, where 210 km/h serves are common. This evolution over the last 20 years has led to an increased interest in tennis research. Competitive tennis athletes need a mixture of anaerobic skills, such as speed, agility and power, combined with high aerobic capabilities. The work-to-rest ratios of competitive tennis athletes range between 1 : 3 and 1 : 5, and fatigue has been shown to greatly reduce the hitting accuracy. Competitive male tennis athletes maintain body fat <12% and have maximal oxygen uptake values >50 mL/kg/min, and as high as 70 mL/kg/min. Results from lactate testing in tennis players are inconclusive as some studies have shown increased levels, whilst other studies have shown little or no change. Further investigation is required to determine the production and utilisation effects of lactate from playing tennis. The average length of time to play a point in tennis is <10 seconds and this has declined substantially in the last 20 years. Further research is needed to investigate tournament performance and its effect on fatigue, recovery, hormonal and injury levels. As the game of tennis continues to change, the physiological parameters must be continually investigated to help provide athletes, coaches and trainers with information that will aid in the development of efficient and productive tennis performance and injury prevention programmes.

Competitive, high-level tennis requires the athlete to have superior skills and training in four major areas: (i) tactical; (ii) technical; (iii) physical; and (iv) psychological. Unlike many other sports, which may require high levels of physical fitness in a few components, tennis players require high performances in most components (figure 1). One of the major problems in tennis research is the variation in the nature of the game itself. Tennis has average points that last <10 seconds (especially on faster surfaces such as hard and grass courts), but matches have the possibility to last >5 hours.[1-3] A tennis match includes intermittent anaerobic exercise bouts of varying intensities and a multitude of rest periods over a long duration, allowing the aerobic energy systems to aid in recovery. The time of contact between the ball and racquet is between 0.003 and 0.006 seconds, and the racquet and ball must be in optimal orientation to execute the desired stroke.[4] Therefore, high-level tennis requires high precision over an extended period of time. Unlike sprinters or weightlifters who must have a majority of type 2 muscle fibres, or endurance athletes who must have a majority of type 1 muscle fibres, tennis players have been shown to be varied between being either predominantly fast or predominantly slow fibre-type athletes.[5]

In order to structure efficient and productive training and recovery programmes, coaches, scientists and players must have a solid understanding of the physiological responses to high-level tennis players. Throughout matches and practice sessions,

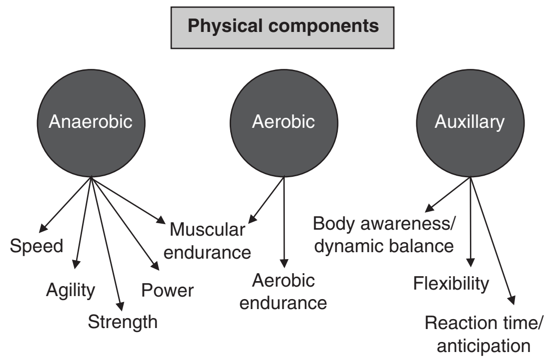

Fig. 1. The physical skills and components relevant to tennis performance.

tennis players need to be able to perform repeated dynamic movements involving acceleration, deceleration, multi-directional agility and explosive jumps, all in a reactive, rather than a pro-active, environment. As fatigue has been shown to reduce tennis-hitting accuracy by as much as 81%,[6,7] a major goal of tennis training should be to avoid the onset of fatigue during competition and training.

As a result of inefficient planning and training, performance improvements may be limited and injury potential may increase. Repetitive strain injuries ('overuse injuries') are the most common type of injuries in the tennis player.[8] A major cause of these injuries has been attributed to the speed of the game.[8,9] The peak velocity of a tennis racquet in the serve has been reported to be 100–116 km/h (62–72 mph),[10] which corresponds to ball velocities of 134–201 km/h (83–125 mph).[9] Since the time of this research, which is >10 years old, the game of tennis has recruited bigger, faster and stronger athletes, due to training, dietary and recovery enhancements, which have led to the increased velocity of all tennis strokes. Organised and planned programmes (i.e. periodised) have been shown to lead to greater performance improvements than non-periodised programmes in collegiate tennis players.[11]

Force production in tennis, as in many other ground-based sports, involves the transfer of ground reaction forces through the ankle, lower- and upper-legs, trunk, upper body and eventually to the tennis racket. Therefore, the forces at the shoulder and arm in a tennis player result from the summation of the kinetic chain activity that starts with the ground reaction force in the legs and proceeds to the upper body, including the shoulder and arm.[9] The hips and trunk function as a centre of rotation and as a transfer link for the large forces generated in the legs to be passed on to the shoulder and arm. Elite tennis players have symmetrical trunk rotational strength.[12] Abdominal muscles must generate, transfer and decelerate forces in the trunk.[9]

The purpose of this review of tennis-specific research is to help athletes, coaches and researchers more effectively use the scientific research to assist high-level tennis players to prepare and train for optimum performance.

1. Physiological Measures

Basic anthropometric and physiological measurements are helpful for coaches, trainers, players and scientists to identify talent, monitor progress and maintain motivation. Tennis athletes compare favourably with athletes in other sports and non-athletes on most anthropometric and physiological measurements.[13-18] However, tennis has several unique physical aspects that are specific to the sport. These include movement patterns and work-to-rest ratios, which need to be understood to train tennis athletes in the most productive and efficient manner.

1.1 Body Fat and Maximal Oxygen Uptake

Body-fat percentages of most tennis players are lower than those of the general population, but are typically not as low as some high-strength and power-sport athletes such as track sprinters and gymnasts (see table I). Tennis athletes perform well on maximal oxygen uptake ($\dot{V}O_{2max}$) testing. $\dot{V}O_{2max}$ values in competitive high-level male tennis players have ranged between 44 mL/kg/min and 69 mL/kg/min[14,19-26] (see table II). These $\dot{V}O_{2max}$ values would classify these individuals as being highly anaerobically trained,[27] as opposed to being highly aerobically trained such as marathon runners. It is interesting to note that players who were considered to be aggressive, attacking players had lower heart rates (HRs) and lower $\dot{V}O_2$ levels during play than baseline players.[22] This information should be applied when designing training programmes specifically for different styles of play. The conclusions from the laboratory tests were that tennis athletes, even with different playing styles, have physiological and anthropometric measures similar to those of endurance athletes.[22] However, this statement should not be misinterpreted. These tennis athletes showed high aerobic capacities, but they should not be compared equally with highly-trained aerobic athletes such as marathon runners. It is important for high-level tennis players to have $\dot{V}O_{2max}$ levels >50 mL/kg/min to perform at an appropriate level on the tennis court, yet having extremely high levels (e.g. >65 mL/kg/min) may not increase on-court performance greater than a highly respectable $\dot{V}O_{2max}$ level of 55 mL/kg/min. This would suggest that training time might be better spent on other physiological, psychological, technical or tactical components of tennis.

1.2 Heart Rate

Physiological stress in tennis is associated with the elevation of HR, which reflects the effort expended during short, intense bouts of play. In tennis matches, there is a general trend towards an increase in $\dot{V}O_2$ and HR as the game progresses, with a decrease during the rest periods between points and games.[22]

During 85 minutes of match play, the mean HR of a college tennis player was 144.6 ± 13.2 beats per minute.[14] The HR and maximal HR reserve were consistent with results from other studies.[21,29-31] This indicated that HR remains significantly elevated above pre-exercise levels, despite the varying intensity and intermittent nature of the game. The mean percentage of maximum heart rate (table III) during play was 86.2% ± 1.0%; however, this was not significantly different from the 82.9% ± 1.2% observed during recovery (excluding the rest periods between points and games).[14] Although this was the mean HR value, the study did not provide the range of HRs. This could have provided a better representation of the start-stop nature of tennis and the explosive bursts, which require high adenosine triphosphate (ATP) use, as well as the decrease in HR during the rest periods between points and games.[32] Mean HRs of tennis players have been shown to be statistically significantly higher when serving than when receiving ($p = 0.001$).[6]

Table I. Body-fat percentage for typical high-level tennis players

Study (year)	Body fat (%) [mean ± SD]	Level	Age (years) [mean ± SD]
Bergeron et al.[14] (1991)	10.6 ± 4.5	College male division 1	20.3 ± 2.5
Bergeron et al.[28] (1995)	8.0 ± 3.0	College male division 1	20.5 ± 1.9
Bergeron et al.[28] (1995)	21.3 ± 4.6	College female division 1	20.3 ± 2.5
Dawson et al.[13] (1985)	11.3 ± 1.8	College/state level male	20.3 ± 1.3

Table II. Comparison of maximal oxygen consumption ($\dot{V}O_{2max}$) values in elite[a] tennis players

Study (year)	No.	$\dot{V}O_{2max}$ (mL/kg/min) [mean ± SD]
Bergeron et al.[14] (1991)	10	58.5 ± 9.4
Elliot et al.[21] (1985)	8	65.9 ± 6.3
Bernardi et al.[22] (1998)	7	65 ± 4
Christmass et al.[23] (1995)	8	54.25 ±1.9
Smekal et al.[25] (2003)	20	57.3 ± 5.1
Faff et al.[19] (2000)	72	62.3 ±4.8

a State level or higher.

Multiple factors may have an influence on HR responses of tennis players. Elite level tennis is frequently played in hot environments, where HR does not solely reflect the intensity of exercise.[13] HRs will increase to help maintain cardiac output with a reduced blood volume due to sweating and skin perfusion.[34] Therefore, higher HRs will be seen in hot conditions.

Average HR values should not be the sole measurement of metabolism, as this would not accurately represent the physiological nature of an intermittent sport such as tennis. The HR variability and ranges during a match are considerable due to the continual stop-start movements and explosive nature of the sport.

One study has suggested that tennis is an aerobic sport because of the long duration and the moderate mean HRs during play.[14] However, the explosive nature of the serve and ground strokes, the rapid changes in direction (requiring high anaerobic capacity) and the requirement for a high percentage of type 2 muscle fibres, do not represent an aerobic sport.[35] Therefore, it would be incorrect to suggest that tennis is a predominant aerobic sport and it might be better to classify the sport as a predominantly anaerobic activity, requiring high levels of aerobic conditioning to avoid fatigue. If HR monitoring is used during training, it would be more beneficial to have the athlete work at higher rates, interspersed with lower rates (adequate rest), than to have them at a constant HR throughout the session. This would attempt to mimick the cardiorespiratory stress that a tennis athlete faces in a match situation.

1.3 Lactate

The production and influence of lactate on human biochemistry is a major concern for optimum performance in many sports. The finding of no changes in plasma lactate during tennis play suggests that there is little reliance on anaerobic glycolysis for ATP production and that numerous opportunities are available for lactate to be cleared.[14] However, this result has not been supported by all of the research on lactate in tennis. Other studies have shown that the pre-match concentration of plasma lactate was 2.13 ± 0.32mM, increasing significantly at the fourth change of end to 5.05 ± 1.04mM and at the sixth change of ends, then remaining elevated until the end of the match.[23] This variation was correlated ($r = 0.71$, $n = 72$) with the estimated play intensity.[32] In this study,[32] the HR did not vary between rallying and recovery or with duration, which supports the findings of Bergeron et al.[14] and Docherty;[29] however, Elliott et al.[21] reported a slight increase in HR during recovery between rallies. The plasma lactate levels during tennis play have produced varying results in the literature and require further investigation.[14,36] A possible explanation could be the level of player observed. Matches involving athletes who play longer points with shorter recovery times are likely to produce higher lactate levels than those who play short points with longer rest periods. In addition, as lactate is a volatile substance, the time frame of sampling must also be standardised. In tennis training and competition, this standardisation might be difficult to practically accomplish.

Table III. Mean percentage of maximum heart rate (PMHR) in male tennis players

Study (year)	No.	Level	PMHR (%)
Christmass et al.[23] (1995)	8	Regional	86
Bernardi et al.[22] (1998)	7	Regional	63.6[a]–82.5[b]
Therminarias et al.[33] (1991)	19	Elite	87
Bergeron et al.[14] (1991)	10	Elite	86.2
Elliott et al.[21] (1985)	8	Elite	79 79.4[c]

a Attacking style of play.
b Baseline style of play.
c Results from separate dataset within same study.

When blood lactate concentrations exceed 7–8 mmol/L, technical and tactical performance declines.[3] However, these lactate levels are not expected during most match conditions because of regular rest periods between points and games, allowing for sufficient aerobic recovery. Some training sessions may elicit higher levels of lactate than match sessions due to exercises of high intensity lasting between 1 and 8 minutes, with little or no rest. Many tennis players train at a much higher practice intensity and duration of hitting sequence than is observed during match play.[7] Coaches and athletes must take into account potential lactate levels when designing exercises. For technical development, it is important for the athlete to be fresher, with low levels of lactate, so that the major focus (technical training) can be achieved effectively. Inducing high lactate levels during training is not a productive way to train tennis athletes as it lacks specificity to the predominant energy system experienced during matches. Appropriate rest must be included in training sessions to simulate conditions experienced during match play and to train tennis-focused energy system development. Rest time between points in a game of tennis can range between 15 and 28 seconds,[1,2,37,38] and extended rest periods after every two games are typically of 90 seconds.

1.4 Testosterone

Although limited tennis research has focused on testosterone levels in competitive tennis, it has been shown in males that a significant increase in plasma testosterone occurs during play.[14] Testosterone increased above pre-exercise concentrations immediately and again 5 minutes after the end of the match.[14] During match play, plasma cortisol levels progressively decreased while plasma testosterone steadily increased.[14] Also, testosterone levels in female collegiate tennis players have been shown to increase over a 9-month tennis and physical conditioning, periodised training programme.[11]

2. Energy Systems and Metabolism

The involvement of human metabolism and energy systems must be understood to help design, develop and implement tennis training and competition programmes. Utilising the correct energy systems during training will improve performance during matches. Although tennis is characterised by periods of high-intensity exercise, it has been argued that the overall metabolic response resembles prolonged moderate-intensity exercise.[14] However, coaches and athletes should not infer from this statement that competitive tennis is a moderate-intensity sport. The average metabolic response does not take into account the inconsistent and high power-output nature of tennis movement and stroke technique. It is self-evident that to consistently hit 210 km/h (130 mph) serves and equivalent ground strokes, it requires high anaerobic ATP production. As most points last <10 seconds,[1,2,13,14,21,24,26,30-33,38-44] it would be remiss to train tennis players in a traditional, aerobic fashion at moderate intensity for long durations. Unfortunately, this is still how many coaches and tennis players train for competition.

Bergeron and colleagues[14] conclude that as plasma lactate does not change (although this result was not supported by other research[23,36]), conditioning for tennis should generally emphasise exercises near, but not beyond, anaerobic threshold. However, this training philosophy might not adequately develop the anaerobic power and explosiveness required to produce effective strokes and movements in tennis players. As tennis requires multiple anaerobic energy systems and focused movement patterns throughout a match or training it would be appropriate to train as specifically for the tennis scenario as possible. Bergeron and colleagues[14] do not believe anaerobic training should be the emphasis (i.e. >50% of the total physical training) of a given training cycle. They argue that the overall metabolic response indicates that oxidative metabolism is the primary mechanism for ATP restoration through the course of an entire tennis match. The adaptations associated with training just below the anaerobic threshold could optimise these ongoing recovery periods.[14] This theory is justified for training for the recovery periods; however, it is also vital to train for the performance periods. Therefore, it could be argued that it would be more beneficial and productive to train the anaerobic-focused energy systems, the majority of the time. Aerobic training will occur during the rest and recovery periods of high-intensity exercise if the work-to-rest ratios are appropriate. As tennis players are athletes that perform high-intensity short-duration sprint activities throughout a match, these athletes should be trained for aerobic development using multiple short-duration sprints (<1 minute), with adequate rest (1 : 3 work-to-rest ratio), to achieve aerobic training benefits.[37] Kovacs[37] provides a more in-depth analysis. It has also been indicated that interval training at high intensities improves aerobic fitness to the same extent as traditional aerobic training.[45]

The duration of recovery, as well as the duration of workloads, is important for the regulation of physiological strain during intermittent exercise. Studies during both sprint and weight training have shown the importance of recovery on subsequent performance.[33,40,46-49]

Power decrements during high-intensity, intermittent exercise, such as tennis, have been related to a continuous degradation of phosphocreatine, thus placing greater demand on glycogenolysis and glycolysis, which increases muscle and blood lactate concentrations. This is associated with large reductions in muscle pH if appropriate rest is not obtained.[43] This rest seems to be obtained in match situations,[37] but many coaches and athletes practice and train without sufficient rest periods. One area of training and testing that needs updating is the traditional test for aerobic endurance in tennis players. The 1.5-mile run test has been used for many years,[17,50,51] but is not representative of the energy system usage or metabolic stress that a tennis athlete encounters. A more specific test would involve short-duration sprints (<30 seconds), in a repetitive manner, to test for tennis-specific endurance.

3. Match Analysis and Work-to-Rest Ratios

The length of a tennis match is highly variable and can range from <1 hour to >5 hours in a five-set match. The majority of tennis players compete in traditional ‘best of three sets’ matches. These matches range substantially in duration, but a tentative average of 1.5 hours has been used in the literature as a typical average match length.[28]

The dietary records of tennis players show males consuming ≈4500 calories per day and females consuming ≈2800 calories per day.[28] However, it should be noted that there is large individual variability in these caloric results. This information is provided to outline the large variations in intake, which is probably due in part to the variability in time and intensity of actual play. Therefore, these values are provided as a guide to caloric needs in tennis, but should not be used to structure individual nutritional guidelines.

The mean duration of the rallies throughout tennis matches can vary substantially depending on the playing surface, playing style, environmental conditions, strategy and motivation. Match analysis obtained during a college tennis tournament reported the average length of a point to be 6.36 ± 4.69 seconds.[1] In a separate study, it was seen that playing style had a large impact on the length of the point.[22] When the player in control of the rally was an attacking player, the average duration of the rallies was 4.8 ± 0.4 seconds.[22] When the player in control of the rally was a whole-court player, rally duration varied with a mean value of 8.2 ± 1.2 seconds (range: 6–11 seconds). When the player in control of the rally was a baseline player, the points, on average, lasted 15.7 ± 3.5 seconds. These differences in duration were shown to be statistically significant ($p < 0.05$).[22]

The percentage of the playing time, with respect to the total time of the match, (on clay courts) has been shown to be ≈21% ± 5.5% for attacking players, 28.6% ± 4.2% for whole-court players and 38.5% ± 4.9% for baseline players.[22] A significant difference was observed between each of these styles of play ($p < 0.05$). A study on hard courts had the percentage of playing time during a match to be ≈20% for all types of players.[29]

The intervals of work and rest during high-level tennis play have been shown to vary. Most high-level matches consist of a work-to-rest ratio between 1 : 3 and 1 : 5, with points having an average length between 3 seconds on some of the faster surfaces (grass, carpet and indoor) that have been classified as category 2 and 3 by the International Tennis Federation (ITF),[52] to ≈15 seconds on the slower surfaces (e.g. clay, ITF category 1[52]).[1,2,13,21,23,24,26,30,33,38-42,44] Although variability in results is due to playing styles, court surfaces, environmental conditions, competitive level of participants, psychological and motivational factors, this information gives a good range for which to develop effective tennis training programmes. Tennis points do not, on average, last >13 seconds and the overwhelming majority of points last <10 seconds (table IV). This information should be used when developing training and testing programmes for tennis players.

4. Fluid Consumption and Hydration

Competitive tennis is typically played in warm and hot environments. Because hypohydration will impair tennis performance[53] and increase the risk of heat-related injury and illness,[54] consumption of appropriate fluid levels is necessary to prevent dehydration and enhance performance. It has been shown that tennis players can sweat >2.5 L/h;[20] however, the gastric emptying rate for beverages, rarely exceeds 1.2 L/h.[55,56] Attempting to keep pace with a sweat rate greater than ≈1.5 L/h is a practical and physiological challenge. Players who ingest >1.25 L/h may feel gastrointestinal discomfort as they compete.[56,57] During a study looking at collegiate tennis players, water consumption of the athlete was at an approximate rate of 1.0 L/h,[28] which may have been due to a subconscious need to avoid the aforementioned gastrointestinal discomfort. Thirst is a poor indicator of body water status and is an insufficient stimulus to prevent a net body water loss during exercise in a hot environment.[20,58] Ad libitum drinking typically leads to involuntary dehydration.[13] One reason for involuntary dehydration is that 1.5L of body water could be lost before thirst is perceived.[59] By this time, impaired exercise thermoregulation has already started.[59] Exercise performance (endurance cycling in a laboratory setting) has been shown to be impaired when an individual is hypohydrated by as little as 2% of their body mass and a loss of 5% can decrease work capacity by ≈30%.[60]

During tennis training and match situations, it is important for athletes to consume adequate fluid and electrolytes. There is some debate as to the best

Table IV. Rally time of tennis matches on different surfaces

Study (year)	Mean rally time (sec)	SD	Surface	ITF surface rating[52]
Christmass et al.[23] (1995)	10.2	0.3	Hardcourt	2
Dawson et al.[13] (1985)	10	0.2	Hardcourt	2
Elliott et al.[21] (1985)	10	0.8	Hardcourt	2
König et al.[39] (2001)	7–10		Hardcourt	2
Morgans et al.[30] (1987)	7.5	0.7	Hardcourt	2
Richers[40] (1995)	8		Hardcourt	2
Smekal et al.[26] (2001)	8.2		Hardcourt	2
Therminarias et al.[33] (1991)	12	1	Hardcourt	2
Chandler[38] (1991)	12.2		Hardcourt	2
Kovacs[2] (2004)	6.0		Hardcourt	2
Kovacs et al.[1] (2004)	6.2		Hardcourt	2
Yoneyama et al.[41] (1999)	6.6		Unspecified	
O'Donoghue and Ingram[42] (2001)	8		Hardcourt	2
O'Donoghue and Ingram[42] (2001)	7.6		Clay	1
O'Donoghue and Ingram[42] (2001)	4.3		Grass	3
Hughes and Clark[44] (1995)	2.52		Grass	3

ITF = International Tennis Federation.

types of fluid to be ingested while on court. Despite the favourable osmotic gradient of water for absorption, most investigators have shown that a carbohydrate (CHO)-electrolyte drink promotes fluid absorption better than plain water.[20,61-63] The two major reasons for this are: (i) without active solute transport, the intestine cannot transport water effectively; and (ii) in the presence of glucose, water transport is enhanced. The actual amount of fluid to be consumed by tennis players during a match depends on the individual, the environment, intensity level, body mass and sweat rate. A tennis player who has a 2.0 L/h sweat rate would need to drink 0.25L during each change of ends (assuming five changeovers per hour) to replace just 62.5% of the fluid lost each hour.[20]

It has been suggested that 200mL of fluid every 15 minutes, is an adequate rate to maintain body fluid balance during moderate to intense exercise at a warm environment (wet bulb globe temperature [WBGT] 27°C).[64] This level of fluid should be increased in conditions that are >27°C WBGT. This recommendation is equal to 1 L/h, which is not even half the amount of fluid that can be lost as a result of sweating.[20] Although recommended fluid intake should be individualised for each player, if this is not possible, it would be appropriate to recommend a fluid intake of ≥400mL of fluid every 15 minutes (1.6 L/h). This volume is chosen because it was slightly higher than the gastric emptying rate,[55,56] which will limit the amount of body fluid losses during hot and humid conditions.

CHO supplementation has been utilised in other sports with varied results. The ingestion of a CHO solution did not improve performance in a 3-hour simulated tennis match;[65] however, this is contrary to previous results carried out on aerobic cycling performance.[66-68] Nevertheless, aerobic cycling performance tests differ substantially from the tennis performance tests, which were primarily anaerobic tasks. There is no apparent benefit in including CHO in fluid-replacement drinks during <2 hours of tennis play. However, when athletes need to play or train for two or three sessions during the same day, it is vital to replenish glucose levels. Negative disturbances of glucose levels occured most frequently after the rest period between a first and second match during the tournament study.[69] Then, while the players warm up for the subsequent match, there was a sudden drop in glucose levels. In this study, the decreased glucose levels did not appear to affect competitiveness; however, in highly competitive situations this could have a large bearing on the attitude and readiness of the player to compete at the highest level.[70] A CHO drink in long-duration cycling activities has been shown to help delay the onset of exercise-induced muscle cramps, but has not been shown to prevent the cramps.[69]

5. Clinical and Practical Applications

The physiology of tennis play is complex becasue of the start-stop intermittent nature and inconsistent length of matches. Therefore, rigid and strict training guidelines are inappropriate. Interindividual variation must be considered when designing training programmes, as mean values from many group research studies may not show statistically significant results, but individual means might show strong or weak responses. Different playing styles, surfaces, ball types and environmental conditions should be major factors for consideration when determining training programmes for high-level tennis players. Recommendations for the design and implementation of training programmes for high-level tennis players include the following:

1. As attacking players will play shorter points, training should incorporate a higher percentage of short, anaerobic-focused speed, strength and power activities.
2. Players with a more defensive style should train with the intent of developing longer points and should focus on developing muscular endurance and train accordingly.
3. All types of players must have a good base level of all physiological areas, as the playing style of the opponent, court surface, environmental conditions and ball type will dictate, to a certain degree, the nature of the physiological requirements.
4. The work-to-rest ratios for training exercises, which are focused on developing tennis-specific endurance, should fall somewhere between 1 : 3 and 1 : 5, in order to simulate the match conditions.
5. The work-to-rest ratios for speed, agility and power training should be much longer to allow for appropriate recovery (from 1 : 25 to 1 : 40).
6. As fatigue limits the hitting accuracy by as much as 81%,[7] it is important to train technical and tactical aspects when athletes are fresh and well rested. Shorter rest periods (3–5 seconds of rest for every second of work) should be used to develop energy systems specifically for improved tennis play.
7. Tennis players should strive for body-fat percentages to be <12% (males) and <23% (females).
8. A $\dot{V}O_{2max}$ level >50 mL/kg/min for males and >42 mL/kg/min for females is recommended as a minimum standard and preferably a higher $\dot{V}O_{2max}$ value is encouraged for tennis athletes to be able to practice and compete at a high level.
9. More emphasis should be placed on developing intermittent, anaerobic performance rather than long-duration, moderate-intensity aerobic exercise.
10. Tennis players can sweat >2.5 L/h,[20,71] yet it is difficult for athletes to comfortably drink >1.2 L/h.[56,57,72] This discrepancy makes consuming adequate fluids during play a physiological challenge. It is recommended that athletes drink ≈200mL during each change of ends in mild temperatures (<27ºC WBGT). Also, it would be highly recommended that each athlete is on a specific hydration routine, which has been developed through the monitoring of sweat changes throughout practice and match sessions. It is recommended that athletes drink between 200mL and 400mL during each change of ends in hot and humid conditions (>27ºC WBGT).

6. Conclusion

Competitive tennis play requires a fine interaction between the tactical, technical, psychological and physical components. However, limited research is available concerning how best to structure and train these four distinct components. Further sport science research is required in all areas of tennis competition and practice, but there seems to be a scarcity of information on recovery, performance, hormonal and injury levels during tournaments and multi-day events. An area of discrepancy in the literature concerns the effects of competitive tennis on lactate levels. Further research is required to determine the production and utilisation of lactate during tennis play. Another area in need of more research is that of tennis-specific endurance; more tennis-focused endurance testing and monitoring is required. As tennis is one of the most popular sports in the world, the need for continual tennis research in all of the sport sciences is required to help develop programmes to be more effective, efficient and safe for improved performance and injury prevention.

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References

1. Kovacs MS, Strecker E, Chandler WB, et al. Time analysis of work/rest intervals in men's collegiate tennis [abstract]. J Strenght Cond Res 2004; 18: e364
2. Kovacs MS. A comparison of work/rest intervals in men's professional tennis. Med Sci Tennis 2004; 9 (3): 10-1

3. McCarthy-Davey PR. Fatigue, carbohydrate supplementation and skilled tennis performance. In: Haake S, Coe AO, editors. Tennis science and technology. Oxford: Blackwell, 2000: 333-40
4. Renstrom PAFH, editor. Tennis. Malden (MA): Blackwell, 2002
5. Mero A, Jaakkola L, Komi PV. Relationship between muscle fibre characteristics and physical performance capacity in trained athletic boys. J Sports Sci 1991; 9 (2): 161-71
6. Davey PR, Thorpe RD, Williams C. Simulated tennis matchplay in a controlled environment. J Sports Sci 2003; 21: 459-67
7. Davey PR, Thorpe RD, Williams C. Fatigue decreases skilled tennis performance. J Sports Sci 2002; 20: 311-8
8. Chandler TJ. Conditioning for tennis: preventing injury and enhancing performance. In: Lees A, Maynard I, Hughes M, et al., editors. Science and racket sports. 2nd ed. London: E&FN Spon, 1998: 77-85
9. Chandler TJ. Exercise training for tennis. Clin Sports Med 1995; 14 (1): 33-46
10. Kibler WB, Chandler TJ. Racquet sports. In: Fu FH, Stone DA, editors. Sports injuries, mechanisms, prevention and treatment. Baltimore (MD): Williams & Wilkins, 1994: 531-51
11. Kraemer WJ, Hakkinen K, Triplett-McBride NT, et al. Physiological changes with periodized resistance training in women tennis players. Med Sci Sports Exerc 2003; 35 (1): 157-68
12. Ellenbecker TS, Roetert EP. An isokinetic profile of trunk rotation strength in elite tennis players. Med Sci Sports Exerc 2004; 36 (11): 1959-63
13. Dawson B, Elliott B, Pyke F, et al. Physiological and performance responses to playing tennis in a cool environment and similar intervalized treadmill running in a hot climate. J Hum Mov Stud 1985; 11: 21-34
14. Bergeron MF, Maresh CM, Kraemer WJ, et al. Tennis: a physiological profile during match play. Int J Sport Med 1991; 12 (5): 474-9
15. Chandler TJ, Kibler WB, Uhl TL, et al. Flexibility comparisons of junior elite tennis players to other athletes. Am J Sports Med 1990; 18 (2): 134-6
16. Chandler TJ, Kibler WB, Stracener EC, et al. Shoulder strength, power, and endurance in college tennis players. Am J Sports Med 1992; 20 (4): 455-8
17. Kibler WB, McQueen C, Uhl TL. Fitness evaluations and fitness findings in competitive junior tennis players. Clin Sports Med 1988; 7 (2): 403-16
18. Mero A, Jaakkola L, Komi PV. Neuromuscular, metabolic and hormonal profiles of young tennis players and untrained boys. J Sports Sci 1989; 7: 95-100
19. Faff J, Ladyga M, Starczewska CJ. Physical fitness of the top Polish male and female tennis players aged form twelve years to senior category. Biol Sport 2000; 17 (3): 179-92
20. Bergeron MF, Armstrong LE, Maresh CM. Fluid and electrolyte losses during tennis in the heat. Clin Sports Med 1995; 14 (1): 23-32
21. Elliott B, Dawson B, Pyke F. The energetics of singles tennis. J Hum Mov Stud 1985; 11: 11-20
22. Bernardi M, De Vito G, Falvo ME, et al. Cardiorespiratory adjustment in middle-level tennis players: are long term cardiovascular adjustments possible? In: Lees A, Maynard I, Hughes M, et al., editors. Science and racket sports II. London: E&FN Spon, 1998: 20-6
23. Christmass MA, Richmond SE, Cable NT, et al. A metabolic characterisation of single tennis. In: Reilly T, Hughes M, Lees A, editors. Science and racket sports. 1st ed. London: E&FN Spon, 1995: 3-9
24. Christmass MA, Richmond SE, Cable NT, et al. Exercise intensity and metabolic response in singles tennis. J Sports Sci 1998; 16 (8): 739-47
25. Smekal G, Von Duvillard SP, Pokan R, et al. Changes in blood lactate and respiratory gas exchange measures in sports with discontinuous load profiles. Eur J Appl Physiol 2003; 89 (5): 489-95
26. Smekal G, Von Duvillard SP, Rihacek CN, et al. A physiological profile of tennis matchplay. Med Sci Sport Exerc 2001; 33: 999-1005
27. Green JM, Crews TR, Bosak AM, et al. A comparison of respiratory compensation thresholds of anaerobic competitors, aerobic competitors and untrained subjects. Eur J Appl Physiol 2003; 90 (5-6): 608-13
28. Bergeron MF, Maresh CM, Armstrong LE, et al. Fluid-electrolyte balance associated with tennis match play in a hot environment. Int J Sport Nutr 1995; 5: 180-93
29. Docherty D. A comparison of heart rate responses in racquet games. Br J Sports Med 1982; 16 (2): 96-100
30. Morgans LF, Jordan DL, Baeyens DA, et al. Heart rate response during singles and doubles tennis competition. Phys Sportsmed 1987; 15: 67-74
31. Seliger V, Ejem M, Pauer M, et al. Energy metabolism in tennis. Int Z Angew Physiol 1973; 31: 333-40
32. Christmass MA, Richmond SE, Cable NT, et al. A metabolic characterisation of single tennis. In: Reilly T, Hughes M, Lees A, editors. Science and racket sports. 1st ed. London: E&FN Spon, 1994: 3-9
33. Therminarias A, Dansou P, Chirpaz-Oddou MF, et al. Hormonal and metabolic changes during a strenuous tennis match: effect of ageing. Int J Sports Med 1991; 12: 10-6
34. Wingo JE, Lafrenz AJ, Ganio MS, et al. Cardiovascular drift is related to reduced maximal oxygen uptake during heat stress. Med Sci Sports Exerc 2005; 37 (2): 248-55
35. Kovacs MS. Applied physiology of tennis performance. Br J Sports Med 2006; 40 (5): 381-6
36. Copley BB. Effects of competitive singles tennis playing on serum electrolyte, blood glucose and blood lactate concentrations. S Afr J Sci 1994; 80: 145
37. Kovacs M. Energy system-specific training for tennis. J Strength Cond Res 2004; 26 (5): 10-3
38. Chandler TJ. Work/rest intervals in world class tennis. Tennis Pro 1991; 3: 4
39. König D, Huonker M, Schmid A, et al. Cardiovascular, metabolic, and hormonal parameters in professional tennis players. Med Sci Sports Exerc 2001; 33 (4): 654-8
40. Richers TA. Time-motion analysis of the energy systems in elite and competitive singles tennis. J Hum Mov Stud 1995; 28: 73-86
41. Yoneyama F, Watanabe H, Oda Y. Game analysis of in-play-time and out-of-play-time in the Davis Cup [abstract]. 5th IOC World Congress on Sport Sciences; 1999 Oct 31- Nov 5; Sydney
42. O'Donoghue P, Ingram B. A notational analysis of elite tennis strategy. J Sports Sci 2001; 19: 107-15
43. Ferrauti A, Pluim BM, Weber K. The effect of recovery duration on running speed and stroke quality during intermittent training drills in elite tennis players. J Sports Sci 2001; 19: 235-42
44. Hughes MD, Clark S. Surface effect on elite tennis strategy. In: Reilly T, Hughes M, Lees A, editors. Science and racket sports. 1st ed. London: E&FN Spon, 1995: 272-8
45. Tabata I, Nishimura K, Kouzaki M, et al. Effects of moderate-intensity endurance and high-intensity intermittent training on anaerobic capacity and VO_2max. Med Sci Sports Exerc 1996; 28: 1327-30
46. Hargreaves M, McKenna MJ, Jenkins DG, et al. Muscle metabolites and performance during high-intensity, intermittent exercise. J Appl Physiol 1998; 84 (5): 1687-91

47. Linossier MT, Denis C, Dormois D, et al. Ergometric and metabolic adaptations to a 5s sprint training programme. Eur J Appl Physiol 1993; 68: 408-14
48. Linossier MT, Dormois D, Geyssant A, et al. Performance and fibre characteristics of human skeletal muscle during short sprint training and detraining on a cycle ergometer. Eur J Appl Physiol 1997; 75: 491-8
49. Delecluse C, Van Coppenolle H, Willems F, et al. Influence of high-resistance and high velocity training on sprint performance. Med Sci Sports Exerc 1995; 27: 1203-9
50. Roetert EP, Brown SW, Piorkowski PA, et al. Fitness comparisons among three different levels of elite tennis players. J Strength Cond Res 1996; 10 (3): 139-43
51. Roetert EP, Garrett GE, Brown SW, et al. Performance profiles of nationally ranked junior tennis players. J Appl Sport Sci Res 1992; 6 (4): 225-31
52. International Tennis Federation. International Tennis Federation approved tennis balls and classified court surfaces. London: International Tennis Federation, 2006
53. Magal M, Webster MJ, Sistrunk LE, et al. Comparison of glycerol and water hydration regimens on tennis-related performance. Med Sci Sports Exerc 2003; 35 (1): 150-6
54. Kovacs MS. Hydration and temperature in tennis: a practical review. J Sci Med Sport 2006; 5: 1-9
55. Armstrong LE, Costill DL, Fink WJ. Influence of diuretic-induced dehydration on competitive running performance. Med Sci Sports Exerc 1985; 17: 456-61
56. Coyle EF, Montain SJ. Benefits of fluid replacement with carbohydrate during exercise. Med Sci Sports Exerc 1992; 24: S324-S30
57. Coyle EF, Montain SJ. Carbohydrate and fluid ingestion during exercise: are there trade-offs? Med Sci Sports Exerc 1992; 24: 671-8
58. Wilmore JH, Costill DL. Physiology of sport and exercise. 3rd ed. Champaign (IL): Human Kinetics, 2004
59. Greenleaf JE. Problem: thirst, drinking behavior, and involuntary dehydration. Med Sci Sports Exerc 1992; 24: 645-56
60. Saltin B, Costill DL. Fluid and electrolyte balance during prolonged exercise. In: Horton ES, Terjung RL, editors. Exercise, nutrition and metabolism. New York: MacMillan, 1988: 150-8
61. Gisolfi CV, Duchman SM. Guidelines for optimal replacement beverages for different athletic events. Med Sci Sports Exerc 1992; 24: 679-87
62. Murray R. Nutrition for the marathon and other endurance sports: environmental stress and dehydration. Med Sci Sports Exerc 1992; 24: S319-S23
63. Murray R, Eddy DE, Murray TW, et al. The effect of fluid and carbohydrate feedings during intermittent cycling exercise. Med Sci Sports Exerc 1987; 19: 597-604
64. MacLaren DPM. Nutrition for racket sports. In: Lees A, Maynard I, Hughes M, et al., editors. Science and racket sports. 2nd ed. London: E&FN Spon, 1998: 43-51
65. Mitchell JB, Cole KJ, Granjean PW, et al. The effect of a carbohydrate beverage on tennis performace and fluid balance during prolonged tennis play. J Appl Sport Sci Res 1992; 6 (2): 96-102
66. Coyle EF, Hagberg JM, Hurley BF, et al. Carbohydrate feeding during prolonged strenuous exercise can delay fatigue. J Appl Physiol 1983; 55: 230-5
67. Hargreaves M, Costill DL, Coggan AR, et al. Effect of carbohydrate feeding on muscle glycogen utilization and exercise performance. Med Sci Sports Exerc 1984; 16: 219-22
68. Mitchell JB, Costill DL, Houmard JA, et al. Effects of carbohydrate ingestion on gastric emptying and exercise performance. Med Sci Sports Exerc 1988; 20: 110-5
69. Jung AP, Bishop PA, Al-Nawwas A, et al. Influence of hydration and electrolyte supplementation on incidence and time to onset of exercise-associated muscle cramps. J Athl Train 2005; 40 (2): 71-5
70. Ferrauti A, Pluim BM, Busch T, et al. Blood glucose responses and incidence of hypoglycaemia in elite tennis under practice and tournament conditions. J Sci Med Sport 2003; 6 (1): 28-39
71. Bergeron MF. Heat cramps: fluid and electrolyte challenges during tennis in the heat. J Sci Med Sport 2003; 6 (1): 19-27
72. Neufer PD, Young AJ, Sawka MN. Gastric emptying during exercise: effects of heat stress and hypohydration. Eur J Appl Physiol 1989; 58: 433-9

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