ISSN 1750-9823 (print)
International Journal of Sports Science and Engineering
Vol. 1 (2007) No. 1, pp. 3-28

Review

The Evolution of Computerised Notational Analysis Through the Example of Racket Sports

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Abstract. By analysing past and current work in racket sports, it was found that notational analysis of sport could be systematically analysed by using these delimitations. *The development of analysis and technology in the analysis of racket sports* The technological developments in notational analysis have inevitably lagged those in the applied computing technology environment. *Application of feedback in racket sports* The main applied areas of objective feedback were found to be: Tactical evaluation, Technical evaluation, Movement analysis, Databases and modelling, *Performance profiling* The definition of profiles is much less a matter of guesswork because of methodological advances. *Reliability* The methods of measuring and calculating the reliability of non-parametric data has grown with research over the last few years. *Areas of Research and Support* More research in modelling in performance analysis is vital as we extend our knowledge and databases into those exciting areas of prediction. It is clear from these analyses of the on-going research and development work in racket sports, that the working notational analyst must have a broad set of skills and be prepared to maintain and extend those skills just as the research in this area develops the knowledge base.

KEY WORDS: Computerised notational analysis, racket sports, sport.

1. Introduction

Squash and soccer were the first sports to be analysed in Britain by way of computerised analysis systems, and squash in particular has been a precursor to the analyses of all those other sports in terms of the development and involvement of computerised notational analysis. This is due to many of the first programmers of analysis software choosing squash as the sport to analyse, squash was seen as a simple game and one that could easily be recorded, because it was played indoors and in a well lit and defined area.

The first hand notational analysis system published in Britain was in fact for tennis (Downey, 1973). This system was never actually used to gather data however due to its complexity. Not only did this system enable the user to record such variables as shots used, position on the court, and the result of the shot, but also the type of spin used in a particular shot. This system was significant as it provided other researchers with a wealth of ideas (Hughes, 1998).

Reilly and Thomas (1976) were very interested in Downey's (1973) concept of recording sporting actions and they recorded and analysed the intensity and extent of discrete activities during match play in soccer. Sanderson and Way (1977) reported devising a system for squash, it seems to be based on the work by Downey (1973). Their hand notation system was created to analyse successful and unsuccessful patterns of play in squash and was further developed by Sanderson (1983) to include symbols to represent shots that were placed upon a diagram of a court. Results obtained from matches were presented using longitudinal and lateral summations next to the different areas of the court. However it took 5 – 8 hours to learn how to use this system, and a further 40-50 hours to analyse the data from one match. Because of these problems inherent in using more sophisticated hand notation systems, computers were used to minimise learning time and process the data gathered. Hughes (1985) began this progression by computerising the processing of the data gathered by hand with the system of Sanderson and Way.

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It is the aim of this paper to trace the development of computerised performance analysis through the examination, as a case study, of the maturation of the process across racket sports, which not only have the most advanced performance analysis support systems, but also have been clearly chronicled in research papers.

2. The development of analysis and technology in racket sports

The advent of computerised technology enabled these first hand notation systems to be further developed and often extended. A computerised version of Sanderson and Way's (1977) data gathering system was produced by Hughes (1985). It was not an exact transfer of the hand notation system onto computer, as compromises had to be made because of the limited memory of the microcomputer available at the time In addition, the ergonomics of the layout of the keyboard, and concerns over the accuracy of defining player position in the old hand system, led to different design specifications, particularly of the player position. As computer technology evolved it was eventually possible to record the data courtside using a microcomputer. But because of difficulties with the speed of the game and the storage capacity, only one player was notated at a time (Hughes, 1985).

Difficulties with data entry and system learning time were reduced with the development of the digitisation pad. Digitisation pads are programmable, touch sensitive, pads, over which one places an overlay with a graphic representation of the playing surface and aptly labelled keypad areas for the actions and the players (Hughes, 1994). A number of studies both in Britain (Hughes and Feery, 1986; Sharp, 1986; Treadwell, 1988) and in the Notational Analysis Centre at UBC, Vancouver (Franks et al., 1986) have used 'Concept keyboards' and Power Pads' respectively. An unusual application of computerised notation, that used a concept keyboard connected to an IBM computer, was that by Tillin (1986), who notated the levels of aggression by female players at Wimbledon. Each shot was given a score from a scale of aggression, determined by pace, placement and from where the ball was taken. The scale was from '1' to '7', '1' being for a totally defensive soft shot, '7' being for an all-out, attacking shot for the line from an attacking position. 'Aggression', in terms of attacking play, was then correlated with the game and match scores to examine whether the successful players were more or less aggressive on the critical points in a game, or in the critical games of a set. It was found that generally players were less aggressive on the critical stages of the match, but that on critical points the player who was losing would be more attacking. Play was found to be progressively more aggressive as each set continued.

Making the use of the analysis systems easier, for non computer-literate operators, was one of the main aims of the development of a voice interactive system by Taylor and Hughes (1988). They were able to demonstrate that a computer 'non-expert' was capable of using the system despite their study being limited by cost, and therefore the sophistication of the technology they were able to use. Intuitively this seems like the most 'user friendly' system, but despite the success of this research, there has been little advance in this area since, although in the 7th World Conference of Performance Analysis, at last someone was presenting another attempt using this interface (Cort, 2006).

Concurrent with developments in how the data were entered into the computer, there were also advances in how the data were displayed post processing. Because there were no graphical software packages at the time, frequency distributions were represented on a two-dimensional representation of the court, very much in the same way pioneered by Sanderson (1983). These were not always so easy to understand, particularly for most coaches and players. Hughes and McGarry (1989) designed a program that presented the data in coloured three-dimensional histograms that could be rotated and viewed from different angles. This made the results of the computer processing easier to understand.

Another step forward in terms of data entry was when the computer programming language visual basic was utilised to write programs that created a graphical user interface. This interface allowed the user to enter data by moving the mouse around the screen and clicking on icons representing the actions that they want to enter. Hughes and Clarke (1995) used this system for the analysis of surface strategies at both Wimbledon (grass courts) and the Australia Open (synthetic courts). They also noted that there were significantly shorter rallies at Wimbledon and indicated the importance of the serve on grass courts, as well as incorporating time factors, and positional data. Later O'Donoghue and Liddle (1998a) analysed time factors in both the men's and ladies games, for both grass and clay surfaces. Badminton has been subjected to analysis also. European circuit standard badminton was studied through the 1996 tournament in Lisburn, Northern Ireland (Liddle & O'Donoghue, 1998). Also recent systems that are programmed using visual basic, and utilise the Windows environment, are interactive with a number of graphics packages making representation far clearer and easier to understand (Hughes, 1994).

Hughes developed a computerised analysis system, based on a hand notation system developed by Hughes and Robertson (1998), that could be entered in real time by the user. Information regarding the number shots in the rally, court position, how the rally ended and with what type of shot is typed in after every rally. The advantage of this system was that 3-D histograms were produced immediately by the computer and could be used to offer the players feedback between games. Once a number of matches involving a particular player were processed the data on that player could be collected together and viewed graphically to display a fingerprint of where and with what shots a certain player hits winners and errors. This Simple Winner Error Analysis Technique is known as SWEAT analysis (Murray et al., 2001). The in-event analysis SWEAT systems, and the post-event full match analysis systems, were used effectively for a number of years. The next development in the systems since 1995 was brought about by doubles squash being made a Commonwealth sport in 1998. It however took until Wells et al. (2004) for an analysis system to be designed to incorporate the larger squash court and the greater number of players.

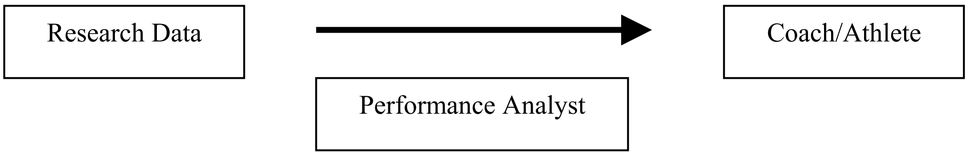

Fig.1. Linear relationships in data gathering and feedback (Hughes, 2004).

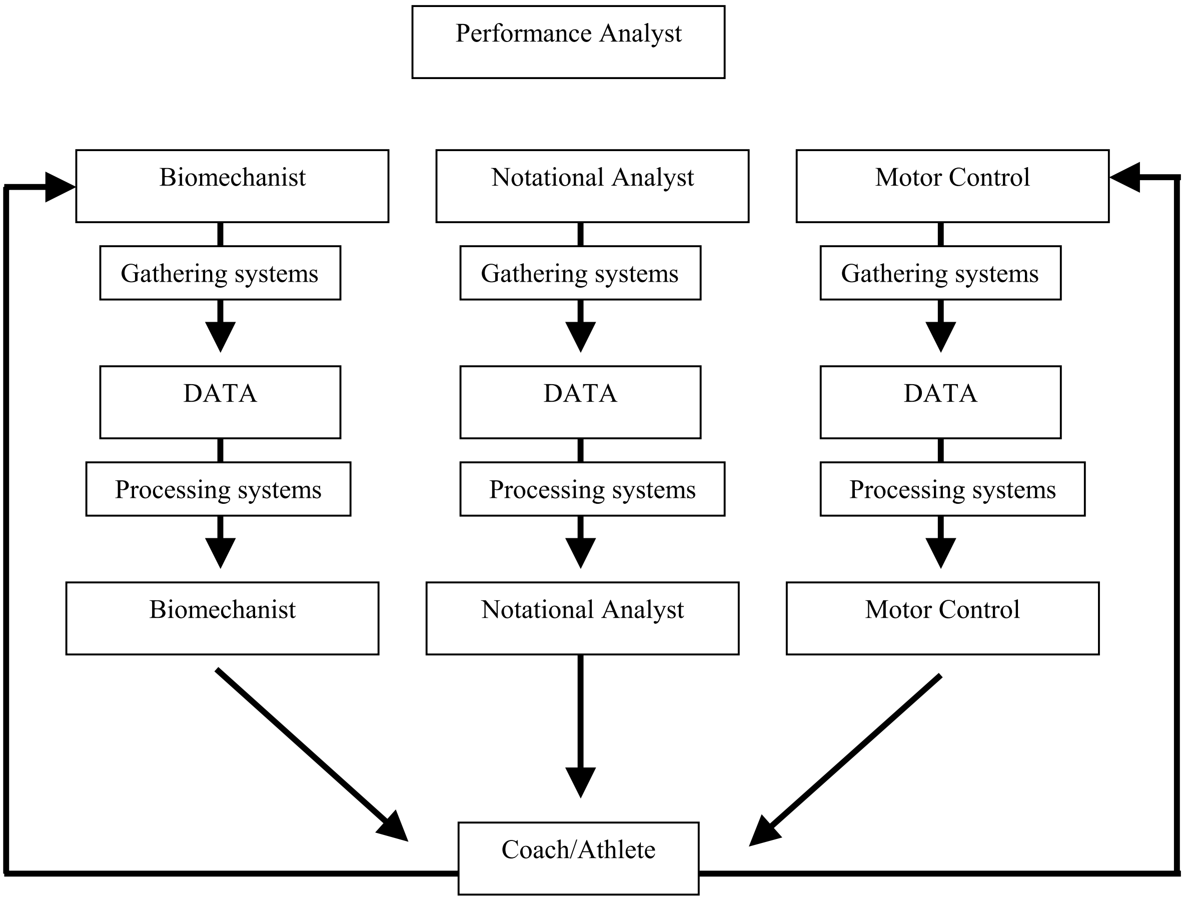

Fig. 2. The role of the performance analyst using early analogue video and computer systems to gather and process performance data for the coach (Hughes, 2004).

The main purpose, at this time, of designing these analysis systems has been to provide objective, quantitative systems for research purposes, if they could also be used for feedback for athletes and coaches then this was a bonus (See Figure 1.). Extensive research carried out by Schmidt (1975) found that feedback, if presented at the correct time and in the correct quantity, played a great part in the learning of new skills and the enhancement of performance (Murray, Maylor & Hughes, 1998). However, research has shown that the more quantitative and objective the feedback the greater effect it has on performance (Franks, Goodman & Miller, 1983; Franks, 1997). This research shows that objective feedback presented at the correct time can be of great benefit to an athlete or team. There are a number of commercial systems that are available for the notational analyst that can considerably enhance the power of feedback, through the medium of video replays and edited video clips. Some of the more successful are appraised here, more detail can be found on the appropriate web-sites.

As such the feedback offered by the squash analysis systems is in exactly the right form to present to squash players and coaches to enhance performance. Due to the multitude of factors that contribute to a squash player's performance, it has been hard to quantify the specific effect that feedback has. Murray, Maylor and Hughes (1998), however, did find that quantitative feedback did induce a significant temporal transition in performance levels for elite and sub-elite players. As complete control conditions were not in place however it makes it hard to gauge the exact effect of the feedback.

The persistent developmental work by these researchers has now led to the advance of the current generation of generic analysis systems that are also linked into digital video for easy retention of a video database and for editing and feedback purposes. Indeed, there are now a large number of commercial systems that are available for the notational analyst that can considerably enhance the power of feedback, through the medium of video replays and edited video clips. Some of the more successful were appraised by Hughes et al., (2002), more recent detail, and they are changing all the time, can be found on the appropriate web-sites.

As lottery money became available to fund sports science support teams, then analysts and other sports scientists, were employed full-time to work with NGB teams, but the data transfer was still strictly linear, (analogue), with little interaction between sports scientists, and the coaches and players were not involved in data capture nor interpretation (Figure 2).

3. Application of feedback in racket sports

Hughes (1994) outlined four major areas within which feedback gathered via computerised notational analysis can be applied to racket sports as tactical evaluation, technical evaluation, movement analysis, and creating databases and modelling.

Tactical evaluation

The first computerised analysis of the tactics of players of varying ability in racket sports was performed by Hughes (1985; 1986) who compared shot distributions of recreational, county standard and nationally ranked squash players using the notational analysis systems he had developed. The data for the distribution of shots played by recreational players showed that they were not skilful enough to play to a 'game-plan' and that they were particularly inaccurate with their straight and cross-court drives. Their frequency of short shots was also a lot higher than that of county or nationally ranked players, and although they hit more winners they hit more errors as well. County players were able to perform tactics involving keeping the ball deep and primarily on the backhand. County players hit significantly more straight drive winners than recreational players and although their short game was significantly more accurate than that of the recreational players it was significantly less consistent than the nationally ranked players. Nationally ranked players used far more complex tactics in their matches employing more of an 'all-court' game. This was facilitated by their superior fitness and technical ability when compared to the other standards of players.

Hughes and Clarke (1995) utilised a computerised notation system for the analysis of surface strategies used at both Wimbledon (grass courts) and the Australia Open (synthetic courts). They also noted shorter rallies and indicated the importance of the serve on grass courts, as well as incorporating time factors, and positional data. Later O'Donoghue and Liddle (1998) analysed time factors in both the men's and ladies games, for both grass and clay surfaces. They indicated that the clay courts of Roland Garros produced significantly longer rallies than the grass courts of Wimbledon, for both the men and ladies. They also indicated that the men's game on both surfaces produced significantly shorter rallies than the women's, however within the methodology there is no indication of the intensity of activity within the time parameters. Using the same two surfaces O'Donoghue and Liddle (1998) extended their research to include an assessment of surface strategy for the ladies game. This research suggested the more dominant role of the serve on grass, also indicating the cause and effect role of net play on both surfaces. It should be noted however, that none of this research conducted an assessment of normative profiling in order that a true representation of the game had been achieved.

A comparison of the game strategies employed by National and International squash players in competitive situation by notation analysis is the subject of researchd by Hong, Chang and Chan (1996). Ten male matches from the Perrier Hong Kong Closed Championship'94 were recorded. Strokes and where the ball landed were recorded, they were identified according to 13 well known types, namely as straight drive (SDr); cross court drive (XDr); boast (Bo); reverse boast (RB); straight volley drive (SVDr); cross court volley drive (XVDr); straight volley drop (SVDp); cross court volley drop (XVDp); volley boast (VB); straight lob (SL); cross court lob (XL); straight drop (SDp); and cross court drop (XDp). The quality of the return shot was depicted by four different categories: "effective", "ineffective", "winning" and "losing". The results obtained from this study coincide with that of Hughes (1996). In the front of the court for instance, the national players played significantly more percentage frequency both of all returns and "losing" shots than the international players. National players played both significantly higher percentage of "ineffective" shots and lower percentage of "effective2 shots than their international counterparts. They also played significantly more shots from the front of the court and less from the back, played significantly more "ineffective" drive, drop and volley shots and less "effective" shots than the international players.

Hughes & Robertson (1998) used computerised notational analysis to re-examine the patterns of play at the elite level and create a 'structural archetype' of elite squash. This in turn enabled the creation of a tactical model of the game at the elite level for men, it enumerated the structures of the rallies and games, shot distribution frequencies, or ratios, across the court, and the percentages of shots played in the 4 corners of the court, enabling individuals to compare their own patterns. It took a further 15 years for a similar study to be performed upon female players of differing standards (Hughes, Wells & Matthews, 2000). The majority of the research conducted in squash has been in the men's game and it has taken a number of years for equivalent studies to take place in the women's game.

Murray and Hughes (2001) outlined and reviewed the development, methodology and application of tactical performance profiles used with elite level male and female English squash players. The aim of the methodology (tactical performance profiles) outlined in this paper was to provide the performers with quantitative analyses, highlighting their own, or an opponent's, comparative strengths and weaknesses. By modelling performance in this way, tactical plans can be based upon empirical evidence as well as the usual subjective observations of the coaches. Several computer systems were used to gather data both in-event and post-event. They were also experimenting with the use of momentum profiles to add information for other members of the sports science support team, this has recently been refined and tested further (Fenwick, Hughes and Murray, 2006). These profiles are then used in conjunction with high-quality edited video tapes, providing the elite performers with both statistical and visual feed forward, the tapes lend visual evidence of these sets of data and heightens the user friendliness of the analyses. The definition of some of the experiences and processes started the process of delineating the generic functions of a performance analyst.

It is very difficult to quantify the effect that these profiles may have upon the performance of the athletes, and to attribute transition of performance to the implementation of these profiles may be somewhat naive. However, considering that the world of elite sport (especially when on the playing field or court) is such a multivariate situation then any singular attribution would be very difficult to achieve. The verbal feedback from the players and coaches was both constructive and positive and has raised several issues around how we, as sports scientists, give our information to elite performers. Nevertheless, the process alone made the players more analytical and focused in their approach to matches and tournaments, which, arguably, is a singular positive effect in itself.

The process itself is one of analysis and, more importantly, of self-analysis and change. These experiences are presented as an exemplar of performance analysis, not because we think that they should be imitated, but that there are aspects of the processes that can be analysed and improved. Perhaps from these we can then define some generic indicators of process for the performance analyst.

Technical evaluation

Technique and tactics are inherently inter-dependent, so that research methods that define technical strengths and weaknesses of given players will also highlight the areas of tactical decisions. Highlighting technical deficiencies or strengths in players can be of vital importance to coaches in their quest to improve the athletes. The analysis systems used over the years (Hughes, 1985; Brown & Hughes, 1995) have been used to show the areas on the court where players hit their winners and errors (the 'N th' shot of a rally) from, and with what shots. To add greater depth to the analyses, and hence the feedback, data upon the N-1 and N-2 shots to errors and winners could also be provided, shots that might not normally be remembered by the coach. If these data are collected from a number of matches, against players of an appropriate standard, then they can give indications of those types of shots that are the strengths and weaknesses of the respective player.

Murray, Maylor and Hughes (1998) recently researched into the effect of computerised notational analysis as feedback on improving squash performance. This study used a similar method to that of Brown and Hughes (1995) on the effectiveness of quantitative and qualitative feedback in squash. It was concluded that both groups reacted positively to the feedback provided and the feedback from notation analysis accounted for an increase in the number of winners and a decrease in the number of errors. From this evidence it is clear that notation analysis has it's uses as an effective practical tool during the coaching of performance.

Full time notational analyst for the Badminton Association of England, Steve Evans has developed various hand notation systems to provide information on badminton play patterns, work to rest ratios and movement analysis. Using the 1998 ladies singles final of the All England Championship, Evans (1998b) analysed rally-ending situations so as to provide tactical match plans for future training sessions. Within the study it was noted that a low winner to error ratio was apparent. The players also showed an increased amount of errors when playing the clear in comparison to other shots. This could have been due to the surrounding environment or increased pressure, it is usually expected that a clear will produce a low winner to error ratio. The smash though will usually have a winner to error ratio greater than one (in men's singles the ratio is 2.2:1, Evans, 1998a). Within this study only one match was analysed therefore care must be taken when interpreting the data. Evans (1998) outlined that ideally a good player profile can be established by using a collection of five matches, 'the more matches one can notate the more accurate an emerging pattern will be,' Evans (1998, p.9).

Furlong (1995) analysed the service effectiveness in lawn tennis at Wimbledon and in clay at the French Open in 1992 as a comparison. Furlong (1995) notated both men's and women's, singles and doubles events to standardise for the fastest and slowest surface. The results showed that the service in doubles was the most effective because most serves were slower to compensate for accuracy so that a strong attacking position at the net could be achieved, which would help in scoring more points.

Hughes and Taylor (1998) compared the patterns of play between six top British U18 players in comparison to six top U18 European and three top U18 American / Canadian elite performers. The hand notation system recorded data using symbols based in four positional zones of the court, data gathering was performed post-event from video. These researchers analysed two tournaments just before the 1996 Wimbledon, which are perceived as 'Warm Up' tournaments. These tournaments were Imber Court, London and I.T.F. Group one tournament held in Roehampton, London, both of a grass surface. Eight matches were recorded over the two venues and the following conclusions were generated:

- U18 British players made more unforced errors from the back of the court.
- Europeans seem to ht more attacking shots from the back of the court.
- U18 British players made more defensive shots from the back of the court.
- U18 British players won more points at the net, where Europeans won more at the back of the court.
- U18 British players executed a low number of winning passing shots in comparison to both Europeans and Americans / Canadians.

All the research carried out on playing patterns in squash have observed male subjects only, apart from a recent study by Hughes, Wells and Matthews (2000) who analysed female squash players. The aim of the study was to define models of patterns of play at different levels in squash for women and analyse the demands placed on players as they ascend through these levels. An additional aim was to define a 'normative profile' and explore how much data were required to reach a 'normal playing pattern'. Using a computerised notation system (Brown and Hughes, 1995) post-event analysis for elite (N=20), county (N=20), and recreational (N=20) were analysed. A dependent t-test was used to establish whether a normative profile had been reached, the profiles of 8 matches were compared with those of 9 and 10 matches, for each of the categories of players. Analysis of variance and chi-squared analysis were used to test for differences in the overall match totals and distributions of shots.

The results produced in this study have clearly distinguished between the playing patterns of women at the different levels of play. It was discovered that elite and county players did establish a playing pattern that could be reproduced reasonably consistently. The recreational players did not produce a normal playing pattern due to lack of significance at a suitable level. Hughes, Wells and Matthews (2000) felt that a normative playing pattern is only achieved when a player plays at top level, the subsequent differences of the recreational player exist because they do not posses a fixed pattern. Their differences were not caused by chance but by the fact that they have no fixed pattern of play. As players work their way up the different standards of play set patterns emerge. The county playing standards showed a set pattern forming, but this will not be fully achieved until that county playing standard reaches the top level of squash, elite level. (Hughes et al., 2000, p91.)

Significant differences were produced on a number of key elements of play across the three standards. There was a significant difference in the total number of shots played per match, ($p<0.05$) and standards of play. Also significant differences ($p<0.05$) were found between all three groups for the total number of shots per rally. The conclusions drawn from this study have similarities to that of Hughes (1986) on his work concerning male subjects. The elite players employed an 'all-court' game, using more complex tactics creating more pressure, due to their higher levels of fitness, covering ability, speed and skill levels. County players showed a consistent attempt on hitting the ball into the back of the court and predominantly on the backhand side. Their shots were less accurate than the elite players, but significantly more accurate than the recreational player. Recreational players adopted a 'hit and run' game due to their inability displaying tactics. They were erratic with their distribution of shots, hitting a high percentage loose to the middle of the court. These studies by Hughes (1986) and Hughes et al. (2000) distinguish between playing patterns of both standards of genders, they are not representative of the junior game in any way. This is due to the differing physiological factors that exist between the two subject areas, for instance being able to retrieve the ball, and also other factors that might contribute to the variance in playing patterns, such as quality of coaching.

Armed with this information the coach can then analyse any technical deficiencies of their players when playing in these particular areas of the court or when playing a certain shot. This in turn will inform the player of tactical considerations of shot sequences. This can be done live in training, or with use of video feedback. Seeing technical faults in the past has been quite difficult on video due to the frame rates. However with introduction of high-speed cameras for feedback purposes, technical analyses of the racket swings and individual player movement can now be scrutinised to the minutest detail.

Movement analysis

Based upon the work conducted by Reilly and Thomas (1976), on movement duration and intensity in soccer, Hughes, Franks and Nagelkerke (1989) designed a tracking system for squash. The tracking system was designed to be used post-match from video at match speed. A ‘Power Pad’ was used to gather the positional data along with the time base (Hughes, 1998). Accurate tracking was enabled by training a video camera on the ‘Power Pad’ and mixing the image from the camera with the footage of the match and transferring it to a single VDU screen. The image of the representation of the playing area on the ‘Power Pad’ was aligned to exactly meet the dimensions of the court on screen. This allowed the operator to be able to focus upon where they were tracking and where the player was moving at the same time. This was shown to be an accurate and reliable method of gathering information regarding player velocities and accelerations.

This system was utilised by Hughes and Franks (1994) in a study comparing the motions of squash players of differing standards. They recorded the distances moved, the average velocities and the accelerations during rallies of four different standards of players ranging from club level to elite internationals. The mean distance travelled by recreational and regular club players was only 12m, which raised some questions about the type and specificity of the training that these players were performing. The study also showed that the then number 1 player in the world, Jahangir Khan, had a physiological advantage over the other top players in the world. It was found that when the data for Jahangir Khan were compared to that of the top six players, including his own data, his acceleration during a rally was 50% greater than that of his opponents.

Hughes and Moore (1998) analysed the patterns of movement concerned with serve and volley tactics in tennis. They indicated that certain types of movement, like skip-check, combined with the ready position were used almost universally, however, some movements, such as running or jumping through a shot, placed pressure on the player often resulted in them losing the rally. They also suggested that losing players exhibited a higher number of post impact steps away from the midline of the court. Richers (1995) also conducted a study regarding movement and physiological profiling of single tennis. She used a time-motion analysis combined with an assessment of sets and repetitions of continuous foot movements. The research suggested that elite tennis players primarily utilise anaerobic metabolic pathways (ATP-PC and Lactic Acid pathways), and also noted that players took similar repetitions of steps across hard, clay and grass surfaces per set, but significantly higher numbers of sets on both hard and clay surfaces, largely owing to the significantly longer duration of each point on those surfaces.

Liddle & O'Donoghue (1998) investigated rally and rest times for each discipline of badminton (apart from mixed doubles) and found mean rest durations to be longer than mean rally durations for all forms of the game. In men's singles, mean rally duration was found to be 9.15 ±0.43s, whilst the mean rest time was 13.84 ±1.16s. These figures differ greatly from those found by Coad *et al.*(1979) and Docherty (1982) (cited in Hughes, M. G., 1994). They found rally length to be around five seconds with five to ten seconds of recovery in between, but did state that the rally length would be expected to be longer at the elite level. However, the study by Liddle and O'Donoghue (1998) was limited in that only four of each men's and ladies' singles, five men's doubles and four ladies doubles matches were notated. This meant that a restricted study size was examined for each discipline. The analysis (Liddle & O'Donoghue, 1998) was performed live using computer notation during matches. This will have removed inaccuracies that arise from post match analysis, caused by such events as stretching of the videotape due to repeated viewing. Conclusions were drawn from the research that training should be specific to the discipline in which performers participate. This is reinforced by the fact that the Badminton Association of England have appointed specialist singles and doubles coaches in recent times.

Pereira et al. (2001) indicated the importance of movement within the game of squash, a concept that is re-iterated by many tennis professionals, even given the differences in reported rally time, intensity, and rest ratios between the two sports. The principle aim of the research undertaken by Pereira et al. (2001) was to link movement patterns form different areas of the court, to establish a normative movement profile. Within the study, movements were operationalised into categories according to the discrete movements of the sport, and later inter-linked during the data analysis. This enabled different movements, from the initial movements, those to the ball, and those at the time of ball striking to be linked together, and when combined with data on the rally outcome, determine the normative movement patterns of winning and losing squash players. Although the outcomes of the research are not directly comparable to tennis, the methodology used represents a new approach in the analysis of patterns of movement. Wells and Hughes (2001) also conducted a similar study in squash, however their methodology differed to Pereira et al (2001) due to the division of front, back, and middle areas of the court, and further sub-divisions on both the forehand and backhand side. This enabled a more specific and relevant analysis of the movement patterns to be established, and served as an accurate tool for future coaching. Such profiles of movement are not currently available in the field of tennis, and if a reliable and valid measure for these movements in tennis could be produced, it would serve as a valuable resource for both coaches and players alike.

Movement analysis in racket sports has enabled a better understanding of the physical demands of the sports and, as a result, the creation of specific training drills to better prepare the players for matchplay. This information can also be used to help strengthen junior players who are currently finding the transition from the junior game to the senior (professional) sport difficult due to the greater physicality of the senior game (Pearson, 1999).

Databases and modelling

Once sufficiently large amounts of data have been collected using notational analysis systems, models of the 'norms' of behaviour of players can be formed. Modelling can be invaluable when predicting how an opponent will play the game.

Mathematical modelling can be used to describe sport and can be applied to racket sports to expose strategic patterns of play. Using the mathematical theory of probability, Alexander et al. (1988) analysed and modelled the game of squash. They first suggested that the actions in squash a series of discrete events with each event having an associated probability function. However this model cannot take into account the human factor of the game such as form and tiredness. They then took these factors into account and were then able to make recommendations for players on how to 'set' the game at 8-8 depending on fatigue and technical ability.

McGarry and Franks (1994) created a stochastic model of championship squash match-play which inferred prospective results from previous performance through forecasting shot response and associated outcome from the preceding shot. Their results were limited however by the fact that players used the same playing patterns against the same opponents but different playing patterns against different opponents. This was in contrast to the work of Sanderson (1983) who found that squash players did not alter their patterns of play against different opponents whether they were winning or losing. These discrepancies could be the result of differing levels of detail in terms of measuring the responses of the players, McGarry and Franks used a very detailed analysis structure, but they do remain a contradiction to the more generally accepted view of the stabilisation of playing patterns.

To try to promote a more attacking style of play in squash, 'point-per-rally' scoring was introduced to all PSA tournaments in 1990 along with the tin being lowered from 19 inches to 17 inches. It was thought that with points on offer when receiving serve as well as being able to play shots lower on the front wall, players would hit more offensive shots, rallies would become shorter and squash would become more spectator friendly. To analyse the differences in the game when using point-per-rally scoring compared to the traditional English scoring method, Hughes and Knight (1995) designed a computerised notational analysis system that utilised a graphical user interface. Surprisingly rallies were found to be marginally, but not significantly longer, when playing using the point-per-rally scoring. There was an increase in winners but no increase in errors, which was attributed to the lower tin.

Further analysis of the scoring systems in squash was conducted by Hughes (1995), when he investigated the scoring structures in tennis and squash. Key terms 'activity cycles' and 'critical points' were described by Hughes as the crucial events that lead up to exciting points in the games. In tennis the activity cycles leading up to a 'game point' were about 3 mins in duration, whereas in squash (and in badminton at that time) it took 15-20 mins to reach a critical point, i.e. game-ball. Hughes realised that in order to make the game more attractive the activity cycles preceding critical points in the games needed to be shortened to make the game more appealing, more exciting. So Hughes recommended playing more, shorter games in squash thereby increasing the number of critical points and hopefully crowd excitement. The new recommended scoring system ('Welsh scoring', based on tennis scoring) meant that games were now first to four points and if the scores were tied at three all then it would be the receiver to decide whether they play to two clear points, or to just one ('sudden death'). Also players would serve for a whole game with the serve alternating between players after each game. This meant that both players would receive the same amount of serves which Hughes (1995) stated would correct the imbalance of previous scoring systems, that dictated that the winner of the previous rally serve the next. The old systems put the receiver at a disadvantage and as such the lesser player was being penalised for not winning enough rallies. This was particularly evident in English scoring when players could only win points when serving. In the new scoring system sets were the first to five games and the match was the best of three sets. A similar scoring system was used at the Grasshopper Cup, a large PSA tournament in 1995, with some positive feedback from the players. Analysis of the effects of rule changes in sport is commonplace with notational analysis being used to create statistical norms or models of performance pre and post rule change. This work is quite unique in that the research was proactive in the need to examine the rules in racket sports and not vice versa.

Full time notational analyst for the Badminton Association of England, Steve Evans has developed various hand notation systems to provide information on badminton play patterns, work to rest ratios and movement analysis. Using the 1998 ladies singles final of the All England Championship, Evans (1998b) analysed rally-ending situations so as to provide tactical match plans for future training sessions. Within the study it was noted that a low winner to error ratio was apparent. The players also showed an increased amount of errors when playing the clear in comparison to other shots. This could have been due to the surrounding environment or increased pressure, it is usually expected that a clear will produce a low winner to error ratio. The smash though will usually have a winner to error ratio greater than one (in men's singles the ratio is 2.2:1, Evans, 1998a). Within this study only one match was analysed therefore care must be taken when interpreting the data. Evans (1998) outlined that ideally a good player profile can be established by using a collection of five matches, 'the more matches one can notate the more accurate an emerging pattern will be,' Evans (1998, p.9).

Hong and Tong (2000) performed a notational analysis investigation into playing patterns of the world's top singles badminton players in competition. The aims of the study were to analyse the percentage distribution of shots and their placement within in the court-areas; the frequency of different serves; how playing effectiveness corresponded with court-area; and the crucial factors that influenced winning or losing a match. The results showed that for male singles players the low serve was most preferable, the majority of shots were returned to the forecourt, and the lob was the most popular shot followed by the smash, net and clear. The forecourt was also where the most "effective" shots where returned, with the rearcourt producing the majority of "ineffective" shots. Furthermore it was found that each game contained on average 47.61 rallies with a mean of 7.37 shots played in each rally. The study concluded that for top-level international players the most important strategy for producing a winning performance was a pressure and attack game.

More recently an unpublished study by Dobson (2001) compared the patterns of play of elite and sub-elite ladies singles badminton. The world's top ten ranked ladies were used to for the elite subjects and the ladies ranked 40-50 worldwide were used for the sub-elite subjects. The study used 17 matches taken from the All England Open and the Korean Open to analyse the variables:

- Frequency of all shots by position and match.
- Outcome by match.
- Outcome by position by match.
- Outcome by shot type by match

Using a hand/computerised notation system it was discovered that the only significant difference ($P<0.1$) for positional shots was found in position 5 (the centre of the court). Sub-elite players were shown to make a significantly higher percentage of errors ($P<0.05$) than elite players but there was no difference found between the two standards with respect to the percentage of winners.

The study concluded that there was a difference in the patterns of play for elite and non-elite players but also identified other reasons for the differences that the system could not analyse. These influencing factors included the general fitness of players and their injury status, the techniques adopted within the game and the financial support available.

A time analysis was performed of both the 1999 Welsh Open in the 3 games to 15 points format, and the 2000 Welsh Open in the 5 games to 7 points format. Post event analysis (Pritchard et al., 2001) allowed repeated viewings to enable the collection of extra data. Performance indicators such as rally length and duration, rest times and game lengths were recorded by hand on computer printed record sheets. The experimental scoring system under trial in 2001 by the International Badminton Federation seems to have the desired effect on elite men's singles. This research allows the following conclusions to be made.

- Mean, mode and median rally lengths have shown no significant change. Means were comparable to those found by Liddle and O'Donoghue (1998), and Liddle *et al.*(1996)
- A significant difference (P=0.025) has been found in the lengths of games under the new scoring system. The average duration has dropped from 19:24min under the old system, to 8:53min under the new one
- Match length has decreased significantly (P=0.025) when defined by the number of rallies played
- A tight match in 3 x 15 format may last up to an hour. This agrees with Turnbull (1992). This has decreased to 45 minutes in 5 x 7 format
- Work to rest ratios were seen to be identical under both forms of scoring
- Critical Points occurred 4.05 times per game under the new scoring. This is an increase from 1.76 per game under the traditional format
- Shorter games containing more Critical Points make badminton more exciting and better suited to television
- There are more breaks in play due to there being more games of a shorter length. This gives time for expert analysis on television coverage
- Spectators will better understand the new scoring format as all ties are the best of 5 games to 7 points, irrespective of which discipline of the game is being played.

The professional men's squash association has recently introduced a new scoring system, with the aim of making the game more appealing to television audiences. It is so far unclear as to whether this change has achieved its aim. The aim of a study by Hughes et al., (2006b) was to analyse any changes in the game structure or differences in the patterns of play occurring amongst the elite of men's squash whilst playing in competition under the old (point per rally to 15) and new (point per rally to 11) scoring systems. This study analysed 6 matches from both scoring systems played by male players ranked in the top 12 in the PSA World Rankings through the use of a notation system designed by Hughes (1995). The analysis of the data gathered compared time structures, incidence of critical points, rally lengths and the winner error ratios and patterns of play. Overall the study determined if the matches were shorter and if more 'critical points' were created through the new scoring system, hence making it more attractive to the television media. The main results gained from the notation system along with further analysis are shown below in table 1, using 10% change as significant difference (highlighted in yellow).

It was concluded that the results showed that the new scoring system produces a significant increase in amount of winners, and decrease in amount of unforced errors per match, using 10% change as significant. The main improvement of the new scoring system was the significant increase in amount of critical points per match, using 10% change as significant. However, is the increase enough to gain the excitement levels in which are produced in a game of tennis, which produces a critical point every 3 minutes. It was also concluded that PPR to 11 scoring had no significant change in patterns of play, but produced shorter games and has increased the amount of critical points compared to PPR to 15 scoring.

Table 1. Structural changes in matchplay under PPR to 11 and PPR to 15 scoring systems.

	Scoring System		
Variable	**PPR to 15**	**PPR to 11**	**% Difference**
Avg. Length of Matches (mins:secs)	70.67	69.33	-1.90%
Avg. Extrapalated Length of Match (mins:secs)	74.88	52.43	-29.99%
Avg. Shots (per Rally)	12.67	12.99	7.89%
Avg. Winners (per Match)	53.41	60.1	12.53%
Avg. Unforced Errors (per Match)	31.79	27.61	-13.15%
Avg. Minimum Critical Points (per Match)	4.17	6.17	48.00%
Avg. Rest between Rallies (s)	11.55	12.71	10.04%

McGarry (2006) examined the space-time patterns of squash players as they move around the squash court in the context of a dynamical system. The phase relations that describe the squash dyad (i.e., where one player is in relation to the other player) demonstrated a strong tendency towards an anti-phase (180°) relation, as expected. When the data from a number of squash rallies (N = 47) were combined a second stable phase relation of 135° emerged, thus indicating the existence of a previously undetected lead-lag phase relation within the squash dyad. The lead phase relation belonged to the server of the rally in each instance. Further inspections of individual squash rallies demonstrated other properties consistent with a dynamical system description, namely the existence of phase fluctuations (i.e., increased variability in the phase relations), phase transitions (i.e., a switch between stable phase relations), and phase slippages as a result of a missing, or extra, phase cycle for one of the two players. Together, these results indicate that the space-time interactions of squash players might usefully be described in the context of dynamical principles of self-organizing (complex) systems. These findings furthermore suggest that the dynamical properties of the squash dyad may contain important information for identifying the squash patterns that we think we see using visual inspection. To examine this supposition we used the point-light method to represent the movements of the two squash players within a rally as contrasted against a distracter set of varying complexities. Interestingly, humans retained the ability to identify the squash dyad beyond chance even when the distracter set contained squash-like properties. Whether a dynamical analysis of these data is likewise discriminatory in its ability to detect squash behaviours from squash-like behaviours remains to be determined in future research.

These new and exciting ways of examining racket sports provide innovative ways of modelling these sports and point the way toward an ongoing series of modelling developments, for example see the work of Hughes, Howells and Hughes (2006) who used how players create perturbations in rallies, as a basis for additional profiling of a player's performance.

4. Performance profiling

The early work of Sanderson and Way (1977) and Hughes (1986) highlighted that the formation of a database of matches could provide information regarding patterns of play that could be considered representative of the subjects used to form the database. The formation of 'profiles' of different groups of players could be a very powerful tool in attempts to understand the sport better and to formulate a successful game-plan prior to matches. As such, a number of studies over the years have attempted to profile different player groups and aspects of the game.

Hughes and Franks' (1994) movement analysis study provided profiles of the movement patterns of male squash players at four different ability levels. These profiles provided a great insight into the physiological demands of the game and as such had a great practical application in the creation of squash specific training drills.

Using the Hughes and Knight (1995) system, Hughes and Robertson (1998) created a 'structural archetype' of elite squash for men and extended it to produce a tactical model of the game. The model was formed using the data gathered from 5 elite level matches. To accompany the model several simple hand notation systems for specific areas of the court were developed and these have been implemented over the years by a number of squads. After the Hughes and Robertson (1998) study questions started to be asked about the validity of profiling studies, and how many matches needed to be analysed to form a reliable profile. Hughes, Wells and Matthews (2000) sought to answer this question as part of their study. They also replicated the study of Hughes (1986) but used female players of 3 different standards as their subjects. During the study they compared the profiles obtained from databases containing 8, 9 or 10 matches to investigate when the profiles had become 'normative', that is stable. Analysis of variance and chi-squared analysis were used to test for differences in the overall match totals and distributions of shots. They found that recreational players did not establish a normative playing pattern but county and elite players did ascertain a pattern that could be considered normative. There was a difference however in the number of matches it took for the county and elite players profiles to become normative. For county players it took 8/9 matches and for elite players it took 6 matches. More data are produced during an elite match due to their greater duration and this could be one reason as to why their profiles stabilise quicker. Also as players improve in standard they are able to sustain set patterns of play due to their greater skill level. The opposite is true of recreational players, who are not skilful enough to play to fixed tactical patterns and so their profiles do not stabilise. This study showed that creating normative profiles is highly dependant on the nature of the data being collected and the ability of the performers.

Intuitively one would assume that the greater the number of matches in the database the more reliable the profile produced would be (Potter & Hughes, 2000). However later work suggested that as a database grows larger it becomes less sensitive to changes in playing patterns and so becomes less accurate (Hughes, Evans & Wells, 2001). Therefore the number of games analysed in the database is of great importance to the reliability of the profile produced.

Research by Hughes, Wells and Matthews (2000) attempted to 'validate' their performance profiles. To establish that a normative profile had been reached, the profiles of 8 matches were compared with those of 9 and 10 matches, using dependent t-tests, for each of the standards of players – no non-parametric software was available. The results showed that the elite players and the county players did establish a playing pattern that could be said to be reproduced reasonably consistently. The recreational players failed to show any real significance at a suitable level, therefore a normal playing pattern was not established. It must be understood that each squash match, even at the same level can differ from one another. A question that arose from this is, how much can they differ before they are suspected that the difference is caused by something other than chance? This was felt to be especially true for the recreational playing standards, where their differences were not caused by chance but by the fact that they have no fixed pattern of play. As players work their way up the different standards of play a set pattern was emerging. The elite players are at a level where a fixed pattern can be established. This method clearly demonstrated that those studies assuming that 5, 6 or 8 matches of performances were enough for a normative profile, without resorting to this sort of test, are clearly subject to possible flaws. It is vital that, in notational analysis, the same care is adopted in examining our validity and reliability techniques.

The nature of the data themselves will also effect how many performances are required – 5 matches may be enough to analyse passing in field hockey, would you need 10 to analyse crossing or perhaps 30 for shooting? The way in which the data is analysed also will effect the stabilisation of performance means – data that are analysed across a multi-cell representation of the playing area will require far more performances to stabilise than data that are analysed on overall performance descriptors (e.g. shots per match). It is misleading to test the latter and then go on to analyse the data in further detail.

Evans (1999) aimed to develop a notation system to record the rally outcome variables of badminton, and test system validity and reliability. This system was used to tackle two basic problems that affect the analyst working in this area of performance analysis. The one problem that was examined which is specific to this study was the affect of new match data on the accumulative mean of each variable of the rally ending badminton profile, in an attempt to quantify the matches necessary to establish templates. For Evans (1999) the number of matches required to establish a template depended on the type of data. For the badminton men's singles player analysed descriptive match data templates were achieved in three to seven matches depending on the limits of error used.

Hughes Evans and Wells (2001) suggested a practical way of examining whether a true performance profile has reached stable means, calculations of percentage variance from the 'end mean' were determined and then plotted appropriately.

Percentage difference calculations were used to evaluate the reliability of system, for intra- and inter-operator observations, producing similar graphs to the Bland and Altman (1989).

% difference = (No. of differing observations / Total no. of observations) x 100

Frequency data, from squash and badminton, were normalised to allow for true comparison of data from matches and games of differing lengths.

Normalised Match Frequency = (Match frequency / No. of rallies in match) x 100

Normalised Game Frequency = (Game frequency / No. of rallies in game) x 50

The cumulative means of each variable were examined over a series of matches/games. At the first point, the number of matches, 'N(E)', where the cumulative mean consistently lay within set 'limits of error' was recorded as the establishment of a normative template of play. These limits of error are a percentage deviation (+/- 1%; +/- 5%; +/- 10%) of the overall data mean about the overall mean.

Let

n = the variable 'number of matches'

g = the variable ' number of games'

N(E) = value of n to reach limits of error

N(T) = total number of matches

Cumulative mean = (Sum of the frequencies of 'n') / n

Limits of error (10%) = Mean N(T) ± (Mean N(T) x 0.1)

Limits of error (5%) = Mean N(T) ± (Mean N(T) x 0.05)

Limits of error (1%) = Mean N(T) ± (Mean N(T) x 0.01)

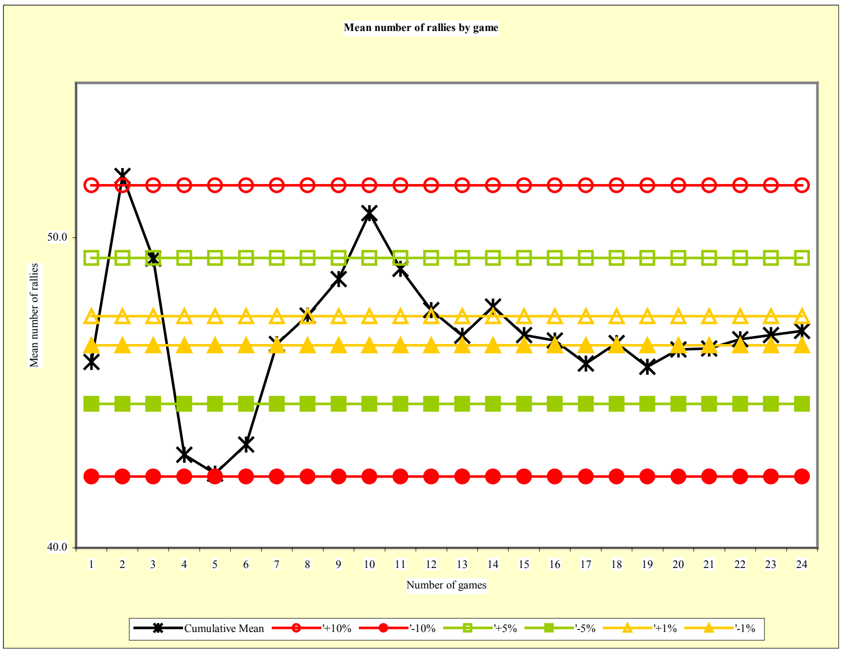

Fig. 3. Example of the % difference plots.

For the working performance analyst the results provide an estimate of the minimum number of matches to profile an opponent's rally-end play. Whilst the results may be limited to badminton, men's singles and the individual, the methodology of using graphical plots of cumulative means in attempting to establish templates of performance has been served. From this study (Hughes et al., 2001) the following conclusions were made:

- This method clearly demonstrated that those studies assuming that 4, 6 or 8 matches or performances were enough for a normative profile, without resorting to this sort of test, are clearly subject to possible flaws. The number of matches required for a normal profile of a subject population to be reached is dependent upon the nature of the data and, in particular, the nature of the performers.
- The number of matches required to establish a profile of elite women's movement was dependent on

the nature of the data. For elite women, profiles were achieved within three to nine matches (under 10% error) depending on the variables being analysed.

- The main problem associated with any primary study aiming at establishing previously unrecorded 'normal' profiles remains reliability and accuracy. Any future studies that proclaim data as a performance profile should provide supportive evidence that the variable means are stabilising. A percentage error plot showing the mean variation as each match/player is analysed is one such technique. This can be adapted to different sports when analysing profiles/templates of performance.

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Confidence intervals

The procedure outlined above is expensive in terms of time when collecting data for the first time and is limited in its applicability in many cases due to fluctuations in factors such as team changes, maturation and the fact that some performances never stabilise. James et al. (2004) suggested an alternative approach whereby the specific estimates of population means are calculated from the sample data through confidence limits (CL's). CL's represent upper and lower values between which the true (population) mean is likely to fall based on the observed values collected. Calculated CL's naturally change as more data is collected, typically resulting in the confidence interval (upper CL minus lower CL) decreasing. Confidence intervals (CI's) were therefore suggested to be more appropriate as performance guides compared to using mean values. Using a fixed value appears to be too constrained due to potential confounding variables that typically affect performance, making prescriptive targets untenable.

From a theoretical perspective, James et al. argued that the use of CI's can also add significance to the judgement of the predictive potential of a data set, i.e. whether enough data has been collected to allow a reasonable estimation. For their investigation a criterion was formulated to test the rate of change of the CI for stability. Initially 95% CI's were calculated for each performance indicator as soon as enough match data had been collected (N = 2) and each time more data was added the new CI was calculated. This meant that CI's could be constructed for each performance indicator after 2, 3 and…. *N* matches respectively. Behavioural frequencies fell outside the 95% CI more often for small data sets and less often as the data set increased. However, this was inevitable as any measure related to the mean of a data set becomes progressively more resistant to change as the data set increases.

The data in table 2 are an example of this type of presentation, it is a very useful way of assessing the stability of an analysts' data. I feel that the more this method is used then the more easily will analysts be able to interpret the CI's in relation to the experimental goals of their research or consultancy work.

O'Donoghue (2005) proposed an alternative technique that represents not only the typical performance of a team or individual but also the spread of performances. The technique also relates the set of performance indicators for a team or individual to normative data for a relevant population of teams or individuals. This provides a useful means of interpreting sports performance data. Grand Slam singles tennis is used as an example of the application of the proposed technique for determining a normative profile of a team's or individual's performance. It is recognised that the mean value for each performance indicator within the typical performance is critically important information that should be supported by, rather than replaced by, percentile bandings.

The aims of the Hughes et al. (2006a) study were to identify what causes perturbations in squash and attempt to create performance profiles of three elite male players using perturbations, comparing these profiles with the more traditional profiling methods based on total patterns of play. A perturbation exists where the usual stable rhythm of play is disturbed by extreme elements of high or low skill. In squash, tennis or badminton a particularly weak or strong shot forces a disturbance in the rhythm of the rally, placing one player at a recognised disadvantage to the other, perhaps in a displaced court location. When perturbations cause the rally outcome this is termed a critical incident. Not all perturbations lead to critical incidents, one player may be under severe pressure, which may be revealed by a good defensive shot, or very quick movement to re establish the original rhythm of the rally. Here the perturbation has caused a transitional period of instability before the system returns to its pre existing state.

Table 2. Mean profiles and 95% confidence limits for the positional clusters of prop, hooker and lock.

	Prop (*n* = 3)***			Hooker (*n* = 1)			Lock (*n* = 4)**		
	Mean	+CL	-CL	Mean	+CL	-CL	Mean	+CL	-CL
Successful Tackles	4.01	4.96	3.06	4.25	5.59	2.91	5.73	6.81	4.64
Unsuccessful Tackles	0.73	1.12	0.33	0.51	1.01	0	0.76	1.15	0.37
Successful Carries	4.25	5.32	3.18	3.51	5.37	1.66	2.20	2.81	1.60
Unsuccessful Carries	0.23	0.44	0.01	0.40	0.80	0	0.03	0.08	0
Successful Passes	1.76	2.46	1.06	0.87	1.68	0.06	1.23	1.76	0.69
Unsuccessful Passes	0.47	0.98	0	0	0	0	0.20	0.33	0.07
Handling Errors	0.33	0.56	0.09	0.27	0.69	0	0.68	0.94	0.41
Normal Penalties	0.68	0.97	0.39	0.40	0.79	0	1.12	1.47	0.77
Yellow Cards	0.05	0.11	0	0.08	0.24	0	0.09	0.20	0
Tries Scored	0.02	0.07	0	0.10	0.31	0	0	0	0
Successful Throw-ins	-	-	-	9.76	11.85	7.66	-	-	-
Unsuccessful Throw-ins	-	-	-	2.94	4.09	1.79	-	-	-
Successful Lineout Takes	-	-	-	-	-	-	4.05	4.83	3.28
Unsucc. Lineout Takes	-	-	-	-	-	-	0.43	0.71	0.15
Successful Restart Takes	-	-	-	-	-	-	0.65	0.91	0.39
Unsucc. Restart Takes	-	-	-	-	-	-	0.59	0.90	0.27

*$p < .05$ **$p < .01$ *** $p < .001$

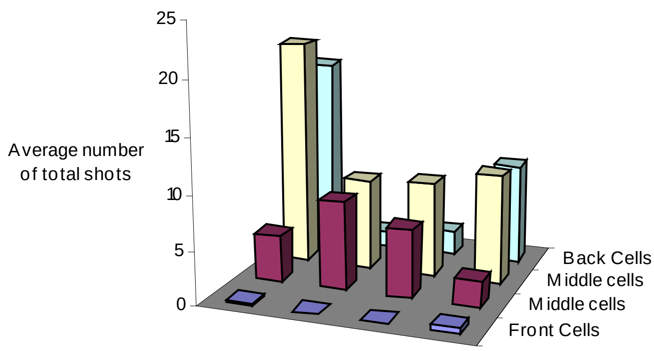

Fig. 4. Position cell from where players are most likely to play perturbations.

Matches were analysed, with a specifically designed hand notation system, on DVD through a laptop, in order to facilitate the use of pause and rewind on the DVD player. This ensured all relevant details were gathered accurately and reduced the amount of errors to a minimum. Once the data were gathered, they were compared to England Squash SWEAT (simple winner error analysis technique) data (Murray and Hughes, 2001).

A percentage difference calculation was used to perform an intra-operator reliability test, overall the highest errors were 5.8% which were deemed acceptable, given the subjective nature of the data. The data produced by the system agree with Mc Garry and Franks (1995) in that perturbations do exist in squash and can be reliably identified. From the results it was shown that drop (34.7), volley drop (18.3) and boast (20.7) are the three main shots that cause perturbations in a squash match. The profiles produced by the perturbations were different to those traditionally used, and accentuated the strengths and weaknesses of the respective players.

Recent research (Hughes et al., 2003), now suggests that, contrary to previous ideas that if an action had a high frequency of occurrences within performances, then relatively fewer matches would be required to obtain a normative profile of this action. For example sides in a typical soccer match will often make 450 passes in a match, whereas they will make about 30 shots on average. Intuitively, one could be forgiven for thinking that an analyst analysing shooting will require more matches to acquire a stable profile than when analysing passing. This is not the case, Hughes et al. demonstrated that shooting stabilises after 4 matches whilst passing was still not stable after 16 matches. They suggest that it is the variance from match to match, not the size of the mean, of these performance indicator data that will determine how many matches are required to reach stability.

These recent research papers demonstrate that this is an interesting area of performance analysis that is being extended all the time. Further research in performance analysis needs to address the problems specific to these particular types of non-parametric data, utilising more advanced techniques such as time series, where appropriate, and perhaps could investigate statistical methods based on the respective variances to predict the number of matches required, thus replacing these empirical techniques.

5. Reliability

It is vital that any data gathering system used within research has been proven to be reliable and in a manner that is compatible with the intended analyses of the data. The data gathered must be tested in the same way and to the same depth in which it will be processed in the subsequent analyses (Hughes, Cooper & Nevill, 2002). The most popular statistical method used over the years to confirm reliability has been correlation. However Bland and Altman (1986) highlighted the need to perform other statistical tests in conjunction with correlation to prove reliability. In a review of 72 notational analysis papers, Hughes, Cooper and Nevill (2002) found that 70% of the studies failed to report any sort of reliability study and of the remaining 30% their methodology was dubious.

Hughes, Cooper and Nevill (2002) researched into analysis procedures for non-parametric data gathered from notational analysis. Two trained notational analysts notated one game and the differences between the two sets of data were compared. In light of the results, they suggested the following conditions should apply to researchers considering reliability studies:

- The reliability test should be examined to the same depth of analysis as the subsequent data processing, rather than being performed on just some of the summary data.
- Careful definition of the variables involved in the percentage calculation is necessary to avoid confusion in the mind of the reader, and also to prevent any compromise of the reliability study.
- It is recommended that a calculation based upon

$$(\Sigma\ (\text{mod}[V1\text{-}V2])/\ V\text{mean})*100\%,$$

(where V1 and V2 are variables, Vmean their mean, mod is short for modulus and Σ means sum of), is used to calculate percentage error for each variable involved in the observation system, and these are plotted against each variable, and each operator. This will give a powerful and immediate visual image of the reliability tests, this should be used in conjunction with the appropriate non-parametric statistical tests so that a clear picture of the absolute difference between the two means, and the respective variance about the means, is obtained. Hughes et al., (2002) went on to demonstrate how insensitive the non-parametric tests of comparison, such as chi-square, Mann-Whitney and Kruskal-Wallis, are to differences between sets of data – no significant difference between sets of data more than 25% apart. They pointed out that this creates difficulties for analysts, and researchers, working with sets of data taken from elite performances, where the differences between winning and losing are as small as 1 or 2 percent. At elite levels of sport, differences as large as 10% between winning and losing performances are rare, so perhaps we need to be defining different types of testing with these sorts of data sets?

6. Current Areas of Research and Support

Most of the support that is currently being offered to England Squash is based upon the work of Murray and Hughes (2001). During their research they offered England Squash various types of feedback from information gathered using the SWEAT and the full analyses systems. Analyses ranging from simple winner and error ratios to complex rally ending patterns were produced from the computerised systems. Using the full analysis system (Brown & Hughes, 1995) they analysed five matches of a particular player and pooled the data from these five matches into a single database. From these data the system is able to produce up to

300 different distribution graphs from the different combinations of shots and positions. This is of course far too much information for coaches and players to use. So Murray and Hughes (2001), using feedback from coaches and players and their years of experience, condensed the information into bullet points that were used as a storyboard to accompany an edited video of the player. After further feedback the information was normalised, converted into percentages and condensed further onto a representation of the court. The representation of the court was divided into 16 sections (in the same manner as the SWEAT system, Hughes & Robertson, 1995) with the areas of the court containing unusual data analysed with respect to shot type. These profiles could be created for winners, errors, and N-1 and N-2 for winners and errors. The profiles were presented at a national squad and the players were very receptive of the style and content of the feedback.

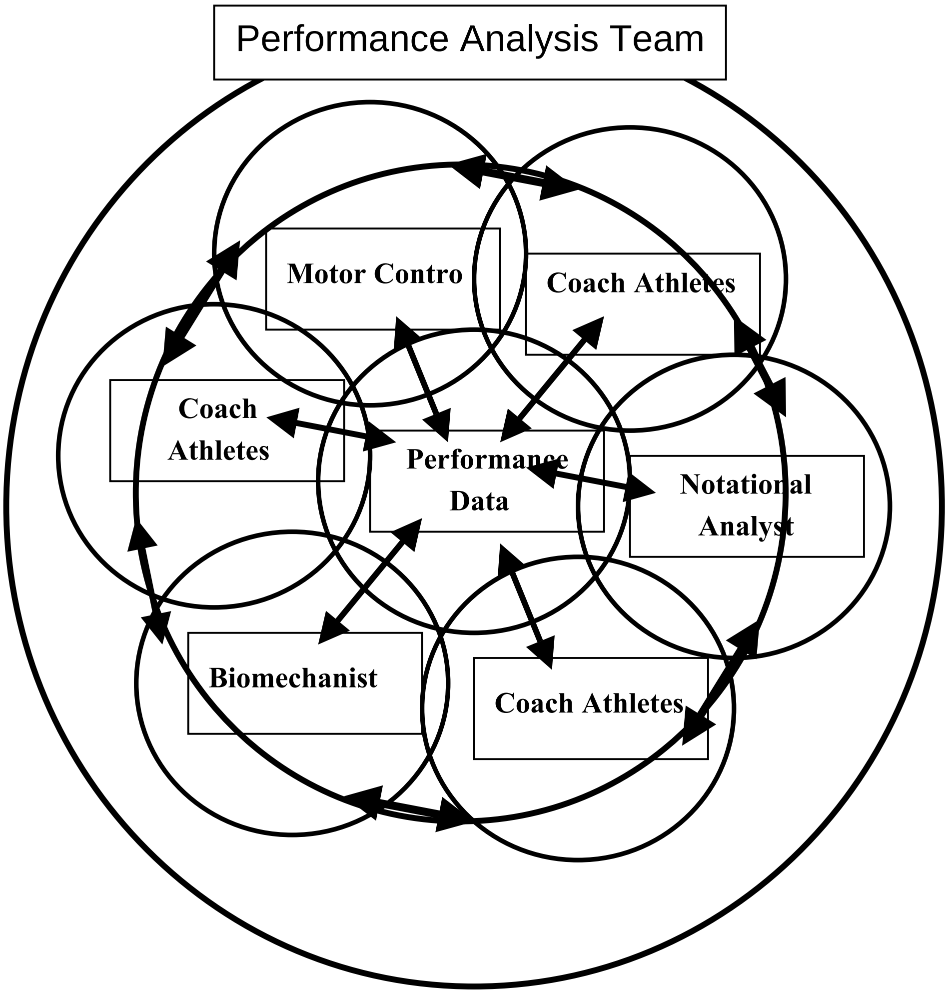

Fig. 5. A digital systems approach to the data sharing that the interactive commercial systems have enabled for performance analysts working with coaches and athletes (apologies to Popper).

The paper by Murray and Hughes (2001) was also the first to introduce the concept of momentum analysis. From the SWEAT analysis they already had all of the information concerning winners and errors during a particular match. By writing a new program they were able to give players a running score (momentum) during a match depending on the rally ending shots. A winning shot by a player was given a '+1' score, an error a '-1' score, and if the opponent hit the rally end shot, or it was a let, the score stayed the same. From this information line graphs could be drawn to visually show any swings in momentum during a match. These lines graphs can also be coupled with data regarding rally length to highlight whether any swings in momentum are perhaps fitness related. This work was born from conversations with the SRA psychologist who was interested to see whether extremes of body language had any effect on the outcome of the next 3 or 4 rallies. By matching up positive or negative forms of body language on tape with points on the graph the psychologist was then able to see how these physical outbursts affected the momentum of the players.

Analysis Guideline: Proposal

Preparation	**Performance Profiling** the starting point for tracking performance	Identify with the coach the areas of strength and areas for development for the player/pairs. This is information that the coaches will have already; it's just a case of making it accessible to me. This is set up using the performance profiling sheets distributed to the coaches. The results are then collated and put in an excel spread sheet format where any changes can be monitored and updated. Do the coach and player agree on strengths and weaknesses?

↓

Technical Analysis in Training & rehabilitation	Dartfish	Use of the Dartfish software to review technical aspect of training for player's personal development goals. This is set up courtside during training sessions. The players and coaches have access to review the technique as they progress through the session. Visual reinforcement assists the coach when giving feedback to the players, reduces the degree of discrepancy. This is available to the coaches and players whenever requested.	↔	Does any of the info here need to be fed back to the Physio/S&C?

↕

Links can be made between technical & tactical analysis

Match Analysis	★Focus X2 ★Notation Sheets ★Match reports ★Stats	**Monitors if the areas identified for development are improving in matches after training.** Templates can be individually designed so that the information being drawn out is specific to the player/pair being analysed. Every bit of information is not always a productive use of time. Files can be created and data can be produced for performances against specific pairs. This information can also be fed into opponent analysis.

↓

Review & Feedback	★CD's / DVD's ★Review sessions with the coach	Relevant information and clips will be passed back to the player on a CD or DVD format depending on the size of the file. It is also possible to compress the data and send the information via email. Coach input is required to feedback to the player and me about which information to save for reviewing. From the analysis of the match, questions should be raised; Why did the player lose a certain match? What do they think, and do the results relate to this? Does the coach agree? Is it something that they have been working on in training? Should this aspect of training be included in the coaching plan? Can they use the strengths from this game in their next game? And so on…..

Fig 6. Analysis guideline proposals for the BA of E players and coaches (Behan, 2006).

The research into momentum analysis was furthered by Fenwick et al., (2006) who analysed matches of elite squash players (N=8 per player; 6 male and 6 female, all in top 40 in the world) to examine the length of the 'peaks' and 'troughs' of momentum in a match. Inevitably large variations were found within each player's set of data, but all of these characteristics of the profiles stabilised to within 10% of their respective means within 6 of the 8 matches, for all the players. The data from each match were summated and the average positive and negative increases in momentum were calculated. A Xi^2 analysis was used to test for inter-player differences and it was found that there were significant differences between patterns of peaks, peak lengths, troughs and trough lengths ($P < 0.05$). Also both the male and female, world #1 players had positive averages much higher than their peers.

Currently, the practical applications of these researches are being used with England Squash. Prior to the World Team Championships in November 2003 the England team were provided with player profiles of all possible future opposition, based on Hughes and Murray (2001). The only difference being that the profiles were created using the SWEAT analysis systems, rather than the full analysis system, due to time constraints and the large number of profiles that needed to be created. Compact discs containing edited video material of the unusual aspects of the relevant player profiles were provided to the players. They were created using the sports analysis package 'Focus'. Also English players competing in the World Individual

Championships in December 2003 were provided with SWEAT analyses of their previous encounters with likely opponents and the respective momentum analyses of these matches. This process was performed relatively quickly due to the large database of matches at the English Institute of Sport. The impressive use, and further recent developments, in feedback both for competition and training and coaching were presented by Murray and Hughes (2006) - an applied demonstration of the strengths and uses of the Focus, Quintic, Dartfish and SiliconCoach software, together with digital video, high-speed video and the best available VDU's for feedback. This 'digital' approach is represented schematically in Figure 5, and also exemplified by current approaches in badminton (See Figures 6 and 7).

7. Future Research

Momentum analysis is a new way of extending performance analysis and the significance of it is not yet fully understood. It does seem apparent however that the results of the analysis combined with the work of sport psychologists can be of great benefit to players in their attempts to maintain focus during matchplay. Further research needs to be carried out as to why the peaks of the top players in the world are longer and steeper than those of the lesser players.

The research being conducted by Perl (2001) into neural networking and fuzzy logic has huge potential for modelling purposes. If models for elite racket sports players can be created, using the theories that he is applying to other aspects of sports science, this could have huge potential for analysts and coaches. The ideal would be to have models created via neural networking that could be used to predict future performance of players taking into account factors such as fatigue, temperature, crowd support etc… These types of applications of fuzzy logic, together with artificial intelligence shells should make ideal models for analysing the coaching process – a 'nettle' few coaching science experts have grasped so far.

To further racket sports analysis perhaps there is something that can be learned from the analyses taking place in soccer and rugby union. Currently there is software being used in these sports called ProZone, with which the movement of the ball and all the players on the pitch is recorded using a number of cameras placed around the grounds. Many elite soccer and rugby professional teams are beginning to make use of these complex systems. Perhaps there is some scope for using this software in racket sports for monitoring movement patterns, distances travelled, velocities and movement with respect to the ball. Vukovic (2003) is currently conducting some research into monitoring movement in squash using an overhead camera. From this video material, velocities and accelerations of players can be calculated.

This work with overhead cameras also has some applications with regard to the research of perturbations in squash. It may well create a methodology that can enable accurate identification of perturbations in a squash rally. Further considerations on this new line of inquiry for sports contests as dynamical systems are detailed in McGarry, Anderson, Wallace, Hughes and Franks (2002). However attempts have been made to identify perturbations quantitatively via measurement of velocities. It has been shown that sudden increases in velocity i.e. large accelerations by the reliably denotes a perturbation. Measuring velocities from the traditional view from behind the court can prove quite time consuming due to the angle of the view. Vukovic (2003) however has designed a program that can automatically calculate all velocities of the players as long as the footage is taken from overhead. Such a system would make identification of perturbations far less ambiguous. This could then lead to the detection of how certain players create perturbations in the game and the tactics they use to induce a rally ending shot. Identification of critical incidents is not just about analysing these most important sets of data, by analysing these perturbations the size of the task of interpreting a performance is reduced by an order of magnitude, i.e. instead of examining 1000's of bits of data it is reduced to 100's of bits. This makes the analyst's task easier.

Squash is potentially an ideal sport for analysing perturbations, and as such has received considerable attention from researchers. It is of a very intense nature and is confined to a small space. The rhythms of the game are easy to see, and the rallies are of a length (mean number of shots at elite level = 14 (Hughes and Robertson, 1997)) that enables these rhythms and their disruption i.e. perturbations and critical incidents, to be more easily identified than other sports. But the other racket sports, although having shorter rally lengths, would also benefit from this approach and it is clear that this development is needed.

The amount of research that has been performed in racket sports means that it is the leading sports area in terms of the level of application of performance and notational analysis. Perhaps rugby can match racket sports in terms of development of its technology, but the work being conducted with the England rugby team is not in the public domain. With regards to published work no other sport has the same depth and width of profiling that racket sports boast. The insight offered by this individual profiling is quite unique. The current male and female England badminton teams receive very complex and thorough performance analysis support including, player profiles on themselves and future opponents, in-event analyses, and full match (every action) post-event analysis on previous matches, edited CD's of technical strengths or faults, motivational DVD's, and very advanced technical analyses using high-speed camera feedback (see Figure 2). This symbiotic relationship between these coaches and performance analysts has only come about however because of the receptiveness and the open minded approach of the coaches and the players.

This excellent relationship can still be built upon and improved. There are still many areas regarding momentum theory and perturbations that need to be explored and explained. Also the work concerning neural networking has enormous potential in terms of modelling the game of racket sports and predicting future results. These are the areas of performance analysis in racket sports that need to be researched in order to take the support offered to the next level.

8. Conclusions

By analysing past and current work in racket sports, it was concluded that notational analysis of sport could be systematically analysed by using the following delimitations, with the ensuing deductions made on the recent research.

8.1. The development of analysis and technology in the analysis of racket sports

The technological developments in notational analysis have inevitably lagged those in the applied computing technology environment. But this gap has decreased over the years as commercial software has become available and video specific computers also came on the market. Current instant communications, via the internet, sophisticated generic analysis systems and video editing software, have enabled teams performing on the other side of the world to be analysed immediately back at home, and receive those analyses and edited videos within hours of finishing their competition.

8.2. Application of feedback in racket sports

Because of several decades of experience, the application of feedback in racket sports can be used as a template that other sports can aspire. The main applied areas of objective feedback were found to be:-

Tactical evaluation
Technical evaluation
Movement analysis
Databases and modelling

By applying any combination of these techniques, it has been shown that these types of enhanced and objective feedback improve performance and increase our understanding of performance. England Rugby has also employed many of these techniques and demonstrated the benefits in winning the Rugby World Cup, 2003.

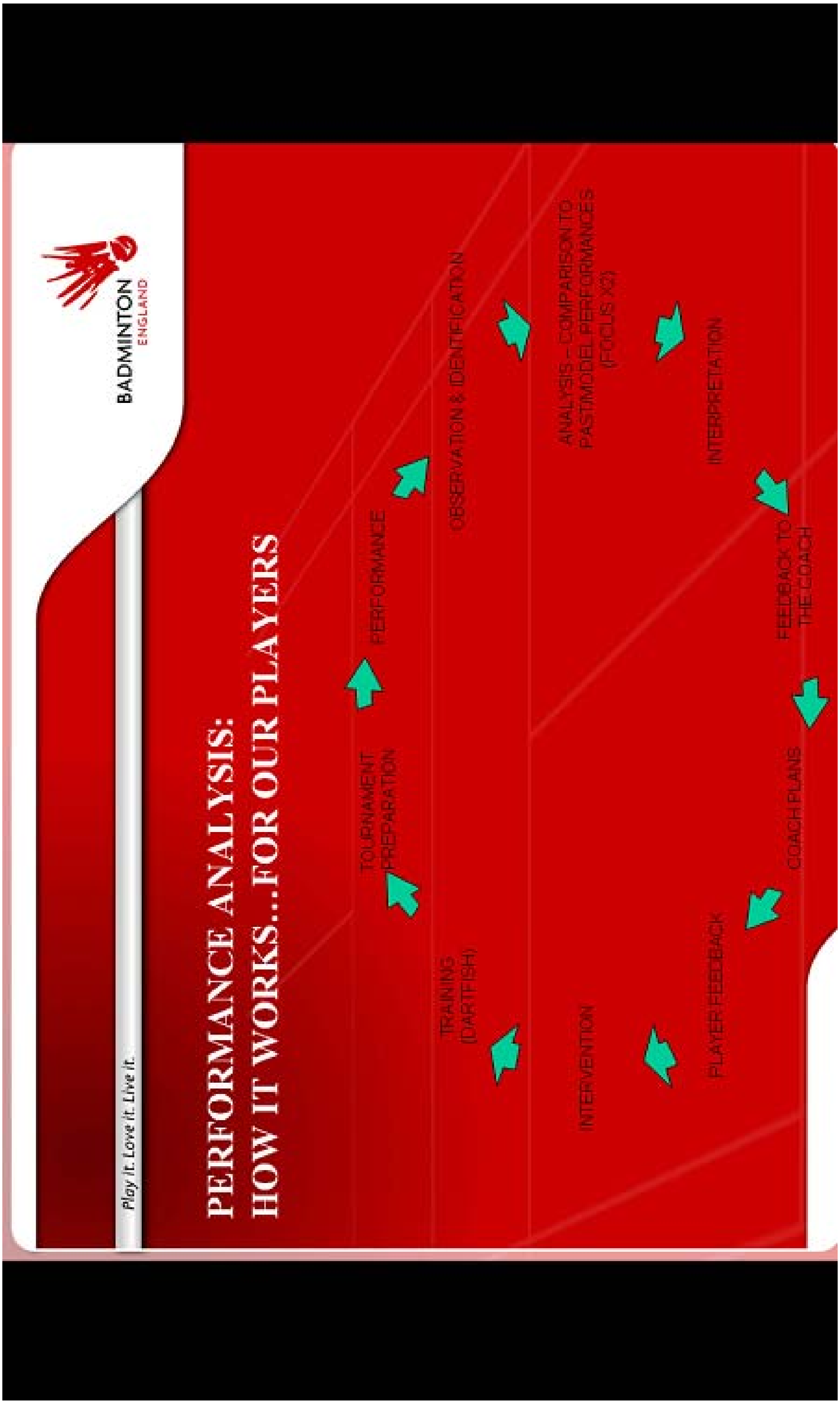

Figure 7. A schematic diagram of the analysis and feedback by the BA of E Performance Analyst (Behan, 2006).

8.3. Performance profiling

Recent applied research has made the definition of profiles much less a matter of guesswork in terms of how accurately a particular profile really represented the way a player or a team performed in general. The use of performance profiling techniques (Hughes, Evans and Wells, 2001); has created a sound empirical method of ensuring the stability of the data profiles. Further, the work of James et al., (2004) have introduced the ideas of using confidence intervals, that enable the use of any number of matches for a profile with some quantitative statement about the quality of the data.

8.4. Reliability

Considerable amounts of recent research have increased knowledge and understanding of the methods of measuring and calculating the reliability of non-parametric data, which are usually the type of data that are gathered and analysed in notational analysis. The statistical methods that we use are improving, but more work needs to be done on making the more sophisticated systems more transparent, in terms of how they relate to the experimental aims of the comparisons, and also the basic practical demand of them being easier to apply.

The sensitivity of the tests needs to be examined – how can we determine the significant differences in performance when the increments of comparison are very small?

8.5. Areas of Research and Support

As the field of notational analysis is becoming more accepted, then we can confidently predict that there will be ongoing research in all these areas defined here. More research in modelling in performance analysis is vital as we extend our knowledge and databases into those exciting areas of prediction. There are also some exciting developments, such as perturbations and momentum, used with current computer developments such as neural networks, that promise exciting possibilities of profiling and even prediction in the near future. Using databases to enable prediction in sport is very difficult, almost impossible, because of the inherent nature of sport. Nevertheless, working towards the extended aims of modelling, and therefore forecasting, must be the most exciting of the ways to further develop performance analysis.

It is clear from these analyses of the on-going research and development work in racket sports, that the working notational analyst must have a broad set of skills and be prepared to maintain and extend those skills just as the research in this area develops the knowledge base.

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