REVIEW

# Applied physiology of tennis performance

M S Kovacs

Br J Sports Med 2006;40:381–386. doi: 10.1136/bjsm.2005.023309

Competitive tennis play requires a combination of the major physiological variables; however, the specifics of these variables have yet to be determined appropriately. General strength and flexibility training have been suggested as being beneficial for performance and injury prevention, yet specific guidelines are lacking. This paper provides a review of specific studies that relate to competitive tennis, and highlights the need for tennis-specific training as opposed to generalised physical training. It identifies specific studies that support the premise that tennis has physiological requirements which need to be understood when designing training and research programmes.

Correspondence to: Mark S Kovacs, University of Alabama, Department of Kinesiology, Tuscaloosa, Alabama 35487, USA; mark@metisperformance.com

Accepted 19 January 2006

Tennis is a sport based on unpredictability. The unpredictability of point length, shot selection, strategy, match duration, weather, and the opponent all influence the complex physiological aspects of tennis play. Designing and implementing training for tennis requires a solid understanding of the many physiological variables critical to optimal performance. Tennis requires short explosive bursts of energy repeated dozens, if not hundreds, of times per match or practice session. Tennis, unlike many other sports, does not have time limits on matches. This can result in matches lasting less than one hour or as long as five hours (in five-set matches). This variability requires successful tennis athletes to be highly trained both anaerobically for performance, and aerobically, to aid in recovery during and after play.

Although tennis is one of the most popular sports worldwide, few extensive reviews have been completed to help provide tennis scientists, coaches, and players with a summary of the tennis research. This information may aid in the creation of training programmes designed to improve performance and reduce injury risk. The information for this evidence based review was obtained using searches on the Medline and Sportdiscus databases with the pertinent tennis articles cross checked for sources and appropriate references examined for relevant information.

## MATCH ANALYSIS AND POINT DURATION

Most tennis players compete in traditional first player to win two sets matches, and these matches vary substantially in duration, but a tentative time of 1.5 hours has been suggested as a typical average match length.[1]

The mean duration of the rallies throughout tennis matches also varies substantially, depending on a multitude of factors including playing style, surface, environment, strategy, level of play, velocity of shot, and motivation. Work–rest intervals during high level tennis play have been analysed, and as expected they show variability.[2] Most high level matches consist of a work to rest ratio of between 1:2 and 1:5, with points having an average length of between three seconds on some of the faster surfaces (grass, carpet, and indoor) to close to 15 seconds (fig 1).[3–17] The mean (SD) duration of points summarised in previous studies was 8.00 (2.58) s. This information should be used as a guide to help structure both on court and off court training programmes for tennis players.

In a recent study during a high level collegiate tennis tournament, the average point length was recorded as 6.36 (4.69) s.[14] An athlete's playing style can have a large impact on the length of tennis points.[18] When the player in control of the rally was an attacking player (hits the tennis ball hard and attempts to come to the net consistently), the average duration of the points was found to be 4.8 (0.4) s.[18] Rally duration varied between 6 and 11 seconds (mean 8.2 (1.2) s) when the player in control of the rally was a whole court player (who plays from the baseline, but is very comfortable coming to the net).[18] The points lasted on average 15.7 (3.5) s when the player in control of the rally was a baseline player (plays the large majority of points from the baseline, hitting ground strokes, and does not prefer to come into the net). This difference in duration was statistically significant ($p<0.05$).[18] The percentage of the playing time with respect to the total time of the match (on clay courts) has been shown to be approximately 21 (5.5)% for the attacking players, 28.6 (4.2)% for whole court players, and 38.5 (4.9)% for baseline players.[18] In an earlier study, the percentage of playing time during match, on hard courts, was approximately 20%.[19] From the research it appears that total playing time is only between 20% and 30% of total match time.[6 20]

## MAJOR PHYSICAL COMPONENTS

### Cardiorespiratory responses and requirements

Maximum oxygen uptake ($\dot{V}O_2max$) is typically used as a major marker of aerobic and cardiorespiratory capacity. In tennis matches there is a general trend toward an increase in $\dot{V}O_2$ and heart rate as the game progresses, with a

**Abbreviations:** ROM, range of motion; USTA, United States Tennis Association

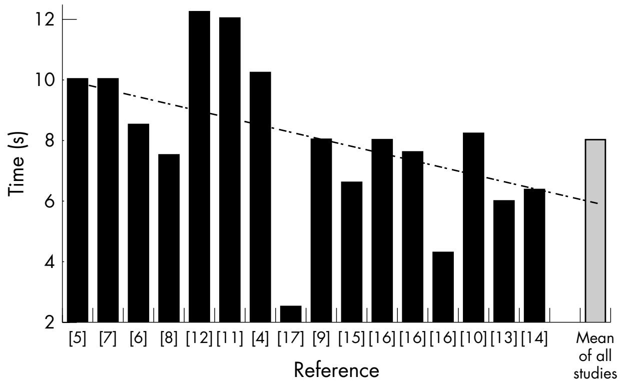


**Figure 1** Mean point duration summary from tennis research. (Reference numbers listed in chronological order on the horizontal axis.) Broken line signifies downward trend of point duration over the past 20 years.

decrease during the rest periods while changing ends.[18] $\dot{V}O_2$max values in competitive high level tennis players have varied between 44 and 69 ml/kg/min, with the overwhelming majority of values greater than 50 ml/kg/min (fig 2).[3 4 7 10 18 20–23] These $\dot{V}O_2$max values would classify tennis players as being highly anaerobically trained.[24] It is interesting that players who were considered to be aggressive attacking players had lower $\dot{V}O_2$ values during play than baseline players.[18] This information should be applied when designing training programmes specifically for different styles of play. From the previous research, it is recommended that high level competitive tennis players have $\dot{V}O_2$max levels generally greater than 50 ml/kg/min to train and compete at the appropriate level. Training should be tailored to an athlete's specific playing style.

Heart rate is a practical method of monitoring intensity during practice. During 85 minutes of match play, a group of collegiate tennis players' mean heart rate was found to be 144.6 (13.2) beats/min.[25] The heart rate and maximum heart rate reserve were consistent with results from other studies.[7 8 19 26] This indicated that heart rate remains significantly increased above pre-exercise levels despite the varying intensity and intermittent nature of the game. Although heart rate is an easily measured index of intensity, it should not be used as the sole measurement of metabolism, as this would not accurately represent the physiological nature of an intermittent sport such as tennis. The heart rate

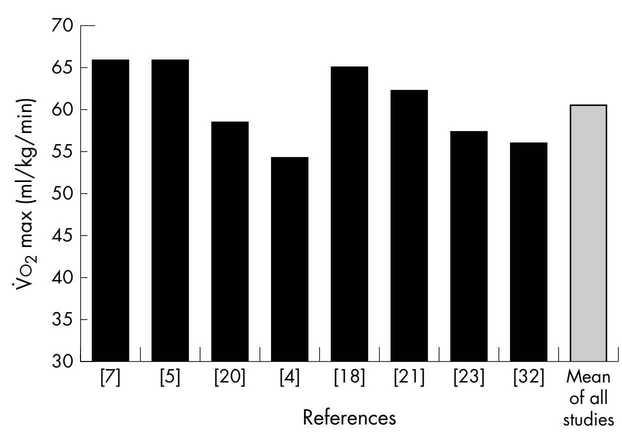


**Figure 2** Mean $\dot{V}O_2$max values from tennis research studies.

variability and ranges during a match are rather wide owing to the continual stop/start movements and explosive nature of the sport. Some previous research has suggested that tennis is an aerobic sport because of the long duration and moderate mean heart rate values during play.[20] However, the explosive nature of the serve and ground strokes, the rapid changes of direction which requires a high anaerobic capacity, and the requirement for a high percentage of fast twitch muscle fibres do not represent typical aerobic focused activities. Therefore, it would be remiss to suggest that tennis is a predominantly aerobic sport; it might be better to classify it as a anaerobic predominant activity requiring high levels of aerobic conditioning to avoid fatigue and aid in recovery between points.

## Speed and agility

Tennis has often been described as a game of continual emergencies because with every shot the opponent hits, a ball can have a different velocity, a different type and rate of spin, be placed in many different parts of the court.[27] This complexity requires tennis athletes to have fast reaction times and explosive ''first step'' speed. Tennis players need to be exceptional movers in a linear direction, but also in lateral and multidirectional movements. A rather practical research study tested the relation between acceleration, maximum velocity, and agility in soccer players. It appears that these three variables are individual, and each specific quality is independent of the other.[28] Thus it is important to train tennis players in the specific movement patterns that are encountered during match play. If specificity principles are used to design training programmes, it would also seem sensible to train tennis athletes using sprint activities that are no longer than the furthest distance that the athlete would run, per shot, during a point. A programme consisting of stop-start sprints of no more than 20 metres would be appropriate.

## Strength

Strength is required in muscles and joints both for performance (ball velocity) enhancement and to reduce injuries (protection of joints, ligaments, tendons, and so on). Solid contact between the racket and the ball is required for optimum stroke execution, and this is influenced by grip strength. A firm wrist is necessary to prevent the racket head from straying from its intended path under the influence of high angular speeds and torques.[29] A maximum grip strength of 600 N has been reported in elite level tennis players, as well as greater grip endurance compared with non-players.[30] Kibler and Chandler[30] also found that grip strength and grip endurance were not well correlated. Therefore, grip strength and grip endurance should be tested separately and trained accordingly. In the tennis serve, it has been shown that the greatest contribution to final speed of the racket head was, in order of importance: upper arm internal rotation, wrist flexion, upper arm horizontal adduction, forearm pronation, and forward movement of the shoulder.[31 32]

The shoulder region is highly involved in all tennis strokes, and it has been shown that shoulder internal, external, and diagonal peak torques contribute substantially to service ball velocity.[33] Thus it is not surprising that the shoulder region has been a major focus of tennis related performance and injury prevention/rehabilitation research. Eccentric muscular contractions play a role in functional activities, but in the tennis shoulder—specifically the rotator cuff—the infraspinatus and teres minor are of major importance during the follow through of the ground strokes, but more specifically the service motion.[34] These two muscles undergo high decelerative eccentric muscle contractions to preserve healthy joint movement.[35] Adequate strength and range of motion (ROM) in the rotator cuff muscles are essential in preventing overhead overuse injuries as they are vital in stabilising and movement throughout the extreme ROM experienced during tennis strokes—specifically the service motion.[29 36]

The speed of the serve or throwing motion depends partly on a rapid and forceful concentric internal rotation in the acceleration phase of the serve.[35] The eccentric phase of training may specifically affect the decelerative phase, which may determine the trajectory and velocity components of performance.[37] Both eccentric and concentric isokinetic shoulder training have resulted in significant power gains, particularly at fast functional velocities, as well as large increases in the explosiveness of the rotator cuff muscles.[37] It should therefore be recommended that tennis athletes include both concentric and eccentric shoulder training in their training programmes for performance improvement.

Upper body strength indices have been the focus of the majority of tennis strength research, even though the majority of tennis injuries have been reported to occur in the lower body.[38] It would therefore be important to include lower body strengthening exercises for tennis players.[39] Unlike the asymmetrical differences seen in upper body strength, lower body strength measures have been shown to be symmetrical in tennis players.[40] Although more research is required into lower body strength and tennis play, it may be beneficial for tennis athletes to undertake both bilateral and unilateral strength exercises to improve performance and reduce the risk of injury.

### Flexibility

Physical demands of tennis cause musculoskeletal adaptations that are sometimes positive (increased strength) and sometimes negative (decreased joint ROM and reduced muscular flexibility). These repeated demands to produce force by muscle shortening can cause a cycle of microtrauma to the tight muscle, followed by scar formation, followed by more microtrauma with continued use.[41] These adaptations can become maladaptations, reducing joint ROM, changing biomechanical patterns, and decreasing the efficiency of force production, thus increasing the chance of injury to the muscle.[42]

Tennis athletes have been shown to have a greater range of internal shoulder motion in their dominant arm than other athletes, but also have smaller range of external shoulder motion.[42] The major reason for this is probably the repetitive service action which increases the internal ROM—a possible performance benefit. However, if the external ROM is not improved the imbalance created, although improving performance in the short term, may lead to muscle and joint injury in the medium to long term.

A study looking at shoulder ROM over the course of a competitive four month collegiate women's tennis season found that internal and external glenohumeral joint rotation did not improve.[43] This suggests that playing tennis alone, without any external shoulder ROM training, is not enough to improve shoulder ROM, which would increase performance. Thus tennis athletes should undertake a shoulder ROM programme, both during the pre- or off-season and during the main competitive season.

Lower back pain and injury are common complaints among elite tennis players,[42] and this correlates with poor lower back and hamstring ROM.[42] Tennis players have been shown to have a smaller ROM in both hamstrings than other athletes, but an even poorer ROM in their back leg, while serving.[42] This poor hamstring ROM may be explained by the need for tennis players to be in the typical "low ready position." This is the most efficient starting position for explosive movement, because of the lowered centre of mass, but it does require the athlete to have the hamstring in a shortened contracted position for long periods. It is vitally important that a hamstring lengthening (stretching) programme is implemented from an early age so that the athlete will still be improving performance by using the low ready position, but will not be (counterproductively) increasing the chance of lower back or hamstring injury resulting from tight and inefficient hamstring/lower back ROM.

Flexibility needs to be individualised. If the ROM is sufficient, excessive flexibility training may induce negative benefits (reduced power output). Thus training time may be spent productively in maintaining flexibility and focusing on other training variables than continually trying to improve ROM.[44]

## PERFORMANCE

### Physical components, age, and rankings

There has been some good practical research looking at links between physical fitness components, age, and tennis ranking in competitive junior players. Correlation studies have been undertaken to determine which physical components have a strong relation with match results and ranking. Only one correlation was found between the results of certain athletic performance tests and the sectional rankings of the junior tennis players—the hexagon test for agility and speed ($r = 0.23$, $p<0.05$).[45] No correlations were found between the athletes' tennis stroke rating (by highest level USPTA tennis coaches) and physical performance tests.[45] Higher correlations were observed between the tennis strokes and national rankings (forehand $r = 0.68$, $p<0.05$; backhand $r = 0.59$, $p<0.05$; service $r = 0.57$, $p<0.05$) than between the tennis strokes and sectional rankings (forehand $r = 0.44$, $p<0.05$; backhand $r = 0.31$, $p>0.05$; service $r = 0.43$, $p<0.05$).[45] Except for the backhand stroke, which did not have a significant correlation with sectional rankings, each stroke was significantly correlated with sectional and national rankings.[45] As stated by the authors, the most remarkable finding of this investigation was that the physical performance tests in advanced young male tennis players (8 to 12 years old) did not predict their ability to play tennis at a competitive level.[45] Agility, however, was the physical ability that most influenced the competitive level of young tennis players. Data from this study did indicate that skills related to tennis strokes may be used to predict success at this age.[45] The lack of physical maturation in males during this age period (8 to 12 years) could be a major explanation for why physical performance was not related to tennis rankings. Dramatic increases in strength, size, and endurance typically occur in boys between the ages of around 12 to 15 years.[46] As tennis players mature, it seems that the major factors affecting their performance alter.

In a study that expanded on that by Roetert *et al*,[45] three levels of elite junior tennis players were tested: USTA National Team (mean age 15.4 years); Development Camp (mean age 13.6 years); and USTA area training centres (age not specified). An analysis to classify rankings with performance tests was able to classify 91.4% of cases correctly.[47] The seven variables that allowed this strong association were: hexagon drill, push-ups, side shuffle, dominant internal shoulder rotation, dominant external shoulder rotation, sit and reach, and sit-up test.[47] Therefore, for talent identification purposes, these previously mentioned seven categories may provide guidance in estimating current and future match play success.

As technical stroke production appears to influence rankings more than physical ability in the younger players, their training should concentrate on effective and efficient stroke mechanics, improving technique and ball placement, with less emphasis on physical conditioning until they reach puberty and beyond. However, a sufficient minimal physical fitness level is still required to endure practice and match sessions.

As junior competitive tennis players age, there seems to be an increase in shoulder problems. As age increases, there is a continual decrease in internal ROM.[48 49] This would suggest that as junior tennis players age, they need to include an internal shoulder ROM programme to prevent the onset of flexibility imbalances.

### Power *v* placement

The relation between power and placement in tennis play is an area of interest. Research has shown that measures of knee extension peak torque, knee flexion peak torque, and shoulder external peak torque were inversely related to cross court ball placement ($r = -0.55$, $p<0.05$; $r = -0.49$, $p<0.05$; and $r = -0.567$, $p<0.05$, respectively).[33] Shoulder diagonal average power was also significantly and inversely related to ball placement during the serve ($r = -0.49$, $p<0.05$).[33] The investigators surmised that the players showing the greatest isokinetic strength and perhaps the greatest ball velocity had the most difficult time with ball placement.[33] These results are an extension of the speed–accuracy trade off, as originally described in Fitt's law.[50] This received support from a study that found no significant correlations between stroke velocity and accuracy.[51] As would be expected, correlations have been found between shoulder strength and the velocity of tennis strokes ($r^2 = 0.68$).[51] Interestingly, in two studies on junior players, flexibility measures were not significantly related to any measure of either ball placement or ball velocity.[33 51] This is different from what was found when similar measures were taken with college players.[52]

### Fatigue and performance

As tennis players practice and play matches that last hours, fatigue is a major concern when designing training programmes. Fatigue has been shown to have a detrimental affect on a player's mechanics,[53] thereby reducing ball velocity (performance), possibly in a protective mechanism to avoid injury by limiting the large ranges of motion and forces in a compromised biomechanical position. Fatigue has been shown to decrease proprioceptive ability,[54] which may lead to protective mechanisms being too slow in response to prevent injury. Fatigue affects sensation of joint movement, decreases athletic performance, and increases fatigue related shoulder dysfunction.[55] Fatigue has been shown to reduce shoulder external rotation, which has been suggested as the possible reason for the performance and force decrements found with extended tennis play.[53]

Apart from the biomechanical consequences of fatigue, the athlete's metabolic and physiological functioning is also reduced. The duration of recovery, as well as the duration of the intensity of work, is important for the regulation of physiological strain during intermittent exercise (tennis play). Studies during both sprint and weight training have shown the importance of recovery on subsequent performance.[56–60] Power decrements in the course of high intensity intermittent exercise, as in tennis, have been related to a continuous degradation of phosphocreatine, thus placing greater demand on glycogenolysis and glycolysis, with increasing muscle and blood lactate concentrations resulting in large reductions in muscle pH.[61] If high intensity intermittent exercise is undertaken with limited rest periods, it will lead to increased fatigability in tennis players, and if this state is continued for more than a few days it can lead to ''overreaching'' or the more dangerous ''overtraining'' syndrome.

The quality of movement patterns and coordination of specific actions in tennis is dependent on the physiological strain produced during short term intermittent exercise. Small changes in the recovery time can produce large changes in performance of the exercise.[61] Tennis players, as would be expected, felt that the longer the rest periods the easier the tennis drill felt. Ferrauti *et al*[61] suggest that a decrease in running speed results in inaccurate stroke preparation, leading to a decrease in stroke speed (performance), as well as possible stroke intention (avoiding errors *v* hitting winners). Therefore, it is important when structuring drills on the practice court that the intention of the drill is understood. When working on technical issues, it is essential to give appropriate rest. It is imperative to use work/rest ratios that provide the coach and athlete with the right environment for optimum outcome. When working on technical skills, it is important to have greater rest than when working on tennis specific movement or energy system specific training.[2]

Hitting accuracy is reduced by as much as 81% when a tennis player is nearing volitional fatigue.[62 63] It has been reported that after a two hour strenuous training session, an increase in ground stroke errors during defensive rallies and an increase in errors on first serves were observed.[64]

Fatigue from maximal tennis hitting has resulted in a 69% deterioration in hitting accuracy of ground strokes and a 30% decline in accuracy of the service to the right hand court.[63] After a fatiguing test, the serve was the most obvious tennis stroke to deteriorate in skill. It was observed in first serve accuracy to the right box but not to the left box. The fatiguing test, employed in this study was a four minute side to side forehand and backhands drill with a 40 second rest period and this was repeated until volitional fatigue.[63] This protocol would induce the intended fatigue, but is not representative of the physiological strain encountered during a match setting, nor of most practice drills. This artificially induced fatigue state will lead to high lactate levels that are not typically seen in tennis play.[20] As tennis competition has average points lasting less than 10 seconds, with rest periods of approximately 20 seconds between points and 90 seconds after every second game, the physiological variables are unlikely to lead to a large accumulation of lactate. Thus accumulating lactate levels are not a major cause of fatigue in tennis match play.

## CONCLUSIONS AND FUTURE RESEARCH

Improving tennis performance is the goal of every tennis scientist, coach, and athlete. The practicality of this information should be applied when designing training programmes for higher level tennis players. Age, sex, style of play, physical components, technical components, tactical components, and psychological components will all determine the success of the tennis athlete. Effective planning and training programmes will help in designing a safe, effective, and productive programme design to help optimise performance.

It is recommended, like all sports, that tennis athletes train in a specific manner to improve tennis-specific performance and reduce injury. Most training drills should simulate the time requirements experienced during match play (5–20 seconds) with appropriate work to rest ratios (1:3 to 1:5). As speed, agility, and maximum velocity movements respond to specific and individualised training, it is important that tennis players focus on training distances seen during match play (<20 metres), with drills combining linear, lateral, and multidirectional movements.

Having good aerobic capacity is important for recovery during play and between sessions. It is recommended that tennis athletes strive for $\dot{V}O_2max$ values greater than 50 ml/kg/min. Having adequate strength levels in all muscles and joints is important, but specific areas of focus should be the shoulder, forearm/wrist, lower back, and core region. Tennis players typically have less than optimal ROM at the shoulder, lower back, and hamstring muscles. As these three areas are vital for optimum performance, continual development should be a major focus of the workout routine.

As tennis has changed dramatically in the last 20 years, more research is needed into all aspects of training. Some quality research was conducted in the 1980s and 1990s, but as the speed of the game, the type of athlete, and the strategy of play have developed, so must the focus of tennis research. Not enough information has been obtained during tournament play and its effects on performance and recovery. Also, there is still healthy debate over whether tennis players are predominantly anaerobic or aerobic athletes and what methods of training are most beneficial and efficient both from a performance enhancement perspective and for preventing injury.

Competing interests: none declared

## REFERENCES


1 **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.
2 **Kovacs M**. Energy system-specific training for tennis. *Strength Condition J* 2004;**26**:10–13.
3 **Christmass MA**, Richmond SE, Cable NT, *et al.* Exercise intensity and metabolic response in singles tennis. *J Sport Sci* 1998;**16**:739–47.
4 **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.London E & F Spon, 1994:3–9.
5 **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.
6 **König D**, Huonker M, Schmid A, *et al.* Cardiovascular, metabolic, and hormonal parameters in professional tennis players. *Med Sci Sport Exerc* 2001;**33**:654–8.
7 **Ellliott B**, Dawson B, Pyke F. The energetics of singles tennis. *J Hum Mov Stud* 1985;**11**:11–20.
8 **Morgans LF**, Jordan DL, Baeyens DA, *et al.* Heart rate responses during singles and doubles tennis competition. *Phys Sportsmed* 1987;**15**:67–74.
9 **Richers TA**. Time-motion analysis of the energy systems in elite and competitive singles tennis. *J Hum Mov Stud* 1995;**28**:73–86.
10 **Smekal G**, Von Duvillard SP, Rihacek CN, *et al.* A physiological profile of tennis matchplay. *Med Sci Sports Exerc* 2001;**33**:999–1005.
11 **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**:10–16.
12 **Chandler TJ**. Work/rest intervals in world class tennis. *Tennis Pro* 1991;**3**:4.
13 **Kovacs MS**. A comparison of work/rest intervals in men's professional tennis. *Med Sci Tennis* 2004;**9**:10–11.
14 **Kovacs MS**, Strecker E, Chandler WB, *et al.* Time analysis of work/rest intervals in men's collegiate tennis. In:National Strength and Conditioning Conference, 2004. Minneapolis: NSCA, 2004;18, e364.
15 **Yoneyama F**, Watanabe H, Oda Y. Game analysis of in-play-time and out-of-play-time in the Davis Cup. In:Fifth IOC World Congress on Sport Sciences, 1999. Sydney, Australia: Sports Medicine Australia, book of abstracts, 1999:204.
16 **O'Donoghue P**, Ingram B. A notational analysis of elite tennis strategy. *J Sports Sci* 2001;**19**:107–15.
17 **Hughes MD**, Clark S. Surface effect on elite tennis strategy. In:Reilly T, Hughes M, Lees A, editors.Science and racket sports. London: E & F Spon, 1995:272–8.
18 **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, Reilly T, editors.Science and racket sports II. London: E & F Spon, 1998:20–6.
19 **Docherty D**. A comparison of heart rate responses in racquet games. *Br J Sports Med* 1982;**16**:96–100.
20 **Bergeron MF**, Maresh CM, Kraemer WJ, *et al.* Tennis: a physiological profile during match play. *Int J Sports Med* 1991;**12**:474–9.
21 **Faff J**, Ladyga M, Starczewska CJ. Physical fitness of the top Polish male and female tennis players aged from twelve years to senior category. *Biol Sport (Warsaw)* 2000;**17**:179–92.
22 **Bergeron MF**, Armstrong LE, Maresh CM. Fluid and electrolyte losses during tennis in the heat. *Clin Sports Med* 1995;**14**:23–32.
23 **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**:489–95.
24 **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**:608–13.
25 **Bergeron MF**, Maresh CM, Kraemer WJ, *et al.* Tennis: a physiological profile during match play. *Int J Sports Med* 1991;**12**:474–9.
26 **Seliger V**, Ejem M, Pauer M, *et al.* Energy metabolism in tennis. *Int Z Angew Physiol* 1973;**31**:333–40.
27 **Groppel JL**. The biomechanics of tennis: an overview. *Int J Sport Biomech* 1986;**2**:141–55.
28 **Little T**, Williams AG. Specificity of acceleration, maximal speed and agility in professional soccer players. *J Strength Cond Res* 2005;**19**:76–8.
29 **Behm DG**. A kinesiological analysis of the tennis service. *NSCA J* 1988;**10**:4–14.
30 **Kibler WB**, Chandler TJ. Grip strength and endurance in elite tennis players. *Med Sci Sports Exerc* 1989;**21**:S65.
31 **Elliott BC**, Marshall RN, Noffal GJ. Contributions of upper limb segment rotations during the power serve in tennis. *J Appl Biomech* 1995;**11**:433–42.
32 **Sprigings E**, Marshall R, Elliott B, *et al.* A three-dimensional kinematic method for determining the effectiveness of arm segment rotations in producing racket head speed. *J Biomech* 1994;**27**:245–54.
33 **Perry AC**, Wang X, Feldman BB, *et al.* Can laboratory-based tennis profiles predict field tests of tennis performance? *J Strength Cond Res* 2004;**18**:136–43.
34 **Chandler TJ**. Conditioning for tennis: preventing injury and enhancing performance. In:Lees A, Maynard I, Hughes M, Reilly T, editors.Science and racket sports II. London: E & F Spon, 1998:77–85.
35 **Duda M**. Prevention and treatment of throwing arm injuries. *Phys Sports Med* 1985;**13**:181–5.
36 **Fleisig G**, Nicholls R, Elliott B, *et al.* Kinematics used by world class tennis players to produce high-velocity serves. *Sports Biomech* 2002;**2**:51–71.
37 **Ellenbecker TS**, Davis GJ, Rowinski MJ. Concentric versus eccentric isokinetic strengthening of the rotator cuff. *Am J Sports Med* 1988;**16**:64–9.
38 **Bylak J**, Hutchinson MR. Common sports injuries in young tennis players. *Sport Med* 1998;**26**:119–32.
39 **Bergeron MF**. Conditioning the legs for tennis. *NSCA J* 1988;**10**:40–1.
40 **Ellenbecker TS**, Roetert EP. Concentric isokinetic quadriceps and hamstring strength in elite junior tennis players. *Isokinet Exerc Sci* 1995;**5**:3–6.
41 **Kibler WB**, McQueen C, Uhl T. Fitness evaluations and fitness findings in competitive junior tennis players. *Clin Sports Med* 1988;**7**:403–16.
42 **Chandler TJ**, Kibler WB, Uhl TL, *et al.* Flexibility comparisons of junior elite tennis players to other athletes. *Am J Sports Med* 1990;**18**:134–6.
43 **Ellenbecker TS**, Roetert EP. Effects of a 4-month season on glenohumeral joint rotational strength and range of motion in female collegiate tennis players. *J Strength Cond Res* 2002;**16**:92–6.
44 **Lindstedt SL**, LaStayo PC, Reich TE. When active muscles lengthen: properties and consequences of eccentric contractions. *News Physiol Sci* 2001;**16**:256–61.
45 **Roetert EP**, Garrett GE, Brown SW, *et al.* Performance profiles of nationally ranked junior tennis players. *J Appl Sport Sci Res* 1992;**6**:225–31.
46 **Kraemer WJ**, Fry AC, Frykman PN, *et al.* Resistance training and youth. *Pediatr Exerc Sci* 1989;**1**:336–50.
47 **Roetert EP**, Brown SW, Piorkowski PA, *et al.* Fitness comparisons among three different levels of elite tennis players. *J Strength Cond Res* 1996;**10**:139–43.
48 **Roetert EP**, Ellenbecker TS, Brown SW. Shoulder internal and external rotation range of motion in nationally ranked junior tennis players: a longitudinal analysis. *J Strength Cond Res* 2000;**14**:140–3.
49 **Kibler WB**, Chandler TJ, Livingston BP, *et al.* Shoulder range of motion in elite tennis players. *Am J Sports Med* 1996;**24**:279–85.
50 **Fitts PM**. The information capacity of the human motor system in controlling the amplitude of movement. *J Exp Psychol* 1992;**121**:262–9.
51 **Signorile JF**, Sandler DJ, Smith WN, *et al.* Correlation analyses and regression modeling between isokinetic testing and on-court performance in competitive adolescent tennis players. *J Strength Cond Res* 2005;**19**:519–26.
52 **Kraemer WJ**, Triplett NT, Fry AC, *et al.* An in-depth sports medicine profile of women college tennis players. *J Sports Rehab* 1995;**4**:79–98.
53 **Murray TA**, Cook TD, Werner SL, *et al.* The effects of extended play on professional baseball pitchers. *Am J Sports Med* 2001;**29**:137–42.
54 **Myers JB**, Guskiewicz KM, Schneider RA, *et al.* Proprioception and neuromuscular control of the shoulder after muscle fatigue. *J Athlet Train* 1999;**34**:362–7.
55 **Carpenter JE**, Blasier RB, Pellizzon GG. The effects of muscle fatigue on shoulder joint position sense. *Am J Sports Med* 1998;**26**:262–5.
56 **Hargreaves M**, McKenna MJ, Jenkins DG, *et al.* Muscle metabolites and performance during high-intensity, intermittent exercise. *J Appl Physiol* 1998;**84**:1687–91.
57 **Linossier MT**, Denis C, Dormois D, *et al.* Ergometric and metabolic adaptations to a 5 s sprint training programme. *Eur J Appl Physiol* 1993;**68**:408–14.
58 **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.
59 **Abdessemed D**, Duche P, Hautier C, *et al.* Effect of recovery duration on muscular power and blood lactate during the bench press exercise. *Int J Sports Med* 1999;**20**:368–73.
60 **Balsom PD**, Seger JY, Sjodin B, *et al.* Maximal-intensity intermittent exercise: effect of recovery duration. *Int J Sports Med* 1992;**13**:528–33.
61 **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.
62 **Davey PR**, Thorpe RD, Williams C. Simulated tennis matchplay in a controlled environment. *J Sports Sci* 2003;**21**:459–67.
63 **Davey PR**, Thorpe RD, Williams C. Fatigue decreases skilled tennis performance. *J Sport Sci* 2002;**20**:311–18.
64 **Vergauwen L**, Spaepen AJ, Lefevre J, *et al.* Evaluation of stroke performance in tennis. *Med Sci Sport Exerc* 1998;**30**:1281–8.

## COMMENTARY

This excellent review highlights the differences between what are the assumed physical attributes required of the tennis athlete and what the science really tell us. Coaches and sports scientists must work together in order to best prepare the tennis athlete, on the basis of the variables outlined in this paper. As discussed by the author, further research is needed, particularly as the game has progressed in recent years. This research needs to be in the competitive environment rather than as controlled studies.

**A J Pearce**
Victoria University, School of Human Movement, Rec and Perf, Melbourne, Victoria, Australia; alan.pearce@vu.edu.au