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Science and the major racket sports: a review

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The major racket sports include badminton, squash, table tennis and tennis. The growth of sports science and the commercialization of racket sports in recent years have focused attention on improved performance and this has led to a more detailed study and understanding of all aspects of racket sports. The aim here, therefore, is to review recent developments of the application of science to racket sports. The scientific disciplines of sports physiology and nutrition, notational analysis, sports biomechanics, sports medicine, sports engineering, sports psychology and motor skills are briefly considered in turn. It is evident from these reviews that a great deal of scientific endeavour has been applied to racket sports, but this is variable across both the racket sports and the scientific disciplines. A scientific approach has helped to: implement training programmes to improve players’ fitness; guide players in nutritional and psychological preparation for play; inform players of the strategy and tactics used by themselves and their opponents; provide insight into the technical performance of skills; understand the effect of equipment on play; and accelerate the recovery from racket-arm injuries. Racket sports have also posed a unique challenge to scientists and have provided vehicles for developing scientific methodology. Racket sports provide a good model for investigating the interplay between aerobic and anaerobic metabolism and the effect of nutrition, heat and fatigue on performance. They have driven the development of mathematical solutions for multi-segment interactions within the racket arm during the performance of shots, which have contributed to our understanding of the mechanisms of both performance and injury. They have provided a unique challenge to sports engineers in relation to equipment performance and interaction with the player. Racket sports have encouraged developments in notational analysis both in terms of analytical procedures and the conceptualization of strategy and tactics. Racket sports have provided a vehicle for investigating fast interceptive actions, hand-eye coordination and perception-action coupling in the field of motor control. In conclusion, science has contributed considerably to our knowledge and understanding of racket sports, and racket sports have contributed to science by providing unique challenges to researchers.

Keywords: badminton, racket sports, squash, table tennis, tennis.

Introduction

The major racket sports include badminton, squash, table tennis and tennis. These games are characterized by a hand-held racket that is used to propel a missile between two (or four) players with the purpose of placing the missile in such a position that one player is unable to return it successfully. They are also characterized by an area of play that has a specified size within which the missile must be contained, and some hurdle that the missile must be above on each play. The unique sizes and shapes of the area of play, the hurdle, missile and racket have evolved to describe the various components and aspects of play.

Racket sports have been played for more than 130 years and in this time there have been many developments. The commercialization of racket sports in recent years has focused attention on improved performance and this has led to a more scientific approach to the study and understanding of all aspects of racket sports. This development, coupled with greater numbers of individuals with an interest in applying their scientific skills to racket sports, has seen a rapid growth in scientific endeavour. This endeavour has had an outlet in specialized conferences and scientific publications and covers a wide variety of scientific disciplines, such as sports physiology and nutrition, notational analysis, sports biomechanics, sports medicine, sports engineering, sports psychology and motor skills. There has never
been a comprehensive attempt to overview current trends and developments in these areas related to racket sports. The aim here is to review recent developments in the application of science to racket sports.

**Sports physiology and nutrition**

The activity in racket sports is intermittent and the physiological demand is determined largely by the surface, equipment, missile characteristics, extent to which the game is contested and by environmental factors such as temperature and humidity. Players can modify the physiological demand by controlling the rest intervals between rallies and between games and sets. A major determinant of the outcome of the game is an individual's physical fitness, which can be influenced by hydration and nutritional status, and so measuring and monitoring these factors have been a major interest to researchers. Research interest has also focused on training regimens to develop fitness to compete at specific levels of competition, and the training effect of recreational play with regard to the health benefits of physical activity.

The duration of competition in racket sports can vary from as little as 6 min in squash (Sharp, 1998) to 5 h or more in tennis (McCarthy-Davey, 2000), although durations of 20–90 min are more common across all racket sports. In addition, the duration of rallies can be as short as 1.5 s or as long as 10 min (both in squash; Sharp, 1998), although periods of 3–10 s are more common across all racket sports. Since the intensity of effort is greatest during a rally, the length of the rally is important to the energy systems utilized. Sharp (1998) has classified the length of rallies into three categories: those that last less than 5 s, those that last 6–20 s and those that last for more than 20 s. These time classifications relate to the anaerobic and aerobic energy sources available to the player, all of which need to be able to deliver higher rates of energy conversion as the standard of competition improves. The work:rest ratio of rallies determines the demand of the game; these have been reported to be around 0.5, but with some variation between the racket sports and between standards of play (Reilly, 1990).

Cardiorespiratory fitness has been traditionally measured by maximal oxygen uptake and a range of values for racket players have been reported by Reilly (1990); more recent data from the literature are summarized in Table 1. These data confirm that racket sports participants possess mainly moderate aerobic capabilities, suggesting that these sports are aerobic in nature, but the range is large so that it is difficult to reach more specific conclusions. This variation may be due to

<table>
<thead>
<tr>
<th>Table 1. Maximal oxygen uptake (ml·kg⁻¹·min⁻¹) in racket players</th>
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<tbody>
<tr>
<td><strong>Sex</strong></td>
</tr>
<tr>
<td><strong>Badminton</strong></td>
</tr>
<tr>
<td>Dias and Gosh (1995)</td>
</tr>
<tr>
<td><strong>Tennis</strong></td>
</tr>
<tr>
<td>Christmass <em>et al.</em> (1995)</td>
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<td>Reilly and Palmer (1995)</td>
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<td><strong>Squash</strong></td>
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<td>Reilly and Halsall (1995)</td>
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<tr>
<td>Mellor <em>et al.</em> (1995)</td>
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<tr>
<td></td>
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<tr>
<td>Mahoney and Sharp (1995)</td>
</tr>
<tr>
<td>Todd and Mahoney (1995)</td>
</tr>
<tr>
<td><strong>Table tennis</strong></td>
</tr>
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<td>Segun and Toriola (2002)</td>
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</tbody>
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*Elite represents national and international players and world-ranked professional players.
differences between protocols or equipment used and so within-study comparisons are potentially more informative. In this regard, Brown et al. (1998) studied the transition from elite junior to elite senior squash. They reported that elite senior players had a 7–9% greater capacity to consume oxygen than elite junior players, suggesting that as well as technical and tactical differences that affect the transition, physiological factors also play an important role. One unique aspect of this study within the racket sports literature was that the researchers used allometric scaling to normalize their oxygen consumption data. They recognized that these data are influenced by body mass, but that a scaling exponent of 0.67 rather than the normal 1.00 should be used. This adjustment did not affect their general conclusion but did reduce the magnitude of the difference between elite junior and elite senior squash. This may in turn have an influence on the training programmes elite junior players undertake to ensure their successful transition to the senior game, with perhaps less effort spent on the development of aerobic capacity and more effort spent on technical and tactical developments than would otherwise have been the case. This conclusion may be relevant to the optimal training of potential elite players.

Physiological stress is associated with the elevation of heart rate and reflects the effort expended during short intense bouts of play. The heart rate generally increases rapidly at the onset of a match and remains elevated, with a tendency to increase further as the match progresses (Fig. 1). Maximal heart rates during the match are close to the age-related maximum expected, and the average over the match often exceeds 75% of this maximum, indicating a high effort during play (see Table 2). These data suggest that there is some variability in heart rate between the racket sports and between standards of play, with the highest heart rate values being in high standards of play in badminton and squash (confirming data presented by Reilly, 1990). The relatively high mean heart rates expected for most standards of play also suggest that racket sports provide a suitable basis for health-related exercise.

Physiological stress is also associated with the accumulation of lactate in blood. During rest, a blood lactate concentration of 1–2 mmol·l⁻¹ is expected (Bergeron et al., 1991; Christmass et al., 1995; Reilly and Palmer, 1995), while during play it is around 3–4 mmol·l⁻¹ (Sharp, 1998), which reflects the aerobic nature of racket sports. However, during intense competition and particularly towards the end of the match, blood lactate concentrations can exceed 10 mmol·l⁻¹ in squash (Sharp, 1998) and in tennis (Bergeron et al., 1991). At least one author (Mikkleson, 1979) has suggested that blood lactate concentration can be affected by hydration, as over 2.5 l·h⁻¹ of fluid may be lost during a match. In tennis, blood lactate concentrations in excess of 7–8 mmol·l⁻¹ have been associated with a decline in technical and tactical performance (McCarthy-Davey, 2000). In contrast, the highest blood lactate concentrations in competitive badminton have been reported to be no more than 5 mmol·l⁻¹. The reason for this is not clear, but may...
Table 2. Heart rates as a percentage of age-related maximum heart rate in racket players

<table>
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<tr>
<th></th>
<th>Sex</th>
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<tbody>
<tr>
<td><strong>Badminton</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hughes (1995)</td>
<td>M</td>
<td>13</td>
<td>80% (over 85% of duration of play)</td>
</tr>
<tr>
<td>Mikkleson (1979)</td>
<td>M</td>
<td>9</td>
<td>95% (elite players)</td>
</tr>
<tr>
<td>Dias and Gosh (1995)</td>
<td>F</td>
<td>5</td>
<td>80% (elite junior players)</td>
</tr>
<tr>
<td><strong>Tennis</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Christmass et al. (1995)</td>
<td>M</td>
<td>8</td>
<td>86% (regional players)</td>
</tr>
<tr>
<td>Reilly and Palmer (1995)</td>
<td>M</td>
<td>8</td>
<td>76% (club standard)</td>
</tr>
<tr>
<td>Bernardi et al. (1998)</td>
<td>M</td>
<td>7</td>
<td>80% (86% for baseline play, 63% for attacking play)</td>
</tr>
<tr>
<td>Ferrauti et al. (1998)</td>
<td>M</td>
<td>18</td>
<td>85% (seniors – mean age 59 years)</td>
</tr>
<tr>
<td>Therminarias et al. (1995)</td>
<td>F</td>
<td>19</td>
<td>87% (hot environment)</td>
</tr>
<tr>
<td><strong>Squash</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reilly and Halsall (1995)</td>
<td>M</td>
<td>7</td>
<td>82% (young club players – mean age 22 years)</td>
</tr>
<tr>
<td>M</td>
<td>7</td>
<td>85% (older club players – mean age 42 years)</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>7</td>
<td>82% (older recreational players – mean age 45 years)</td>
<td></td>
</tr>
<tr>
<td>Graydon et al. (1998)</td>
<td>M</td>
<td>8</td>
<td>75% (young club players)</td>
</tr>
</tbody>
</table>

well simply reflect the fewer data available in this game. During a training session, Hughes (1995) manipulated the work:rest ratio and found that for a work time of 20 s and a work:rest ratio of 0.5, blood lactate increased to 7.2 mmol·L⁻¹. The association between intensity of effort and blood lactate concentration has been reported by Sharp (1998). He observed blood lactate concentrations during a highly contested game of squash. At one point during the fourth game, one player was close to winning the match and made a great effort to win. His blood lactate concentration at the end of the game increased to 9.2 mmol·L⁻¹ (preceding that it did not exceed 4 mmol·L⁻¹), but the effort was not enough to win the game. In the final game, the player was observed to slow the pace to give himself a chance to recover; at the end of the game, his blood lactate concentration dropped to 5.7 mmol·L⁻¹, an indication of the physiological success of his strategy. However, he was too fatigued to win the final game and lost the match. Sharp (1998) commented on the adage that one should not be merciful to a tiring opponent who may recover given time, with lower blood lactate and renewed vigour and confidence.

Muscle strength and endurance, joint range of motion and flexibility have been identified by Chandler (1998) as other important elements of fitness for the racket player. Data on grip strength have been more widely reported than these other characteristics, possibly due to its ease of measurement and its obvious importance for holding and controlling the racket. Grip strength is evaluated using a hand grip dynamometer and values as high as 600 N have been reported in elite squash players (Sharp, 1998), although lower values of around 500 N have been reported by Todd and Mahoney (1995). Sharp suggested that a range of 400–450 N for men and 300–350 N for women is required to ensure that the racket is held firmly during play. In elite junior male squash players, Mahoney and Sharp (1995) reported an asymmetry in grip strength with the dominant limb being 13% stronger than the non-dominant limb. In elite tennis players, Kibler and Chandler (1999) reported a hand grip strength of 600 N and a greater grip endurance than for non-tennis players. They also found that grip strength and grip endurance did not correlate well and suggested that both should be measured. Kramer and Knudson (1992) reported that the mean grip strength of junior college male and female tennis players was 467 N and 300 N, respectively, and that these values did not change significantly over 30 maximal trials, which led the authors to consider these tennis players to be resistant to fatigue. The greater grip strength and grip endurance of elite tennis players (males 509 N, females 377 N) over non-tennis players has recently been confirmed by Davey (2002), although not all of these differences were significant. Other measures of strength have been reported. Using a back and leg dynamometer, Reilly and Benton (1995) reported that female regional tennis players had 40% greater back strength and 15% greater leg strength than club players. Todd and Mahoney (1995) reported data on muscle endurance, as indicated by the number of sit-ups completed in one minute, but again no comparative data are available. Laboratory studies have also been conducted to evaluate muscle...
strength using a muscle function dynamometer. Chandler et al. (1992) reported that female college tennis players produced a significantly higher strength during internal rotation in the dominant arm than the non-dominant arm and this difference was attributed to the stretch–shorten muscle action required in the tennis serve (see 'Biomechanics' section below). Although considered an important aspect of fitness, it is surprising that there are such limited laboratory-based data on racket players’ strength. Flexibility is often measured by a simple sit-and-reach test, with Reilly and Benton (1995) reporting greater flexibility in regional female tennis players than club tennis players. However, in elite junior tennis players, Kibler et al. (1988), using both sit-and-reach and goniometric measurements, reported a high incidence of poor flexibility in the trunk, lower limb and upper limb. Chandler et al. (1990) reported tennis players were less flexible than non-tennis athletes in the shoulder and arm joints. Chandler (1995) suggested that the reduced flexibility in the upper limb is a reflection of the adaptations that players make to the repetitive, short-duration, high-velocity musculoskeletal demands of tennis and one might expect similar characteristics in other racket sport players. In squash, Todd and Mahoney (1995) reported sit-and-reach data for elite male players but no comparisons were made. Locke et al. (1997) stated that the precise requirements for strength and flexibility in squash have not been documented and no further data appear to be available in the subsequent literature for squash players or, indeed, badminton and table tennis players.

Environmental temperature plays a large part in the physiological stress that a player experiences. While indoors games can be played in an air-conditioned environment, this is generally only available at the highest standards of play. Furthermore, games such as tennis are mostly played out of doors in the summer and court surface temperatures during a tournament can exceed surrounding air temperatures because of the enclosed nature of the stadium and reflection of radiant energy. Despite this, there has been little reported research into the direct effects of temperature. One exception is the study of Hansen (1995), who examined the change in physiological responses over a squash playing season where temperatures ranged from an average of 16 to 27°C. He computed a ‘discomfort index’ based on dry and wet bulb temperatures to take account of both temperature and humidity. He found that as the discomfort index increased, so did average heart rate, post-exercise rectal temperature and sweat loss. The rating of perceived exertion increased, but not significantly, suggesting that players adjusted their intensity of play to cope with the increasingly demanding environmental conditions. Therminarias et al. (1995) reported data on female tennis players who were asked to play a hard tennis match under hot conditions (28°C) with limited fluid intake. They reported elevations in heart rate, rectal temperature and fluid loss. Some of their participants suffered from cramps and heat stroke, which were thought to be also related to their biological status (low plasma magnesium and calcium concentrations, decreased ability to utilize blood glucose) before the match. It is clear that heat is an important factor affecting play, but no data are available on the tolerance and adaptations of players. This is particularly important as players move from one thermal environment to another for competitive purposes.

Dehydration is one of the more direct consequences of playing in the heat and there has been much interest in the effects of hydration status on performance in racket games, particularly as fluid intake is one of the main strategies for coping with performance in the heat and delaying the onset of fatigue (Kay and Marino, 2000). Kavasis (1995) tried to determine the fluid needs of young children playing practice and competitive tennis in a warm environment and reported that when fluid was freely available, children drank an average of 0.43 of a litre over a 90 min match. This was generally sufficient for their needs, but during competitive play there was a tendency to drink less and fluid intake was below the calculated replacement needs, suggesting a danger of dehydration. McCarthy et al. (1998) also investigated the fluid losses and intakes for young tennis players. They reported a fluid intake of 1.09 litres over an average of 86 min of play, although the temperature and humidity were greater than in the study of Kavasis (1995). In tennis, players are able to drink fluids frequently because of the breaks in play as they change ends, but the same is not true in the other racket sports and so hypohydration may become more of a problem. In squash, Brown et al. (1998) investigated the fluid loss of elite players during international competition in a hot and humid environment. Although players were able to drink freely during the match, they still lost an average of 2.37 l·h⁻¹, with a fluid deficit (after having ingested fluid) of 1.5 l·h⁻¹. They also found that fluid loss was directly dependent on the duration and intensity of play and by the environmental conditions within the court. These data were used to inform pre-, intra- and post-match hydration strategies.

Fatigue develops as the duration and intensity of physical exertion increase during racket play and is affected by environmental temperature and hydration status, as already discussed, as well as initial core temperature and degree of acclimatization (Kay and Marino, 2000). Fatigue affects the performance of racket skills and is manifest by poor positional play and
by mistimed or mis-hit shots, which lead to a decline in the accuracy of shots played. Vergauwen et al. (1998) found that after a strenuous training match over 2 h, errors in playing both ground strokes and first serves increased. Davey et al. (2002) reported that during an exhaustive tennis simulation test, tennis players’ hitting accuracy of ground strokes decreased gradually to end up 69% lower than at the start, while service accuracy to the right court declined by 30% at the end of the test (although, interestingly, service accuracy to the left court was unaffected). The tennis test used induced volitional fatigue in just 35 min and yielded a blood lactate concentration of 9.6 mmol·l⁻¹, an average heart rate of nearly 100% maximum and a rating of perceived exertion of a maximum of 20. Clearly under this regimen of testing, players were required to perform at levels that would not be sustained during a game. This research led the authors to propose guidelines for players in training to not exceed a blood lactate concentration of 8 mmol·l⁻¹, a heart rate of 180 beats·min⁻¹ and a rating of perceived exertion of 16. In contrast, Ferrauti et al. (2001) found that in a 30 shot intermittent tennis speed and accuracy test, as the duration of recovery decreased from 15 to 10 s, blood lactate reached 9.0 mmol·l⁻¹ but the number of target hits increased and the number of errors decreased, suggesting that even under this amount of fatigue players were still able to perform skilfully. Nevertheless, this retention of skill is not likely to remain for longer periods of play and the effect of progressive fatigue is that tennis skills will deteriorate. It may be supposed that the same effect would be evident in other racket sports.

Training regimens have been designed on the basis of the physiological data reported above, which place players under similar physiological demands to those which they would experience during the game, so that they will improve their aerobic and anaerobic fitness in a context appropriate to the game. Davey (2002) described an intermittent test used for tennis. This test is unusual as it is designed to elicit exhaustion quite rapidly and uses a work time of 40 s and a work:rest ratio of 6. Sharp (1998) described the practice of ‘shadow training’ in squash in which a player has to follow an imaginary opponent around the court. Several work times (30–60 s) and work:rest ratios (0.5:2) were used that produced similar blood lactate concentrations and heart rates as would be found in a competitive match, thereby confirming that the training modality was a suitable training stimulus for competitive play. Hughes and Fullerton (1995) described an aerobic test for badminton that used a work time of 3 min and a work:rest ratio of just under 0.4. They reported that after training using this protocol, blood lactate concentration following the test procedure was reduced from 4.3 to 2.7 mmol·l⁻¹. The lower blood lactate concentration would have beneficial effects on fatigue and the performance of skilled shots as noted above. Chandler (1995) recommended that a training programme should include strength and conditioning as well as aerobic and anaerobic components. He outlined the detail of such a programme that contains activity designed to improve muscle strength, endurance, flexibility and aspects of aerobic fitness and agility. Conditioning programmes have been designed specifically for the development of speed, quickness and agility for senior tennis players (Miller et al., 2001) and for improving the ability to lunge in tennis (McClellan and Bugg, 1999).

Nutritional status is important for success in racket play, as it affects a player’s ability to train, play and recover from exercise. The total energy requirements of racket sports are similar, apart from squash, for which they are higher than the others (Reilly, 1990; MacLaren, 1998). The energy expended must be replaced by food intake to prevent loss in body mass, so an additional energy intake of up to 9000 kJ·day⁻¹ may be required (MacLaren, 1998). The extra energy intake is best in the form of carbohydrate, as the nature of racket play (intermittent bursts of intense activity lasting for many minutes) is such that the main source of energy is muscle glycogen. Nutritional strategies such as glycogen loading in the few days leading up to a competition have been of value in a range of sports and are likely to have the same benefits in racket sports, although this does not appear to have been specifically demonstrated. MacLaren cautioned against ingesting carbohydrates too close to the start of a game, but carbohydrate supplementation during play is considered beneficial. Several studies have shown that consuming drinks with the correct content of water, carbohydrate and electrolytes, for optimal absorption by the gut, can lengthen the duration of exercise considerably. McCarthy-Davey (2000) summarized the small number of studies on tennis in which the effect of carbohydrate supplementation during play has been investigated. The findings are mainly positive, with reports of improved alertness, concentration and coordination and reduced errors through play. Graydon et al. (1998) investigated the effect of a carbohydrate drink on shot accuracy in squash. They tested shot accuracy before and after a simulated game in which players had access to a carbohydrate drink or placebo. Those players who used the carbohydrate drink maintained their accuracy at the end of the third game and were 19% better than those who had taken the placebo drink. Similar results have been reported by Davey (2001) for the performance of tennis skills. Carbohydrates should also form the basis of post-match meals, which helps in the restoration of muscle and liver...
glycogen. Other nutritional requirements, such as protein, vitamins and minerals, are capable of being met through a varied diet (MacLaren, 1998).

Specific substances may affect metabolic and neuromuscular functioning. One such substance is caffeine and its effect on female tennis players has been investigated by Ferrauti and Weber (1998). The effect of caffeine has been reported as equivocal across a range of sports and in this study the authors also reported that a dose of 364 mg for men and 260 mg for women during a tennis match had no major effects on their performance. They did suggest that caffeine may have some small effect on the regulation of blood glucose at the start of play, which may benefit players who frequently complain of hypoglycaemic symptoms early in the game, and that the stimulating effect of caffeine may have a positive effect on players’ perceptions of their competitiveness at the end of a long match. Concern about the misuse of other substances has led international governing bodies to instigate anti-doping programmes. Kahn (2002) described the programme in operation by the International Table Tennis Federation (ITTF), with an average of 50 samples being taken at each major World or Olympic championship since 1990.

In summary, although much is known about the general physiological demands of racket play and the physiological characteristics of players, there are many gaps in the literature, particularly in connection with table tennis. This may be because the physiological requirements are less in table tennis, which uses lightweight equipment, a small court area and typically has matches of shorter duration. It is clear that activity in racket sports is intermittent in nature and games are contested in a way that allows players to adjust the duration of rest to suit their physical fitness. Players need good aerobic fitness because the duration of the game is relatively long, but also good anaerobic fitness because of the short periods of high-intensity play. The available physiological data can be used to formulate training programmes to provide an appropriate training stimulus whether it be for health or competitive benefits. Fatigue develops as the game progresses and errors increase. As in most sports – other things being equal – the greater the sport-specific fitness, the more likely it is that a player will win. Players may develop strategies of play to exploit the inferior fitness or greater fatigue of their opponent, or in turn may develop strategies to defend against their own fitness or fatigue. It appears that the effects of fatigue are increased as environmental temperature and humidity increase, but can be delayed by appropriate nutritional planning, which includes pre-, intra- and post-match strategies based around the ingestion of carbohydrates and fluids.

Notational analysis

Notational analysis is the process of recording and analysing the movements made by players during play and has been widely applied to racket sports. The data collected are related to the position, action, time and outcome of an event in the game; consequently, notational analysis is characterized by an extraordinarily large amount of data. Recent developments in technology have had a major influence on the way in which these data are collected, analysed and fed back to the coach and player. Early attempts at notational analysis used a hand notation system (in squash; Sanderson and Way, 1977), but the introduction of computers and graphical user interfaces in the last decade has transformed the process. The development of generic computer packages has enabled customized notation systems to be designed. Consequently, researchers have tended to develop and use systems for their own requirements, which has led to a range of systems being used to analyse racket sports. The reliability of customized notation systems is generally high, particularly if a single researcher who has a good knowledge and understanding of the game operates the system (Wilson and Barnes, 1998; O'Donoghue and Ingram, 2001). Hughes (1998) identified five main functions of notational analysis: (i) analysis of movement, (ii) tactical evaluation, (iii) technical evaluation, (iv) database development and modelling, and (v) educational use for player and coach, all of which have some role in the improvement of performance in racket sports. Notational analysis has become a sophisticated tool for data collection and racket sports are highly suitable for its use.

The analysis of movement has led to a better understanding of the demands players are exposed to in the performance of racket sports. Information of this type has been reported earlier in terms of work times and work:rest ratios in tennis, squash and badminton. This information has had a direct impact on the design of training regimens for improved fitness. In badminton, Liddle and O'Donoghue (1998) used a computerized notation system to establish the general shot characteristics of the men's and ladies' events during the 1996 season. They found that average rally lengths ranged from 6.35 to 9.15 s and rest periods from 11.03 to 15.01 s, with the longer rally associated with the shorter rest period. The differences they noted between the men's and ladies' game led them to suggest that there should be different training regimens for men and women. An analysis of the same tournament a year later (O'Donoghue, 2000) showed some important differences between the two seasons. Of particular note is the average duration of men's single rallies, which was reduced from 9.15 s to 6.70 s. More recently, Pritchard...
et al. (2001) reported average men’s rally times at the 1999 and 2000 Welsh Open (a similar standard of play) as 7.27 and 8.11 s, respectively. An analysis of world-class performances (Carbello and Gonzalez-Badillo, 2003) reported a mean rally length of 6.40 s. These data indicate that there is some variability in play between tournaments even at the same standard of play. In tennis, particularly on slower surfaces (ITF category 1 surface such as clay and synthetic), players often ‘run around a shot’ to play a shot on their forehand rather than backhand (an inside out forehand) and it would be expected that this would have an effect on the recovery of a player back to the central position. Hughes and Moore (1998) examined whether this movement influenced the end of rally result. There were few occasions (less than 4%) when the player did not regain the ready position. However, the more steps a player had to take to play a shot, the less likely he or she was to win the rally. Not surprisingly, positional inadequacies place the player under greater stress, which results in reduced success. O’Donoghue and Ingram (2000) examined the strategies used by elite male and female players on different surfaces in Grand Slam tournaments. Women’s rallies were significantly longer than men’s rallies and rallies on a clay surface were significantly longer than those on hardcourt or grass, with the longer rally duration being associated with a greater proportion of baseline rallies. In squash, Hughes and Knight (1995) examined the effect of two different scoring systems on the playing patterns of elite players. The English system of scoring only allows a player to gain a point when he or she holds service, while the point-per-rally scoring, introduced in 1988, allows the player who wins a rally to gain a point regardless of whether serving or not. This change was introduced to make the game more attractive to television audiences and it was expected that rallies would be shorter and there would be less defensive play. The length of rallies remained unchanged, but there was an increase in attacking play and a reduction in let/stroke appeals, which would support the idea that point-per-rally scoring would lead to a more appealing game for television audiences. In table tennis, Drianovski and Otcheva (2002) reported on the shots used and shot reliability (the number of a shot type played that was successful as a percentage) at the 1998 World Championships and found that this ranged from 78% for the top spin shot to 34% for the drop shot. Takeuchi et al. (2002) used notational analysis to investigate the effect of the newly introduced 40 mm ball (compared with the previous 38 mm ball), which increased the number of shots in a rally by 10–32% within the various events. This finding would support the rationale for the introduction of the larger ball, which was to produce a better experience for spectators.

Tactical evaluation of play is a major area of interest to notational analysts. In tennis, it is thought that the serve has a major influence on the outcome of the game and Furlong (1995) investigated differences between male and female players in singles and doubles events. The serve was more dominant in the men’s than the ladies’ game and in doubles than singles. Furthermore, he analysed the men’s singles from 1979 to 1992 and found little change in the importance of the serve over this period. Furlong concluded that the advance of equipment technology and improved player fitness and strength had little effect on the effectiveness of the serve. World championship tennis is characterized by play on different surfaces and it is well known in the game that the grass surface is ‘fast’ while the clay and synthetic surfaces are ‘slow’. Consequently, there has been much interest in the effect of surface on tennis play. Surprisingly, Furlong (1995) found that there was no significant difference in the speed of the court (grass vs clay) on the dominance of the serve. Hughes and Clarke (1995) examined the difference in patterns of play between grass and synthetic surfaces as used in the Wimbledon and Australian Open tournaments. There were fewer shots per rally and shorter rally lengths on grass. The time of play was similar between the two surfaces, which meant that the rest time between rallies was longer on grass, perhaps reflecting the shorter but more intense play on grass. The success of the serve was not influenced by the surface, in agreement with Furlong (1995), but 11% more returns were produced on the synthetic surface. There were more winners and fewer errors hit on grass than on the synthetic surfaces and play was closer to the net on grass but closer to the baseline on the synthetic surface, both findings reflecting the more attacking game associated with the faster grass surface. These results were supported by O’Donoghue and Liddle (1998b), who reported that in ladies’ singles tennis, more points were won at the net and there were fewer baseline rallies when playing on grass compared with clay. In a later study, O’Donoghue and Ingram (2000) found that players were more successful when they moved to the net as a part of an attacking ploy, and were less successful when drawn to the net by their opponent. In 1996, two new types of ball were introduced so as to slow down the ‘fast’ grass surface at Wimbledon and speed up the ‘slow’ clay surface at Roland Garros. O’Donoghue and Liddle (1998a) reported that despite the performance characteristics of these new types of ball, the rally length on clay was still significantly longer than on grass (Fig. 2). However, the mean rally length at Wimbledon in 1996 was significantly longer (3.69 s) than that reported in 1992 (2.52 s; Hughes and Clarke, 1995), suggesting that the new types of ball did have some effect on playing characteristics on grass.
The technical proficiency of players can be evaluated using notational analysis, although there have been fewer studies of this area of application. Taylor and Hughes (1998) compared the patterns of play of elite junior squash players from Britain, Europe and North America. They were able to establish that British players had technical deficiencies on their backhand when playing ground strokes. They were better than the Europeans when volleying but less skilled than the Americans, who had a better all-round technical ability and were able to adapt easily to different surfaces and different tactics. There would seem to be scope for more application in this area.

Database development and the modelling and prediction of performance are practical due to the volume of data available from notational analysis. Using data from squash, Hughes and Robertson (1998) tried to define a template for the men’s game (Fig. 3). Their goals were to define the general characteristics of play of elite players in competition and to provide data on: patterns of play (rally length, number of shots, shots per rally, time of rally and so on); distribution of serves, long and short shots, and volleys; positional information on players when specific shots were played; and the tactical response of a player to shots played into the back and front corners. Recent reports (e.g. Lynch et al., 2001; Wells and Hughes, 2001) have extended these tactical models to cover elite female senior and junior squash play, respectively, and provide a database for future comparisons.

Fig. 2. (a) Distribution of rally lengths in ladies’ singles tennis. (b) Distribution of rally lengths in men’s singles tennis (reproduced with permission from O’Donoghue and Liddle, 1998a).
stability of tactical play over time was investigated by O'Donoghue (2001), who compared several characteristics of Grand Slam tennis play from one season to another (1997–98 to 1998–99) and found that, for most variables studied, there was little difference between the two seasons. He concluded that the process of notational analysis was sufficiently robust to be used as a research tool. With this in mind, Hughes (1998) noted that the models defined for elite men’s squash have changed over time as players have become fitter and the equipment has improved. He reported that over a period of 15 years, the number of shots per rally has decreased from 20 to 14. A model that would predict the outcome of competition squash was developed by McGarry and Franks (1995). They used a stochastic model of squash play to decide the outcome of each shot played in a rally and applied this from the quarter finals stage of a national Open Tournament. The decision regarding the outcome of each shot was based on the outcome data of actual shots played by each player, which allowed a probability matrix to be outlined for each player depicting the likely shot response to each preceding condition. The results of the modelling were remarkably successful, suggesting that a player’s playing profile from past performances can be used to predict the outcome of future events. The authors suggested that this type of model may be used to identify optimal tactical strategies for adoption against a particular opponent. Despite its attractiveness, the idea does not appear to have been developed further.

Intervention to improve players’ knowledge and understanding of the game has been used in squash to determine whether this type of feedback can influence their performance. Brown and Hughes (1995) studied two small groups of players, one of which received quantitative feedback from a notation system, while the other received qualitative feedback from a video replay. The quantitative analysis of some preliminary matches enabled the researchers to provide specific information on areas of weakness to each group, but they noted no difference between the groups in their subsequent play as a result of the intervention process. Murray et al. (1998) also investigated the effect of detailed quantitative feedback on the performance of elite and sub-elite squash players and found evidence of an improvement in performance as a result of the feedback intervention. They suggested that this is an important research area for which a larger controlled study should be conducted.

In summary, notational analysis is a tool that has been widely applied to study a variety of aspects of racket sports. As a tool it is generally considered reliable if applied by experienced operators who have some understanding of the game they are notating. Notational analysis has helped to establish a range of game characteristics that have been useful in defining training practices and strategic aspects of play. It has been applied for a sufficiently long time to enable evolutionary features within the racket sports to be detected. Research effort has been devoted to defining tactical models of play for different levels of the game. While this is mainly evident in squash, it is clearly a significant role for notational analysis and future effort should be devoted to widening this approach to cover different standards of play and all racket sports. Although notational analysis has promise in many directions, one – its use to provide feedback to players and coaches – has received less attention. This reflects the conceptual and practical difficulty associated with this task, but is a worthy goal for future notational analysis research.
Biomechanics

Biomechanics is that branch of sports science that tries to identify the mechanical characteristics that affect performance and cause injury. It is concerned with the technique used to perform various skills. The advance of technology in recent years has enabled detailed three-dimensional kinematic analyses of racket skills to be undertaken. It has also allowed selected kinetic characteristics of racket skills to be established. These methods of investigation have enabled biomechanists to investigate the underlying mechanisms used in performing racket skills.

Qualitative technique analysis has been used frequently to study the skills of racket players, aided by the use of high-speed cine film to observe the detail of fast shots. The most notable early research was by Plagenhoef (1971), who reported on the patterns of movement in tennis skills. This enabled players and coaches for the first time to understand the complexity of movement associated with fast powerful actions like the serve. Subsequently, there was substantial research effort into badminton by Gowitzke and Waddle (1979, 1986), who used cine film at 400 Hz to analyse qualitatively fast overhead and underarm strokes. By placing tape along the length of the forearm, they were able to establish that racket-head speed in the power strokes was derived substantially from rotation of the forearm about its longitudinal axis. Furthermore, their qualitative analyses were able to establish the specific technique used in many badminton strokes and in several cases they were able to show that the way in which players actually performed contradicted coaching descriptions found in the literature. Specifically, these were to do with the importance of wrist flexion, pronation of the forearm and endorotation of the upper arm. The qualitative analysis method described above, when combined with a good knowledge of underlying biomechanical principles, can be a powerful tool and Lees (2001) has illustrated how this may be applied to badminton using the slower but more affordable video recordings. A three-dimensional qualitative analysis for the forehand stroke in table tennis has been described by Kasai and Mori (1998), illustrating the specific and basic techniques used by players, while some general descriptions and principles of movement for striking skills in general have been outlined by Elliott (2000).

Quantitative technique analysis has developed as a result of technological advances and in particular has allowed three-dimensional analysis to be undertaken. Basic three-dimensional analyses of racket skills have established some data for joint angles, linear and angular velocities and ball speeds for the tennis serve (van Gheluwe and Hebbelinck, 1985; Elliott et al., 1986; Papadopoulos et al., 2000), the tennis backhand drive (Elliott et al., 1989a), the tennis forehand drive (Elliott et al., 1989b) and the tennis volley (Elliott et al., 1988). An extension of the basic three-dimensional approach has been made by Bahamonde (2000), who computed the angular momentum of body segments during the tennis serve. Angular momentum was built up in the trunk and transferred to the racket arm so that at impact the arm and racket had 75% of the total angular momentum generated. There appear to be no basic three-dimensional data on skills in any of the other racket sports. There has, however, been substantial research interest in the detailed way in which fast shots (like the serve in tennis and the smash in badminton) are made, especially in relation to the importance of wrist flexion, pronation of the forearm and endorotation of the upper arm. To examine these characteristics of movement, a specialized marker system and analysis method are required. The first attempt to do this was reported by van Gheluwe et al. (1987), who investigated the tennis serve. They attached several markers to the wrist, elbow and upper arm and from the reconstructed three-dimensional location of these markers during the performance of the tennis serve they were able to quantify the magnitude of pronation of the forearm and endorotation of the upper arm, both of which were considered important to the production of a high-speed racket head. Using a similar approach, Tang et al. (1995) examined the kinematics of the badminton forehand smash. They reported on forearm pronation, wrist flexion–extension and ulnar and radial deviation, and found that although there is considerable wrist joint motion about its two axes of rotation, the most important was pronation of the forearm. They further suggested that the increased supination of the forearm just before its rapid pronation constituted a stretch–shorten cycle, which served to enhance the speed of the movement as referred to below.

A mathematical analysis method for obtaining all rotations of the arm segment was presented by Sprigings et al. (1994). A series of markers was used to define segment positions and orientations (Fig. 4), which allowed a full three-dimensional description of segment rotations, including flexion–extension, abduction–adduction and internal–external rotation of the upper arm, lower arm and hand. This method allowed the relative importance of individual segment motion to end-point velocity to be determined and, when applied to the tennis serve, showed that the greatest contribution to final speed of the racket head was upper arm internal rotation (29%), followed by wrist flexion (25%), upper arm horizontal adduction (23%), forearm pronation (14%) and forward movement of the shoulder (9%). These results contradict earlier reports about the importance of forearm pronation, but one might expect the more detailed analysis of Sprigings et
al. to be the more accurate. This method was used by Elliott et al. (1995) to examine the tennis serve in more detail. They reported the same order of importance as above, although the percentages differed slightly. They also reported that the elbow extension played a negative role (−14%) by reducing the forward velocity of the centre of the racket at impact. A similar approach by Wang et al. (2000) led to a rather different conclusion. For the flat serve in tennis, they concluded that the power of the serve (presumably racket head velocity) comes from the rotation and bending of the trunk and elbow extension and is in partial agreement with the findings of Bahamonde (2000). Clearly, there are some issues of interpretation that need further attention. The method of Sprigings et al. has been used to examine the effects of upper limb contributions to velocity of the racket head in the forehand drive in squash (Elliott et al., 1996) and the effect of the forehand grip on upper limb contributions to racket head velocity in a tennis forehand shot (Elliott et al., 1997), but appears to date not to have been applied to other shots in tennis or squash or other racket sports.

The mechanisms underlying performance have been investigated using kinematic methods. One is the sequence of movements made in a multi-segment action, the proximal-to-distal sequence, widely applicable to actions that require high end-point velocity such as shots in racket sports. The data referred to above have enabled Marshall and Elliott (2000) to reflect on the adequacy of this principle. They commented that the traditional concepts of proximal-to-distal sequencing are inadequate to describe the complexity of racket shots and that our better understanding of the contribution that specific segments make to end-point velocity, including the role of forearm pronation, means that these should be taken into account when coaching racket skills and developing training or injury prevention programmes. A second mechanism underpinning performance is the stretch–shorten cycle. When a muscle and tendon complex is pre-loaded and then stretched, it can generate a greater force at the start of the forward movement than if it were not pre-loaded. Enhancement of performance in arm movements can be as high as 22% (Elliott et al., 1999) but is reduced as the time interval between the stretch and the shortening motions increases beyond 1 s. This has wide application to many skills and although no specific research appears to have been conducted on racket shots, Elliott (2000) commented on the likely role that this has during the tennis serve backswing, where the muscles that cross the elbow and shoulder joints are stretched. It may also be used in the rapid forearm supination–pronation movement referred to by Tang et al. (1995) above.

The kinetic analysis of racket skills has received less attention. In relation to performance, there has been an interest in the effect of grip forces on the interaction between tennis racket and ball, but Elliott (1995) concluded that a high grip force is not the major factor in controlling post-impact ball velocity for centrally hit balls, although it is important if balls are hit off-centre. In relation to injury, the way a racket is gripped is thought to be one factor influencing the onset of tennis elbow. Knudson (1991) measured the contact forces between the hand and the racket as players performed backhand drives. The less experienced players held the racket with a lower grip force so at impact the racket would undergo a greater acceleration and thus dis-
placement. Such a forced displacement of the wrist extensor muscles would place additional stress on their attachment points and Knudson suggested that this could be a causative factor in 'tennis elbow'. Also in relation to injury, Elliott et al. (2003) reported on the shoulder and joint torques in the tennis serve and commented on the high stress imposed on the elbow during the stretch phase of the backswing. Further work on these topics in racket sports does not appear to have been conducted, although Fleisig et al. (1996) reported on a range of shoulder and elbow kinetic data for throwing and baseball pitching skills. Lees and Hurley (1995) measured the ground reaction forces and estimated lower limb muscle forces during the badminton lunge. They reported vertical and horizontal forces of 1.47 and 0.92 body weight, respectively, and noted that there was some difference between players of varying skill, with the less skilled players generating the higher forces. Less skilled players may well lack the movement skills to reduce the load they experience and, as a result, would be more susceptible to injury.

Electromyography (EMG) has been used to detect patterns of muscle activation but there have been very few applications in racket sports. Recently, Sakurai and Oh-tsuki (2000) reported EMG data on the muscles that control wrist actions (the extensor carpi radialis and flexor carpi radialis) in the 50 ms before impact. They showed an extension–flexion–extension sequence of muscle activity that relates to the preparatory 'cocking' movements of forearm supination–wrist extension–radial flexion, followed by the action movements of forearm pronation–wrist flexion–ulnar flexion that provide the power at impact and then, finally, a burst of muscle activity immediately after impact to slow the action during the follow-through. In a comparison of skill, they found that this sequence of muscle activity was well defined and consistent in skilled players, but small and inconsistent in unskilled players. Their results suggested that the unskilled players had not been able to control the important final motions of the stroke before impact adequately, so lost power in their shot.

In summary, biomechanical methods have been used to investigate a range of racket skills qualitatively and quantitatively. The general characteristics of racket skills and some underlying mechanisms of performance are well understood. Recent developments of suitable quantitative kinematic analysis methods have enabled researchers to quantify the relative contribution that segments make to performance, although there is not full agreement about the way in which these complex three-dimensional data are interpreted. To date, the application of these methods has been dominated by a small number of research groups and applied to a small number of racket skills. It is evident that there needs to be further application of these methods to a range of racket skills and also across all of the racket sports. There has been little investigation of the effect of fatigue on racket skills. There has been little development of kinetic analysis methods to quantify joint torques and power production and only a small interest in the evaluation of the player–racket interface. These areas are ripe for further research interest, particularly as they have some relation to injury.

**Sports medicine**

The detail of injury in racket sports is not well documented, largely because of the few epidemiological studies in this area and differences between them with regard to definitions and methods used to collect and report data. Nevertheless, racket sports are generally considered to be less likely to lead to injury than many other sports, with the incidence of injury being reported as 0.01 or less per 1000 h of exposure in racket sports compared with over 10 per 1000 h in soccer (Larson et al., 1996). Specifically, in badminton (Kroner et al., 1990) and in squash (Locke et al., 1997), the frequency of injury has been found to be less than 5% of sports injuries presenting at hospital casualty clinics. Compared with other sports, it would appear that racket sports are relatively safe.

Injuries mostly involve the musculoskeletal system, with the incidence of both acute and overuse injuries being reported as similar in some studies (e.g. Mohtadi and Poole, 1996), while overuse injuries have been reported to be more common in others (e.g. Safran, 2000). Specific risk factors appear to be important, notably age, skill, sex, equipment and surfaces. Differences in prevalence of injury between the sexes appear small in relation to the location of injury, with females appearing to receive more wrist injuries and males to receive more elbow, knee and hip injuries (Safran, 2000). Injuries are located more frequently in the lower extremity in tennis, badminton and squash (Kroner et al., 1990; Locke et al., 1997; Bylak and Hutchinson, 1998), although trunk and spinal injuries are also common in tennis (Chard and Lachman, 1987). The latter finding has been related to the rapid twisting and tilting movements of the trunk during serving and playing ground strokes and has led to a high incidence of low-back pain in professional tennis players (Marks et al., 1988), while the former finding has been related to the large forces created during the performance of lunging movements and rapid changes of direction. Upper limb injuries are important and, because they are often uniquely related to racket sports, attract more interest. Of particular relevance in this category are...
elbow and shoulder injuries. Head and neck injuries are significant and unique in racket sports because of the contact of racket or ball with the head, although not generally high in prevalence. These injuries are of particular concern in squash where players compete in close proximity to each other, swinging their rackets at head height, and where the ball is similar in size to the eye socket. The latter types of injuries are easily controlled with the use of a protective eye guard.

Some injuries are dealt with in more detail in the literature and reflect the interest in racket-specific injuries, especially elbow and shoulder injuries. Because of the relevance of these injuries to racket sports, they will be considered rather than the more numerous lower joint injuries. The common term 'tennis elbow' is mostly used to describe lateral humeral epicondylitis (Renstrom, 1995), but can also be used to describe medial and posterior humeral epicondylitis (Mohtadi and Poole, 1996; Ellenbecker and Mattalino, 1997). The structures implicated in tennis elbow are primarily the tendon of the extensor carpi radialis brevis and secondarily the tendon of the extensor carpi radialis longus and extensor digitorum (Ellenbecker and Mattalino, 1997; Pluim, 2000). While both an inflammation response and degeneration can occur in the tendon, the latter appears to be the more accepted mechanism causing 'tennis elbow' pain and so the term 'tendinosis' is preferred to tendinitis (Renstrom, 1995).

The incidence of tennis elbow over a playing career is high, with an incidence of 31–57% having been reported in adult tennis players (Renstrom, 1995; Ellenbecker and Mattalino, 1997; Pluim, 2000). Age is an important risk factor in tennis elbow, with players over 35 years being more susceptible. Sex does not appear to be a factor, with the weight of evidence suggesting no significant differences between males and females (Renstrom, 1995; Ellenbecker and Mattalino, 1997). Frequency of play is thought to be a risk factor, with those playing more frequently being more likely to suffer from tennis elbow. Most of the interest in tennis elbow has been within the sport of tennis and, as a consequence, risk factors associated with tennis have been suggested. These are related to style of play or equipment (Renstrom, 1995). Studies of styles of play have focused on the backhand drive in which faulty backhand stroke has been implicated, although the serve has also been identified as a problematic stroke. During the accelerating forward phase of the backhand ground stroke, there is a lot of activity in the wrist (carpal) extensor muscles and these have been found to be more highly active in players with tennis elbow (Kelley et al., 1994). It is thought that in these players the stroke is performed with a leading elbow and more open racket face. This is also associated with an ulnar deviation of the wrist (producing a dropped racket head) during elbow extension. These actions would elongate the extensor muscles, placing them under greater stress, and causing the extensor carpi radialis brevis to rub and roll over the lateral epicondyle of the humerus. A combination of stress causing microtears and friction from rubbing and rolling begins the process of deterioration, which, if unrecognized and untreated, will lead to an injury. Equipment has also been implicated in tennis elbow due to its contribution to faulty stroke production (racket weight and grip size) and factors that cause excessive vibration (racket flexibility, head size, composition, balance, string characteristics). It is thought that the vibration induced in the racket due to impact is transmitted through the arm and muscle to produce an additional load on the tendons at the lateral epicondyle. Pluim (2000) provides specific advice on the selection of rackets to minimize the chance that poor racket characteristics will lead to or aggravate tennis elbow. Tennis elbow is also evident in squash and badminton, but a detailed investigation into causative factors in these games has not taken place.

Injuries to the shoulder joint are related to inflammation and impingement of the rotator cuff muscles and tendons. Inflammation is due to repetitive microtrauma received from the stresses imposed by hitting and overhead serving, while impingement is the direct compression of soft tissue between the harder (boney) parts of the joint, and both are usually associated with instability of the glenohumeral joint (Blevins, 1997). As this injury is usually associated with loss of strength in the external rotators and loss of flexibility in internal rotation of the upper arm, evaluation of both strength and flexibility is recommended (Bylak and Hutchinson, 1998). There are many causes of rotator cuff injury, but in racket sports a player's improper technique and imbalance in the strength of shoulder internal and external rotator muscles are factors. During fast overhead shots, rapid speeds of movement and rotation and high forces are produced (Fleisig et al., 1996). At the time of maximum external rotation where the arm is primed to make the shot, the shoulder's internal rotator muscles contract eccentrically, generating a high force. The resultant forward movement produces high accelerations that must be decelerated at the end of the range of movement. Shoulder muscles are susceptible to injury at these two extreme positions in the movement. Other causes are related to the anatomical structure of the glenoid cavity, defined by the shape of the acromion, which can precipitate impingement (Blevins, 1997). Instability of the shoulder joint is due to inadequacies in the ligamentous stabilizers resulting from inherent laxity and/or gradual stretching from repetitive stress and dislocation. Laxity will cause unusual deformation of the shoulder joint during
external rotation of the upper arm and can increase the likelihood of impingement. Poor muscle strength or balance can also be factors preventing sound motion of the shoulder joint. Thus, technique, flexibility and strength are extrinsic factors, while joint laxity and anatomical structure are intrinsic factors, in shoulder rotator cuff injury.

In summary, the detailed pattern of injury in racket sports is not well established, but injury risk is considered low compared with many other sports. Information is more widely available for tennis and badminton, but sparse for squash and non-existent for table tennis. There is a large body of literature regarding the treatment of specific injuries, although most of this is related to upper limb injuries, especially tennis elbow. There is a good clinical understanding of the medical factors associated with tendinitis and tendinosis injuries, and the aetiology, treatment and rehabilitation for these injuries are well documented. The causative mechanisms of tennis elbow and rotator cuff injuries have been speculated upon in the literature and relate to a combination of intrinsic factors such as age and anatomical structure, and extrinsic factors such as training errors (frequency of play), technique (stroke production) and equipment (racket properties). There has been little effort devoted to a similar understanding of acute injuries to the lower limb in the literature on rackets sports medicine, although these may well have been subsumed within other sports for which lower limb injuries are more prevalent (such as running and field games).

**Sports engineering**

There are four items of equipment that are important to all racket sports: the racket, the missile (ball or shuttle), the surface and footwear. These are controlled to a greater or lesser extent by the international governing bodies and may change from time to time as a result of advances in technology or attempts to control the evolution of the game. Research on tennis and table tennis has been stimulated by recent or proposed changes in ball, racket and surface regulations. Also of interest to player and scientist are the interactions between racket and ball, ball and surface, and player and surface.

Racket characteristics have changed markedly in recent years, largely as a result of the development of new materials and improved manufacturing processes using computer-aided design solutions (Sol, 1995). The modern racket can be made lighter, stronger, stiffer and yield greater power than one manufactured 20 years ago, and modern rackets can be produced that make it easier for beginners to learn and for recreational players to enjoy the game more (Brody, 2000). The testing of tennis rackets remains a popular area for research and recent reports have detailed the performance of various racket designs on, for example, post-impact ball speed [wide body and oversized rackets allow greater speeds, Kawazoe (1995)]; low inertia rackets allow greater serve speeds, Mitchell *et al.* (2000); super-light rackets produce lower ball speed for off-centre impacts, Kawazoe and Tomosue (2000)], vibration [super-light rackets produce more vibration, Kawazoe and Yoshinari (2000)]; vibration damping can be customized to reduce vibration, Iwatsuba *et al.* (2000) and string characteristics [elastic and frictional properties affect speed and spin, Cross (2000)]. These findings have implications for both performance and injury. Brody (2000) provides a good overview of contemporary tennis racket technology.

Missile characteristics have also changed in recent years. There are now three types of tennis ball designed for use on specific surfaces with the object of speeding up play on slow surfaces and slowing down play on fast surfaces (Coe, 2000, p. 33). The specification of tennis ball characteristics is controlled by the International Tennis Federation (ITF), but in random testing of 1500 newly manufactured and unused balls during the 1998 season, only 56% were found to conform to the rules of tennis (Coe, 2000), and included balls used at the Grand Slam competitions! This has led to a research interest in the performance of tennis balls, which is determined by their flight and bounce characteristics. The flight path of the ball is determined by the aerodynamic drag and lift coefficients. Pallis and Mehta (2000) reported the drag coefficient for tennis balls to range from 0.48 to 0.63 depending on size (regular ITF type 1 or oversized ITF type 3) and state of use. Chadwick and Haake (2000) reported similar values of 0.5–0.6 for various tennis balls, but when spin at 1600 rev. min⁻¹ was applied this increased to 0.8. A lift coefficient of 0.2 was reported under this circumstance. Bounce is defined by the coefficient of restitution, with Caffi and Casolo (1995) reporting values for pressurized balls between 0.7 and 0.4 as impact speed increased from 15 to 40 m s⁻¹. These values were about 0.2 greater than over the speed range for pressureless tennis balls. Rose *et al.* (2000) studied the variation in coefficient of restitution with temperature, which changed little (range 0.37–0.42 for an impact velocity of 35 m s⁻¹) over the range 0–40°C. Again, pressurized balls had a coefficient of restitution about 0.2 greater over the range of temperatures than the pressureless balls. In table tennis, the effect of increasing the diameter of the ball has been a major topic of research interest. The International Table Tennis Federation (ITTF) was concerned that the ball speed was becoming too fast for spectators and wished to
investigate the effect that an increase in ball diameter (from 38 to 40 mm) and mass (2.5 vs 2.8 g) would have on the game. Xiaopeng (1998) reported that the larger diameter and lighter ball produced a forehand smash speed (15.4 m·s⁻¹) that was 13% lower than that produced with the standard ball, and a spin (105 rev·s⁻¹) that was 21% lower than that produced with the standard ball. The larger heavier ball showed a reduction in both speed and spin but not as great as the larger lighter ball. More recent reports (Tang et al., 2002; Zhang, 2002) have confirmed the earlier general findings on the effect of speed and spin. The larger heavier ball was officially adopted from 2000. While different types of badminton shuttlecock and squash ball exist, there appears to be no recent literature investigating their characteristics.

Surfaces used in tennis are of many different types and it has already been noted that, even at the highest standard of competition, the characteristics of the surfaces vary considerably, ranging from fast grass to slow clay. In addition, new manufacturing techniques have made available a wide selection of carpet surfaces that are attractive to clubs. Surfaces have their own inherent properties which can be established by mechanical testing of surface pace, slip resistance, traction and shock absorbency; Cox (2000) described tests used to quantify the effects of wear on these characteristics. The ITF has recently characterized surfaces as type 1, 2 or 3 depending on their ‘pace’ and this is coordinated with the designation of three ball types (1, 2 or 3) so that the correct ball may be used on the appropriate surface (Coe, 2000). In table tennis, although the surface used is essentially the same, variability in surface performance has been noted (Harrison, 2002) and has been attributed to the effects of paint, temperature and humidity on its friction properties.

Footwear requirements for racket sports are similar to many other sports in terms of cushioning, rear foot and forefoot control and comfort. In addition, there is a need for footwear to withstand the sideways forces produced during side skipping and lunging movements. Research into court shoes has been conducted over several years and with much of our basic understanding about footwear performance established, there have been few recent developments in court shoe design. Recently, Hreljac (1998) reported that individuals respond uniquely to different tennis shoes with varying midsole hardness during a sidestep landing and lateral drive-off. He recommended that single-subject designs are needed when evaluating variations between sports shoes.

The interaction between missile and racket has been mathematically defined for tennis balls by Brody (1997) and the equations which govern this interaction are dependent on the mass, inertia, dimensions and velocity of the racket and ball. Goodwill and Haake (2000) used these relationships to model the interaction between tennis racket and ball and found good agreement between theoretical and practical rebound velocities. In table tennis, Limoto et al. (2002) have documented the effect of ball size (38 and 40 mm diameter) on the interaction between tennis ball and racket.

The missile-surface interaction has been modelled for tennis balls to consider oblique impacts where the ball deforms and friction affects the interaction with the surface (Dignall and Haake, 2000). The particular combination of ball and surface mechanical properties determines the rebound speed, angle and spin rate and Dignall and Haake included all of these in their simulation experiments. These factors define the tennis ball as type 1, 2 or 3, or determine the variable performance of the table tennis surface as noted above. Pratt (2000) undertook a similar investigation and showed that, when in contact with the ground, the tennis ball never rolls without slipping and the sliding friction reduced the horizontal velocity of the ball travelling at 55 m·s⁻¹ by almost 30%.

The interaction between player and surface is determined by the friction and impact absorption properties of the surface and footwear. Smith and Lees (1995) reported data for the horizontal friction forces applied to the shoe during lunging movements in badminton. The number and type of lunges made in a game of badminton were quantified and the typical forces for each type of movement established to quantify the stress applied to different parts of the shoe. The authors reported friction forces of 0.5–0.7 body weight, which were directed along the front and front lateral parts of the shoe for the racket side of the body, but the rear lateral direction for the non-racket side. Thus there is an asymmetry in shoe use and wear. Dixon et al. (2000) reported on the impact-absorbing characteristics of three tennis playing surfaces (acrylic, asphalt and rubber-modified asphalt) when players were asked to run over a sample placed over a force platform. There were no differences in vertical impact force but there was a small delay to peak force in the rubber-modified asphalt, leading to a reduction in the rate of loading. Furthermore, there were also some systematic changes in the kinematic characteristics of players' ankle joint as they ran over the surface. Dixon et al. suggested that the reduced rate of loading improved the cushioning associated with that particular surface, but the change in joint kinematics may be a factor in inducing injuries in players.

In summary, there has been much research on the mechanical properties of tennis rackets and tennis and table tennis balls and their interaction with racket and
Surface. Research interest in this topic has been generated by the recent or proposed changes by the ITF and ITTF. The experimental and analytical methods now available to researchers are sophisticated and much detailed knowledge has been generated about these items of equipment, their interaction with each other and their effect on playing performance. In contrast, there has been little or no equivalent research into the other racket sports, even though similar changes in racket and missile equipment have taken place. The interaction between player and surface remains an under-developed area of research. While surfaces and shoes are amenable to mechanical testing in isolation, their combined effect on player performance and potential injury remains poorly understood.

Sports psychology

During racket play, many psychological characteristics are important. The notion of mental toughness is, not surprisingly, of great importance in racket sports, due to the individual nature of competition and the speed, intensity and intermittent nature of play. Mental toughness is underpinned by several psychological skills and can be developed in players. This process is reliant on the appropriate evaluation of the psychological capacities and needs of a player, as well as an appropriate programme of intervention. Psychological characteristics related to anticipation and decision making have been investigated within the context of visual search skills. The development of racket skills has been the interest of research in motor control and learning, and applications to motor skill training regimens have followed.

Psychological skills training involves several stages. Terry (1995) has identified five: assessment, education, implementation, problem solving and evaluation. There is much documentation on the first of these steps, which can use one or more methods, including psychometric testing, performance profiling, interviews and performance observation. In squash, Mahoney and Todd (1998) described the use of a Psychological Skills Inventory for Sports that enabled them to establish baseline data for male and female junior squash players on six cognitive characteristics (anxiety, concentration, confidence, mental preparation, motivation and team focus). Jones (1995) reported the use of the Sport-Related Psychological Skills Questionnaire with an elite racket player. Terry (1995) referred to a tennis-specific questionnaire (Tennis Test of Attentional and Interpersonal Style) as well as other more generic psychometric tests for personality and imagery. Another approach to baseline assessment is 'performance profiling'. This is an athlete-driven procedure and focuses on what is important to the athlete. Jones (1995) described this process as one where a player is asked to identify the qualities or characteristics that an ideal player possesses. In this example, the player is then asked to rate the importance of each of these to an ideal performer and then to rate his or her own skill on each. The difference between the ideal and the self-assessment provides the basis for the psychological skills intervention, with the biggest discrepancy indicating the area of most perceived need. Jones described an application to a world-ranked tennis player that consisted of a baseline assessment using performance profiling and psychometric testing. From this, an intervention was devised based on imagery, cognitive restructuring, relaxation and simulation training. Jones reported the positive effect that 6 months of this programme had on the player, who subsequently won a major world tournament for the first time.

Performance profiling can be used in groups as well as with individuals, and with coaches involved in the process as well as players. Potter and Anderson (1998) described how they applied this process to groups of regional junior table tennis players (Fig. 5). The group was asked to identify a list of qualities or characteristics of the ideal player from previously pooled individual performance profiles. The agreed list contained 13 characteristics and players were asked to complete the performance profile for themselves and the coaches for their player. The outcome of this exercise formed the basis for determining the psychological skills intervention, which, with limitations on time and finance, occurred in group workshop sessions. It is apparent from the nature of the assessment process that the intervention [comprising an educational and an implementation process – Terry's (1995) second and third stages] is tailored to the needs of the individual or group and so this tends not to be the subject of reported research. Limited information is also available regarding the problem-solving and evaluation stages of the programme. These tend to be reported as the outcome of case studies (Jones, 1995) and subjective evidence reported through qualitative research (such as that on burnout in tennis players; Gould et al., 1996). This latter source of evaluation has recently become more extensive, with methodological issues associated with qualitative research being addressed by Biddle et al. (2001). Terry (1995) provided data from a Consultant Evaluation Form for tennis players and reported very high player satisfaction with the psychological skills training programme. Moran (1995) described the views of international tennis coaches and reported that these coaches were keenly aware of the role that psychological skills training could play in the successful performance of tennis players. Moran also commented that the specific effect that psychological skills training has had
on players' performance, and when and how the skills are used, all need to be established. This clearly gives much scope for future investigations.

The nature of, and the interaction between, certain psychological states has also been of interest within racket sports. Smith and Jones (1998) investigated the relationship between anxiety and performance for tennis players of differing skill. In skilled players at least, a certain amount of anxiety can be facilitative to performance. They distinguished between the magnitude of anxiety and its directionality, the latter referring to whether players were more or less anxious than they thought they should be. The authors used only qualitative methods based on individual interviews with players, which were then transcribed into themes relating to aspects of anxiety. They reported that there were both facilitative and debilitative themes. These had an impact on players' self-confidence and in practical terms was reported to affect their performance on skills, particularly the first serve. Eubank and Collins (2000) investigated the changes in anxiety before and during competition in national and regional standard youth tennis players. Anxiety intensity changed little from pre-match to competition in those players who regarded their anxiety as being facilitative, whereas in those whose anxiety was debilitative it reduced markedly from pre-match to competition. This interaction also appears to mediate the coping strategies each group used and in this regard the authors suggested that the direction of anxiety could be an indicator of the effectiveness of their coping strategies. Although the studies reported above were concerned with developing a better understanding of the nature of the psychological constructs, they would provide a useful basis for psychological skills training also.

Mental quickness is another important aspect of the psychological process and Singer (1998) distinguished this characteristic from physical quickness, which relates to the movements that a player makes. Mental quickness is associated with several information-processing abilities. The player must be able to attend to the most salient aspects of the opponent's performance, be able to pick up cues about the opponent's shot selection, have an ability to anticipate and to make decisions quickly and then to react. As noted above, many of these skills can be trained, and Singer (1998) recommended some off-court preparation, which included imagery or visualization strategies, as well as some on-court training drills. Falby (1998) described the use of imagery for enhancing the performance of table tennis players. This was incorporated within a general psychological skills training programme that included relaxation, video observation of top players performing selected skills, imagery and then physical practice of these skills followed by feedback. The programme was evaluated within a series of three case

![Fig. 5. The performance profile showing the self-assessment for a table tennis player, where all ideal assessments were scored as 10 (reproduced with permission from Potter and Anderson, 1998).](image-url)
studies, and although the findings were equivocal, they were sufficiently promising to lead Falby to suggest that this process should be investigated in more detail. Lapszo (1998) constructed a device to develop the anticipatory, decision-making and movement skills appropriate to table tennis. Play in table tennis was simulated using a series of lights that came on at predetermined times and locations to simulate the passage of the ball from one point of the table to another. The player had to move to strike the imaginary ball and the times of the stimulus and movement were recorded. In contrast to what Lapszo expected from the literature, the reaction and movement times and anticipation differed between players of differing ability. He concluded that the device has both a diagnostic as well as a training function.

One ability that has received attention in racket sports research is the way in which players pick up cues from their opponent. The use of visual search strategies in tennis was described by Williams et al. (1998). They were able to identify the real time direction of gaze from an eye movement tracking system when a player was receiving a serve (Fig. 6). They also identified which parts of the opponent’s movements were attended to as the serve took place. The more skilled players focused initially on the arm–racket–shoulder and then tracked the ball as it was tossed into the air. Lower-ranked players focused on the expected ball toss area or followed the ball from toss to apex. The skilled players were able to follow the flight of the ball more smoothly than the less skilled players. The authors also suggested that these skills can be improved after specific training. In another study, Williams et al. (2002) showed that less skilled tennis players who received perceptual training based on the visual search behaviours of more expert tennis players, improved their performance in both laboratory and field-based tests of anticipation. More recently, for junior tennis players, Farrow and Abernathy (2002) examined whether anticipatory skills can be learnt using implicit video-based perceptual training. This consisted of a scheme whereby players (in the place of the receiver) were given film of a tennis server to watch but no specific instructions as to what they should attend to, and had to estimate the serve speed, implicitly establishing relationships between the service kinematics and the service outcome. Comparison was made with a group that was given explicit instruction as to what they should attend to. The results showed that the implicit learning group members significantly improved their prediction accuracy after the training intervention.

Fig. 6. The scene observed using the split-screen approach. The right side of the screen shows the image from the external scene camera highlighting the participant’s movements during the return of serve, while the left side of the screen illustrates the typical image obtained from the head-mounted scene camera with visual point-of-gaze highlighted by the cross-hairs (reproduced with permission from Williams et al., 1998).
compared with the explicitly instructed group, but this dissipated about 4 weeks later. The authors concluded that video-based perceptual training does have the capacity to improve perceptual performance and transfer into the game environment, while the implicit nature of the training minimizes the instructional complexity of the training. The durability of the effect, though, requires further investigation.

Shots played in racket sports are interceptive tasks and successful performance in these types of task depends on the visual information about the approaching ball and an ability to predict the accuracy of its flight path and time of arrival. Players predict the interception point between racket and ball using a combination of tracking the ball’s early flight before any movement of the racket arm is made to stabilize the ball’s image in early flight, followed by eye–head stabilization during the final period of flight to stabilize the scene image immediately before contact. Rodrigues et al. (2002) conducted an experiment with table tennis players in which the cue time – the time players were given to make a shot to the right- or left-hand side of the table – progressively reduced. When cue time was 520 ms, shots made were accurate, but for the shorter cue times (327 ms), one or other of the two stabilizing methods was absent and accuracy of shot deteriorated. A minimum amount of time (these and other data suggest at least 300 ms) is required to predict ball flight and to initiate movement to intercept it. As predictability about future position decreases (due to ball spin and/or drag) and the time for decision making reduces (due to ball speed), it is evident that the success rate of interception will reduce, thus emphasizing two of the key features of racket sport play and providing a mechanism for the trade-off between speed and accuracy.

In summary, psychological issues cover a vast array of human behavioural, cognitive and motor abilities. Racket sports have provided a vehicle for exploring their characteristics and interrelationships. In some cases, this has been of interest but in others (especially those related to anticipation and interception) it has been because racket sports place a unique demand on the individual player for speed and accuracy within a rapidly repeating sequence of similar movements. This has provided a suitable vehicle for investigating fundamental characteristics of human performance and that understanding has been translated into improved training programmes. It is apparent from the brief review above that it is firmly believed that most, if not all, psychological abilities can benefit from training, and the development of suitable training programmes for the unique demands of racket sports is an ongoing task.

Concluding remarks

There has been a great deal of endeavour in the application of science to racket sports, but this has been variable across both the racket sports and the scientific disciplines. Perhaps unsurprisingly, most attention has been paid to tennis, the most popular and commercial of the racket sports. Also unsurprisingly, research has been largely discipline-based with little interdisciplinary study. Much is known about the nature and unique characteristics of racket sports, but there is still tremendous scope for further research effort, not least because of the changing nature of the games.

Racket sports require a unique combination of aerobic and anaerobic fitness, of speed, power, agility, flexibility and strength, of perception and action, of technical skill, and of awareness and control, and scientists have been able to comment on these qualities. In particular, science has been helpful in: defining training programmes to improve players’ fitness; guiding players nutritionally and psychologically in their preparation for play; informing players of the strategy and tactics used by themselves and their opponents; providing insight into the technical performance of skills; understanding the effects of equipment on play; and accelerating the recovery of players from injury.

Racket sports also pose a unique challenge to scientists and have provided a vehicle for investigating certain phenomena. For example, racket sports provide a good model for investigating the interplay between aerobic and anaerobic metabolism and the effect of nutrition, heat and fatigue on performance. They also have driven the development of mathematical solutions for multi-segment interactions within the racket arm during the performance of shots, and this has contributed to our understanding of the mechanisms of both performance and injury. They have provided a unique challenge to sports engineers in relation to equipment design and interactions. Racket sports have encouraged developments in notational analysis both in terms of analytical procedures and the conceptualization of strategy and tactics. Racket sports have also provided a vehicle for investigating fast interceptive actions, hand–eye coordination and perception–action coupling in the field of motor control.

Scientific research has contributed to a developing understanding of racket sports; racket sports have contributed to the development of scientific methodology. This review has attempted to draw together the threads of this interplay with the hope that it provides a platform and stimulus for further endeavour.
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