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The evolution of racket sport science—a personal reflection

Introduction

The purpose of this paper is to review and reflect on the developments and directions of racket sport science over the last half century or so. It is not a review in the conventional scientific sense—this would be too large an undertaking—but a personal view, the reflection of a career in sports science and of a contributor to racket sport science.

I divide the evolution of racket sport science into three phases but there are no firm dates which delineate them. The first phase is that in which racket sport science was evident as an interest to scientists, where many important issues were addressed, and where the underpinning methodology and the opportunities offered by technological developments were explored. The second phase is that to which I have had most direct personal experience. From an early career in sport science, through the First World Congress of Science and Racket Sports, to the necessary end point of every career, this phase has witnessed a tremendous growth in racket sport science. The third phase is that of recent years where the International Governing Federations have become actively involved in using and promoting racket sport science. This has influenced the quantity, and in particular the quality, of racket sports science to the extent that it is now possible to support special issues of journals dedicated solely to racket sport science.

The reflection on the evolution of racket sport science presented here is through the eyes of a sport scientist whose main area of interest in the field of biomechanics. I have not restricted this paper to just that field however, as racket sport science is truly multidisciplinary. It does mean though that some of the scientific areas discussed will take a more overarching rather than a detailed view. It also means that there will be an imbalance in the way scientific fields of endeavour are dealt with. Inevitably some of the important fields of study that underpin racket sport science are omitted. Not because of their lack of importance, but due to my lack of knowledge and experience in these fields.

The first phase

The first phase is characterised by the impact that traditional disciplines—such as physics, engineering, physiology, medicine and ergonomics—have had on racket sport science. There is no defining start to this period but by the 1970s one is aware that there are significant papers published in racket sport science by individuals from these disciplines. Typically these individuals have had a keen interest in sport in general, and racket sports in particular. They have applied their academic knowledge, skills and abilities together with their access to advance measuring and analytical equipment to understand racket sport related problems.

A good starting point to illustrate this phase is the particle physicist Howard Brody (1932–2015). He became interested in tennis racket performance as a consequence of a chance exposure to the innovative large-head tennis racket. The Prince Graphite was developed by Howard Head (an aeronautical engineer who made innovative skis, and later innovative tennis rackets). The racket quickly developed a reputation as being easier to play with, particularly for the inexperienced player. Brody applied well-established mechanical principles to investigate numerous issues related to the performance of this racket and published what was the first main stream scientific paper on tennis rackets (Brody, 1979). He discovered that the 'sweet spot' (centre of percussion) of a large-head racket compared to a conventional racket was closer to the centre of power of the racket making it easier and more pleasant to play with. Further, the area of power (the area where the ball will be given maximum rebound velocity) was larger in a large-head racket than a conventional racket. In further research he demonstrated that the larger head racket was less susceptible to twisting (due to a higher polar moment of inertia). He made the counter-intuitive finding that the rebound power was greater when the strings were slack as opposed to tight. His explanation was that while the strings were elastic the ball was not, and so the slacker strings were able to store and return energy to the ball and produce less ball deformation, thus enabling the ball to retain more of its energy for the return. His research continued for many years during which he investigated the influence on tennis racket performance of string material, string thickness, vibrational frequencies, impact shock, and racket size and shape. He also researched tennis ball performance related to surface, spin and flight to name a few of his areas of interest. His research findings were encapsulated in a definitive text book (Brody, 1987).

Craig Sharp (1933–2018) was a veterinary scientist who had an interest in muscle physiology. He was also a keen squash player, occasionally a professional squash coach, and through his love of sport became a convert to sports physiology. He is widely considered to be one of the founding fathers of sports science in the UK. He researched widely in sports, but it is his research into squash that is noteworthy, as much of this was 'applied research' at a time when more fundamental research was in vogue. He outlined the physiological demands of squash in terms of cardiorespiratory fitness, muscle endurance and strength, muscle power and flexibility and proceeded to establish normative data for each of these fitness categories, for male and female players at elite, national and local levels of performance. Sharp was one of the first to investigate physiological parameters during play, providing data on heart rate, body temperature, sweat rate, blood pressure, oxygen consumption and lactic acid levels. He was particularly interested in the types of training that players could use to develop fitness for match-play and together with his research student he investigated ghosting training protocols to induce varying levels of lactic acid accumulation (Hammond, 1984). He found that a 45 s work–45 s rest protocol best replicated match-play and after a 12 week training program his experimental group showed a significant drop in blood lactate compared to a control group. He also noted an individuality in response, with some players showing little effect of training, while others demonstrated a marked improvement. This individual response to training led Sharp to point out that there are other attributes to racket performance than just fitness, including racket skills, movement ability and tactical sense along with a good psychological approach to competition. Consequently, he advised that squash players at national level need individual assessment and training programmes. It is apparent from this brief overview of his work that Sharp was at the forefront of racket sport science. His review (Sharp, 1998) provides a detailed account of the systematic approach he took to the scientific analysis of his sport.

John Whiting (1929–2001) was an early pioneer in motor skills and visual perception applied in a sports context. Like many of his era, he began his career as a physical educationalist but developed an interest in the underlying mechanisms of human performance. His book *Acquiring Ball Skill* (Whiting, 1969) provided a detailed account of the performance and acquisition of ball skills and was essential reading for aspiring physical educationalists at the time. Unlike physics and physiology where the underlying scientific principles had been well developed (although not necessarily applied to racket sports), the underlying scientific theories supporting motor skills was (and still is) a matter of debate. Whiting can be credited with bringing the work of traditional motor control scientists such as Bernstein (1967), Adams (1971) and Schmidt (1975) to the attention of sports scientists. He was an excellent squash player himself and he is known for the phrase 'keep your eye on the ball' (Savelsbergh & Davids, 2002). This practical phrase was supported by his research into catching where it was found that viewing the ball too early or too late in its trajectory led to decreased performance. This finding drew attention to the importance of the periods for which the ball is seen and not seen and is applicable to sports involving interception, particularly racket sports. Racket sports provided Whiting with a vehicle for investigating the processes of perception and action involved in the performance of interceptive actions. One of his early investigations led to the 'operational timing hypothesis' (Tyldesley & Whiting, 1975). The hypothesis postulated that high levels of consistency in ball impact demonstrated by expert table tennis players meant that they only need to attend to the input and decision making component of performance rather than the production of the stroke as a beginner would need to do. The moment of interception of a ball with bat requires prior muscular initiation of the stroke to occur through a 'motor program'. The 'operational timing' hypothesis postulated that the expert, through practise, would have developed a consistent motor program such that the processing demands on the performer were reduced to that of 'input timing' only. The idea of consistency of performance fitted neatly into the prevailing theories of motor programming at the time (Adams, 1971; Schmidt, 1975) although more contemporary views promote the variability associated with such movements within the context of dynamical systems theory (Williams, Davids, & Williams, 1999).

These three pioneers of racket sport science were not alone in developing a foundation for racket sport science. They are typical of scientists who 'broke the mould' by moving from their original field of training to develop ideas and applications to racket sports that have been influential. They are scientists who have influenced me.

The second phase

The second phase is characterised by the application of scientific principles to racket sports from within a sports context. The typical researcher would be an individual who could be characterised as a sport scientist, trained in a scientific discipline and be mostly or wholly concerned with the application of their scientific expertise to sports in general, and racket sports in particular.

This phase saw an increased opportunity to publish racket sport research through conference participation. Interest was developing in conferences which had a sport, as opposed to a discipline, focus. The World Commission of Science and Sports (WCSS) was created in the early 1980s as an umbrella organisation whose underlying philosophy was to create a bridge between the science of sport and its practice. The broad aim was to bring together, by means of a Congress, scientists whose research interests lay in specific sports and the practitioners in those sports who were interested in obtaining current scientific information. A further aim was to ensure that the scientific findings presented at each Congress were made widely available and easily disseminated to both scientists and practitioners. In the following decade successful World Congresses were organised on a four year cycle in swimming, football, golf, cycling, and winter sports. Eventually, it was recognised that

Table 1 Location of World Congresses of Science and Racket Sports with the number of papers published in each Congress proceedings

Congress	Date	Location	Published papers
1	1993	Liverpool, UK	44
2	1997	Lillishall, UK	40
3	2003	Paris, France	44
4	2006	Madrid Spain	42
5	2015	Suzhou, China	31
6	2018	Bangkok, Thailand	23

racket sports should also be represented and so the First World Congress of Science and Racket Sports was organised and held in Liverpool in the summer of 1993 (Reilly, Hughes, & Lees, 1995).

The series of World Congresses in Science and Racket Sports and their subsequent published proceedings (Reilley et al., 1995; Lees, Maynard, Hughes, & Reilly, 1998; Lees, Kahn, & Maynard, 2004; Lees, Carbello, & Torres, 2009; Kondrič, Zhang, & Xiao, 2017; Kondrič & Cabello-Manrique, 2019) provides an historical record of the research in racket sport science (**Table 1**). An analysis of the domicile of principle authors, the sport focus of published papers, the popularity scientific topics, and the themes evident in well-supported topics have been recently outlined (Lees, 2019). In brief, it was shown that with regard to the principle authors of a paper, a greater number were domiciled in Europe followed by Asia, researched tennis followed by table tennis and would study physiology followed by notation analysis. Also noted was the domicile, racket sport and fields of study which were poorly represented.

This is also the phase in which areas of racket sports research opened up due to the availability of computers and software. Notational analysis was a laborious and unloved manual task but the field was transformed with the computerization of data collection and analysis. A similar effect was noted in biomechanics with specialized data processing software becoming commercially available. Physiology benefitted from the miniaturisation and transportability of equipment.

Developments in computerised notation analysis

Computerised notational analysis, also known as match analysis, has become an important area for racket sport research and practice as a result of the technological innovations in image recording and computer applications. Knowledge of how players play their game has always been of interest but obtaining this information was a time-consuming process. A rare example of the recording of the duration of rallies and the work–rest ratios in squash has already been mentioned (Sharp, 1998). This, and the earliest report of match analysis in racket sports by Sanderson and Way (1977), used a hand notation system based on symbols that could be recorded during a match. The limit to the application of this system was the amount of information that could be transcribed in real time, and the time-consuming nature of the subsequent analysis. The advent of desktop computing enabled data analysis to be undertaken more quickly and results to be presented to coaches and players in a user friendly way. The field was also enhanced by the availability of video recordings which enabled matches to be viewed repeatedly and in slow motion. Further, video recordings of world tournaments could be made widely available which meant that research on top players during major international championships was possible for the first time. The field was further enhanced by the availability of touch sensitive pads for data input and the integration of video and computer technology, both of which made data input easier and more replicable. The field has continued to develop technologically and currently attempts are being made to automate the entire data collection and analysis process (Lara, Vieira, Misuta, Felipe Arruda Moura, & Leite de Barros, 2018).

The developments in hardware and software took place at the same time as the underpinning rationale for notation analysis. Hughes (1995, 1998) described the purposes of computerised notation analysis as (1) analysis of movement, (2) tactical evaluation, (3) technical evaluation, (4) statistical compilation and (5) educational use for coaches and players', and its applications as (1) the provision of feedback, (2) the development of databases, (3) the identification of areas requiring improvement and (4) player evaluation. The theoretical and practical context in which computerised notation analysis sits is excellently documented in Hughes and Franks (2004).

The barriers for entry into computerised match analysis are not high, and as a result there have been a large number of research groups who have reported their findings in the literature. The papers from the World Congresses of Racket Sports and the International Journal of Performance Analysis, for example, have yielded a typical cross section of applications. Those that have proved most useful have addressed specific issues where a comparison of performance at a given moment in time is of interest. This has been demonstrated in studies that have compared, for example, the effect of changing scoring systems in squash (Hughes & Knight, 1995), badminton (Petrinovic-Zekan, Pedisic, Ciliga, & Kondrič, 2009) and table tennis (Zhang & Hohmann, 2004); the effect of surfaces on game characteristics (O'Donoghue & Ingram, 2001); the effect ball and racket characteristics (Bo & Xianghai, 2017); and the differences between genders (O'Donoghue & Liddle, 1998).

Many more research papers have been published. While each study in itself has value and contributes to the wealth of material in this area, the shear vastness of possible topics has meant that cohesion in the field, which might lead to advancement at a conceptual level, is absent. In a rare paper for the field, McGarry (2009) discusses various issues intended to direct future research. In particular he refers to the importance of identifying significant game behaviours—that characteristic of an individual which might be representative of the underlying mechanisms of performance and which may open the door to prediction of future events. To date this approach does not appear to have gathered momentum, although recent papers on this issue in table tennis provide a more contemporary comment (Fuchs et al., 2018; Zhang, Zheng Zhou, & Yang, 2018).

Rather, computerised match analysis has become a popular tool for player feedback. Practical applied match analysis is the short-term analysis of individual matches useful to players, coaches and the media (O'Donoghue, 2004). The availability of computer and video technology, together with low cost but sophisticated software for analysis, has enabled both in-house and commercial analysis services to be provided for training and competition at national level and increasingly at club level as well. There is a growing number of companies providing a bespoke service to individual players. It seems that as computerised notation analysis has grown and matured it is has become a tool whose feedback ability to players has become its most important characteristic.

Developments in biomechanics

The rapid technological developments referred to above have also had a major impact on the field of biomechanics applied to racket sports. The performance of racket skills has always been of interest to physical educators, coaches and biomechanists but the dominant skills of racket sports, the serve and the smash, represent some of the most complex movements that humans perform. Attempting to quantify and understand the mechanisms of performance of these skills and their relationship to the game has been no easy task despite having been the focus of attention for biomechanists for some considerable time.

Early researchers who made an impact in this field were Barbara Gowitzke and David Waddell. Their specific interest was in badminton and, in particular, the power strokes (Gowitzke & Waddell, 1979). They obtained images of power strokes using a 16 mm high speed cine camera operating at up to 400 Hz. Current researchers might be unaware that this equipment was of military grade, and at the time, only available on loan from specialist research laboratories. It was not only expensive to purchase but also expensive to run. A 100 foot role of film might last a few seconds at most in the camera before running out, and would take at least the first half of the recording for the camera to build up to its maximum speed. Much of the recording was of little use for quantitative analysis. Nevertheless, images from these recordings were of very high visual quality and enabled a qualitative analysis of the movement to be undertaken. The authors were able to confirm that the power stroke was performed by medially rotating the upper arm and pronating the forearm. These two movements, essential to the power shot, had been suggested by earlier researchers (see Waddell & Gowitzke, 2000, for a review) but it was their research that firmly established these movements as essential to the power shot.

The quantitative analysis of sports skills represents the main focus of biomechanical studies and with an increasing availability of cine cameras (albeit operating at a more manageable speed of 50–100 Hz) this method was soon applied to racket sports. Two dimensional kinematic descriptions of tennis strokes followed (Elliott, 1995; Lees, 2009) but the kinematics of joint movement were limited to descriptions in one plane of movement only. The development of three dimensional (3D) analysis systems, utilising two cameras with a predetermined calibration frame, enabled researchers to extend their kinematic analyses to define the movement of a joint in three anatomical planes (flexion–extension, abduction–adduction, internal–external rotation). Researchers were now able to provide data to quantify the observations made by Gowitzke and Waddell (1979). The first attempt to do this was reported by van Gheluwe, Ruysscher, and Craenhals (1987) who attached several markers to the wrist, elbow and upper arm and, from the reconstructed 3D location of these markers, were able to quantify the magnitude of rotation of the upper arm and forearm in the tennis serve. Sprigings, Marshall, Elliott, and Jennings (1994) reported a full 3D description of segment rotations including flexion–extension, abduction–adduction and internal–external rotation of the upper arm, lower arm and hand for the tennis serve. Using a similar approach, Tang, Abe, Katoh, and Ae (1995) reported the forearm pronation, wrist flexion–extension and ulnar and radial deviation in the badminton forehand smash. More recently Gordon and Dapena (2006) were able to include the effect of trunk motions into their analysis of the tennis serve in addition to the arm motions as detailed above. All of these studies demonstrated that power strokes in racket sports are produced by the limb rotations as proposed by Gowitzke and Waddell (1979) and have produced valuable data which quantifies this action.

Advances in technology have had a major impact on biomechanical analyses in the last decade. The difficulty of obtaining 3D data based on cine film limits the number of analyses that can be conducted. For this reason the use of opto-electronic systems for automatic data collection have been developed. These are based on the tracking of reflective markers using video technology. Since its introduction in the early 2000s the hardware and software have developed such that multicamera systems operating at up to 400 Hz are now common place in most serious biomechanics laboratories. These systems give rapid, almost immediate, data from a movement enabling a greater number of individuals, trials and conditions to be investigated. A recent report McErlain-Naylor, Miller, King, and Yeadon (2017) used an 18 camera system operating at 400 Hz to investigate the badminton jump smash. They used 25 subjects of national and international level of performance, each performing three trials. Such an analysis would have been impossible only a few years ago.

The methods used by biomechanists to obtain kinematic data on racket skills have advanced such that experimental studies investigating the underpinning mechanisms of performance can now be conducted. It has taken half a century to get to this point and while the methodology is now available to undertake advanced studies, the wider application of the method is still limited by expense and, as markers must be put onto the player, an inability to analyse competitive games. It has continued to be a specialist tool, unlike computerised match analysis which has become more ubiquitous as technological developments have occurred.

Developments in exercise physiology

The scientific principles underpinning physiological performance in exercise have been well established by leaders in the field and by the pioneers of sports physiology. The elements of physical fitness (see for example Sharp, 1998) are well known and the physiological parameters that reflect fitness such as maximum heart rate, O_2 max and blood lactate concentration during or immediately after play have been routinely reported in the literature. A range of blood and urine metabolites, fluid ingestion and loss, body composition, muscle strength, muscle fibre composition, bone density, as well as detailed characteristics from expired air gas analysis all form a part of the physiological profile of racket players that are of interest to researchers. The technological developments in exercise physiology have revolved around the development of equipment for quicker, more automated analyses, the ability to use smaller fluid samples, particularly finger prick blood samples, and the portability of measurement and analysis equipment for use in the field and for instantaneous measurements of some of the parameters mentioned above.

It has been noted (Lees, 2019) that in racket sport research the physiology of tennis is the topic most frequently reported. It follows that papers in this area will provide a rich source of information and cover all aspects of the game and investigative approaches. For example, metabolic characteristics of male singles tennis players have been reported for players at national (Zieman & Garsztka, 2009), state (Christmass, Richmond, Cable, & Hartmann, 1995), and club levels (Reilly & Palmer, 1995), for young players (Girard & Millet, 2004) as well as seniors (Ferrauti, Weber, Struder, Predel, & Rost, 1998), and for disabled players (Huang, Lin, Kuo, & Huang, 2017). Researchers have examined many other physiological issues and the range of research in tennis, and increasingly in the other racket sports, is remarkable.

One area of the physiology in racket sports that has recently emerged is the efficacy of field tests for monitoring players and identifying talent. While laboratory tests have been the foundation of physiological testing in most sports, recent research has questioned their value for racket sports. This is because game-specific technical skills are predominant factors in racket sports and their relationship with physical performance factors is complex. In athletics, the relationship between say, oxygen consumption and endurance running, is clearly expressed by a laboratory test. The same is true of a laboratory test on anaerobic power (e.g. Wingate test) and sprint performance. For racket sport performance the same is not true due to the complex combination of fitness and performance skills required. In order to overcome this difficulty, field tests for racket sports have developed and have become particularly popular. Fernandez-Fernandez, Ulbricht, and Ferrauti (2014) have recently reviewed laboratory and field tests for a range of fitness measures in tennis (aerobic endurance, anaerobic endurance, strength and power, and speed and agility). They concluded that a regular test battery performed at different periods of the year has the value of allowing an individual's performance profile to be obtained which can then be used for regular monitoring of performance and for prescribing individual training interventions on an ongoing basis. This would lead to a more efficient design of physical training programmes, saving time for more tennis-specific training.

An understanding of the physiological demands and the physical fitness requirements of a racket sport is important for knowing how players might perform and compete more effectively. It is interesting to note that field testing, often considered to be a low-cost alternative for monitoring players fitness levels has, in racket sports, shown itself to be of rather more value. The complex interaction of fitness and technical skill production hold out the promise that tests involving both elements are likely to be more predictive than traditional physiological tests alone.

The third phase

The third phase is characterised by the incorporation of sports science into the administrative world of racket sports as represented by the International Governing Federations (IGFs). The typical researcher would be a sport scientist, who would have a close association with the national and/or international governing body of their particular racket sport. They would likely contribute the sports coach education programme, be undertaking research on players at a high level facilitated by the national or international governing body, be contributing both scientific research papers and high level coaching articles and possibly be in receipt of a grant from their respective Federation.

The IGFs of racket sports have progressively introduced a sports science dimension into their operation across several fronts. This is typically controlled by a Sport Science and Medical Committee. As well as their main function (to advise the parent committee on issues relating to science and medicine) their proactive initiatives have ranged from encouraging research relevant to coaching programmes, organising conferences, producing in house scientific publications, offering research grants, commissioning research and in some cases supporting a dedicated research laboratory.

IGFs, seeking racket sport specific knowledge to assist coaches and players, have encouraged researchers to participate in their Coaches' Conferences. For example, Waddell and Gowitzke (1977) reported their research findings regarding the biomechanics of badminton power strokes at the First International Badminton Coaching Conference held in conjunction with the World Badminton Championships in Malmo, Sweden in 1977. The International Tennis Federation (ITF) organised their first Worldwide Coaches Workshop in 1979.

Table 2 The number of papers addressing topics addressed in the ITF's Coaching and Sports Science Review after 50 issues as given by Crespo and Over (2010)

TOPIC	*N*
Psychology	75
Coaching, training & teaching	60
Physical conditioning	59
Mini-tennis, play & stay	51
Planning, periodisation and talent ID	46
Technique and biomechanics	46
Coach development	40
Tactics	36
Medicine and nutrition	34
Miscellaneous	19

IGFs have subsequently found advantage in organising their own scientific conferences. The International Table Tennis Federation (ITTF) began their series of biannual sports science conferences in 1989, with their congress in 2019 representing the 16th in that series. The ITF followed suit in 2000 with their first conference (Haake & Coe, 2000), and the 2nd and 3rd conferences in the series were held in 2003 and 2007, respectively. In some cases IGF conferences have run in tandem with other racket sports conferences in order to take advantage of organisational and administrative efficiency. An example of this is the 3rd World Congress of Science and Racket Sports and the 8th International Table Tennis Federation Sports Science Congress which ran jointly in 2003 (Lees et al., 2004). This was followed by a similar combination in 2015 (Kondrič et al., 2017). In both cases the conference was associated with a Table Tennis World Championship. Scheduling scientific congresses with World Championships has proved a useful way to provide coaches with exposure to high level scientific research, and for researchers to interact with high level coaches.

The IGFs have produced racket sport specific scientific publications. For example, the ITF introduced their Coaching and Sports Science Review in 1993 and have produced 3 issues a year since. In a review of progress after 50 issues, Crespo and Over (2010) reported a total of 506 articles classified into several topics. These topics and their rank order (Table 2) are a clear indication of the areas of interest to tennis coaches and researchers. The Sport Science and Medical Committee of the ITTF have recently produced a special issue of the *Journal of Sports Sciences* dedicated to table tennis (Faber & Lames, 2018) containing 17 papers covering the topics of biological sciences, physiology and nutrition, sports medicine and biomechanics, sports performance and social and behavioural sciences performance. These examples represent sustained commitment to research and a willingness to showcase racket sport research at the highest level.

The IGFs also have introduced research sponsorship programmes. Of note is the programme introduced by the Badminton World Federation (BWF) in 2013. The BWF wished to encourage and widen interest and investment in applied research in Badminton, to improve the quality and quantity of scientific material available to coaches and Badminton practitioners and to contribute towards the increased knowledge of performance and safety at the international level for coaches and players. The sponsorship program has continued annually since and has to date completed five years of operation. The monetary value of the research allocation has steadily increased, as has the number of applicants seeking support. Typically grants would support students undertaking MSc or PhD programmes of research and has proved to be an economical way to support high quality research in badminton. An analysis of project topics (Lees, 2019) suggests that the topics have a more 'applied' character to them, as would be expected given the source of funding. It is interesting to see that testing and training topics are popular, and that topics concerned with health and player development are also represented. Both male and female individuals have been studied, their playing abilities range from recreational to elite performers, and their ages from junior to senior. The ITF also have a program for sponsoring primary research and many of the outputs from this program support their in house scientific journal as mentioned above. IGF sponsored research not only encourages research in the specific racket sport, but also helps to build up a critical mass of expertise in that area. It can encourage research to support their initiatives, as in the case of the BWF, whose 'Shuttle Time' project (a schools badminton programme supporting the principle that children should lead a healthy and active life) is a subject of several sponsored research projects.

In special cases an IGF may choose to undertake their own research to remove any actual or perceived manufacturer or researcher bias. It has always been the case that scientific information has been necessary to inform and control the development of equipment. Commercial companies have taken advantage of new materials, technologies, and manufacturing techniques to improve the racket, ball/shuttle, strings/rubbers, footwear, and playing surfaces. Conformity testing is a basic necessity for an IGF but in recent years IGFs have engaged in sport technology to proactively change equipment in order to achieve desired effects on performance, mainly for the purposes of improving the spectator experience. For example, in 1997 the ITF introduced its own Technical Centre with a laboratory and staff whose task was to test and research into all aspects of the game and to provide support to the ITF Technical Commission on decisions relating to technical issues (International Tennis Federation, 2019). In 2003 it installed its own wind tunnel for ball testing, and later an air cannon for the high speed projection of tennis balls required in research investigations (see for example, Haake, Carré, & Goodwill, 2003).

It is also worth noting that some National Federations have sponsored research to further their domestic programs. One excellent example is a testing program introduced by the German Tennis Federation between the years 2009 and 2013. It established a biannual nationwide physical tests for 1052 of the best male and female junior squad players. The data obtained are used for basic talent identification as well as the development of training guidelines, including individualized training programs. The players were tested in March and September each year and were evaluated using a battery of standard anthropometric and physical performance tests (Ulbricht, Fernandez-Fernandez, & Ferrauti, 2013). The tests consisted of measurement of grip strength, push ups, sit ups, vertical jumps, repetition jumps, 20 m sprint, a tennis specific sprint test, serve velocity, medicine ball throws and a hit and run tennis test. By combining the scores of certain tests it was possible to identify 4 performance factors of strength, speed and jumping, upper body power and endurance. The normalised data for each performance factor was plotted for an individual on a two-dimensional 'spider' diagram with the vertical axis representing power (+) and speed and jumping (–), while the horizontal axis represented strength (+) and endurance (–). Data from subsequent tests can also be plotted enabling a comparison, not only between individuals and a 'norm' but also for individuals as they develop over time. A later study (Ulbricht, Fernandez-Fernandez, Mendez-Villanueva, & Ferrauti, 2016) used these data to investigate the impact of fitness characteristics on tennis performance in adolescent players. Results showed that serve velocity and upper body power were the variables most correlated with tennis performance (i.e. national youth ranking) in both female and male tennis players. Moreover, national selected players showed better performance levels than their regional counterparts in serve velocity, medicine ball throws and specific endurance. The findings underlined the importance of certain physical attributes and suggested the need to include these parameters in training.

The IGFs of racket sports have, over recent years, engaged with sports science, not only to support and promote their own game, but to foster a culture where the value of scientific endeavour is appreciated and respected by all. Acceptance and adoption of racket sport science into the consumer led field of the IGFs is surely a sign that racket sport science has come of age.

Concluding remarks

This paper has reflected on a journey, a personal journey, but also a journey for racket sport science. The beginnings of racket sport science, over 50 years ago, can be traced to the early pioneer researchers who, through their love of the game, gambled their future by edging away from their parent academic discipline towards a virgin field of discovery. They were able to make the transition and lay the foundations for others to follow. And follow they did. Growing opportunities for scientific research emerged during the expansion of educational opportunities in western society during the end of the 20th century, combined with the advancement of technology and the availability of computers, hundreds of individuals now had the possibility to develop their scientific skills, as the pioneers had done, through the love of their sport. The need to communicate their findings to the wider world was met by the scientific conference which, from humble beginnings developed into an opportunity for regular international meetings. The legacy of the meetings, the published proceedings, provides an historical record of this. Bridging the gap between scientist and practitioner has always been an ambition of sports scientists and is realised through working closely with the IGFs of racket sports. The IGFs have engaged with racket sport scientists forming a symbiotic relationship which has served to enrich the field.

The examples used to illustrate this journey reflect a personal choice. Space, as always, dictates a limit but it would have been possible to have reported on other areas which have made a significant contribution to racket sport science. In particular, I mention the areas of behavioural psychology, motor skills, sports medicine and nutrition. All of these areas have the history and depth of application to warrant consideration. It is also necessary to mention areas that are not included which do not seem to have, or have in ways that have not impacted on me, the same influence on racket sport science as those topics referred to above. I mention the fields of sociology and coaching science. The reasons for this are not clear to me but may reflect, in the former case, the paradigm differences between the 'quantitative' and the 'qualitative' sciences. In the latter case it may be that those researching into aspects of the coaching process (**Table 2** contains a range of coaching-related topics) feel more at home in a setting other than the rigorous setting of the traditional scientific conference. One hopes that there may be a fourth phase in which these areas become as influential to racket sport science as the other areas detailed here. The journey is far from over, but the path ahead is smoother than the path behind.

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