INTRODUCTION

Badminton is one of the most popular spectator and participant sports in the world. Over one billion people watched it on television when it made its debut at the Olympic Games in Barcelona in 1992. Yet, for such a popular phenomenon very little scientific research has been conducted on the sport when compared with other athletic pursuits commanding large followings such as swimming (Costill, Maglischo & Richardson, 1992) or soccer (Ekblom, 1994).

The purpose of this manuscript is to summarize the current state of knowledge regarding scientific studies in badminton and attempt to determine future directions that research could take with the largest racket sport in the world. It is not the author's aim to repeat summaries from in the past - some of the papers quoted (e.g. Gowitzke & Waddell, 1979) already provide a lot of the information. Rather, the intent of the paper is to provoke questions and provide thoughts of new challenges to be taken up by sport scientists around the world.

Most scientific work in badminton has been performed either in biomechanics or physiology - these two areas will make up the main body of the paper - although other areas - perceptual psychology and anthropometry - will also be covered. While there has been some published sports psychology research conducted in badminton (e.g. Sanderson & Ashton, 1981), a lot of the papers are in the general sports psychology area or in motor learning (e.g. Wrisberg & Liu, 1991) and could apply to a variety of sports, rather than being specific to badminton. These topics are not within the scope of this paper but the applied sports psychology area pertaining specifically to badminton is clearly one region that should be studied in the future.

BIOMECHANICS

Until 1977 practically all the technical aspects of the game were covered in coaching literature based on observation of performance and authors' own experiences. The ground breaking work of Waddell & Gowitzke (1977a, 1977b) presented at an international coaching conference in conjunction with the 1st World Badminton Championships questioned the traditional concept of the importance of the "wrist snap" in producing overhead forehand power and "flicking" for backhand power. Instead they showed the importance of rotation of the upper and lower arm segments, especially the contribution forearm pronation in overhead forehands and forearm supination in overhead backhands. Since then, many studies using high-speed cinematography, electromyography and electrogoniometry have supported this notion (Jack, Adrian & Yonedaka, 1978; Waddell, 1978; Gowitzke & Waddell, 1978; Gowitzke & Waddell, 1979; Jack & Adrian, 1979; Sakurai, Ikeyami & Yabe, 1987; Tapley & Barlett, 1988; Hong, 1993; Tang, Abe, Katoh & Ae, 1995).
This brings to light an interesting concept - the fact that top players were becoming top players in spite of what coaches were telling them to do. As Waddell & Gowitzke (1977a) observed "... the coach is under the delusion that power in the strokes results from his instructions." They also point out that the early inability of the coaches to perceive what was actually happening in, for example, the overhead forehand was due to the speed at which it occurs. The time duration from the beginning to the end of the stroke is only in the order of 0.1 sec (Waddell & Gowitzke, 1977b; Tang et al, 1995).

It is however worth noting that as early as 1969 Poole made the comment that "all badminton strokes are made with forearm rotation", a finding that he further confirmed in his doctoral dissertation (Poole, 1970). Quite clearly this is one example of the sports scientists being ahead of the coaches!

Quantitative analysis of the speed of the shuttle leaving the racket in a forehand smash (male) has been extrapolated to over 100 m sec\(^{-1}\) in one player (Gowitzke & Waddell, 1978), considerably faster than that of the ball leaving the racket in present day tennis serves. Average shuttle velocities post-contact across a group of players are between 50 - 75 m sec\(^{-1}\) (Gowitzke & Waddell, 1978; Jack & Adrian, 1979). However these studies on shuttle speed were all carried out in the late 1970's. Given that racket technology has improved considerably since then to produce more "power" (according to the manufacturers) from the racket head, it would seem appropriate to once again measure racket head and shuttle velocity as we approach the millenium.

Some recent studies on the serve in tennis (Elliott, Marshall & Noffal, 1995) and the forehand drive in squash (Elliott, Marshall & Noffal, 1996) have shown the importance of upper arm internal rotation in contributing to most of the racket head speed in these sports. Both these papers question the idea of complete proximal to distal sequencing - the kinetic link theory (a view ascribed to quite recently in badminton (Tang et al, 1995)) - in generating maximum racket head speed. The also attribute the action of pronation of the lower arm as a means of positioning the racket rather than a major contributor to racket head velocity. Given that similar movement patterns have been found in the overhead strokes of badminton, tennis, squash and racquetball (Jack, Adrian & Yoneda, 1978), the contribution of upper arm internal rotation over that of pronation cannot be overlooked in badminton. The lighter racket used in badminton may argue for a greater use of pronation in producing power through a faster "countermovement" which uses the elastic stored energy in the muscles and tendons and the use of the myotatic stretch reflex (Gowitzke, 1978). However, the dominance of upper arm internal rotation in the forehand (and possibly external rotation in the backhand) is certainly an area that should be investigated in the future using the procedures of Elliott et al (1995, 1996). Only Sakurai et al (1987) and Tang et al (1995) have filmed or videoed shots using more than two cameras simultaneously and given the complexities of badminton shots it is perhaps more appropriate that a three-dimensional perspective is gained to fully understand the strokes.

Additional biomechanical studies are also needed on other strokes in the game, especially the forehand and backhand drives, where the lack of an angle between the racket and forearm suggests that the role of pronation and supination in these strokes may not be as important as in the overhead strokes (Tang et al, 1995).

Lees & Hurley (1995) measured external ground reaction forces and estimated internal muscle forces obtained in a badminton lunge movement using players of low, medium and high ability. The magnitude
of both vertical and horizontal forces for impact loading was higher in the low and medium ability players and lowest in the most experienced players, who possessed movement skills to reduce the severity of impact.

Forces in the muscles on the front of the leg were lower than those forces seen during running (Harrison, Lees, McCullagh & Rowe, 1986) but larger in the muscles on the rear of the leg (especially hamstrings and gluteals). Mean forces of 17.5 times body weight were estimated in the gluteal muscles of the lunging leg in trained players; this would necessitate large eccentric contractions occurring here leading to the delayed onset muscle soreness commonly experienced by badminton players in this region of the body. A compliant (elastic) musculature in badminton players is therefore important to allow these high forces to be dissipated on landing and reduce the trauma on muscle fibres (Wilson, Wood & Elliott, 1991).

Because of the large forces generated in these muscles it is also difficult to stop the movement in the direction of the lunge and recover quickly after playing the shot. Wirhed, Johansson & Lindberg (1983) proposed that the major difference in movement between the "faster" Asian players and the "slower" European players was in the Asian's superior eccentric strength in the lunge.

Studies by Wilson (Wilson, Murphy & Pryor, 1994; Walshe & Wilson, 1997) lend further evidence to the role of eccentric strength in jumping type movements. High levels of muscular stiffness are associated with inhibition of depth jump performance especially at heights greater than 60 cm (which rely heavily on eccentric contraction). Rate of concentric force development was faster however in individuals with stiffer musculature. Asian players are renowned for the elasticity of their muscles (which would aid the eccentric braking phase of the lunge); the extra "stiffness" of European players would only contribute to an increase in the concentric phase of the lunge. This ability to stop quickly may outweigh any added benefits of being able to start faster.

Recent work by Wilson, Murphy & Giorgi (1996) suggests the rate of eccentric force development may be the critical component in sports that require jumping type movements. They further suggest this is best developed by a combination of weight and plyometric type training - something which forms a major part of Asian badminton programmes. The rate of eccentric force development may be a key component in players displaying superior movement on the court - further studies in this area of training in relation to badminton movement are certainly worth pursuing.

The demands of badminton are such that it is one of the few sports where elite players have a greater injury risk in training than in competition (Jørgensen & Winge, 1990). Recent summaries of badminton injuries can be found in Krøner, Schmidt, Nielsen, Yde, Jakobsen, Møller-Madsen & Jensen (1990), Jørgensen & Winge, (1990) and Jørgensen & Hølmich (1994).

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**PHYSIOLOGY**

Badminton is a difficult sport to study in the physiological sense primarily because of its intermittent nature.
Various publications have investigated the physiological demands of badminton using heart rate (Docherty, 1978; Coad, Rasmussen & Mikkelsen, 1979; Mikkelsen, 1979; Abe, Haga, Kato, Nakatani, Ikarugi, Usuiyama & Togashi, 1989; Abe, Haga, Nakatani, Ikarugi, Usuiyama, Togashi & Ohta, 1990; Ghosh, Mazumdar, Goswami, Ahuja & Puri, 1990; Hughes, 1995; Liddle, Murphy & Bleakley, 1996), blood lactate responses (Mikkelsen, 1979; Abe et al, 1989, 1990; Ghosh et al, 1990), notation (Liddle et al, 1996) and gas analysis during simulated matches (Abe et al, 1989, 1990; Faccini & Dal Monte, 1996). Lei, Deng & Lu, quoted in Chin, Wong, So, Siu, Steininger & Lo (1995) estimate that 60 - 70% of the energy yield during play is derived from the aerobic system while 30% comes from the anaerobic systems.

The hypotheses from these studies are that badminton players work at a high percentage of their maximal aerobic power (VO2max), work at or very close to maximum heart rate (especially in singles) but have only a moderate energy yield from the anaerobic lactic system. The relatively low blood lactate readings, when players are working close to maximum heart rate, have been explained by the role of myoglobin in acting as a store of oxygen to provide energy (Mikkelsen, 1979) and oxidation of muscle lactate in the rest periods between rallies (Faccini & Dal Monte, 1996).

Lo & Stark (1991) suggest early work on the work-rest ratio in badminton (ca. 5 seconds work to ca. 9 seconds rest) is now outdated and the work period for elite players is currently of the order of 7 - 10 seconds. Recent evidence by Spriet (1995) suggests that in 10 seconds of maximal activity the role of glycolysis may be more important than was previously thought. The implications on the bioenergetics of badminton may therefore suggest a greater reliance on the anaerobic lactic energy system if the average rally length has increased. It would be good to gain some intra-muscular evidence of what is happening in regards to the energy systems at elite level badminton but the logistics of this may make it impossible.

Unfortunately many of the above publications have taken a laboratory approach in studying a sport that is not conducive to laboratory study. The very nature of the game makes it hard to determine what is happening, physiologically, during a game of badminton. As Faccini et al (1996) observed "…there may be an error in presuming work intensity only from heart rate" and "… muscle lactate production estimated from plasma lactate is probably underestimated in this kind of activity." So much is dependent upon a variety of factors - age, standard of players, standard of opposition, the type of game being played (attacking versus defensive) and the environmental conditions encountered.

Ømosegård (1996) provides an excellent theoretical summary of the physiology behind the game of badminton, including reference to several unpublished manuscripts. In the current era, it appears elite badminton singles players possess well-developed aerobic systems (VO-2 max figures for males >65 ml kg-1 min-1; for females ca. 60 ml kg-1 min-1), relatively high isometric strength (especially in the legs) and good ability to deliver energy from the high-energy phosphate systems. Ømosegård (1996), also using data provided by Mikkelsen (1979) affords a good explanation of the demands placed on the muscles during a game and the relative imbalance between the racket leg and the non-racket leg in girth, muscle fiber area, muscle fiber composition, capillarisation and oxidative enzyme levels. This provides good evidence that badminton, per se, results in significant, peripheral aerobic adaptations to the racket leg.

A recent abstract (Baum, Hoy, Kerst, Leyk, Papadopoulos & Eßfeld, 1997) questions traditional
measures of fitness (VO2 max on a treadmill) as a means of quantifying endurance in badminton. There was no close correlation in this study between results from a treadmill test and a badminton-specific test of endurance. Indeed other papers have devised badminton specific on court tests (Chin et al, 1995; Hughes & Fullerton, 1995) using increased velocity of movement in a badminton specific situation.

While the consensus in practically all studies is that badminton players do require a well-developed aerobic system (although how to measure this may be debated), it must also be remembered that the explosive jumping movements in badminton gain their energy from the breakdown of high-energy phosphates (ATP and Creatine Phosphate). The exact mix of training required to optimize this is constantly under debate. Badminton provides a good example of a sport requiring "mixed" training (aerobic versus anaerobic; metabolic versus neural) and would act as a good model for physiologists wanting to investigate this area.

Many questions still remain unanswered in considering the physiology of badminton: Is heart rate a good quantitative indication of workload in a sport such as badminton where much of the activity is above the head and a combination of aerobic and anaerobic energy yield is needed? Does the rise in blood lactate mirror a rise in muscle lactate and is this only due to the patterns of play in the previous two or three rallies or is it always at a higher level compared with rest? Is the increased oxygen consumption in a match due to aerobic demands of the game or contribution to recovery of the anaerobic energy systems?

Much elite level badminton is played in Asia in conditions of high thermal stress. The American College of Sports Medicine has indicated various danger levels of thermal stress for competitive sports (American College of Sports Medicine, 1984). A Wet Bulb Globe Temperature (WBGT) of > 28°C is considered the level where competition should cease. Frequently in Asia, under television lights, the ambient temperature on court is close to 40°C and this, combined with a relative humidity in the 80-90% range would place high thermal stress on players. A recent study (Garrett & Boyd, 1996) has shown greater thermal strain associated with intermittent activity compared with continuous activity eliciting the same total workload. Therefore from a health perspective, badminton in these conditions should come under scrutiny and a thorough investigation should be performed.

No scientific study has investigated WBGT conditions on the badminton court in a hot, humid environment and this, along with core temperature monitoring of players in these conditions would be well worth investigating.

The physiological load that is hardest to measure is the constant change of direction that characterizes badminton. The energy cost of rapid eccentric contractions followed by a rapid concentric contractions time after time in a rally is very difficult to quantify. Given that this eccentric contraction may be one of the major determinants of success in elite Asian players (Wirhed et al, 1983), further research into this area is needed.

Finally, most of the physiological research in badminton has been performed on European players while the Asian countries tend to dominate the sport at an elite level. Some data from elite Chinese players has appeared - mean VO2max values of 63.4 (SD 4.0) for males and 53.3 (3.6) ml kg-1 min-1 for females (Miao & Wang as quoted in Chin et al (1995)) and mean blood lactate levels close to 4 mmol l-1 at the
end of matches (Lei, Deng & Lu as quoted in Chin et al (1995)). However it seems appropriate that until the scientific community can gain data from more Asian players we still do not have a complete understanding on the physiology of badminton. While this information may be available in National Sports Training Centers, the challenge to Asian sport scientists is to publish this material in peer-reviewed journals.

**PERCEPTUAL PSYCHOLOGY**

One discipline in which badminton has been comparatively well researched is that of perceptual psychology. Abernethy's work in the late 1980's (Abernethy, 1988, 1989; Abernethy & Russell, 1987a, 1987b) demonstrated that expert badminton players can anticipate where their opponent is going to place the shuttle better than novice players do. This was due to expert players picking up information earlier in the stroke sequence (167 - 83 ms prior to contact with the shuttle) and their ability to gain information from their opponent's racket arm despite identical visual search strategies being used in the two groups (Abernethy & Russell, 1987a, 1987b).

Further study showed that some expert-novice difference was still apparent regardless of the degree of expertise (Abernethy, 1989) or the age of the players (Abernethy, 1988). However older experts (adults) showed a better ability to predict opponents shots earlier in the stroke sequence than younger experts (12 - 16 year olds).

Put in simple terms, this demonstrates that the longer a player has played badminton, the better his or her anticipatory skills will be. The challenge for coaches is to "fast-track" these skills to allow better perceptual awareness of opponents. Some recent papers (Starkes & Lindley, 1994; Abernethy, 1996) using video training may provide the solution for coaches and this is certainly worth exploring in the future.

**ANTHROPOMETRY**

At international level badminton caters to a wide range of body builds. Singles players tend to look more ectomorphic and less mesomorphic than doubles players. Nevertheless, there are enough exceptions around that it would be unwise to make a general statement. Bush (1989) compared elite and recreational English players and suggested the ideal build for badminton to be an ecto-mesomorphic physique.

Bush (1992) investigated the body composition of elite male English and Korean junior badminton players. He found significant differences only in sitting height (Koreans taller - surmising a lower center of gravity which would be conducive to movement around the court) and two skinfold sites (supra-iliac oblique and supra-iliac vertical - Koreans lower). However there were tendencies for the Koreans to be less endomorphic, more mesomorphic and less ectomorphic than the English group.
Further comparisons between Asian and European players would appear appropriate especially at senior level.

**SUMMARY**

Some aspects of badminton have been well documented but most are still not widely understood or open to debate as new information becomes available. One obvious gap in the scientific literature is a comparison between Asian and European players in a wide range of areas. Badminton is one of the few worldwide sports where Asian countries dominate at elite level. The paucity of scientific information on the largest and fastest racket sport in the world is perhaps a reflection on the difficulty in accurately measuring many of these variables. Nevertheless the challenge has been issued to sport scientists to assist coaches in developing the game. Hopefully this paper will stimulate future studies so that we can gain more information about a sport that is so popular around the world, and yet one which, in scientific terms, we still know so little about.

**REFERENCES**


